Prepared in cooperation with
Washington State Department of Ecology

Southwest Washington Coastal Erosion
Workshop Report

by

Guy Gelfenbaum
George M. Kaminsky
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Guy Gelfenbaum[1], George Kaminsky[2], Christopher R. Sherwood[3], and Curt Peterson[4]

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Contents

1. Introduction

The problem of coastal erosion along the southwest coast of Washington State has intensified. There is much speculation about its causes, but virtually no scientific or technical data have been collected. Millions of Federal and State dollars are scheduled to be spent for protection from continuing erosion. Reliable technical data and analysis of the littoral system are critical components to developing cost-effective solutions, managing resources, protecting life and property, and preventing costly damage. Without sound scientific information, communities and agencies cannot engage in meaningful land-use planning and decision-making, and instead are responding on a crisis-by-crisis basis to each erosion event.

Critical erosion problems along the southwest Washington coast are numerous. Some sites have experienced long-term erosion and are now so critical that costly remediation is being considered. For example, erosion rates at Cape Shoalwater have been over 45 m/yr for the last 75 years. Erosion here has been responsible for the deterioration of navigation facilities at the Port of Willapa Harbor, threats to the $10 million (annual crop) cranberry industry, undercutting of a public highway, and the loss or relocation of numerous homes. Other sites along the coast have only recently experienced high rates of erosion. For example, the recent breach of the South Jetty at the entrance to Grays Harbor was a threat to navigation, with potential losses to the City of Westport facilities, and State Park land and facilities. Erosion in the Westport area alone has required $8 million in repairs to date. Another erosion hot spot is at Ocean Shores, just north of the north jetty at the entrance to Grays Harbor. This coastline had been accreting since the jetty was constructed in the early 1900's, but recently has begun to erode, threatening the nearby development.

Emergency actions can result in sudden and disruptive engineering remedies that are relatively short-term solutions, and neglect regional processes and long-term impacts. In addition, both coastal erosion and remediation measures can have an impact on public health and safety, and affect biological resources (e.g., shellfish habitat) that sustain the regional economy. To obtain a broader understanding of the coastal-erosion problem and enable federal, state, and local agencies to predict and avoid emergencies, Congress approved the initiation of a Washington coastal erosion study by the U. S. Geological Survey's (USGS) Coastal and Marine Geology Program with participation by state and local governments.

The USGS and Washington Department of Ecology co-sponsored the Southwest Washington Erosion Workshop to begin the study. The objective of the workshop was to convene a group of regional experts to discuss the state of scientific knowledge regarding erosion problems along the southwest coast of Washington. The workshop was held March 19-21, 1996 in Ocean Shores, WA and included 40 participants, predominantly scientists and engineers, with a few local managers and planners. The topics covered during the workshop included: Present-day erosion on the Washington coast; Historical erosion and accretion along the coast; Holocene coastal development; Sediment sources and sinks and; Processes controlling sediment erosion and accretion. The workshop included one and a half days of short technical talks, two field trips, and a half day of break-out group discussions. This report is a compilation of extended abstracts from the workshop, a summary from the break-out groups, and an initial discussion of a sediment budget for the Columbia River littoral cell.

Acknowledgments:

I would like to thank Fred Budweg and Steve Tew for their assistance during the workshop and field trip. The staff of the Shilo Inn, Ocean Shores, Washington for providing excellent facilities and the city of Westport for providing the bus transportation for the field trip. Thanks also to Cindee Politano for preparing the workshop report.

2. Southwest Washington Coastal Erosion Study Workshop

SOUTHWEST WASHINGTON EROSION WORKSHOP

WASHINGTON STATE DEPARTMENT OF ECOLOGY

A Technical Meeting for Scientists and Engineers

MARCH 19-21, 1996

WORKSHOP AGENDA

Tuesday, March 19 ***(Whale Room)***

0830	USGS Coastal Erosion Studies	G. Gelfenbaum, USGS
0845	A State perspective on coastal erosion	G. Kaminsky, WA Dept of Ecology
0930	Geomorphology and net shore-drift of the Pacific Coast of Washington State	M. Schwartz, W Washington Univ
1000	Coastal accretion and erosion in southwest Washington, an historical perspective	J. Phipps, Grays Harbor College
1030	BREAK	
1100	Communities and coastal erosion	C. Gale, WA Dept. of Ecology
1200	LUNCH *(Whale Room)*	
1300	The erosion history of Cape Shoalwater, WA	T. Terich, W Washington Univ
1330	Grays Harbor and Willapa Bay shoreline erosion study	V. Shepsis, Hartman & Assoc.
1400	Transport and accumulation of river-derived sediment on the Washington continental shelf	R. Sternberg, Univ of Washington
1430	Current systems, substrate controls, and channel migration in Willapa Bay, Washington	L. Phillips, USGS
1500	BREAK	
1530	Framework of Holocene sedimentation in the Columbia littoral cell	C. Peterson, Portland State
1600	Proposed analysis of Columbia River sediment budget	H. Nelson, USGS

1630	Group Discussion - Sediment Budgets	
1745	CASH BAR AND HORS D'OEUVRES (*Whale Room)*	
1830	DINNER (*Whale Room)*	

Wednesday, March 20 (*Whale Room)*

0800	Short Field Trip to Beach Outcrop (wear boots) Meet in Parking Lot	B. Atwater, USGS (Leader)
1000	Neotectonic influences on sediment transport along the southwest Washington coast	S. Palmer, WA DNR
1030	BREAK	
1100	Review of changes of sediment transport regime in the Lower Columbia River	D. Simpson, Petrovich-Nottingham and Drage, Inc.
1200	LUNCH *(Whale Room)*	
1300	Ocean disposal of dredged material at the mouth of the Columbia River	H. Moritz, Corps of Engineers
1330	Erosion of ebb-tidal deltas on the Washington coast-a long term trend	C. Sherwood, Battelle Marine Sciences Lab
1500	BREAK	
1530	Group Discussion - Framework, Processes, Budgets	
1830	DINNER *(Whale Room)*	

Thursday, March 21

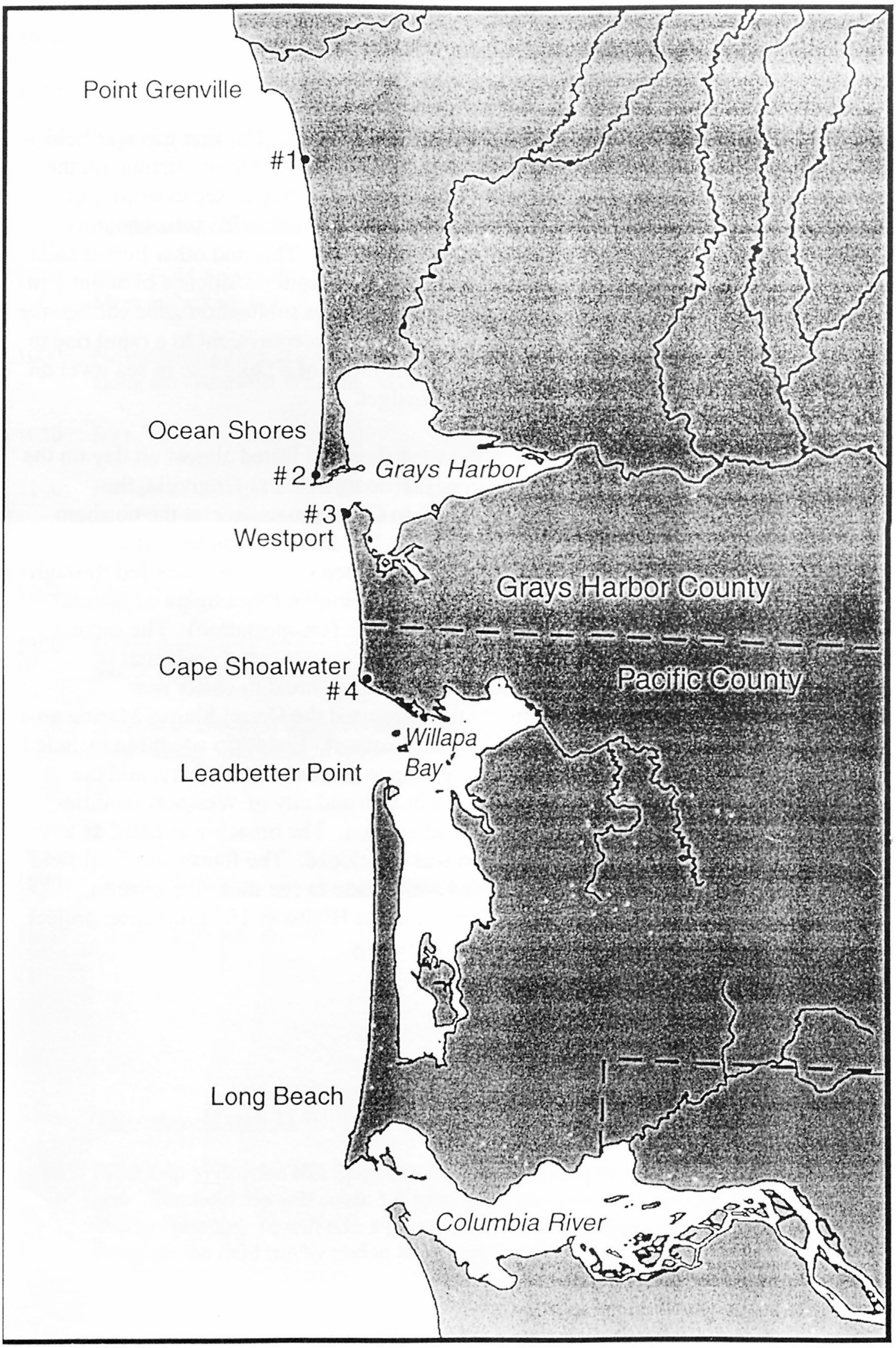
0800 Field Trip to Erosion Hot Spots (*Meet in Parking Lot*) Bring cameras and foul-weather gear. The field trip will cover 3-4 spots from Moclips south to Cape Shoalwater. If weather permits, we will take a passenger ferry across Grays Harbor. We intend to complete the field trip by mid to late afternoon.

Field Trips

Two field trips were included as part of the technical workshop. The first trip was held on the morning of March 20th at a site 1/4 mile east of the Ocean Shores airfield on the west shore of Grays Harbor. Brian Atwater (USGS) led the group to see examples of wave-washed buried soils exposed at low tide. The exposure of buried soils contains huge spruce stumps and runs almost continuously for 600 m. This and other buried soils along the coast were produced when the coast experienced rapid subsidence of about 1 m. The rapid subsidence is believed to be associated with a large subduction zone earthquake that occurred around 300 years ago. This rapid subsidence is equivalent to a rapid rise in sea level and the group discussed the possible ramifications of a rapid rise in sea level on the position of the shoreline and on the sediment budget.

The second field trip was held at the end of the workshop and lasted almost all day on the 21st of March. This trip covered four sites from just south of Point Grenville, the northern extent of the Columbia River littoral cell, to Cape Shoalwater, at the northern entrance to Willapa Bay (see map of field trip sites). The first site was near Moclips, where participants observed broad, sandy beaches and steep bluffs, and were led through a discussion of the local geology by Steve Palmer (Washington Department of Natural Resources) and Lynn Moses (Washington Department of Transportation). The second site was to the Ocean Shores north jetty, to see the long-time accreted coast that is presently suffering erosion. The recent erosion is a serious threat to costly new development near the shoreline. Participants then departed the Ocean Shores Marina on a passenger ferry across Grays Harbor to the city of Westport. Field trip site three included stops to see the erosion at Half Moon Bay, the entrance channel, South Jetty, and the beach fill project. The South Jetty experienced a breach and city of Westport facilities and Westhaven State Park were at risk from rapid erosion. The breach was filled as a temporary measure while a long-term solution was developed. The fourth and final field trip site was at Cape Shoalwater. Several stops were made to see shoreline erosion, channel migration, loss of homes in North Cove, and the Highway 105 protection project. This site concluded the field-trip portion of the workshop.

Southwest Washington Erosion Study



Southwest Washington Erosion Workshop Field Trip Sites

Workshop Abstracts

A state perspective on coastal erosion

George M. Kaminsky, Washington Department of Ecology, Olympia, WA

Coastal evolution, shoreline change, and sediment resource reduction along the southwest Washington coast greatly concern citizens and governmental agencies. Historical accretion rates in the region have slowed significantly while certain shoreline reaches of the region have experienced severe historical and recent erosion. A recent breach at the Grays Harbor south jetty has underscored the vulnerability of navigation facilities and potential impacts to the regional economy already distressed by declining timber and fisheries resources. Coastal communities have been alarmed by a substantial reduction of sediment supply from the Columbia River combined with the disposal of enormous quantities of clean dredged material in deep water. Recent evidence of the prehistoric Cascadia subduction zone and the significant threat of near source tsunamis has emphasized the need for improved management strategies that protect life and property and sustain the economic and ecological health of the southwest Washington coast.

Coastal changes are complex and difficult to quantify or to discern the magnitude of physical processes responsible without an improved understanding of the regional littoral system. Many site-specific studies have shown qualitative evidence of the effect from regional processes, but no studies have specifically investigated the relative contribution of natural and anthropogenic influences on regional and site specific areas. Understanding these processes and influences is essential for coastal and estuary entrance management, risk reduction, and preservation of beaches, dunes, and associated wetlands.

State and local agencies are in great need of reliable measurements, quantitative information, and predictions of erosion trends and beach stability. There are few consistent historical records of local shoreline conditions and a void of basic monitoring data. In general the southwest coast has not been studied in depth, and most of our understanding about its development and processes is qualitative and speculative. The ability to anticipate forthcoming erosion conditions would facilitate long-term planning and help to make sound management and regulatory decisions. Without improved scientific knowledge of the regional coastal dynamics, it will be increasingly difficult to prevent costly damages, mitigate hazards, reduce vulnerabilities, and protect coastal resources.

Over the past few years, the State has funded coastal erosion studies for projects at Grays Harbor and Willapa Bay. This year, the Washington State Legislature has recognized the need for the study and abatement of coastal erosion in the region of Willapa Bay, Grays Harbor, and the lower Columbia River. This new mandate is directed toward investigating regional erosion processes in the littoral cell from the Columbia River to Point Grenville. This section of the outer Washington coast has the most development pressure and the most uncertainty of its long-term stability. The State has also requested the assistance of the US Geological Survey in studying the coastal region. These recent studies present the opportunity to gain a fundamental understanding and develop solution alternatives within the context of the regional system.

Coastal erosion over the past century has been generally confined to a few specific sites, most notably at Cape Shoalwater at the north entrance to Willapa Bay, and at Westport at the Grays Harbor south jetty and adjacent Point Chehalis, Half Moon Bay, and South Beach. Most of the beaches have been accretional. However, within the last decade, chronic erosion has occurred at nearly all the headland points, Fort Canby (Benson Beach) at the Columbia River north jetty, Leadbetter Point at the north end of Long Beach Peninsula, and Ocean Shores at the Grays Harbor north jetty.

While we do not have a complete understanding of the causes and time scales of all local erosion events, preliminary synthesis of information suggest the erosion may be indicators of a much larger regional problem and certainly demonstrate that the beaches are not stable as commonly believed. This presentation is intended to develop some of the most pressing questions and issues and stimulate discussion on coastal erosion in southwest Washington. In consideration of these questions, one should also ask, what is their relative importance and can they be confidently or quantitatively answered? In addition, what would be a practical approach to answering questions that require more data and research?

QUESTIONS AND ISSUES

Longshore Drift

Qualitative studies have shown a net northerly transport of sand from the Columbia River. However, the rapid and significant accretion of sand at the Grays Harbor north jetty indicate a significant southerly component. Are there local nodal points in sediment transport direction, and if so, why? Can incident wave directions account for apparent reversals to the dominant regional trend? Has the longshore drift been influenced by the jetties and estuary entrance deepening?

Since construction of the Grays Harbor north jetty in 1917, the shoreline at Point Brown has prograded seaward several thousand feet. Is future beach stability dependent on the condition of the Grays Harbor north jetty? If so, will the north jetty be maintained? How far north does the jetty contribute to coastal accretion?

Bathymetric Changes

Large volumetric sand deposits have been lost from the entrances to the Columbia River and the Grays Harbor. The loss of extensive offshore bars and shoals results in increased energy delivered to the shoreline. To what extent does slope steeping and bottom deepening exist along the stable reaches of the shoreline? How far up and down coast from the shoreline adjacent to the estuary entrance does increased energy levels have a significant impact?

Columbia River Changes

The Columbia River is the source of modern sediment for the beaches of southwest Washington. Can sediment discharge rates and a sediment budget be accurately estimated? Can the long-term reduction of sediment supply from dredging operations and dam construction be quantified? What is the effect of a reduced sediment supply on the stability of the beaches in southwest Washington? What is the lag time for a reduction to result in coastal erosion?

Dredging Activities

The management of dredging activities and dredged material disposal has been debated among local, state and federal agencies for many years. As a preliminary estimate, over 150 million cubic yards of material has been dredged from the three major estuary entrances. Most of this material has been taken out of the littoral system by disposal in deep water or in upland areas. How significant is the dredged material and are there more appropriate uses?

Climate Change:

What are the effects of sea-level changes associated with El Nino that occurs every 4 to 10 years? How do El Nino s affect the wind patterns, which may shift dominant wave and current directions. These changes as well as other interannual and longer term variations of climate may contribute to coastal erosion, flooding and shoreline orientation.

Seismic Activity

Earthquakes have caused rapid subsidence along the southwest Washington coast. How has subsidence affected the shoreline position and sediment budget? Have subsidence events been compensated by coastal uplift? Have tsunamis and other episodic events contributed to shoreline and landform changes?

Dune Processes

Extensive dune complexes exist in southwest Washington although little is known about their development and accretion rates. Pronounced primary, secondary, and tertiary dune fields as well as broad relatively level sand fields persist south of the Copalis river entrance. What is the effect of European beach grass planted to stabilize the dunal areas?

Willapa Bay

Why did the north entrance of the bay suddenly become erosional in the late 1800's to early 1900 's? Is there a correlation of erosion with the construction of the Grays Harbor south jetty? Are the coastal changes related to large scale geologic processes or tectonic forces? Will the existing severe erosion trend slow down, stop, or reverse? Will a new southerly channel form naturally?

SUMMARY

A thorough scientific discussion is needed to begin addressing these and other questions of vital importance to the state and local communities. An assessment of the state of the knowledge of coastal erosion processes in southwest Washington will be helpful in evaluating existing problems and for developing a clear set of objectives for future study efforts. Statements from the scientific community will aid in public education and in identifying research needs to better understand coastal changes and hazards affecting the state and local communities in southwest Washington.

Geomorphology and net shore-drift of the Pacific Coast of Washington State

Maurice L. Schwartz, Western Washington University, Bellingham, WA
Thomas A. Terich, Western Washington University, Bellingham, WA
James Mahala, Western Washington University, Bellingham, WA
Hiram S. Bronson III, Western Washington University, Bellingham, WA

During the 1980s we carried out geomorphologic and net shore-drift studies along the outer coast of the state of Washington. This report is an abridged version of two previous publications on our findings. For such purposes, the Pacific Coast of the State of Washington (Fig.1) can be conveniently divided into three sectors: Southern (I), Central (II), and Northern (III).

Geomorphology

The southern and northern regions are clearly different from one another, while the central region has some of the characteristics of both (Terich and Schwartz, 1981).

Southern region (I). The southern region of Washington's Pacific Coast extends from the mouth of the Columbia River, dividing the states of Washington and Oregon, north to the Copalis River (Fig. 2). The beaches of this region are strikingly uniform. They are composed of wide, fine-sand intertidal zones, backed by low-lying parallel dune ridges and troughs with dune vegetation. Two very large estuaries, Willapa Bay and Grays Harbor, interrupt the linearity of this part of the coast. Both are protected from large ocean waves by sandspits. Long Beach Peninsula, the longest spit, extends 30 km north from Cape Disappointment near the Columbia River. It has grown from large volumes of sediment delivered to the coast by the Columbia River. The beaches of this entire southern region owe their existence to sediment delivered from the Columbia River and transported with a northerly drift. The volume of sand movement to the north diminishes by entrapment in the two large estuaries, accretion on the beaches, and loss down submarine canyons that intersect the continental shelf. The beaches of this region are generally accretional with a steady supply of sediment from the Columbia River. Adjustments, both natural and man-made, are occurring to the shoreline of this region.

Central region (II). North of the Copalis River the physical form of the coast changes significantly (Fig.3). The central coastal region presents a blend of linear beaches and steep cliffs. The contribution of Columbia River sediment to the beaches of this region is little, but a plentiful supply is available from five rivers that empty to this coast and active sea-cliff erosion characteristic of this central region. The physical character of the beaches change from wide, fine to medium sand between the Copalis and Moclips rivers to steep, narrow, variable fine to coarse-grain beaches along the remainder of the region. The variability of beach sediment is attributed to the geological differences in the sea-cliffs which supply much of the eroded sediment. The unstable geology of the central coastal region leads to active landslides, and slump blocks are most commonly found in the Quinalt Formation, a relatively young formation composed of moderately dipping sandstones and siltstones. The landslides result from structural weakness of siltstone and continual erosion of these relatively soft rocks.

Northern region (III). This region stretches north from the Hoh River approximately 80 km to Cape Flattery (Fig. 4). It is noted for its scenic beauty, consisting of high rugged sea-cliffs nesting small isolated pocket beaches and broad hard rock wave-cut platforms with numerous offshore sea-stacks. The sea cliffs are a complex geology of interfingered sandstones and conglomerates of continental and marine origin. Tertiary volcanics penetrate the sandstones and conglomerates forming high resistant promontories. A blanket of Quaternary glacial sands and gravel overlies many of the lower harder rock assemblages, providing evidence of the former glaciation of the Olympic Peninsula. The highest cliffs along the entire Washington coast are found at Cape Flattery, the northernmost promontory along the coast. The entire Cape is surrounded by wave-cut platforms that attest to increasing wave attack. Cape Flattery marks the end of Washington State's open exposure to the Pacific Ocean. Beyond the Cape, the coastline turns toward the southeast into the relatively quieter waters of the Strait of Juan de Fuca.

Net shore-drift

Net shore-drift indicators used were some combination of: sediment accumulation and erosion at groins and other obstacles, spit development, headland-bay or log-spiral beaches, direction of stream diversion, beach width and height, sediment-size gradation, changing bluff or cliff morphology along the coast, uniquely identifiable sediment, and nearshore bar development and orientation (Schwartz, Mahala, and Bronson, 1985). Predominant waves in this region are from the southwest, forcing most net shore-drift to the north; but local reversals occur: a) in the wave shadow of headlands, b) where there are changes in coastal orientation, c) over shoaling at ebb-tidal deltas, and d) where waves are refracted around islands or sea-stacks.

Southern region (I). Net shore-drift in the most southerly drift cell of the study area is to the south, towards the North Jetty of the Columbia River (Fig. 5). This is a rather short distance; and there is an equally short sector of sediment transport to the north towards Cape Disappointment. From Cape Disappointment net shore-drift continues to the north, uninterrupted, for approximately 40 km along Long Beach Peninsula, to the end of the recurved spit at Ledbetter Point on the south side of the Willapa Bay inlet. Along the inner north side of the Willapa Bay inlet, net shore-drift is to the southeast into the bay. On the outer coast, there is a drift cell which begins at Cape Shoalwater and ends at the South Jetty at Point Chehalis on the south side of the inlet to Grays Harbor, with drift to the north. On the north side of the inlet to Grays Harbor, there is net shore-drift to the south, ending at the North Jetty at Point Brown. Where net shore-drift begins again to the north, there is the start of a long drift cell (approximately 57 km); extending into the Central region (II) past the mouths of the Copalis and Moclips rivers to terminate at Point Grenville.

Central region (II). As noted, Point Grenville is the end of a long drift cell that began in the Southern region (I) farther to the south (Fig. 6). The next sector of net shore-drift is to the north, from Point Grenville to the mouth of the Quinalt River at Cape Elizabeth. From Cape Elizabeth net shore-drift is to the north, terminating at Pratt Cliff; then again to the north, past the mouth of the Queets River, to the Hoh River mouth.

Northern region (III). There is a short sector of net shore-drift, to the north, from the mouth of the Hoh River towards Hoh Head; then, in succession. four more short sectors, in the same direction, to Taylor Point (Fig.7). North of Taylor Point, along a stretch known locally as Third Beach, net shore-drift seems to be to the south. Approaching La Push net shore-drift on Second, then First Beach, is to the north. Another southerly reversal to the overall trend has formed a spit developed to the south across the mouth of the Quileute River. North of this spit, there are five short, discrete sectors of northerly net shore-drift; the northernmost-four being bracketed by headlands. The next drift cell, upcoast, consists of a short reversal to the south. Along the coast west of Ozette Lake there are four more sectors of northerly net shore-drift, the last terminating at Sands Point. North of Sands Point, there is a short southerly net shore-drift cell, but between that drift cell and the Tskawahyah Island tombolo there are two separate northerly sectors of drift. In the lee of the tombolo, net shore-drift is the south. From here, a short and then somewhat longer drift cell, both with drift to the north, extend up the coast to Point of the Arches. On the north side of Point of the Arches, there is located the last sector of southerly net shore-drift. At the north end of this pocket beach, and in an adjacent one to the north, there are two more drift cells with net shore-drift, in both, directed toward the north. There is no net shore-drift along the outer coast of Cape Flattery due to the almost pervasive presence of plunging sea-cliffs or bare, rocky wave-cut platforms.

References

Schwartz, M.L., Mahala, J., and Bronson III, H.S., 1985, Net shore-drift along the Pacific Coast of Washington State; Shore and Beach, v. 53, no. 3, 21-25.

Terich, T.A., and Schwartz, M.L., 1981, A geomorphic classification of Washington State's Pacific Coast: Shore and Beach, v. 49, no. 3, 21-27.

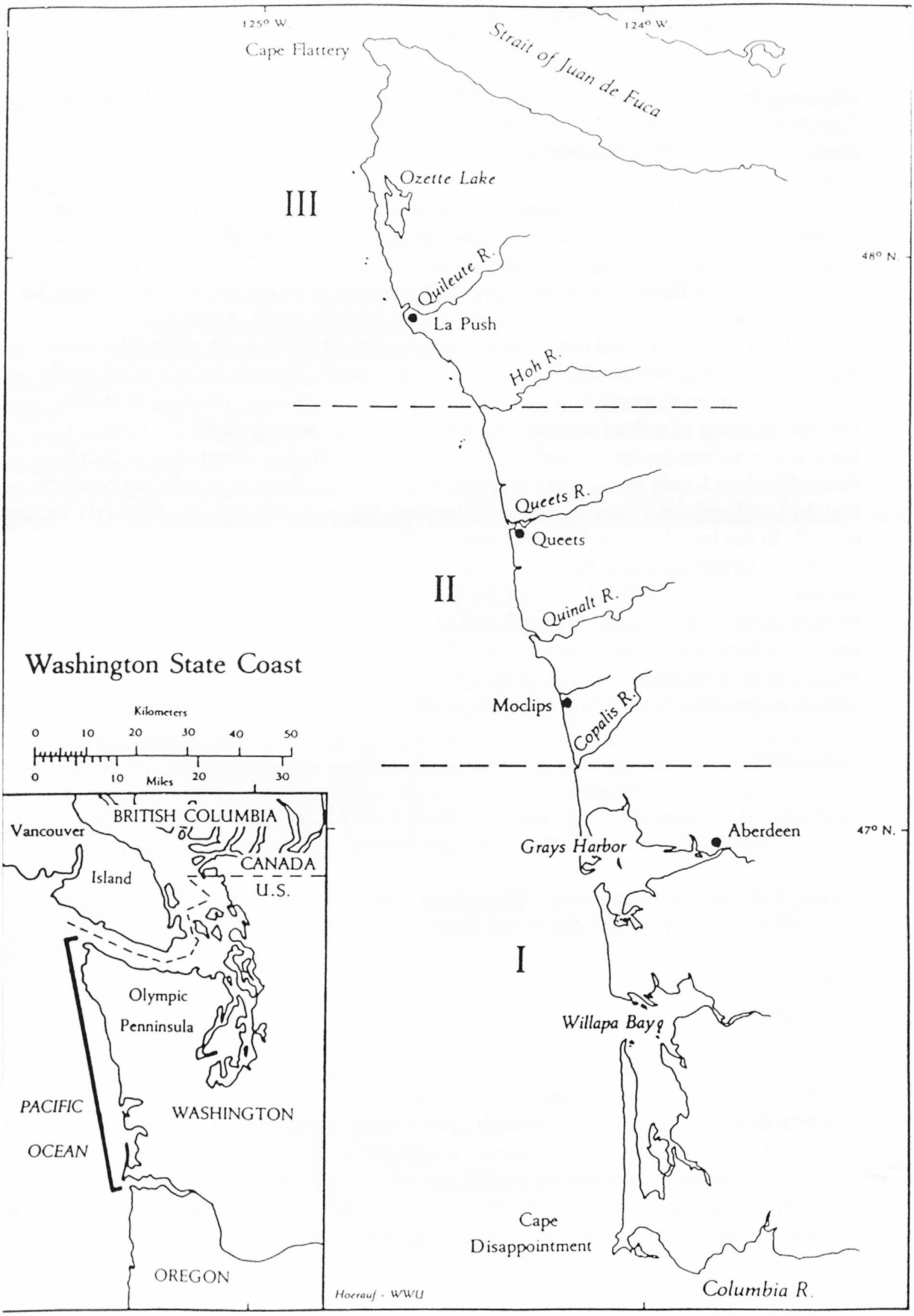


Fig. 1. Washington State coast.

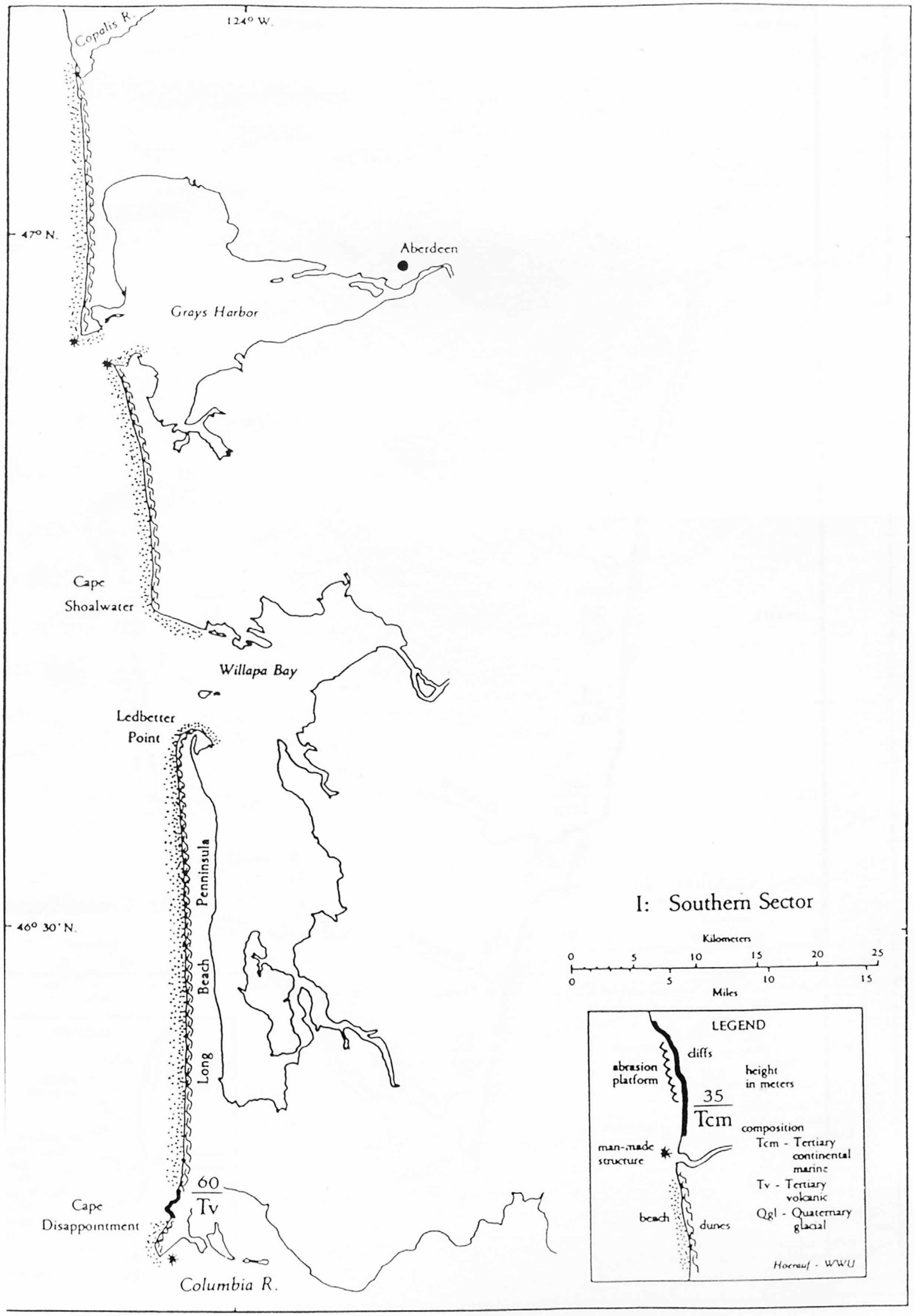


Figure 2: Southern Sector (I)

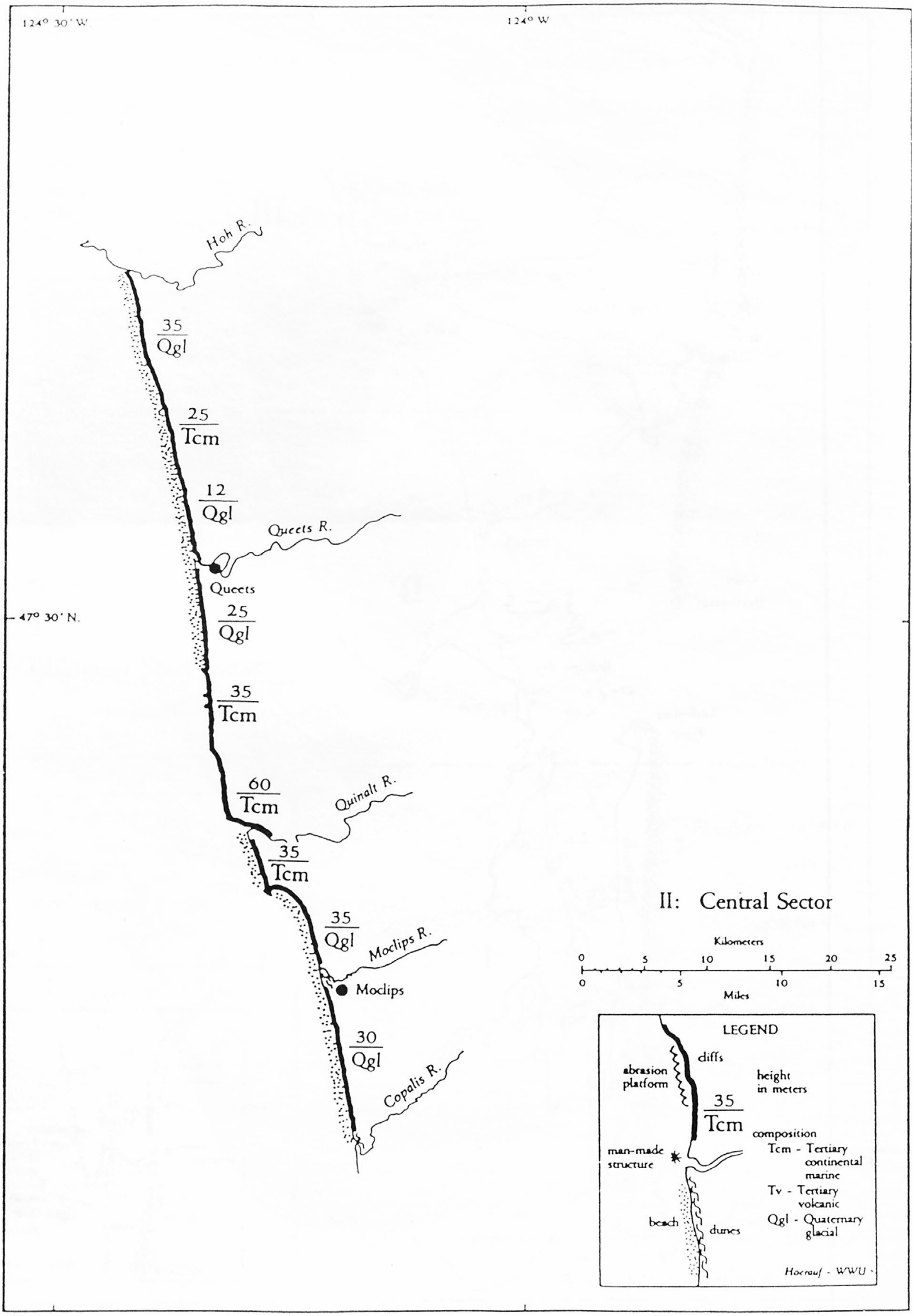


Figure 3: Central Sector (II)

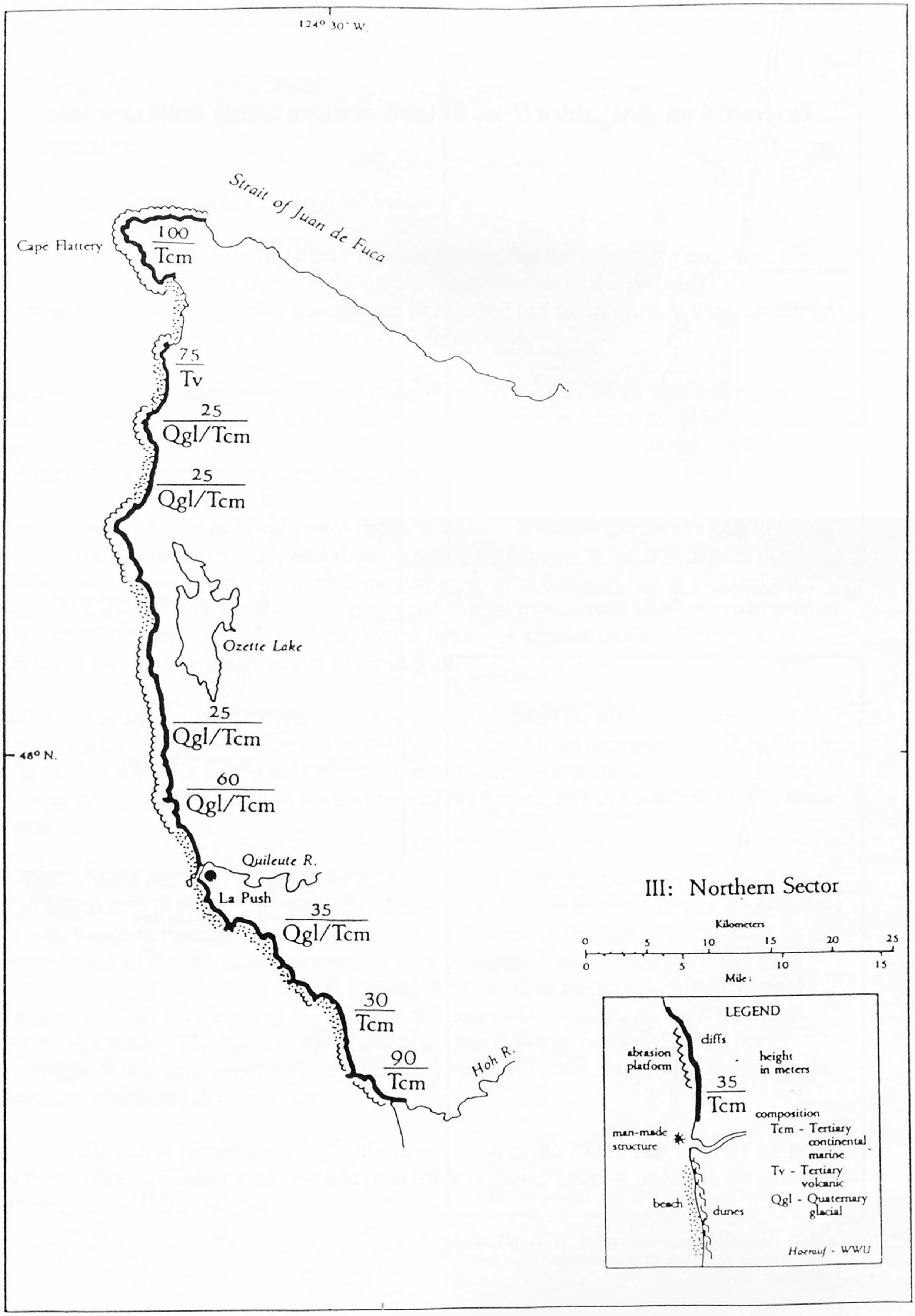


Figure 4: Northern Sector (III)

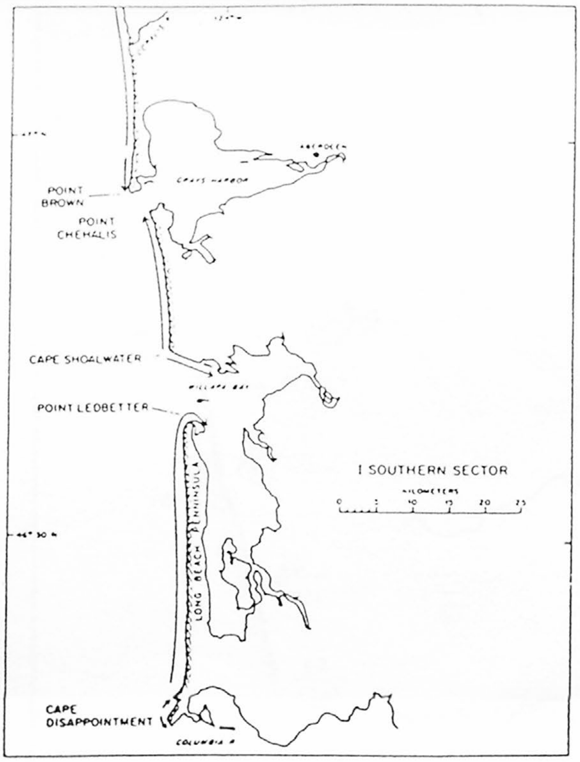


Fig. 5. Net shore-drift along the southern sector (I) of the Pacific coast of Washington State.

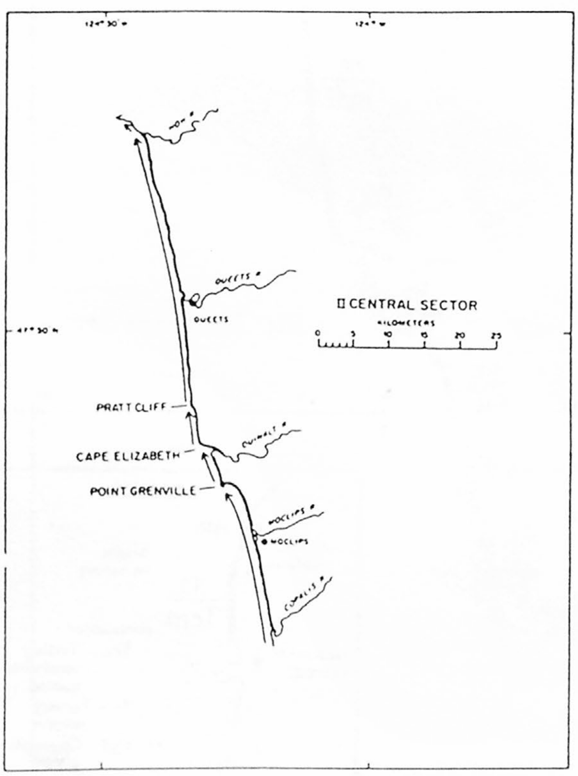


Fig. 6. Net shore-drift along the central sector (II) of the Pacific coast of the pacific coast of Washington State.

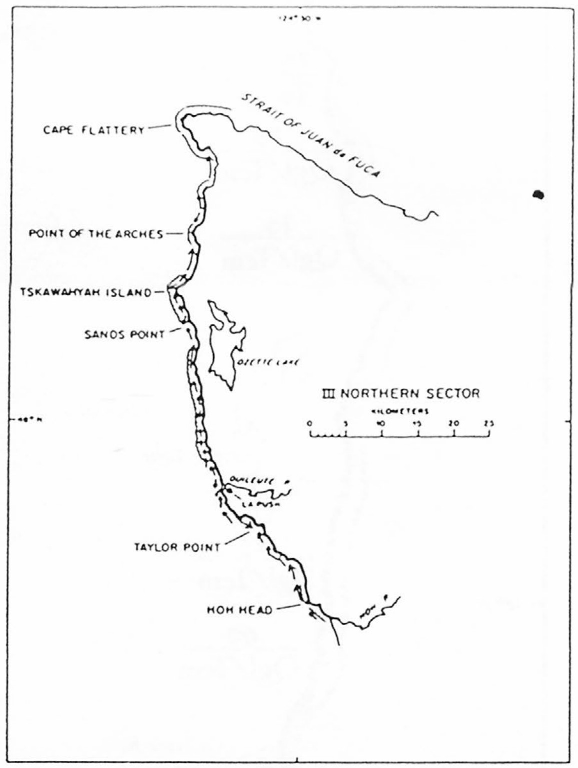


Fig. 7. Net shore-drift along the northern sector (III) of the Pacific coast of Washington State.

Coastal accretion and erosion in Southwest Washington, an historical perspective

Jim Phipps, Grays Harbor College, Aberdeen WA

It has been well established by heavy mineral studies that the source of beach sands in southwest Washington is from the Columbia River. Studies of the mid-shelf silts, contaminated with radioactive tracers born in Hanford and transported to the system via the Columbia also show a net northerly drift component.

As this river of sand moves northward along the coast it experiences withdrawals to deeper water via the submarine canyons. Sand is also removed from the system by the estuaries (Grays and Willapa Harbors) and by beach accretion. Once past Copalis rocks the accretional beach becomes erosional and sea cliffs replace dunes.

The interaction of the northward moving sand and the estuarine entrances tends to force these entrances to move northward. Such is presently the case at the mouth of Willapa Harbor, where "wash-a-way" beach is moving at an annual rate of 150 to 250 feet per year. The mouth of Grays Harbor experienced similar movement (150 feet per year from 1862 to 1891) before it was stabilized by the jetties. A smaller model of this process occurs at the mouth of the Copalis River as well.

But much of the Columbia River sediment supply has been cut off by the building of dams. Starting with Bonneville in the 1940's, dams have been constructed over the entire U.S. part of the river so that only a few miles of running water remain. Approximately 90% of the quarter of a million square miles of the watershed has been "cut-off" by these dams.

However there has been a significant lag between the dam completion and the sediment starvation of coastal Washington. Part of the reason for this is the huge submarine supply of sand know as Peacock Spit. Peacock Spit was formed at the turn of the century by the construction of the jetties at the mouth of the Columbia. These structures jetted out a huge quantity of sand which formed Peacock Spit north of the mouth of the Columbia. Peacock spit has been eroding to replenish the nearshore sediment supply. But it is essentially gone. The result is a plethora of erosional events occurring along the shoreline. While each event may be influenced by local factors, the sizable change in the sediment supply is the pacemaker.

This conclusion is corroborated by studies completed in the 1990s that indicate for most of the southwest Washington beach system the accretional phase is over and the system is starting to become erosional.

Communities and coastal erosion

Chuck Gale, Washington Department of Ecology, Olympia, WA

It doesn't take a rocket scientist to see that there are problems out there, but to the scientists in the room these are interesting problems. In fact how many of you have actually been down and walked around right here in Ocean Shores, just down the street at the north jetty where several condominium buildings are too close to the edge of a rapidly eroding dune? Quite a number of you have. What are we going to do about that? What's Ocean Shores going to do about that? That's a real problem. It's not just a problem for the local community. It's all of us - we, the greater community. "Our" community has to help figure out what to do. Put yourselves in the shoes of the owner, the city, a regulatory agency. What can you do? What is responsible action?

The City of Ocean Shores and the Department of Ecology, is soon going to be faced with permit applications from people who want to "DO" something there, people who need to "DO" something there. This erosion problem at Ocean Shores, like the problems in any number of other locations along the southwest Washington coast have appeared as crises in the lives of communities. And sure, there have always been voices out there who have said "That that land out there, that's all accreted, quite recently in fact - geologically, quite recently - it could erode again." But that's not enough, it's not enough of a discussion to help solve these problems, and we all know that. The purpose today is not to tell you what is happening or where the erosion problems are that communities face. You've seen that evidence. You've seen the pictures right here this morning. In fact, the charge for our coastal erosion initiative, and for all of you here, is to figure out just what is happening beyond the symptoms that everyone sees - then try to understand why.

Some history of the area; along this sandy beach area of coastal Washington, which, as we've all heard, as we all know, is a dynamic area. The Columbia River has been moving sand into the sea for centuries - along this strip, most land use decisions are made at the local level. There are several cities, a couple of counties, two tribes and even a couple of states.

Recently, the Department of Ecology received money through a supplemental budget process. A single line item in a budget bill dozens of pages long was to support efforts to help understand these coastal erosion issues. That money supports our share of our work here together, some portion of that appropriation is dedicated to being passed through to local communities to facilitate their direct support of our efforts together, and therein lies the tale - the "OUR" here keeps getting broader and bigger. The primary reason that funding made it into a state budget, apart from the coincidence that the area is largely in the home district of the current state Senate Majority Leader - is that local governments supported it. They asked for it. The real call for support came from local governments who have problems. If Ecology alone were to have asked for that money, no one would likely have heard.

The very language of the budget is instructive. The item in the official budget request through the Governor's Office to the Legislature was entitled "Coastal Communities Stabilization." When the request made it all the way through the legislative process into a supplemental budget bill and wound up on the Governor's desk for signature, it was reduced to the phrase a budget provides "for the study and abatement of coastal erosion in the region of Willapa Bay, Grays Harbor, and the lower Columbia River".

In general, it seems to be particularly difficult, as scientists, to communicate the risks associated with any natural hazard - both personal and environmental. And by natural hazards, meaning the basic "earth, air, fire and water" type hazards. Those that result from coastal processes we're looking at here are in that category.

As scientists, your social purpose is to rationally examine and understand - in short, to gain predictability. And by doing that, the social "hope" is to allow sound decisions to be made. This all sounds very rational and very logical, but here are a few facts to give you a better feeling for what's at risk with an example of the livelihoods at risk. The cranberry crop - from the area just north of Cape Shoalwater - has an annual value of about $9 million. If the state highway goes out, if it falls into the sea, - a road which acts like a dike for the bogs - the salt water backwater has put that industry substantially at risk, not to mention that relocating the road is tens of millions of dollars. Weyerhaeuser recently spent $9 or $10 million in modernization of barge facilities in Raymond, but can't reliably get in and out of the harbor; and by the way, that mill is, at least currently, the largest employer in north Pacific County.

Also, there are the risks to homes and public facilities and navigation and whole towns and livelihoods around Westport. The list goes on and on. How can these communities cope? Especially since, in Washington State, the local communities have the largest burden of coping. The power and the authority of land use law rests largely at the local level. Although there are state level laws like the Shoreline Management Act and the Growth Management Act; they are "developed" - or implemented, if you will - through planning processes at the local level. The state primarily has an oversight role - largely the state's responsibility is to assure that local planning efforts comply with provisions of the law.

Even though we as a state agency can - and do - appeal some local land use decisions, our right to do so isn't really much different than any citizen. This is a legacy of Washington's "populist" past. It's a legacy that causes county commissioners to be reluctant to prohibit an activity unless they are convinced of the likelihood of some public harm, more likely of some public financial risk. This isn't cynical. And this is our heritage. But this is where the scientists come in. To help the community you must describe and communicate. You must create the framework for sound, socio-political actions, actions which may even seem to inhibit personal liberty. Thomas Hobbes, the 17th century liberal philosopher, asserted that human liberty can only be guaranteed when individuals come together in commonwealth, raising the human individual by purposeful action, raising the human condition from a "state of nature" of "each against all" (hopefully by well informed, purposeful action). Taken together, the liberty of each individual is advanced. That observation applies to conflicts we obviously still struggle with today.

So how do we, as scientists, how do we, as public servants, help strengthen our community? We use science as the tool to build social decisions. We "inform" action. Some would call it "political ecology".

The definition of "political ecology" is the human organization of interactions of nature - our "negotiations with nature" about how and where we live. There are two aspects at work here, the scientific and the political. The first is the "descriptive"; the what IS - that's the science. The second is the what OUGHT to be - that's the "political".

Practically putting our work on the ground, Ecology's vision has five basic elements:

The first is Local Teamwork, where stakeholders cooperate; it's about leadership and identifying needs, about resolving issues and coordinating activities.

The second is Government Teamwork, where multi-disciplinary teams are drawn from different levels and sectors of governments, based upon the needs of the area and responsible to improve coordination. This can be planned and formal or loosely ad hoc - whatever works.

The third is Focused Assistance, where issues within an area receive focused financial, technical and regulatory assistance needed to help resolve problems.

Fourth, and very important, is Integrated Resource Information, where environmental and resource management agencies cooperate in collecting data and in developing and maintaining integrated resource information, in systems that allow information to be developed and shared on a geographic basis. The more broadly accessible, the better.

The fifth element is Public Education and Involvement - all parties can work together to coordinate public education and empower local citizens and communities to protect and enhance their own natural resources.

These are all simple common sense items. But in the way government agencies work, they are, in fact, fairly new. They are not business as usual. Perhaps the most radical thing is that at their base, environmental issues aren't scientific issues, they are social issues. They're about what kind of world we want to live in. What kind of world we want for our children to live in - and science is the tool. I'm talking about facilitating actions that are politically, economically, and environmentally responsible. In a democracy, those actions cannot be taken in an authoritarian manner by any level of government or any institution or by ignoring any level of government or institution or interested party. We have to work together because we are all here.

As we go about trying to bring some sense of order to our activities, our goal is to have more presence in the area, to be more "OF" the area, and to coordinate our efforts more effectively with local stakeholders, local interests, and local governments. "WE", together in a larger sense, will be facilitating regular public gatherings, perhaps focused on specific issues, but "WE" will try to keep the context straight.

The actions we take together, in order to be of any practical good fundamentally, have to meet the needs of a community; ... they have to address the real issues of all members of the community. We will need to keep reminding people of the broad view of issues. That broad view that is necessary in order to truly deal with the economic and environmental issues in a responsible manner. We will constantly remind people that the community of interests is large and broad and that no one may be left out. We will constantly encourage all of us to consider our actions in the larger context, mindful of the immediate and the cumulative effects of our proposed actions.

There are some guiding principles:

The first is respect for - and understanding of - natural processes. As much as possible we need to work with them and not against them. This is certainly common sense.

Focus on fundamental causes of problems. Some problems, in fact maybe most problems as we first see them, are symptoms of something bigger. While certain fixes of symptoms are prudent and necessary, always look for what caused the problem in the first place. Short-term fixes need to be part of a long-term strategy. Consider what's going on in the "whole", not just a little problem spot - the real problem is probably bigger then you think.

Maintain open participation with the public and the agencies, and - even in times of serious disagreement - it's always a mistake to lose communication. Don't burn any bridges. Examine the issues systematically, your conclusions will mean more. If you have looked at an issue and something new comes up, look at it again. There's as much value in the setting up process which will ALWAYS be available to deal with or avoid new problems as there is for simply solving problems of the past. Stay engaged.

Address other resource protection goals besides your own; all of these issues are irrevocably connected.

Finally, truly seek - and truly examine - innovative ways to deal with your problem.

Now on top of all that, we're also up against the reality - the difficulty - of undertaking environmental management today. Here's an example that's more "traditionally" environmental to make the point. We all know that environmental management historically has been focused on pollution, some intrusion to our environment. We have, over the last 20 or 30 years, cleaned up, we have controlled. The targets by and large were big - big businesses, big municipalities - and yes, it has been "successful". There are real things we can point to as successes.

But a large share of the public is disappointed. They thought dealing with big sources would some how "solve the problem". But still there isn't enough water, land, or - in our case - sand to support the people, the plants, and the animals in a large portion of this state. And dealing with problems as they arise is difficult because increasingly our existing regulatory structures seem like using a chain saw to cut a loaf of bread. In the public's mind, tension between individual rights and environmental protection, or even public safety, is confusing. People are unsure that the tradeoffs are worth it.

As more immediate "context", the population growth of Washington State, is growing at a rate of 100,000 people per year, since 1990. There are currently 5.4 million people living in Washington, the result of twice the national average growth rate. They would all like "waterfront".

As population grows, government is shrinking. Most of us here come from government; you know the antagonism toward government - "It's ineffective and unreasonable," stated more kindly than most of us are used to hearing. So how can we all function? How can we DO anything? Our overall goal has to be to foster stewardship.

Programs must be based on "places" - and on the interconnected, interdependence among "places" - and on knowledge of those "places".

Also, focus on prevention - it's cheaper, it's faster, than fixing after the fact.

We must improve government performance - results, not conflict and process; ... broader access to information, and sharing power through collaboration.

As scientists, you have to come together to understand the foundations of problems that are very important to coastal communities. That's your part of the bargain. You must be pure in your science to gain the knowledge, but you must recognize that communities don't work on some scientific principle - they are about how people want to live their lives. They are full of values and contradictions. Communities rarely get beyond informed "crisis management". But science is the foundation - it's the soundness. Society doesn't depend on a strict authority of science. It uses science to build. It collaborates knowledge and values. It becomes a social process. Science alone is not authoritative. Our science is a public process. It will be publicly accountable.

My time is finished and since most of you are geologists, here is a "geologist" joke:

Q: "How would a geologist describe this piece of paper?" (blank, plain white sheet)
A: "It appears to be planar and rectilinear, and whitish in color - at least from <u>this</u> side."

That is the "IS" part; but with your help, our communities can complete the thought, the "OUGHT to be " part, " ... and we ought to use it like a piece of paper."

The erosion history of Cape Shoalwater, Washington

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One of the most prominent features along the southwest coast of Washington State is the Long Beach Peninsula, a 43 km long (27 mile) spit north of the Columbia River (Figure 1). The spit shelters Willapa Bay from the Pacific Ocean, save a channel opening to the north of the Long Beach Peninsula. Across the channel, a smaller much less prominent spit (Cape Shoalwater) grew to the south into the Willapa channel. Presumably, these two spits have advanced and retreated narrowing and widening the channel entrance. Since the turn of the century however, Cape Shoalwater has shown a steady pronounced erosional retreat (Levenseller & Terich, 1986).

One of the earliest U.S. Coast and Geodetic Survey charts published in 1911, with surveys and triangulations taken in 1871 and 1891 respectively, show the Cape as a pronounced south trending spit projecting southeasterly onto Willapa Channel. The smooth configuration of its shoreline reveals no evidence of erosion. The next chart, published in 1912, with survey data from 1911, clearly shows erosional retreat (Figure 2). Thus the onslaught of the erosion must have begun sometime between 1891 and 1911. Comparative measurements of these two charts reveal a total shoreline retreat of approximately 760 m (2500 ft), an average annual recession rate of about 45 m/yr (150 ft/yr) since the mid 1890's. Four years later, the 1916 chart shows the southern projection of the spit to be completely missing. Subsequent studies during the 1960's conducted by the U.S. Army Corps of Engineers corroborated the ongoing erosional retreat between 42m/yr (140 ft/yr) and 75m/yr (250 ft/yr) (U.S. Army Corps of Engineers, 1967). The Corps estimated the amount of shoreline retreat to 1994 (Figure 3).

During the seventy-five year period of erosion (1890-1965), Cape Shoalwater has retreated a total of 3750m (12,500 ft). There is no other place along the Pacific Coast of the United States that has experienced such a rapid and sustained erosional history. The erosion lead to the loss of several private properties, the Willapa Lighthouse, a Coast Guard station, the severing of State Highway 105 and replacement of a local pioneer cemetery.

The causes of the erosion remain a perplexing problem. The long-term sustained retreat of the Cape suggests regional sediment starvation. The recent breaching of the beach just south of Gray's Harbor jetty sustains this argument. However, beyond these two episodes of erosion, there is little recent information pointing to long term regional sediment losses in the region. In fact, up to the mid 1970's, the Long Beach Peninsula was experiencing a net shoreline accretion along its southerly reaches (Phipps & Smith, 1978).

More likely, the erosion of Cape Shoalwater and recent breaching just south of the Gray's Harbor jetty are due to local and regional sediment dynamics as noted along the Oregon coast by Peterson et. al. (1990). It has been established that between 1891 and 1983, the Willapa Channel thalweg migrated to the north nearly 3000 meters, about 33 m/yr, closely approximating the 36 m/yr average retreat rate of the Cape (Levenseller & Terich, 1986). What is forcing the channel to migrate northward is unclear. The long period of erosion has significantly widened the channel entrance into Willapa Bay. In 1873, the straight line distance between Ledbetter Point, the northernmost point of the Long Beach Peninsula and Cape Shoalwater was approximately 4,75 km (2.96 mi). In 1983, that same distance had widened to 9.75 km (6.09 mi).

Extensive shoals have developed in the channel over this time period. Study of the patterns of shoals reveals the development of an embryonic shoal migrating southward from Cape Shoalwater across the channel welding on to a much larger shoal just south of the channel (Figure 4). If this is a persistent cyclical pattern, the progressive growth of shoals on the south side of the channel thalweg might be the forcing factor pushing the tidal channel to the north, closer to Cape Shoalwater, thus perpetuating the erosion.

It is clear that the channel dynamics have changed significantly over the last several decades and the channel thalweg has migrated to the north. The cause of that migration maybe site specific, but more likely due to a much larger picture of changes in sediments dynamics within the larger littoral region stretching from the Columbia River to Grays harbor.

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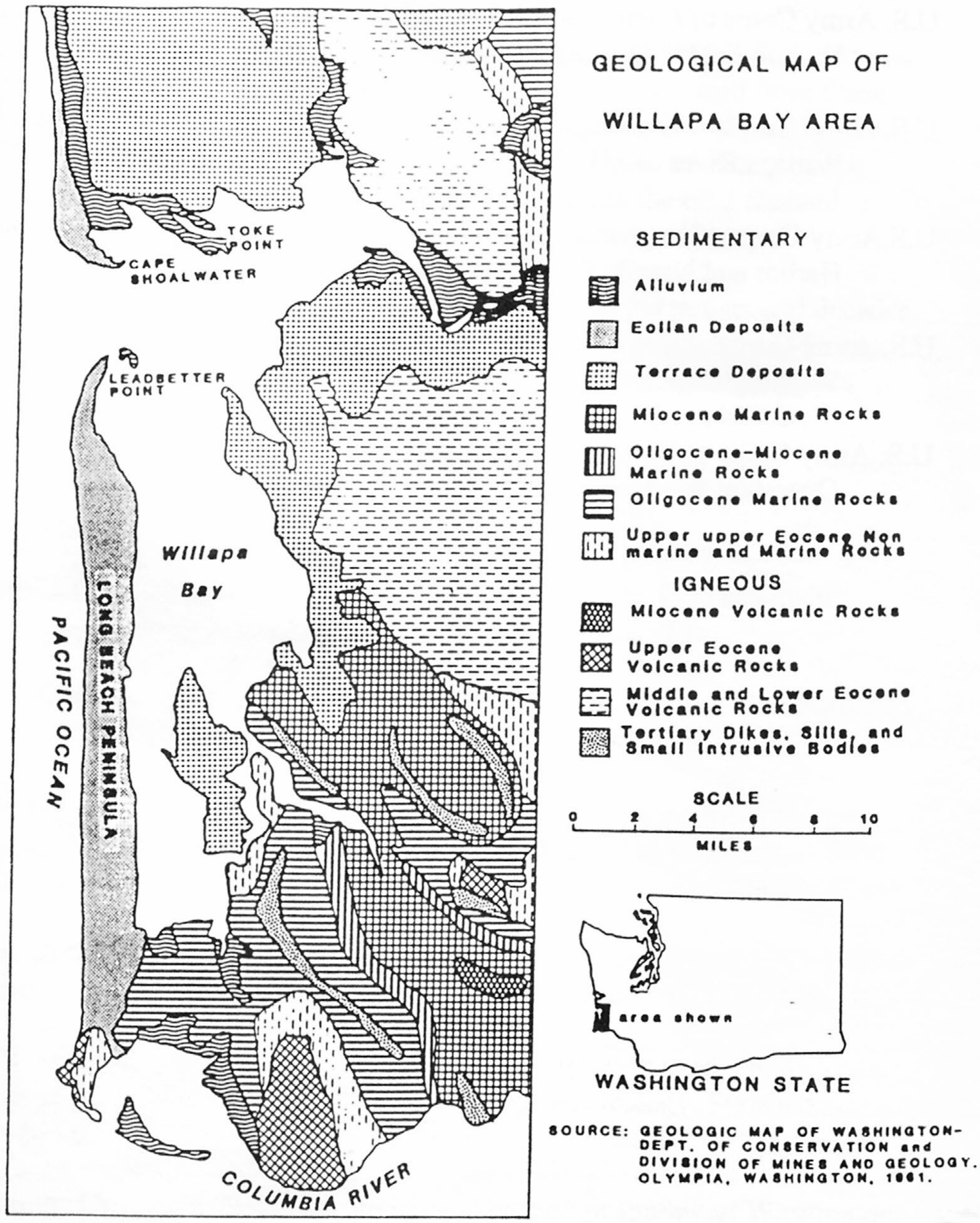

Figure 1. Location and regional geology of Willapa Bay and Cape Shoalwater

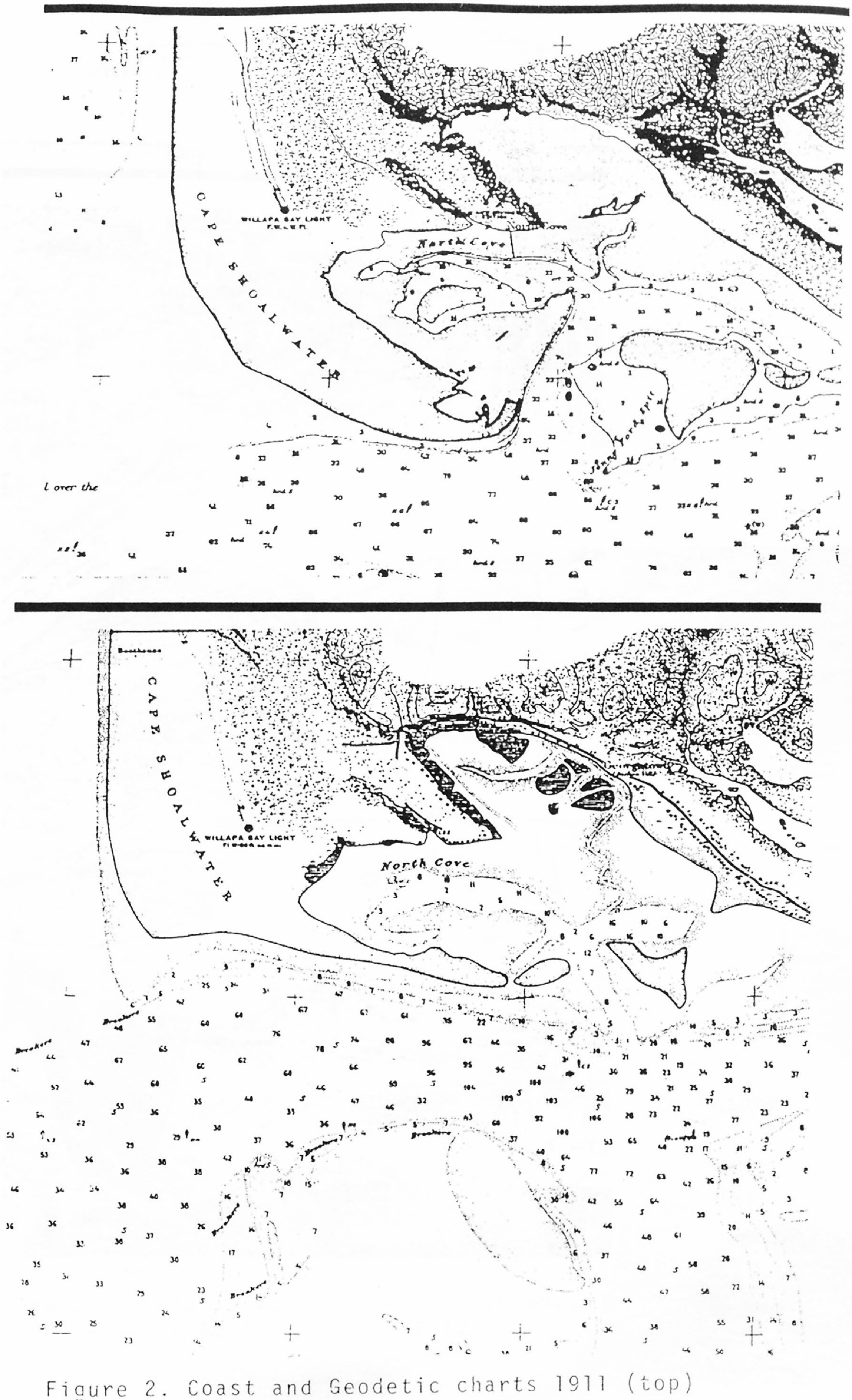

Figure 2. Coast and Geodetic charts 1911 (top)
1912 (bottom)

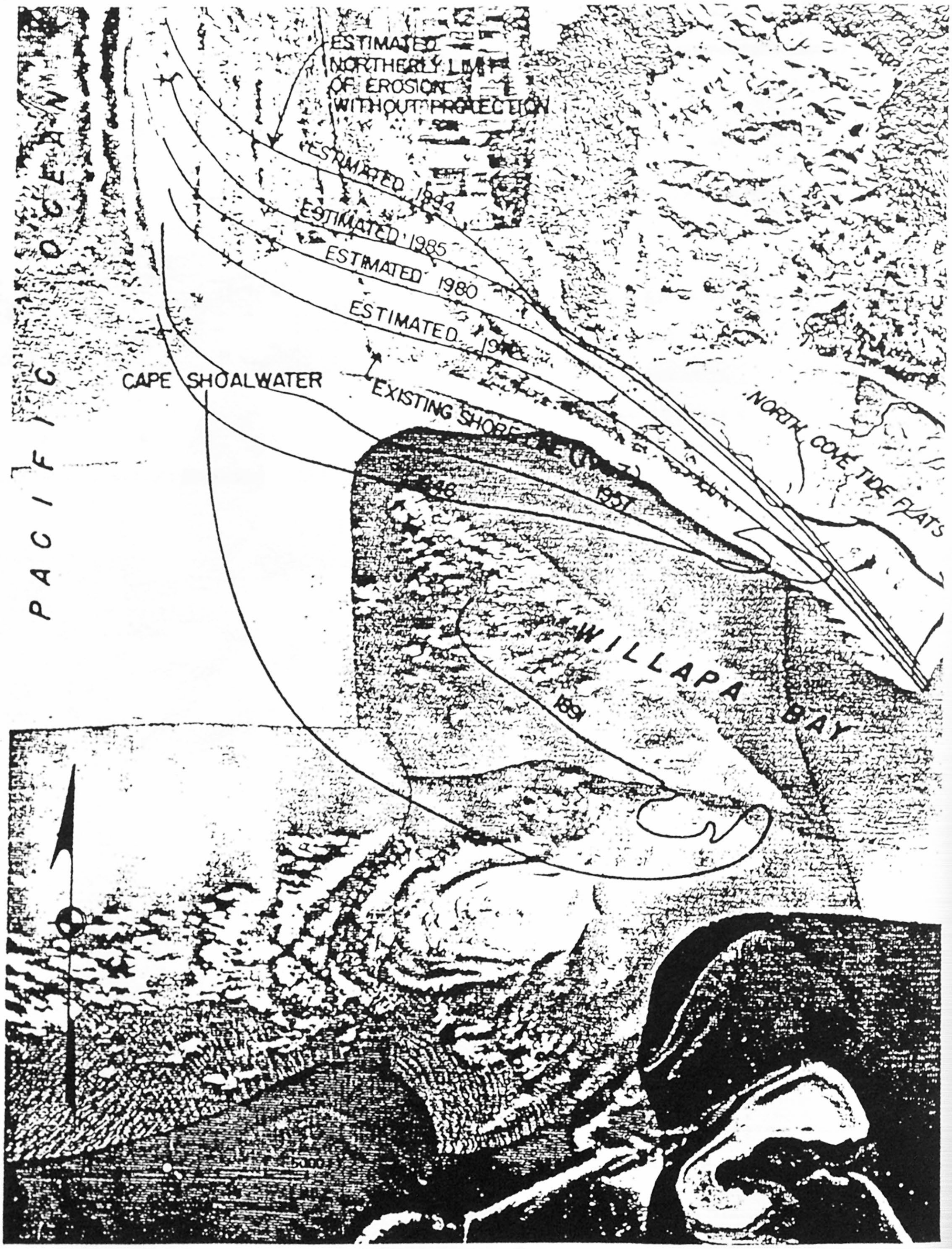

Figure 3. U.S. Army Corps of Engineers estimates of of shoreline change at Cape Shoalwater.

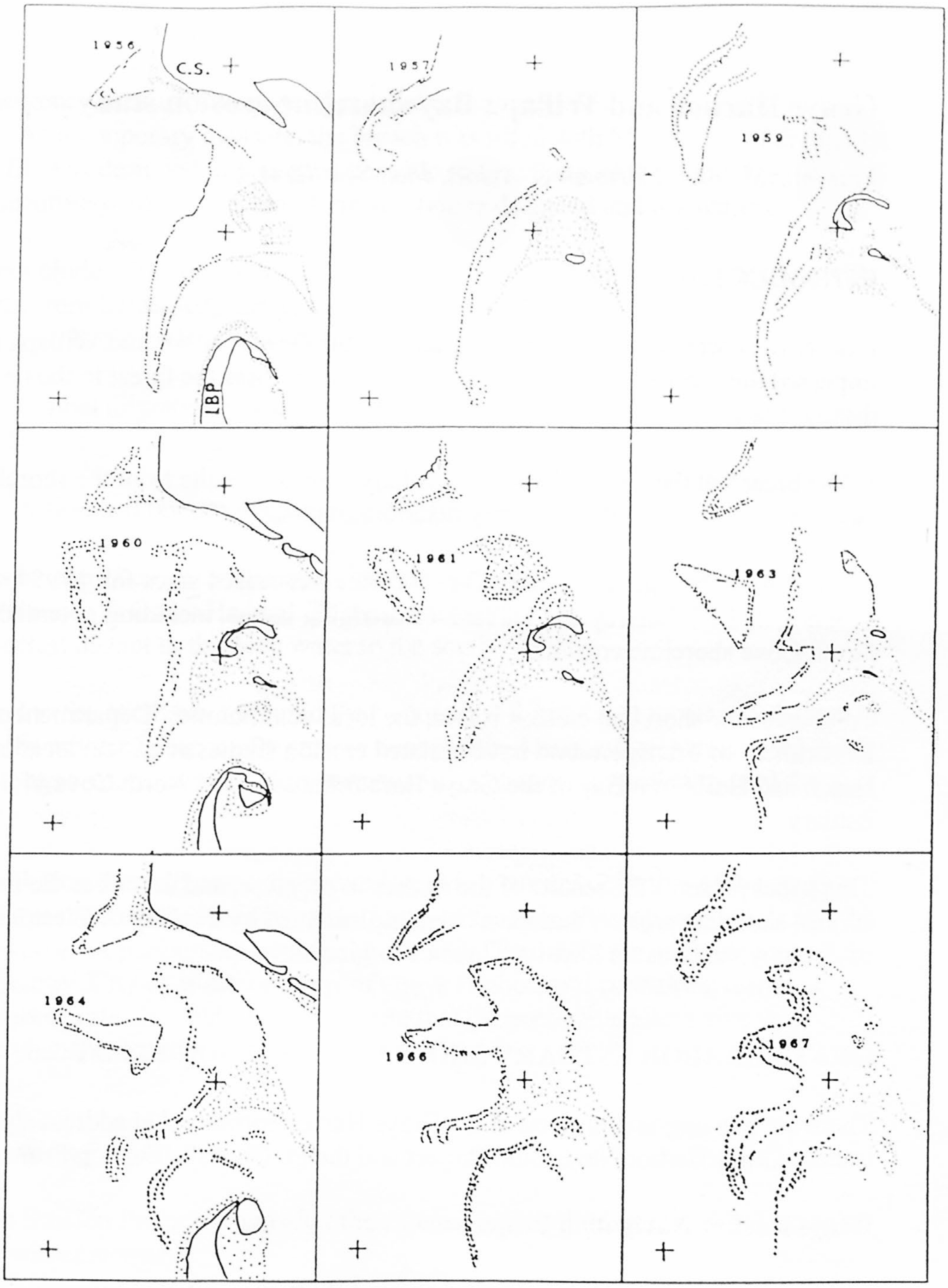

Figure 4. Shoaling dynamics within the Willapa Channel 1956-1967.

Grays Harbor and Willapa Bay shoreline erosion study

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INTRODUCTION

Extensive shoreline erosion at the entrance of the Grays Harbor and Willapa Bay has impacted the economy of local communities and imposes the threat to the navigation in these estuaries.

• The breach at the Grays Harbor South Jetty, a direct results from the shoreline erosion, has increased the risk of South Jetty deterioration.

• Navigation through the Willapa Bay entrance has ceased since fall 1995 because of shoaling in the waterway and unresolved dredging issues, including potential impact on North Cove shoreline erosion.

To address the shoreline erosion issues, the local communities, Department of Ecology, and Department of Transportation have initiated erosion studies at critical locations: South Beach and Halfmoon Bay of the Grays Harbor Estuary, and North Cove of the Willapa Bay Estuary.

This paper presents the results of the studies in progress, and describes the measures to control shoreline erosion that have been implemented by the City of Westport, Department of Ecology, and Seattle District Corps of Engineers.

GRAYS HARBOR ESTUARY SHORELINE EROSION STUDY

There are two ongoing projects at the Grays Harbor entrance that address shoreline erosion issues: Grays Harbor Navigation Project and the Pt. Chehalis Erosion Protection Project.

Grays Harbor Navigation Project

The Grays Harbor Navigation Project erosion study was initiated following the breach at the South Jetty that occurred on December 10, 1993. The breach imposed a danger for the Grays Harbor Navigation Project, and has resulted in severe erosion to the adjacent shorelines of Grays Harbor. It was found that, if no action to effect breach closure was taken, the deep natural channel would be redirected through the breach. This situation would generate a dramatic long-term increase of erosion at the South Beach and deterioration of the South Jetty. If this condition was allowed to develop, navigation through the existing channel will be compromised. Additionally, it would pose a threat to the City of Westport's infrastructure and eventually it's physical existence.

Temporary emergency measures were designed and completed in fall-winter 1994, and summer 1995. As a temporary measure, the breach was filled with 750,000 cy of dredged material. This fill was designed to prevent a possible re-breaching of the South Jetty for at least three consecutive years, until a long-term solution is designed and implemented.

Our study has concluded that the threat for navigation in Grays Harbor, in conjunction with the breach, arises from South Jetty deterioration and potential failure. South Jetty deterioration and probable undermining of the foundation has resulted from two major factors:

- Natural deep channel migration to the south and exposure of the north toe of the jetty to depths over 60 ft.

- South Beach erosion and bottom deepening along the south toe of the jetty.

Deep natural channel movement to the south has resulted from the ebb and flood current patterns at the entrance to Grays Harbor. This pattern is driven by the bottom depth gradient, the shortest distant to the deep water to the south.

Currents directed to the south have scoured the bottom and formed a deep natural channel in the entrance. This process is especially erosive during coincidence of storms and ebb tide. This channel captures more currents, thus perpetuating a channel migration toward the south.

The long term solution that addresses the above issues is a current objective of the study. The study is now at the stage of identifying the range of feasible alternatives, and design the preferable alternative. A partnership between the Seattle District Corps of Engineers, DOE, Grays Harbor County, City of Westport, Port of Grays Harbor, and consulting team has been formed to accelerate the study and make sure that the preferable alternative will provide a comprehensive solution.

Pt. Chehalis Erosion Project

The Pt. Chehalis Erosion Project began after the extensive shoreline recession in December 1994 caused by winter storms.

Erosion continued at Point Chehalis (South of Halfmoon Bay) during the winter of 1994-1995.

Emergency measures implemented by DOE and the City of Westport (85,000 cy of sand placed at the beach) were effective only for the 1994-1995 winter period. At the end of this period, 80% of the protection (sand) eroded from the upper beach, and the Point Chehalis shoreline was again exposed.

To protect Point Chehalis from substantial erosion and flooding damages (until a long-term solution is implemented), the City of Westport, DOE, and the Corps of Engineers agreed to design and implement a temporary protection measure under a Corps of Engineers Section 111 Authority.

Three alternatives to remedy the problem were considered: revetment, energy dissipation berm, and beach fill. The beach fill alternative was selected for implementation.

Due to delays in the permitting and bidding processes, the alternative was not completed as it was originally designed. Construction began in the end of October and continued under severe storm conditions. Only 300,000 cy of dredged material was placed as beach fill which never extended above water more than 100 ft offshore. Additionally, extreme wave conditions during this period moved material into nearshore trough.

Respectively, the expected effectiveness of the fill has not been achieved. However, even under these circumstances, the fill provided protection for the existing shoreline for one year. What was especially remarkable, no flooding event has occurred during fall-winter period 1995-1996. Data from field measurements indicates that a nearshore channel was partially filled with the dredged material and the depth in front of the revetment decreased significantly. This condition has increased flood protection for Westport.

It should be noted that these two ongoing projects are integrally related and interdependent. Any long-term solution for the Navigation Project must solve erosion problems at Pt. Chehalis and South Beach. It is most important that the interested parties: Port of Grays Harbor, Corps of Engineers, City of Westport, Department of Ecology, and other agencies combine their efforts to find and implement a comprehensive solution for the problem.

WILLAPA BAY ESTUARY SHORELINE EROSION STUDY

The Willapa Bay erosion study has been initiated to identify the cause(s) of the continual erosion at the North Cove, and design of a long-term solution to State Highway 105 and community properties.

It was found that North Cove erosion has resulted from natural migration of the deep natural channel. This migration has been observed since the end of the last century.

Based on the analysis of bathymetric data for the period 1842-1993, we identified that the channel migration to the North is stipulated by cyclical breaching of the north bar - North Cove offshore extension. Conceptually the process of breaching is described as follows:

The breach occurs when the length of the bar reaches the critical point. The bar usually extends to the south or south-west direction that diverts currents and increase flow pass. Hydraulic resistance increases thus augments the hydraulic gradient. During appropriate tide and wave storm conditions the bar breaches at the north and flow relocates into the breach. Hydraulic resistance reduces, and tidal currents are redistributed between South and North channels. Increase flow in the North Channel forces the channel migration to the North. Then the process of bar extension and breaching repeats.

Our preliminary assessment indicates that the natural period of breach cycle was approximately 15-20 years. We believe that this cycle has been changed since the dredging in the Willapa Bay Bar (1928).

Based on the hydraulic analysis of the tidal currents we develop the conceptual approach for the North Cove erosion protection. This approach anticipates South Channel activation and redistribution of the tidal currents between North and South Channels. Understanding the extreme complexity of the involved processes and inability to model these processes, we recommend to continue the study based on test channel pilot project. Prior to the test channel design we are planning to update bathymetric data, and obtain and analyze the field data from current measurements in Willapa Bay in 1995-1996.

The data presented in this paper describes the results of the study in progress and should be considered as preliminary. We are planning to publish the final results upon the study completion.

Current systems, substrate controls, and channel migration in Willapa Bay, Washington

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The inlet to Willapa Bay, Washington consists of a dynamic complex of shoals and tidal channels (figure 1). The present main channel into the bay is approximately a kilometer wide and as much as 30 m deep. In the past 105 years, the main channel has shifted northward nearly 3.5 km, and its former traces are now occupied by extensive shoals (figures 2, 3, 4). East of the northward migrating segment of the channel system the channel takes on a north-south alignment. The north-south trending channel is 1 to 2 km wide and extends the length of the bay. The channel is bounded by broad sandy subtidal shoals and intertidal flats.

Willapa Bay encompasses a total area at high tide of 348 km^2 of which 170 km^2 represent tidal flats, 127 km^2 represents subtidal flats to 6m below mean low water, and 51 km^2 represents the deep tidal channels below 6 m water depth (figure 1). Willapa Bay is classified as a mesotidal estuary. Tidal currents are strong, averaging 1.3 m/s at maximum flood and ranging from 2.1 to 3.1 m/s on maximum ebb at the entrance of the bay (U.S. Coast and Geodetic Survey, 1962). The tidal currents that develop from these tides erode the substrate within the channels, produce distinctive flood- and ebb-dominated areas within the channel system, and apparently control the lateral channel migration within the bay.

Side-scanning sonar surveys, high resolution bathymetric profiling, geophysical profiles, diving observations, velocity profiles, and oriented cores define the processes and sedimentary features within the main channel system of Willapa Bay. This study reports on processes and features from data obtained between 1973 and 1976 in Willapa Bay.

The sediment in Willapa Bay consists mainly of well-sorted fine sand and mud. The sand is mostly introduced from the ocean, whereas, the mud is contributed primarily by river discharge. The sediment texture in the estuary varies depending on the location and topographic position (figure 5). From the mouth of the estuary well into the central part, sand dominates the sediment both in the channels and tidal flats. In the upper parts of the estuary, mud gradually replaces sand as the dominant sediment, first on the tidal flats and ultimately within the channels (Clifton and Phillips, 1980).

The floors and flanks of the main channel are covered by large-scale bedforms up to 3 m in height whereas the sandy subtidal and tidal flats contain ripples and locally small-scale bedforms (Anima and others, 1989). The bedform fields are the result of strong tidal current flow. Repeated side-scan sonar surveys during ebb and flood tidal conditions show a preferred ebb- and flood-current dominance of bedform orientation within the channel system (figure 6) (Clifton and Phillips, 1980). The flood currents dominate in the main channel floor in the northern part of the channel and along the eastern flank of the northern part of the north-south trending channel. Ebb oriented bedform fields characterize much of the southern part of the channel floor and flanks as well as the western part of the northern channel and flanks. Sand banks, tidal current ridges, separate the ebb and flood oriented bedform fields in the northern and central part of the channel system. Velocity profiles also show an ebb- and flood-current dominance within their respective ebb and flood controlled bedform fields in the northern channel system (figure 7). Oriented cores (134 cores) obtained within the main channel contain unidirectional large- to medium-scale crossbed cosets with abundant reactivation surfaces and confirm the regions of ebb and flood current dominance identified by repeated side-scan surveys (figure 8) (Clifton and Phillips, 1980). The cores along with diving observations also identify the substrate into which the main channel is eroding and apparently controlling lateral channel migration. Along the eastern channel margin and floor of the north-south aligned channel, "hard" overconsolidated mudstone of unknown age outcrops or underlies a thin gravel-shell lag on the channel floor (figures 9 and 10). Only limited eastward lateral migration of the north-south trending channel and essentially the same channel depths exist along the eastern margin of channel since 1897 indicating a "bedrock " control on erosion.

In the northern part of Willapa Bay the channel is eroding into bioturbated and laminated "soft" silty to sandy clay. The silty clay underlies sand or a thin gravel-shell lag on the channel floor. The silty clay also forms the north and eastern channel flank where bedforms cover the older estuarine deposit (figures 9 and 10). The silty mud deposit may represent Holocene tidal flat or accretionary bank deposits formed within the paleovalley of the ancestral Willapa River. Geophysical profiles in the northern part of the channel (Hill and others, 1981) show apparent southeast gently dipping strata. The inclined strata may represent bedrock or accretionary bank deposits of the Holocene estuarine channel or fluvial valley fill.

The northward lateral migration of the northern section of the Willapa Bay channel is the result of erosion by strong currents cutting into the "soft" Holocene substrate deposited within the paleovalley of the Willapa River. Rapid erosion will continue until the northern channel segment reaches the 67 to 70 m high bluffs composed of uplifted Pleistocene estuarine channel deposits of crossbedded sand and gravel found directly to the north of the present channel (Clifton and others, 1989). Once the Holocene silty clay deposits are removed by northward channel migration undercutting of the easy erodable Pleistocene bluff sands will result in extensive slumping. Reduced or slowing of the northward migration of the channel system may then occur as the slumped sediments will have to be removed by the tidal currents.

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Figure captions

Figure 1. Bathymetry of Willapa Bay, Washington. The main tidal channel ranges from 1 to 2 kilometers in width and locally is more than 30 m deep. Broad subtidal and intertidal flats occur adjacent to the channel.

Figure 2. Profiles across the entrance to Willapa Bay, Washington in 1887, 1954, 1978, and 1992. The broad shallow areas lie within the zone of breaking waves for which no data are available. See figure 1 for locations. Figure modified from Clifton and others, 1989.

Figure 3. Bathymetric contours of northern Willapa Bay, Washington constructed from NOAA smooth sheets containing soundings for years of 1987, 1911, 1922, and 1955. Depth contours in meters.

Figure 4. Bathymetric contours of northern Willapa Bay, Washington constructed from NOAA smooth sheets and navigation charts containing soundings for years of 1966, 1976, and 1992. Depth contours in meters.

Figure 5. Sediment texture in Willapa Bay, Washington. Sand dominates the central and northern part of the bay as well as the deep channel floors. Sand grades to mixed sand and mud and finally mud in the upper parts of the estuary.

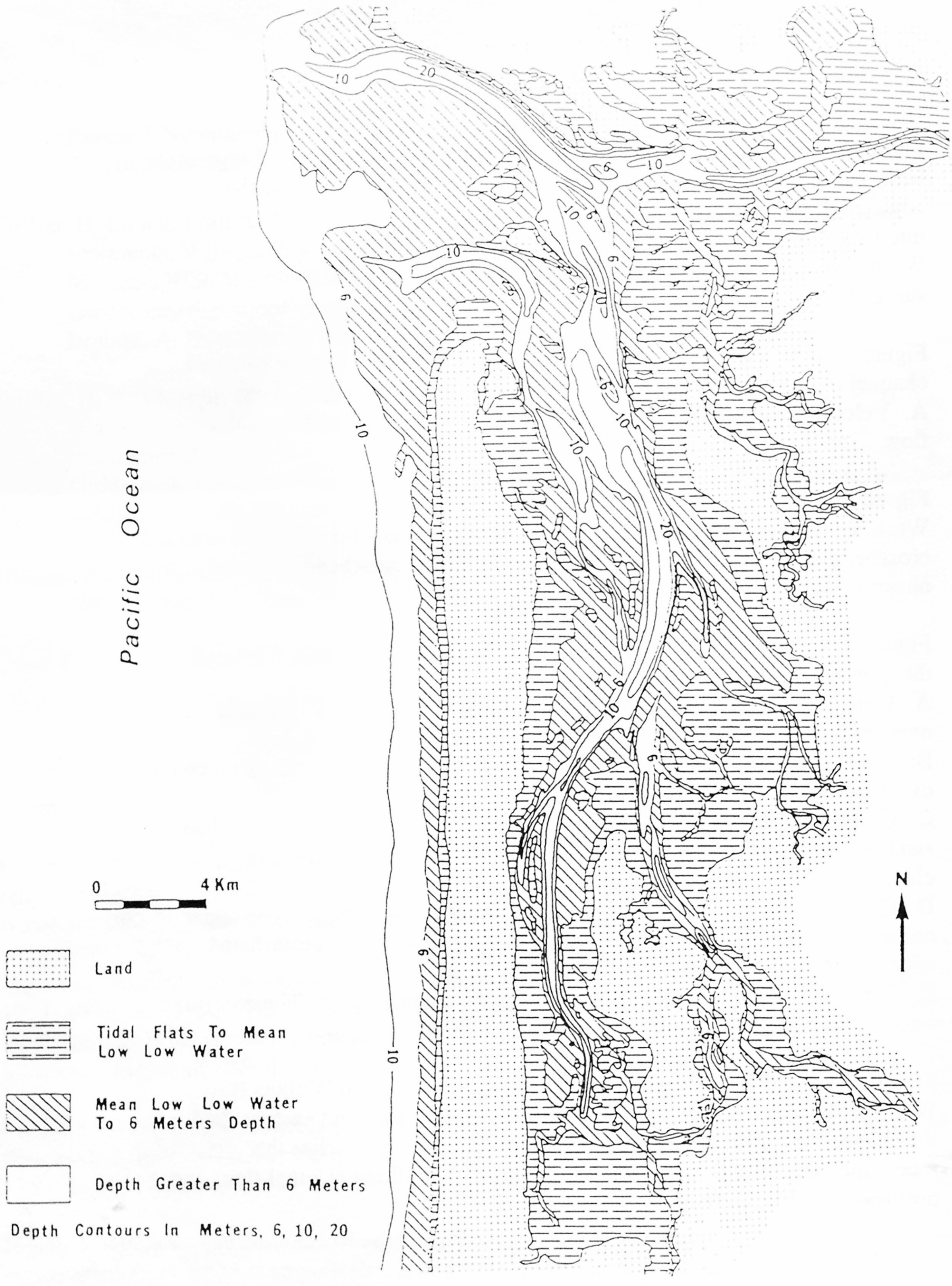
Figure 6. A. Bedform distribution in Willapa Bay, Washington. Large-scale bedforms cover the main channel floor and subtidal and intertidal flats adjacent to the mouth of the bay. Ripples cover much of the sandy intertidal flats. B. Ebb and flood current pattern in Willapa Bay, Washington. The current pattern determined from repeated side-scan sonar surveys.

Figure 7. Current-velocity profiles obtained in ebb- and flood-dominated channel regions during a 2.1 m tidal exchange in Willapa Bay, Washington. A. Velocities during flood tidal flow. B. Velocities during ebb tidal flow. See figure 10 for location of bathymetric profile.

Figure 8. Cross-stratification in oriented cores obtained in Willapa Bay, Washington showing regions containing unidirectional ebb and flood oriented crossbedding in the main channel system. Bimodal crossbedding is only observed at the crests of the tidal current ridges.

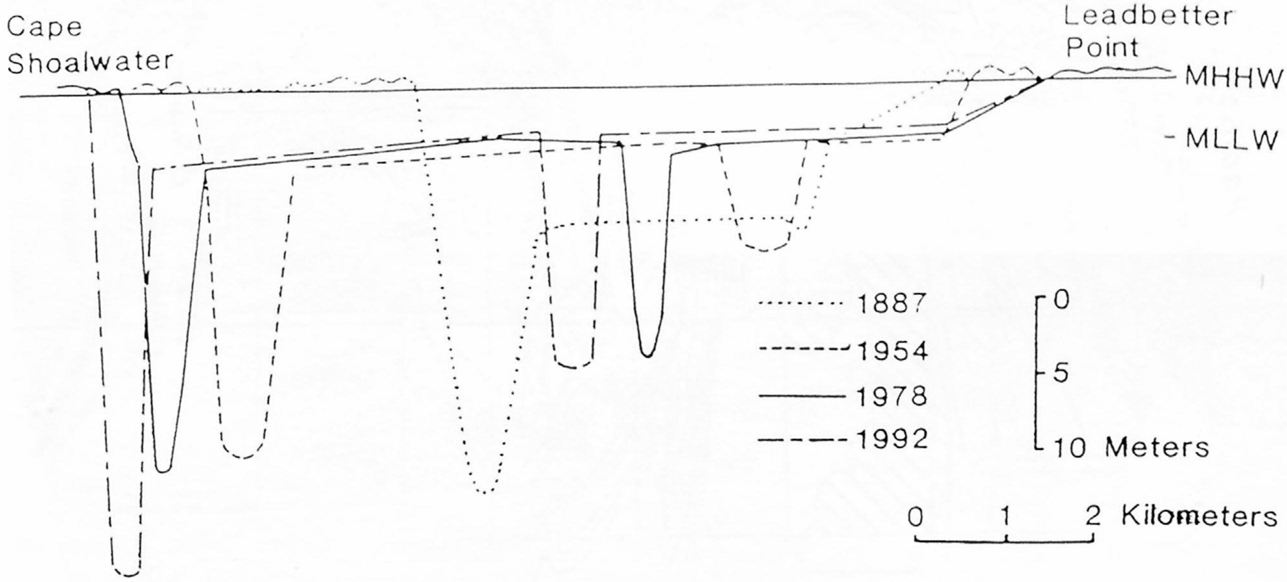
Figure 9. Cores from the main channel system in Willapa Bay, Washington that penetrate bedrock or Holocene estuarine sediments.
A: Core taken at 11 m depth in flood dominant channel floor. Crossbedded sand overlies a gravel lag and "hard" indurated mudstone at base of core.
B: Core taken at 11 m depth in flood dominant channel floor. Crossbedded sand overlies a gravel-shell lag and "hard" indurated mudstone.
C: Core taken at 8.5 m depth at south end of tidal current ridge. Crossbedded sand overlies a shell lag and intensely bioturbated "soft" sandy silty clay.
D: Core taken at 11 m depth in flood dominated channel floor. The upper 15 cm consist of crossbedded sand overlying a shell lag and "soft" bioturbated silty mud.
E: Core taken at 9 m depth in flood dominated channel floor. The core consists of bioturbated "soft" silty mud.

Figure 10. Bathymetric profiles across the main channel in Willapa Bay, Washington. Mudstone outcrops along the channel floor and eastern flank of the channel. Soft Holocene sandy silty clay apparently overlies the mudstone on profile B-B' and underlies the northern flood channel floor and northeastern channel flank.



Pacific Ocean
0
4 Km
Land
Tidal Flats To Mean Low Low Water
Mean Low Low Water To 6 Meters Depth
Depth Greater Than 6 Meters
Depth Contours In Meters, 6, 10, 20
N

Figure 1



Cape
Shoalwater
Leadbetter
Point
MHHW
MLLW
1887
1954
1978
1992
0
5
10 Meters
0
1
2 Kilometers

Figure 2

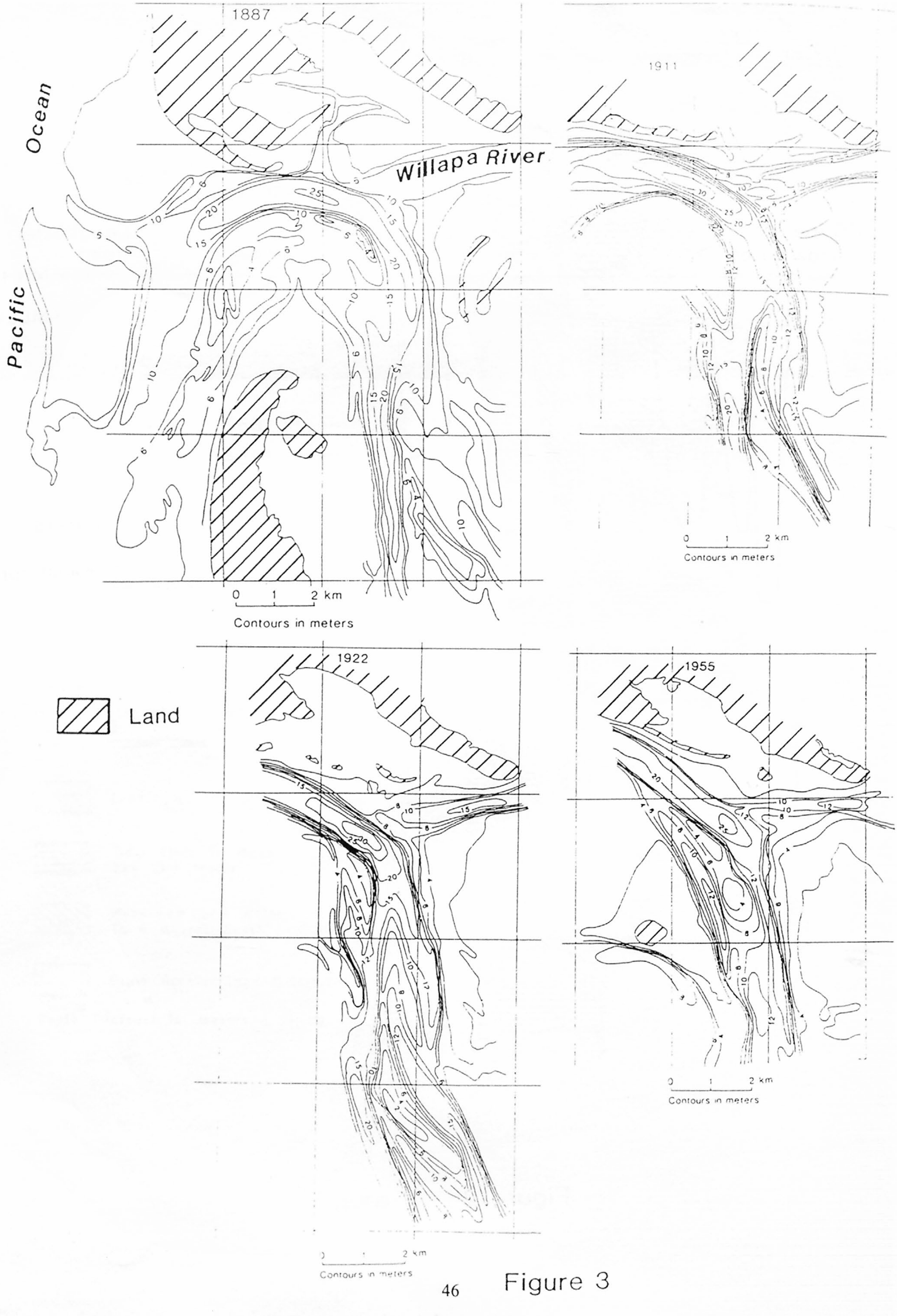

1887
Pacific
Ocean
Willapa River
0 1 2 km
Contours in meters
1911
0 1 2 km
Contours in meters
Land
1922
0 1 2 km
Contours in meters
1955
0 1 2 km
Contours in meters

Figure 3

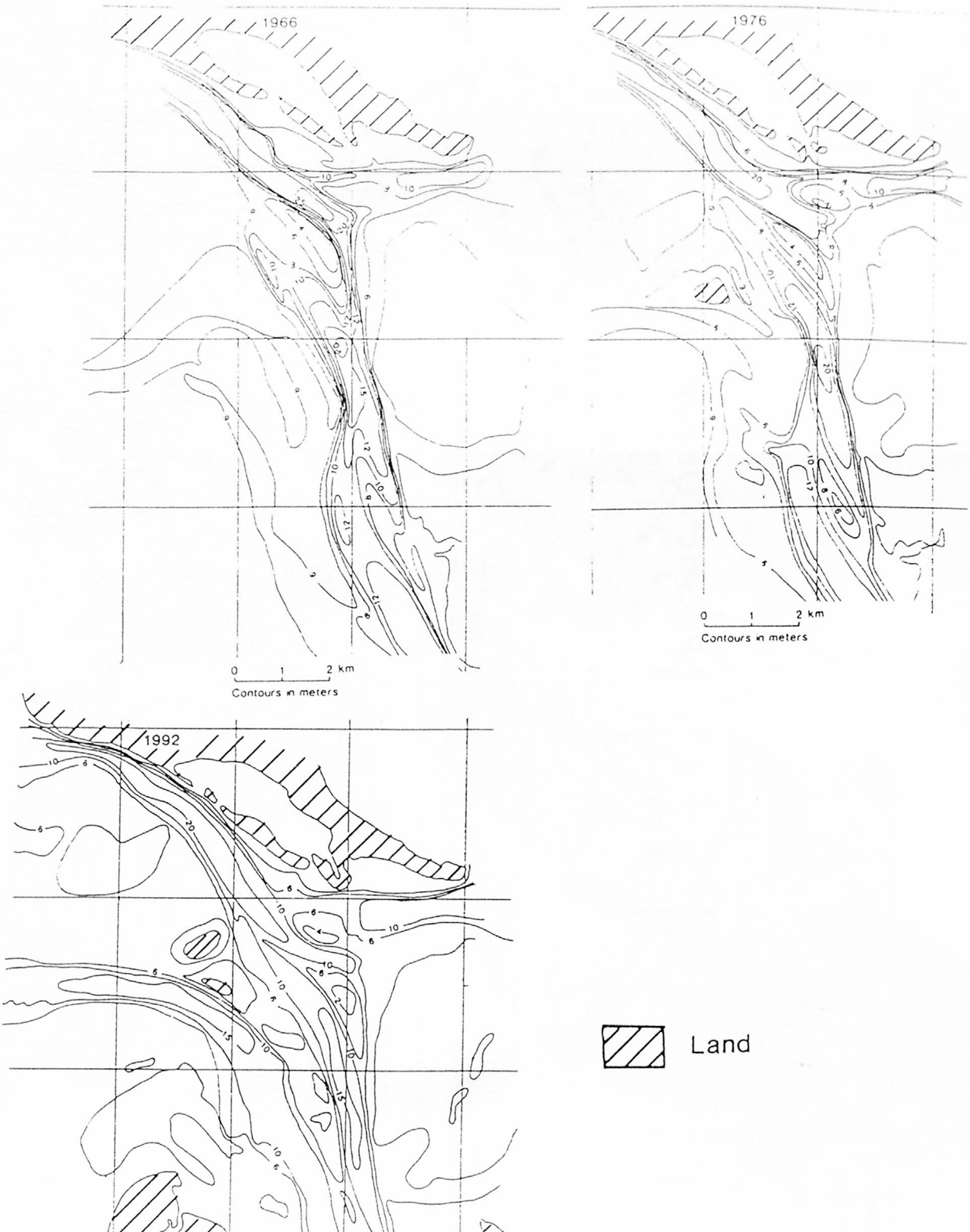

1966
0 1 2 km
Contours in meters
1976
0 1 2 km
Contours in meters
1992
0 1 2 km
Contours in meters
Land

Figure 4

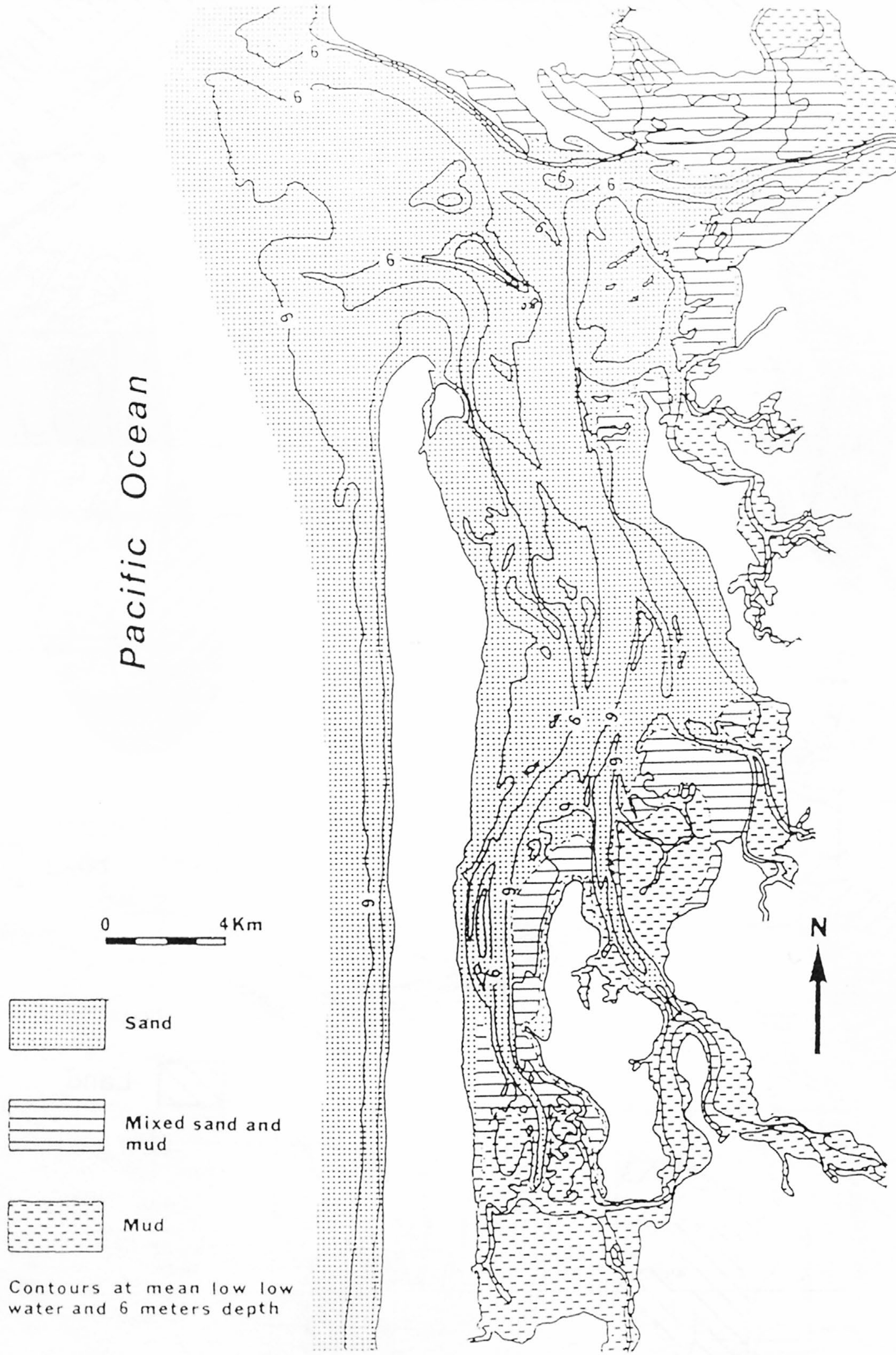
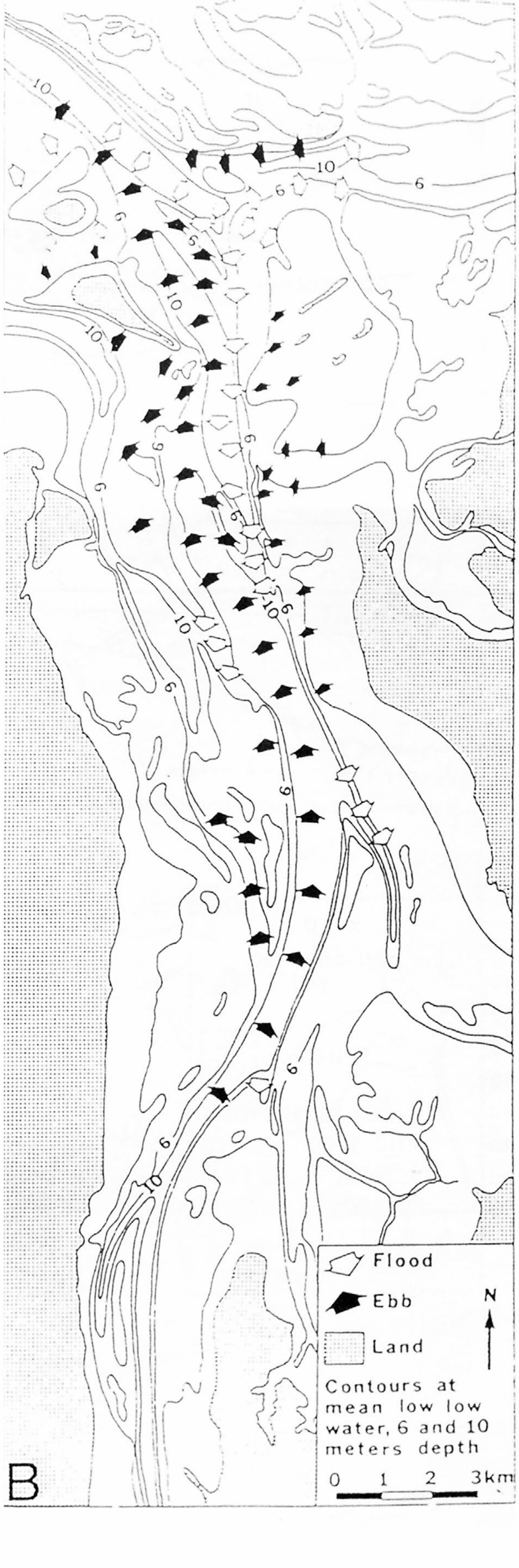

Pacific Ocean
0
4 Km
Sand
Mixed sand and mud
Mud
Contours at mean low low water and 6 meters depth
N

Figure 5



10
6
Flood
Ebb
Land
N
Contours at mean low low water, 6 and 10 meters depth
0 1 2 3km
B

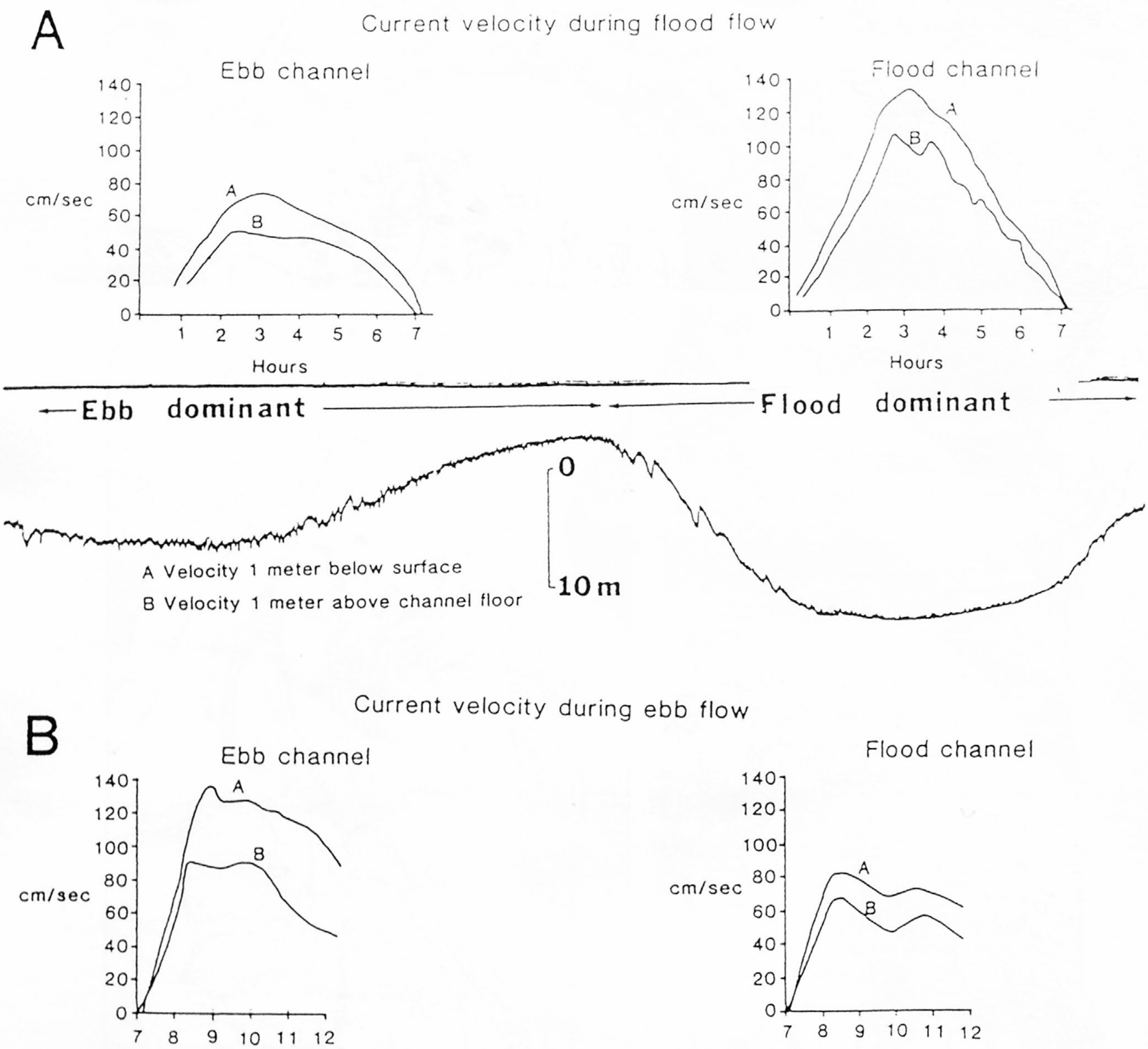

A
Current velocity during flood flow
Ebb channel
Flood channel
cm/sec
Hours
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7
A
B
Ebb dominant
Flood dominant
0
10 m
A Velocity 1 meter below surface
B Velocity 1 meter above channel floor
B
Current velocity during ebb flow
Ebb channel
Flood channel
cm/sec
7 8 9 10 11 12

Figure 7

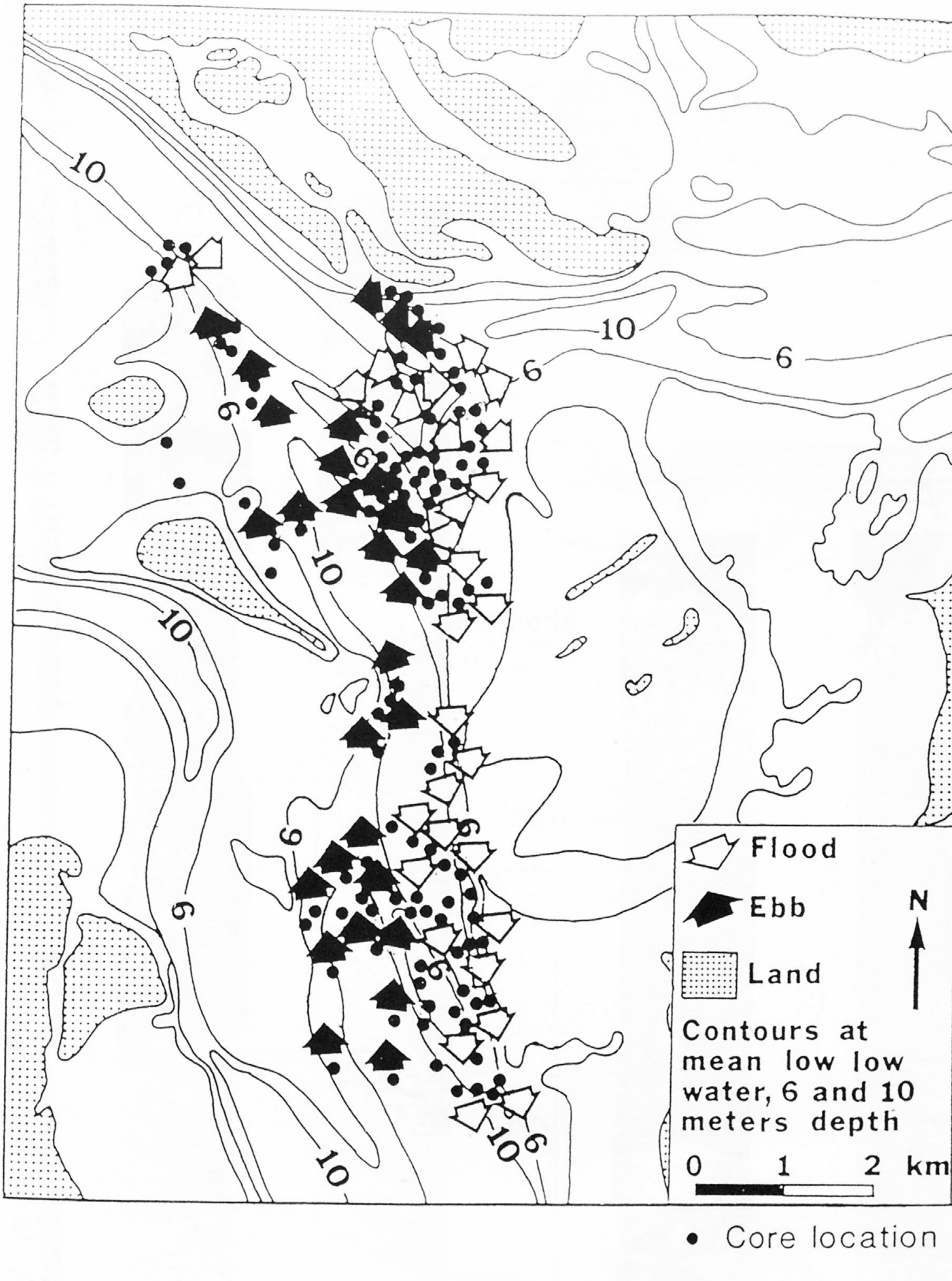
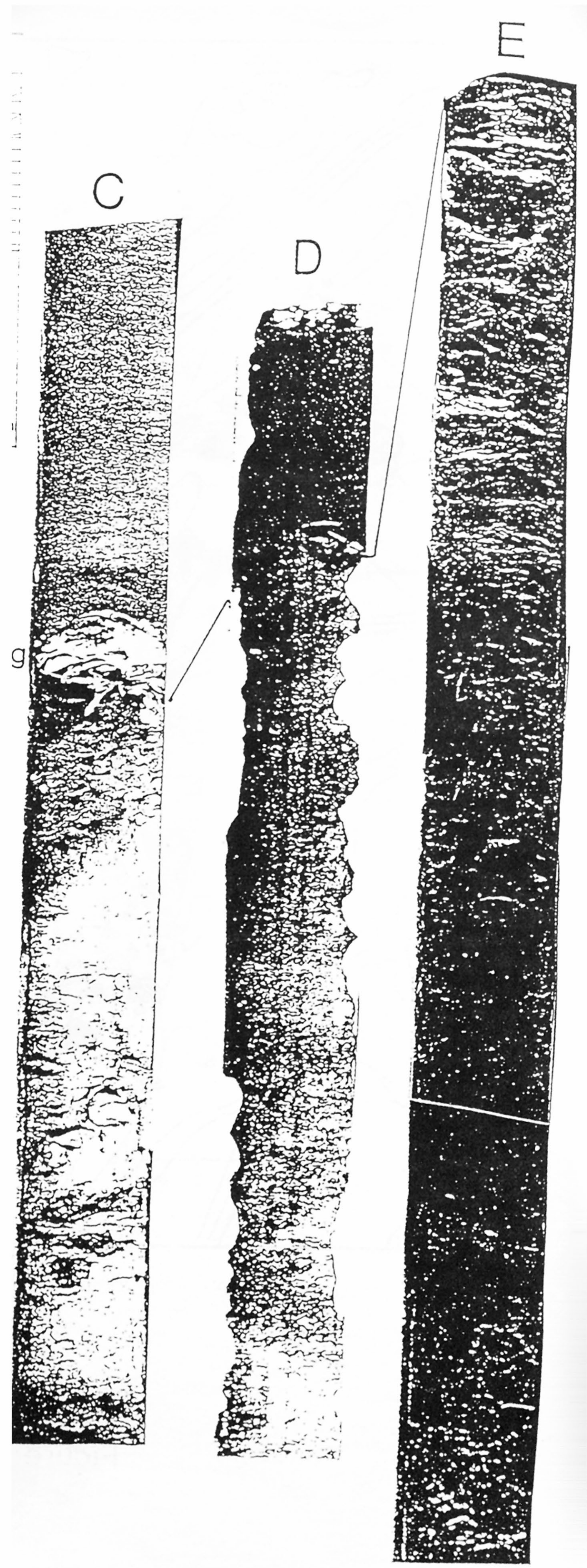

10
10
6
6
6
6
10
10
6
6
6
10
6
10
Flood
Ebb
N
Land
Contours at mean low low water, 6 and 10 meters depth
0 1 2 km
• Core location

Figure 8


C
D
E
g

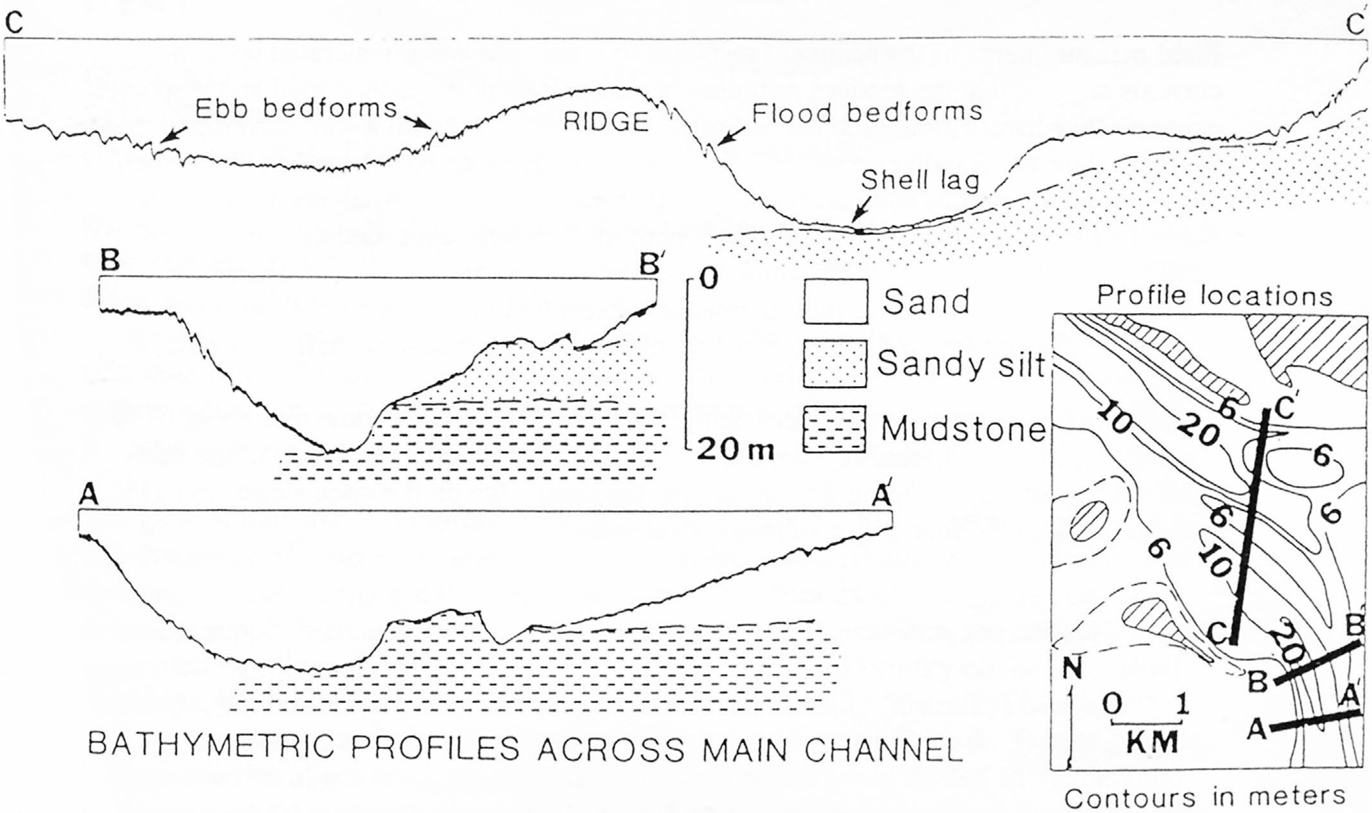

C
C'
Ebb bedforms
RIDGE
Flood bedforms
Shell lag
B
B'
0
20 m
Sand
Sandy silt
Mudstone
Profile locations
A
A'
10
20
6
N
0 1
KM
BATHYMETRIC PROFILES ACROSS MAIN CHANNEL
Contours in meters

Figure 10

Transport and accumulation of river-derived sediment on the Washington continental shelf, USA

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The combined results of many physical oceanographic, geochemical and geological investigations provide a coherent picture of the sedimentology of the Washington continental shelf. The major source of modern sediment is the Columbia River. Sediment on the shelf is transported by bottom currents resulting from surface wind stress and gravity waves which occur as individual storm or wave events lasting one to several days, primarily during the winter months.

Field measurements of the sediment response to wind- and wave-generated bottom currents suggest that the modern sediment is transported as suspended load and disperses primarily northward parallel to the isobaths and is associated with a well-developed mid-shelf silt deposit. Smaller quantities of sediment are transported seaward over the shelf edge into the numerous submarine canyons that incise the shelf. Analysis of available wave data suggests that thresholds of sediment motion were exceeded on the order of 22%, 16%, and 1.5% of the time annually on the inner, central, and outer shelf respectively. Bottom current measurements suggest that threshold conditions were exceeded 13% and 6% of the time annually on the inner and central shelf respectively.

Measurements of accumulation rates using 210Pb geochronology show that about 67% of the annual sediment discharge from the Columbia River is being deposited in the mid-shelf silt deposit; 6% is being deposited over the shelf edge on the open slope, and 11% is accumulating in the four major submarine canyons.

Proposed analysis of Columbia River sediment budget

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Following are two items to explain and outline the approach to estimating the late Quaternary Columbia River sediment budget. The first **ITEM 1** is an abstract, Table 1 and Figure 5 showing the method of analysis used to determine sediment budgets of the Ebro River. The second **ITEM 2** is a list of data types from numerous workshop sources that will be necessary to estimate the Columbia River budget. The success of budget estimates will depend upon the present existence of most of the listed data sets and cooperative use of these sets that we hope can be initiated at this workshop.

ITEM I

ESTIMATED POST-MESSINIAN SEDIMENT SUPPLY AND SEDIMENTATION RATES ON THE EBRO CONTINENTAL MARGIN, SPAIN
(from Nelson et al., 1990, Marine Geology, v. 95, p 395-418)

Because of the thorough data base of seismic profiles, radiometric ages, and stratigraphic time markers such as the subaerial Messinian surface, the sedimentation rates and Ebro River sediment discharge can be estimated for different periods and environments of the Ebro continental margin. New values for sediment discharge (i.e., 6.2 vs. previous estimates of 2-3.5 million tons/yr) for the Holocene highstand are more reliable but remain minimum estimates because a small proportion of Ebro sediment advected to the Balearic Rise and Abyssal Plain cannot be accounted for, especially during lowstands.

The general highstand conditions of the Pliocene, similar to the Holocene, resulted in a low discharge of Ebro River sediment (ca. 6.5 million tons/yr) and an even thickness of sediment across the margin that deposited at rates of about 24-40 cm/ky. In contrast, sediment supply increased two-to-three times during the Pleistocene, the margin prograded rapidly and deposition occurred at rates of 101-165 cm/ky on the outer shelf and slope, but basin floor rates remained anomalously low (21-26 cm/ky) because sediment is drained and broadly dispersed eastward in Valencia Trough. During the late Pleistocene rise of sea level, the main depocenters progressively shifted shoreward and sedimentation rates greatly decreased from 175 cm/ky on the upper slope during the early transgression to 106 cm/ky on the outer shelf and then to 63 cm/ky on the mid-shelf during the late transgression as the river sediment discharge dropped to half by Holocene time. Maximum sedimentation rates occur in active depocenters of sediment dispersal such as the Holocene delta (370 cm/ky) or the youngest Pleistocene Oropesa channel-levee complex (750 cm/ky) where deposition rates increase by an order of magnitude or more compared to average Ebro shelf (38 cm/ky) or base-of-slope rates in the Pleistocene (21 cm/ky).

The sedimentation rates verify the importance of sea level control on the progressive change in location of depocenters and amount of sediment supply, but Pleistocene climatic change and deforestation alone can be observed to double river sediment

discharge. The latter observation helps explain the anomalously high deposition rates in Pleistocene turbidite systems compared with older systems that may be controlled more by tectonic and sea level changes alone.
During the past 2,000 years, in contrast, man has controlled deposition in the Ebro margin system; first, by deforestation that more than doubled river sediment discharge and shelf deposition rates to equal those of Pleistocene time; second, by river dam construction that reduced sediment discharge to less than 5% of normal Holocene discharge. Similar recent discharge reductions from the Nile and Rhone Rivers suggest that loss of the majority of the river sediment supply in the Mediterranean Sea may result in significant erosion of biologically and agriculturally important lobate delta areas.

ITEM 2

NEEDS FOR COLUMBIA RIVER SEDIMENT BUDGET ANALYSIS

1. Holocene and Pleistocene seismic stratigraphic thicknesses for subaqueous delta, shelf mud blanket, slope mud drape, Astoria Fan and Cascadia Channel turbidite systems.

2. Radiocarbon and lead 210 age longitudinal and transverse transects for all of the above Columbia River depocenters for late Holocene, early Holocene, and late Pleistocene strata. These high resolution age data will be partially provided by ongoing paleoseismicity studies.

3. Sediment transport partitioning studies to determine proportion of present-day Columbia sediment load that ends up in littoral cells, shelf mud blankets, slope mud drapes, Washington and Oregon canyons, and deep-sea turbidite depocenters.

4. Information on pre-dam Columbia River sediment loads.

5. Information on post-dam Columbia River sediment loads.

6. Information on denudation rates of the Columbia River drainage basin for late Pleistocene, Holocene, and modern time periods.

Neotectonic influences on sediment transport along the Southwest Washington coast

Stephen P. Palmer, Washington Department of Natural Resources, Geology and Earth Resources Division, Olympia, WA

Research conducted during the last decade has led to the recognition that the southwest Washington coast lies along an active convergent margin and consequently has been subjected to numerous plate interface earthquakes during the late Holocene. These interface earthquakes typically have resulted in rapid subsidence of the coastal area as indicated by the preservation of buried marsh upland soils and "ghost" forests; the most recent of these earthquakes to affect the southwest Washington coast occurred about 300 years ago (Atwater, 1987; Atwater and Yamaguchi, 1991). Investigations along the Oregon, northern California, and British Columbia coasts also indicate sudden coseismic subsidence at about 300 ybp (Darienzo and Peterson, 1990; Clarke and Carver, 1992; Clague and Bobrowsky, 1994; Nelson and others, 1995). In this presentation I will review the work of a number of researchers who have been investigating the seismotectonics of this convergent margin, and will conclude with some questions and comments concerning the possible effects of neotectonics on coastal processes and sediment transport along the southwest Washington coast.

The plate interface earthquake that apparently occurred along the southwest Washington coast approximately 300 years ago resulted in sudden submergence of the shoreline and estuaries of Willapa Bay and Grays Harbor. Initial estimates of the amount of subsidence caused by this event were on the order of at least 0.5 m along the east side of Willapa Bay (Atwater, 1987) to at least 1.3 m to 1.5 m at Netarts Bay, Oregon (Darienzo and Peterson, 1990). More recent estimates of sudden subsidence along the Niawiakum River using diatom assemblages suggest a minimum of 0.8 m to 1.0 m to a maximum of approximately 3.0 m during the 300 ybp earthquake (Hemphill-Haley, 1995). Subsidence effects extended as far inland as Aberdeen in the Grays Harbor area, and somewhat upstream of the town of Skamokawa on the Columbia River.

A sudden relative sea level rise of 1.0 m or more could be reasonably expected to result in rapid erosion of the shoreline along the sandy barrier spits bounding Willapa Bay and Grays Harbor. A recent investigation used ground penetrating radar to map a series of buried erosional scarps across the Willapa barrier spit, and Vibracore drilling and trenching to evaluate the details of these scarps (Meyers and others, 1996). The drilling results indicate that heavy mineral lag deposits are the cause of the strong GPR reflections from these scarps. AMS dates from wood fragments and charcoal recovered in the Vibracores indicates that four of the scarp-forming erosional events could broadly correlate with age estimates for past plate interface earthquakes along the Cascadia margin. The formation of the youngest, and most shoreward, of these scarps may be related to the latest (300 ybp) subduction earthquake to occur along the southwest Washington coast. The GPR data also show a continuous, shoreline-parallel accretionary depositional sequence along the beach and upper shoreface shoreward of this erosional scarp. Loss of the GPR signal below depths of 7 m to 11 m indicate either a brackish/saltwater zone or a underlying lithofacies change (Jol and others, 1994).

Geodetic observations along coastal areas that experienced downdropping during the 1964 Alaska (Good Friday) earthquake and Nankai Trough (Japan) earthquakes of 1944 and 1946 (Thatcher, 1984) show that a substantial amount of the coseismic subsidence is recovered within a few decades after the event. Current uplift rates along the Pacific Northwest coast have recently been estimated using tide gauge records and repeated leveling surveys (Dragert and others, 1994; Mitchell and others, 1994). Mitchell and others (1994) show positive uplift rates along the Washington coast north of Point Grenville and south of Willapa Bay, and negative uplift (i.e., net subsidence) along the intervening section of the Washington coast. However, their estimates along the region of net subsidence may be limited by lack of long-term tide gauge data available for this section of the coast, and the incompleteness of the existing first-order leveling network in southwest Washington. Dragert and others (1994) present a convincing set of leveling and tide gauge data that shows recent net uplift rates of 3 mm/yr to 4 mm/yr along the southern coast of Vancouver Island, and a clear landward trend of decreasing uplift.

Sudden subsidence of the southwest Washington coast about 300 years ago likely resulted in massive erosion of the existing beach and foredune area. A number of questions that have possible significance to present-day coastal sediment budgets may be asked. For example, what volume of material was eroded due to the coseismic subsidence? Where did it go? What was the long-term fate of this eroded material, i.e., did it simply stay wherever it went 300 years ago, or has it returned to be deposited along the accreting barrier spits? If the latter, what proportion of the beach accretion along the Washington coast is from this sediment reservoir, and what proportion from sand transported from the Columbia River mouth after the coseismic subsidence? When did the bulk of the beach accretion occur? Within decades of the 300 ybp event, or more recently?

Likewise, the interseismic strain accumulation since the 300 ybp earthquake may have significant effects on coastal erosion and accretion. Some basic questions include: Is relative sea level along the southwest Washington coast presently rising or falling? Is the existing geodetic and tide gauge data adequate to answer this question? Is the present rate of change of relative sea level greater or less than the average rate since 300 years ago? How important are the effects of relative sea level changes to sediment transport, deposition and erosion?

One interesting consideration about the possibility of detecting the erosional scarp from the 300 ybp interface earthquake is that it provides a geographic and chronological marker that can be used to estimate the volume of sand accreted to the beach area since this tectonic event. I decided to perform some ballpark calculations on accreted sediment volumes based on the results reported in Meyers and others (1996). From their GPR profile and location map, I measured approximately 300 m of beach accretion since 300 ybp (the distance from the scarp to the present shoreline) with a thickness of approximately 8 m (the average depth of the shoreline-parallel accretionary sequence). I assume that this rectangular wedge was deposited along the entire 90 km of the southwest Washington coast. This yielded a total accreted volume of 200 x 10^6 m^3.

During the talks three presenters gave estimate of the pre-dam sediment volume leaving the mouth of the Columbia River; the range of these estimates was from 5-10 x 10^6 m^3/yr. In his presentation Sternberg suggested that about 15% of the sediment leaving the Columbia River would be transported to the inner shelf and consequently available for beach accretion. Using this percentage and the reported estimates of sediment supply from the Columbia River, I obtained a range of 0.8-1.5 x 10^6 m^3/yr of material transported to the inner shelf and potentially available for beach accretion. Two other estimates of available sediment supply were given during the presentation. Jim Phipps suggested that the erosion of Peacock Spit on the north side of the Columbia River has been on the order of 1.8 x 10^6 m^3/yr (maximum) since dam construction, and might be a sediment source replacing the pre-dam supply to the inner shelf and beach system along the southwest Washington coast. Curt Peterson presented an estimate of 1.3 x 10^6 m^3/yr of beach accretion based on a long term average since the mid-Holocene. All of these estimates of yearly sediment supply to the inner shelf and beach system are in general agreement (at least within a factor of two).

Given these estimates of yearly sediment supply in 300 years a total volume of 240 to 450 x 10^6 m^3 would be available to the inner shelf and beach system. These estimates suggest that there is adequate, if not excess, sediment supply to account for my ballpark estimate of 200 x 10^6 m^3 accreted since the 300 ybp interface earthquake. However, 1.5 m of sudden subsidence of the southwest Washington coastline during this earthquake would result in an estimated 300 m of beach retreat (Peterson, written communication, 1996). This would yield roughly the same volume of sediment as my estimate for accretion since 300 ybp. If there is any validity to my line of reasoning then there is a large volume of sediment that must be somewhere in the inner shelf/beach system, but has not been accreted to the beach proper. One likely area to hold this unaccounted sediment volume would be on the inner shelf, where lack of data precludes any estimate of sand accumulation rates.

Another interesting aspect to the beach accretion is that it appears that a significant amount of the total accretion has occurred during historical times. However, if a significant amount of post-seismic rebound occurred during the first few decades after the 300 ybp interface earthquake (following the pattern observed after the Nankai Trough and Good Friday earthquakes), then a considerable amount of beach accretion should have occurred before historical times. The response of beach accretion to interseismic uplift will apparently contribute yet another level of complexity to understanding southwest Washington coastal processes.

Two conclusions regarding southwest Washington coastal processes can be made. This is not a passive continental margin where only eustatic sea level rise need be considered, and the ultimate effects of neotectonics on coastal processes are poorly understood.

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Framework of Holocene sedimentation in the Columbia littoral cell

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Jim Phipps, Grays Harbor College, Aberdeen, WA
Derald Smith, University of Calgary, Alberta, CAN

The Columbia littoral system is spatially defined by anomalously high hypersthene: augite ratios that terminate at Point Grenville to the north and Tillamook Head to the south. Abrupt changes in beach width accompany these sharp mixing gradients, indicating a bounded littoral cell some 165 km in length. The distinctive orthopyroxene-rich minerologies extend to the mid-shelf mud lens offshore of the Columbia River but, are diluted by augite-rich sands in the inner-shelf offshore of Grays Harbor. In addition to the wide beaches, the onshore sinks of Columbia River sand include the progradational spits and overlying dune fields at Clatsop Plains, Long Beach Peninsula, and Grays Harbor. The major inshore sand sinks are Willapa Bay and Grays Harbor, both dominated by Columbia River sand-source mineralogy in their lower reaches.

The early-Holocene age structure of the developing Columbia cell system is constrained by seismic and bore hole pre-Holocene contacts at the base of TST valley fills. These contacts occur in the lower Columbia River valley (-96 m at 12-13 ka Missoula Flood scours) and the Grays Harbor spit (-60 m at 11,000 RCYBP). Basal TST dates above wave-cut platforms on the mid-inner shelf have yet to be established. The only deep vibracore on the shelf, taken immediately north of Cape Disappointment, reached refusal in dense sand at 10 m depth subsurface. This core was not available for age-dating due to pending litigation. High-resolution ORE-Uniboom seismic in the inner-shelf, north and south of Grays Harbor, reveals a shallow platform covered by 8-10 m of sediment in 20 m of water depth. Comparison of this pre-Holocene contact to sea-level curves from Grays Harbor suggest probable basal inner-shelf dates of 7 ka. Late-Holocene progradation of contiguous shorelines began at about 3-4 ka at the Clatsop Plains, 4-5 ka at Grays Harbor north spit, and 5-6 ka Willapa spit, shortly after the decline in rate of sea-level rise (stating about 7 ka).

Sea-level curves are well constrained for the entire Holocene period (0-11 ka) from Grays Harbor. Depositional levels in Willapa Bay are very-well constrained for back-bay tidal marshes, extending from 0 to 5 ka. Earlier (mid-Holocene) depositional levels have yet to be established in Willapa Bay. Tidal flat and tidal shoal depositional rates in the lower reaches of Willapa Bay are not known. The Mazama tephra (7,000 RCYBP) provides a widespread key bed throughout the lower Columbia River valley fill but, mid-late Holocene radiocarbon dates from this tidal basin are few in number. Recent coring in the lower Columbia River islands for paleoseismic analysis probably reaches back 2-3 ka. A widespread tephra (Mt St Helens set W eruption) provides a prehistory key bed at about 1480 AD throughout the lower Columbia River valley. The seaward edges of progadational dune fields (<300 RCYBP) have been dated at the southern Clastsop Plains and Willapa spit, Additional GPR-surveys and vibracoring are needed to verify late pre-historic shoreface positions throughout the Columbia littoral cell.

Late-Holocene sediment accumulation rates have been estimated at widely-varying levels of resolution for several parts of the Columbia cell system. Sediment accumulation rates in the Grays Harbor basin dropped from $2x10^6$ m^3yr-1 to 0.5 $x10^6$ m^3yr^{-1} during late-Holocene time. Additional work is needed to partition this total sediment accumulation into Columbia River sand accumulation. Corresponding fill rates for the Willapa Bay are not known. As noted above, a lack of shelf vibracores and corresponding late-Holocene radiocarbon dates precludes estimation of sand accumulation rates for the inner-shelf. Progradational barrier-dune complexes are estimated to have late-Holocene accretion rates of 0.4 m yr^{-1} Grays Harbor; 0.5 m yr^{-1} Willapa Bay, and 0.6 m yr^{-1} Clatsop Plains. Assuming a mean 20 m thick shoreface-dune package these accretion rates could translate into about 8 $m^3yr^{-1}m^{-1}$ or $1.3x10^6$ $m3yr^{-1}$ for the 165 km long cell. The longshore variability of shoreface-dune accretion rates in late-Holocene time have yet to be established. However, modern-beach sand volumes in the Columbia littoral cell suggest longshore variability on the order of 700-7,000 m^3 m^{-1} linear shoreline, with a mean of about 3,500 m^3 m^{-1} of linear shoreline. Modern foredune volumes have yet to established.

Unlike much of the PNW coast, the progradational-beaches of the Columbia River sand sheet are largely backed by dunes. The beach-backshores do not cut into late-Pleistocene marine terraces except near Cove Beach and north of Moclips. Therefore, the sand source of the late- Holocene sand sheet is considered to be dominantly first cycle. Grain rounding of orthopyroxene in the 125-175 micron fraction shows a distinct break between pre-historic river and beach control samples. Therefore, the Columbia River tidal basin is considered to be a net-source though late-Holocene time. A distinctive lamellar pyroxene (possibly Tillamook Head source) has been found in the mouth of the modern Columbia River sediments where it reaches trace amounts relative to the non-opaque HM fraction. If verified, this tracer might indicate some beach sand mixing in the lowest-reaches of the Columbia River in modern times. The lower Columbia River valley is estimated to have accumulated $8.5x10^6$ $m3yr^{-1}$ of bedload (sand) during the early-mid Holocene. This basin fill rate dropped to $3.6x10^6$ $m3yr^{-1}$ during the late-Holocene period, indicating at least $5x10^6$ $m3yr^{-1}$ of bedload bypassing during the last 7 ka. Additional constraints on tidal-basin morphology and sediment level-age dating are needed to verify long-term throughput of Columbia River sand.

The most sensitive, and easily measured, reservoirs of late pre-historic surplus sand-supply are the beaches and foredunes. However, these reservoirs were likely influenced by short-term impacts from coseismic-subsidence and interseismic-uplift (ave. 500 year recurrence interval), El Nino interannual-variations of directional wave-climate (>30 year recurrence interval), and changes in accommodation space associated with dune-ridge and barrier-shoal dynamics (recurrence intervals unknown). Nevertheless, these prehistoric records (pre-dam and -dredging) provide baseline rates of sand supply and accumulation in the Columbia cell. More importantly, the late-Holocene accumulation rates address long-term sediment partitioning into the various onshore, offshore and inshore reservoirs, potential residence times within these reservoirs, and response of these reservoirs to infrequent but catastrophic events.

Review of changes of sediment transport regime in Lower Columbia River

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A detailed study of hydraulic and sediment processes in a portion of a reach of the lower Columbia was conducted in 1985. Several observations made in the study reach have general applicability to the lower 140 miles of the Columbia, and thus have implications to the sediment supply of the southwest Washington coast. Several quantifiable acts point to a sediment deficit being experienced in the lower Columbia. The following information on natural and engineered processes is provided as documentation to quantify many of the impacts to the system that most are qualitatively aware of.

Geology

Older volcanic rocks of the region downstream from the mouth of the Columbia gorge form a valley filled with Pleistocene Portland delta gravels. The Columbia channel through this material was in turn filled with sands and gravels. As the sea level rose at the end of glaciation, silts and clays were deposited over the area. Sea level has fallen from its highest stand, leaving a Columbia channel contained by resistant clayey deposits and occasionally by rock outcrops and gravel deposits. This material differs from the river's present alluvium.

This Recent alluvium and bank material is firm silty clay, relatively stable, but subject to slow erosion in some river bends. Modern channel materials are found along banklines as dredged sand and gravel. These deposits consist of coarse sand and gravel with very little fine material. Whetten et al. (1969) described the bed load sediments as mainly andesitic volcanic materials derived from Mt. St. Helens. These modern channel sediments are considered similar in composition to the ancient channel deposits of the Pleistocene and Holocene described by Hoffstetter (1984) as the Columbia River Sands aquifer.

The Columbia history is marked by drastic changes in factors that define the channel form and process. Examples are catastrophic floods, then cutoffs of water and sediment, change in base level and uplift of its middle reach. The channel is not presently in equilibrium in the sense that a river would be if it had the present hydrology and the full ability to adjust its bed and banks, platform shape, slope, etc. Compared to this unconstrained case, the existing Columbia has larger bend radii, a smaller width-to-depth ratio, and a smaller sediment load.

The Columbia River appears to have inherited its present channel and bed characteristics from a time when the sedimentary environment was far different from today's. The lower Columbia River below the Columbia River gorge is a channel dominated by the effects of sea level change. The channel of the lower Columbia is stabilized by bank materials of resistant cohesive silt-clay beds deposited during the last rise of sea level (6,000 to 3,500 years before present). The channel position has changed very little from the 6600 year old buried channel and may be relatively stable at present.

Processes controlling erosion in the study area occur at various scales and over various time periods. The conditions which exist at the Sauvie Island shoreline result from site-specific river reach and river system processes, active in the past as well as the present. Few rivers the size of the Columbia show so much impact from active geologic change. The absence of a flood plain and the presence of numerous rapids in much of the middle reach of the river indicate the channel has not yet developed an equilibrium--in a geomorphic sense--with the results from surface and geologic events.

River Engineering

Dredging History

Dredging by the Corps of Engineers began in the area in 1895. The purpose is for maintaining navigation depths. Authorized channel depth changed from 20 feet to 30, 35, and 40 feet in 1912, 1930, and 1962, respectively. Increasing channel depth led to a large increase in the amount of dredging as the new channel was established, then decreased slowly thereafter. The majority of the work has been on the Vancouver Bar and Channel, where dredged quantities approached 1,825,000 cubic yards in 1934 and again in 1966.

Dredged materials from Corps operations are deposited on river banks in the most economical location. The material is usually placed on the inside of bends in the river where local velocities are lowest and re-entrainment of the sand is minimized. Material is placed on erosion sites only when it is most economical from a disposal standpoint.

The most intensive dredging operations in the area since 1968 have been done by the Port of Portland. The Corps of Engineers issued permits for the Port of Portland to dredge in three areas near the mouth of the Willamette River. Those areas are located between Columbia River miles 101.5 and 105, between Willamette River miles 1 and 8, and in Oregon Slough. The Port of Portland bas been authorized to dredge to a depth of -80 feet Columbia River Datum downstream from Hayden Island and to -55 feet CRD upstream of it. The authorized volumes over the last 18 years are 26,000,000 44,000, and 2,086,000 cubic yards for the Columbia, Willamette and Oregon Slough areas, respectively. The Port of Portland recorded dredging quantities of nearly 35,000,000 cubic yards from the Columbia River in the period of 1968-1985, and is expected to continue to remove material until all the desired borrow material has been obtained. The quantity of material dredged by the Port of Portland is substantial compared to approximately 56,000,000 cubic yards that have been dredged by the Corps of Engineers in the area since 1895. The material dredged by the Port is used as fill for a development site and is not placed on the banks. As a result, this material is permanently removed from the river system.

The past few decades have seen a decrease in required maintenance dredging, even as the authorized depth was increased. As the navigation project has been deepened, dredging and pile dike construction initially intensified. This activity tended to concentrate flow velocity in the center of the channel. Material dredged from the bed was disposed on bankline areas. As a generalization, sand was not to be found on banklines between Bonneville and the estuary until dredging operations placed it there. In recent years, required dredging, and therefore disposal of sand, have diminished. As ships became larger and more numerous, ship wake energy impinging on the bankline tended to become greater. The now-familiar sandy spots on the banks are showing effects of net removal.

Hydropower projects have affected the sediment supply to the lower river by modifying the hydrology of the Columbia. Channel modifications significant to hydraulics have coincided with trends in ship traffic. Dam construction has created much storage in the system and, it is logical to assume, must have great effect on sediment supply. However, a complete and quantitative study has not been carried out on upstream entrapment. It is known that regulation has decreased the frequency and magnitude of significant sand transporting events. Major bed forms now appear less frequently than before.

The sediment discharge-water discharge relationship has changed over the last 30 years as a result of lower sediment concentrations. That, combined with a more regulated flow-duration curve, indicates a reduction of about 80 percent in average annual sediment load at Vancouver. Removal of river sand in the Portland area traps about 85 percent of the sand load moving close to the river bed. Geologic studies of past cutoffs in Columbia sediment supply and changes in shoreline position near the mouth should provide some insight to the dependence of beach width on levels of Columbia River sediment supply.

Erosion of the ebb-tidal deltas on the Washington coast - A long-term trend

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The ebb-tidal delta off Grays Harbor has eroded substantially since the beginning of this century. Comparison of bathymetric surveys shows that erosion has occurred in the entrance channel, the offshore bar, and the nearshore region off South Beach. Only the nearshore region off North Beach has been depositional. A total of about 153 million cubic yards of sediment was removed from the four regions between 1900 and 1990, an average loss of 4.5 m at an average rate of 5 cm/yr (Fig. 1; Burch and Sherwood, 1992). Changes of similar magnitude have taken place on the ebb-tidal delta off the Columbia River, where an average loss of 1.4 m occurred in the entrance area between 1868 and 1958 at an average rate of 1.6 cm/yr (Sherwood et al., 1990). In both cases, similar changes in the morphology of the inlet and ebb-tidal delta occurred following jetty construction. The changes included rapid accretion of the subareal spits both north and south of the jetties, rapid deepening of the entrance channels, removal of the shallow subtidal delta between and immediately seaward of the jetties, and gradual accretion of a new ebb-tidal delta in deeper water. In contrast to the original morphology, the modern ebb-tidal deltas are located farther offshore, are much deeper, and contain less sediment. These trends show no sign of changing, and the sediment losses are probably permanent.

The morphological changes were not unexpected; they were, mostly, the intended result of jetty construction. However, the engineering goal was to move sediment to more convenient locations, not to remove sediment entirely, and the long-term loss of sediment from the ebb-tidal complex as a whole has unwelcome implications. In particular, removal of sediment from the nearshore region can only exacerbate erosion problems on the beaches adjacent to the jetties. The erosional trends demonstrate that the rate at which material has been removed from the modern ebb-tidal deltas has exceeded the supply rate. This loss of sediment from the ebb-tidal deltas raises questions relevant to issue of regional coastal erosion on the Southwest Washington coast. First, what caused this erosion, and are the causes local or regional in extent? Second, if the causes are local, do the observed changes near these developed inlets have any bearing or influence on less developed stretches of the Washington coast?

Scanty data suggest the following hypothetical answers. Erosion of the ebb-tidal deltas is not a result of long-term changes in sea level, wave climate, or fluvial sediment supply, but rather a response to local changes in waves and currents caused by jetty construction. The causes and responses are local in extent, and do not reflect regional or historical changes. This explains the unsatisfying correlation among climate indices and erosional trends at the entrance to Grays Harbor, and among transport capacity and changes at the mouth of the Columbia River. However, the loss of sediment from ebb-tidal deltas is an important consideration in regional sediment budgets for three (again hypothetical) reasons: 1) erosion of the ebb-tidal deltas has provided a significant (but one-time) source of sediment to the regional sediment budget, 2) the ebb-tidal deltas used to act as reservoirs of sediment that could buffer local beaches against rapid permanent erosion or deposition, but can no longer serve that function, and 3) erosion of the ebb-tidal deltas makes the inlet more effective barriers to littoral transport. The evidence for these hypotheses is mostly anecdotal, and one of the objectives of the Southwest Washington Erosion Study should be to test them and evaluate their implications.

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Ocean disposal of dredged material at the mouth of the Columbia River

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Mouth of the Columbia River - Physical Setting

The Columbia River flows into the Pacific Ocean at the boundary between Oregon and Washington (figure 1) and is the second largest river in the United States in terms of river discharge. The course of the Columbia River is 1,210 miles long, dropping over 2,600 feet from its Canadian headwaters to the sea, draining an area of approximately 250,000 square miles. The Columbia River accounts for 60% (winter) to 90% (summer) of the total freshwater discharge into the ocean between the Canadian border and San Francisco. The Columbia River estuary is the largest fluvially dominated estuary in the Pacific Northwest [CREDDP 1984]. The tidal prism of the Columbia River estuary is about 730 mi^2-ft [Lockett 1967].

The river's discharge is marked by a high seasonal variability, typically ranging from 100,000 to 400,000 cfs. Highest discharges occur during May through July due to snowmelt and rain runoff. Lowest flows occur during late summer and early fall [Neal 1972]. The average river discharge is presently about 265,000 cfs. Annual riverine discharge statistics are shown for the Columbia River (at the Dalles Dam) in figure 2. Peak river flow at river mile 30 during the flood of February 1996 was at least 950,000 cfs [Knutson 1996]. The physical characteristics of the Columbia River estuary differ from those of most North American estuaries: River discharge is much greater, salinities are much lower, tidal forcing is greater, and bottom sediment is less stable. Flushing time for the Columbia River's estuarine waters is 2-5 days, whereas the flushing time for many other estuaries may require weeks or months: The average flushing time for Chesapeake Bay is about 1 year.

Although the Columbia River is known for its low turbidity, swift river currents move a significant amount of bedload sediment, acting to shift sand islands and form sand waves up to 14 ft tall on the channel bottom. Presently, the amount of sediment contributed by the upper Columbia River (above Bonneville Dam) is very small compared to the net discharge. Relatively little suspended sediment is retained in the main stem of the estuary. The predominant sediment type in the main channels of the estuary is sand with finer silts and clays prevalent only in the upper estuary and peripheral bays [Roy et al 1982]. In terms of the overall estuary, average bottom sediments have been characterized as having 1% gravel, 84% sand, 13% silt, and 2% clay [Hubbell and Glenn 1973 and Roy 1982]. Fine sediment, which is normally transported in suspension, comprises only a small percentage of the sediment deposited in the estuary. Approximately 67% of the total sediment discharge from the Columbia River is transported to the continental shelf of Washington [Sternberg 1986]. Previous studies indicate that some of the sandy sediments within the Columbia River estuary may have been recently transported into the estuary from adjacent nearshore and shelf regions.

Littoral Drift

Historically, the Columbia River has been a major source of sediment to the northwest coast. On the oceanside, the mouth of the river is flanked by broad sandy beaches. To the immediate south, lies Clatsop spit where the beach is backed by substantial dunes. To the north, lies Peacock spit and a rocky headland (Cape Disappointment) which anchors the shore (figure 1).

A difference of opinion exists regarding the direction of predominant littoral drift in the vicinity of the Mouth of the Columbia River (MCR) entrance [Lockett 1967]. Several observations have been advanced which indicate that the predominant direction of littoral drift is from south to north [Ballard 1964]:

- Wave analyses indicate a net northerly wave energy flux is predominate in the winter months.
- A smaller median grain size of beach sand is found south of the MCR entrance.
- The *presence* of the massive shoal formation (Peacock spit) to the immediate north.
- The migration of Sand Island to the north in recent history.

Contrary observations which could lead one to conclude that the predominate littoral transport is from north to south have also been advanced [Lockett 1967]:

- The *shape* of the massive shoal formation of Peacock Spit bulges seaward and curves toward the south, past the north jetty.
- The shoreline for approximately 3 miles south of the MCR has experienced periods of recession and erosion since construction of the entrance jetties.
- During the period from 1877 to 1958, the area to the immediate north of the MCR entrance had shoaled approximately 317,000,000 cy, while the area to the immediate south had lost about 504,000,000 cy of sedimentary material. The north jetty and associated estuarine flow would be presumed to act as a littoral barrier.

Although the northerly wave flux during the months of December - March is a documented fact, the remainder of the year is characterized by lesser waves and currents approaching the coast from the north. It may be possible that the weaker wave/current regime present during a period of 7 months could generate littoral movements which approach or exceed the volumes experienced during the more energetic 5-month period of the year. Collective consideration of the above observations illustrates that further study is needed to fully resolve the littoral transport issue at the MCR.

The issue of "north vs. south" littoral transport at MCR is an important consideration for the USGS regional shoreline erosion study proposed for the southwest Coast of Washington. It is recommended that the USGS study area include the coastline from MCR south to Tillamook Head, since this area comprises the southern end of the Columbia River "littoral cell". The proposed USGS study should determine the relative age of sandy sediments distributed within the Columbia River estuary and along the active coast both north and south of the MCR. This data would establish the temporal linkage of the MCR with regional sediment budget. Although the sandy sediment on the SW Washington coast originated from the Columbia River, it is not known how long ago it was deposited.

Disposal Of Dredged Sediments

The deep draft navigation project located at the ***Mouth of the Columbia River*** (MCR) consists of a dredged navigation channel 6.6 miles long which extends through a jettied entrance between the Columbia River and the Pacific Ocean (figure 1).

Substantial quantities of sediments have been dredged near the Mouth of the Columbia River (MCR) since 1885, when dredging was initiated by the U.S. Army Corps of Engineers (USACE) to establish a 30-foot deep channel across the entrance bar formed by Clatsop spit. The natural channel had averaged about 25 feet deep and shifted frequently both during and between seasons. In order to maintain a consistent 30-foot channel across the bar, the south side of the river entrance was jettied between 1885-1889. Additional channel deepening to 40 feet was begun in 1905. In 1913, the north side of the entrance channel was jettied to prevent shoaling from Peacock spit. The north jetty is approximately 2.5 miles long and the south jetty is 6.6 miles long.

The MCR channel entrance was deepened to 48 feet in 1956. The channel was deepened to its present authorized depth of 55 feet in 1984. The authorized project (Rivers and Harbor Act of 1884, 1905, 1954; and Public Law 98-63) provides for a 2,640-foot-wide channel across the Columbia River Bar. The northerly 2,000 feet of the channel was deepened to -55 ft MLLW (plus 5 feet for over dredging), and the southerly 640 feet of the channel was deepened to -48 ft MLLW (plus 5 feet for over dredging).

The MCR project has two main shoaling areas. The outer (ebb tidal) shoal extends from approximately river mile (RM) -1.6 to RM -1.0. The inner (flood tidal) shoal, Clatsop Shoal, extends from approximately RM 0.0 to RM 2.6, beginning on the south side and crossing the channel near RM 1.0 [Siipola & Braun, 1995]. In its present configuration, the entrance channel at MCR requires annual dredging of 3-5 million cubic yards of fine-medium sand (shoal deposits) to maintain the navigation channel at the authorized depth.. The sandy dredged material is placed in EPA designated ocean dredged material disposal sites. Dredging at the MCR is performed by hopper dredges.

MCR Ocean Dredged Material Disposal Site Management

As many as 10 ocean dredged material disposal sites (ODMDSs) have either been proposed or utilized by the Portland District for disposal of sandy dredged material dredged from the MCR entrance channel. Since 1945, ODMDSs A & B have been the primary locations where MCR dredged material was placed (figure 3). These two ODMDSs are located on the westward boundary of the ebb-tidal shoal and are convenient for disposal of sediments dredged from both the outer and inner bars at MCR.

The ambient seabed elevation at ODMDS A and B ranges from -85 ft to -60 ft MLLW and -160 ft to -80 ft MLLW, respectively. ODMDS B has received most of the MCR dredged material as concerns arose that sediments deposited in ODMDS A might migrate north back into the entrance channel. Since 1956, approximately 160 million cubic yards of sand have been dredged from the entrance channel at MCR and placed in 4 ODMDSs: Sites A, B, E, and F.

Site E was established in 1973 in part because dredged sediments placed at this site are potentially beneficial as sand nourishment for adjacent beaches along the north jetty. The continual use of site E is also partially in response to a 1979 request from the Washington State Parks Department (Department of Ecology) for preferential use of ODMDS E in order to enhance sand by-passing and retard erosion of the coastal beaches north of MCR. ODMDS E is now used only during spring and early fall when nearshore sediment transport of material from the site is thought to be northward along Long Beach (Peacock Spit). ODMDS E is not used during the midsummer when the nearshore currents are believed to flow southward, across the entrance channel. Because ODMDS E is only 1,000 ft north of the entrance channel, the volume of dredged material placed at this site is restricted to a maximum of 1 million cy annually.

Figure 4 (dashed line) denotes the official boundaries for the EPA designated ODMDSs at MCR. The EPA approved configuration for each ODMDS was governed by the requirement to minimize the benthic area of impact due to openwater disposal of dredged sediments. The area size of designated ODMDSs at MCR was based on:

ODMDS length = average dumping run for one dump
= (disposal vessel speed while dumping) **x** (time to empty disposal vessel)

ODMDS width = average turn during one dump = disposal vessel turning radius while dumping

ODMDS long axis orientation = preferential approach-heading during dredged material disposal.
(site orientation is set by disposal vessel operators and is based on dumping efficiency and vessel sea-keeping due to incident wave direction)

Recent Management Actions for MCR ODMDSs

After final EPA approval of the MCR ODMDSs in 1986, disposal site management became increasingly proactive in the year to year operation of ODMDSs. Disposal site management has been progressively improved and enhanced in order to maximize site capacity utilization of the EPA designated ODMDSs. The unintended consequence of using the aerially restricted ODMDSs has been creation of potentially adverse impacts to navigation at MCR, by mounding of placed dredged material (figure 3). The rapid accumulation of dredged material within ODMDSs A and B (formation of high mounds) during the late 1980s and early 1990s is attributed to three factors:

(A) The restriction of dredged material disposal within relatively small EPA-designated ODMDSs, rather than in large unconfined areas and in a dispersive manner of placement.

(B) Increased use of split-hull hopper dredges, which promote the vertical accumulation of dredged material placed on the seabed within the ODMDSs.

(C) The improvement in navigation allowing for precise positioning control during disposal.

Due to recent mounding problems at ODMDSs A and B, those two sites and ODMDS F were expanded in 1992 (figure 4, solid line). Temporary expansion of these sites' boundaries have been coordinated with regional resource agencies and special management options have been implemented [Siipola & Braun 1995]. Site E has not been expanded since it has shown no signs of dredged material accumulation or mounding.

Consistent annual bathymetric surveys at MCR ODMDSs have been conducted since 1983; the x,y,z data has been digitally stored. Since 1992, ODMDS surveys have been conducted twice annually, before and after the dredging season (April-May to September-October). Sediment sampling has been conducted at MCR by USACE and NMFS.

Requirements for New or Expanded ODMDSs at MCR

Section 103 of the Ocean Dumping Act and section 404 of the Clean Water Act require that field-verified, state of the art procedures be used for the assessment of possible physical impacts due to the operation of proposed ODMDSs. The recent operational performance of the ODMDSs at MCR indicates that existing sites are inadequate. A key to successful ODMDS designation and long-term management is knowing in advance (or reliably predicting) the fate of dredged material placed at the ODMDS. To meet this need at MCR, several numerical models are being used for the analysis of dredged material placed at new or expanded ODMDSs. Results from the numerical modeling of dredged material behavior at MCR will guide proposed ODMDS expansion and ensure that longterm management of the sites meets operational requirements. Expanded or new MCR ODMDSs will be expected to fulfill a minimum life-cycle of 20 years and accommodate the additional volume of disposed dredged material associated with the Columbia River Channel Deepening. Requirements for successful ODMDS expansion and management at MCR will:

♦Locate ODMDSs within the zone of siting feasibility: Conduct dredging disposal activities in an efficient manner by minimizing haul (transit) time for hopper dredges and scows from point of dredging to point of disposal.

♦Avoid environmental and navigation impacts due to annual dredged material disposal operations: Enhance bathymetric dispersal of dredged material placed at ODMDSs for split-hull vessels by using a placement grid template to evenly distribute dredged material placement in sensitive areas.

♦Where practical, enhance transport of suitable dredged material placed at ODMDSs into the littoral zone.

♦Minimize cumulative build-up of placed dredged material, from multiple dredging disposal operations (long-term use of ODMDS): Designate ODMDSs with large aerial configuration and manage sub-units of an ODMDS on an annual rotational basis.

♦Provide ODMDS capacity for disposal of new work and maintenance dredging material originating from MCR, estuarine, and riverine dredging sites.

Present Numerical Modeling and Data Collection Activities at the MCR ODMDSs

Under the USACE Dredging Research Program (DRP), several sediment fate numerical models were developed or enhanced in order to improve the reliability of site management of ODMDSs. These numerical models incorporate state-of-the-art techniques for simulating the behavior of dredged material placed in open water, and account for a variety of disposal operations and environmental conditions. In the context of short- and long-term goals for ODMDS management at MCR, the DRP models are being used to rationally justify the expansion of key MCR ODMDSs and optimize site capacity/utilization. Predictions of sediment fate behavior can only be as good as the poorest estimate for the forcing environment (i.e. waves, currents, and other processes). To meet this data need, techniques were developed under the DRP and are used to generate synthetic oceanographic data for use in the new sediment fate models.

To enhance fate prediction of dredged material placed at MCR ODMDSs and at other locations nation wide, a four year Monitoring of Completed Coastal Projects (MCCP) study is being conducted by USACE to verify relevant numerical models and optimize ODMDS designation and management strategies. The broad objective of the USACE Monitoring of Completed Coastal Projects (MCCP) program is to improve project purpose attainment, design procedures, construction, methods, and O&M techniques for Civil Works projects located on the coasts and Great Lake shores of the United States. The MCCP objective is achieved through a national program of intensive field monitoring at selected Civil Works coastal projects maintained by USACE. Insight gained through the MCCP at MCR will be used to reduce life cycle costs at similar Civil Works projects nationwide.

The MCCP at MCR was jointly initiated in fiscal year 1995 by WES and Portland District, USACE through funding/program management provided by Headquarters USACE. A major component of the MCCP at MCR will be collection of prototype wave and current data at pre-determined locations along the ebb-tidal shoal. The above study will be completed in four phases.

PHASE I: Analysis of existing information, selection of candidate ODMDS(s) to study, formulation modeling strategy for this MCCP, and development/refinement of a prototype data collection program. Compare synthetically generated data to existing environmental data sources.

PHASE II: Begin collection of prototype data at MCR and conduct initial numerical modeling work with available data obtained in Phase I. Make required improvements to DRP models and the field data collection plan.

PHASE III: Complete prototype data collection, perform modeling with new prototype data and compare to modeling results based on available data obtained in phase I.

PHASE IV: Assess applicability of DRP models and synthetic data sets, summarize results, compile the generic modeling methodology, and provide technology transfer.

As a first step toward modeling sediment fate at MCR ODMDSs, existing oceanographic information was consolidated for use in the modeling effort. Existing data relevant to the environmental processes which govern sediment transport in the water column and on the seabed at MCR ODMDSs have been resolved and parameterized. These data sources include: MCR bathymetry, waves, currents, and physical sediment parameters. This activity constituted Phase I of the MCR - MCCP, which was completed in December 1995 [USACE 1995]. Phase II of the MCR-MCCP is now in progress. Separate complimentary USACE studies affiliated with the Columbia River Channel Deepening project are also underway. The proposed USGS regional shoreline erosion study would enhance existing data sources and provide additional synergy to the present USACE MCR activities.

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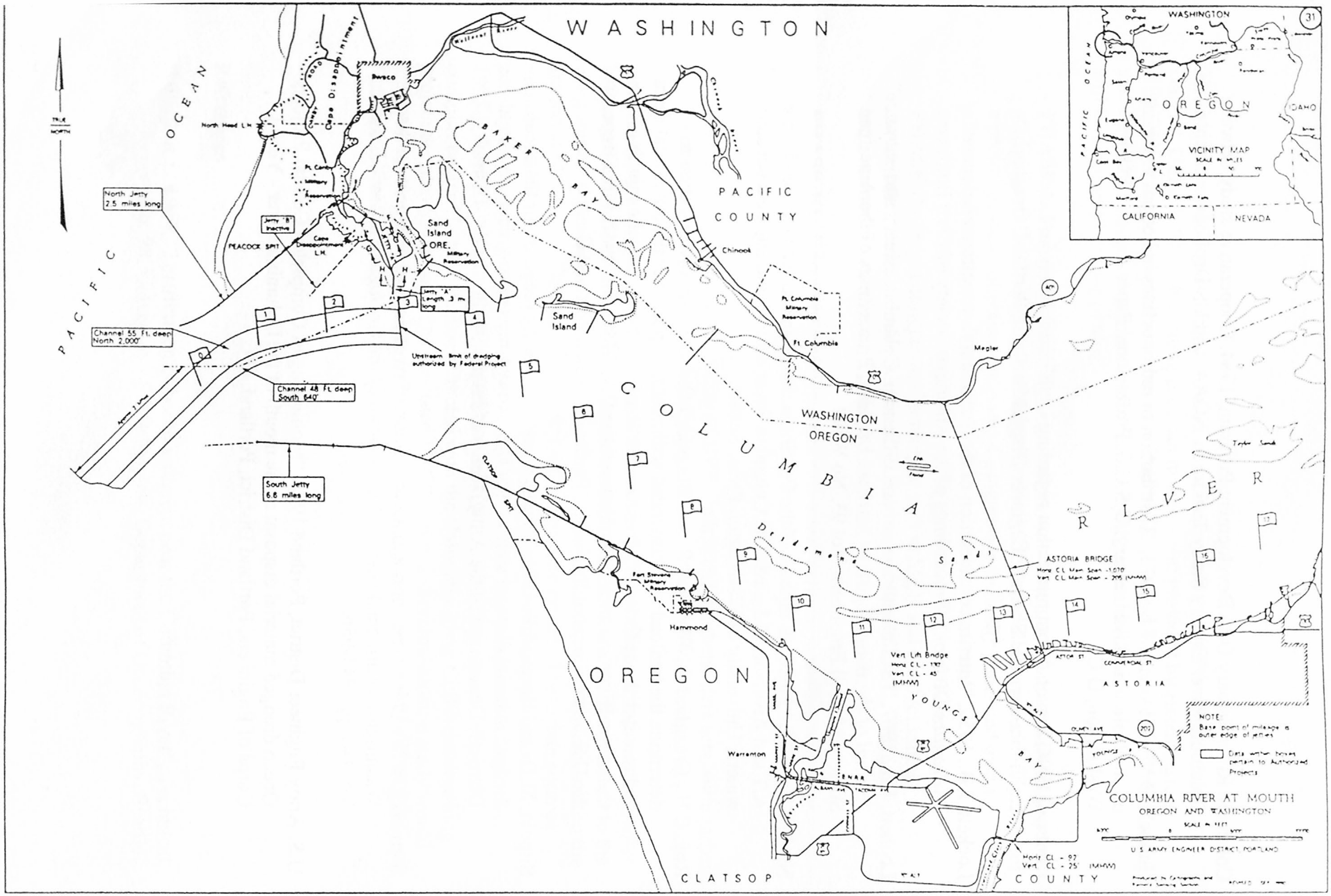

WASHINGTON
PACIFIC OCEAN
TRUE NORTH
North Head L.H.
Cape Disappointment
Ilwaco
BAKER BAY
PACIFIC COUNTY
Chinook
North Jetty 2.5 miles long
Jetty "B" Inactive
PEACOCK SPIT
Cape Disappointment L.H.
Sand Island ORE.
Military Reservation
Jetty "A" Length .3 mi long
Sand Island
Ft. Columbia Military Reservation
Ft. Columbia
Megler
Channel 55 Ft. deep North 2,000'
Channel 48 Ft. deep South 640'
Upstream limit of dredging authorized by Federal Project
South Jetty 6.6 miles long
COLUMBIA
WASHINGTON
OREGON
RIVER
Desdemona Sands
ASTORIA BRIDGE
Fort Stevens Military Reservation
Hammond
OREGON
Vert. Lift Bridge
YOUNGS BAY
ASTORIA
Warrenton
NOTE:
Base point of mileage is outer edge of jetties
Data within boxes pertain to Authorized Projects
COLUMBIA RIVER AT MOUTH
OREGON AND WASHINGTON
U.S. ARMY ENGINEER DISTRICT, PORTLAND
CLATSOP COUNTY
WASHINGTON
OREGON
IDAHO
CALIFORNIA
NEVADA
VICINITY MAP

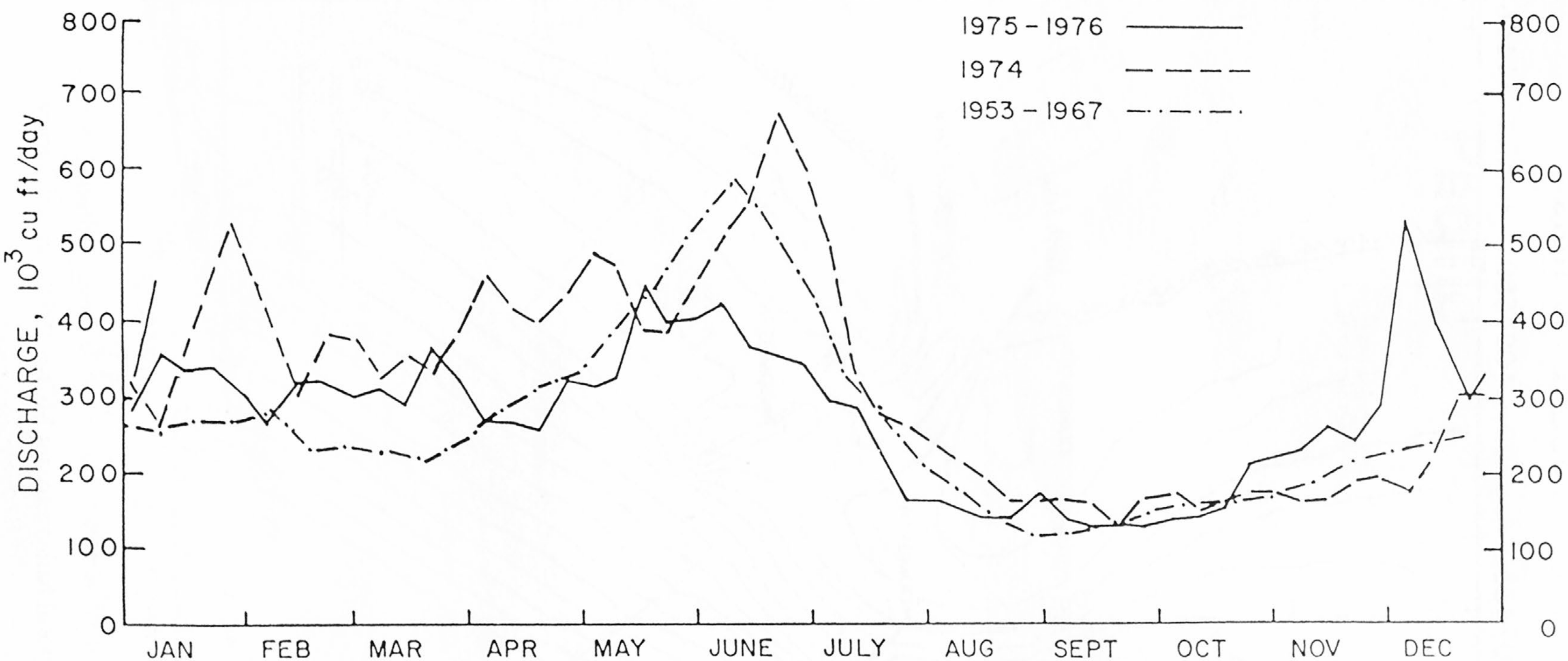


Figure 2. Columbia River discharge curves for 1974, 1975-76, and 15-year mean for 1953-1967 (Barnes 1972).

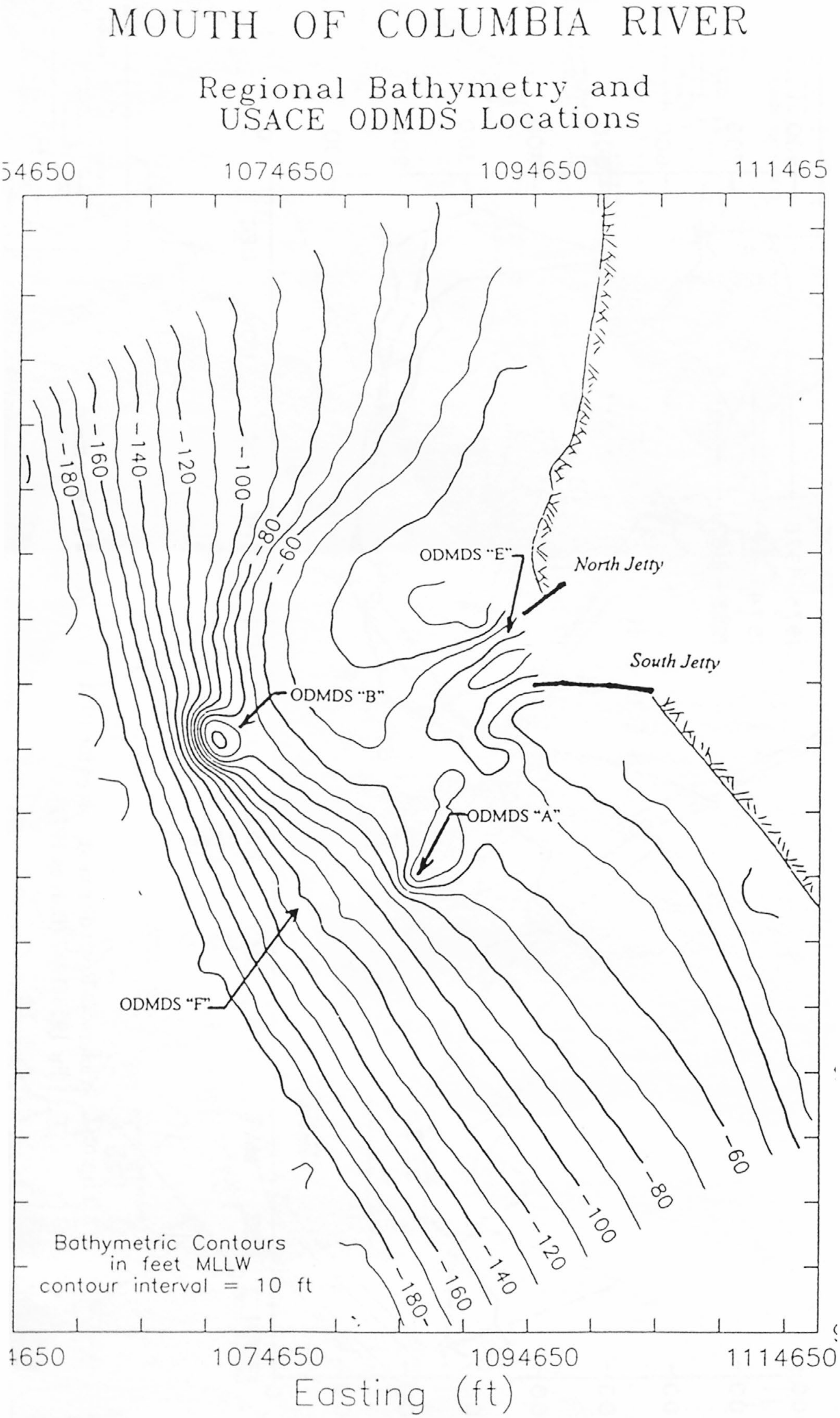


Figure 3. Regional bathymetry for MCR - 1994 approach survey

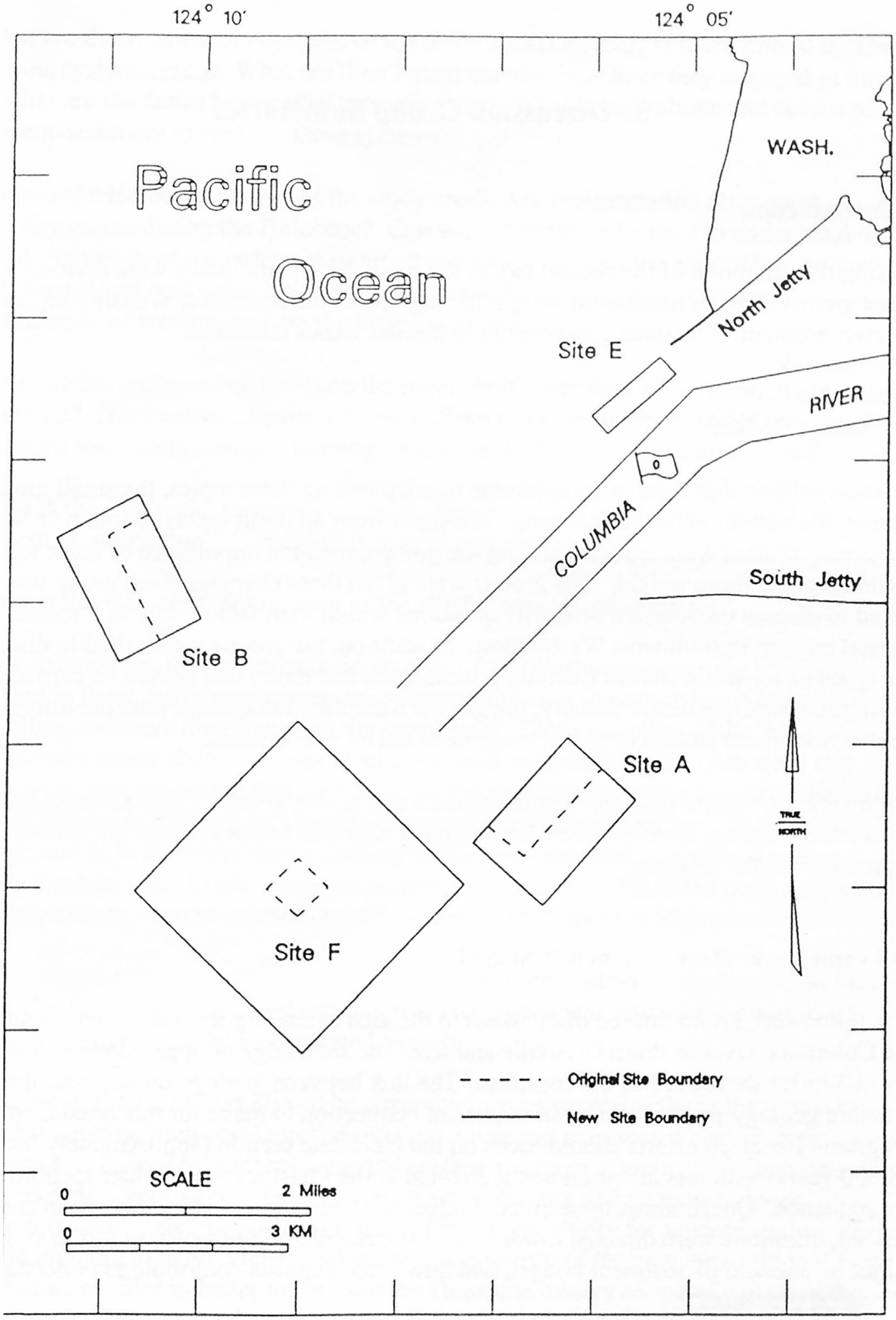


Figure 4. Mouth of the Columbia River ocean dredged material disposal sites

3. Discussion Group Summaries

a) Introduction

During the afternoon of the second day of the workshop, participants were divided into three groups to focus discussion on specific aspects of the southwest Washington coastal erosion problem. The three groups were to discuss issues related to:
- Framework
- Processes
- Sediment Budget

Acknowledging that there is considerable overlap among these topics, the small group format allowed for enhanced exchange and input from all participants. Moreover, where questions or ideas were repeated among the groups, then the importance of those topics could be given more weight. The groups were given three charges. Each group was asked to discuss the relevant scientific questions within their sub-theme, as it relates to coastal erosion in southwest Washington. In addition, the groups were asked to discuss the types of scientific studies (including techniques and tools) that should be carried out to address these questions. Finally, the groups were asked to discuss how the information gained from these studies could be made most useful to end users.

Following are reports from moderators of each discussion group. These sections have been edited, but not have not been substantively changed, so they reflect the course of discussions at the meeting.

b) Framework: Dave Twichell (USGS) Discussion Leader

The framework group limited discussions to the area extending from somewhat south of the Columbia River to Point Grenville and from the shelf edge or upper slope to a line about 3 miles shoreward of the coastline. The link between geology on land and the offshore geology was viewed as an important connection to make for this coastal erosion program. Research efforts should focus on the Holocene section (approximately last 18,000 years) with less attention being directed at the Pleistocene and older sections of the sequence. Questions as to sediment budget were not addressed by this group and, instead, questions were directed toward the Holocene record preserved in this area; how it might be a record of sediment budget, and how these deposits contribute to understanding of coastal processes.

Several important scientific questions were raised regarding the Geologic Framework and the coastal erosion problem.

* What are the sedimentary systems of the study area (i.e., shelf system, littoral system, estuarine systems, etc.)? What are their lateral extents, how have they changed in time, and what are the facies boundaries between them? What is the volume and source of Holocene sediment in each of these systems?

* What is the Holocene history of the study area? Are sedimentation rates constant, or have they varied during the Holocene? Can this information be used to understand the natural variability of the sediment supplied and removed from the area? How do the shelf, barrier spit, and estuarine deposits record variations in rates of sediment accumulation or erosion, and are the histories in phase?

* What are the sedimentary facies on the inner shelf? Are they all modern, or are some of them relict? Have anthropogenic activities affected the sedimentary facies (i.e., has the inner shelf sand sheet changed lithology since damming of the Columbia River?

* What is the "bedrock" geometry of the study area, and how has it influenced the sites of sediment accumulation? Does (did) it control present location of barrier spits and inlets?

* What is the Holocene stratigraphy of the shelf, barriers, and estuaries?

* How extensive is the recent tectonic activity of the Washington margin, how is it recorded in these differing sedimentary systems, and how important has it been in controlling sediment distribution in the study area? Tectonic activity falls into two parts: 1) Are there minor changes of sea level associated with earthquakes (Atwater's and others work indicates there are), and do these events affect the entire length of the study area uniformly, or are they localized (submerged shorelines might provide some insight to this); and 2) Is there any active faulting in the study area and how does it influence shelf sedimentation? Could the deposits exposes along the cliffs in the northern part of the study area be used to extend the tectonic record back into the Pleistocene?

What types of data are needed to answer these questions? Most of the discussion focused on the shelf and barrier spit systems, but it is recognized that estuaries are part of the puzzle and will need to be incorporated as well.

On the shelf, the first phase should be a reconnaissance survey of the entire study area using bathymetry, high-resolution seismic profiling, and side-scan sonar imaging techniques, followed by a vibracoring and surface sediment sampling. Follow-up studies might include complete coverage side-scan sonar surveys of key areas to more completely understand the surficial sediment facies variability for process studies, deeper seismic imaging to better understand the tectonic history of the area, or additional cores and seismic profiles to better understand the Holocene history of specific parts of the area.

Geologic mapping on land varies in its level of detail from area to area. A unified compilation of the surficial and shallow subsurface geology is needed. Aerial photographs need to be gathered and the historical shoreline change compiled for the whole study area. On the barrier spits, a more extensive network of ground-penetrating radar profiles and cores are needed to more fully understand the history of these systems.

The surf zone will need to be mapped, but time will need to be spent to assess the availability and feasibility of tools for working in this high-energy area (i.e. surfboards and jet skis may be fun, but do they give us what we need?).

Who are the users of these results? There are several levels at which the results from the framework part of this project would be useful. One suggestion by members of the discussion group was that a "Coastal Atlas" could be produced that summarized the topography/bathymetry, sediment inventory, surficial geology, shallow subsurface geology, shoreline change, tsunami runup, etc. that would be useful for land-use planners, public works officials, the Army Corps of Engineers, and the general public. The results from the framework part of the project also should be directly fed into designing and planning the processes component of the project, and hopefully will provide an historical perspective to the studies of sediment budgets and influence of tectonic framework on these budgets.

c) Processes: Chris Sherwood (CSIRO) Discussion Leader

The Processes Discussion Group agreed that the ultimate goal of the SW Washington Coastal Erosion Study is to further our ability to predict coastal evolution in the region. The words "coastal evolution" include erosion, accretion, and morphological change, without placing relative merit on any of the three processes. To be testable, our scientific understanding of coastal evolution must allow for quantitative predictions. The ability to predict phenomena provides a critical test of our scientific understanding of the processes involved. In an applied problem like coastal erosion, reliable predictions are also immediately useful and valuable to the public. Therefore, the study should endeavor to make reliable predictions of coastal evolution.

To be responsive to the needs of local residents, businessmen, developers, and resource managers, our predictions must answer specific questions. For example, users might ask:

* How long will my investment (house, business, marina) be there?
* Can I protect my investment from coastal erosion?
* What is the likelihood of a tectonic event (e.g., sudden subsidence of the coastal region)?
* What hazards associated with a tectonic event are likely to affect my investment?

Part of the research planning should involve the intended users and determine, specifically, what they would like to know about coastal processes like erosion. A more complete list of questions posed by potential users of the study results should be made. They should be used to focus the study efforts. An atlas of predicted coastal evolution might answer many of these questions, and was suggested as a primary product of the study. The group agreed that an atlas with maps indicating likely future areas for erosion, accretion, tsunami hazard, and other features related to coastal evolution would be a good product that could transmit study results to users.

Any study will have to deal with working constraints: Space Scales, Time Scales, Uncertainty, Project Budget. There was lengthy discussion about the scope of the study, and the problems posed by the range of space and time scales at which important processes operated. The common problem of expanding and integrating processes observed on small space and time scales to regional and historical scales was discussed. The group recognized that our understanding of sediment-transport processes was not sufficiently complete to implement them in a deterministic manner on a large scale and that, even if it were, our knowledge of forcing and boundary conditions is not sufficiently detailed to obtain accurate results. The reality of a limited research budget adds another constraint. Designing the best research program, therefore, means finding the optimal balance among the various "degrees of freedom" represented by time scales, space scales, accuracy and precision in results, and research budget.

With the objectives and constraints in mind, the group began to focus on specific scientific questions that could be addressed by the project. The following list of scientific questions about processes that result in coastal evolution was generated:

* Littoral cells - Where are they, what are their key characteristics, and how do they change? Complete characterization of littoral cells includes defining the volume of sediment they contain, the processes which drive transport in the cells, the mean rates and directions of sediment transport in the cells, the variability and associated time scales for changes in transport and sediment volumes, and the long-term trends.

* Role of climate variations and trends - How has the El Nino cycle, local sea-level trends, and other long-term variability in the weather affected coastal erosion?

* Role of anthropogenic changes - How has construction of jetties, dredging, dam construction, dune modification, resource extraction, and changing land-use practices affected sediment supply and coastal erosion?

* How does the circulation near the inlets determine sediment erosion and accumulation?

* How do ocean swells, local wind waves, tidal currents, and estuarine circulation combine to control sedimentation and erosion in the system?

* What is the sediment budget for the southwest Washington coastal system? How much sediment is input to the system (from rivers and coastal erosion) and how much is lost to depositional environments on the outer shelf, slope, canyons, and fans, or by permanent removal to downdrift regions beyond the study area, such as south of Tillamook Head, or north of Point Grenville? What are the sedimentary budgets for individual compartments within the system (nearshore regions, barrier beaches, ebb-tidal deltas, tidal shoals, mudflats, etc.) and how do they change over time?

The group discussed several testable hypotheses. These questions may be better addressed if posed in the form of hypotheses to be tested during the study. The following list of hypotheses was generated:

* Supply of sediment from the Columbia River has decreased.

* Reduction in Columbia River sediment will lead to an increasingly erosional environment on the southwest Washington coast.

* There is an offshore boundary for the littoral zone.

* There is an equilibrium profile that is maintained and shifts (up and down, or onshore/offshore) with depositional or erosional events.

* Extreme events dominate the system.

An overriding hypothesis is that anthropogenic changes have affected the system. More specifically, the group hypothesized:

* Jetty construction has affected deposition and erosion on adjacent spits and flood- and ebb-tidal deltas.

* Dune modification and stabilization has affected aeolian transport rates and beach sediment volumes.

* Introduced species (e.g., Spartina) have changed sedimentary processes in shallow bays.

* Dredging has relocated significant volumes of sediment and produced bathymetric changes that alter sedimentary processes.

* Drift logs have a significant impact on beach stabilization and erosion, and their numbers and extent has changed.

* Uplands land use (logging, farming, development, fertilization, irrigation return) has changed, and the changes have affected coastal sedimentary processes.

* Resource exploitation (e.g., oyster farming, razor-clam harvesting) has affected coastal sedimentary processes.

* Diking, bank stabilization, remedial habitat creation, and other activities have affected tidal prisms, sediment supply, and sedimentary processes.

An extension of these hypotheses is:

* Large-scale modifications to the system, such as orientation of jetties and channels can influence coastal evolution,

and a corollary is;

* Radical changes in breakwater and jetty design, or re-alignment of channels, could be used to change (and improve) coastal evolution.

The growth of shoals and spits on the north side of inlets (e.g., Peacock Spit, North Beach of Grays Harbor) may be explained with several hypotheses, some of which are contradictory:

* The net accumulation is a product of southward sediment transport interrupted by the jetty.
* The net accumulation is a product of convergence in net northward transport.
* The shoals are artifacts of channel orientations.
* The shoals are products of seasonally varying wave energies.

Specific hypotheses concerning parts of the system were also posed:

* Willapa Bay is migrating northward.
* The South Channel of Willapa Bay will someday become the dominant channel for tidal exchange, effectively halting the northward migration, at least temporarily.

The above is only a partial list of hypotheses; additional general hypotheses may help to outline our current understanding of the systems, and additional specific hypotheses may be posed and tested to determine our ability to predict coastal evolution processes at a useful scale.

Ideally, the following measurements, data, and models would be available to test these hypotheses:

* Time series of nearshore and beach bathymetry and topography (beach profiles, dune or cliff retreat rates, time series of historical shoreline position).

* Time series and/or hindcast capabilities for ocean waves and currents (buoy records, mooring records, models).

* Time history (and predictions) of local sea level (tide-gage records, geodetic records, earthquake models).

* Bottom-sediment data (maps of surface and stratigraphic distribution from grab-samples, cores, and high-resolution seismic or radar profiles).

* Time series of river flow and sediment discharge for the Columbia River, Copalis River, Chehalis River, and tributaries to Willapa and Grays Harbor.

* Sediment-transport measurements to verify process models.

* Identification and distribution of tracers.

* A diagnostic process model to investigate relative influence of various forcing and boundary conditions.

* An accessible prognostic model for users to assess impact of changes to the system.

Not all of these measurements and data sets will be available, and the models will be limited in resolution. The actual measurements, data, and models needed will be chosen to answer specific questions or test specific hypotheses.

d) Sediment Budget: Curt Peterson (Portland State Univ) and Rod Moritz (Corps of Engineers)

Identify users of study results: who is impacted by erosion, and what are the biggest impacts?

Affected users include:

* Users of navigation infrastructure.
* Land-use planners, planners/developers/managers/engineers/consultants.
* Local citizens committees, fisherman, and fisheries resource managers.
* The US Army Corps of Engineers, regulatory agencies, environmental agencies (both Federal and State).

Is the project predominantly applied science, or basic science?

The group noted that there is a trade-off between providing immediate answers for (perceived) problems in the short-term, or performing a longer-term study that is designed to provide a foundation for solving problems in the future.

Products and Marketing

The group listed several products that the study should produce.

* Reliable predictions of future changes in the coastline. These would include data that could be used in determining set-back maps to protect future coastal development. The predictions should be local in nature, and provide a way of accessing the integrated results of the project. A probabilistic approach should be used in product generation.

* Outreach and education of interested constituents should be stressed. Information should also be solicited from citizens and local officials, in part to build local support for the project, and in part because the needs of these constituents form the basis for questions to be addressed by study investigators.

* A data base and bibliography should be compiled to catalogue existing information for retrieval and use by investigators and the public. The data base must be easily accessible, reliable, and widely available, possibly via the Internet.

Study products may need to be provided in a variety of forms to various users and investigators. The processes of differentiating and massaging data for different purposes means that both raw and processed (e.g., interpreted) data products should be provided. A formal review and approval control structure might be necessary. Issues of how "meta-data" should be formatted and distributed should be addressed, along with overall issues of quality control, indexing, and contents description. Geographical information system (GIS) issues, such as the whether a GIS should be used primarily for map-making or as a data base were deferred for later, but it was agreed that data should be acquired and stored in a manner compatible with later incorporation in a GIS. Later in the discussion, the group noted the need for annual project milestones: specific data and analysis products to ensure that the project was supplying suitable returns for the invested project funds.

Questions posed to guide the study should be unbiased, and study results should provide definitive answers. Ideally, questions should be posed in terms of testable null and alternative hypotheses. For example:

* What is the baseline condition; i.e., what were the prehistoric conditions in the study area in the late Pleistocene and early Holocene?

* How have the dams on the Columbia River affected the shoreline?

* First, ask: what is the influence of the Columbia River on the SW Washington Coast? How much area does it influence, and over what time scales? In order to answer this, the study must determine the condition of the Columbia River over time, and the conditions on the southwest Washington coast over time. In the river, it is vital to determine the changes in the sediment budget in the reservoirs, and changing contribution of soil erosion as land-use practices have changed.

These raise the question: how far back should we extend these studies, and how far into the future can we predict trends? The same questions apply to spatial scale: how far need we extend studies to understand the system, and over what scales can we predict change? Relevant time scales include the 50-y economic lifetime for projects, the 100-y "realizable" life for physical impacts of major projects (e.g., jetties and dams), and the 200-y time scale for cyclical changes in tectonic processes. The aerial extent of the study should extend from the estuaries to the abyssal plains. Studies of the estuaries is clearly important because they provide sediment to the outer coast, but determination of the sand fraction (which forms beaches) in the muddy total load is problematic. One approach is to correlate supply rates with accumulation rates in nearshore, mid-shelf, and offshore regions (including the abyssal plains). This must be approached by correlation with nearshore budgets.

The group agreed that an assessment of sediment impoundment behind the dams was critical. Possible measurement techniques include cores, high-resolution seismic stratigraphy, and differencing of repeat bathymetric surveys.

The group suggested that study of the affects from the subduction quake in 1700 could help determine shoreface erosion and accretion rates.

Several processes that cause or affect coastal erosion were listed by the group:

* Annual variations in alongshore sediment transport, with changes in both direction and magnitude.
* Localized effects of estuarine circulation near the inlets.
* Long-term variability of alongshore transport (including fluctuations in magnitude and potential changes in direction).
* Coupled effects of El Nino and regional oceanic circulation on alongshore transport and onshore/offshore transport.
* The role of beach-ridge complexes...are they built by cross-shore processes or alongshore processes?

A partial list of data needed includes:

* Evaluation of existing cores in abyssal regions
* Collection and analysis of gravity cores from the midshelf mud blanket to prepare an isopach map.
* Evaluation of changes in the inner shelf and shoreface region through analysis of existing or new bathymetric data, shallow high-resolution seismic data, and dated cores.

e) Summary of Discussion Groups

Several common themes emerged from all discussion groups. First, all three groups discussed issues nominally assigned to other groups. This tendency confirms the need for an integrated interdisciplinary approach to defining the study. The framework group recognized that the geological underpinnings of the region were relevant if they influenced processes controlling the supply and distribution of sediment. The process group and the sediment budget group viewed coastal erosion as two sides of the same coin. It became clear that, in some cases, determination of sediment budgets would shed light on the sedimentary processes that control coastal erosion (particularly over the long term). On the other hand, it is the cumulative effect of processes that determines sedimentary budgets. It was generally surmised that the rates of key processes have changed in historical time in response to human activities. It was also recognized that there are natural cycles and episodic events that have probably also affected rates of sand transport and accumulation in the last several hundred years, and that this natural variability will make it harder to identify the "real" cause of recent beach erosion.

Most of the participants naturally approached the problem from the perspective of their own discipline. Fundamentally, the study is about sand: where it comes from, how it is moved, and how the supply and transport patterns have changed over the years to cause beaches to accrete and erode. Because most of the sand has, as its provenance, the Columbia River, the supply of sand from the river and changes in that supply are apparently one key to fluctuations in beach sand supply. Because contemporary fluvial and coastal oceanic processes combine to transport the sand, spatial and temporal variations in their action, combined with the availability of sand, ultimately determines the distribution of sand. The processes operating today and in the future are the only processes relevant for predictions, but the integrated effect of the processes which acted in the past have produced the coastal evolution we can observe today. These processes operate within the context of local sea level and river gradients on a terrain established by the framework geology, which also cannot be ignored. In addition, there is storage of sand over geologic time scales in deposits of Holocene and Pleistocene age that cannot be omitted from the budget calculations. The transport processes are difficult to measure, and nearly impossible to extrapolate over sufficient time and space scales to determine their integrated effects, so many of the participants recommended studies to determine the integrated result of past processes. These approaches include analysis of bathymetric changes and stratigraphic interpretation of cores and seismic data. Study planners will have to determine which approaches are likely to be more practical, or provide a more direct return on invested effort.

All of the groups recognized that, to be successful, the study should provide relevant (meaning immediately useful) products to the people affected by erosion on the southwest Washington Coast. All noted that to accomplish this, input from local citizens, businessmen, politicians, resource managers, and agency bureaucrats was needed from the start. And, to provide value for these ultimate users of the study, it should generate products designed for public consumption and practical application. To ensure that the study produces reliable products in a timely fashion, many of the group members recommended that good management and quality-control practices be used. Finally, there was widespread agreement that, unless the study was conducted with a high regard for scientific quality, the benefits would be short-term and illusory.

4. Columbia River Littoral Cell Sediment Budget - Identification of Compartments and Pathways

Coastal erosion on the southwest Washington coast may be related to long-term changes in supply of sand from the Columbia River. To test this hypothesis, a history of the sources, reservoirs, and sinks of Columbia River sand must be compiled and examined. In addition, rates of past, present, and future transport from sources, through reservoirs, to sinks must also be examined. In an attempt to asses the state of our knowledge, and to begin a discussion of the fate of Columbia River sand, a sediment budget will be examined. Preliminary numbers attached to this sand budget can be used to test the hypothesis and guide further research. The following sections outline a conceptual framework for evaluating the sediment budget for the Columbia River littoral cell. Ultimately, a well developed, quantitative sediment budget for this littoral system will allow for predictions of future shoreline position based on the sediment supply.

Study Area

The southwest Washington coastal system has natural boundaries that coincide closely with the distribution of sand derived from the Columbia River. Geographically, the boundaries extend along the coast from Tillamook Point, OR to Point Grenville, WA. The eastern boundaries trace the maximum elevation of Holocene fluvial deposits along the lower Columbia River valley (below the Bonneville Dam) and fluvial and estuarine deposits along the lowlands of coastal Washington. For most purposes, the eastern boundary and the shoreline are nearly identical. The western boundary extends to the limit of significant sand deposits. On the central Washington shelf, the boundary is somewhere on the outer shelf but, near submarine canyons, the boundary extends down to the submarine fans.

Compartment Size

A proposed set of budget compartments is shown in Figure 1. Each compartment is intended to represent a generalized sedimentary environment, but most actually incorporate several sedimentary environments. Each compartment is connected with adjacent and distinct compartments by a limited number of transport pathways. When numerous sedimentary environments are grouped (e.g., islands and filled regions in the Columbia River Estuary), the objective has been to simplify the compartments and remove detail that obscures the overall budget. On the other hand, some continuous environments (such as the nearshore zone) have been subdivided to correspond with adjacent beaches. In these cases, the objective has been to clarify the connections and sand exchanges among geographically adjacent compartments. To some extent, the size of the compartments must be chosen to match available budget data. Where detailed data are available, it will be easy to sum budget terms within a compartment. Difficulties will arise when data are only available over large geographic regions that include several compartments; in these cases, good judgment will be required to subdivide rates or inventories correctly.

The large size of the compartments suggests that the shortest reasonable time scale over which "instantaneous" fluxes can be reasonably estimated (or measured, or calculated) are entire transport events. This time scale might be as short as a single tsunami or a single tidal cycle, or as long as a several-day storm or flood. Ideally, the compartments are defined so that fluxes during an event will have a well-defined direction. That is, transport across the entire boundary of adjoining boxes is in the same direction for the entire event. For example, during a beach-erosion event, eroded sand can be transported offshore from a beach compartment to a nearshore compartment. Alternatively, during periods of fair weather, sand may move from the nearshore to the beach compartment. Over long periods of time, transport in both directions will occur, and a net flux can be calculated. The longest period over which we can expected fluxes to remain constant is probably a few tens of years.

For purposes of inventory, the compartments have vertical sections that correspond to the time-stratigraphic column shown as an inset to Figure 1. As a starting point, we can use stratigraphic information to relate deposits to inventory changes over geological periods.

Inventory, Flux, and Long-Term Net Flux

The budget is to be quantified for a number of compartments that are more or less fixed in space. At any given time, each compartment contains an inventory of sand that can be expressed in terms of mass of sand [kg]. It will probably be convenient to convert sand mass to sediment mass by dividing by a sand fraction [kg/kg] specific to each compartment, and to in situ volume [m^3] by dividing with a universal bulk density [kg/m^3]. In this manner, sand inventories can be related to the area of the compartment [m^2] and the mean thickness of sedimentary deposits [m]. Sedimentary processes result in fluxes of sand from one compartment to another. Fluxes are mass-transport rates [kg/s], which are nominally instantaneous. By integrating all fluxes into (and out of) a compartment over some period of time (say one year), long-term net fluxes can be determined [kg/yr]; these can be divided by bulk density, area, and fraction of sand in the final deposit, and time interval to obtain average deposition (or erosion) rates [m/yr].

Fluxes occur exclusively along the transport pathways indicated with thick lines in Figure 1. The conceptual model should be modified if other quantitatively important pathways are identified. The pathways are, in general, bi-directional . A few of the pathways are unidirectional; these are indicated in Figure 1 with arrows. Transport rates include both natural phenomena and human activity (e.g., dredging). The goal is to identify a system of compartments and pathways with transport that will be unidirectional at the event time scale. If such a system can be identified then it is possible, at least theoretically, to estimate fluxes for individual events and integrate over time to determine net fluxes and inventory changes in each compartment. If long-term fluxes can be assigned to each of the pathways, then long-term changes in sand inventory can be estimated for steady-state conditions. Conversely, long-term estimates of changes in sand inventories can be used to constrain transport rates.

Compartments identified in the sediment budget

Sources of Sand

The primary source of sand is the Columbia River, which provides sand with three provenances: the main basin east of the Cascade crest (East Side); the Cowlitz and Toutle River drainages (Cowlitz/Toutle), which provide sediments from lahar deposits on the west flank of Mt. St. Helens; and other west-side river basins, including the Willamette, Lewis, and White Rivers (West Side). Much smaller sources of sand include the Chehalis River (Chehalis River) and erosion of bluffs near Copalis Point (Copalis Bluffs). Transport from these sources is one way, and they are shown in Figure 1 as rounded boxes. There are no other significant sources of sand for the coastal system. Erosion of pre-Holocene deposits, supply from other rivers, and littoral transport from other systems is considered negligible. The contribution from erosion of Pleistocene deposits is unknown and may also need to be considered.

Reservoirs and Estuaries

Sand may be accumulating in reservoirs in the western sub-basin and along the main stem of the Columbia River (Dams). Sand transported from the East Side may be diverted to this compartment and, under some circumstances, the reservoirs might act as a source of sand contributing to supply from the West Side.

Estuaries store, at least temporarily, most of the sand delivered to them by rivers. The proposed framework includes several river channel and estuary compartments for sand budget estimates. The lower Columbia River channel (Lower CR Channel) includes large sand supplies associated with bar deposits and large bedforms. In general, river beds aggrade at low rates and, in the absence of human alterations to the system, most sand supplied to the upper end of the lower CR channel might transit the reach and enter the estuary. The net accumulation rate caused by permanent storage within the reach might be estimated from stratigraphic evidence. However, due to damming of the Columbia River and channel maintenance activities probably means that recent sediment fluxes do not reflect longer term Holocene rates. In particular, human activities have resulted in permanent removal of sand from the river channel, and changes in channel sand storage patterns. A compartment (Fill) has been added to specify sand permanently removed from the active channel system by dredging and filling activities, sand mining, etc., and a compartment (Pile Dikes) has been designated to represent temporary storage of sand (e.g. in accumulations behind pile dikes) in the altered river system. In the estuary proper (CR Estuary), sand may be temporarily stored in bars, shoals, estuary beaches, and mudflat (Mudflats) or permanently removed to diked islands, artificially fill, or dredge-spoil islands (Islands & Fill).

Compartments are also assigned to the other large estuaries in the study area (Grays Harbor) and (Willapa Bay). Note that the proposed transport is unidirectional into Willapa Bay. Although this is not strictly true, it may be sufficiently accurate for budget purposes. Also, direct exchange between the beaches and estuaries is not included. This decision was made to simplify the budget framework, and is based on the argument that the associated transport processes (e.g. erosion of the landward side of the beaches or aeolian transport from the beaches to the estuaries) is negligible. If these transport processes cannot be neglected, then the pathways must be considered and added to the framework.

Beaches, Nearshore Regions, and Ebb-Tidal Deltas

As noted above, compartments representing beaches flank entrances to the three estuaries. Beach compartments (Clatsop Spit, Peacock Spit, Long Beach, S. Beach, and Ocean Shores) include the foreshore, dunes, and overwash platforms in back-beach lagoons. In the proposed framework, beaches only exchange sediment with adjacent nearshore compartments (NS) or with adjacent ebb-tidal deltas (ETD). This acknowledges the key role that these areas play in both temporary and long-term storage of sand. The present framework is not sufficiently detailed to address changes in erosion or deposition within a littoral cell. If this framework suggests changes in sand inventory for beach compartments that match overall changes, then more detailed modeling within individual littoral cells will be warranted.

Mid-Shelf Compartments

The mid-shelf region has been subdivided among three compartments (Mid Shelf). These are regions of the shelf separated by submarine canyons that interrupt alongshelf transport. Although the mid-shelf regions play a less dynamic role in the sand budget, they are important to include because they provide long-term sand storage, and several geological estimates of shelf deposition rate have been made that allow the mid-shelf compartments to place useful constraints on other boxes.

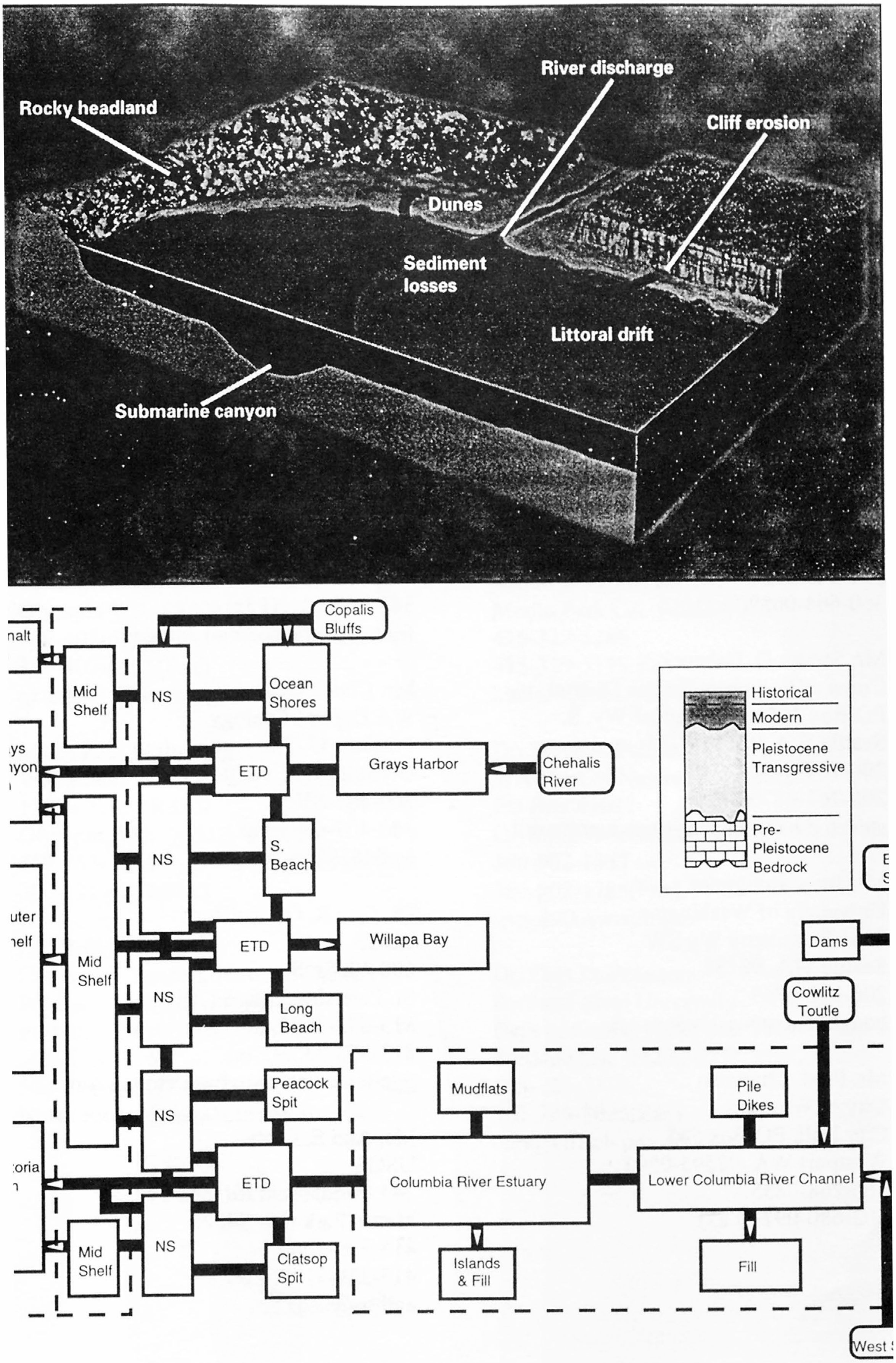
Ultimate Sinks of Sand

Several compartments represent sinks for sand in the coastal system. These include the submarine fans and abyssal plains (Astoria Fan, Grays Harbor Fan, and Quinalt Fan) and the outer portion of the central Washington continental shelf and slope. These offshore sinks are grouped in a single dashed box in Figure 1. Also included as sink compartments are diked islands, and artificially filled areas in the estuary and along the riverbanks. Transport is one way into all of these sink compartments.

Conservation of Sand

At any given time since the Pleistocene, the sand budget must balance over the entire system. That is, the sum of all sand from the five source compartments, must equal the amount delivered to the six sink compartments plus the amount accumulating in other compartments. Long-term estimates of deposition rates in the sink compartments can be used to place minimum lower limits on the sand supply from the various sources. Likewise, comparisons of long-term deposition in the lower Columbia River valley (shown in Figure 1 as a dashed box that encompasses the Columbia River estuary and the lower Columbia River valley) and long-term supply from the Columbia River may be used to put constraints on the supply to coastal regions beyond the estuary.

Coastal Sediment Budget



re 1. Schematic block diagram of dominant components of a coastal sediment budget (uppe
letailed components of the Columbia River sediment budget (lower). (NS = nearshore,
= ebb-tidal delta)

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