Attachment A

Sediment Trend Analysis and Acoustic Bottom Classification in the Mouth of the Columbia River (Implications to Dredged Material Disposal and Operations and Coastal Erosion)

By

GeoSea Consulting Ltd.

Funded By

EPA, Region 10 and USACE, Portland District

2001

UNITED STATES ARMY CORPS OF ENGINEERS
CENWP-EC-HR
PORTLAND, OREGON

and

WEST CONSULTANTS
BELLEVUE, WASHINGTON

(Contract No. DACW57-00-D-0003, Task Order No.07)

A SEDIMENT TREND ANALYSIS (STA®) AND AN ACOUSTIC BOTTOM CLASSIFICATION (ABC) IN THE MOUTH OF THE COLUMBIA RIVER: *IMPLICATIONS TO DREDGE DISPOSAL OPERATIONS AND COASTAL EROSION*

By:

Patrick McLaren, Ph.D., P.Geo.
Steven Hill, Ph.D., P.Eng.
GeoSea® Consulting (Canada) Ltd.
789 Saunders Lane
Brentwood Bay, BC, V8M 1C5
Canada

April 2001

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

1.0 INTRODUCTION

1.1 Background

The US Army Corps of Engineers is responsible for the navigational maintenance of the entrance to the Columbia River, including the jetties and navigational channels (Fig.1). The latter include the mouth of the Columbia River and main stem Columbia River federal navigational channels. Dredged material from the mouth is placed offshore in EPA designated disposal sites. These have been recently enlarged and their use increased. If authorized, material from the Columbia River, including its estuary, will also be placed in offshore EPA designated sites (Ocean Dredged Material Disposal Sites; ODMDS). The fate of the material placed at these sites is of prime interest in their management and monitoring. To obtain this information GeoSea was contracted by the Corps under subcontract to West Consultants to carry out two types of studies.

The first uses a technique known as Sediment Trend Analysis (STA®), which was invented and developed by GeoSea. STA derives patterns of net sediment transport from relative changes in the grain-size distributions of bottom sediments. In addition, the technique defines the dynamic behavior of the sediments with respect to erosion, deposition or equilibrium. Such knowledge provides a clear indication of how dredged material introduced into the marine environment is likely to behave.

The second study, known as Acoustic Bottom Classification (ABC), is a method of inferring and mapping sea-bottom characteristics based on an analysis of the returning echo from a standard depth sounder. It provides complementary information to the STA, and has the advantage of more-or-less working itself during the fieldwork necessary for STA.

To encompass all disposal sites associated with the Columbia River mouth, the study area was chosen to extend from inside the river mouth seaward to the 350-foot isobath. This area is divided into three regions each with a different sampling density based upon the complexity of the bathymetry and level of interest. Area A lies between the 350 and 120-foot isobaths, thereby encompassing a proposed Deep Water Site (Fig.1). Area B includes the entire river mouth including the north and south shelves, the ebb delta, and the river itself. Finally Area C incorporates Peacock Spit, a region of specific interest given that the beaches between the North Jetty and North Head are known to be eroding. Thus the fate of material placed at the proposed shallow water site (ODMDS E) is of prime concern.

1.2 Objectives

The specific objectives of this study are as follows:

(1) Collect about 1,250 sediment grab samples from the study area.

(2) Analyze all samples for their complete grain-size distributions and input into a Geographic Information System (GIS).

(3) Classify and map, using information from the grab sampling program and the acoustic data collected from ABC, bottom types (including the area presently being affected by the ongoing disposal program) from the river to a depth of 350 feet, and include this information in the GIS.

(4) Undertake STA using proprietary software developed by GeoSea in order to establish the patterns of net sediment transport, areas of erosion, deposition, and dynamic equilibrium.

(5) Discuss (i.e., compare and contrast) the results of STA with the present understanding of processes as described in previous and ongoing work.

(6) Use the results of the grain-size analyses, ABC, and STA to:
  (i) Delineate sediment transport pathways and their dynamic behavior throughout the study area;
  (ii) Identify sediment sources and sinks;
  (iii) Identify the areas potentially impacted by disposal operations;
  (iii) Propose optimum locations for specific process measurements required to determine transport rates, if desired;
  (iv) Determine the probable long-term fate of dredge material.
  (v) Advise, if applicable, on disposal options to mitigate undesirable affects or, conversely, determine areas where dredge material could be placed to ensure optimum benefits such as beach replenishment on Peacock Spit.

1.3 Field Methods

Sediment grab samples were collected from Aug. 23 to Sept. 7, 2000, using *GeoSea*, a 50 foot steel motor-sailor equipped with a hydraulic winch and Shipek grab sampler. This grab sampler enables the top 10 to 15 cm of sediment to be sampled. Many of the nearshore samples were collected with a 12-foot, hard-bottom inflatable speedboat (Caribe) equipped with a depth sounder, a small electric winch, and a portable grab sampler. Positioning was achieved on the speedboat with a hand held Differential GPS (Garmin GPS75 and Garmin GBR21), providing a typical accuracy of ±5.0 m. *GeoSea* itself was equipped with Trimble DS212L GPS with a 2 to 5 m accuracy in differential mode.

In most instances, samples were obtained at predetermined locations (Fig.1); however, where shoreline structures (jetties, pilings etc.) interfered with navigation, a sample was collected as close as practical to the planned position. Representative samples from each successful grab were stored in plastic bags and transported to the GeoSea laboratory in Brentwood Bay, BC, for grain-size analysis.

Samples were collected on a regular, hexagonal grid with a spacing of 1,000 m over the deep-water region (Area A, Fig.1). Areas B and C were sampled at a spacing of 500 and 250 m respectively. A total of 1,252 sample sites were visited, at 21 of which, a sample could not be obtained. A sampling site was designated a failure after at least two drops of the grab failed to retrieve a sample. Failures were generally in deep water (typically greater than 200 ft) and were likely the result of difficult swell conditions rather than the presence of a rocky or scoured bottom. Sites where samples were unobtainable are mapped as “No Sample” (Fig.2).

During the sediment-sampling program, ABC was undertaken continuously with the vessel’s echo sounder, a dual frequency SITEX CVS-108DF, and a 200kHz QTCView system. For this survey the QTCView was set up to encompass a depth range from 5 m to 100 m. The acoustic data were logged from *GeoSea* to a computer together with position and time. Classification information was merged with the results of the grab sampling program and with field notes to produce the best classification catalogue for the region. Full details of the ABC program are included in Appendix II.

1.4 Grain-Size Analyses

All samples were analyzed for their complete grain-size distribution using a Malvern MasterSizer 2000 laser particle sizer. The laser-derived distributions were combined with sieve data for particles larger than 1500 microns in diameter using a merging algorithm developed by GeoSea Consulting[1]. The size distributions were entered into a computer equipped with proprietary software to establish sediment trends and transport functions. A more complete description of the grain-size analytical technique is provided in Appendix III

2.0 STA THEORY

The technique to determine the sediment transport regime utilizes the relative changes in grain-size distributions of the bottom sediments. The derived patterns of transport are, in effect, an integration of all processes responsible for the transport and deposition of the bottom sediments. The latter may be considered as a facies that is defined by its grain-size distribution. The original theory was first published in McLaren and Bowles, 1985; a more up-to-date version is described in Appendix I, which is briefly summarized in the following paragraphs.

---

[1] The grain-size data (listed in Appendix II) are supplied on a disk as an Excel worksheet containing sample locations and the complete phi distributions of the sediments.

Suppose two sediment samples (D_1 and D_2)[2] are taken sequentially in a known transport direction (for example from a river bed where D_1 is the up-current sample and D_2 is the down-current sample). The theory shows that the sediment distribution of D_2 may become finer (Case B) or coarser (Case C) than D_1; if it becomes finer, the skewness of the distribution must become more negative. Conversely, if D_2 is coarser than D_1, the skewness must become more positive. The sorting will become better (i.e., the value for variance will become less) for both Case B and C. If either of these two trends is observed, sediment transport from D_1 to D_2 can be inferred. If the trend is different from the two acceptable trends (e.g. if D_2 is finer, better sorted and more positively skewed than D_1), the trend is unacceptable and it cannot be supposed that transport between the two samples has taken place.

In the above example, where the transport direction is unequivocally known, $D_2(s)$ can be related to $D_1(s)$ by a function X(s) where 's' is the grain size. The distribution of X(s) may be determined by:

$$X(s)= D_2(s)/D_1(s)$$

X(s) provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular grain size being eroded, transported and deposited from D_1 to D_2.

2.1 Interpretation of the X-Distribution

The shape of the X-distribution, relative to the D_1 and D_2 distributions, enables an interpretation of the dynamic behavior of bottom sediments as follows (see Fig.A-6; Appendix I):

(1) Dynamic Equilibrium: The shape of the X-distribution closely resembles the D_1 and D_2 distributions. The relative probability of grains being transported, therefore, is a similar distribution to the actual deposits. This suggests that the probability of finding a particular grain in the deposit is equal to the probability of its transport and re deposition (i.e., there is a grain by grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium.

(2) Net Accretion: The shapes of the three distributions are similar, but the mode of X is finer than the modes of D_1 and D_2. Sediment must fine in the direction of

---

[2] A sample is considered to provide a representation of a sediment type (or facies). There is <u>no direct time connotation</u>, nor does the depth to which the sample was taken contain any significance (provided, of course, that the sample does, in fact, accurately represent the facies). For example, D_1 may be a sample of a facies that represents an accumulation over several tidal cycles, and D_2 represents several years of deposition. The trend analysis simply provides the sedimentological relationship between the two. It is unable to determine the rate of deposition at either locality, but frequently the derived patterns of transport do provide an indication of the probable processes that are responsible in producing the observed sediment types.

transport; however, more fine grains are deposited along the transport path than are eroded, with the result that the bed, though mobile, is accreting.

(3) Net Erosion: Again the shapes of the three distributions are similar, but the mode of X is coarser than the D_1 and D_2 modes. Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing net erosion.

(4) Mixed Case: A Mixed Case trend is one where the sequence of samples produces significantly acceptable statistics for both Net Erosion and Net Accretion. Such a finding is usually taken to be analogous to the case of Dynamic Equilibrium, but it may be more correctly interpreted to mean that the environment undergoes periodic accretion followed by periodic erosion, and both events have been "captured" in the samples used to make up the trend.

(5) Total Deposition (I): Regardless of the shapes of D_1 and D_2, the X-distribution more or less increases monotonically over the complete size range of the deposits. Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a "rain" of sediment that fines with distance from source. Once deposited, there is no further transport. No Total Deposition (I) – type dynamic behavior was found for the mouth of the Columbia River study.

(6) Total Deposition (II): More recently, a fifth form of the X-distribution has been discovered. Occurring only in extremely fine sediments when the mean grain-size is very fine silt or clay, the X-distribution may be essentially horizontal (Fig.A6-E). Such sediments are usually found far from their source (compared with Deposition (I) sediments in which size-sorting of the fine particles is taking place, and therefore the source is relatively close). The horizontal nature of the X-distribution suggests that their deposition is no longer related strictly to size-sorting. In other words, there is now an equal probability of all sizes being deposited. This form of the X-distribution was first observed in the muddy deposits of a British Columbia fjord and is described in McLaren, et al., 1993. Again, no X-distributions for this type of deposition were found in the mouth of the Columbia River.

2.2 Interpretation of a Trend

In reality, a perfect sequence of progressive changes in grain-size distributions is seldom observed in a line of samples, even when the transport direction is clearly known. This is due to complicating factors such as variation in the grain-size distributions of source material, local and temporal variability in the X(s) function, and a variety of sediment sampling difficulties (i.e., sample doesn't adequately describe the deposit; it's taken too deeply; not deep enough etc.).

Initially, a trend is easily determined using a statistical approach whereby, instead of searching for "perfect" changes in a sample sequence, all possible pairs contained in the sequence are assessed for possible transport direction. When one of the trends exceeds random probability within the sample sequence, we infer the direction of transport and calculate X(s). The precise statistical technique is described more fully in Appendix I. The statistical acceptance of each trend is provided in Appendix IV.

Despite the initial use of a statistical test, various other qualitative assessments must be made in the final acceptance or rejection of a trend. Included is an evaluation of R^2, a multiple correlation coefficient defining the relationship among the mean, sorting and skewness in the sample sequence (R^2 values are shown in Appendix III). If a given sample sequence follows a transport path perfectly, R^2 will approach 1.0 (i.e., the sediments are perfectly "transport-related"). A low R^2 may occur, even when a trend is statistically acceptable for the following reasons: (i) sediments on a presumed transport path are, in reality, from different facies, and valid trend statistics occurred accidentally; (ii) the sediments are from a single facies, but the chosen sequence is only a poor approximation of the actual transport path, and (iii) extraneous sediments have been introduced into the natural transport regime, as in the case of dredged material disposal. R^2, therefore, is assessed qualitatively, and when low, statistically accepted trends must be treated with caution.

To analyze for sediment transport directions over 2-dimensions, a grid of samples is required. Each sample is analyzed for its complete grain-size distribution and these are entered into a computer equipped with appropriate software to "explore" for statistically acceptable trends. The technique to explore for transport pathways is initially undertaken randomly[3] (i.e., up and down the coast, perpendicular to the coast, lines of samples running east-west, north-south etc.). As familiarity with the data increases, exploration becomes less and less random until a single and final coherent pattern of transport is obtained[4]. On completion of an interpretation, each transport line may then be used to derive a corresponding X(s) function from which the behavior of the bed material on the transport path is inferred.

---

[3] The term "random" is used loosely in that it is not strictly possible to remove the element of human decision-making entirely. The important aspect of the initial search for sediment trends is that it is undertaken with no preconceived concept of transport directions. It is, however, assumed that there will be a net sediment transport pattern and that changes in the grain-size distributions throughout the study area will not be random. The derivation of the final patterns may be likened to communication theory, which in the case of extremely noisy signals, requires the "discovery" of a "message" as the proof that the message does indeed exist.

[4] At present, the approach of obtaining the final derivation of the net sediment transport pathways relies on assessing and removing "noise" qualitatively. The GeoSea trend programming is specifically designed to do this in that all sample distributions may be readily compared with one and other (and excessively noisy distributions discarded), the best sediment types can be determined for the analysis, and the relationships among all the sample pairs may be assessed. Because we are unable to know the exact nature of the "noise" that we may be confronted with, it is difficult at this stage to devise a quantitative technique to eliminate it. To do so is the subject of much on-going research both by GeoSea and at various universities.

3.0 PHYSICAL SETTING

The Columbia River, having the second largest discharge in the United States averaging 7,500 m^3s^{-1}, enters the Pacific Ocean between Washington and Oregon through an entrance largely controlled by jetties and dredging (Fig.1). With a mean tidal range of 2.0 m, peak ebb flows of 2.4 ms^{-1}, and an average annual offshore wave height of greater than 2 m, conditions at the mouth have a deservedly dangerous reputation (Moritz, et al.).

About 9.7 million metric tons of sediment is supplied to the estuary each year, most of which is carried in suspension (Simenstad et al., 1990). Sherwood and Creager (1990) modified this value to 7.6×10^6 mt y^{-1}, which is thought to be considerably less than historical values of $10 - 15 \times 10^6$ mt y^{-1} prior to dam construction. Immediately offshore of the estuary mouth, shelf circulation is influenced by the southward flowing California current augmented by surface winds that are predominantly from the north-northwest. In winter, the northward flowing Davidson Current dominates the shelf attaining maximum strength from winter storm patterns from the south (US Army Corps of Engineers, 1999). These patterns coincide with the generally accepted view that the direction of net sediment movement along the Oregon and Washington coasts is northward on both the shelf and beaches (Sherwood and Creager, 1990).

Since the late 1800's, an effort to stabilize the mouth of the Columbia River in the interests of shipping has been continuous. Construction of the South Jetty began in 1885 and an extension was completed between 1903 and 1914. The North Jetty followed and was in place by 1917. Following jetty construction, adjacent beaches grew rapidly for several decades. In recent years, however, accretion rates have not only slowed but rapid erosion is now taking place. Furthermore, upstream dams are thought to have decreased the natural Holocene sediment loads by at least 72 per cent (Nelson, et al., 1998).

Dredging actively began in 1903 (Sherwood et al., 1990). Of particular interest to this study is the presence of six dredged material disposal sites (North Jetty Site, ODMDS A, B, E and F, and a Deep Water Site. Figure 1 shows each site together with their expanded boundaries. With the exception of the Deep Water Site that has not yet been used, each of these sites has been receiving material dredged from the Columbia River mouth. According to data supplied by the US Army Corps, Portland District, nearly 100 mcy have been disposed of since 1980 at these sites. Of this total, A has received 21 %, B 32 %, E 35 %, and F the remaining 10 %. The North Jetty Site was first used in June 1999 when an additional 1.05 mcy (1%) were placed there (Fig.3). Mounding is known to have occurred at A, B, and F and has affected local wave climate; however, E is evidently located in a sufficiently high-energy area to preclude any significant degree of dredged material accumulation (US Army Corps of Engineers, 2001).

4.0 RESULTS

4.1 Acoustic Bottom Classification (ABC)

The full theory, data analysis and results for the ABC survey are described in Appendix II.

4.2 Sediment Trend Analysis

As seen from Figure 2 and Table 1, the sediments obtained from the study area are composed principally of sand. Samples containing muddy sand are scattered fairly randomly in water depths generally greater than 60 feet. A few samples could be classified as sandy mud, and these are found in water depths of more than 190 feet. The number of samples other than pure sand was insufficient to derive separate trend interpretations for each facies; the best trends were obtained by treating all the samples as a single sediment.

Table 1: Breakdown of sediment types found in the mouth of the study area (see Fig.2)

	SEDIMENT TYPE[5]	NO. OF SAMPLES	PERCENTAGE
1	Sandy Gravel	0	0
2	Gravel	0	0
3	Gravely Sand	0	0
4	Sand	1,138	91
5	Muddy Sand	88	7
6	Sandy Mud	5	0
7	Mud	0	0
9	No sample sites	21	2
	TOTAL	1,252	100

Following the calculation of numerous sample sequences to determine significant trends, a total of 186 lines were selected to provide a pattern of transport (Fig.4). The trend statistics for each line are provided in Appendix IV. The net sediment transport pathways

---

[5] The sediment types use 20% and 50% as "cut-off" limits. For example, sand has less than 20% of any other size; sandy mud has greater than 20% sand, but less than 50%; muddy sand has greater than 20% mud, but less than 50%; etc. The few types of sediment containing three modes (i.e., a muddy, sandy gravel) although obviously "noisy" distributions, were still successfully included in the STA.

are shown in Figure 5. For ease of discussion, the pathways are grouped into various areas (or Transport Environments; Figure 6 and Table 2). A Transport Environment is defined as an area within which transport lines are associated by a common source and, to some extent, dynamic behavior. Generally, transport lines cannot be continued from one TE into another, and so a region in which transport lines naturally end (and begin) is a boundary between Transport Environments. Representative X-distributions[6] to illustrate the dynamic behavior derived from sample lines are referenced in Table 2, and their graphs are shown in Appendix V.

---

[6] An X-distribution is a function derived from the grain-size distributions contained in a sample line. It is used to describe the dynamic behavior of the sediments along the transport pathway defined by the sample line. The X-distribution may be thought of as a function that describes the relative probability of each particle being removed from an "up-current" sediment sample, and being deposited in a "down-current" sample. The shape of the X-distribution relative to the distributions of the sediments making up the sample line is used to define dynamic behavior (see Fig.AI-6).

TABLE 2: SUMMARY OF THE SEDIMENT TRANSPORT LINES MAKING UP EACH TRANSPORT ENVIRONMENT (FIGURE 6)

TRANSPORT ENVIRONMENT (TE) (Figure 6)		1: COLUMBIA RIVER		2: NORTH JETTY		3: NEARSHORE SHELF			4: MID SHELF		5: OUTER SHELF
SUB-ENVIRONMENT	1A: SOUTH GYRE	1B: RIVER CHANNEL	1C: NORTH GYRE	-	3A: INNER SOUTH SHELF	3B: SOUTH SHELF TO NORTH SHELF	3C: OUTER SOUTH SHELF	4A: MID-SHELF SOUTH	4B: MID-SHELF CENTRAL	4C: MID-SHELF NORTH	-
LINES (Figure 4)	1 to 3	4 to 6	7 to 14	15 to 36	37 to 46	47 to 60	61 to 70	71 to 97	98 to 112	113 to 144	145 to 186
NO. OF LINES	3	3	8	22	10	14	10	27	15	32	42
MEAN R2 VALUE	0.89±0.10	0.94±0.01	0.82±0.16	0.89±0.10	0.77±0.10	0.57±0.28	0.76±0.13	0.89±0.11	0.83±0.08	0.86±0.16	0.92±0.11
NET ACCRETION NET EROSION DYNAMIC EQUILIBRIUM MIXED CASE	100% 0% 0% 0%	100% 0% 0% 0%	50% 25% 25% 0%	36% 45% 18% 0%	0% 100% 0% 0%	0% 100% 0% 0%	20% 50% 0% 30%	100% 0% 0% 0%	20% 0% 0% 80%	9% 34% 25% 31%	19% 7% 74% 0%
REPRESENTATIVE X-DISTRIBUTIONS (APPENDIX V)	Fig. AV-1	Fig. AV-2	Fig. AV-3 Fig. AV-4 Fig. AV-5	Fig. AV-6 Fig. AV-7 Fig. AV-8	Fig. AV-9 Fig. AV-10	Fig. AV-11	Fig. AV-12 Fig. AV-13	Fig. AV-14	Fig. AV-15	Fig. AV-16 Fig. AV-17 Fig. AV-18	Fig. AV-19 Fig. AV-20

4.2.1 Columbia River (TE's 1A, 1B, and 1C).

These lines indicate that sediment transport in the main channel (TE 1B) of the Columbia River is seaward (ebb-directed), with a return flow on either side (TE 1A and TE 1C). Columbia River sediments appear to be accreting in the main channel, but reach their farthest seaward extent in the region between the two jetties, after which they lose their "signature" by mixing with marine sediments defined by TE 3.

R^2 values are highest in the main channel, but drop somewhat in the north and south gyres. This is likely due to the relatively few number of samples that do not allow for the best pathways to be determined. Although Net Accretion dominates in both the gyres, there is a mix in dynamic behavior on the north side of the river where the channels to Ilwaco and into Baker Bay undoubtedly contribute to a more complex system. Further sampling would likely show a greater detail of sediment pathways and their dynamic behavior for this area.

4.2.2 North Jetty (TE 2)

These lines originate on the North Jetty Disposal Site. They show a clockwise gyre emanating from the disposal site, and circulating sediment around the bay formed between the two jetties (Jetty A and the North Jetty). The trends terminate in the Navigation Channel. It is probable that these trends all could have been part of the TE 1 (the Columbia River environment) or TE 3 (the Nearshore Shelf environment). However, the active dumping in the North Jetty disposal site appears to have created a new and extraneous source for the sediments in the bay between the jetties. Most of the trends show Net Erosion and these are confined principally to transport close to the shoreline. It appears that material is eroded from the disposal site and probably added to the deposition occurring inside the Navigation Channel. The transport lines making up the central portion of the bay tend to show Net Accretion, although the westernmost lines are in Dynamic Equilibrium. R^2 values are relatively high, but quite variable, a finding that could be expected given that the trends are likely a mix of "natural" and extraneous sediments emanating from the North Jetty Disposal Site.

4.2.3 Nearshore Shelf (TE's 3A, 3B, and 3C).

This environment encompasses the nearshore shelf on both sides of the Columbia River. Overall, transport is northwards and the trends are diverted into, and back out, of the Columbia River. TE 3 is broken into three areas. The first, (Inner Shelf; TE 3A), shows sediment rounding the South Jetty and crossing the breaker zone associated with the northwest side of Clatsop Spit. The lines join in with the Columbia River channel sediments (TE 1), where they cross over the channel to merge with the clockwise gyre associated with TE 2. Essentially all the trends show Net Erosion, reflecting high-energy transport associated with the significant breaker zone north of Clatsop Spit. R^2 values are not particularly high, probably reflecting sediment disturbances caused by channel dredging, and mixing with the Columbia River sediments of TE 1.

The second sub environment (TE 3B) consists of lines that round both the South and North Jetties, thereby providing a link between the south and north shelves. As the paths cross the Ocean Dredged Material Disposal Site located beyond the end of the North Jetty (ODMDS E; Fig.1) they veer to the north and northeast towards shore. Although there is virtually no sedimentolgical evidence for the large volumes of material disposed of in ODMDS E, the R^2 values drop significantly for these lines, probably because of the "foreign" dredged material joining into the transport paths.

The third sub-environment is located on the outer south shelf. The trend lines parallel the northward regime of TE 3B and merge into the latter in the vicinity of the navigation channel. None of these lines crosses a disposal site and as a result, R^2 values are relatively high. Like the previous environments, most of these lines also show predominantly Net Erosion, although there are two Net Accretion lines (67 and 68) in the southern portion of the area.

4.2.4 Mid Shelf (TE's 4A, 4B, and 4C)

These lines all originate in the vicinity of ODMDS B (Fig.5) where they emanate to the south, north and landwards. Broken up into 3 sub-environments, TE 4A trends south and eastwards, the latter forming a counterclockwise gyre that merges with the northerly pathways of TE 3C. All the lines show Net Accretion and R^2 values are relatively high with the exception of Lines 91 to 95 which directly cross over ODMDS A (R^2 for these lines is 0.81 ± 0.04 compared with 0.90 ± 0.11 for the remaining lines which do not cross the disposal site).

TE 4B trends eastwards up the slope to curve northwards merging with the pathways defined in TE 3B. Some of these lines (98, 99, and 100) cross ODMDS E where they terminate on Peacock Spit. They suggest that material from the disposal site is being deposited on the northern flank of Peacock Spit. Otherwise, all the lines produced Mixed Case trends. Although R^2 values are reasonably high, they are lower than those found for 4A and 4C, probably because most of the lines in 4B are associated with ODMDS E. The Lines in TE 4C trend essentially northwards and show a variety of dynamic behaviors, although Mixed Case and Dynamic Equilibrium trends dominate.

4.2.5 Outer Shelf (TE 5)

These lines show a transport regime emerging from deeper water bringing sediment towards shore to merge with the east and west lines of TE 4. R^2 values are quite high reflecting little anthropogenic influence on the sediments. The trends are mostly in Dynamic Equilibrium, although there are a few Net Accretion lines, particularly in the northern half of the regions.

5.0 DISCUSSION

5.1 Process Implications

5.1.1 Columbia River (TE 1) and North Jetty (TE 2) Transport Environments

There are few lines of evidence in the literature that provide convincing support for or against the patterns of net transport determined for these two environments. The most complete synthesis of sediment transport, based on bedform morphology, is found in Sherwood and Creager (1990); however, the overlap between the two studies is confined only to the mouth area between the North and South Jetties, landward to the eastern finish of the sampling program. Their findings showed this region to be dominated by reversing bedforms in the spring and fall, with a larger number of unidirectional, seaward bedforms occurring in winter. Some of the elements contained in the winter map of bedform distributions agree quite well with the STA pathways; but Sherwood and Creager suggested that the net of reversing transport is predominantly landwards in this area which, except in a few specific locations (e.g., adjacent to the channel side of Clatsop Spit) is contrary to the STA.

Nevertheless, the STA agrees well with several of the essential conclusions made by Sherwood and Creager. For example, TE 1 shows the source for sediments inside the main entrance to the estuary to be derived from the Columbia River. Sherwood and Creager surmised from their evidence that local and marine sources can only be minor compared with the source that the river provides. They also could not confirm that bedload sediment is transported out of the estuary (the STA suggests that it is not), and finer sediment in the deeper water may be entering and leaving the estuary through the tidally dominated entrance (again the STA shows sediment moving into and out of the estuary entrance).

The overall morphology of the river suggests that channel flow is concentrated on the south bank past Astoria and Hammond, after which it is directed northwest to impinge the north bank between Jetty A and the North Jetty. As a result, both Clatsop Spit and the channel between the two jetties have tended to migrate northwards (US Army Corps of Engineers, 2001). It appears likely that the protrusion of Jetty A into the outside of the main channel bend is causing a clockwise gyre to form between the two jetties resulting in the transport patterns determined for TE 2. In addition the flood tide will also produce a similar sediment transport pattern. Thus the directions of sediment transport within TE 2 may be the result of both flood and ebb directed currents.

The uniqueness of TE 2 (i.e., that it is a separate Transport Environment) is likely due to the presence of disposed material in the North Jetty Site, which is providing an extraneous new sediment source. There is some evidence from the grain-size data of material leaving the disposal site and circulating in the pattern derived by the trends (e.g., see Figure 7). Had there been no disposal, it is likely that TE 2 would be merely an extension of TE 1B (Columbia River Channel) or even TE 3A (Inner South Shelf).

5.1.2 Nearshore Shelf (TE 3)

From a review of the existing literature, there seems to be general agreement that the net direction of littoral transport is northwards on the seaward side of the Columbia River mouth. This direction may be correlated with the northward flowing Davidson Current that prevails during the winter months, as well as the prevalence of the strongest storms coming from the south and southwest. Not reported in the literature, however, is the relationship between Clatsop Spit south of the entrance and Peacock Spit on the north side. If transport from south to north dominates, it follows that Peacock Spit cannot really be a spit (i.e., a coastal landform trending in the direction of the dominant littoral drift) Rather it fits the morphology of a downdrift offset where the beach on the downdrift side of the inlet is seaward to the beach on the updrift side. Downdrift offsets are formed by a combination of strong ebb currents that collide with a longshore current to produce a shoal on the downdrift side (Bruun, 1978). In this case, the shoal is the erroneously named Peacock Spit. Downdrift offsets are less common than updrift offsets and the explanation in this case is probably, at least in part, geological since the north side of the Columbia River is stabilized by bedrock (i.e., Cape Disappointment).

The suggestion that the coastal landforms found on either side of the Columbia River is a downdrift offset requires that the dynamics associated with the mouth of the Columbia River must provide a bypassing system whereby sediment is able to be transported across its entrance from south to north. That such a bypassing system exists is supported by plan views of the entrance over time. In 1844 Clatsop and Peacock Spits are evident as sand bodies, but Peacock Spit does not have the morphology of a spit. In 1876, Clatsop Spit still exists, but Peacock Spit has broken apart, forming a large bar in the middle (Fig.8). Such changes can be expected in sand bodies associated with a sediment bypassing system, simply through relatively small perturbations in river flow, storm activity and sediment supply. In 1895, the first part of the South Jetty was completed and the sand body associated with Peacock Spit totally disappeared as the breakwater temporarily blocked the northward movement of sand. By 1910 the barrier effect of the South Jetty was overcome and sand is seen again on the north side, as a sediment bypassing system becomes re-established (Fig.9). To lend further support to the concept of a sediment bypassing system crossing the mouth of the Columbia River forming a downdrift offset, similar downdrift offset morphologies (suggesting similar bypassing systems) are seen at the entrances to Willapa and Grays Harbors to the north (Fig.9).

The transport of sediments into and out of the entrance is supported by the known estuarine circulation, which is characterized by the flood favoring the southern side of the river channel (along the south jetty and Clatsop Spit) and the ebb flow dominating the northern side (Sternberg et al., 1977). On a local scale, the patterns of transport in the vicinity of ODMDS E and Peacock Spit as determined by bathymetric changes (Fig.11), agree extremely well with the findings of the STA for the same area.

5.1.3 Mid Shelf (TE 4)

The radiating pattern of sediment transport defining this environment originates out of ODMDS B (Fig.5). This location is a "sediment-parting zone", a term first introduced by Stride (1963). Such a term may, at first, seem paradoxical in that it implies an area that is able to maintain a continuous source of sediment. STA carried out in a number of estuaries and marine environments has found parting zones to be relatively common (e.g., they have been defined in the Bristol Channel, Carmarthen Bay, and Morecambe Bay in the UK, the Waddenzee tidal basins in Holland, and in Washington Narrows, Puget Sound). In these studies, it has been argued that parting zones, which clearly cannot provide a continuous supply of sediment forever, must be periodically loaded with sediments during extreme events (An obvious event in this case could be an exceptionally high sediment yield from the Columbia River), after which more "normal" transport processes distribute the sediments into the derived patterns of transport. On the other hand, this parting zone might be simply eroding into the foreslope of the Columbia River Mouth Bar that was an actively prograding feature at a time of greater sediment yields out of the Columbia River. Quite probably, the disposal of dredged material is helping to keep the parting zone replenished as mounding has been documented at the disposal site.

There are several lines of evidence to support the radiating pattern of transport found for this environment. Comparative bathymetry at ODMDS B has documented a similar radiating dispersal pattern of the mounded material (Mark Siipola, pers. comm., 2001). Early work using bottom drifters also show a similar landward transport (Morse et al., 1968, reported in US Army Corps of Engineers, 1991). It is highly likely that wave induced oscillatory currents are of sufficient strength at these depths to induce sediment motion (Sternberg and Larson, 1976). The radiating pattern may be in response to the morphology of the bar and landward moving bottom waters caused by the large amount of outflowing freshwater across the sea surface from the Columbia River.

5.1.4 Outer Shelf (TE 5)

The driving forces for the patterns of transport in TE 5 are likely similar to those described for TE 4. In this deeper water facies, the landward movement of sediment does not have a central focus, which ODMDS B at the base of the bar has provided for TE 4. In the deeper waters of TE 5, the bar morphology is no longer present, and the transport of sediment is roughly across the lines of bathymetry.

5.2 Implications for dredging and disposal operations

As is seen in Figure 5, most of the pathways cross the dredged entrance channel at an angle ranging from a few degrees to perpendicular. In general terms, the greater the angle between a dredged channel and the net transport pathways, the greater will be the trapping effect of the channel. The dredged entrance channel would, therefore, appear to be an effective trap for the sediments in TE 3 and 4B, and much of 4A (Fig.6). ODMDS A lies in TE 4A, and in 1958 this site was temporarily discontinued when it was suspected, on the basis of bottom current data, that material was being returned to the navigation channel (US Army Corps of Engineers, 1999). Certainly the findings of the STA confirms a direct route from ODMDS A back to the navigation channel (Fig.5). Most of the trends crossing the channel are either showing Net Erosion (TE 3B) or Mixed Case (TE 4B) which is both erosion and accretion occurring down the transport path. It might be expected that more Net Accretion should be present in lines associated with the channel; however, the sampling density only allowed one or two samples on any particular transport line crossing the navigation channel; an insufficient number to delineate a separate dynamic behavior from the rest of the line. Undoubtedly, a separate, dense sample grid in the channel and its immediate vicinity would reveal distinct depositional trends occurring inside the channel.

With the exception of TE 1B (the Columbia River Channel) which parallels the dredged channel, it appears that most of the deposition occurring in the mouth is the result of marine sediments in their passage from south to north. It is perhaps for this reason that there is virtually no identifiable "sedimentological signature" associated with any of the disposal sites (i.e., marine sediments are dredged and placed in marine disposal sites with very little change in their textural qualities). The ABC Analysis also failed to find a unique signature associated with either dredging or dredged material disposal (Appendix II). Another reason, and not mutually exclusive of the first, is that the environment is sufficiently dynamic to allow rapid dispersal and mixing with "natural sediments" out of the disposal sites.

The only exception is seen in the dispersal out of the North Jetty Site (TE 2). Various textural characteristics (notably sorting, Fig.7) roughly follow the patterns of transport as determined by the STA. There is evidence for seabed lowering occurring along the south side of the North Jetty (trend lines adjacent to the jetty show Net Erosion; see Lines 15 to 22, Fig.4). The dredged material disposal program has been designed to help replace this loss (US Army Corps of Engineers, 2001); however the trends also suggest that material from the disposal site may be contributing to deposition in the main navigation channel. Disposal in the North Jetty Site appears, therefore, to be a double-edged sword in that the consequences are not altogether favorable.

With respect to the desirability of using one disposal site over another, the findings of the STA suggest that all disposal sites presently being used (as shown on Fig.1) are, to some degree, dispersive. The rate of dispersion is undoubtedly depth related with material moving out of deeper sites more slowly than shallower ones. The following is a brief outline of the consequences of using each site:

ODMDS A: As discussed above, its location evidently insures the return of material back to the dredged channel. For this reason, it would seem undesirable to continue using this site.

ODMDS B: At least some of the pathways indicate a return to the dredged entrance channel, although it might be only a small proportion. If it is undesirable to have this site as one that is non-dispersive, this site should be avoided.

ODMDS E: This is the most highly dispersive site of all. Little, if any, material is being returned to the dredged entrance channel, making this probably the most desirable site (with the possible exception of ODMDS F). Again, if dispersion is undesirable, this site should not be used. It is the most favorable site to ensure replenishment of coastal sediments to the north (discussed below).

ODMDS F: There is only a very small likelihood of sediment return from this site. The amount will increase if the expanded area to the northeast is used, as more of the pathways circulate back to the dredged channel in this region.

5.3 Implications for coastal erosion

The results of the STA clearly show that the nearshore shelves and beaches on both sides of the Columbia River mouth are sediment starved (i.e., most of the lines in TE 3 are undergoing Net Erosion). The amount of sand from the Clatsop side of the river mouth is, therefore, insufficient to maintain the shelf and associated beaches on the north side. Given that Peacock Spit formed rapidly following jetty construction, it appears likely that the amount of sediment from the Columbia River able to join into the northward regime has been greater in the past. Very little sediment from the Columbia River itself is being made available to the beaches. According to Sherwood and Creager (1990), there was roughly twice the sediment yield from the river prior to dam construction. Today, the source for the coast is mainly marine, although the sediment source from the outer bar (TE 4) may have originally been Columbia River sediment.

At present there is some controversy over where to place material dredged from the navigation channel. Given the considerable erosion problems to the north, disposal in ODMDS E is clearly a desirable location. However, it must be stressed that the shelf in its entirety is sediment starved, and placing temporarily trapped material from the channel onto ODMDS E will be insufficient to replenish the beaches or to halt the erosion. Additional material, such as from the Columbia River channel, would be required.

6.0 SUMMARY AND CONCLUSIONS

(1) STA was performed on 1,231 samples taken from the Columbia River Mouth. Concurrent with the sediment sampling program, an Acoustic Bottom Classification (ABC) was carried out to water depths of 100 m. In all, nearly 850 km of sea bottom were mapped by ABC.

(2) Nearly all the samples (91%) consisted of pure sand (i.e., <20% of any other size fraction). The few muddy sand and sandy mud samples were confined mainly to water depths of >60 ft.

(3) 186 samples sequences were found to describe the sediment transport regime of the Columbia River Mouth. These were divided into 5 principal Transport Environments (TE)

(4) It was found that the Columbia River itself has a relatively minor effect on the overall sedimentation. Deposition from the river could be traced in the main channel only to a little beyond Jetty A (to about RM 2).

(5) A clockwise gyre has formed between Jetty A and the North Jetty in response to the ebb flow in the river. The same transport paths could be expected during the flood.

(6) The entrance is dominated by a nearshore/littoral transport regime extending from the south side, into and out of the entrance and onto the shelf on the north side. This pattern conforms to the concept that Peacock Spit is not a spit in the morphological sense of the word, but rather it is a downdrift offset. Historically, Peacock Spit, compared to Clatsop Spit, is an unstable sand body that easily breaks up into bars and rejoins the land depending on variations in sediment supply, waves and currents, storm activity etc. This behavior is typical of bars that are formed in a sediment bypassing system which, in this case, is from south to north across the river mouth. The driving process for this regime is likely the Davidson Current, which is strongest in winter, and storms from the south.

(7) Farther offshore at the seaward base of the ebb delta, the pathways radiate landwards. Probably coincidentally, they originate at ODMDS B, a site where mounding of disposed material is known to occur. Wave action, the outflowing freshwater from the Columbia River, and the morphology of the delta are likely responsible for the derived patterns.

(8) In the deep water portion of the study area, trends are dominantly landward.

(9) The grain-size data, the STA, and the results of the ABC all failed to find an identifiable "sedimentological signature" associated with dredging in the channel, or with the disposal sites. This suggests that the material being dredged is more or less identical to the "natural" sediments, or the dispersal of dredged material is rapid and quickly diluted with the natural sediments. These two reasons are probably not mutually exclusive of each other.

(10) At least some of the material disposed of in Sites B and A is likely to return to the navigation channel. Sites F and E, on the other hand, are located in environments where the transport pathways show that a return is unlikely.

(11) The STA shows that the nearshore shelf on both sides of the entrance is sediment starved with the result that the coasts are eroding. Material placed in ODMDS E is very likely to help maintain beaches to the north. However only material from the channel will not be sufficient to replenish beach material, or to halt erosion. A larger supply of sediment would be required from elsewhere, the Columbia River being the most obvious source.

7.0 ACKNOWLEDGMENTS

Sincere thanks are extended to Mark Siipola of the Portland District, US Army Corps of Engineers for instigating and supporting this project. The efforts of Dr. Ray Walton of West Consultants in managing GeoSea's subcontract are gratefully acknowledged.

On board help during the sampling program include Daniel Eggers and Leo Kreymborg of West Consultants, and Patrick Hill (student). Dušan Markovic of GeoSea provided field support and analyzed all the samples. Dr. Steven Hill (GeoSea) carried out the ABC portion of the project, and undertook quality control, sample design and computer support throughout the duration of the study.

8.0 REFERENCES

Bruun, P., 1978: Stability of tidal inlets; theory and engineering. Elsevier Scientific Publishing Co., 509p.

McBean, K, 1936: The Columbia River entrance, the wrecks and marine history of its development. Columbia River Maritime Museum, Astoria, Oregon © 1987.

McLaren, P., and Bowles, D., 1985: The effects of sediment transport on grain-size distributions. Journal of Sedimentary Petrology, 55, 457-470.

McLaren, P., Cretney, W.J., and Powys, R.I.L., 1993: Sediment pathways in a British Columbia fjord and their relationship with particle-associated contaminants. Journal of Coastal Research, 9, 1026-1043.

Morse, B.A., Gross, M.G., and Barnes, C.A., 1968: Movement of seabed drifters near the Columbia River. Proceedings of the American Society of Civil Engineers. Journal of Waterways and Harbors, 99WWI, 91-103.

Moritz, H.R., Kraus, N.C., Hands, E.B., and Slocum, D.B., 1999: Correlating oceanographic processes with seabed change, mouth of the Columbia River, USA. Paper presented at Coastal Sediments '99, Long Island, NY.

Nelson, C.H., Wolf, S.C., and Dunhill, G., 1998: Dams and potential effects on delta and coastline erosion. *In* Southwest Washington Coastal Erosion Workshop Report, 1998. Gelfenbaum, G., and Kaminsky, G.M. (Editors). USGS Open-File Report 99-524,. 129-139.

Sherwood, C.R., and Creager, J.S., 1990: Sedimentary geology of the Columbia River Estuary. Progress in Oceanography, 25, 15-79.

Sherwood, C.R., Jay, D.A., Bradford Harvey, R., Hamilton, P., and Simenstad, C.A., 1990: Historical changes in the Columbia River Estuary. Progress in Oceanography, 25, 299-352.

Simenstad, C.A., Small, L.F., McIntire, D.C., Jay D.A., and Sherwood, C., 1990: Columbia River estuary studies: an introduction to the estuary, a brief history, and prior studies. Progress in Oceanography, 25, 1-13.

Sternberg, R.W., and Larson, L. H., 1976: Frequency of sediment movement on the Washington continental shelf: a note. Marine Geology, 21, M37-M47.

Sternberg, R. W., Creager, J. S., Glassley, W., and Johnson, J., 1977: Aquatic disposal field investigations Columbia River disposal site, Oregon, Exhibit A: Investigation of the hydraulic regime and physical nature of bottom sedimentation. Technical Report D-77-30. US Army Engineer Waterways Experiment Station, Vicksburg, Ms

Stride, A.H., 1963. Current swept sea floors near the southern half of Great Britain. Quarterly Journal of the Geological Society of London, 119, 175-199.

US Army Corps of Engineers, 1999: Integrated feasibility report for channel improvements and environmental impact statement; Columbia and Lower Willamette River Federal Navigation Channel. Appendix H, Volume 1: Ocean Dredged Material Disposal Sites Main Report and Technical Exhibits.

US Army Corps of Engineers, 2001: Utilization of MCR Ocean Dredged Material Disposal Sites during 2000 and recommendations for 2001.

Figure 1: Location map, place names used in text, and sample locations

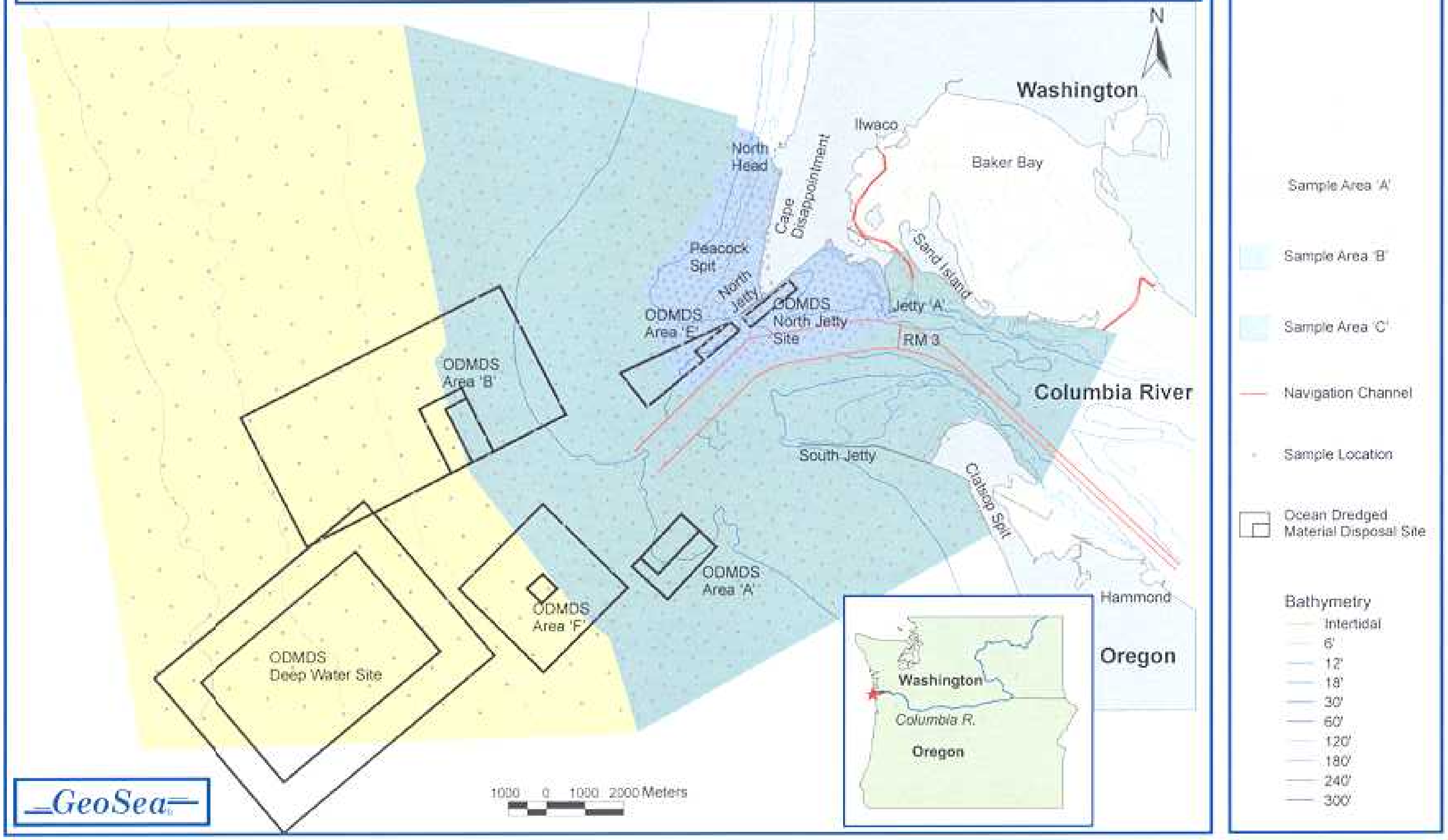


Figure 2: Sediment Types

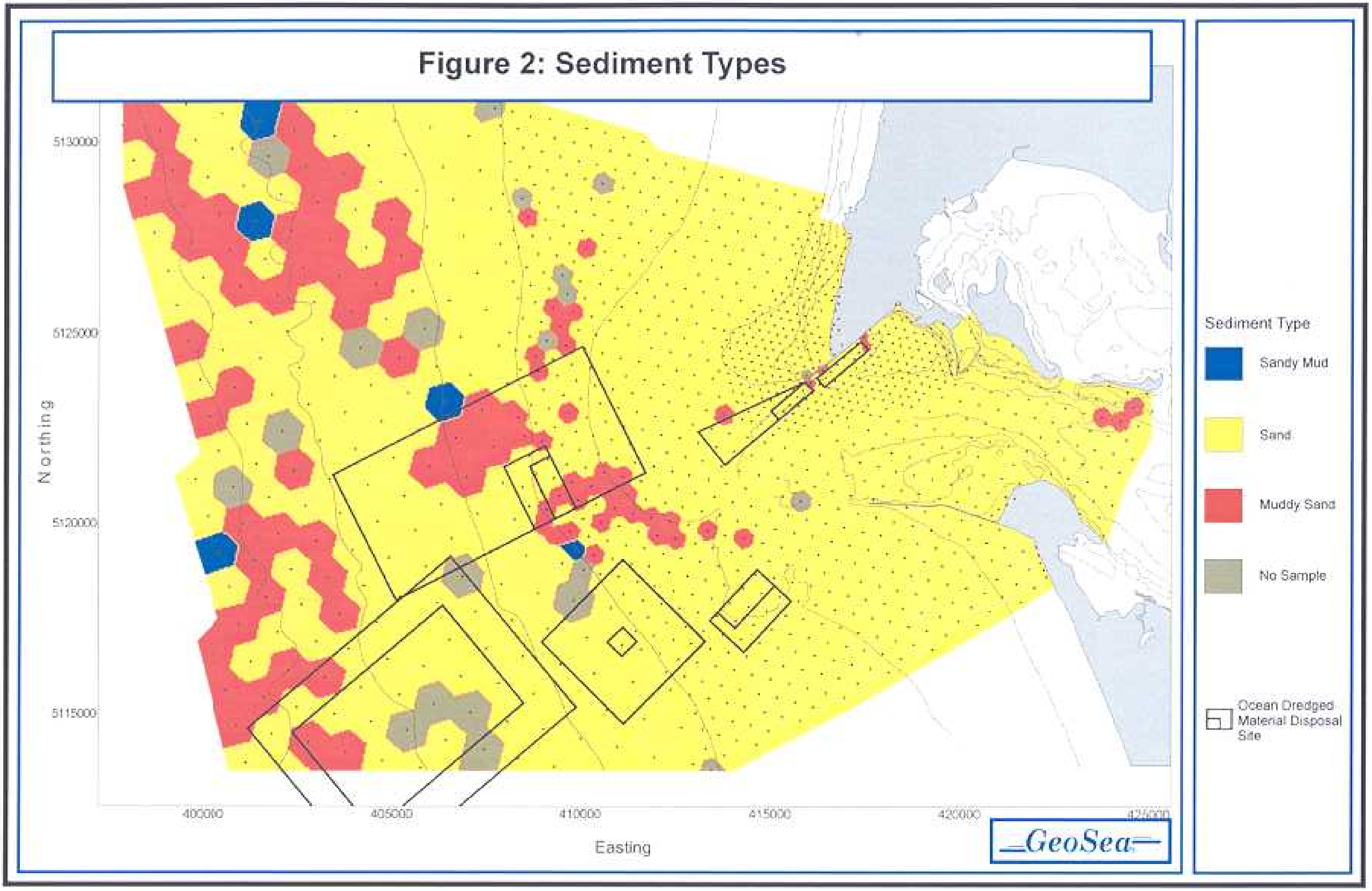


Figure 3: Amounts of dredged material disposed of since 1980
(data provided by Portland District, USACE).

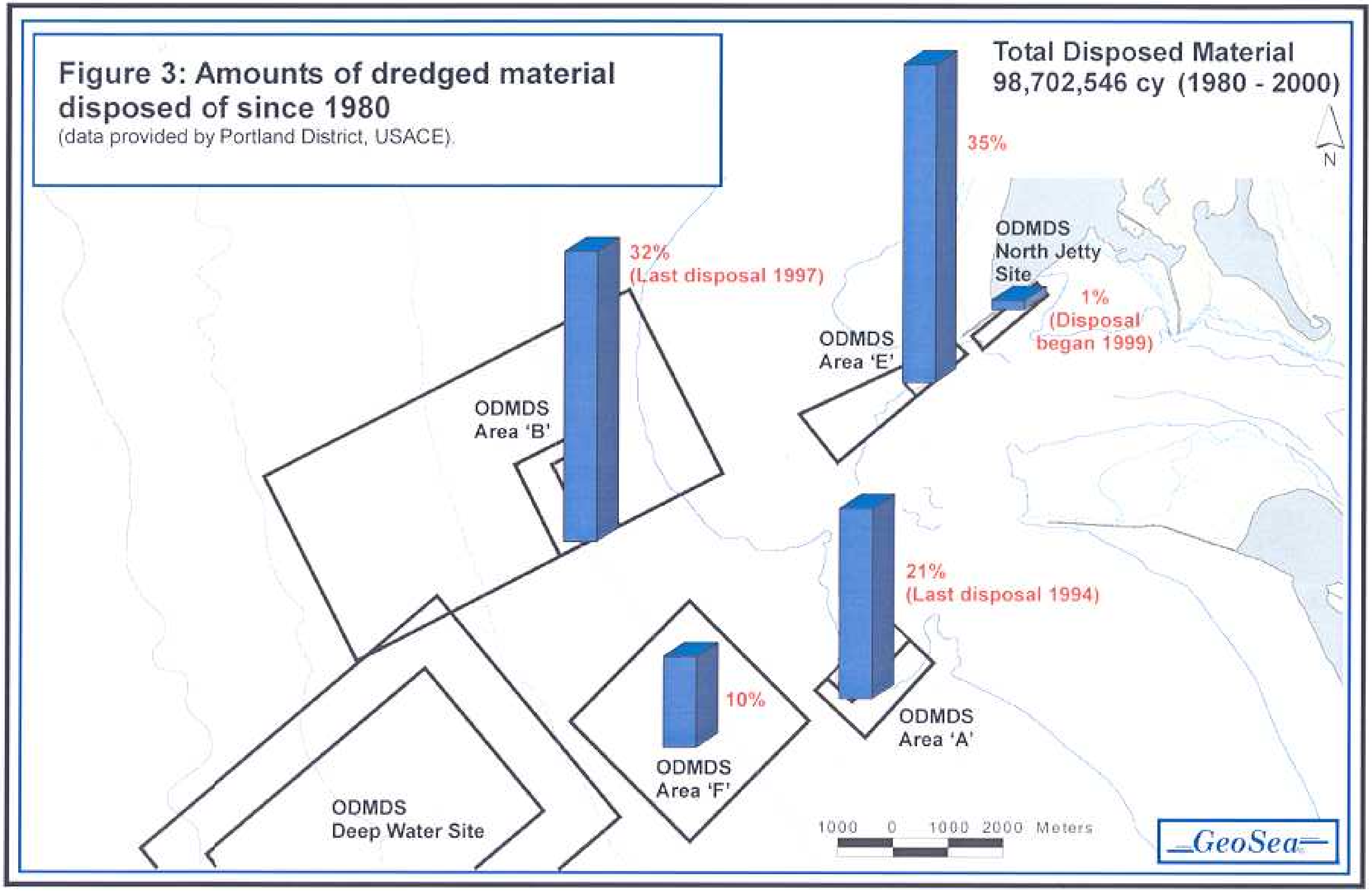


Figure 4: Sample lines used to determine net sediment transport pathways (see Appendix IV).

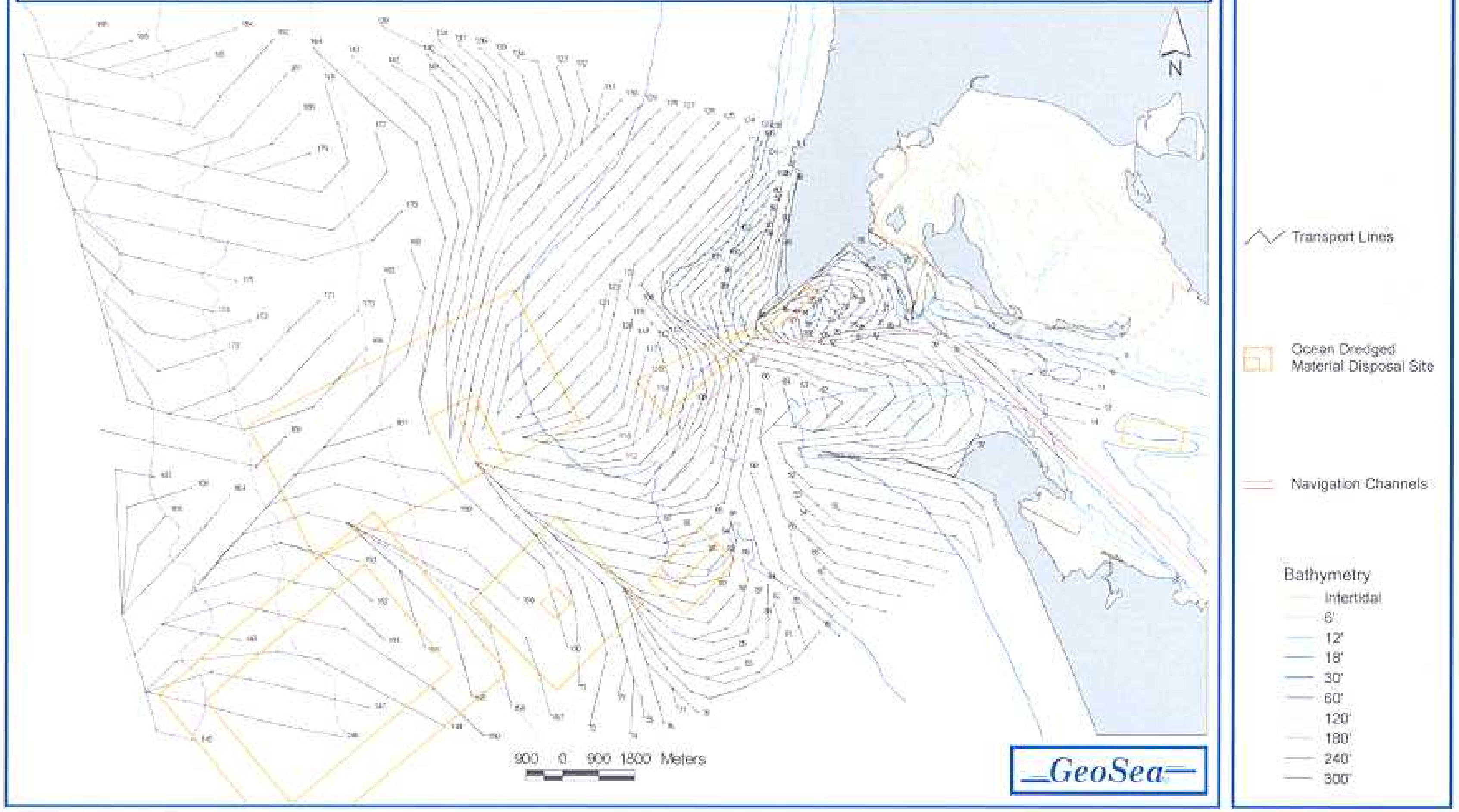


Figure 5: Net sediment transport pathways.

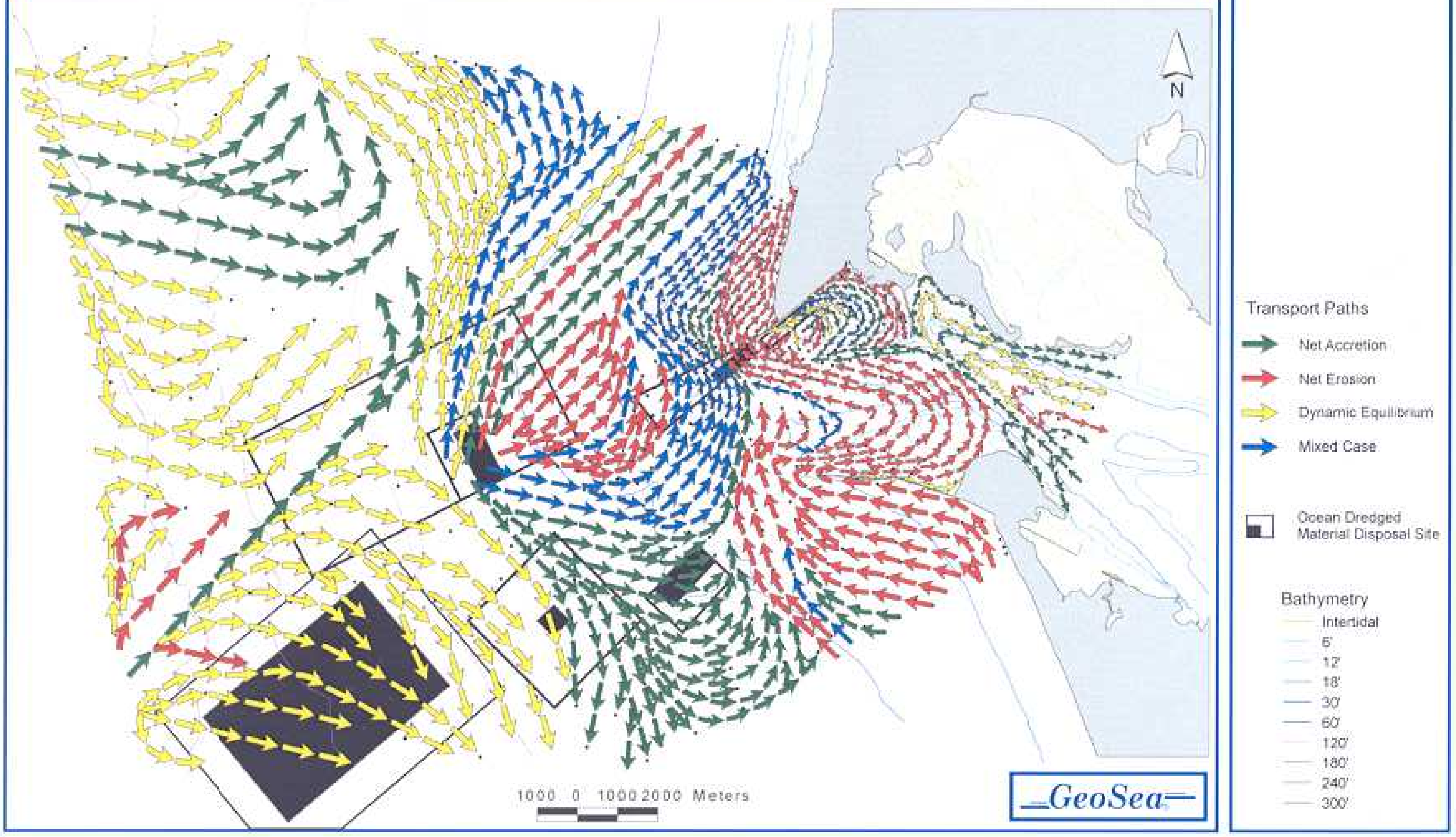


Figure 6: Sediment transport environments.

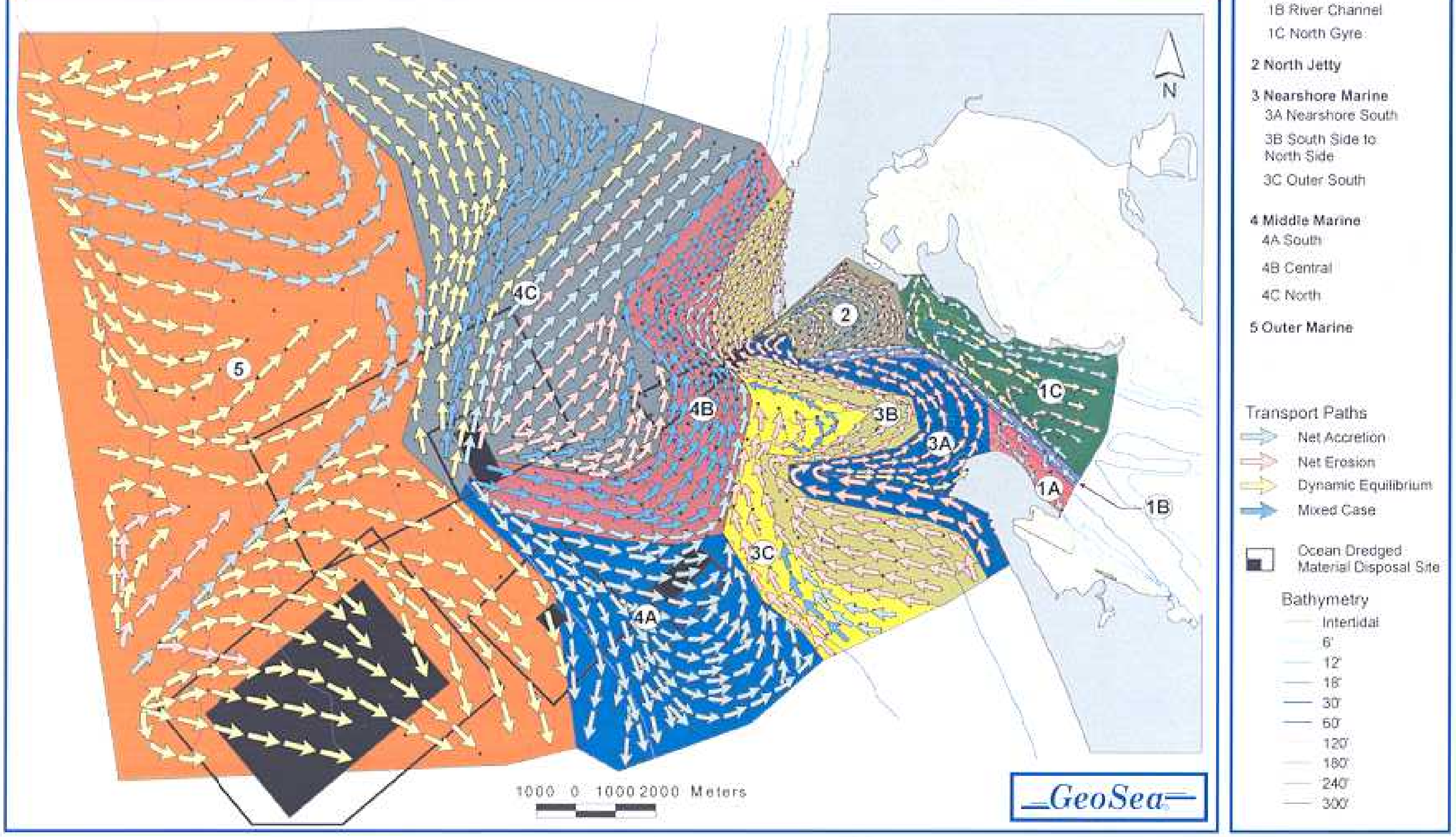


Figure 7: Map of sediment sorting suggesting that material is emanating from the North Jetty Disposal Site in a clockwise circulation.

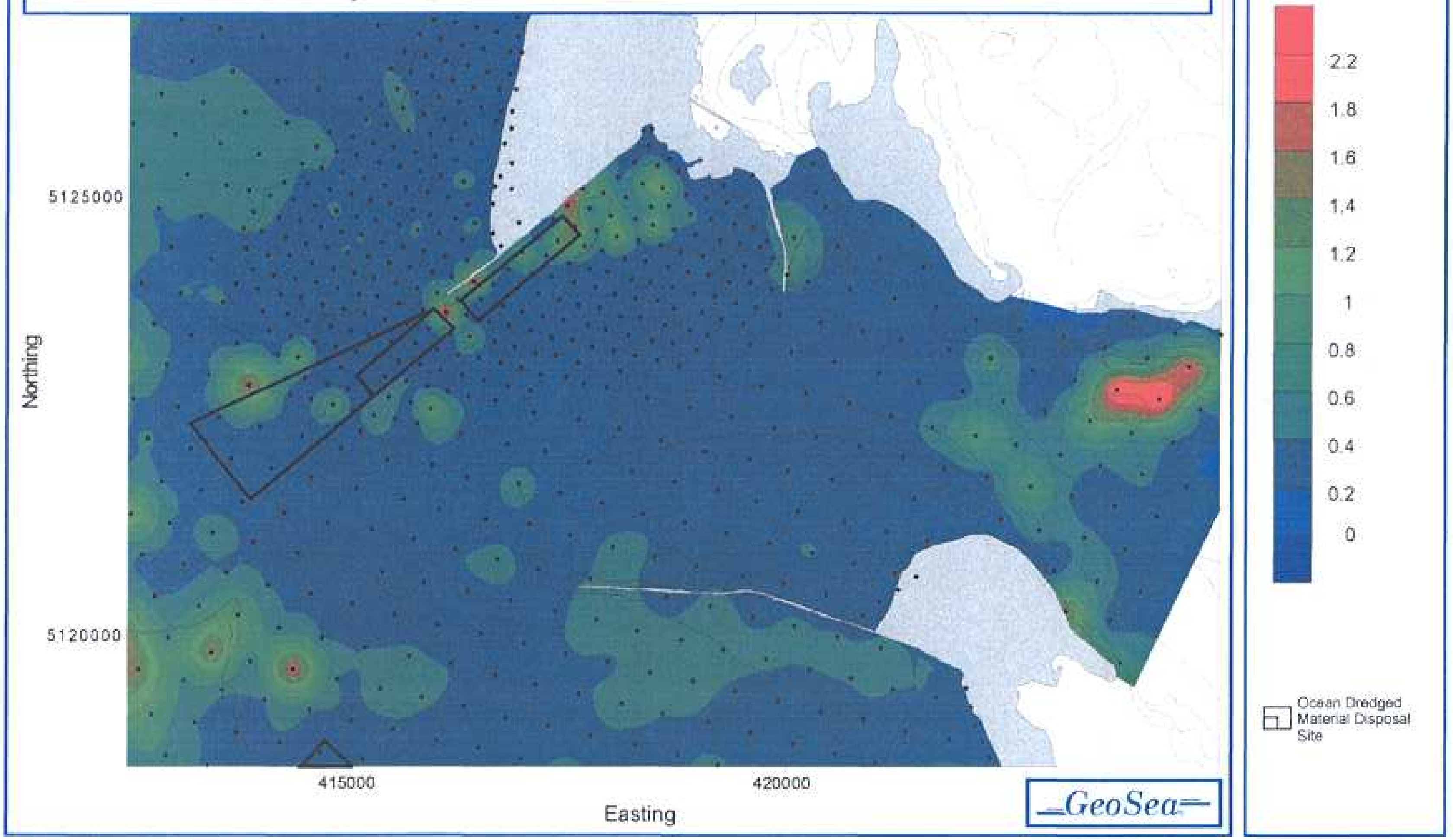
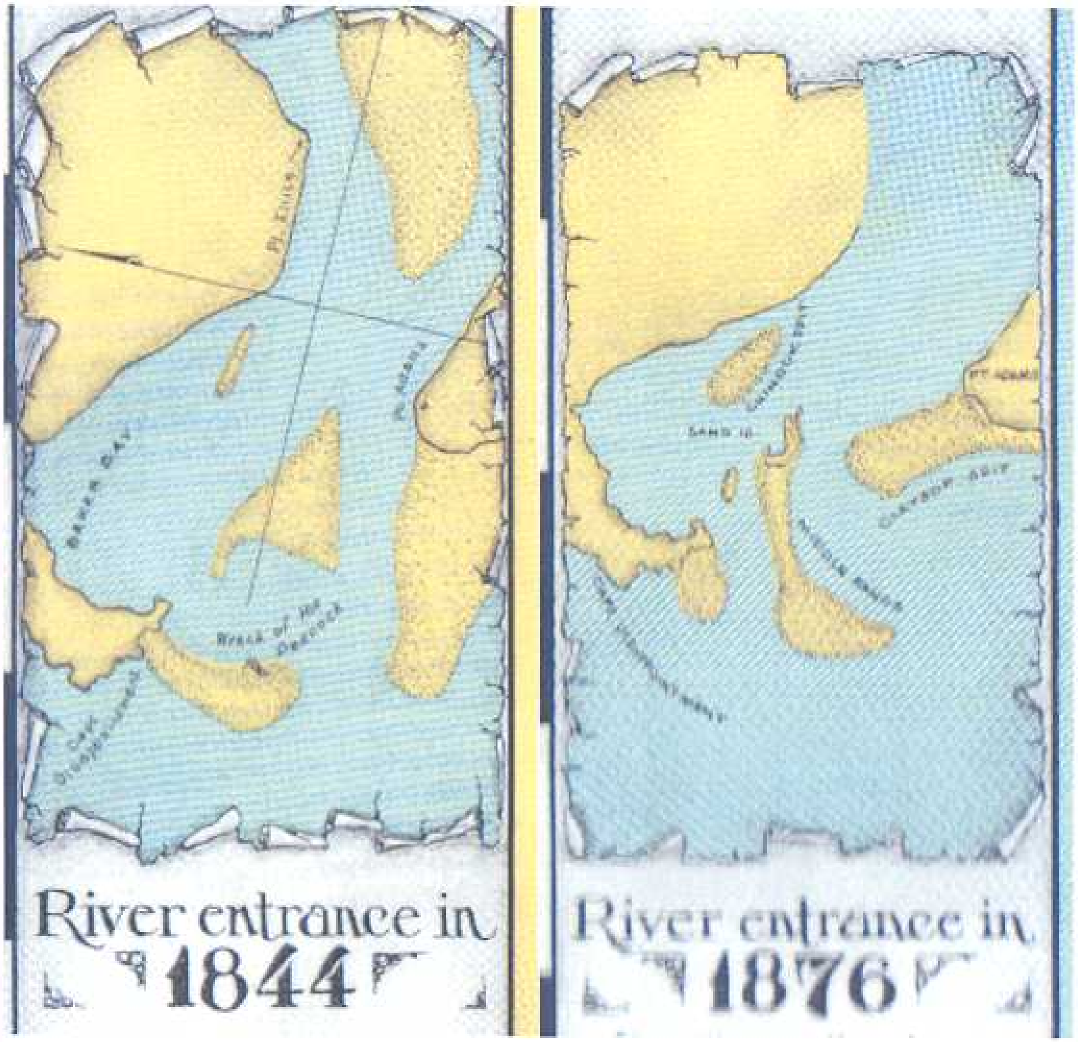


Figure 8: The river mouth in 1844 and 1876 (from McBean, 1936).
The sand body known as Peacock Spit is unstable, forming bars, or coalescing with the shoreline in response to small changes in sediment supply, flow conditions or storm activity.



River entrance in 1844

River entrance in 1876

Figure 9: The river mouth in 1895 and 1910 showing the re-establishment of the sediment by-passing system from south to north following the construction of the South Jetty (maps from McBean, 1936).

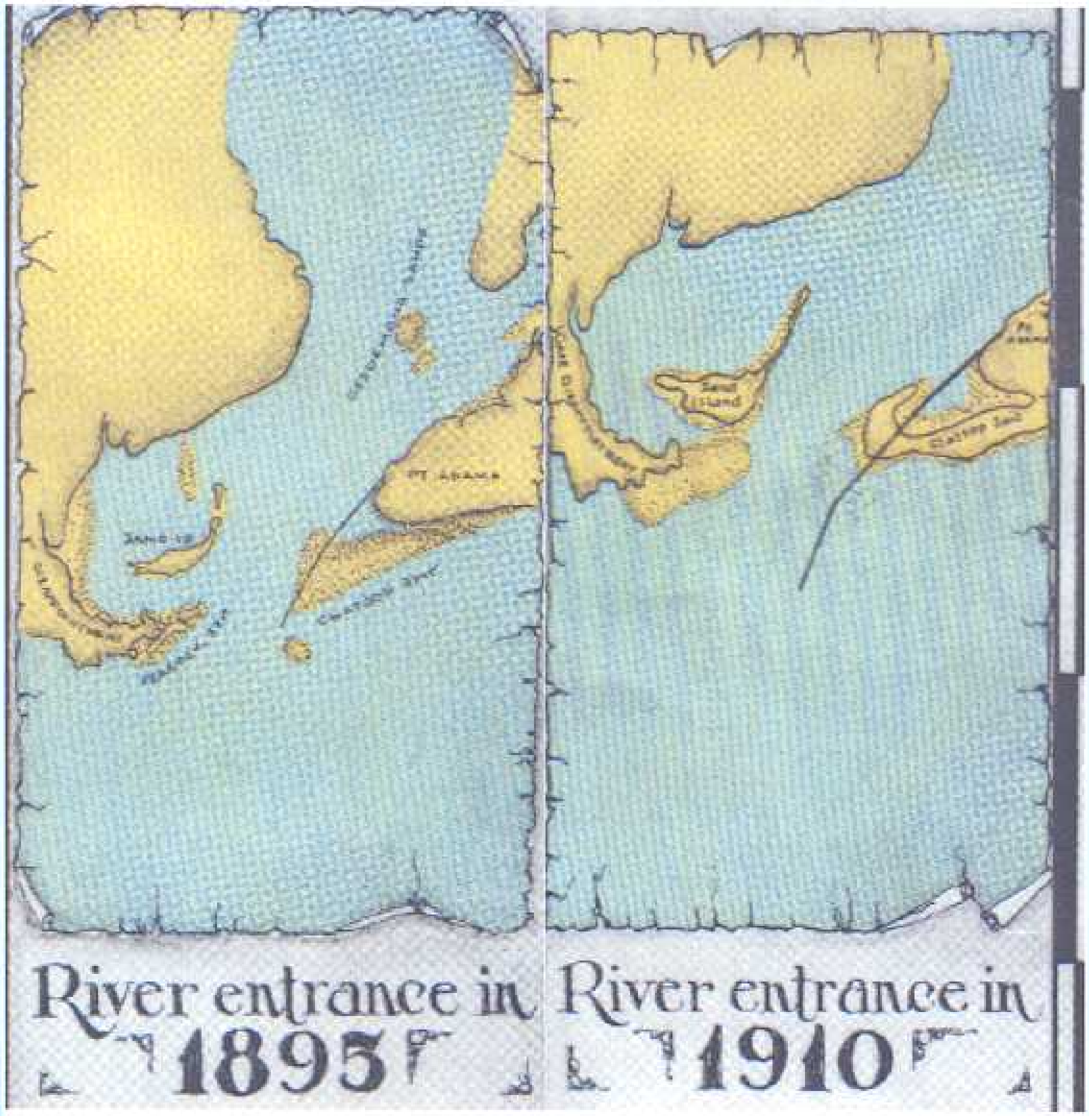
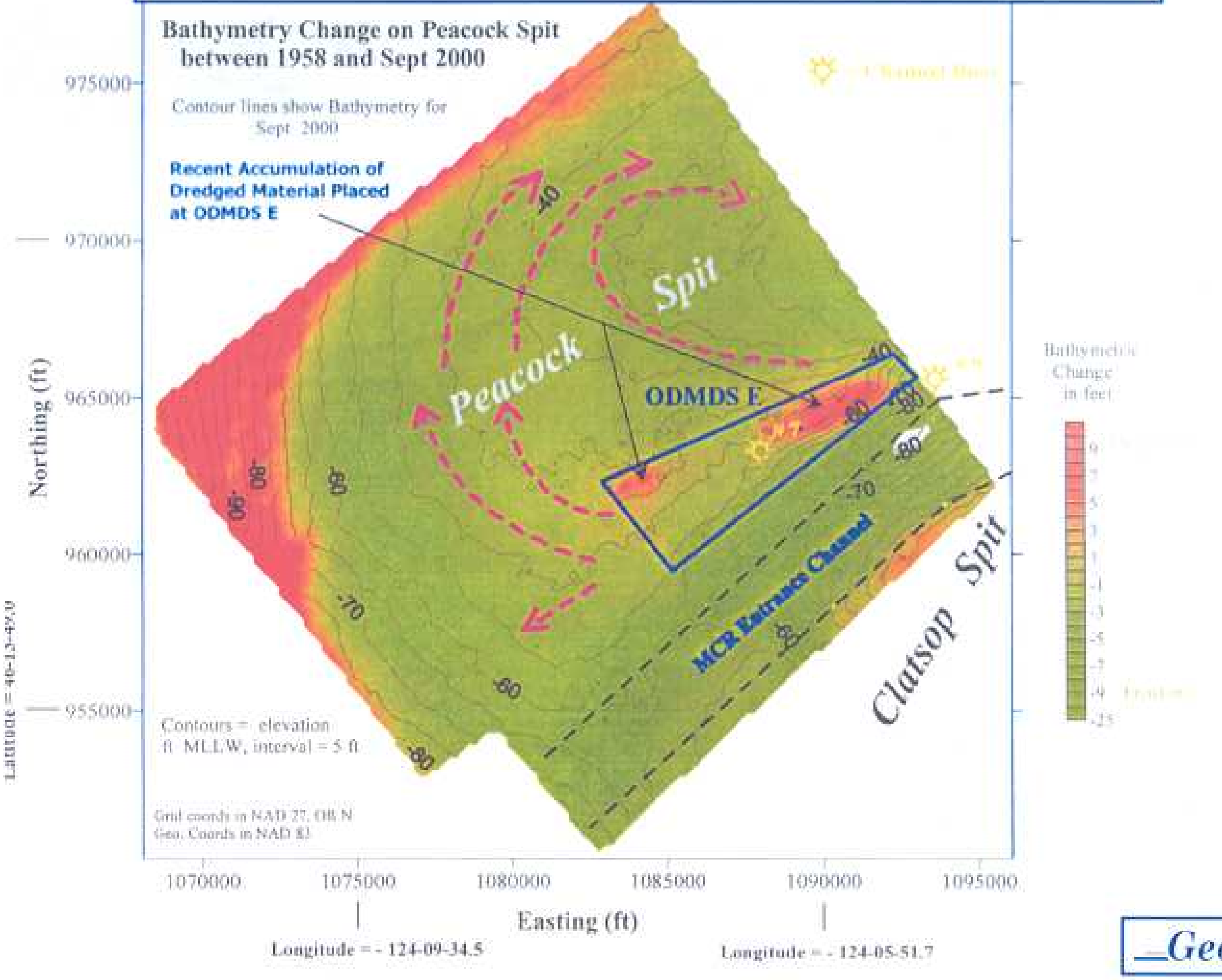


Figure 10: Plan view of the coast of Washington showing downdrift offset morphology at Willapa and Grays Harbors.

Figure 11: Inferred directions of sediment transport on Peacock Spit.

(US Army Corps of Engineers, 2001)



GeoSea