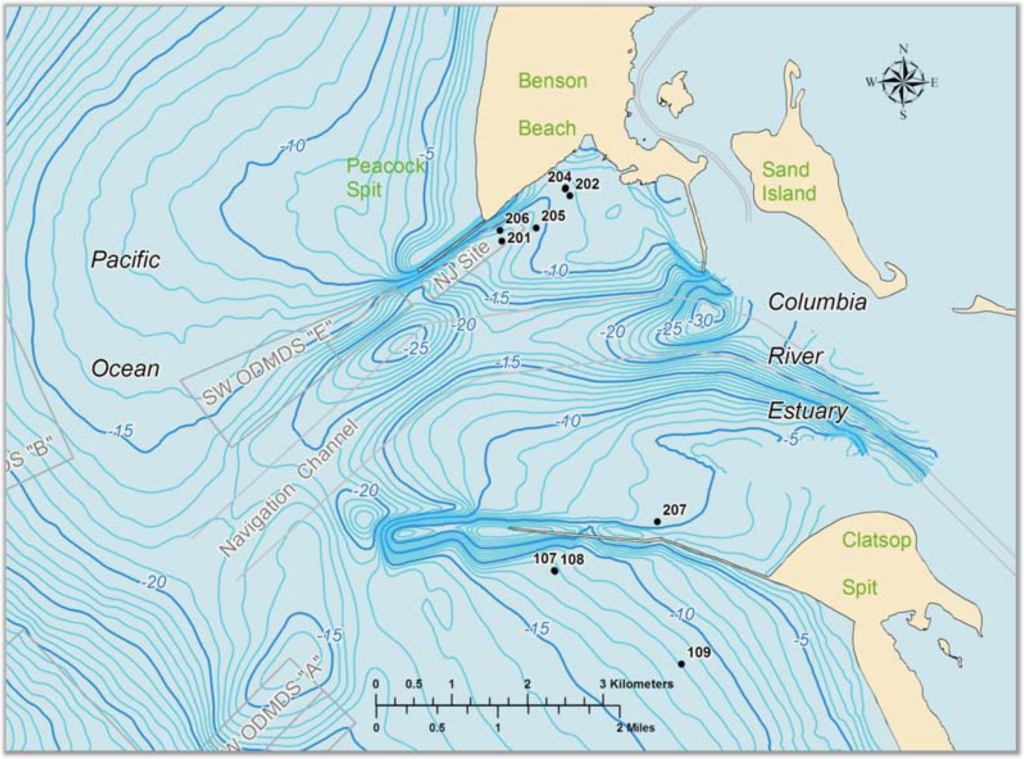

Vibracores at the Mouth of the Columbia River
Final Report

June 2005
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US Army Corps
of Engineers

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Prepared in support of U.S. Army Corps of Engineers
and Washington Department of Ecology
Cooperative Agreement

Vibracores at the Mouth of the Columbia River
Final Report

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Purpose and Objectives

In support of a cooperative agreement between the US Army Corps of Engineers and the Washington Department of Ecology, a vibracoring project was developed in July and August and implemented in September, 2003. This work supports the collaborative Benson Beach Phase III studies and other alternatives to improve the beneficial use of dredged material.

The vibracores were needed to provide vital seafloor surface and subsurface sediment data to further evaluate the proposed dredged material re-handling area along the Columbia River north jetty. Determining the composition and distribution of subsurface material is essential to determining the feasibility of dredging a sump area to bypass sand to the north side of the north jetty. The information obtained from the vibracores was used to resolve finer-scale sedimentary units beyond the capabilities of a new seismic survey, and help to optimize the location of the potential sump.

Vibracores in the vicinity of the Columbia River south jetty were needed to begin to assess the suitability of the existing subsurface for supporting the jetty, and provide greater insights into the severity of erosion problems and the existing habitat that could be affected by dredged material placement operations.

The specific purposes of the project were to:

- document the dredgebility of the seabed substrate south of the Columbia River north jetty for evaluating alternatives for dredged material placement at Benson Beach,
- document the character of the substrate and its spatial variability along the Columbia River south jetty for the proposed south jetty dredged material disposal site, and
- determine foundation characteristics at select locations along the south and north jetty.

Through discussions with the Corps of Engineers, 7 locations were selected to collect vibracores to 20 ft length as shown on Fig. 1, sites A-G. The plan included collecting two cores at sites A, C, F, and G; 1 core for minimum disturbance of sample, not to be driven to absolute refusal, and 1 core driven to refusal or to the entire extent of sampling tube to determine gross changes in sediment profile. The total number of cores intended for collection was 11 cores for the 7 sites.

Although there had been preliminary discussions with others that suggested obtaining 30-ft cores would be beneficial, in follow-on discussions with the Corps of Engineers, the determination was made that 6-m (20-ft) cores would be sufficient to make the assessments required. The potential sump would likely be dredged to a maximum of 15 ft into the subsurface. While obtaining deeper cores is possible, it would likely require utilizing a larger vessel, which would then compromise the ability to collect shallow-water cores.

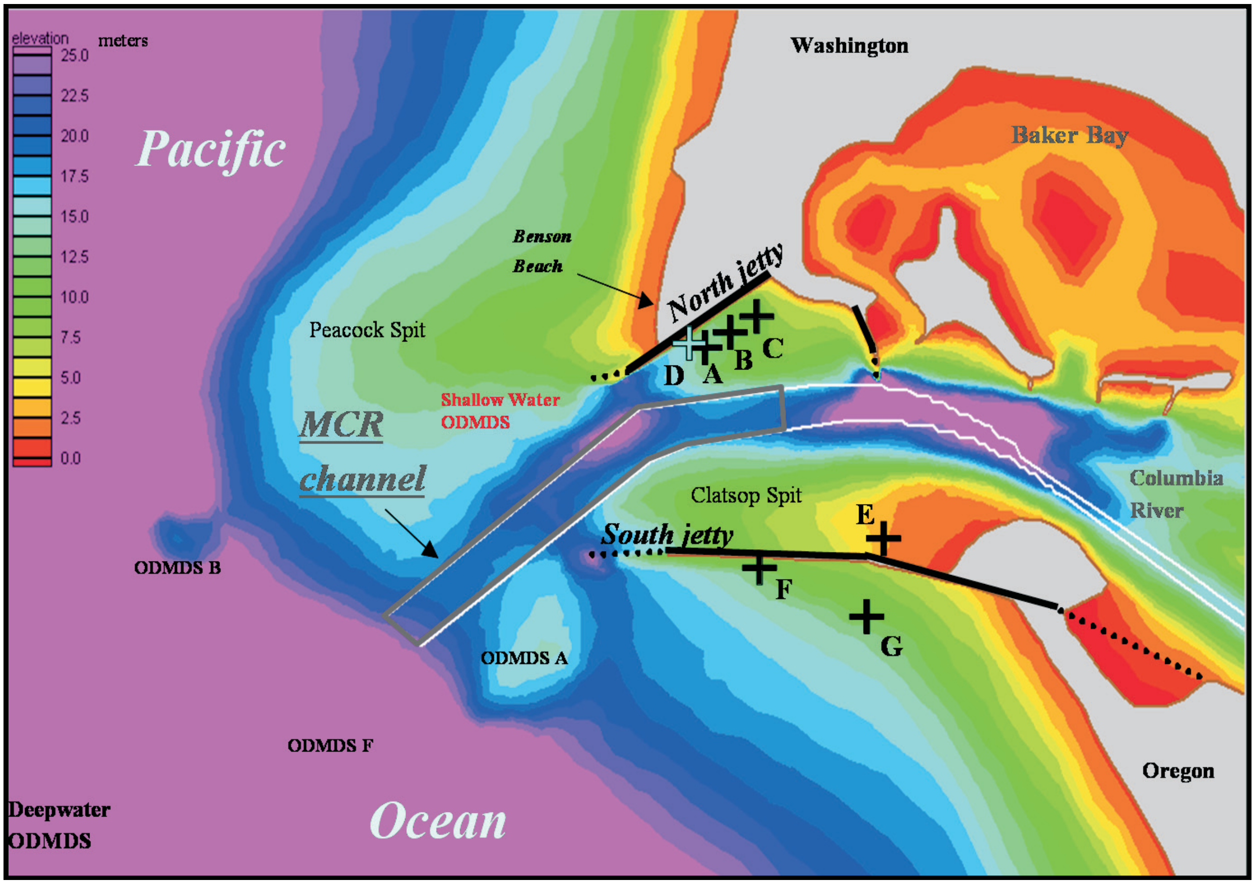

Fig. 1. Planned locations of vibracore sites of this project (figure by R. Moritz).

Planning and Preparation

The planning and preparation of the vibracoring project began in July 2003. Tasks involved in this effort included: a competitive cost and performance evaluation, solicitation of bids, mobilization planning of vibracorer gear; arranging for the manufacturing and acquisition of core barrels; acquisition of research vessel services; scheduling of core laboratory facilities; preparation of a GIS database; acquisition of field and laboratory equipment and supplies; and making various other logistical arrangements.

The evaluation of cost and performance of contracting various vibracoring equipment and operational services revealed that the most cost-effective means to implement the vibracoring project was for the Washington Department of Ecology to organize a program similar to that performed by the Washington Department of Ecology in 2002. This program included the mobilization of a light-weight, portable Australian-designed vibracorer, trained operators, and a vessel and crew to deploy the vibracorer. The Australian-designed vibracorer has successfully obtained 6-m cores in many other sandy shoreface environments, including along the inner- to mid-shelf of the Columbia River littoral cell in August 2002. Other vibracorer systems capable of obtaining 6-m cores typically require a larger vessel, which often can not operate in the shallow water depths required in this project. The 75-ft research fishing vessel, "Olympic", based in Newport, Oregon, and utilized by the Washington Department of Ecology in 2002, was retained for charter services to deploy the vibracorer. The mobilization and operation of the vibracorer was made possible through arrangements with the Virginia Institute of Marine Science.

The Oregon State University (OSU) core laboratory in Corvallis, OR was selected for core processing based on lab availability, overall facilities, and proximity to the Port of Newport. The OSU core lab is funded by the U.S. National Science Foundation and has state-of the art facilities for core processing, analyses, and archival. For this coring program, initial core processing included splitting, brief logging (visual descriptions) and photography. OSU also has facilities for x-radiography of cores, which were used in subsequent processing.

Coring Methodology

Vibracores were collected using the vessel "Olympic" (Fig. 2) which has an elaborate rigging system, large aft working deck and capacity for cold storage to maintain core quality for the period of field work. The starboard outrigger and three-point lift system enabled the vibracorer to be deployed over the starboard side. A stabilizer, suspended from the port outrigger, reduced roll and thereby improved the stability of the boat as a coring platform. The use of this vessel enabled the collection of cores in water depths as

Fig. 2. Photo of the 75-ft vessel "Olympic" used to collect the vibracores.

shallow as 7 m. The captain and crew had an excellent working knowledge of the Columbia River entrance channel and jetty areas which was essential for successful completion of the project.

Fig. 3. Photo of the 7-m high vibracorer (Quaternary Resources, Ltd.) suspended from the starboard outrigger of the "Olympic". The upper 4 m of the tower are shown.

The Australian-designed vibracorer (Fig. 3) has a lightweight, 7-m high aluminum frame fitted with 3 retractable legs and 6.1 m aluminum barrels. The relatively light vibrating head delivers maximum vibration energy to the barrel, with little energy expended on vibrating the head. A special feature of this system is that the barrel and head are contained within, but not attached to, the frame. Their ability to freely rotate within frame improved the capability of the corer to penetrate quickly through difficult substrates. Typical vibrating times for this corer have ranged from 90-125 seconds depending on seabed conditions, substrate and response of the corer.

The electrically-driven vibracorer system consisted of:

- 5kVA, 220 Volt, 3-phase vibrating head with 100 m cable and driven with power supply from the vessel
- 7-m aluminum tower with 3 collapsible legs
- 6.1-m (20-ft) extruded aluminum core barrels (80 mm OD, 76 mm ID, 2 mm wall thickness)
- stainless steel core catchers
- support equipment including tools
- miscellaneous supplies including end caps, tape, string, and gillnet floats.

Fig 4. Photo of the vibracorer suspended above the deck of the "Olympic" for deployment over the starboard side of the vessel.

The core barrel, with the core-catcher installed, was painted with red paint prior to being attached to the vibrating head (rationale discussed below). After the barrel was attached to the head, within the coring frame, the entire rig was raised from the deck and deployed over the starboard side (Fig. 4). The corer was brought alongside the vessel where the three legs were lowered and secured (Figs. 5 and 6).

The coring tower was then lowered several meters into the water to allow the frame to fill with water. As the coring tower was lowered to the seabed, the electric cable was paid out slowly. The length of cable let out was based on the water depth and local currents so that only the necessary length of cable was deployed (extra cable could have become tangled around the corer and resulted in difficulty raising the corer and/or damage to the equipment).

Fig. 5. Photo of crew adjusting the retractable legs of the vibracorer.

Operators determined the rate of progress of the corer in penetrating the seabed through a "gillnet float" indicator system. Small 6-inch foam floats were attached at 1.5-m intervals through the center of the coring tower, so that the vibrating head released the float as it passed a particular point (1.5 m, 3.0 m, and 4.5 m of penetration). The operator monitored the time that it took the floats to rise to the surface, as well as measured the length of cable deployed. If the floats did not release, or a substantial time elapsed since the last release, and no additional cable was paid out, then the barrel was not penetrating the seabed and the operator would cease vibration (see discussion on page 15 for potential negative consequences of extended vibration without continual penetration).

Fig. 6. Photo of vibracorer suspended at starboard side of the "Olympic".

Once the vibracorer was on deck and secured, the red paint on the barrel was examined closely to determine the depth of core penetration into the seabed (Fig. 7). (Note: A spring-action "gate" at the base of the coring tower scraped the barrel as it passed, just before it entered the sediment, which partially removed the paint and scored the barrel.) The penetration depth (i.e., length along the barrel from the core catcher) was measured and recorded, for later comparison with the length of recovered sediment in the core barrel. Cores were labeled, placed in the vertical position to settle and drain, and secured to the aft A-frame net spool of the vessel (Fig. 8). Later, the cores were cut into 1.5-m sections, the sediment at the cuts between sections was briefly described and recorded, and the ends of each core section were sealed with an end cap and electrical tape (blue at the top of each section, green at the

Fig. 7. Photo of scrape marks along a core barrel indicating progressive penetration into the seabead, with the abrasion mark closest to the top of the barrel denoting maximum penetration.

bottom). The core sections were then stored in the refrigerated hold of the vessel until removal for transit to OSU.

The core labeling scheme in this project followed the scheme developed for the August 2002 vibracoring project in order to facilitate the addition of this project's cores to the vibracore database and archiving system.

The core identification and labeling scheme was:

Columbia River Littoral Cell – sub-cell location identifier – Core No. / Section No.

*Example: CRLC-CP-107 /1 (*CRLC-Clatsop Plains-Core No. 107/Section 1)

Sept. 2003 Project:	
CP: Clatsop Plains	100 series (cores 107-109)
MCR: Mouth of the Columbia River	200 series (cores 201-207)
August 2002 Project:	
LB: Long Beach	300 series
GL: Grayland Plains	500 series
NB: North Beach	700 series
MS: Midshelf	900 series

Fig 8. Photo of core processing aboard the "Olympic" while docked at the Port of Astoria. Immediately after collection, cores were secured in an upright position to settle and drain, and within several hours, final measurements of recovery and penetration were made, and each core was then cut into 1.5-m sections for storage in the refrigerated hold of the vessel (photo by R. Gammisch).

Other core identifiers included:

- arrow points to top of core
- end cap tape color code:
  - blue = top of section
  - green = bottom of section
- TOC: top of core
- EOC: end (bottom) of core

Shipboard Coring Operation

Mobilization of the vessel *M/V Olympic* and vibracorer equipment occurred at the Port of Newport, Oregon on September 3-4, 2003. The Washington Department of Ecology and Central Washington University provided overall coordination, direction, and technical support including materials for the coring operations. The Virginia Institute of Marine Sciences (VIMS) was responsible for mobilization and operation of the vibracorer. The *M/V Olympic* captain and crew navigated the vessel and operated the rigging for deployment and recovery of the vibracorer.

All personnel on the vessel were involved with vibracorer operations. Personnel:

Chief Scientist:	George Kaminsky (Washington Department of Ecology)
Geologist:	Marie Ferland (Central Washington University)
Vibracorers:	Robert Gammisch and Wayne Reisner (VIMS)
Captain & Winch:	Terry N. Thompson, *M/V Olympic*
Vessel Crew & Winch:	Todd Gidlund, *M/V Olympic*
Vessel Crew:	Al Davis, *M/V Olympic*

The timing and length of each coring day was determined by a combination of core location, weather (wind speed and direction as well as visibility due to fog), sea state (seas/swell), velocity of local surface and bottom currents, and time restrictions to pass over the Columbia River entrance bar based on tidal elevation and cycle. Figs. 9 and 10 show the predicted tides and tidal currents near the mouth of the Columbia River during the period of field operations. Table 1 provides relevant meteorological and wave data measured by the National Data Buoy Center station 46029. The likely presence of dense fog can be surmised when the dew point temperature is significantly less than the water temperature.

The timing and duration of the coring project were constrained by a large weather front moving onshore, whereby the light northwest winds (~3 m/s) would be changing to moderate southwest winds (> 6 m/s) by mid-day on Saturday, September 6. The National Weather Service forecast indicated that the southwest winds would increase substantially beginning on Monday, September 8 and persist for over 4 days. Within these overall project duration constraints dictated by the large weather patterns, the operating window for the collection of cores within the mouth of the Columbia River (MCR) was further constrained by the influences of local and tidal currents on the vibracorer and vessel anchorage. Typically, vibracoring in the MCR was performed during a flooding tide.

The vessel was positioned by the vessel's GPS system. No corrections have been made for the offset between the GPS antennae and the vibracorer location – these were within 6-8 m of each other (acceptable "target" circle). The core position fix was taken when the vibracorer just touched the seafloor; readings were recorded in latitude (N) and

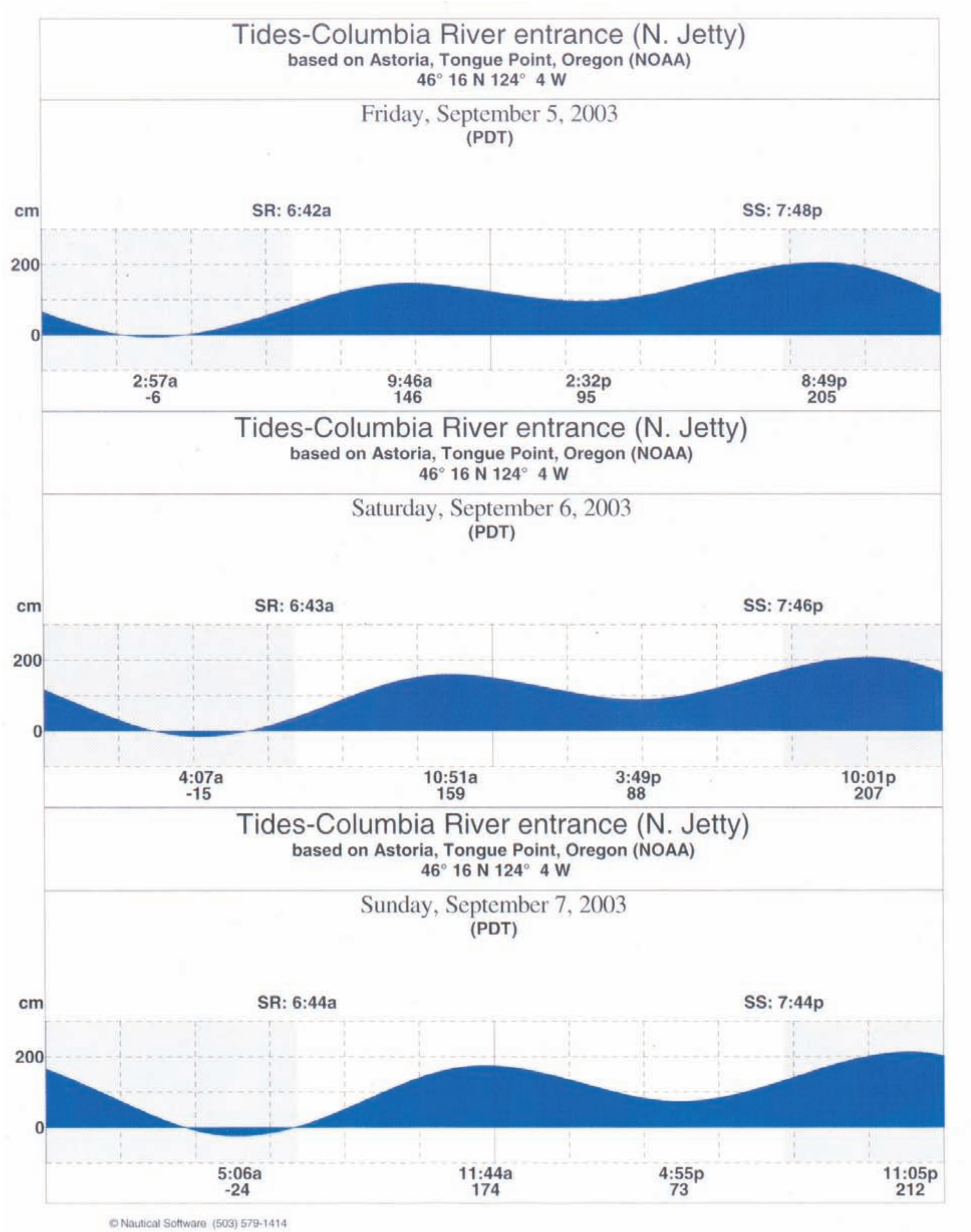

Fig. 9. Predicted tides at the mouth of the Columbia River during the coring operations.

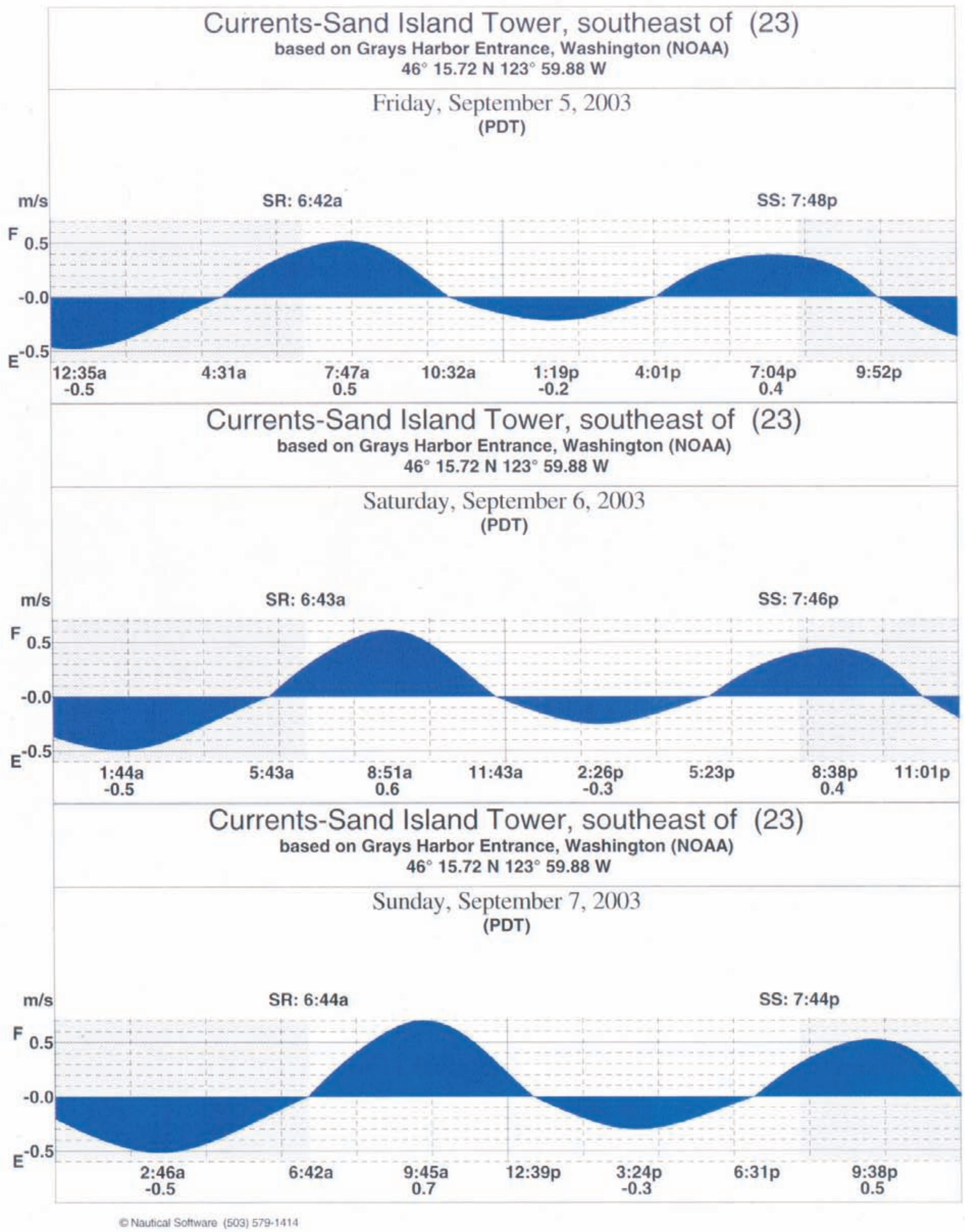

Fig. 10. Predicted tidal currents at the mouth of the Columbia River during the coring operations.

Table 1. Measurements of meteorological and wave conditions from the National Data Buoy Center Station 46029, Columbia River Bar during the coring operations.

Date	Time (PDT)	Wind Direction		Wind Speed & Gust (m/s)	(m/s)	Wave Height (meters)	Wave Period (sec)	Atmos Pressure (mm)	Air Temp (°C)	Sea Temp (°C)	Dew Point (°C)	Cores taken
9/5/2003	12:00 AM	340°	NNW	5	5	1.7	10	1015.0	14.8	13.4	13.8	
9/5/2003	1:00 AM	340°	NNW	5	5	1.5	10	1014.7	14.8	13.4	13.9	
9/5/2003	2:00 AM	340°	NNW	5	5	1.4	10	1014.7	14.5	13.6	13.7	
9/5/2003	3:00 AM	340°	NNW	4	5	1.3	9	1014.8	14.4	13.6	13.8	
9/5/2003	4:00 AM	340°	NNW	4	4	1.4	9	1015.3	14.1	13.7	13.7	
9/5/2003	5:00 AM	340°	NNW	5	5	1.3	10	1015.5	14.1	13.6	13.5	
9/5/2003	6:00 AM	340°	NNW	4	5	1.4	9	1015.7	14.1	13.6	13.6	
9/5/2003	7:00 AM	350°	NNW	2	3	1.3	10	1016.2	13.7	13.6	13.2	
9/5/2003	8:00 AM	340°	NNW	2	3	1.2	9	1016.1	13.6	13.4	13.3	
9/5/2003	9:00 AM	350°	N	2	2	1.1	9	1016.3	13.6	13.4	13.5	
9/5/2003	10:00 AM	350°	N	5	6	1.3	9	1016.4	13.3	13.3	13.2	
9/5/2003	11:00 AM	350°	N	3	5	1.2	9	1016.4	12.9	13.3	12.9	
9/5/2003	12:00 PM	360°	N	4	5	1.1	9	1016.1	12.7	13.3	12.6	
9/5/2003	1:00 PM	10°	N	3	4	1.1	9	1016.3	12.2	13.4	12.1	
9/5/2003	2:00 PM	10°	N	3	3	1.1	9	1016.1	11.7	13.3	11.7	
9/5/2003	3:00 PM	20°	NNE	2	2	1.0	8	1016.2	11.4	13.3	11.3	
9/5/2003	4:00 PM	40°	NE	2	2	1.0	9	1016.0	11.4	13.3	11.3	
9/5/2003	5:00 PM	340°	NNW	2	2	1.0	8	1016.0	11.7	13.4	11.6	203 at 5:05 PM
9/5/2003	6:00 PM	340°	NNW	3	3	1.0	8	1016.5	12.1	13.6	12.0	
9/5/2003	7:00 PM	340°	NNW	2	3	0.9	9	1016.3	12.7	13.7	12.6	204 at 7:03 PM
9/5/2003	8:00 PM	330°	NNW	4	4	0.8	8	1016.3	13.3	14.1	13.0	205 at 7:41 PM, 201 at 8:26 PM
9/5/2003	9:00 PM	320°	NW	4	5	0.9	14	1016.3	13.6	14.2	13.2	
9/5/2003	10:00 PM	340°	NNW	4	5	0.8	14	1015.6	13.6	14.4	13.5	
9/5/2003	11:00 PM	330°	NNW	5	6	0.8	9	1015.6	13.9	14.8	13.9	
9/6/2003	12:00 AM	350°	N	4	5	0.8	9	1015.0	13.3	14.9	13.2	
9/6/2003	1:00 AM	350°	N	3	4	0.8	14	1014.0	13.3	14.9	13.2	
9/6/2003	2:00 AM	320°	NW	3	3	0.9	9	1014.1	12.9	14.8	12.9	
9/6/2003	3:00 AM	340°	NNW	3	4	0.9	8	1013.4	12.5	14.4	12.5	
9/6/2003	4:00 AM	300°	WNW	2	3	0.9	8	1014.0	12.1	14.1	12.1	
9/6/2003	5:00 AM	---	---	0	1	0.9	9	1014.3	12.1	14.1	12.0	
9/6/2003	6:00 AM	---	---	0	1	0.9	7	1014.2	12.1	14.1	12.1	
9/6/2003	7:00 AM	190°	S	3	3	0.9	8	1014.5	12.3	14.1	12.2	109 at 6:52 AM
9/6/2003	8:00 AM	180°	S	4	5	0.9	8	1014.0	12.8	14.1	12.8	107 at 7:58 AM
9/6/2003	9:00 AM	180°	S	4	5	0.9	7	1014.1	12.9	14.1	12.9	108 at 8:37 AM
9/6/2003	10:00 AM	180°	S	3	4	1.0	8	1013.7	13.3	14.1	13.3	207 at 9:55 AM
9/6/2003	11:00 AM	180°	S	4	5	0.9	8	1013.5	13.4	14.1	13.3	
9/6/2003	12:00 PM	170°	S	5	7	0.9	8	1012.6	13.3	13.7	13.2	
9/6/2003	1:00 PM	180°	S	5	6	0.9	7	1012.3	13.3	13.7	13.2	
9/6/2003	2:00 PM	190°	S	5	6	1.0	8	1012.4	13.3	13.7	13.2	
9/6/2003	3:00 PM	200°	SSW	6	7	1.0	7	1012.6	13.3	13.9	13.2	
9/6/2003	4:00 PM	200°	SSW	5	6	1.0	8	1012.8	13.5	14.1	13.5	
9/6/2003	5:00 PM	200°	SSW	5	6	1.0	7	1012.7	13.6	14.1	13.6	
9/6/2003	6:00 PM	190°	S	4	5	0.9	8	1013.2	13.7	14.1	13.6	
9/6/2003	7:00 PM	180°	S	6	7	0.9	7	1012.8	13.7	13.9	13.6	
9/6/2003	8:00 PM	180°	S	5	6	1.0	7	1013.3	14.0	13.6	14.0	
9/6/2003	9:00 PM	170°	S	6	7	1.1	13	1013.1	14.1	13.6	14.0	
9/6/2003	10:00 PM	190°	S	6	7	1.1	7	1013.3	14.4	13.6	14.1	
9/6/2003	11:00 PM	180°	S	7	9	1.3	8	1012.7	14.2	13.7	14.1	
9/7/2003	12:00 AM	180°	S	8	9	1.4	7	1012.1	14.1	13.7	14.1	
9/7/2003	1:00 AM	200°	SSW	8	9	1.6	8	1012.2	14.2	13.7	14.1	
9/7/2003	2:00 AM	190°	S	8	9	1.8	8	1011.8	14.1	13.3	14.0	
9/7/2003	3:00 AM	190°	S	7	8	1.7	8	1011.6	14.3	13.4	14.1	
9/7/2003	4:00 AM	190°	S	7	8	1.7	6	1011.6	14.2	13.3	13.9	
9/7/2003	5:00 AM	180°	S	7	8	1.6	8	1011.8	13.9	13.5	13.8	
9/7/2003	6:00 AM	170°	S	7	9	1.7	8	1011.3	13.9	13.6	13.8	
9/7/2003	7:00 AM	220°	SW	5	6	1.7	6	1011.9	14.1	13.3	14.0	
9/7/2003	8:00 AM	200°	SSW	5	6	1.6	8	1012.3	14.2	13.6	14.0	
9/7/2003	9:00 AM	190°	S	4	5	1.6	8	1012.5	13.7	13.4	13.6	
9/7/2003	10:00 AM	200°	SSW	3	3	1.5	6	1012.6	13.6	13.3	13.6	
9/7/2003	11:00 AM	190°	S	3	4	1.5	6	1013.0	13.7	13.3	13.6	
9/7/2003	12:00 PM	190°	S	3	4	1.5	6	1013.2	14.1	13.3	14.0	202 at 12:00 PM
9/7/2003	1:00 PM	180°	S	4	4	1.5	8	1012.9	13.7	13.3	13.6	206 at 12:38 PM
9/7/2003	2:00 PM	180°	S	4	5	1.5	6	1013.1	13.7	13.3	13.6	
9/7/2003	3:00 PM	190°	S	5	6	1.4	8	1013.3	13.7	13.3	13.6	
9/7/2003	4:00 PM	180°	S	5	5	1.3	8	1013.2	13.7	12.9	13.6	
9/7/2003	5:00 PM	170°	S	5	6	1.2	7	1013.5	14.1	13.3	14.0	

longitude (W). These were later converted to Washington State Plane coordinate system. Water depth was determined from the vessel's fathometer, with readings recorded in fathoms. The depth indicated was from hull transducer to seabed. A correction factor of 2.74 m (9 ft) needs to be added to recorded water depth to bring it to the actual water depth at the time of coring. Water depth listed in Table 2 is not corrected for transducer or for tide. The water depth at the core sites based on bathymetric surveys referenced to the NAVD 88 vertical data is provided in the Core Descriptions section (see discussion and Table 5).

To maintain the vessel on site while coring, a one or two point anchoring system was used. The decision to use one or two anchors was based on current speed and direction relative to wind and wave direction and safe operating distance from structures and/or shallow shoals. At most coring sites, a single bow anchor was used with the boat oriented into the (sometimes strong) currents.

Vessel positioning was significantly affected by locally variable, and sometimes opposing, surface and bottom currents, and wind speed and direction. Due to the spatial and temporal variability of currents within the MCR, the boat captain favored the use of a single bow anchor, particularly while operating in the vicinity of the jetties. On a few occasions the vessel drifted off-target more than was desired. However, due to the significant time constraint imposed by a shift in weather conditions, repositioning the vessel closer to the target location was not feasible in most cases. Opposing currents did, on occasion, affect vibracorer operations during extraction from the seabed. Prior to extraction of the core barrel from the seabed, the vessel was maneuvered into position over the vibracorer, to ensure slow winch hoisting and vertical pullout. The corer was lifted and lowered via an overhead line attached to the main winch, and the operator independently lowered the power cable so that he could sense when the rate of penetration slowed or the corer encountered resistance.

Given the initial ideal weather conditions that would not persist past Saturday afternoon, the coring operations began as early as possible on Friday, September 5, during slack water and rising tide at the north side of the Columbia River entrance, when light northwest winds were favorable to operating in the vicinity of the North Jetty. Coring began at site C at approximately 5 p.m. (PDT) on September 5. Core MCR-203 vibrated for 2:18 minutes to refusal. The core barrel did not penetrate any further for 1 minute of vibrating. The core barrel was extracted, and close examination revealed that it had rotated repeatedly in place without further penetration, which deeply "scored" the barrel at that depth position. In an attempt to obtain additional recovery, the next core was vibrated for 2:39 minutes on the second attempt at site C. Upon hoisting the vibracorer to the surface, we found that the barrel had broken off at the collar (where it meets the vibrating coring head). On the third attempt, we allowed the corer to vibrate for 1:57 minutes and again we found that the barrel had broken off at the collar (Fig. 11). On the fourth attempt we vibrated for 1:30 minutes, yet obtained slightly greater recovery for core MCR-204 (366 cm) than for core MCR-203 (338 cm). This result indicated that it was not necessary, or even desirable, to vibrate the core for an extended period because the vibracorer achieved maximum penetration quite quickly and extended vibrating might easily result in loss of the entire core. At this

Fig. 11. Photo of vibracorer at site C with core barrel broken off at the collar, located below the vibracorer head (photo by R. Gammisch).

point a decision was made to stop vibrating the corer once the corer stopped penetrating for a substantial time (approximately 30-45 seconds) to avoid subjecting the core barrel to intense stress which could result in either breakage or reduced recovery.

Once two cores (MCR-203 and MCR-204) were collected at Site C, the vessel was navigated to site B, further to the west along the North Jetty. Upon anchoring at approximately 7:40 p.m., a slight increase in wind speed from the north drifted the vessel further to the south than anticipated, however, due to the approaching fog and setting sun (7:48 p.m.) and the forecast of a reversal of wind direction by the following morning, it was decided to collect the core at this location, rather than invest more time in positioning the vessel closer to the target. At site B, core MCR-205 penetrated rather quickly with 470 cm of recovery obtained in only 39 seconds.

As the end of daylight approached and with the fog density increasing, core MCR-201 was collected at Site A at 8:26 p.m. The core barrel penetrated to its full extent (580 cm) in 2:02 minutes. Due to this maximum penetration obtained and the deteriorating visibility, it was decided to not take an additional core at this site, but to proceed to site D nearby. However, by the time the vessel approached site D, a thick fog severely limited visibility and the captain determined that it was too unsafe to anchor in such close proximity to the north jetty.

Coring operations continued the following day at site G with light southerly wind and wave conditions. The vessel was positioned on site at 6:50 a.m. and the collection of core CP-109 began at 6:52 a.m. The first two gillnet floats, indicating penetration to over 3.0 meters, surfaced within 1:30 minutes. Subsequent penetration was slower and the third float, indicating an additional 1.5 m of penetration, surfaced after an additional 2:15 minutes. The total vibrating time was 3:49 minutes, the longest for the entire project. The core barrel penetrated to its full extent of 580 cm.

The vessel was stationed at site F at 7:46 a.m. By this time, the wind speed and gusts from the south increased by 1-2 m/s however the vessel did not drift to the north as much as expected upon anchoring. Core CP-107 was vibrated for 1:46 minutes to refusal with indications of difficult penetration. The core barrel penetrated to 300 cm with a significant abrasion ring noted on the barrel at 205 cm. A second core, CP-108, was then collected, penetrating to 250 cm in 1:31 minutes.

Following the collection of core CP-108 at 8:38 a.m., the vessel was navigated around the Columbia River south jetty along its north side to site E, located on Clatsop shoal within the inlet. With favorable winds from the south and slack tide, the vessel carefully navigated to very shallow water of less than 7 m. Core MCR 207 was collected at 9:56 a.m. with the top of the corer tower just above water level. The core barrel penetrated 430 cm in 1:45 minutes.

With increasing southerly wind speeds, the vessel departed the site for the Port of Astoria to process the collected cores and wait for more favorable conditions to continue collection of cores along the north jetty. Strong southerly winds and increasing seas prevented the feasibility of attempting the collection of additional cores on September 6. Core processing commenced at the Port of Astoria and continued until approximately 8 p.m. (Fig 8). Measurements of penetration and recovery were made, core catchers were removed, and cores were cut into 1.5-m sections and stored in the refrigerated hold of the vessel. It was decided to not open the core sections in the field for two reasons. The forecasted change to unfavorable operating conditions necessitated collecting as many cores as possible as quickly as possible. Secondly, it appeared that we were collecting high quality cores, because we found that extended vibrating was not desirable and decided to limit the vibration period for all cores rather than drive some cores to absolute refusal.

With approaching daylight and slack tide on September 7, the vessel navigated to the mouth of the Columbia River to resume coring operations. However, strong southerly winds and wave heights approaching 2 m prevented the feasibility of safely attempting the collection of cores close to the north jetty. A phone call was made to Mr. Rod Moritz, coastal engineer of the Portland District Corps of Engineers, to discuss the status of the coring operations and the priorities for collection of the remaining cores. It was decided that as soon as the weather conditions would allow, we would attempt the collection of a core at site D, as close to the north jetty as the Captain deemed safe, and the collection of an additional core approximately 100 m to the southeast of Site C.

Fortunately, by the time of the next slack tide, the southerly wind speed decreased significantly from about 8 m/s to 3 m/s, providing more favorable conditions to attempt coring operations adjacent to the north jetty. The vessel was positioned on-site at the alternate location for site C at 11:59 a.m. Core MCR-202 penetrated 491 cm with 2:00 minutes of vibration. During coring the vessel drifted over the corer and it was difficult to reposition the vessel precisely to obtain a vertical pullout. The core barrel kinked at 334 cm upon pullout and had to be cut in two sections to remove the barrel from the corer tower. The barrel was significantly scored at 360 cm, indicating that it had remained at that depth for some time before penetrating further.

The vessel was then quickly navigated to as close to Site D as possible. The vessel was on station at 12:33 p.m. and core MCR-206 quickly penetrated to its full extent of 580 cm with 1:30 minutes of vibration. The recovery of this core was 572 cm, the maximum for the entire project.

With the changing tide and increasing wind speed and wave heights, it was determined not feasible to attempt an additional core at Site A, where two cores had been originally proposed. Due to the strong northward current and forecast for worsening wind and wave conditions over the next few days, it was not economically justified to attempt additional cores. A total of 10 vibracores from 12 attempts were obtained during the field operations of September 5-7, 2003. Fig. 12 shows the locations of the collected cores and Table 2 provides specific information about each core.

Table 2. Information on cores collected in this project.

Transect name and Core ID		COE Site	Position (decimal degrees) Latitude (N)	Longitude (W)	Water Depth (uncorrected) *(Fathoms)*	*(Feet)*	*(Meters)*	Date (m/d/yr)	Start Time (PDT)	Vibration Time (sec)	Penetration (cm)	Recovery (cm)
CRLC-MCR	201	A	46.26795	-124.07287	6.60	39.6	12.1	9/5/2003	20:26:47	122	580	530.0
CRLC-MCR	202	C-Alternate	46.27367	-124.06158	4.70	28.2	8.6	9/7/2003	12:00:09	120	491	456.0
CRLC-MCR	203	C	46.27460	-124.06240	4.50	27.0	8.2	9/5/2003	17:05:11	138	382	338.0
CRLC-MCR	204	C	46.27447	-124.06245	4.70	28.2	8.6	9/5/2003	19:03:04	95	360	366.0
CRLC-MCR	205	B	46.26970	-124.06712	5.50	33.0	10.1	9/5/2003	19:41:49	39	374	470.0
CRLC-MCR	206	D	46.26915	-124.07337	---	---	---	9/7/2003	12:38:43	90	580	572.0
CRLC-MCR	207	E	46.23547	-124.04410	2.60	15.6	4.8	9/6/2003	9:55:05	105	430	423.0
CRLC-CP	107	F	46.22913	-124.06135	5.80	34.8	10.6	9/6/2003	7:58:27	106	300	301.0
CRLC-CP	108	F	46.22903	-124.06125	5.90	35.4	10.8	9/6/2003	8:37:00	91	250	219.0
CRLC-CP	109	G	46.21868	-124.03888	5.45	32.7	10.0	9/6/2003	6:52:10	229	580	509.0

Laboratory Processing

The core sections (of up to 1.5-m lengths) were removed from the vessel's cold storage at the Port of Newport on Monday afternoon, September 8. Table 3 lists the number of sections per core and the length of each section. The inventory was checked to ensure that all sections were present. The core sections were placed vertically in barrels and transported to OSU for core logging, storage, and archiving. Once the vibracore sections arrived at the OSU core lab, they were immediately placed in the 36,000 cubic-foot refrigerated storage facility.

Core processing began Tuesday morning, September 9 and continued through Saturday, September 13. For initial core processing, the cores were split (Fig. 13), photographed, briefly logged (visual descriptions; Fig. 14) and sampled. The archive half of each core section was placed on a horizontal platform illuminated by four bright lights. Digital photographs were taken at 10 cm intervals with approximately 50 percent overlap between successive photos. This overlap ensured that no distortion would be seen when the individual frames were joined to construct the photomosaic image (Appendix A). The digital core photos were downloaded to CDs and catalogued.

After the photographs for each core section were completed, the archive half of the core section was placed alongside the working half and a measuring tape on a work table (Fig. 14). Visual descriptions of the cores included disturbance (if any), color using the Munsell Color Classification Chart, grain size at various depths, occurrence of shells and other organic material, and general observations/comments. Samples were also identified for grain-size analysis and dating by the radiocarbon technique. After logging, both core halves were covered with plastic wrap, sealed, put in labeled plastic "D tubes" (Fig. 15), and placed in the OSU cold storage room (Fig. 16).

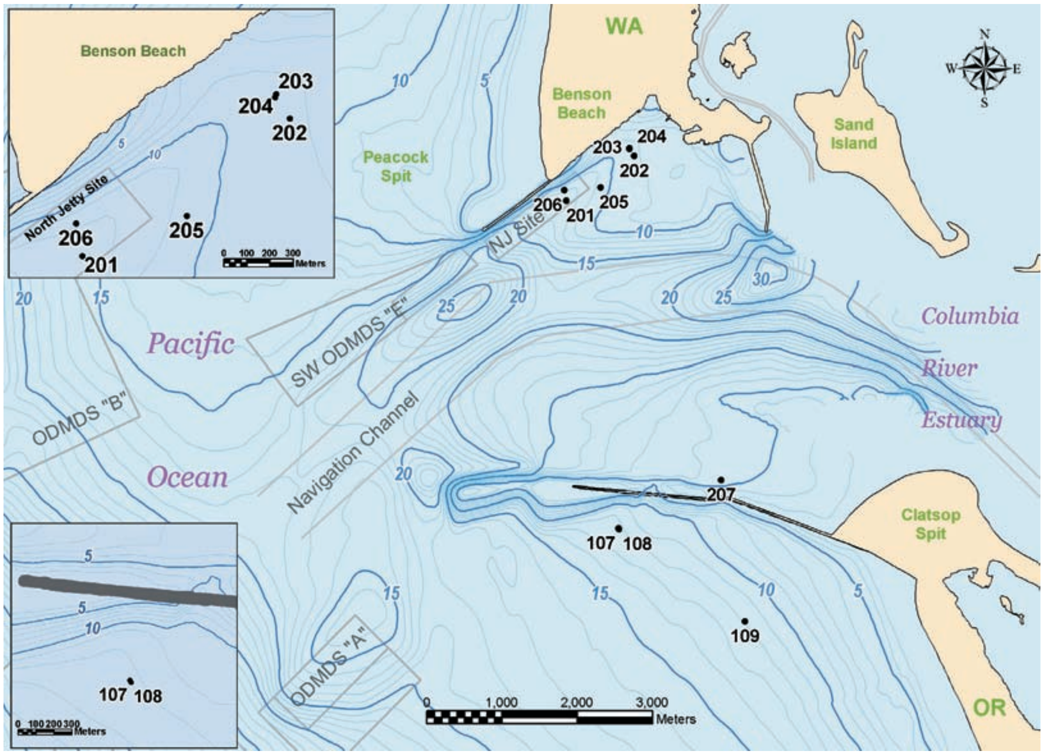

Fig. 12. Map of the locations of the cores collected in this project.

Table 3. Core sections and section lengths.

Site Name	Section	Depth Interval
COE Site A	201/1	0-150 cm
MCR 201	201/2	150-300 cm
	201/3	300-450 cm
	201/4	450-530 cm
COE Site C-Alternate	202/1	0-135 cm
	202/2	135-285 cm
MCR 202	202/3	285-435 cm
	202/4	435-456 cm
COE Site C	203/1	0-120 cm
MCR 203	203/2	120-241 cm
	203/3	241-338 cm
COE Site C	204/1	0-150 cm
MCR 204	204/2	150-300 cm
	204/3	300-366 cm
COE Site B	205/1	0-101 cm
MCR 205	205/2	101-214 cm
	205/3	214-329.5 cm
	205/4	329.5-470 cm
COE Site D	206/1	0-150 cm
MCR 206	206/2	150-300 cm
	206/3	300-450 cm
	206/4	450-572 cm
COE Site E	207/1	0-150 cm
MCR 207	207/2	150-300 cm
	207/3	300-423 cm
COE Site F	107/1	0-150 cm
CP 107	107/2	150-301 cm
COE Site F	108/1	0-150 cm
CP 108	108/2	150-219 cm
COE Site G	109/1	0-150 cm
CP 109	109/2	150-300 cm
	109/3	300-450 cm
	109/4	450-509 cm

Comparison was made between penetration depth and the length of recovered sediment in the core (Table 2) as a means of evaluating the reliability of the core data and the actual depth to various sediment horizons. While ideally, penetration depth would equal length of recovered sediment, differences between the two values are common and may be attributed to a number of causes:

- Recovery less than penetration could be due to compaction of sediment during the coring process (common with most corers and especially common when a hard substrate is encountered which causes the sediment within the barrel to be compacted until the corer penetrates that particular layer, or the vibrating is halted).
- Recovery more than penetration could be due to *expansion* of the sediment in the barrel as the core is brought to the surface and the pressure is reduced (especially common in organic-rich muddy sediment that contains gas).
- Recovery less than penetration could be due to *loss of sediment* as the corer is raised to the surface

(especially when particularly fine sand was cored and/or sea conditions resulted in surging of the vessel during recovery of the coring tower). Attempts to minimize this loss were made by plugging or capping the core catcher/cutter as soon as vibracorer was on deck.

In all cores collected for this project, the recovery was within +/- 15% of penetration (see Table 2), which is better than average based on the cumulatively averaged experience of the geologist and operators on board (MF, RG, and WR) and similar to results obtained throughout the CRLC in 2002. Together with the descriptive comments about 'disturbance' made when each core section was opened, the Recovery/Penetration indicates that these cores are of a high quality.

Fig. 13. Photo of cutting core sections length-wise. Once the core barrel was cut on opposite sides, a wire was pulled through the sediment to split the core in half;

Fig. 14. Photo of core logging. Sediment properties and sedimentary structures are observed and recorded on core logs.

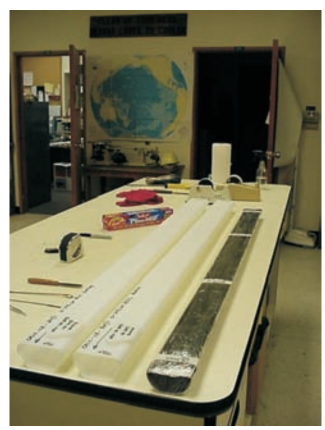

Fig. 15. Photo of core half sealed and labeled for archiving in "D-tube".

Fig. 16. Photo of the set of archived- and working-half core sections stored in "D-tubes" in the refrigerated facility of the OSU Core Laboratory.

Detailed Laboratory Analysis

Following the initial core processing and reporting on preliminary interpretations (Kaminsky and Ferland, 2003b), detailed analysis commenced including x-radiography, sediment sampling and grain size analysis, biogenic material sampling and dating by the radiocarbon method. In addition, detailed core logs were constructed following the results of these analyses.

X-radiography

X-ray images of the each of the cores were taken at OSU. Each core section was labeled and marked in decimeter units during filming. The films were scanned and the digital images (covering approximately 30 cm length of core) were later adjoined to produce a complete mosaic for each core section. The x-ray mosaics were then aligned with the photo mosaic images (Appendix A) for analysis and interpretation. Many of the x-ray images revealed features that were not visually apparent on the surface. The images were used to look for indications of disturbance, aid with the interpretations of the cores, and to locate shell material for sampling and dating. The digital x-ray images can be viewed at a range of scales to see details that may not be apparent at the scale of the printed mosaics in Appendix A.

During logging of the cores, it was difficult to decisively determine whether the sharp boundaries between mud and sand laminae were in some cases, actually erosional surfaces. However x-radiographs, paired with the core photographs and detailed core logs, provided the necessary additional data to understand and interpret the nature of the contacts between sand and mud in the laminated units. As will be discussed in the following sections, several definite incongruities suggest that erosional events occurred within the intervals of laminated sand and mud deposition.

Grain Size Analysis

One to three sediment samples were collected from each core section for grain size analyses. The sediment intervals are sufficiently spaced among (primarily sand) units and were selected to enhance the interpretation of sedimentation rates and depositional processes corresponding to age dates of selected intervals. The grain size analysis provides greater certainty about the qualities of the subsurface sediments near the Columbia River north jetty, and their suitability for use as beach fill material. Vertical gradients in grain size suggest possible changes in deposition or erosion. Grain size statistics also provide the means for more rigorous analysis or interpretation of sediment sources, sinks, dispersal pathways, cross-shelf sorting, and morphological equilibrium.

Grain size analysis for this project was performed on 55 sediment samples by the US Geological Survey in Menlo Park, CA. Sediment analysis was completed at ¼ phi intervals from –2.00 to 11.50 phi. The analysis of fines was performed on samples that have 3% or more fines with a small-volume Coulter counter. The analysis of the intermediate fraction was performed with settling tube.

The principle results of grain size statistics, based on the methods of Folk and Ward (1957), are given in Table 4. The results show a general trend of coarser sediments from east to west and from north to south along the Columbia River north jetty, with the coarsest sand found in core 201. Other observations of the grain size results are discussed later in this report.

Radiocarbon Dating

Radiocarbon dates were needed to determine the age of several key sedimentary units (e.g., the laminated mud unit) and in order to 'ground-truth' areas that have been characterized predominantly by deposition or erosion on the historical surveys. The dates are important to document the spatial variability of sediments of particular ages and to compare the long-term rate of sediment accumulation. Especially for the MCR cores, significant differences in the sedimentary sequence and age were observed among cores that were relatively close together. Some of the reasons for this are addressed below, and in the Discussion section.

During logging of the vibracores, samples of biogenic material (primarily shells and wood) were collected for possible dating by AMS radiocarbon analysis. In general, samples considered to be "ideal" for dating were those that were found in the center (away from the edges of the barrel) of an undisturbed core, and appeared to be in depositional position. Wood fragments or organic-rich sediments were carefully extracted from the core and put in a labeled vial or sample bag, and immediately stored in the refrigerator until being submitted for AMS analysis. Samples of organic plant material were dried and hand-picked to select only the fibrous, brown organic matter; charcoal was specifically removed since it may represent much older wood. Sediment

Table 4: Summary results of grain size analysis.

Core		Depth Interval (cm)	median (phi)	mean (phi)	sorting (phi)	median (mm)	mean (mm)	sorting (mm)	% Gravel	% Sand	% Mud	% Silt	% Clay
CP	108/1	10-15	2.60	2.56	0.43	0.16	0.17	0.74	0.32	99.31	0.37	0.37	0.00
CP	108/1	65-70	1.73	1.64	0.49	0.30	0.32	0.71	1.50	96.98	1.52	1.52	0.00
CP	108/1	117-122	1.32	1.30	0.31	0.40	0.41	0.81	0.00	99.67	0.33	0.33	0.00
CP	108/2	163-168	1.61	1.61	0.28	0.33	0.33	0.82	0.00	99.94	0.06	0.06	0.00
CP	108/2	199-204	1.73	1.70	0.32	0.30	0.31	0.80	0.00	99.34	0.66	0.66	0.00
CP	109/1	10-12	2.30	2.34	0.39	0.20	0.20	0.76	0.61	96.70	2.69	2.69	0.00
CP	109/1	45-50	2.45	2.43	0.32	0.18	0.19	0.80	0.00	98.51	1.49	1.49	0.00
CP	109/1	115-120	2.12	2.14	0.28	0.23	0.23	0.82	0.00	98.51	1.49	1.49	0.00
CP	109/2	195-200	2.12	1.93	0.66	0.23	0.26	0.63	0.00	98.12	1.88	1.88	0.00
CP	109/2	265-270	1.24	1.32	0.38	0.42	0.40	0.77	0.00	98.96	1.04	1.04	0.00
CP	109/3	345-350	1.26	1.31	0.30	0.42	0.40	0.81	0.00	100.00	0.00	0.00	0.00
CP	109/3	418-422	2.66	2.66	0.39	0.16	0.16	0.76	0.00	95.41	4.59	3.63	0.97
CP	109/4	495-500	1.59	1.70	0.62	0.33	0.31	0.65	0.00	98.04	1.96	1.59	0.37
MCR	201/1	10-15	1.99	1.97	0.25	0.25	0.26	0.84	0.15	98.31	1.54	1.54	0.00
MCR	201/1	75-80	1.75	1.70	0.32	0.30	0.31	0.80	1.28	97.82	0.90	0.90	0.00
MCR	201/1	130-135	1.27	1.27	0.47	0.41	0.41	0.72	1.99	95.72	2.29	2.29	0.00
MCR	201/2	250-255	1.78	1.78	0.25	0.29	0.29	0.84	0.32	98.69	0.99	0.99	0.00
MCR	201/3	365-370	1.67	1.64	0.18	0.31	0.32	0.88	0.00	99.40	0.60	0.60	0.00
MCR	201/4	520-525	1.75	1.73	0.28	0.30	0.30	0.82	0.00	99.00	1.00	1.00	0.00
MCR	202/1	5-10	1.96	1.98	0.31	0.26	0.25	0.81	0.00	98.92	1.08	1.08	0.00
MCR	202/1	110-115	1.93	1.91	0.22	0.26	0.27	0.86	0.00	99.61	0.39	0.39	0.00
MCR	202/2	210-215	1.94	1.87	0.23	0.26	0.27	0.85	0.00	99.81	0.19	0.19	0.00
MCR	202/3	355-360	2.00	1.99	0.20	0.25	0.25	0.87	0.00	99.71	0.29	0.29	0.00
MCR	202/3	420-430	2.42	2.42	0.30	0.19	0.19	0.81	0.00	98.50	1.50	1.50	0.00
MCR	203/1	5-10	2.35	2.38	0.40	0.20	0.19	0.76	0.33	98.56	1.12	1.12	0.00
MCR	203/1	55-60	2.04	2.05	0.33	0.24	0.24	0.80	0.45	98.43	1.12	1.12	0.00
MCR	203/1	80-85	2.54	3.01	1.13	0.17	0.12	0.46	0.08	81.77	18.16	15.57	2.58
MCR	203/2	150-155	2.48	2.47	0.25	0.18	0.18	0.84	0.00	98.87	1.13	1.13	0.00
MCR	203/2	200-205	2.50	2.51	0.24	0.18	0.18	0.85	0.00	98.75	1.25	1.25	0.00
MCR	203/3	325-330	2.46	2.45	0.29	0.18	0.18	0.82	0.00	99.34	0.66	0.66	0.00
MCR	204/1	25-30	2.20	2.21	0.33	0.22	0.22	0.80	0.00	99.04	0.96	0.96	0.00
MCR	204/1	70-75	2.96	3.08	0.59	0.13	0.12	0.66	0.50	90.27	9.22	9.18	0.05
MCR	204/1	140-145	2.53	2.53	0.41	0.17	0.17	0.75	0.00	95.28	4.72	4.22	0.50
MCR	204/2	230-235	2.50	2.50	0.26	0.18	0.18	0.84	0.00	97.92	2.08	2.08	0.00
MCR	204/3	350-355	2.56	2.57	0.35	0.17	0.17	0.78	0.00	98.68	1.32	1.32	0.00
MCR	205/1	10-15	2.02	1.98	0.36	0.25	0.25	0.78	0.00	99.85	0.15	0.15	0.00
MCR	205/1	90-95	1.88	1.86	0.24	0.27	0.28	0.85	0.32	98.97	0.71	0.71	0.00
MCR	205/2	135-140	1.67	1.58	0.39	0.31	0.33	0.76	0.17	99.78	0.04	0.04	0.00
MCR	205/2	178-183	1.28	1.28	0.43	0.41	0.41	0.74	1.85	97.46	0.69	0.69	0.00
MCR	205/3	235-240	2.02	2.02	0.27	0.25	0.25	0.83	0.00	99.26	0.74	0.74	0.00
MCR	205/3	310-315	1.85	1.79	0.28	0.28	0.29	0.82	0.00	99.13	0.87	0.87	0.00
MCR	205/4	425-430	1.71	1.65	0.34	0.31	0.32	0.79	0.35	99.18	0.47	0.47	0.00
MCR	206/1	50-55	2.02	2.01	0.29	0.25	0.25	0.82	0.00	99.39	0.61	0.61	0.00
MCR	206/1	89-91	2.46	2.45	0.29	0.18	0.18	0.82	0.00	99.48	0.52	0.52	0.00
MCR	206/2	220-225	1.66	1.66	0.38	0.32	0.32	0.77	0.00	99.77	0.23	0.23	0.00
MCR	206/2	275-280	1.74	1.74	0.27	0.30	0.30	0.83	0.05	99.18	0.77	0.77	0.00
MCR	206/3	380-385	1.75	1.77	0.20	0.30	0.29	0.87	0.00	99.49	0.51	0.51	0.00
MCR	206/4	545-550	1.90	1.86	0.20	0.27	0.28	0.87	0.00	99.48	0.52	0.52	0.00
MCR	207/1	15-20	2.21	2.19	0.39	0.22	0.22	0.76	0.12	99.21	0.67	0.67	0.00
MCR	207/1	50-52	2.27	2.30	0.49	0.21	0.20	0.71	0.00	95.76	4.24	3.34	0.90
MCR	207/1	125-130	2.51	2.49	0.35	0.18	0.18	0.78	0.00	97.51	2.49	2.49	0.00
MCR	207/2	205-210	2.31	2.30	0.30	0.20	0.20	0.81	0.00	99.42	0.58	0.58	0.00
MCR	207/2	285-290	2.29	2.29	0.29	0.20	0.20	0.82	0.00	99.67	0.33	0.33	0.00
MCR	207/3	375-380	2.44	2.42	0.31	0.18	0.19	0.81	0.00	97.77	2.23	2.23	0.00
MCR	207/3	413-418	2.20	2.22	0.33	0.22	0.21	0.80	0.00	99.63	0.37	0.37	0.00

was removed to reduce the potential for contamination by small sand-sized shell particles that would affect the radiocarbon result.

In all cases, the freshest material available was selected for dating. Shells or other fragments of carbonate, such as sand dollars or barnacles, were preferentially selected if they retained some original color, and/or luster, and did not show signs of surface abrasion or boring by marine organisms. In addition to color, and surface luster, "freshness" was determined by examining samples under a microscope to identify potential causes of contamination (for example, small encrustations or borings by organisms younger than the selected shell). If a non-encrusted sample was available, it was selected preferentially. If not, then the surfaces of the carbonate fragment were scraped to remove the potential source of contamination. Where sufficiently large fragments were sampled, shells were identified prior to radiocarbon dating. Samples that could not be identified as either shell, barnacle, or sand dollar are described as 'carbonate'. Occasionally, carbonate material that did not meet the 'freshness' criteria just described were selected for analysis if no other material was available and the depth interval was considered important/pivotal for interpretation.

Approximately three times as many samples were collected and archived, as were dated. Before a decision was made to date a particular sample, the core log was studied in detail to determine which interval(s) would provide the most valuable information to assist in the interpretation. Most often, intervals close to (above or below) a sedimentary contact were selected for dating. Contacts between sedimentary units may represent an erosional event, a change in depositional energy or the dominant process, or in sediment supply. Additional samples, spaced between sedimentary contacts, were sent for dating in order to calculate long-term sediment accumulation rates. In some cores, the scarcity of datable material, or of material deemed to be of reasonable quality, necessitated dating a sample from another depth interval.

Radiocarbon ages were obtained from analysis of shells, other carbonate fragments (such as sand dollars and barnacles), fine organic fragments, and pieces of wood. All samples were analyzed by the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. Often, multiple samples were selected within a single vibracore to obtain a well-spaced chronologic history of sediment accumulation (e.g., core 206). However, lack of datable material sometimes prevented dating of preferred intervals. In some cores, specific intervals were targeted in order to determine the age of a specific depositional unit (e.g., cores 109, 207).

The "best" and most representative radiocarbon dates are obtained at sites where the rate of sediment accumulation is high, such as adjacent to the Long Beach Peninsula. In contrast, the Clatsop shelf is generally characterized by erosion, or lower rates of accumulation (Buijsman et al., 2003; Kaminsky and Ferland, 2003a,b). The dating of material in an eroded sedimentary deposit results in long-term sediment accumulation rates that may not represent the actual rate of accumulation for a particular sedimentary unit within the sequence. The Columbia River entrance channel is highly variable and subjected to multiple processes, including ebb and flood tidal flows, storm-induced waves, daily river discharge, and peak river flows during floods. Furthermore, prior to jetty construction, there were many changes in the size, shape and number of channels and shoals within and around the entrance. These conditions generally result in complex patterns of erosion and deposition and hence it is difficult to determine a meaningful long-term rate of sediment accumulation.

A significant and relevant problem inherent in radiocarbon dating is the potential transportation of older material to the depositional site (i.e., the core site). It is usually impossible to estimate the likely age of material prior to dating, except where a carbonate fragment is heavily 'bleached' or abraded, and appears "old" (in which case it is unlikely to be selected as a preferred sample for dating). Floods often transport large volumes of sediment and organic debris downstream, and may erode and redeposit sediment within a river channel. Columbia River floods represent a dominant and pervasive process affecting the entrance channel; 7 of the 10 cores were collected along the margin of the present-day channel, and the remaining cores were collected at sites that were previously within the entrance channels during various periods prior to jetty construction. Given the dynamic nature of this environment, it is possible (even likely) that sediment contained within the vibracores has been deposited, eroded and re-deposited multiple times. Despite these constraints and complications, radiocarbon dating is an essential tool in the analysis and interpretation of vibracores. Although it may not be appropriate to extrapolate rates of sediment accumulation, radiocarbon dates do provide a maximum time-frame for the depositional history.

In addition to submitting samples from the 2003 cores for AMS analysis, five age dates were obtained from cores collected previously on the Clatsop Plains inner shelf. These dates were prioritized to determine the age of the some intervals within the laminated mud units, and to hypothesize about the environment in which they were deposited, based on comparison with the MCR and Clatsop shelf cores collected in 2003 (see discussions of individual cores for results). These additional radiocarbon dates provide further documentation of the erosional (or at least non-depositional) nature of the Clatsop shelf, since the apparently-relict mud units are quite near the surface of some cores.

Calibrating Radiocarbon Ages

Calibrating radiocarbon ages of samples containing carbon (fragments of shell, sand dollar, barnacle, plants or wood) is a complex process and only a brief summary will be described here. After death, organisms (plant or animal) no longer take up any carbon from the atmosphere or water. Carbon 14, which is the radioactive isotope of Carbon, begins to decay from that time. There is a known relationship between the proportions of the various isotopes of carbon in living organisms (although there are some assumptions and uncertainties that are discussed below). The proportion of Carbon 14 remaining in the sample can be determined, and this is referred to as "fraction modern." The measured radiocarbon age of the sample is determined based on the fraction modern and a correction. This first correction is made to adjust the age because there are differences in the Carbon 13 values (a non-radioactive isotope of Carbon) in marine carbonate (shells, sand dollars, barnacles) vs. plants or wood. This correction usually increases the age of marine carbonate by approximately 410 years and also enables calculation of the error range associated with the measured radiocarbon age (i.e., +/- 30 years). However this measured radiocarbon age is not equivalent to the actual age. Several other corrections and calibrations are required before it can be compared to other dated materials.

Organisms that grow in seawater incorporate marine carbon. This is older than the carbon in the atmosphere and the difference in age depends on the specific ocean and depth of water in which the organisms lived. The measured radiocarbon age is adjusted using a marine reservoir correction, which reduces the age of the sample. There are uncertainties involved in this correction because values have been determined only for large regions, not specific sites, and areas where marine and fresh waters mix receive carbon of different ages. So samples from the shelf adjacent to a large river may have incorporated carbon from the ocean and the river. This introduces some uncertainty (lack of accuracy). This correction is not necessary for samples of wood or plants, so their measured radiocarbon age is not affected.

After both corrections have been made, the age should be calibrated using a standard program. The sample is calibrated to correct for the known variations in the long-term atmospheric production of Carbon 14. Published studies indicate that radiocarbon has not been produced in the atmosphere at the same rate over the last 50,000 years. This affects the proportion of Carbon 14: Carbon 13: Carbon 12 and thus the calculations to determine the age of a sample. Samples are calibrated, regardless of whether they are marine carbonate or wood. However, the calibration does not follow a general trend of increasing or decreasing the measured age. The production rate of radiocarbon has often fluctuated both above and below the modern value. The age of one sample might increase during calibration and a sample that is 350 years older may decrease during calibration, which might result in very similar calibrated ages for both samples that had measured radiocarbon ages that varied by 600-800 years.

Sample results from the NOSAMS laboratory that are ">Modern" cannot be calibrated (e.g., Core 109, 254-255 cm). The fraction of modern material is large enough, that statistically it is not possible to produce a realistic age given errors inherent in the measurement and age calculations. In addition, samples of marine carbonate that produced a measured radiocarbon age of less than about 350 years were also not able to be calibrated because once the marine reservoir correction is subtracted, the calibrated age is a negative number (e.g., Core 206, 91 cm). There is a notation for these samples in the data tables for individual cores as "cannot calibrate." The MCR cores contain proportionately more young samples than the Clatsop Plains or Long Beach shelf cores.

The radiocarbon age and the error reported by the laboratory (NOSAMS, W.H.O.I.) were entered into the well-respected calibration program, CALIB REV4.4.2 (University of Washington). Other data that were input into the program included the sample number, depth in the core, the regional value for the marine reservoir correction factor for the ocean adjacent to Washington and Oregon (398.0 +/- 25), and whether the sample was marine carbonate or wood/plant matter. The program incorporates this information and compares the result to the Carbon 14 production curve to produce a calibrated age. The calibrated age is reported as "1 sigma" and "2 sigma" age ranges, and these were used to interpret the cores and to estimate generalized rates of sediment accumulation in the various regions (MCR, Clatsop Plains, and Long Beach).

Radiocarbon dating is an essential tool for studying sediments deposited within the last 30,000-45,000 years. Using reputable laboratories, and obtaining large numbers of dates, increases the value and consistency of the data. However, the uncertainties in individual dates must be recognized. Radiocarbon ages are best used as an approximation to identify patterns of sediment deposition and accumulation.

Core Logs

After the initial descriptions of the cores were made in the laboratory, detailed core logs were constructed based on the results of the above analyses. The core logs provide additional information such as evidence of bioturbation, descriptions of finer-scale sedimentary structures, contacts, and gradients, composition and abundance of shell material and tracer sediments or minerals, and interpretations of depositional processes and environments found within the cores. A graphic core log is presented following the detailed description of each core in the following section.

Most core logs contain grain size descriptions followed by three numbers, such as "(0/99/1)". These numbers represent the ratio of (%gravel/%sand/%mud). The descriptions occur adjacent to the diamond symbols, each of which represents the depth within the core of a quantitative grain size analysis. The diamond symbols show the measured values for mean grain size, whereas the connecting line shows the grain-size variation based on visual descriptions of the cores that are not accounted for by the widely-spaced samples. The unconnected square dots on the right graph are sorting values (in phi units) for analyzed samples. If no symbols appear on the graph, then no sediment samples were analyzed from the core. All cores were described and logged to estimate the grain size and sorting.

The graphic logs also identify the depths of contacts, pebble lags, and radiocarbon ages determined by AMS analysis of carbonate (mostly shell and barnacle) and wood samples. The type of material analyzed by AMS is shown in parentheses after the age.

Core Descriptions

Preface

The core sites are located with respect to the north and south jetties, however it is important to consider the pre-jetty geography when reading these descriptions because the cores sampled sediment deposited prior to jetty construction. This section describes the historical setting in which the cores were located to provide a perspective of the dynamic sedimentary environment in which the cores were collected.

Prior to jetty construction, the mouth of the Columbia River typically had two entrance channels and a broad and shallow ebb-tidal delta complex extending from Peacock Spit on the north to Clatsop Spit on the south. The Charles Wilkes survey of 1841 shows the channel depth across the bar was 9.6 m (5.25 fathoms), and reveals massive shallow shoals (< 7.5 m) extending seaward and southwest of Cape Disappointment, seaward of Point Adams (subaerial Clatsop Spit), and across much of the center of the entrance (Middle Sand-bank) and lower estuary (Fig. 17). These extensive sand banks separated north and south channels that were typically 11-13 m deep in the lower estuary. The entrance was a dynamic zone of migrating channels, with adjacent regions of active erosion and deposition.

The Columbia River south jetty was constructed across Clatsop Spit between 1885 and 1895 to a length of approximately 6.8 km. Initially, the jetty confined the tidal currents, deepening the entrance channel. The jetty deteriorated under influence of the waves and currents, and the entrance channel shoaled and moved to the northwest. The south jetty was extended between 1903 and 1913. The north jetty was built across the large shoal of Peacock Spit between 1913 and 1917, featuring a length of 3.8 km. Jetty construction reduced the width of the river mouth by two-thirds, from approximately 9.6 to 3.2 km.

Overlays of the vibracore sites onto a series of early historical bathymetric charts reveal substantial natural and human-induced changes that have occurred at the MCR, and provide context for interpretation of the cores. In particular, the early charts illustrate the fluctuations between vastly different depositional environments and the temporal and spatial scales of depth change that has occurred at the vibracore sites over a period of just 73 years between 1841 and 1914. To provide a frame of reference, the position of the jetties and the 1926 and 1999 shorelines are also plotted on the historical charts.

Digital images of the historical charts were rectified in ArcMap 9.0 in reverse-chronological order, i.e., from most recent (1914) to oldest (1841), so that feature-to-feature georeferencing could substitute for bench marks, as bench-marks were sparse or non-existent in the oldest charts. A first-order polynomial affine transformation was used in the registration of each chart. The total RMS error increased with the age of the chart, from a low of 19.3 m in 1914, to 37.7 m in 1870, and to a high of 171 m in 1841. The best accuracy within the charts tends to be in the vicinity of the MCR, due to the distribution of control points, so the positions of the shorelines, depth soundings and jetties within and around the MCR tend to be better than these RMS errors.

Fig. 17 shows the vibracore locations plotted on the 1841 survey by Charles Wilkes. This survey reveals that cores 201-206 collected along the Columbia River north jetty were all located on a large sand spit extending from the Cape Disappointment headlands. The closest depth soundings to the southeast indicate that the water depth at these sites was shallower than 16 ft (4.9 m). The wreck of the Peacock, after which this spit was later named, is shown much farther to the south in what is now the middle of the modern-day inlet between the jetties. To the east of this southward-reaching submerged spit is the north channel that runs in a north-south direction from Cape Disappointment. Cores 107 and 108 are at the center of the confluence between the north channel and the south channel, with the south channel running east-west through the entrance. Cores 107 and 108 are located in water depths of 5 fathoms (9.1 m) in the center of the south channel where it begins to deepen with the confluence with the north channel. The deepest part of this confluence is 9.25 fathoms (35.2 m) located approximately 870 m to northwest of these core sites. Core 207 is located in 7.1 m water depth (the mapped boundary between the 4 fathom and 22.25 ft depth) at the margin between the north channel and a large shoal referred to as Middle Sand-bank. Similarly, Core 102 is located in about 4 fathoms (7.3 m) water depth, on the southern flank of the ebb delta, referred to as South Breaker. Core 102 is apparently located along an abandoned channel, as nearby soundings indicate depths of 7 fathoms (12.8 m), whereas the shoreface to the south is at 4.5 fathoms (8.2 m). Core 101 is located in uncharted waters that are as shallow as 15 ft (4.6 m) towards the north, and 13 fathoms (23.8 m) towards the southeast. Core 109 is along the southern margin of the south channel in 4 fathoms (7.3 m) water depth.

Fig. 18 shows the vibracore locations plotted on the 1851 US Coast Survey, which reveals significant change in the configuration of the Middle Sand-bank (now referred to as Middle Sands) and the south channel over the 10-yr period from the previous survey. The Middle Sand-bank in the 1841 survey now extends over 5 km to the southwest, as does the south channel, which now cuts through the westward-extending "South Breaker" of 1841. Cores 107 and 108 are located towards the eastern margin of the north channel in about 4 fathoms (7.3 m) water depth, and Core 207 is located to the east-northeast on the margin of the Middle Sands in about 13 ft (4.0 m) water depth in a similar setting as in 1841. Core 101 is located closer to the southern terminus of the Middle Sands in 5.5 fathoms (10.1 m) water depth. Core 102 is located in the thalweg of the south channel in 6 fathoms (11 m) water depth, and Core 109 is located along the western margin of the Middle Sands in about 15 ft (4.6 m) water depth. Cores 201 to 206 appear to be in a similar setting as in 1841.

Fig. 19 shows the vibracore locations plotted on the 1870 US Coast Survey chart, within which the hydrography is from 1868. Relative to core sites 207, 107, 108, and 101, the Middle Sands has migrated westward so that these sites are now located to the east of this shoal. Core 207, which had been on the western margin of the Middle Sands in 1841 and 1851, is now located towards the center of the south channel in water depths of at least 6 fathoms (11 m). Cores 107 and 108 remain in about 4 fathoms (7.3 m) water depth, but now on the western margin of the south channel, and Core 101 is now near the southwest terminus of the Middle Sands in water depth of ~10 ft (3.0 m). Cores 109 and 102 now reside along the western margin of the south shoal (now labeled as Clatsop Spit) in 3.75 fathoms (6.9 m) water depth. Cores 201 to 206 appear to be in a similar setting as previously, but there are now depth soundings to the northeast, suggesting these sites are now along the center axis of the north spit, in water depths of less than 12-14 ft (3.7-4.0 m).

Fig. 20 shows the vibracore locations plotted on the U.S. Army Corps of Engineers survey of 1883. The 1883 survey shows an extensive and dense coverage of depth soundings at the MCR just prior to commencement of the south jetty construction. All depth soundings are in feet and wide dark lines are the 18-ft (5.5-m) contour and the fine lines are the 24-ft (7.3-m) contour. It is worthy to note that all core sites, including

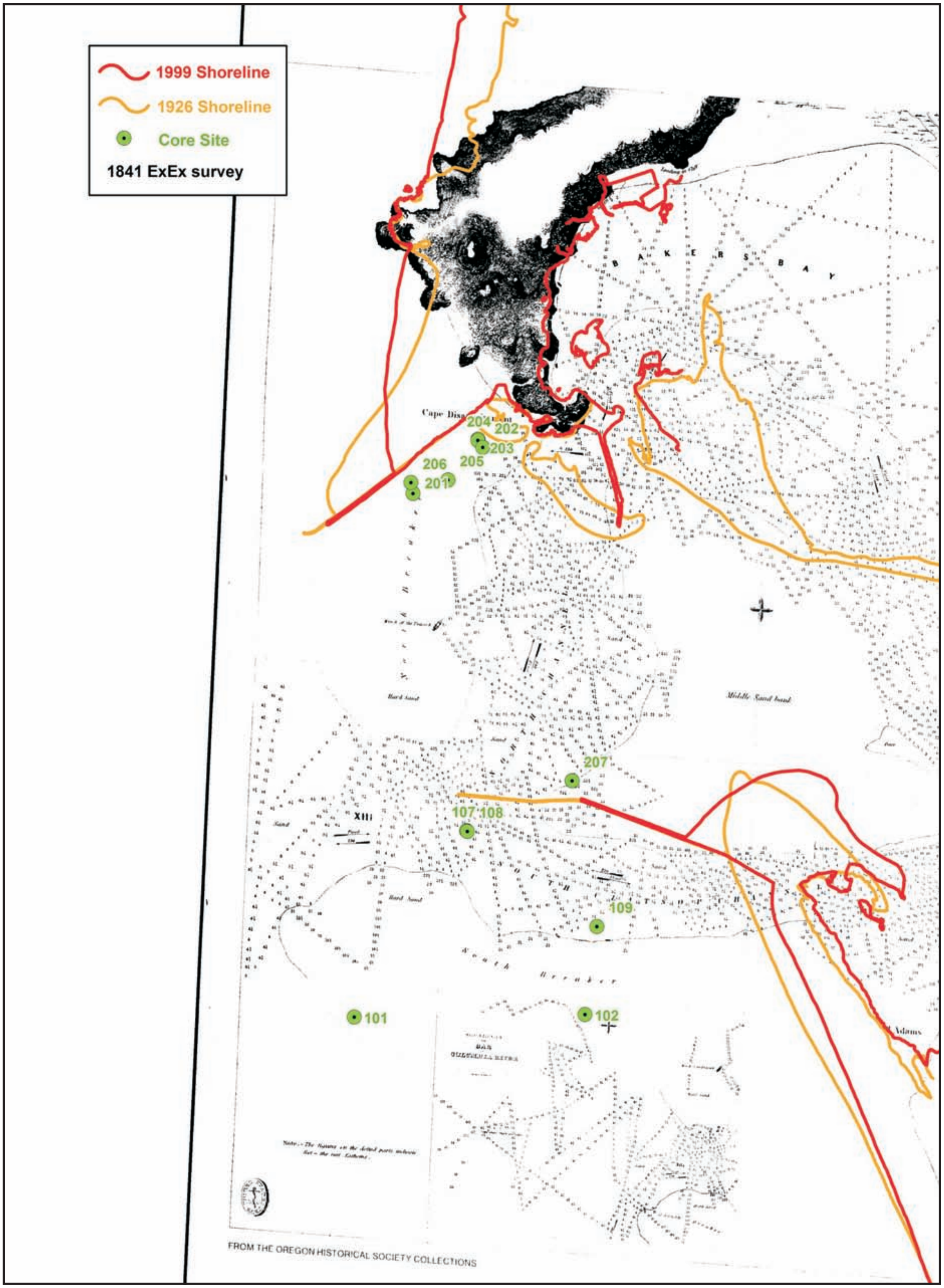

Fig. 17. Vibracore locations, jetties and 1926 and 1999 shorelines plotted on the 1841 U.S. Exploring Expedition survey by Charles Wilkes. Depths in channels are in fathoms (≥4); depths on sand banks are in feet (≤23).

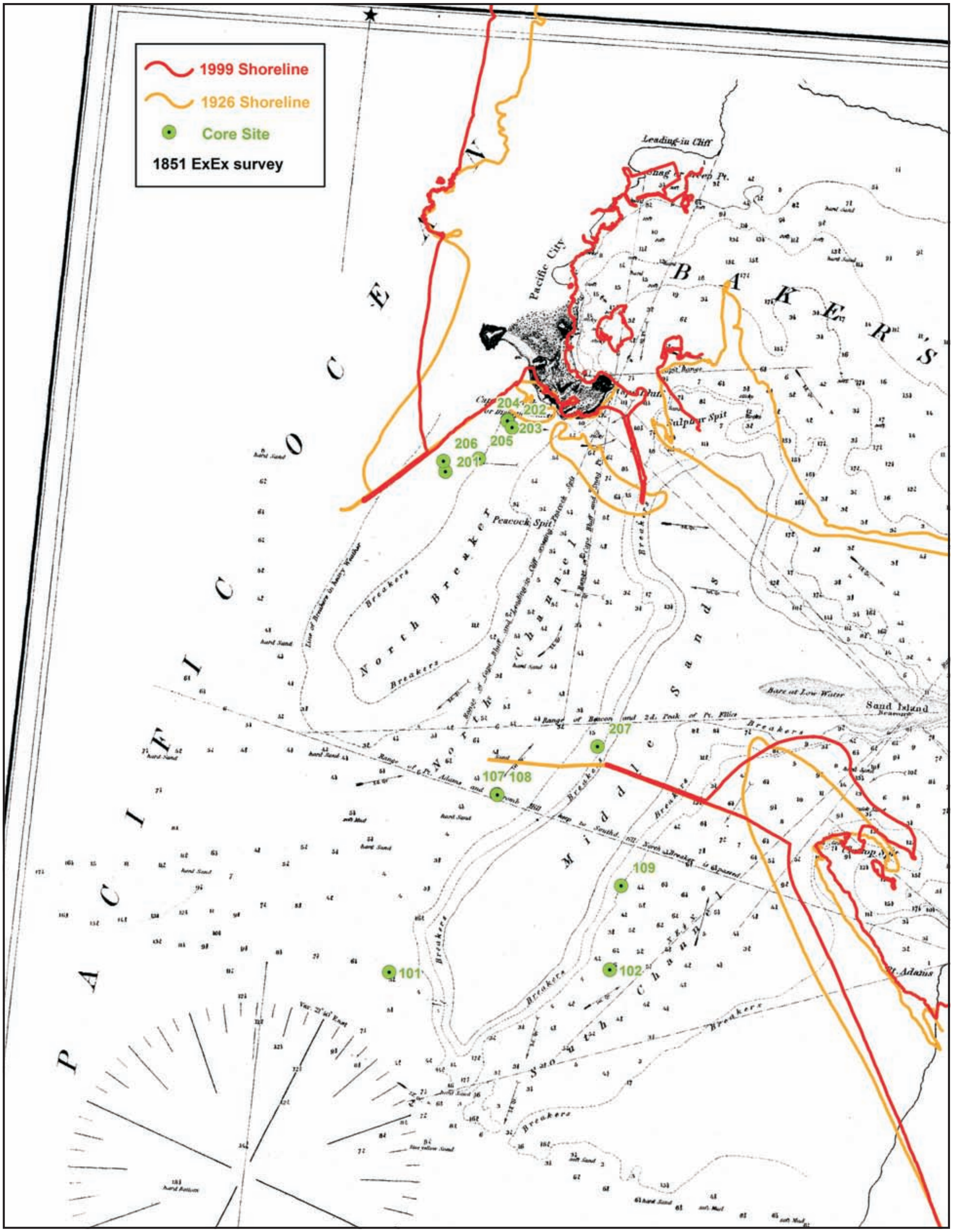

Fig. 18. Vibracore locations, jetties and 1926 and 1999 shorelines plotted on the 1851 U.S. Coast Survey chart, within which the hydrography is from 1850. Depths in channels are in fathoms (≥3); depths on sand banks are in feet (≤18) below MLLW.

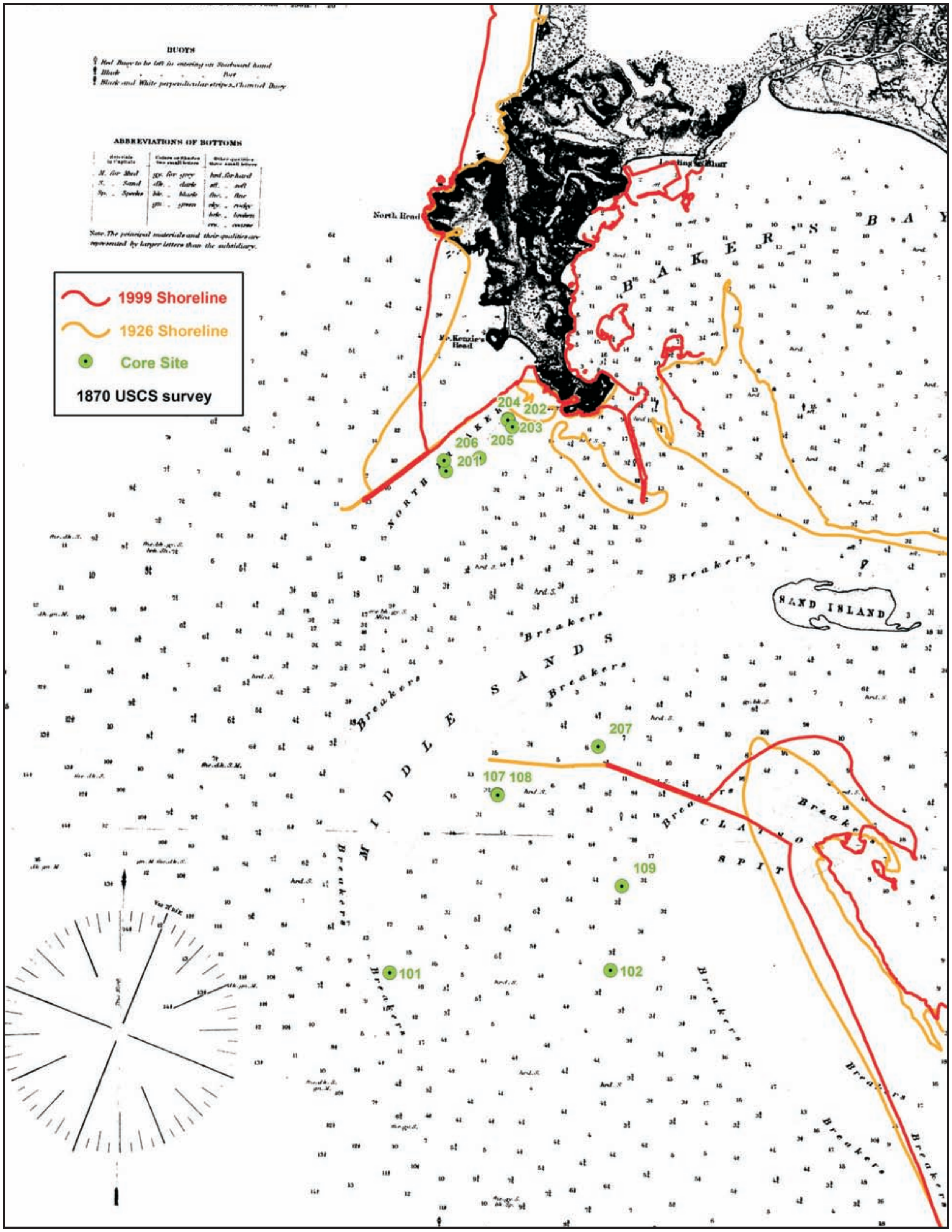

Fig. 19. Vibracore locations, jetties and 1926 and 1999 shorelines plotted on the 1870 U.S. Coast Survey chart, within which the hydrography is from 1868. Depths in channels are in fathoms (≥3); depths on sand banks are in feet (≤18) below MLLW.

101 and 102, are within the 24-ft (7.3-m) depth contour of the ebb-tidal delta that extends from shore to shore across the entrance. A major change of the entrance conditions from previous surveys is that the Middle Sands no longer exists, and a single, wide channel exists in the center between Cape Disappointment and Point Adams. Sand Island, which previously represented the eastern extent of the Middle Sands, is now pushed substantially northward toward Baker's Bay. The Middle Sands appears to have been dispersed in all directions: (1) to the north and south within the entrance, (2) to the inner southwest portion of Peacock Spit, across the previous location of the north channel, (3) to the westward edge of the ebb tidal delta, and (4) to the southwest flank of the ebb tidal delta. The main channel diverges much farther seaward, cutting across Peacock Spit in the north. The configuration of the channel and shoals compared to the previous surveys suggest large river discharges may have contributed to the changes. Core 207 is along the margin of Clatsop Spit and the entrance channel at the 22-ft (6.7-m) depth contour, as are cores 107 and 108, located in 25 ft (7.6 m) water depth. The deepest portion of the main entrance channel near cores 107 and 108 is 39 ft (11.9 m), located 730 m to the north-northwest. Core 101 is located near the outer edge of the bar in 22 ft (6.7 m) water depth. Cores 109 and 102 are located in 16 ft (4.9 m) water depth along the margin of a southern spit and a lesser landward channel running north-south between this shoal and the much shallower Clatsop Spit. Cores 202, 203, 204, and 205 remain situated on a very inner portion of Peacock Spit; a transect less than 600 m south of these cores indicates water depths of just 1-2 ft (~0.5 m). Cores 206 and 201 are located along the 18-ft (5.5-m) depth contour at the margin of Peacock Spit and the minor north channel that bisects Peacock Spit.

Fig. 21 shows the vibracore locations plotted on the U.S. Army Corps of Engineers survey of 1902. This survey illustrates the effect of the partially-built south jetty on the MCR and a continuation of shoal migration and dispersal. Clatsop Spit partially emerged as a barrier connecting Clatsop Plains to the south jetty at a point 3.7-4.7 km northwest of Point Adams. The shallowest portion of Peacock Spit of less than 18 ft (5.5 m) becomes confined to an area mostly to the south and east of McKenzie Head, and the north-south channel along the eastern side of Cape Disappointment of not less than 21 ft (6.4 m) water depth in earlier surveys, filled in to less than 14 ft (4.3 m) water depth. The bathymetry at most core sites deepens relative to the depths recorded in all previous surveys. At this time Core 207 is located in 27 ft (8.2 m) water depth just 240 m north-northwest of the seaward end of the partially constructed south jetty. Cores 107 and 108 remain in water depths of about 25 ft (7.6 m), whereas Core 101 is now located in 46 ft (14.0 m) of water, over twice as deep as in 1883. Core 102 is located on the shoreface in 28 ft (8.5 m) and Core 109 is located in 19 ft (5.8 m) water depth. Near Cape Disappointment, the bathymetry at cores 206 and 201 deepens to between 20-26 ft (6.1-7.9 m), and Core 205 is located on the margin of Peacock Spit in 16 ft (4.9 m) water depth. Cores 202, 203 and 204 remain on the top of a deeper Peacock Spit in water depths of less than 14 ft (4.3 m).

Fig. 22 shows the vibracore locations plotted on the U.S. Army Corps of Engineers survey of 1914. This survey shows the completed construction of the south jetty and the partial construction of the north jetty. At this point, the area of both Peacock Spit and Clatsop Spit within the entrance appears to have expanded in size. Core 207 is located

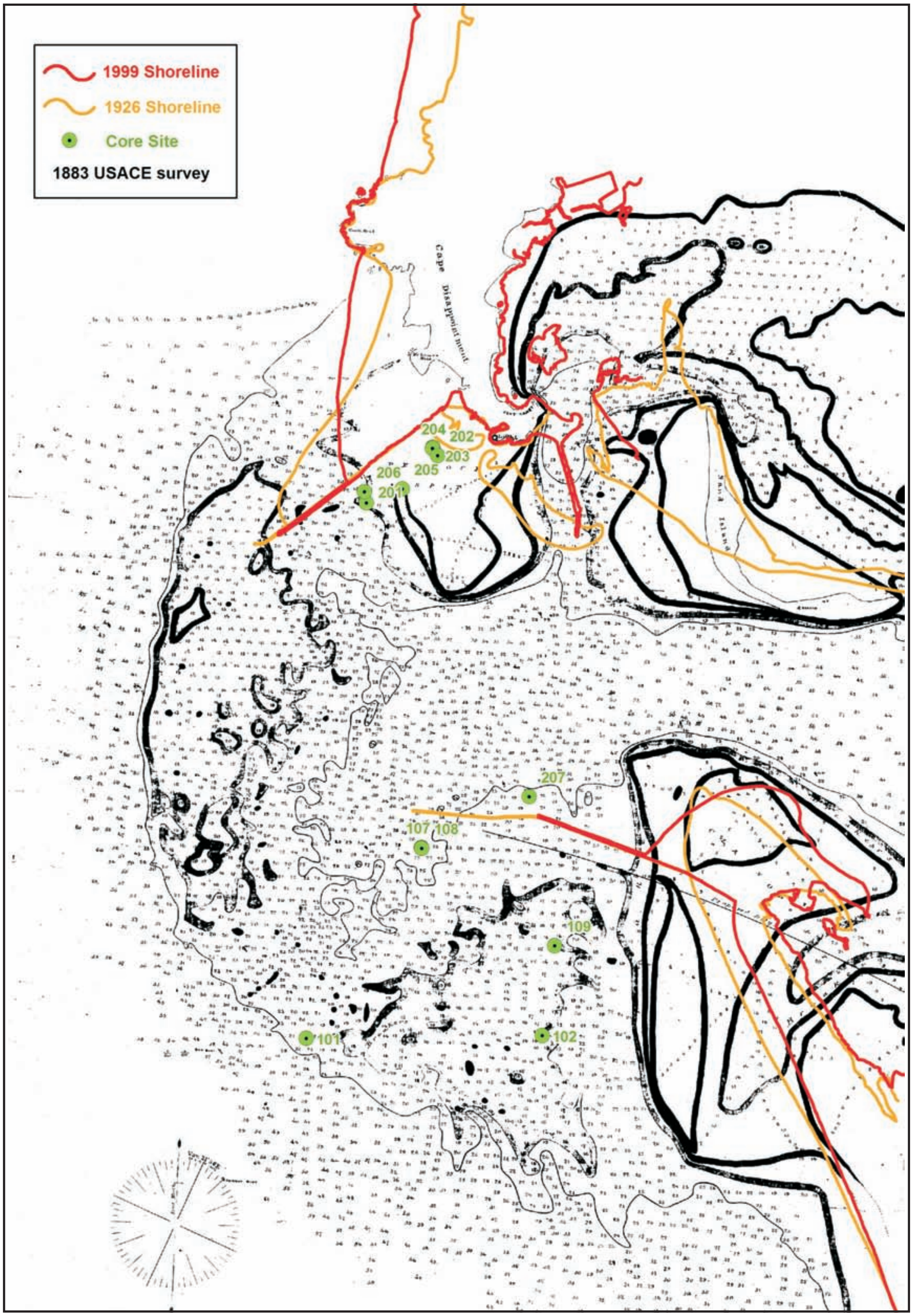

Fig. 20. Vibracore locations, jetties and 1926 and 1999 shorelines plotted on the U.S. Army Corps of Engineers survey MC-1-35 of July and August 1883. Depths are in feet below MLLW.

in shallower water of 21 ft (6.4 m), as are cores 107 and 108 in depths of 22 ft (6.7 m). Core 102 is now in 34 ft (10.4 m) water depth and Core 109 is in 27 ft (8.2 m) water depth. Near Cape Disappointment, cores 201 to 206 appear to be all on Peacock Spit, likely in water depth shallower than 14 ft (4.3 m).

Regional bathymetric changes for three historical periods are shown in Figs. 23, 24, and 25. These figures were developed from merged regional bathymetric surfaces performed by Buijsman et al. (2003) and include the location of the vibracores collected in 2002 (Kaminsky and Ferland, 2003). These figures illustrate the regional, decadal to century-scale morphological changes primarily attributed to the construction of the Columbia River jetties.

Table 5 provides a summary of historical seabed depths at the core sites. Water depths for years 1841 to 1914 are obtained directly from the overlays of historical charts discussed above, where either the closest sounding or an interpolated value was selected; the depths are reported in m, relative to NAVD88. The original surveys are assumed to be referenced to the MLLW datum at Astoria and the conversion to the NAVD88 datum is only -0.02 m (Buijsman et al., 2002). Because this correction factor is much less than the accuracy of the original depth soundings, it is not applied. For the years 1926 and 1958, depths were obtained from merged and 50-m gridded bathymetry data developed by Buijsman et al., 2002. For 2003, the reported water depths for the cores are obtained from 50-m gridded bathymetry comprised of data collected in 2000 and 2003 by the U.S. Army Corps of Engineers (USACE), Portland District, and in 2003 by the US Geological Survey and the Washington Department of Ecology (Coastal Profiling System, CPS). Water depths at cores 201 to 206 are derived from 2003 USACE gridded data. Water depths at cores 207 and 109 are derived from 2003 USGS-Ecology gridded CPS data, and water depths at cores 101, 102, 107 and 108 are derived from 2000 USACE gridded data. Water depths are in meters below the NAVD88 datum (not reported in negative values).

It should be noted that the only core site which experienced net accumulation from the pre-jetty era to 2003 is at core 207 (up to 5.5 m accumulation since 1868). These data suggest core 207 (4.23 m length) is comprised only of sediment deposited at this site since 1868. Relative to the water depth in 2003, all other core sites experienced a minimum of 3.1 m net erosion since 1902 or earlier. Although this significant erosion trend may enhance the probability that the cores are mostly comprised of sediment deposited prior to 1841, the “active depth” of the bottom (e.g., due to episodic events or migrating shoals, channels, or bedforms) within the MCR may also be on the same order of magnitude. The only core sites that show net accumulation since 1958 are 205 and 206, next to and within the North Jetty disposal site.

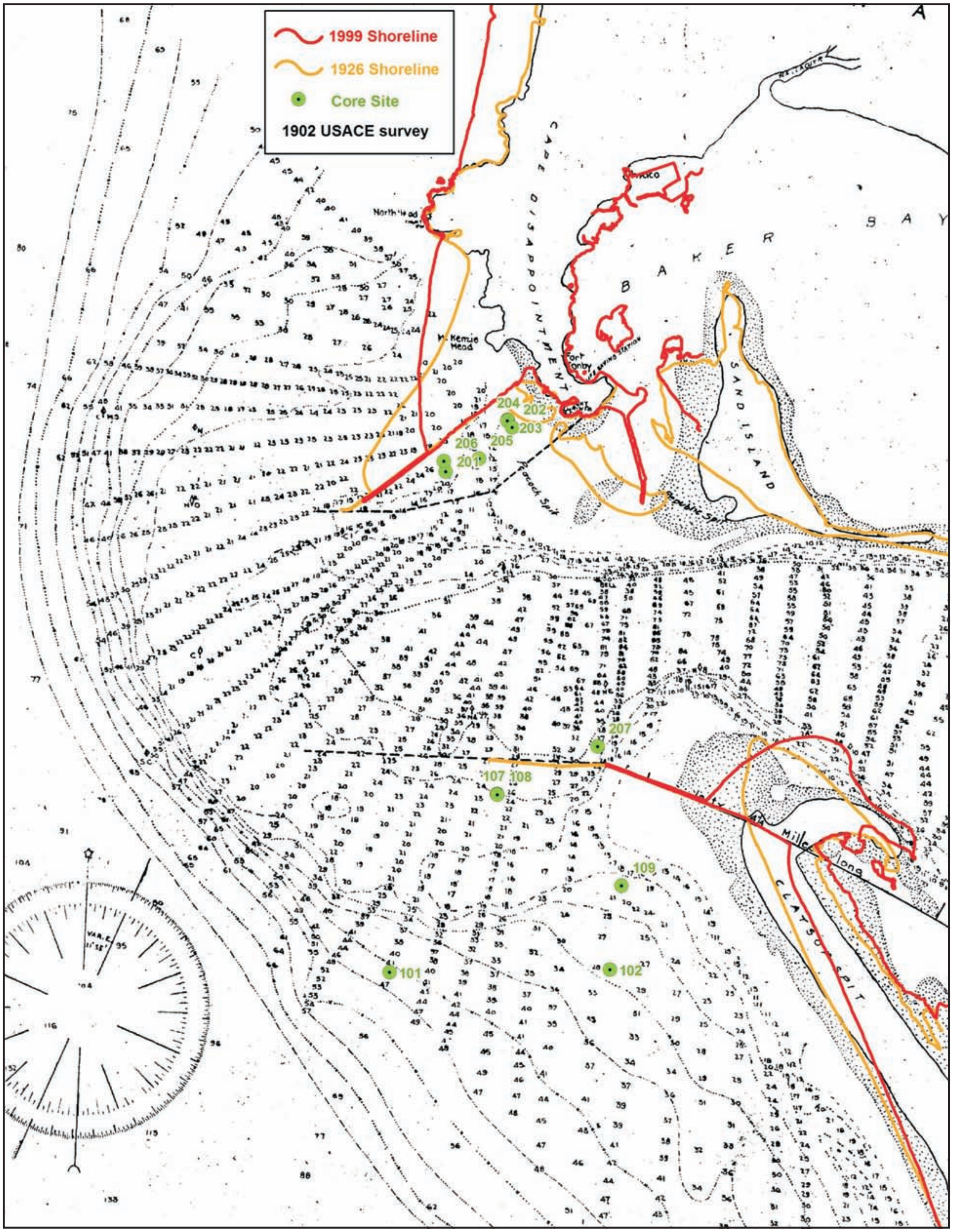

Fig. 21. Vibracore locations, jetties and 1926 and 1999 shorelines plotted on the U.S. Army Corps of Engineers survey MC-1-78 of June 1902. Depths are in feet below MLLW.

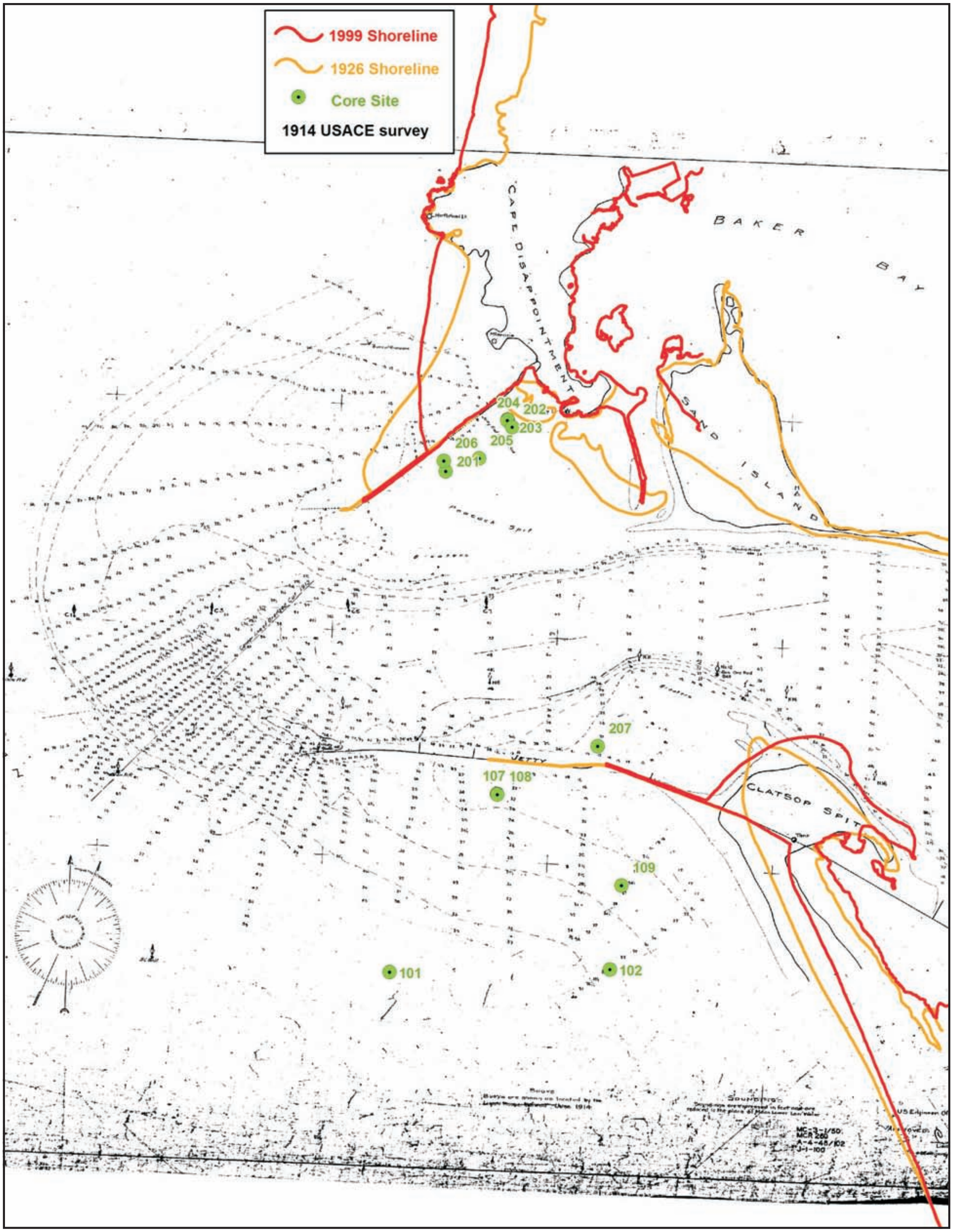

Fig. 22. Vibracore locations, jetties and 1926 and 1999 shorelines plotted on the U.S. Army Corps of Engineers survey MC-1-122 of May 1914. Depths are in feet below MLLW.

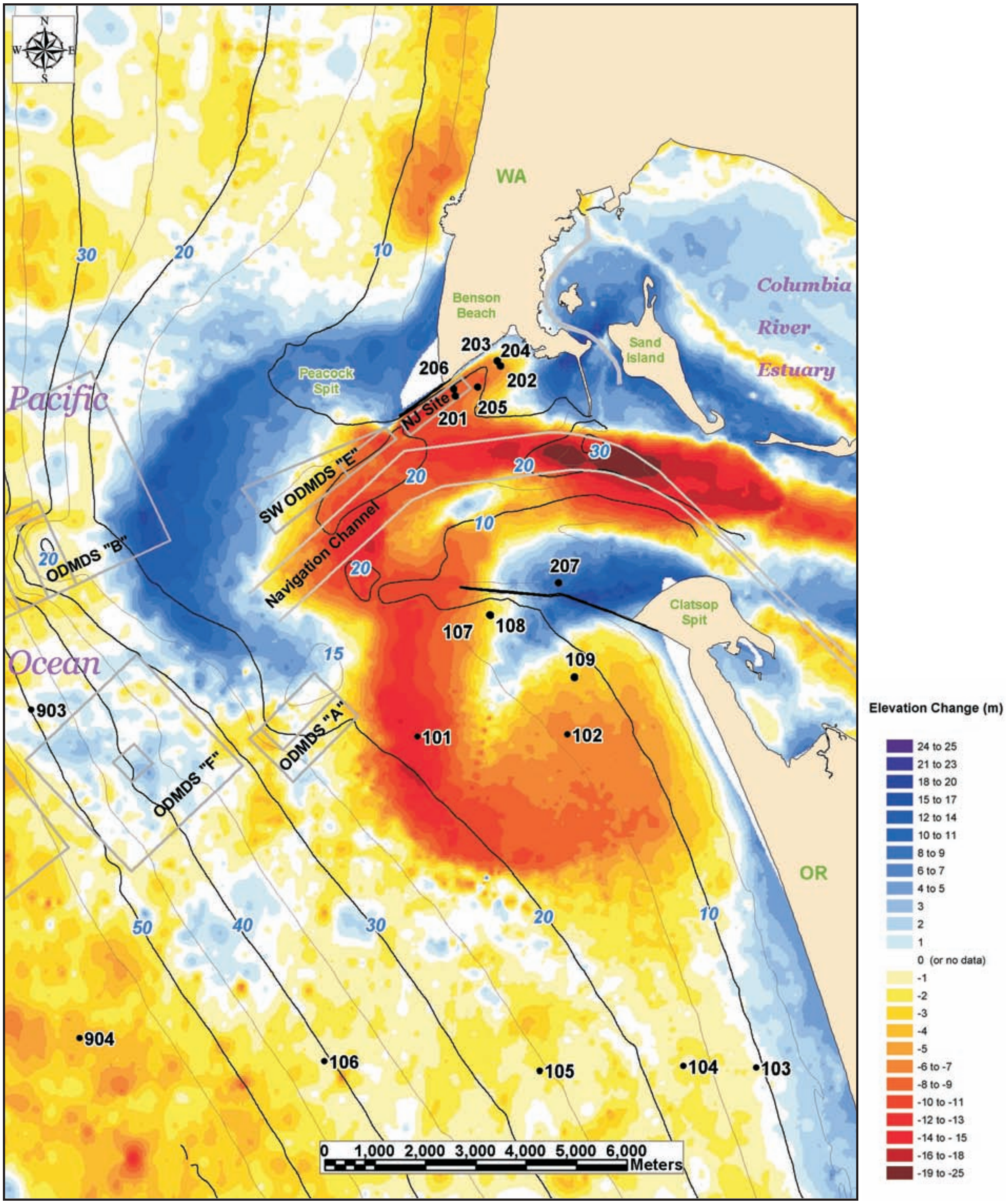

Fig. 23. Locations of vibracores collected in previous study in 2002 by the authors and this project shown with historical bathymetric change from Buijsman et al. (2003) during the period 1868 to 1935 (1877 to 1926 for shelf; 1868 to 1926 for delta; and 1868 to 1935 for entrance and estuary). Bathymetric contours in meters NAVD88 derived from data from 1998-2003.

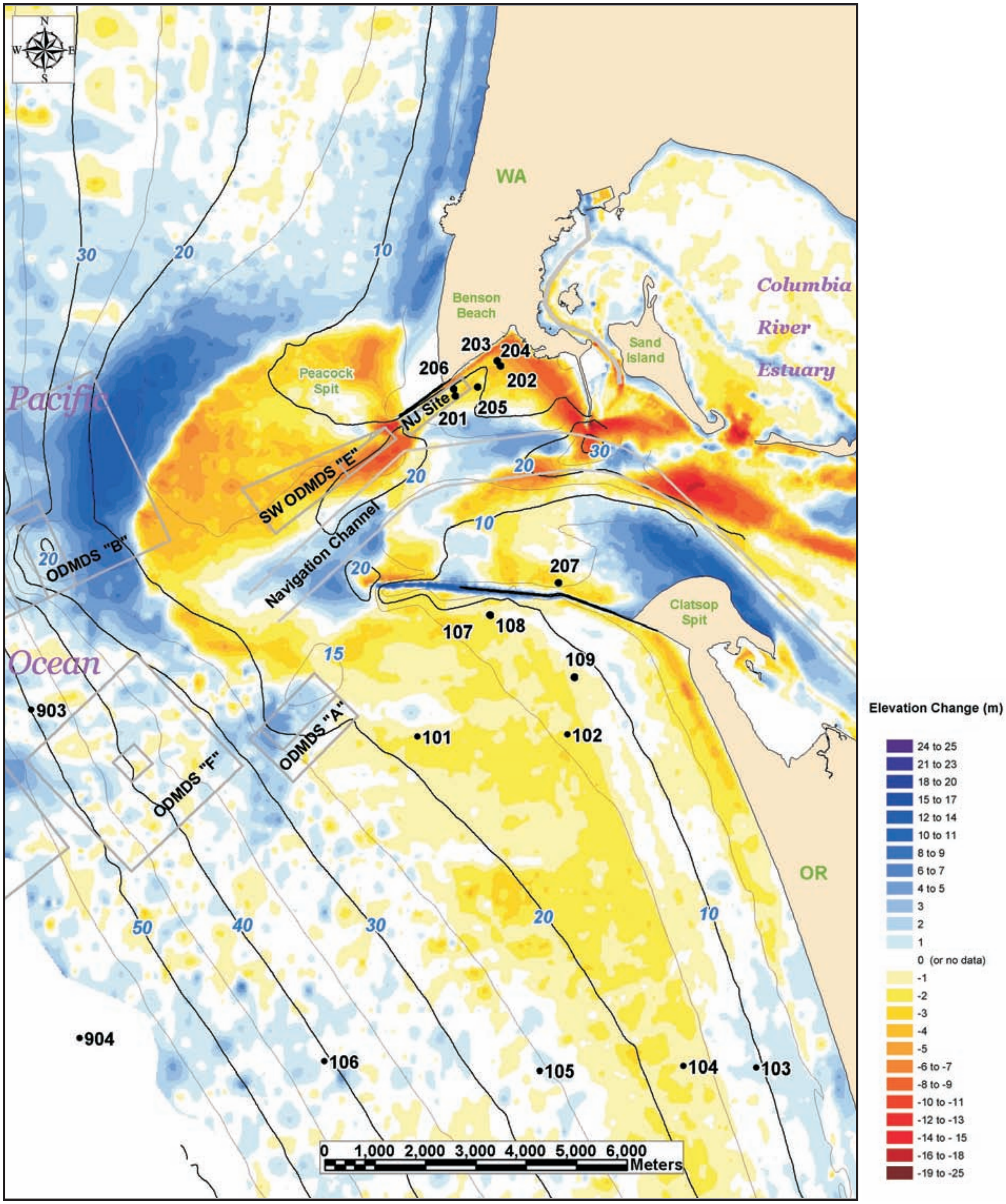

Fig. 24. Locations of vibracores collected in previous study in 2002 by the authors and this project shown with historical bathymetric change from Buijsman et al. (2003) during the period 1926 to 1958 (1935 to 1958 for entrance). Bathymetric contours in meters NAVD88 derived from data from 1998-2003.

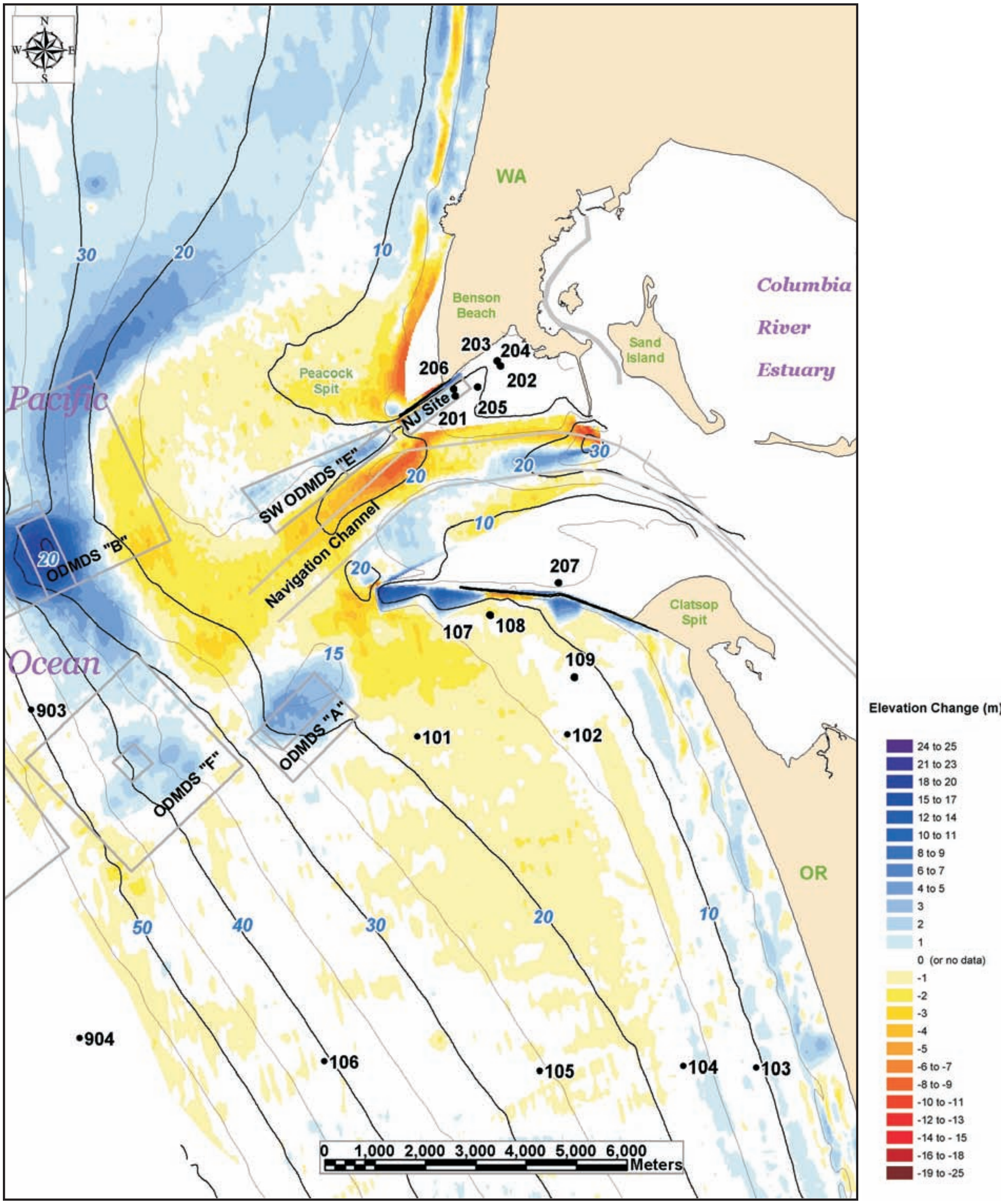

Fig. 25. Locations of vibracores collected in previous study in 2002 by the authors and this project shown with historical bathymetric change from Buijsman et al. (2003) during the period 1958 to 2000. Bathymetric contours in meters NAVD88 derived from data from 1998-2003.

Table 5. Summary of historical water depths at core sites in m below NAVD88. Red indicates erosion relative to previous survey; blue indicates accumulation relative to previous survey.

	Year								
Core #	**1841**	**1851**	**1868**	**1883**	**1902**	**1914**	**1926**	**1958**	**2003**
101	4.6	10.1	3.0	6.7	14.0	NA	16.1	17.7	18.4
102	7.3	11.0	6.9	4.9	8.5	10.4	12.6	14.2	14.6
107	9.1	7.3	7.3	7.6	7.6	6.7	10.0	11.1	12.2
108	9.1	7.3	7.3	7.6	7.6	6.7	10.0	11.1	12.2
109	7.3	4.6	6.9	4.9	5.8	8.2	10.3	11.2	11.8
201	<4.9	<4.9	<3.8	5.5	7.0	<4.3	9.4	12.3	12.3
202	<4.9	<4.9	<3.8	0.5	<4.3	<4.3	5.1	8.8	9.2
203	<4.9	<4.9	<3.8	0.5	<4.3	<4.3	4.7	8.4	9.3
204	<4.9	<4.9	<3.8	0.5	<4.3	<4.3	5.0	8.4	9.3
205	<4.9	<4.9	<3.8	0.5	4.9	<4.3	8.1	10.7	10.6
206	<4.9	<4.9	<3.8	5.5	7.0	<4.3	11.2	12.9	11.7
207	7.1	4.0	11.0	6.7	8.2	6.4	2.8	5.3	5.5

Introduction to Core Descriptions

Detailed core descriptions are supported by the graphic logs, the core photographs and the x-radiographs. These descriptions are based on the original core logs and all available data, including grain size analyses and radiocarbon ages. The core descriptions are arranged from south to north, beginning with those located on the Clatsop Spit/shelf and finishing with the MCR cores along the Columbia River north jetty.

Several potentially unfamiliar terms are used in the following descriptions and so are described here. The term 'rip-up clast' is used to refer to a mass of consolidated mud that appears to have been eroded as a mass from another location, and was transported and deposited elsewhere. The distance traveled is not inferred, but may be small. The term 'carbonate' is used to describe fragments that cannot be specifically identified as shell, sand dollar or barnacle. In some cores, discrete sedimentary layers appear to have been 'dragged down' by the vibracorer as it penetrated. The sides of these layers bend downward toward the core barrel. This is not a depositional feature or indicative of a naturally-formed contact between sedimentary units.

The radiocarbon ages of organic material (wood, plant fibers) from all MCR cores suggests that 'old' organics are delivered river during floods (dates on organics are 600-1600 years). In contrast, the ages of carbonate fragments (shell and barnacle) are generally much younger (within the last 600 yrs), which suggests that most of deposition in the Columbia River channel must be more recent than the age suggested by the dates returned for organic matter (see earlier discussion of transportation of old organics during river floods). The ages of carbonate fragments should also be considered a maximum age for deposition of the sediment. For example, shells and barnacles that died and were deposited 500 years ago (and would produce that radiocarbon age) could subsequently have been eroded and re-deposited 100 years ago. That later depositional event is important in terms of understanding sediment mobility and accumulation, but it is not recorded by the older radiocarbon date.

Clatsop Cores (107, 108, 109)

Core 107

Core 107 is 301 cm long and was collected in 12.2 m water depth just south of the outermost section of the south jetty, at the same site as CP-108. As cores CP-107 and 108 were collected at the same site, it was decided that detailed analyses would be conducted on only one of these cores. As CP-108 was selected for detailed analysis, the grain size depicted by the dashed line on the log for CP-107 is based on visual and hand lens descriptions only. No radiocarbon dates have been obtained, but all geological evidence indicates that CP-107 contains a similar stratigraphy as that recorded in 108 (see below) and was therefore likely deposited at the same time.

Core 107 contains well-sorted sand throughout and no sharp contacts or distinctive sedimentary units, either visible or distinguishable in the x-radiograph (see Appendix A). The grain size is fine to very fine sand in the upper 90 cm, then coarsens to fine-medium sand between 90, and 255 cm, and it fines again slightly from 255 to 301 cm (see Fig. 26). The sand is generally lithic-rich and subangular and contains occasional 1-2 mm sized mica flakes. A subtle vertical structure between 60-95 cm is identifiable in the photograph and the x-radiograph. It is 'filled with' very fine and very well-sorted mottled sand and encased with slightly reduced sand, which suggests that it is likely a burrow (possibly of a large bivalve).

The sand in core 107 contains very few carbonate fragments. Occasional shell fragments were noted at 13.5, 63, 94, 119, and 121-123 cm. Sand dollar fragments were identified at 31 and 112 cm. Both shell and sand dollar fragments occurred in slightly greater abundance from 255-298 cm. Most of the shell fragments are small and not identifiable, however a mussel fragment was identified at 122 cm. These carbonate fragments

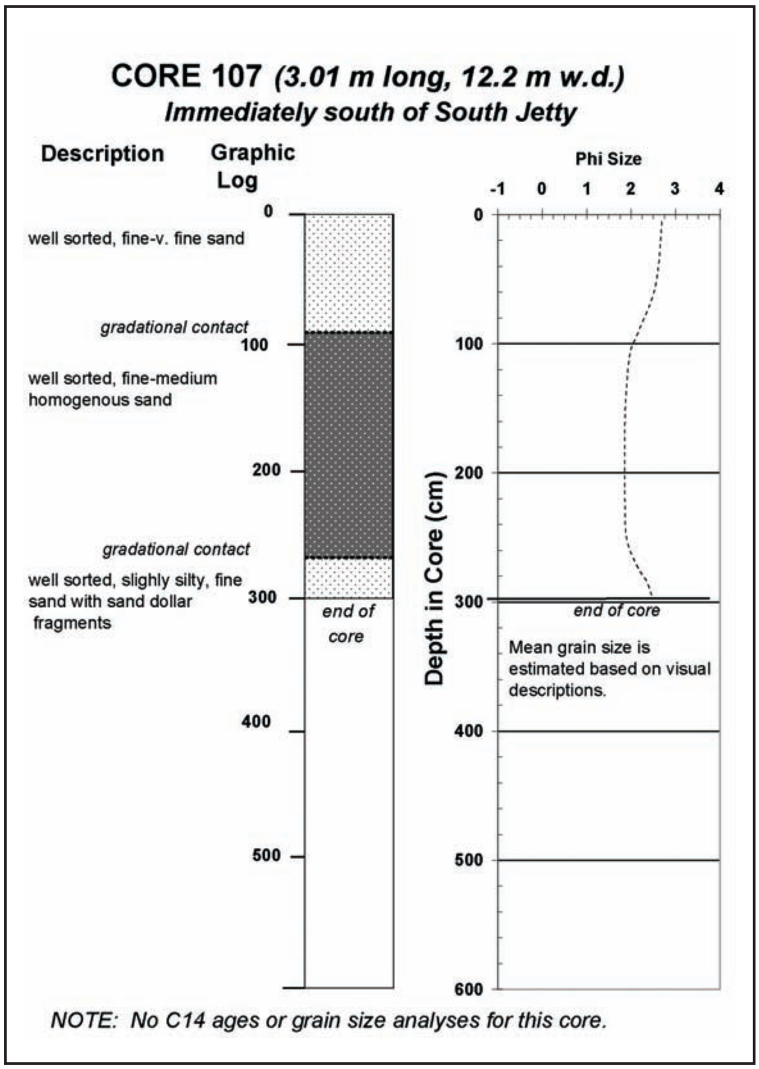

Fig. 26. Descriptive log of core CP-107.

are typical of a shallow, high-energy coastal environment. There were also small pebbles at 22, 104 and 295 cm.

This core appears to be mostly undisturbed sediment, however the basal 30 cm includes fragments of red paint (see core photograph, Appendix A). This paint was likely scraped from the barrel as the core penetrated the seafloor (through abrasion by the sand surrounding the barrel), and then the paint may have been 'sucked up' with sediment as the core barrel was being removed from the seabed.

Core 108

Core 108 is 218 cm long and was collected in 12.2 m water depth just south of the outermost above-water section of the south jetty, at the same site as CP-107. It contains predominantly clean, well-sorted sand with some grain size variations and several discrete lenses of laminated mud and organics, or muddy sand (1-2 cm thick).

These form sharp contacts with sand above/below the mud layers (see core photograph, Appendix A). In most cases, these laminated sand/mud intervals are also visible on the x-radiograph as well-defined horizontal layers (see x-radiograph, Appendix A). The presence of these well-defined and horizontal layers indicates that this entire core sequence is undisturbed.

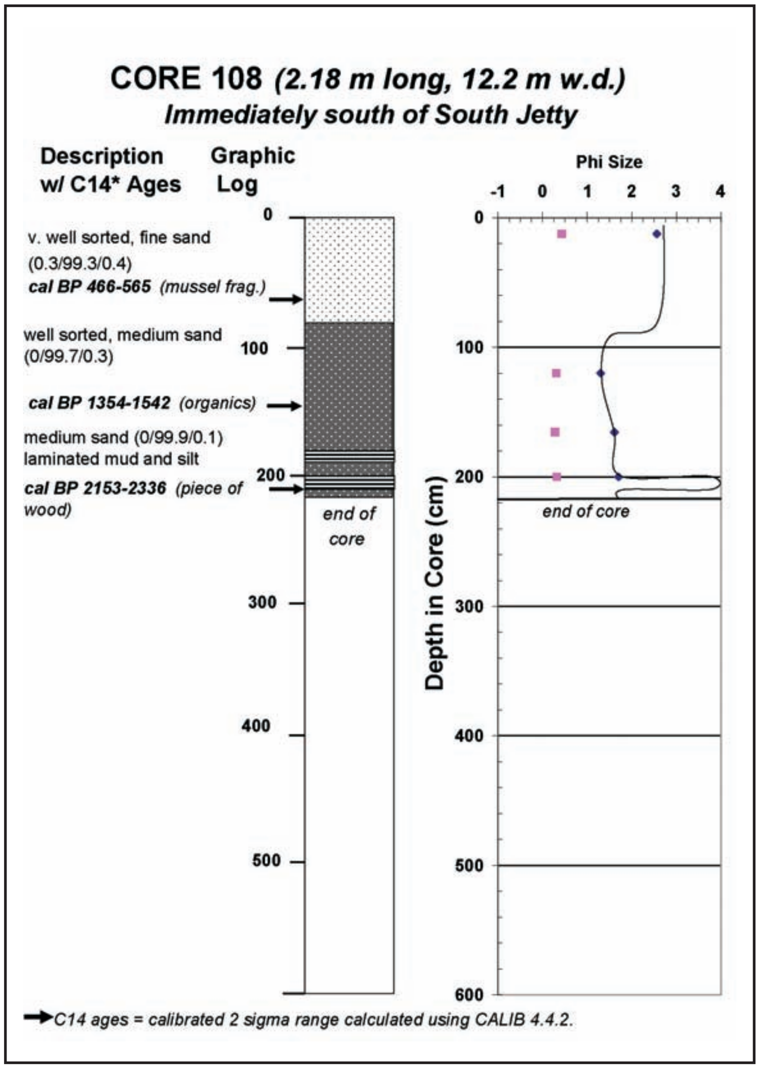

Fig. 27. Descriptive log of core CP-108.

These sand/mud intervals likely represent flood events of the Columbia River, when significant amount of suspended sediment is deposited in, and seaward of, the entrance channel of the Columbia River. As the river floodwaters flow through the deep sections of the entrance channel, suspended fine sand settles out first followed by mud. Thus, flood events produce 'couplets' of fine sand and mud that are deposited quite rapidly, and multiple couplets could be deposited in a single year. To be preserved however, the laminated sand/mud deposits would have to be covered with sand before they are mixed or reworked (by organisms or waves). The laminated sand/mud intervals show no sign of bioturbation (by organisms) which further supports the interpretation that they were quickly buried by sand. It appears that very few mud layers have been preserved, relative to the total number which might have been deposited over historical and late Holocene time. This is not surprising given the shallow water depth and location within the entrance channel/ebb delta at this site prior to jetty construction. The area has been continually reworked through the migration of channels and spits at the Columbia River entrance.

The grain size grades from fine sand in the upper 80 cm, to medium (to coarse) sand from 80-182 cm (see Fig 27). Below the slick mud lens at 185 cm, the sand fines slightly toward the base of the core. The sand is generally lithic-rich and subangular to subrounded; grains become more rounded as their size increases. Occasional 1-2 mm sized mica flakes are present, and these are more abundant from 140-180 cm. Two 'pockets' of slightly finer sand occur between 90-110 cm and 155-160 cm, and may be the remains of infilled burrows. Although no definitive burrow structures could be identified, the small pod of organics and small shell fragments at 100 cm (see photograph, Appendix A) are suggestive of a burrow.

The sand contains occasional shell fragments at 14-18, 44, 65-77 cm, 96-99, and 132-141 cm. No carbonate fragments were identified below 170 cm. A large, nearly whole sand dollar was found on the sediment surface at the top of the core (see core photograph, Appendix A). Sand dollar fragments were identified at 7, 18, 65-70, 116-120, and 164 cm. The shell fragments are small and not identifiable. A small disc-shaped pebble of mudstone was found at 83 cm, below the mud layer.

As cores CP-107 and 108 were collected at the same site, CP-108 was selected for detailed analysis. Results of grain size analyses appear on the graphic logs (Figs. 26 and 27) as well as in Table 4. Radiocarbon dates have been obtained on three samples within this core:

Depth in Core 108	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
65-70 cm	mussel shell frag.	1310 +/- 25	Cal BP 466-565
140-141 cm	organics in sand	1580 +/- 35	Cal BP 1354-1542
211 cm	piece of wood	2240 +/- 25	Cal BP 2153-2336

Although these three dates suggest moderately uniform long-term rate of sediment accumulation on the shelf at this site, data from other sites (CP 109 and MCR cores) suggest that 'old' organic material may have been transported down the Columbia River and then deposited on the shelf. As a result, the sediment contained in CP 108 may have been deposited more recently than suggested by the calibrated ages of the dated samples at 140 and 211 cm.

Core 109

Core 109 is 509 cm long and was collected in 11.8 m water depth south of the south jetty, off Clatsop Spit. The long core sequence contains varied sedimentary units including many, well-defined horizontal layers that indicate that this entire core is undisturbed (see core photograph and x-radiograph, Appendix A). The top 35-40 cm is characterized by sand with discrete layers including gastropod shells (8-9 cm), rip-up clasts (14-19 cm), shells and pebbles (20-24 cm), and mud (24-28 and 35-38 cm). Sharp contacts separate each of these layers (see photograph, Appendix A). From 40 to 245 cm the core is predominantly well-sorted, silty fine sand with rare shell fragments. The sand coarsens slightly downward and contains several horizontal mica-rich zones, rather than discrete layers, between 80-140 cm (Fig. 28). A discrete organic-rich layer occurs at 188-200 cm (seen in the photograph but it is not apparent in the x-radiograph, Appendix A), and below this the sand is fine to very fine. The upper 250 cm of this core contain almost no datable material, except very near the surface, and this was considered too young to be worthy of dating.

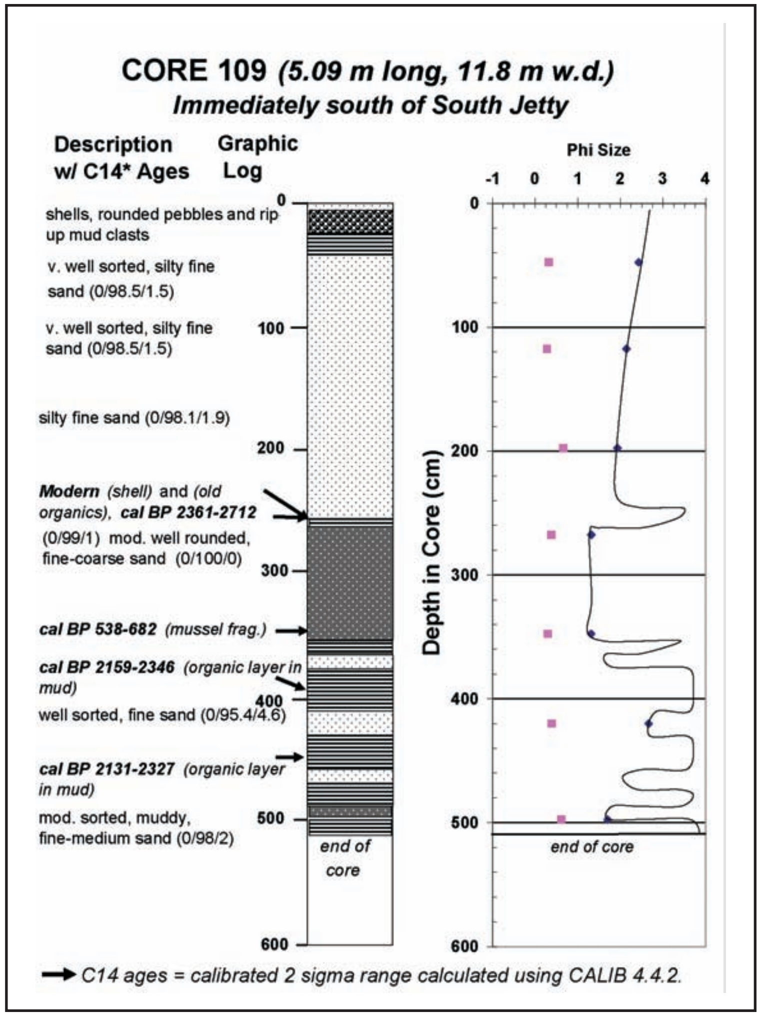

Fig. 28. Descriptive log of core CP-109.

A relatively sharp contact at 244 cm marks the top of a coarser sand unit that extends to 352 cm. The moderately well-rounded, fine-coarse sand contains a clast of muddy sand, mud and organics (244-251 cm), an organic-rich layer (254-255 cm; see C14 results below), occasional shell fragments, shells (2 small mussels at 334 and 347 cm), and 2 well-rounded pebbles (271 cm). A sharp but irregular (non-horizontal) contact occurs at 352 cm. Several small clasts of mud (called 'rip-up' clasts) can be seen just above the contact and indicate that an erosional event initiated the deposition of the coarser sand unit after removing some of the underlying laminated mud.

The basal 157 cm of the core (352-509 cm) contains laminated mud and sand separated by several thicker intervals of fine-very fine sand (365-376, 418-429, 460-472, and 490-502 cm). Individual mud laminae are 0.5-2 cm thick and often comprised of much more clay than silt. In most cases, the laminated mud is also visible on the x-radiograph as dark horizontal layers (see x-radiograph, Appendix A). Although no shell fragments were found in this unit, many mud laminae were organic-rich and some were dated (see radiocarbon results below). The lack of shells and the proportion of mud in numerous laminae suggest that this unit might have been deposited at the margin of the previously wide entrance of the Columbia River (see Figs. 17-20) as muddy sediment was delivered by river floods. The lamina within the >1m thick sequence have not been bioturbated or disturbed (see x-radiograph and photograph, Appendix A) which suggests that they were buried quickly and/or that there few burrowing organisms. There are several laminae that appear to be truncated at a slight angle (388-390 cm and 397-398 cm) and may represent erosional events associated with tidal currents or subsequent Columbia River floods.

4 depositional units:

0-40 cm = pebbles, shells, and rip-up clasts suggest primarily erosional conditions on the Clatsop inner shelf after the south jetty affected sand supply to this area.

40-244 cm = fining-upward sand deposited in a migrating channel that was infilled at the MCR.

244-352 cm = erosional event initiated the deposition of the coarser sand unit.

352-509 cm = marginal area within the Columbia River entrance channel containing sediment deposited during floods

Radiocarbon dates

Depth in Core 109	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
254-255 cm	shell fragment	>Modern	cannot calibrate
254-255 cm	organics in mud	2470 +/- 35	Cal BP 2361-2418
347-348 cm	mussel shell frag.	1450 +/- 40	Cal BP 538-682
397-398 cm	organics in mud	2270 +/- 25	Cal BP 2159-2346
459 cm	organic-rich mud	2210 +/- 30	Cal BP 2131-2327

Two samples were dated from the same organic-rich mud layer (254-255 cm) but yielded very different results. The organics are ~2400 years old and were likely transported down the Columbia River during a flood event that exhumed them from earlier depositional sites along the river. The young shell may have been living on the shallow shelf and was incorporated into the organic-rich layer during deposition. This would suggest that the top 250 cm of sediment in this core was deposited moderately quickly and recently which is possible given the shallow water depth at this core site and its position adjacent to an active entrance channel and prograding barrier spit.

A mussel shell fragment sampled just above the erosional contact at 347 cm returned a calibrated age of ~600 years BP (see table for exact range). The erosional contact, and the coarser grain size of this unit, may represent high-energy conditions at the site as the entrance channel shifted northward to its present position. The thick, laminated mud unit (352-509 cm) was likely deposited at the margin of the Columbia River entrance channel when it was located south of the present south jetty. Preservation of the non-bioturbated laminated mud was probably due to moderately rapid burial by channel or ebb delta sands. It is difficult to constrain the timing of deposition, given that most of the dated organic matter in the mud laminae may be relict (transported down the river and redeposited).

As an additional check on the age of the near-surface mud deposit in this core, a sediment sample from 24-28 cm depth interval was analyzed for the presence of the Cs-137 radioisotope. The sample had no detectable level of Cs-137, indicating that deposition occurred prior to the 1950s.

MCR Cores (207, 201, 202, 203, 204, 205, 206)

Seven cores were collected in shallow water between the jetties at the MCR. Six of these are located on the south side of the north jetty, and the seventh core was collected from the north side of the south jetty adjacent to the terminus of Clatsop Spit (core 207). It should be remembered that this is a highly dynamic environment and sedimentation history at the core sites has almost certainly been characterized by multiple depositional and erosional events. In addition, there is some potential uncertainty in the early dredging history of the area when record-keeping was less complete.

Core 207

Core MCR-207 is 423 cm long and was collected in 5.5 m water depth just north of the south jetty, on the northwest submerged terminus of Clatsop Spit. The core mostly contains very well-sorted, homogenous fine sand throughout, which has accumulated in the protected lee of the spit and the south jetty. Inclined laminations, assumed to be inclined bedding planes, occur from 210-300 cm and 332-355 cm in the core. They are easily seen in both the photographs and the x-radiographs and may represent growth of the submerged ‘toe’ of the northwestward prograding spit. Horizontal bedding is well preserved at most other depths in the core, which indicates that this core has experienced essentially no disturbance during/after vibracoring. Generally, the sand is lithic-rich and subangular throughout, although there are several mica-rich intervals between 115-125 cm, at 220 cm, and from 397-401 cm.

There is one thick laminated mud interval from 49-102 cm in the core (visible in the x-radiograph and the photograph, Appendix A), which has sharp upper/lower contacts with the otherwise homogenous sand. Slick, organic-rich mud is interbedded with muddy sand and occasional layers of organic fragments. A thin laminated unit (or rip-up clast?) was encountered at 361-367 cm.

The entire core contains very few carbonate fragments in the dominantly lithic sand, which limited the material available to date. Barnacle fragments collected in sand above and below the inclined bedding planes yield calibrated ages of <500 years, and accumulation rates of approximately 100 cm/100 years. Organic fragments were separated from the mud at 94 cm and dated to determine the time of deposition of the laminated sediment in the upper meter of the core. The calibrated age range is 548-662 cal BP, which is older than both of the underlying dates on carbonate fragments (see Fig. 29). This suggests that 'old' organic material has likely moved down the Columbia River during floods and been deposited more recently than its radiocarbon age suggests. Based on similar results for other cores, we conclude that the ages determined for carbonate samples generally more accurately approximate the time of deposition, although they represent a maximum age for the reasons discussed earlier. In particular for this core, the historical hydrographic surveys indicate core site 207 accumulated up to 5.5 m of sediment since 1868, which suggests the carbonate dates are on the order of 100-300 years older than the actual time of deposition. Shell or barnacle fragments deposited in the inlet would have been remobilized as channels migrated, naturally or due to changes associated with building the jetties.

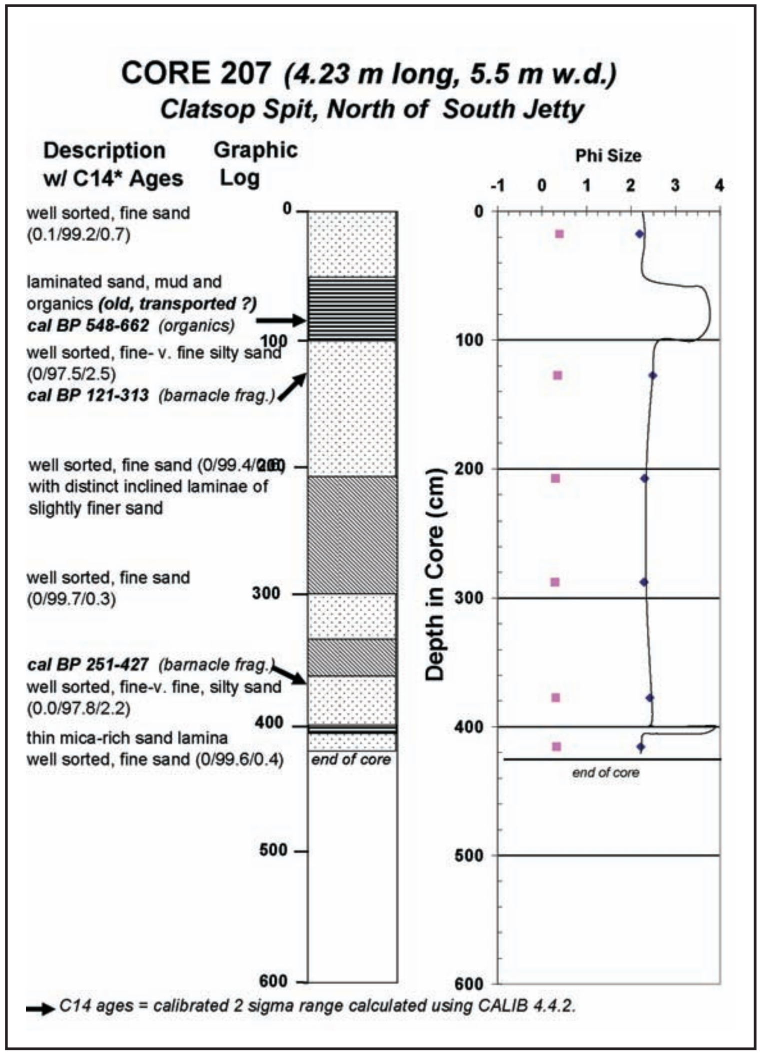

Fig. 29. Descriptive log of core MCR-207.

Depth in Core 207	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
94 cm	organics in mud	635 +/- 45	Cal BP 548-662
127 cm	barnacle fragment	995 +/- 35	Cal BP 121-313
375 cm	barnacle fragment	1070 +/- 40	Cal BP 251-427

As an additional check on the age of the sediment deposits in this core, 2 sediment samples were analyzed for the presence of Cs-137 radioisotope, which would indicate that deposition occurred after the 1950s. Muddy samples analyzed from 54-55 cm and 58-63 cm depth intervals had no detectable levels of Cs-137.

Core 201

Core MCR-201 is 530 cm long and was collected in 12.3 m water depth just south of the north jetty, close to the site of MCR-206. It contains well-sorted, fine to medium sand throughout and lacks sharp contacts, except for several thin laminated mud units that are slightly visible in the x-radiograph (also see Fig. 30). The grain size of the non-mud units coarsens slightly to medium sand from approximately 100-140 cm, and contains slightly more silt and coarse sand which slightly reduces the sorting (see grain size data). Generally, the sand is lithic-rich and subangular throughout, although it also contains noticeable but occasional 1-2 mm sized mica flakes between 330-355 cm (apparently associated with carbonate fragments; both are less dense than lithic sand).

The thin laminated units are spaced throughout the length of the core and often contain organic-rich lenses. These mud lamina likely represent deposition during major floods on the Columbia River. Although floods are common events, not all deposits will be preserved given the high-energy conditions of the Columbia River channel and inlet (note the location and water depth of the core site, Fig. 12). Some of the laminated units contained organic-rich mud laminae and/or pieces of wood (103 cm, 303-306 cm, and 233-237 cm). The wood fragment at 303-306 cm was dated.

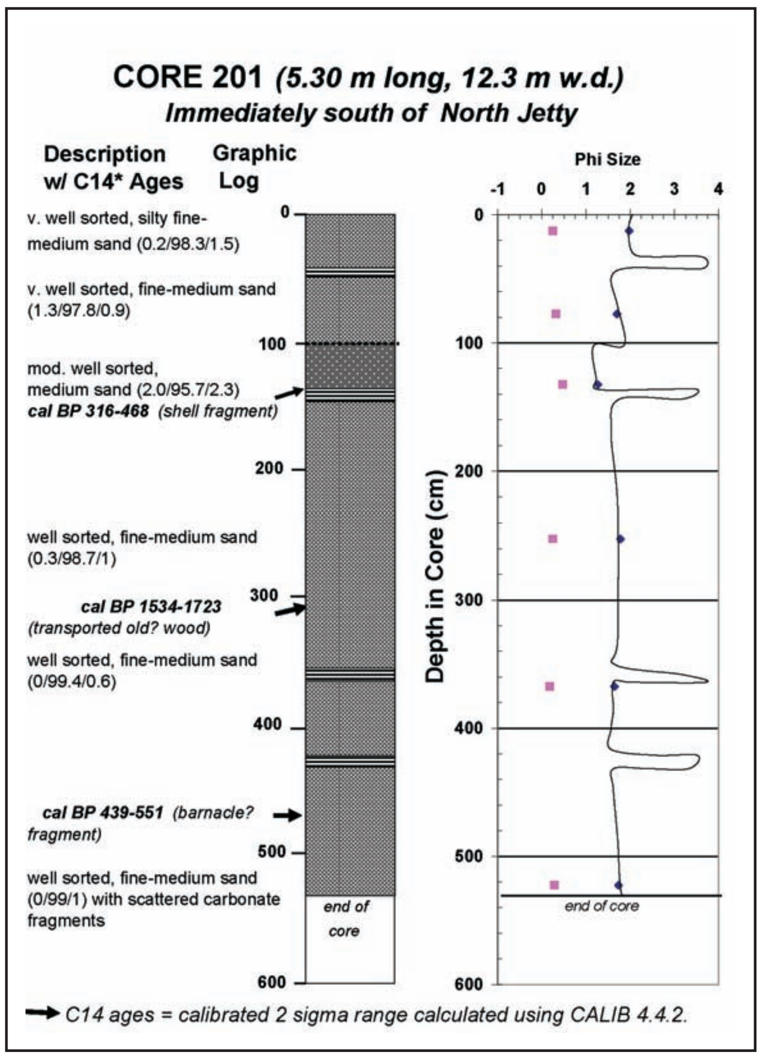

Fig. 30. Descriptive log of core MCR-201.

Some laminated mud units within this core appear to be slightly rotated and broken in places (see Fig 30). This may be the result of high-energy flood events that eroded mud as 'rip-up clasts' that are later deposited downstream. The rotated and broken mud clasts can also result from rapid penetration of the vibracorer and then movement of the mud lenses vertically as the vibrating continues but the corer has stopped penetrating, usually due to frictional resistance along the barrel. This second interpretation is supported by the x-radiograph, which indicates that the lower section of this core might be somewhat disturbed.

Most of the sand within the core contains very few carbonate fragments. Instead, occasional carbonate fragments were noted within a few intervals from 14-29 cm, 111-139 cm, 177-220 cm, 330-355 cm, and from 470-520 cm. The interval from 111-139 cm contains the highest density of carbonate and largest-sized fragments. This may represent a period of higher energy that seems to have eroded the upper surface of the mud unit (where the contact is sharp and irregular), and then deposited coarser and less-well-sorted sand and shell fragments. Elsewhere in the core, the carbonate was comprised primarily of small fragments and therefore difficult to identify. Where partial identification was possible, the carbonate was shell and barnacle fragments. The presence of barnacles is consistent with this location which is close to the extensive bedrock headland of Cape Disappointment, at the mouth of the Columbia River. The overall lack of carbonate in this core likely reflects high terrigenous sediment input from the Columbia River, especially during floods.

Depth in Core 201	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
138 cm	shell fragment	1160 +/- 25	Cal BP 316-468
303-306 cm	piece of wood	1730 +/- 40	Cal BP 1534-1723
474 cm	barnacle? fragment	1280 +/- 35	Cal BP 439-551

Radiocarbon ages were determined for three samples in MCR-201. The calibrated ages indicate that the two carbonate samples are relatively young (<550 yr BP), whereas the piece of wood is significantly older (~1600 yr BP). This result was observed in most other MCR cores, leading to the deduction that flood events primarily result in deposition of ‘old’ organic matter, including pieces of wood, whereas carbonate fragments tend to be much younger. Floods do mobilize organic matter stored on the floodplain and along river banks. We conclude that the ages determined for samples of carbonate more accurately approximates the time of deposition, although they may also be deposited, eroded and redeposited multiple times.

Accumulation rates are difficult to determine in a river channel such as the Columbia River, which contains highly mobile sediment that has likely been eroded and redeposited numerous times. If we assume that the dated piece of wood was ‘old’ before it was transported, the radiocarbon ages on carbonate fragments within MCR-201 suggest that the sediment was deposited in the last 500 years. This yields a long-term accumulation rate of ~1 m/100 years, which is entirely feasible given rates of delivery and transportation of sediment within the lower Columbia River system.

Core 202

Core MCR-202 is 456 cm long and was collected in 9.2 m water depth just south of the north jetty, close to the site of MCR-203 and 204. It is composed entirely of sand, and contains two units separated by a sharp, but visually subtle contact at 366 cm (see Fig. 31; not seen in the x-radiograph, Appendix A). The upper unit is very well-sorted, homogenous fine sand with occasional (infrequent) shell fragments (see Fig. 31). The sand below the contact is very well-sorted, very fine sand and contained essentially no identifiable shell fragments (this sand appears slightly more grey in the core photograph, Appendix A). The vibracorer appeared to have difficulty penetrating when it reached a depth of approximately 360 cm, based on field notes and the on-board inspection of the outside of the core barrel which was scraped. The coincidence between the location of the scrapes on the barrel, and the depth of the very fine sand unit, suggests a possible cause for the disturbance seen in core 202 (red paint flecks apparent in the core photograph, Appendix A).

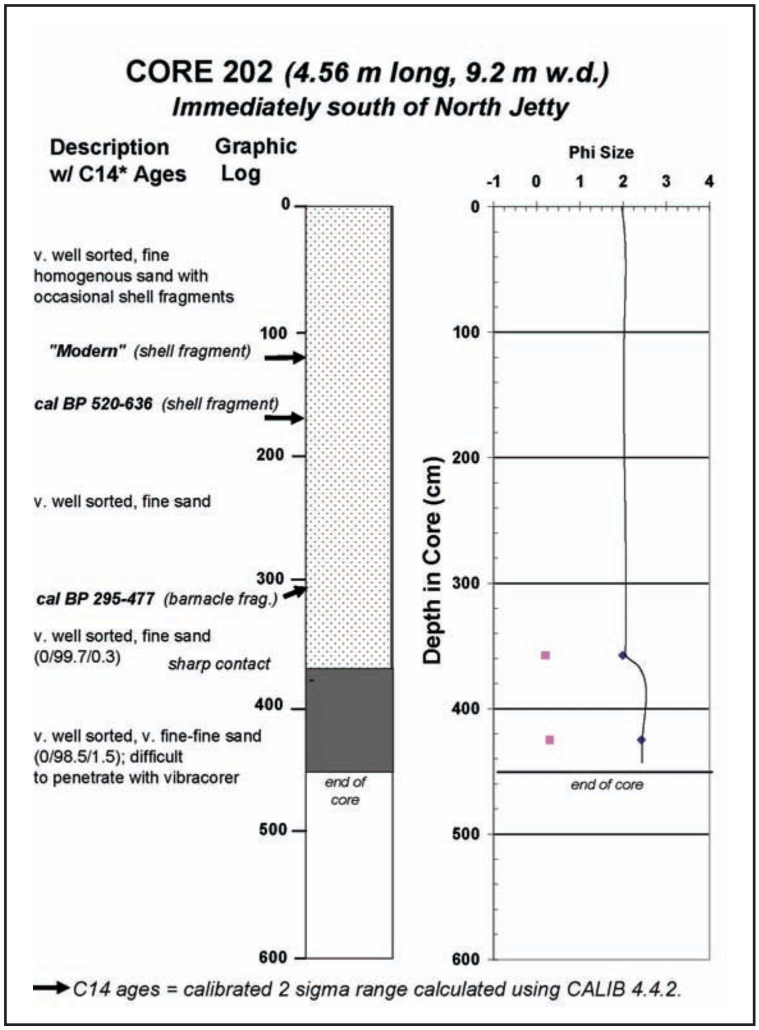

Fig. 31. Descriptive log of core MCR-202.

There are no shell or pebble lags in the core, although there is a possible burrow structure from 220-236 cm (see core photograph, Appendix A). The vertical structure is encased with slightly darker sand (likely due to organics) and fine shell fragments. Several small pieces of wood were identified below the burrow.

Depth in Core 202	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
112 cm	barnacle fragment	>Modern	cannot calibrate
167 cm	mussel shell frag.	1390 +/- 30	Cal BP 520-636
304 cm	barnacle fragment	1150 +/- 45	Cal BP 295-477

Radiocarbon ages were determined for three samples in MCR-202. The calibrated ages indicate that the three carbonate samples are all relatively young (<630 yr BP). The samples at 167 cm and 304 cm are not in correct stratigraphic order, however this is not seen to be surprising given the highly dynamic nature of the Columbia River channel. Sediment and shell fragments are likely to be eroded and re-deposited multiple times.

Core 203

Core MCR-203 is 338 cm long and was collected in 9.3 m water depth just south of the north jetty, close to the site of MCR-202 and 204. This core contains a much more varied sedimentary sequence than Core 202 (see core photograph and x-radiograph, Appendix A). The uppermost unit is composed of well-sorted fine to very fine sand (see Fig. 32), with scattered shell fragments (mostly 2-5 mm in size). There is a sharp, but irregular contact at 60-68 cm (see core photograph, Appendix A), with well-rounded pebbles and larger shell and sand dollar fragments in a matrix of fine sand. There are also 'pods' of reduced organics and mica fragments. There is another sharp, but irregular contact from 75-79 cm. Moderately well-sorted, very fine sand occurs beneath the contact. The thin pebble and shell layer may represent a small channel infill sequence, but it is not possible to make a conclusive statement.

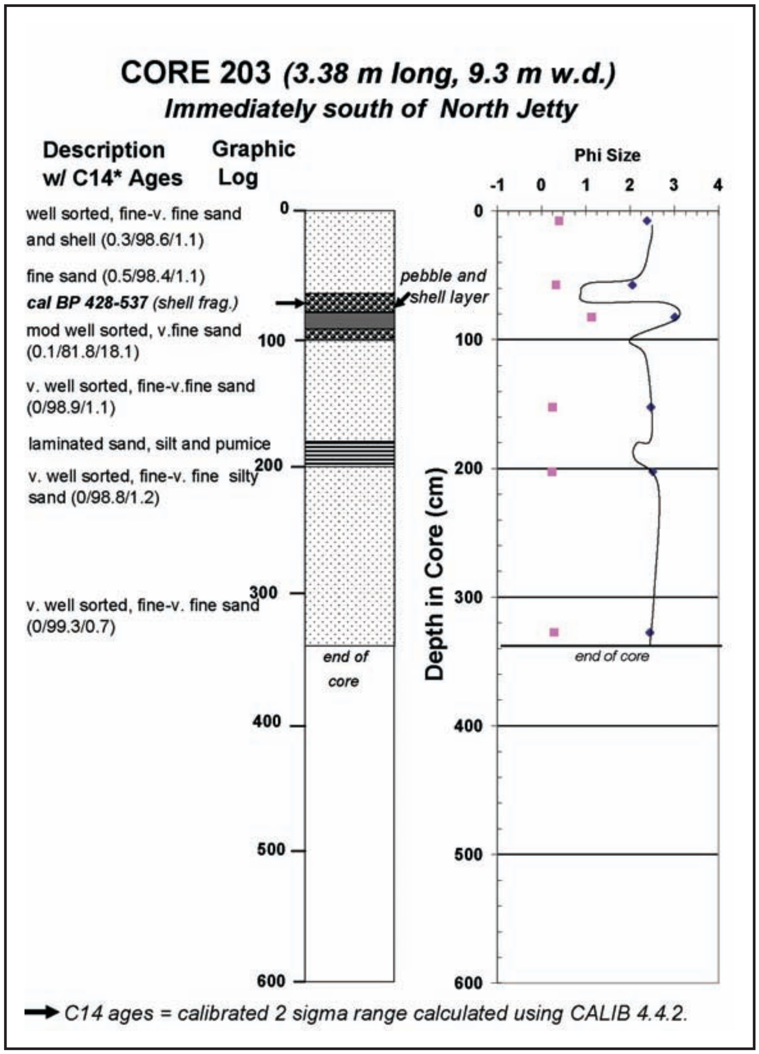

Fig. 32. Descriptive log of core MCR-203.

Two more pebble-rich zones occur beneath this feature. The first is a 'pod' of pebbles and coarser sand, with shell fragments, from 84-92 cm, and the second is a pebble-rich layer that occurs at 99-101 cm (see core photograph, Appendix A). Between the two is a vertical structure of slightly lighter sand that may represent a burrow. The exact relationship between the features is unclear.

The sediment within the core between 100-170 cm is very well-sorted, fine to very fine sand (and some silt) with essentially no shell fragments except at the very base of the unit. The sand appears to be bedded, although this is difficult to see on the photograph of the core due to the homogenous grain size. There is a sharp (slightly disturbed) contact at 170 cm, and another sharp contact at 200 cm. Between the two contacts is a finely laminated unit of alternating sand and silty mud; each laminae is ~2 mm thick (see both the x-radiograph and the core photograph, Appendix A). Several of the lamina between 191-198 cm are very light in color and contain pumice. These are likely from one of the eruptions of Mt St Helens, but not necessarily the 1980 eruption.

The sand below the contact at 200 cm to the base of the core at 338 cm is homogenous very well-sorted, fine to very fine sand that contains no apparent shell fragments. There was no obvious change in sediment that would prevent continued penetration of the vibracorer, although it is possible that the very fine sand intersected at 360 cm at site 202 prevented the corer from penetrating any further.

Depth in Core 203	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
67-68 cm	bivalve fragment	1260 +/- 35	Cal BP 428-537

A radiocarbon age was determined for a sample at 67-68 cm in MCR-202. The calibrated result indicates that the bivalve fragment is relatively young (<540 yr BP), which is similar to the dated samples from nearby core 202.

Core 204

Core MCR-204 is 366 cm long and was collected in 9.3 m water depth just south of the north jetty, close to the site of MCR-202 and 203. This core contains a relatively uncomplicated sedimentary sequence (see Fig. 33 and core photograph, Appendix A). The uppermost unit is composed of very well-sorted fine sand, with virtually no shell fragments. There is a sharp contact at 58-59 cm (see core photograph and x-radiograph, Appendix A), between the clean, fine sand and a silty, organic-rich unit. The organics form the uppermost part of a laminated muddy sand and mud sequence which is 25 cm thick. A sharp, angular contact at 82-85 cm marks the base of the laminated sequence, below which there are 'pods' of organic-rich and mica-rich sand. Note that these are similar to the 'pods' identified at a similar depth in Core 203. There may be some disturbance to the core beneath the contact as diagonal features can be seen in the x-radiograph (from 100-138 cm). Horizontal laminations from 138-148 cm in silty, fine sand (see core photograph and x-radiograph, Appendix A) indicate that the base of this core section is not disturbed.

The horizontal laminations are apparent from 160-185 cm (see photograph and x-radiograph, Appendix A), but the extremely homogenous sediment below that depth contains no apparent structures or shell fragments. Grain size and sorting are quite constant throughout the lower 3 m of the core (see Fig. 33). No pebbles were found in the core.

As cores MCR-203 and 204 were collected at the same site, it was decided that AMS analyses would be conducted on only one of these cores. The lack of shells or shell fragments in Core 204 contributed to the decision not to date material from this core. Although several small pieces of wood were sampled in the basal 20 cm, it was decided that these were likely relict (old) wood transported down the Columbia River and hence did not represent the time of deposition. While no dates have been obtained for MCR-204, the geological evidence indicates that MCR-204 contains a similar stratigraphy to that recorded in MCR-203 (see above) and was therefore likely deposited at approximately the same time.

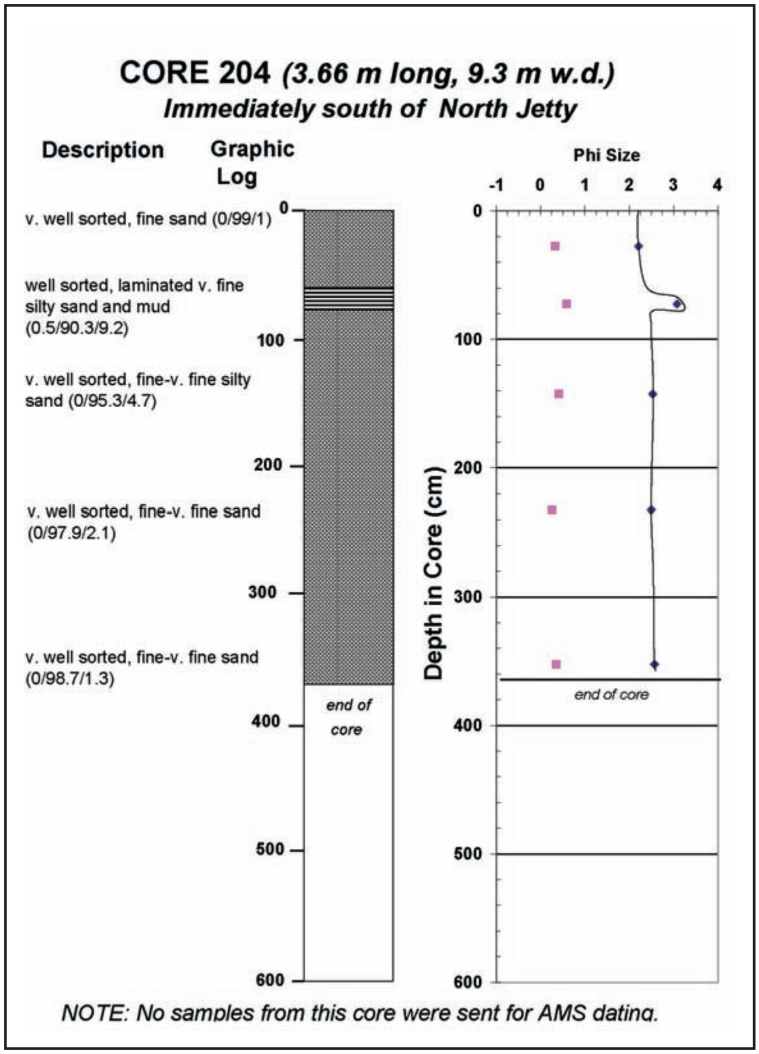

Fig. 33. Descriptive log of core MCR-204.

Core 205

Core MCR-205 is 470 cm long and was collected in 10.6 m water depth south of the north jetty, between the sites of MCR-202/203/204 and the sites of 206/201. This core contains mostly well-sorted, fine-medium lithic-rich, subangular sand with relatively few shell fragments. More specifically, there is a zone, from approximately 85-100 cm, of shell fragments and rounded mafic pebbles in slightly coarser sand (see Fig. 34). Below this interval, the sand gradually coarsens downward to a sharp contact at 183 cm. Above the contact, there are more shell fragments and the sand is medium to coarse grained and less well sorted than elsewhere in the core. Immediately above and at the contact, bedding planes are convex downward (presumably deformed, or 'dragged down' due to coring). There is a horizontally laminated unit of alternating silty mud and sandy mud lamina extends to 224 cm (each laminae is 1-2 cm thick; see core photograph and x-radiograph, Appendix A).

A sharp but irregular contact from 217-224 cm separates the laminated unit from the underlying sand (see Fig. 34). Below the contact there is clean, well-sorted fine-medium sand with few shell fragments. There are several mud clasts that are oriented diagonal to the core barrel and one which appears to be a sphere (see core photograph and x-radiograph, Appendix A). It is actually a disc that is a 1-cm-thick mud lamina that has presumably been rotated due to vibracoring. These mud lamina may have been closely associated and moved apart due to vibrations during coring. Small 'chips' of red paint (from the outside of the barrel) are present in the lower 1.5 m of this core and suggest some disturbance during coring. The sand from 300-470 cm is well-sorted fine-medium grained, although it becomes slightly coarser and contains a few sub-angular pebbles in the basal 25 cm. The pebbles appear as dark grey-brown clasts in the core photographs and they are visable in the x-radiograph. Several barnacle fragments were identified and thought to be derived from the adjacent bedrock headland. There are also several mussel shells and unidentifiable shell fragments in this interval.

Depth in Core 205	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
191-192 cm	organics in mud	1330 +/- 30	Cal BP 1179-1299
310-315 cm	barnacle fragment	1020 +/- 45	Cal BP 131-396

Radiocarbon ages were determined for two samples in MCR-205. A 1-cm thick lamina of organic matter was sampled from 191-192 cm, within the laminated unit. The calibrated age is 1179-1299 cal BP. A barnacle fragment from ~310 cm yield a much younger age of 131-396 cal BP that fits with other MCR cores and indicates moderately fast rates of sediment accumulation in the channel. This relationship has been identified in several of the MCR cores, with the ages determined for organics always being significantly older than those for carbonate fragments, and supports our conclusion that the organics represent older (relict) material that has been transported down the Columbia River during flood events.

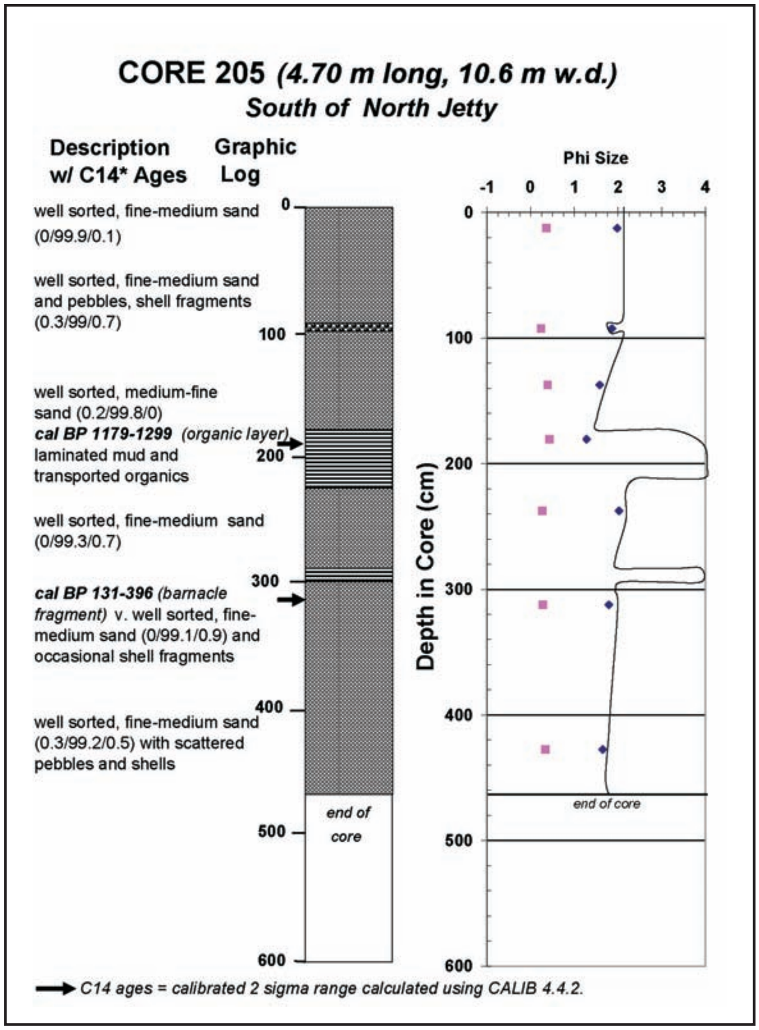

Fig. 34. Descriptive log of core MCR-205.

Core 206

Core MCR-206 is 572 cm long and was collected in 11.7 m water depth just south of the north jetty, close to the site of MCR-201. It contains well-sorted, fine to medium sand throughout and lacks sharp contacts, except for those associated with several laminated mud intervals that are visible in the x-radiograph (also see Fig. 35). The grain size of the sand is finest in the top meter, and then coarsens slightly down toward 250 cm. Generally, the sand is lithic-rich and subangular throughout.

The thickest laminated unit occurs between 250-266 cm and appears to be in situ, with strong horizontal bedding extending across the width of the core. There is a 7 cm-thick organic mat that was dated. Several other laminated muddy intervals are spaced throughout the length of the core and, as discussed for MCR-201 (above), these mud lamina likely represent deposition after major floods on the Columbia River. As in core MCR-201, some of the laminated mud units within this core appear to be slightly rotated and broken in places (see Fig. 35), which might suggest that they are 'rip-up clasts'. The multiple laminated mud units between 390 and 445 cm may have been partly disturbed during vibracoring, which enabled sand to move in between the mud units and displace them slightly. The sand along the edges of the barrel and the subtle appearance on the x-radiograph support this conclusion. A wood fragment at 434-441 cm was dated.

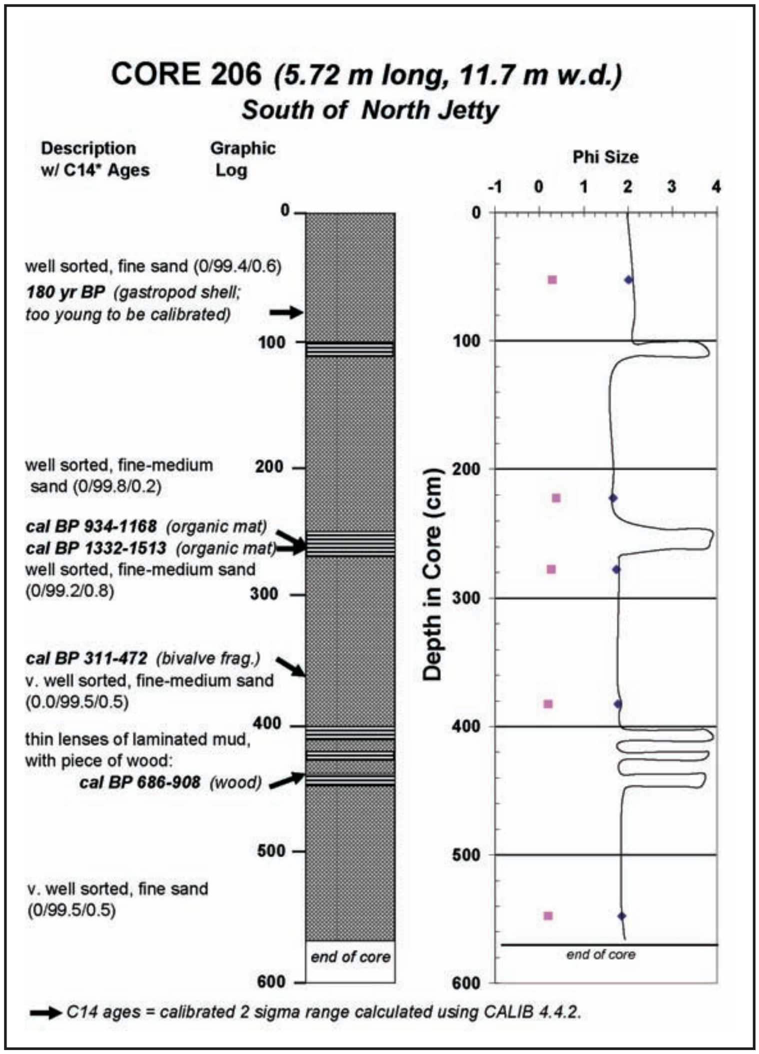

Fig. 35. Descriptive log of core MCR-206.

Occasional carbonate fragments were noted within several intervals including from 32-48 cm, 91-145 cm, 174-240 cm, 346-375 cm, 470-495 cm, and at the base of the core (see Fig. 35). The intervals from 230-240 cm and 346-375 cm contain the largest carbonate fragment, including an unidentified bivalve lying horizontally along bedding, at 364 cm. A small mussel shell is associated with a loosely-filled/void space in the core (see x-radiograph at 235 cm, Appendix A).

Radiocarbon ages were determined for two pieces of shell, including a small and very fresh gastropod at 91 cm (likely a "Purple Dwarf Olive"). The calibrated ages can be used to calculate an approximate accumulation rate of 100 cm/100 years for the upper 364 cm of the core. Two samples from the organic mat associated with the thick muddy interval at 260 cm were analyzed and their calibrated ages are significantly older than the dated bivalve fragment at 364 cm. This suggests once again that a flood of the Columbia River may have mobilized 'old' organic matter that had been stored on the floodplain and along river banks. If so, we conclude that the ages determined for carbonate samples more accurately approximates the time of deposition. The piece of wood from 434-441 cm yielded a calibrated age of 686-908 Cal BP, which may or may not have been deposited shortly after the tree or branch died.

Depth in Core 206	*Material Dated*	*Radiocarbon Age (yrs BP)*	*Calibrated Age Range (yrs)*
91 cm	gastropod: "Olive"	180 +/- 40	too young -cannot calibrate
260-263 cm	organics from mat	1520 +/- 25	Cal BP 1332-1513
260-263 cm	organics from mat	1120 +/- 45	Cal BP 934-1168
364 cm	bivalve fragment	1160 +/- 30	Cal BP 311-472
434-441 cm	piece of wood	855 +/- 35	Cal BP 686-908

Detailed analyses of closely-spaced MCR-201 and 206 suggest that these cores contain a similar sedimentary record and all of the sediment was deposited within the last 500-1000 years.

Summary of Clatsop Spit Cores

The vibracores collected near/south of the Columbia River south jetty included one core collected on Clatsop Spit in very shallow water (< 7 m at time of coring, site 207). The two cores collected at site F (core 107 and 108) show generally similar subsurface sedimentary units (Fig. 36). Both cores are comprised of very fine-fine sand overlying fine to medium sand, although core 107 extended deeper into another fine sand unit with sand dollar and shell fragments at the base of the core. The contacts between the sand units in core 107 were gradational. Core 108 was shorter, but contained several thin intervals of laminated mud/sand, as described above. Moderately thick intervals of the laminated mud/sand unit were encountered near the top of core 207 and the base of core 109, in which the bottom 1.7 m of the core is mostly mud. Core 109 also contained an unusual moderately sorted, fine-coarse sand that was not identified in other cores.

Analysis and interpretation of vibracores obtained from the Clatsop shelf indicates that long-term erosion has occurred over much of the inner shelf.[1] This conclusion is supported by quantitative measurements of shelf surface elevation made over the last ~100 years (Figs. 23-25). There are several pieces of evidence in the vibracores for long-term erosion of the inner shelf. These include the laminated mud and sand unit that occurs near the top of many cores, 'old' radiocarbon ages, winnowed or lag deposits, and inferred rip-up clasts and mud clasts.

1 The statements in this summary are drawn from all nine vibracores collected on the Clatsop shelf, i.e., both the 2002 vibracore project and this project.

The laminated mud and sand unit occurs in most of the cores on the Clatsop shelf (cores 101, 102, 105, 106, 108, 109), and all but core 108 contain > 10 cm of continuous mud/sand couplets. In order for these units to be preserved in shallow water on this high-energy shelf, they would have to be buried soon after deposition. The lack of bioturbation in these units supports this hypothesis of rapid burial. It is possible that the laminated mud and sand units were deposited at the margin of the once-wide and dynamic entrance with at least 2 major channels (north and south) with a large sand bank/shoal in the middle, and large, shore-connected shoals extending from the south (Clatsop Spit) and the north (Peacock Spit). Rapid burial would be possible (indeed likely) as ebb delta shoals shifted and deposited sand. Erosional events were likely, and are probably recorded in the cores as sharp, angular contacts within the laminated unit that cut bedding at a low angle (see core 109, 397-398 cm, and core 105, 316 cm). There are very similar units in cores from the Fraser River delta in Canada (Monahan et al., 1997).

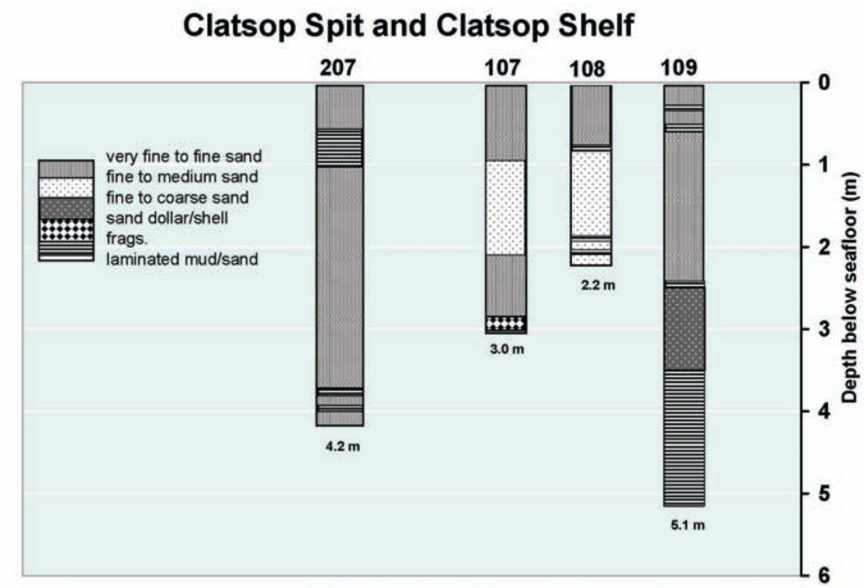

Fig. 36. Core logs showing basic sedimentary units observed in the cores collected along the Columbia River south jetty.

Samples from laminated units on the Clatsop shelf have been analyzed by AMS and the results indicated that these units are 'relict' (were not deposited in the last 1000 years). The age of the organics within the laminated mud are oldest in the south (> 4000 years BP; cores 105, 106) and younger in cores just south of the south jetty (2000-2500 yr BP; cores 108, 109). In addition, in all cores where organics have been dated, the ages are older than those determined for dated carbonate fragments in the same cores (shell, sand dollar, barnacle). The discrepancy in ages between organic matter and carbonate supports the hypothesis that the organic matter was probably old when it was eroded from the Columbia River catchment or floodplain, prior to being transported down the river and discharged during peak floods (especially during the spring freshets), and deposited near the margins of the ebb delta. In addition, these old dates near the surface indicate that relatively little sediment has accumulated on the Clatsop shelf since that dated material was deposited, and/or that sediment has been eroded.

The mud laminae of the laminated units on the Clatsop shelf are somewhat resistant to erosion because they are composed of clay-rich mud and therefore semi-consolidated. This enables them to be eroded and transported as 'mud clasts" that can be transported and redeposited as clasts, rather than disaggregating into individual mud particles. These mud clasts appear in many of the Clatsop shelf cores, and are inferred to be 'rip-up clasts'. These clasts occur most commonly in erosional settings where mud has been deposited and is available to be eroded. They provide additional evidence that parts of the Clatsop Plains lower shoreface/inner shelf have been erosional over the long term (at least since the early 1900s). Also, in general, the vibracores contain relatively little carbonate material, compared with cores from other continental shelves. This is perhaps not surprising, given the substantial size and volume of land-derived sediment contributed by the Columbia River. A few cores contain intervals of relatively higher concentrations of shell and/or sand dollar fragments and slightly coarser sand. This coarser sand was likely deposited by high-energy flows, when the axis of the channel was located here. High-energy flows would also winnow the finer sand and result in somewhat coarser-than-average grain size for the remaining sand (which was cored).

The Clatsop inner shelf cores generally contain a coarser fraction (and mean size) of sand (assumed to be from the Columbia River) than elsewhere in the littoral cell for comparable depths. Table 6 shows the grain size results for near-surface sediment samples (generally within the top 30 cm of core) for Clatsop shelf cores and Long Beach shelf cores.

Even coarser sediment (assumed to be from the Columbia River) is also found at certain depth interval within some of the Clatsop cores, and the MCR cores, but not in other cores to the north. Table 7 shows similarly-coarse mean grain sizes of samples from the Clatsop shelf cores and MCR cores.

These mean grain sizes suggest that the high-energy entrance channel contains the coarsest Columbia River sand that is not found on (dispersed to) the shoreface (or even on the beaches in significant quantity). On the beaches, the Long Beach median (D50) grain size is 0.16-0.21 mm; the Clatsop Plains median (D50) grain size is 0.16-0.17 mm (Ruggiero et al., 2005). The comparable coarse sand at depth within the CP cores closest to the Columbia River (101, 108, 109) is indicative of a higher-energy and/or erosional setting where fine sediment is winnowed away and coarser sediment is deposited. The coarser sediment deposits are consistent with the previous locations of the entrance channel(s) (Figs. 17-20), as well as the net erosion of the seabed that has occurred since the late 1800s (Table 5).

Additional evidence for long-term erosion on the Clatsop shelf is provided by radiocarbon dates of carbonate material from two cores. In each core, the dates are not in stratigraphic order because an older date occurs above a younger date. In core CP 104 (located in 17.3 m water depth, Fig. 25) a bivalve fragment collected at 112-116 cm depth interval returned a calibrated age of 2302-2480 BP whereas another bivalve fragment at 184-189 cm had a >Modern age. This result suggests that the seabed has been actively

Table 6. Mean grain size of near-surface sediment samples from the Clatsop and Long Beach shelf.

Clatsop shelf			Long Beach shelf		
Depth (m)	Core	Mean (mm)	Depth (m)	Core	Mean (mm)
10.8	103	0.16	12.2	305	0.17
11.8	109	0.20	17.3	302	0.11
12.2	108	0.17	18.2	303	0.15
14.6	102	0.19	31.4	306	0.13
18.4	101	0.20	31.8	301	0.12
25.6	105	0.18	41.1	307	0.11
40.5	106	0.15	44.7	304	0.07

Table 7. Mean grain size of sediment samples from the Clatsop shelf and MCR cores.

Depth (m)	Core	Depth interval (cm)	mean size (mm)
18.4	101/1	90-94	0.27
12.2	108/1	65-70	0.32
12.2	108/1	117-122	0.41
12.2	108/2	163-168	0.33
12.2	108/2	199-204	0.31
11.8	109/1	115-120	0.23
11.8	109/2	195-200	0.26
11.8	109/2	265-270	0.40
11.8	109/3	345-350	0.40
11.8	109/4	495-500	0.31
12.3	201/1	10-15	0.26
12.3	201/1	75-80	0.31
12.3	201/1	130-135	0.41
12.3	201/2	250-255	0.29
12.3	201/3	365-370	0.32
12.3	201/4	520-525	0.30
9.2	202/1	5-10	0.25
9.2	202/1	110-115	0.27
9.2	202/2	210-215	0.27
9.2	202/3	355-360	0.25
9.3	203/1	55-60	0.24
10.6	205/1	10-15	0.25
10.6	205/1	90-95	0.27
10.6	205/2	135-140	0.33
10.6	205/2	178-183	0.41
10.6	205/3	235-240	0.25
10.6	205/3	310-315	0.29
10.6	205/4	425-430	0.32
11.7	206/1	50-55	0.25
11.7	206/2	220-225	0.32
11.7	206/2	275-280	0.30
11.7	206/3	380-385	0.29
11.7	206/4	545-550	0.28

reworked to nearly 2 m along this shallow shoreface. Relatively old dates out of stratigraphic order were also found at lower depths in this core. A bivalve fragment at 322 cm returned a calibrated age of 4646-4841 BP, while a shell fragment at 464-472 cm had a calibrated age of 3705-3966 BP. Together, the dates in this core suggest recent sedimentation at the toe of the progradional (upper shoreface) sediment wedge over relatively older reworked sediment. In core CP 106 (located in 40.5 m water depth, Fig. 25) a bivalve fragment collected at 76-77 cm returned a calibrated age of 5529-5769 BP, whereas another bivalve fragment at 184-185 cm returned a younger calibrated age of 4849-5109 BP. This result is more likely when there is a slow rate of sediment accumulation, and sediment is eroded and redeposited locally. In addition, both of these relatively near-surface samples are old (another indicator of an erosional setting), in sharp contrast to core LB 307 located in 41.1 m water depth on the Long Beach shelf, where a well-preserved Nassarius perpinguis shell at 221 cm below the surface returned a calibrated age of 123-294 BP and a Macoma shell at 408 cm below the surface had a calibrated age of only 547-658 BP.

The only exception to the trend of long-term erosion on the Clatsop shelf occurs in the shallow nearshore zone, adjacent to the central Clatsop Plains. In core CP 103 located in 10.8 m water depth a sand dollar fragment at 133 cm returned a calibrated age of 501-614 BP, another sand dollar fragment at 237 cm had a calibrated age of 531-645 BP, and another sand dollar fragment 548-549 cm returned a calibrated age of 1716-1883 BP. These dates indicate sediment accumulation on the upper shoreface at rates on the order of 30 cm/100 years. This nearshore accumulation is not surprising given the history of long-term progradation of the Clatsop Plains (Kaminsky et al., 1999; Peterson et al., 1999).

Summary of MCR Cores

The vibracores collected along the north jetty (MCR-201 to 206) were largely comprised of either very fine-fine sand, or fine-medium sand, depending on location. Fig. 37 shows the overall pattern of visually observed transitions between different material, for example contacts between mud and sand and transitions from coarse to fine sediment.

Most of the vibracores contained intervals of finely-laminated (interbedded) mud and sand, with sharp contacts between the laminated mud/sand and the clean sand intervals. In some cases these laminated intervals were very thin (several 'couplets' of mud/sand in 5-10 cm of core length; core 201) whereas in other cores, the laminated intervals were 20-40-cm thick (many more mud/sand couplets in thicker intervals in cores 206, 205, 204, 203). Cores 205 and 203 also contained relatively thin intervals (~ 5-15 cm) of pebbles and/or shell fragments (Fig. 37). These intervals occur between 60-75 cm and 85-95 cm in core 203, and between 90-100 cm, 175-183 cm, and 445-465 cm in core 205. Core 202 contained a basal unit of very well-sorted, very fine sand (bottom 70 cm of the core). This was apparently responsible for the lack of easy penetration of the core barrel into the seabed. During coring operations, the barrel progressed well until that depth and then slowed markedly. In addition the barrel was heavily 'scored' at that penetration depth. Experience elsewhere indicates that such fine, well-sorted sand often does inhibit penetration because the well-packed fine sand grains are effectively inter-locked and not able to be rearranged over very small distances to allow the barrel to move through the sediment.

Seven cores were collected in shallow water adjacent to the highly dynamic entrance channel between the Columbia River jetties. The sedimentation record at the core sites includes multiple depositional and erosional events, which likely occurred both before and after emplacement of the jetties, though the long-term record since jetty construction shows an erosion trend in this area (Figs 23-25 and Table 5). This increases the uncertainty of sediment accumulation rates, as does the potential uncertainty of the early dredging history of the area when record-keeping was less complete. Neverthess, it is worthy to note that cores 201 and 206 similarly exhibit significant change (+/-) due to position along the channel (e.g., coarser, well-sorted sand), whereas cores 202 to 205 similarly exhibit accumulation trends that suggest smaller fluctuations in a more protected environment (e.g., densely-packed units of very well-sorted fine sand).

Analysis and interpretation of vibracores obtained from the Columbia River entrance indicate that most of the cores contain clean, lithic-rich sand which is slightly coarser than that being deposited on/adjacent to the Long Beach Peninsula. The coarser sand size is possibly the result of the location of the axis of the main channel in this region, which would be accompanied by high-energy flows and winnowing of the finest sediment. This would result in the deposition of slightly coarser sediment relative to other locations. The sand generally contains little shell or other carbonate material, which made it more difficult to obtain samples for radiocarbon analysis. Fortunately, there was a notable increase in barnacle fragments in the MCR cores, compared with the Clatsop shelf, due to proximity to bedrock outcrops around Cape Disappointment. Results that were obtained returned calibrated ages of 120-630 Cal BP for shell and barnacle fragments (for details, see discussion and tables of individual cores). Dates on carbonate within the cores indicate overall rates of sediment accumulation from <100 cm/100 yrs (cores 201, 202, 205) to 200 cm/100 yrs (core 207). The long-term trend of sediment accumulation that has been identified in the cores does not necessarily

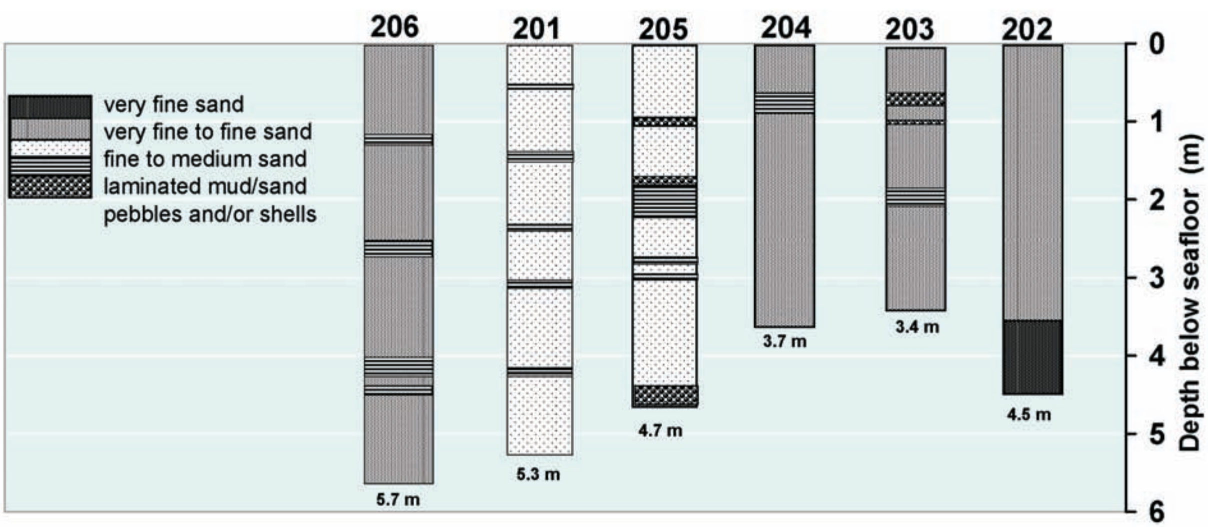

Fig. 37. Core logs showing basic sedimentary units observed in the cores collected along the Columbia River north jetty.

contradict the historical evidence of erosion near the north jetty. There are processes operating at two different time scales. The long-term rate reflects sediment accumulation over thousands of years as a result of net sediment supply from the Columbia River, while the historical period has been characterized by decadal- to century-scale redistribution of sediment at the MCR.

As discussed previously, the MCR cores contain mostly clean sand, with occasional intervals of interbedded or laminated mud and muddy sand. The intervals are relatively thin (~10-30 cm), and individual mud lamina are generally 0.5-1 cm thick. The laminated intervals contain some organic-rich laminae (thin layers of plant and/or wood fragments) that were dated and found to be 700-1600 Cal yrs BP, compared with the ages of the carbonate of 120-630 Cal BP. The organics incorporated into the laminated intervals are older than shell or barnacle fragments in the same cores. This repeats the pattern that was observed on the Clatsop shelf indicating that 'old' organic matter has been remobilized and transported downstream during Columbia River floods.

The laminated mud units sampled in the MCR cores appear to represent a modern analog for those cored on the Clatsop shelf, south of the south jetty. A comparison of MCR cores 204 (60-80 cm) and 205 (183-214 cm) with CP cores 102 (7-73 cm) and 106 (501-543 cm) shows the similarity in the thickness of individual laminae. Some mud layers within the laminated intervals of several of the MCR cores also exhibit erosional contacts with the overlying sand (which is slightly coarser and less well sorted). This reinforces the hypothesis that periods of erosion and reworking are common at the margins of the dynamic Columbia River entrance channel.

It is very difficult to determine the likely rate of short-term sediment accumulation from AMS analysis on samples from the MCR vibracores. This is especially so since the cores contain evidence of multiple depositional and erosional events and fluctuations in sedimentation on all time scales. The radiocarbon method does not permit dating of historical deposits and muds. However, the pre-1900 ages of the dated shells that were sampled above the mud layers indicate that the mud was deposited prior to potential anthropogenic contamination by extensive production of industrial or shipping wastes (heavy metals, etc). Mud samples analyzed for Cs-137 in core 207 (the only MCR core site where the bathymetric surveys show significant post-jetty accumulation) came up negative, indicating that the mud was deposited prior the 1950s.

Discussion of Prehistoric and Historical Setting

In prehistoric time, the Columbia river valley was located farther to the south than the present location of the mouth. Fig. 38 shows the lowstand surface (>14,000 BP) interpreted from seismic reflection data (Twichell and Cross, 2001) and reveals the shape and the position of the ancient Columbia River valley that runs between the north and south transects of the Clatsop shelf cores. For reference purposes, the 1999 shoreline, jetties, and the modern bathymetric depth contours in 20-m intervals are included in the figure. As sea level rose by some 110 m over 14,000 years, the river valley filled with sediment as the environment transitioned from fluvial to estuarine. Twichell and Cross

(2001) indicate that as recent as 3,000 BP, the Clatsop Plains was narrow and did not extend as far north as they do now. Rather, the river mouth was even wider than it has been in recent historical time prior to jetty construction. This implies that the ebb-tidal delta of a few thousand years ago also extended farther to the south than in historical time. Evidence in the vibracores indicates long-term erosion of the inner shelf which is consistent with a narrowing and substantial reduction in the size of the ebb delta, from its previous, more southerly extent. As the environment transitioned from ebb delta to shoreface, the sediment of the delta was redistributed, resulting in a lowering of the seabed, as the historical and core data indicate.

The early historical surveys provide additional insight into the amount of change at the Columbia River entrance that has likely occurred over thousands of years. A comparison of surveys shows that the MCR has been a dynamic region characterized by rapid changes in the pattern of sediment deposition and erosion. It is known that the number of channels has fluctuated between one and two, and the location and depth of the channel(s) has varied dramatically. The earliest surveys of the MCR in 1792 and 1798 show a single entrance channel bounded by broad shoals to the north and south (Figs. 39 and 40). The 1841 survey (Fig. 17) shows an extremely different configuration with Middle Sand-bank filling a significant portion of the area that had been the main channel and which now sits between the north and south jetties. The entrance channels were located to the north and south of this shoal. Middle Sands exists in an elongated configuration on subsequent surveys conducted in 1851 and 1868. In 1883, there is again only one entrance channel and Middle Sands does not exist in its previous location. Instead, sediment appears to have been deposited seaward and to the south as an ebb delta.

The substantial differences between these channel-shoal configurations can be possibly be explained by fluctuations in peak flows on the Columbia River. Gedalof et al. (2004) reconstructed mean water year (October to September) flow on the Columbia River at The Dalles, Oregon since 1750 using tree-ring chronologies, and concluded that persistent low river flows occurred during the 1840s that were probably the most severe of the past 250 years. The extremely low flows apparently enabled sediment to accumulate within the entrance channel as Middle Sands. Measured river flow at The Dalles began in 1879, and the third- and fifth-highest maximum recorded daily discharge since that time occurred in 1880 and 1882. These record-high peak flows are a probable cause for the near-total dispersal of the sediment that comprised Middle Sands shown in the surveys of the mid 1800s. The historical record indicates the extremely dynamic nature of this environment, and it is reasonable to assume that similar events have occurred for thousands of years, and certainly since sea level reached its present position.

The fluctuations in river flows and coastal processes, (and more recently, the construction of the jetties) have likely contributed to the age and pattern of sediment deposition in the MCR region. As Middle Sands, and other shoals including the ebb delta, were dispersed and reorganized during spring floods, shell fragments previously deposited in the sediment would also be redistributed and redeposited. If dated, these shell fragments would yield ages that reflect their actual age, and not the time of

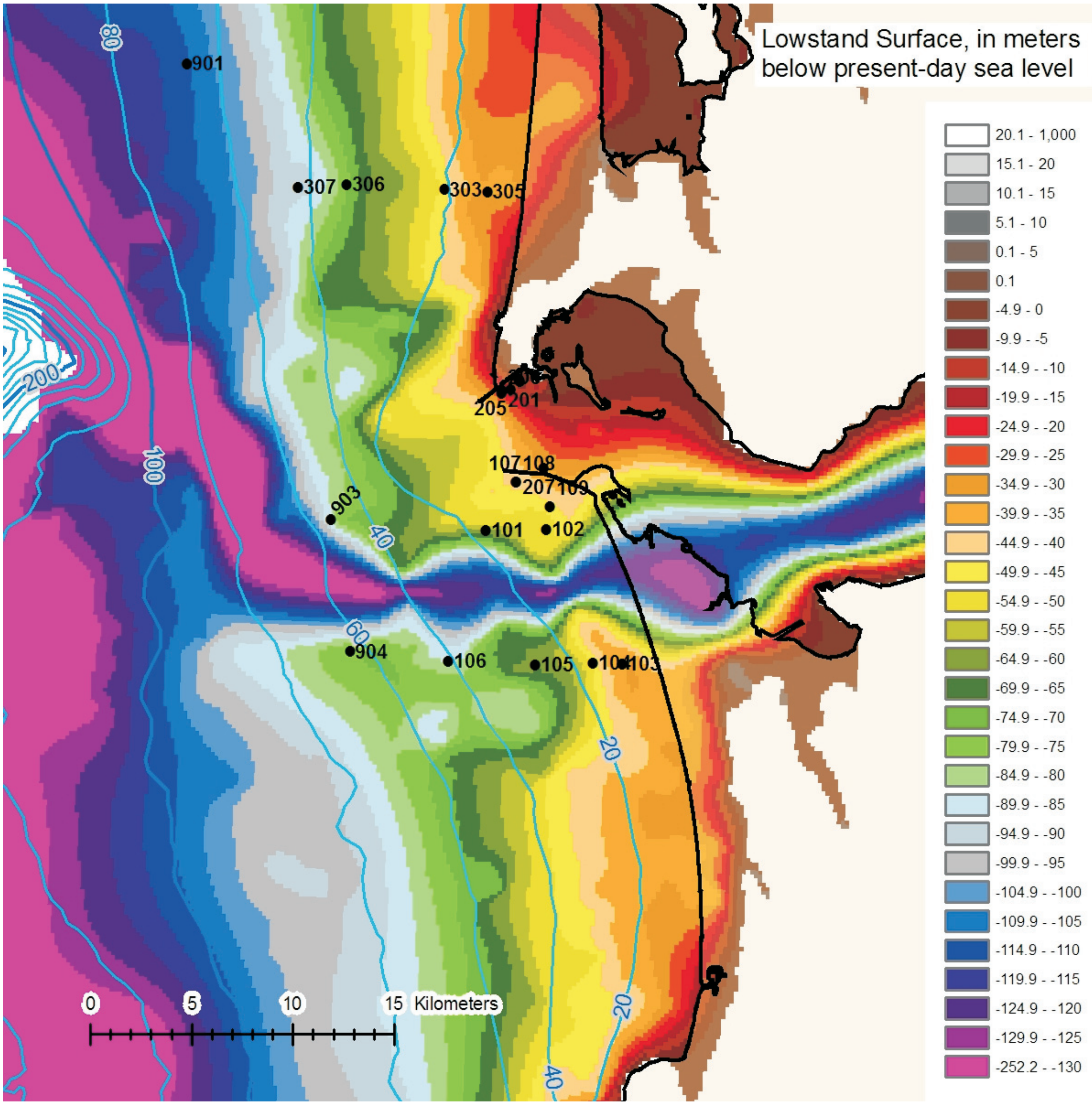

Fig. 38. Vibracore locations, jetties, 1999 shoreline and the modern bathymetric depth contours in 20-m intervals plotted on the lowstand surface (>14,000 BP) interpreted from seismic reflection data (Twichell and Cross, 2001).

redeposition. In this way, carbonate fragments with calibrated ages of, for example, 400-600 years, represent the maximum age of the sedimentary sequence, but not necessarily the actual time of deposition.

Some of the cores collected at the margin of the present MCR channel (201-207) contain laminated mud and sand units relatively near the surface. These were likely deposited during spring flood events on the Columbia River, when a large quantity of suspended sediment was delivered to the coast. The fine sediment would be preferentially deposited in deeper sections of the channel, especially where fresh and salt water masses meet (this enhances the process of flocculation, or clumping of muds into larger particles that sink to the seabed). Sand/mud 'couplets' derived from suspended sediment could accumulate with each major spring flood/freshet (see previous discussion of core 108) and thus multiple couplets might accumulate in a single year. Mud lamina would only be preserved however, if a sand wave or shoal migrated over the top of the mud and buried it, and thus prevented its erosion by subsequent high-energy events. It would not be difficult to mobilize sand on the shoals within the dynamic entrance channel, and for this sand to prograde over the laminated deposits in the previous channel as the channel migrates to a new equilibrium position.

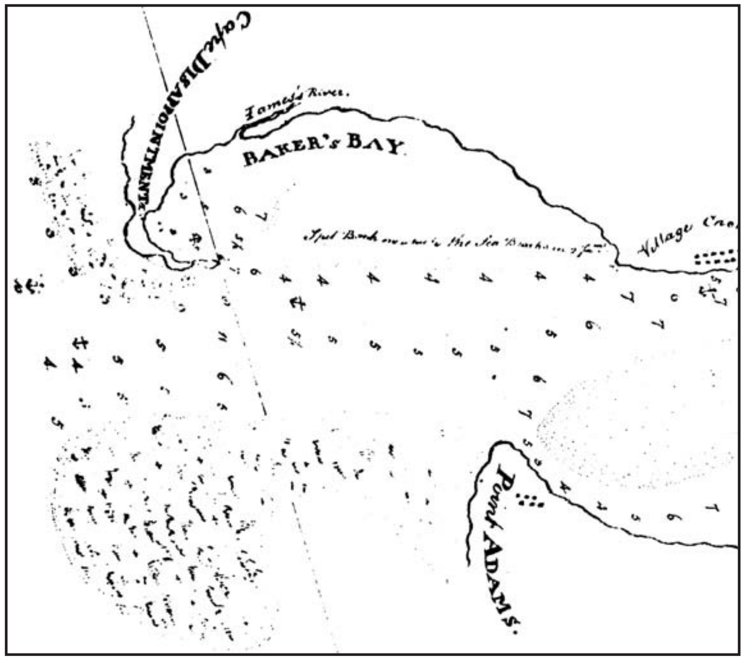

Fig. 39. Lieutenant Broughton's sketch of the Columbia River entrance from survey in October 1792.

Synthesis of Core Results

The core results obtained in this study are synthesized with a variety of data, information, and knowledge derived from a number of related studies. In particular, the cores collected in this project are interpreted within the context of cores collected in 2002 (Kaminsky and Ferland, 2003) on the shoreface along the Columbia River littoral cell. Through integration with analysis of the 2002 cores and analysis of historical shoreline and bathymetric changes, this project has leveraged additional insights that may not have otherwise been realized. In this section, results of the core analysis are synthesized with other data to provide additional information related to key topics of interest: erosion of the Clatsop shoreface, substrate characteristics, jetty foundation, and sediment budget.

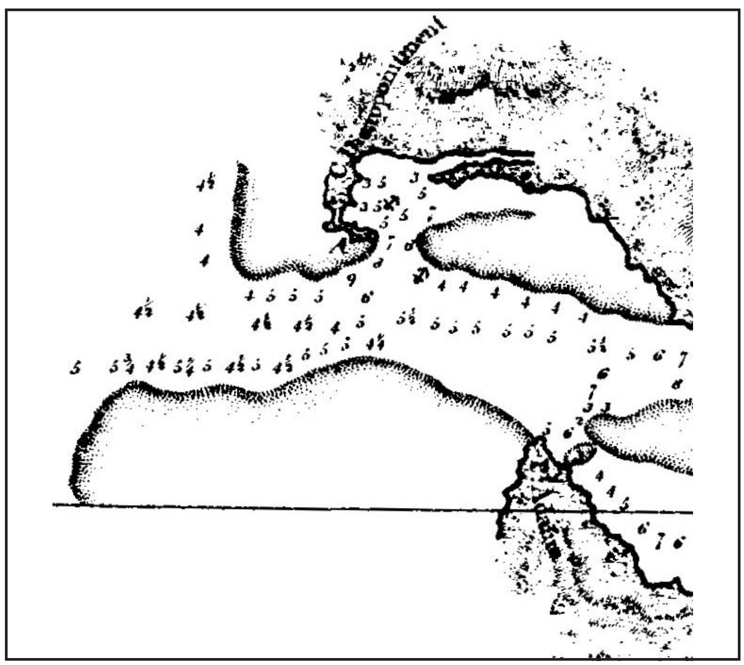

Fig. 40. Captain George Vancouver's 1798 map of the Columbia River entrance.

Erosion of the Clatsop Shoreface

When put in context of the core results obtained from the Clatsop and Long Beach shelves and historical bathymetric changes, the cores in the vicinity of the MCR reveal similarities and trends relative the long-term dynamics and regional setting. The radiocarbon ages and inferred accumulation rates derived from the vibracores are consistent with the historical bathymetric changes observed on the Clatsop inner shelf. Relatively old radiocarbon dates occur at shallow depths within vibracores 101, 102, 105 and 106 and indicate very low sediment accumulation rates in the same areas where high rates of historical seabed erosion have been measured. Similarly within core 103, young dates occur at moderately deep core depths and indicate moderately high accumulation rates on the upper shoreface where historical seabed accumulation has been measured. In core 104, recent accumulation over old and out-of-sequence dates are consistent with the trends shown in Figs. 23-25. The old (and shallow) radiocarbon ages found on the Clatsop inner shelf are in sharp contrast to the much younger (and deeper) radiocarbon ages found on the Long Beach inner shelf. The pattern of older radiocarbon ages and relict mud deposits in the southern-most and offshore Clatsop inner shelf cores and progressively younger dates associated with these deposits in the onshore and northerly direction is consistent with the northward migration of Clatsop Spit over the past few thousand years and the subsequent movement of the ebb delta (Twichell and Cross, 2001).

There are several pieces of evidence in the vibracores for long-term erosion of the Clatsop inner shelf. These include the laminated mud and sand unit that occurs near the top of many cores, near-surface 'old' radiocarbon ages, winnowed or lag deposits, inferred rip-up clasts and mud clasts. Furthermore, radiocarbon dates on carbonate that are out of stratigraphic order are indicative of re-working in a low sedimentation or erosional setting. In this way, the cores "ground-truth" and extend the value of the historical bathymetric change data. Together, there is abundant evidence that the Clatsop shelf has signficantly eroded over historical and late Holocene timescales.

The historical erosion of the Clatsop shelf has been most severe in the vicinity of core 101, often near the crest of the ebb-delta in the pre-jetty surveys. From 1868 to 1883 there was 3.7 m of vertical erosion at this site, and from 1883 to 2000 there was an additional 11.7 m of erosion at this site (Table 5). Shoreface lowering at core site 102 from 1883-2000 was similar at 9.7 m, while at core 109, it was 6.9 m from 1883-2003. Both cores 101 and 102 contain laminated mud units in the shallow subsurface. In core 101, the relict mud unit is less than 10 cm below the seabed and it is only 85 cm below the seabed in core 102 (see core photographs, Appendix A). Fig. 41 shows the shoreface profile change from 1868 to 2000 at these core sites. The profile change shows the adjustment from an ebb shoal environment to a shoreface environment. The apparent shoal feature in the more recent profile is actually Ocean Dredge Material Disposal Site A, where more than 18.25 million m^3 of dredged material was placed during 1956-1994.

The locally-concentrated zone of shoreface erosion on the Clatsop shelf is primarily a response to the construction of the jetties which reduced ebb tidal currents across the Clatsop shoal, which enabled increased wave-driven onshore sediment transport

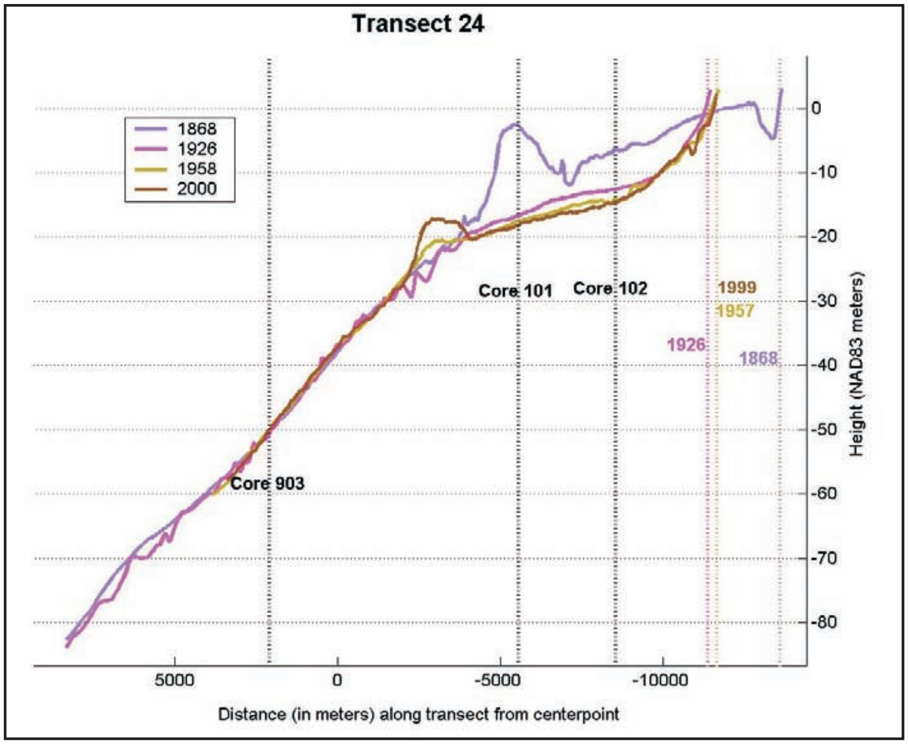

Fig. 41. Shoreface profile change from 1868 to 2000 at a transect passing through core sites 101, 102, and 903.

(Kaminsky et al., 1999). Evidence of relict material just below the seabed also supports the conclusions of Kaminsky et al. (2001) that, as the supply of sand from the Columbia River has rapidly declined (and possibly been eliminated over the historical period), the Clatsop Plains lower shoreface is deflating towards a deeper equilibrium profile. As erosion of the lower shoreface into relict semi-consolidated mud deposits continues, the availability of the shelf to supply beach-quality sand will be diminished. However, the mud deposits are thought to be thin and discontinous laterally, due to localized deposition in prior entrance channels, and therefore likely to be less cohesive than if there was an areally extensive and thick mud deposit. As a result, the laminated mud units would not be very resilient to exposure to high wave/current energy over a prolonged period of time.

Substrate Characteristics

Most of the sediment encountered in the MCR cores is well-sorted, clean sand (very fine to medium grain size). The generally homogenous sand is comprised of quartz and lithic grains, from the Columbia River, that contains very little carbonate (shell, sand dollar or barnacle fragments). The coarser sand found in the MCR cores along the north jetty is comparable to the coarser sand found in cores 101, 108 and 109 and is indicative of high energy and/or erosional conditions of an entrance channel. The finer sands have been winnowed and dispersed to the adjacent shelf and beach environments. Mud that is deposited may be subsequently reworked and transported offshore by tidal currents and river flows, or it may be buried by sand and preserved. Major reorganization of the river mouth and entrance channel prior to jetty construction would have liberated buried mud.

Moderately thick intervals of laminated mud/sand units were encountered in the cores near the south jetty (e.g. 150 cm of core 109, 50 cm in 207, 70 cm in core 101). In contrast, the laminated mud/sand units found in the cores along the north jetty were much thinner. The laminated mud units in the MCR cores (and especially in core 207) represent a modern (recent) analog for those cored on the Clatsop shelf, south of the south jetty. However, the mud found in all cores appears to have been deposited prior to the onset of the industrial age based on radiocarbon dating and Cs-137 analysis.

None of the vibracores contained evidence of hardpan or other cemented sands, and none contained readily identifiable relict Pleistocene sediment (commonly heavily oxidized). All of the sediment was unconsolidated sand, silt or mud, with no gravel intervals identified, although isolated pebbles were occasionally present.

If this area in the vicinity of the MCR cores were dredged, the mud would be dispersed and it is likely that the sand fraction of the sediment would provide good material for beach nourishment. Grain sizes are generally compatible for beach and littoral drift nourishment, although more detailed analysis is warranted for estimation stability vs. mobility.

Jetty Foundation

In terms of jetty stability, the cores indicate that the jetties have been built on sand shoals that have many laminated mud/sand units interspersed over various depths. There does appear to be a significant spatial variability of these units over short distances both in terms of presence/absence of the units, depth intervals of the units among adjacent cores, and the thickness of the units. It is not clear the extent to which the structural stability of jetties might be affected, but differences in the subsurface material in subsurface (e.g. sand vs. mud) might account for some of the subsidence. Muddy sediment generally contains a higher water content when deposited, compared with sand. Through time, as more sediment is deposited on top, the mud units will naturally "dewater", which results in natural subsidence of the entire Columbia River delta sequence. The mud units could potentially compact more rapidly with additional loading (e.g. through placement of additional rock or dredged material), thus exacerbating jetty subsidence.

The south jetty appears to be much more susceptible to jetty foundation problems than the north jetty. The vibracores suggest that thicker mud deposits are preserved on the Clatsop Spit than on Peacock Spit, which implies that more subsidence due to loading is likely for the south jetty than the north jetty. Furthermore, the mud deposits on Clatsop Spit appear to be more recent due to the channels and shoals that have actively migrated (within just a few decades or less of jetty construction) across much of the profile on which the south jetty was built. The recentness of the sediment deposits upon which the south jetty was constructed may have been a factor in the amount of settling that the south jetty has experienced. In contrast, the north jetty appears to be built on a more solid natural substrate. Over historical time most of Peacock Spit on which the north jetty was constructed remained shallow and intact. The inner-most vibracores (202, 203, and 204) reflect this environment with a substrate comprised of very well-sorted homogeneous fine to very fine sand that was difficult to penetrate with the vibracorer. At depth, this densely-packed sand unit is supported by bedrock that dips seaward from the Cape Disappointment headlands (see interpreted lowstand surface in Fig. 38). A more-detailed local seismic reflection survey and interpretation by David Evans and Associates (2003) suggests a steeper-dipping bedrock surface, where in the vicinity of core 204, is approximately 52 m below mean lower low water (MLLW), about 43 m below the seafloor. The bedrock substrate beneath Peacock Spit contrasts with an even deeper substrate under the south jetty that was filled as sea level rose and the river channel migrated northward through the area where the south jetty was built.

To illustrate the possible effect of recent channel fill (of which some portion may be mud) on the jetty stability, Figs 42 and 43 overlay historical bathymetric data with the digitized 1957 shoreline and jetty. Fig. 42 shows the 1868 bathymetry where the deepest part of the south channel passes just to the east of the "knuckle" on the south jetty. The gap in the jetty indicates the location of severe jetty deterioration (to below mean lower low water) in 1957 and is co-located with the deepest part of the south channel in 1868. Fig. 43 shows the 1868 bathymetric contours overlaid on the 1883 survey. This overlay reveals that the channel filled by as much as 39 feet, from 59 feet deep in 1868 to 20 feet deep in 1883, a span of only 15 years. The construction of the south jetty began in 1885 and was completed to the "knuckle" by 1895. Therefore the channel fill had only been in place between 17 and 27 years before being loaded by the jetty. By 1957 the portion of the jetty built on the deepest channel fill subsided. Fig. 44 shows this section of the jetty as mapped on the 1957 National Ocean Service Topographic Sheet (NOS T-Sheet) #10352. It is reasonable to assume that some of the channel fill is mud because the nearby core 207, which was located at the margins of the south channel in about 35 feet of water depth likewise contained a significant portion of mud. Mud supplied by the large river floods would have likely settled in the deepest portion of the channel before extending to the margins, and would have also had a higher preservation potential than at core 207. Regardless of mud content in the subsurface, the channel fill appears to be much more susceptible to toe scour and/or settling than the older and more stable shoal areas such as Peacock Spit. This jetty section east of the "knuckle" has been rehabilitated three times since its construction (1931-1932, 1961, and 1982). Presently this section is the most susceptible to failure and in need for emergency repairs (USACE, 2004). Fig. 45 shows a photograph of this the jetty section taken in 2004.

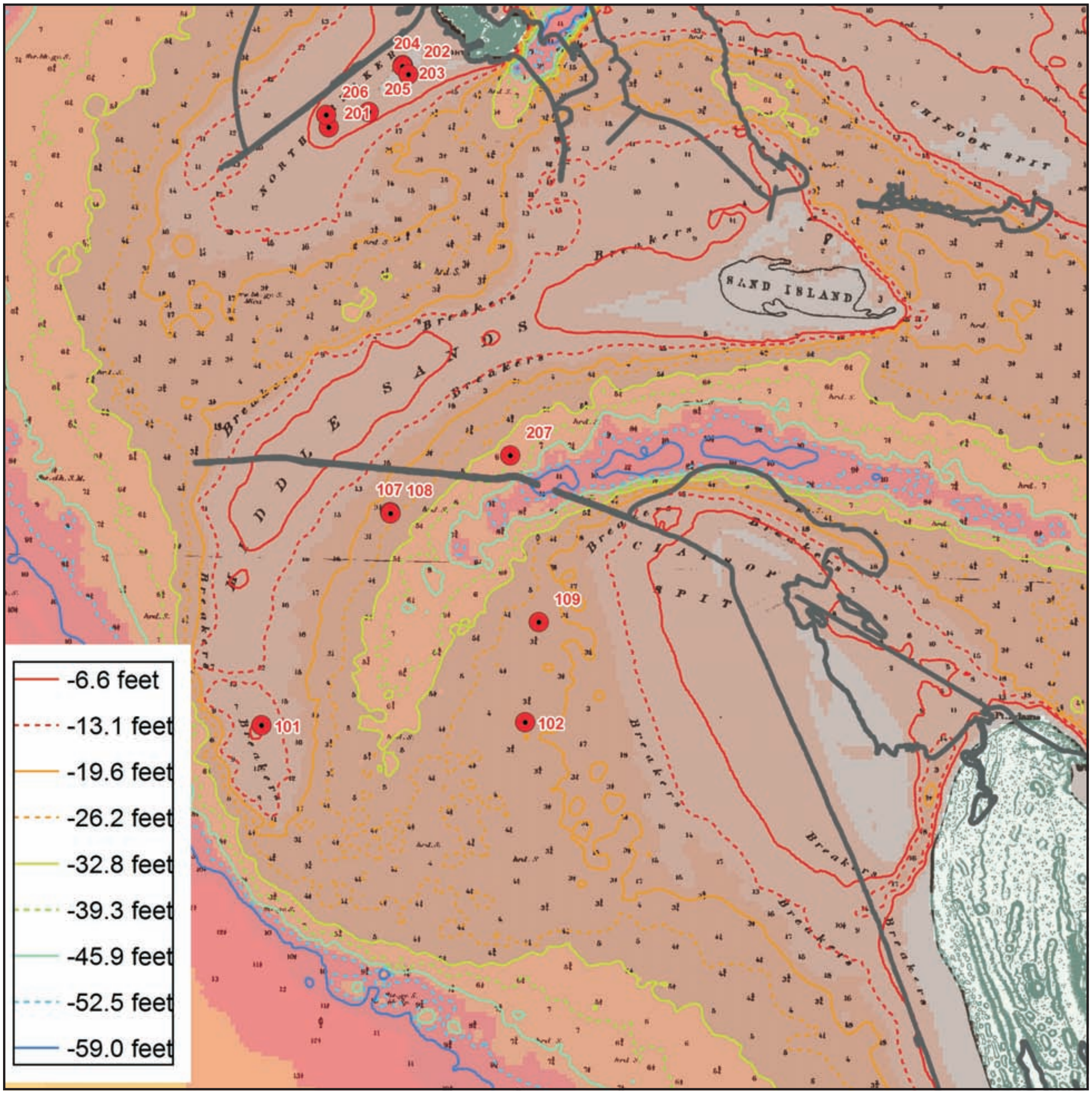

Fig. 42. Vibracore locations and 1957 jetties and shoreline plotted on 1868 bathymetry where the deepest part of the south channel passes just to the east of the "knuckle" on the south jetty. The gap in the jetty in 1957 is co-located with the deepest part of the south channel in 1868.

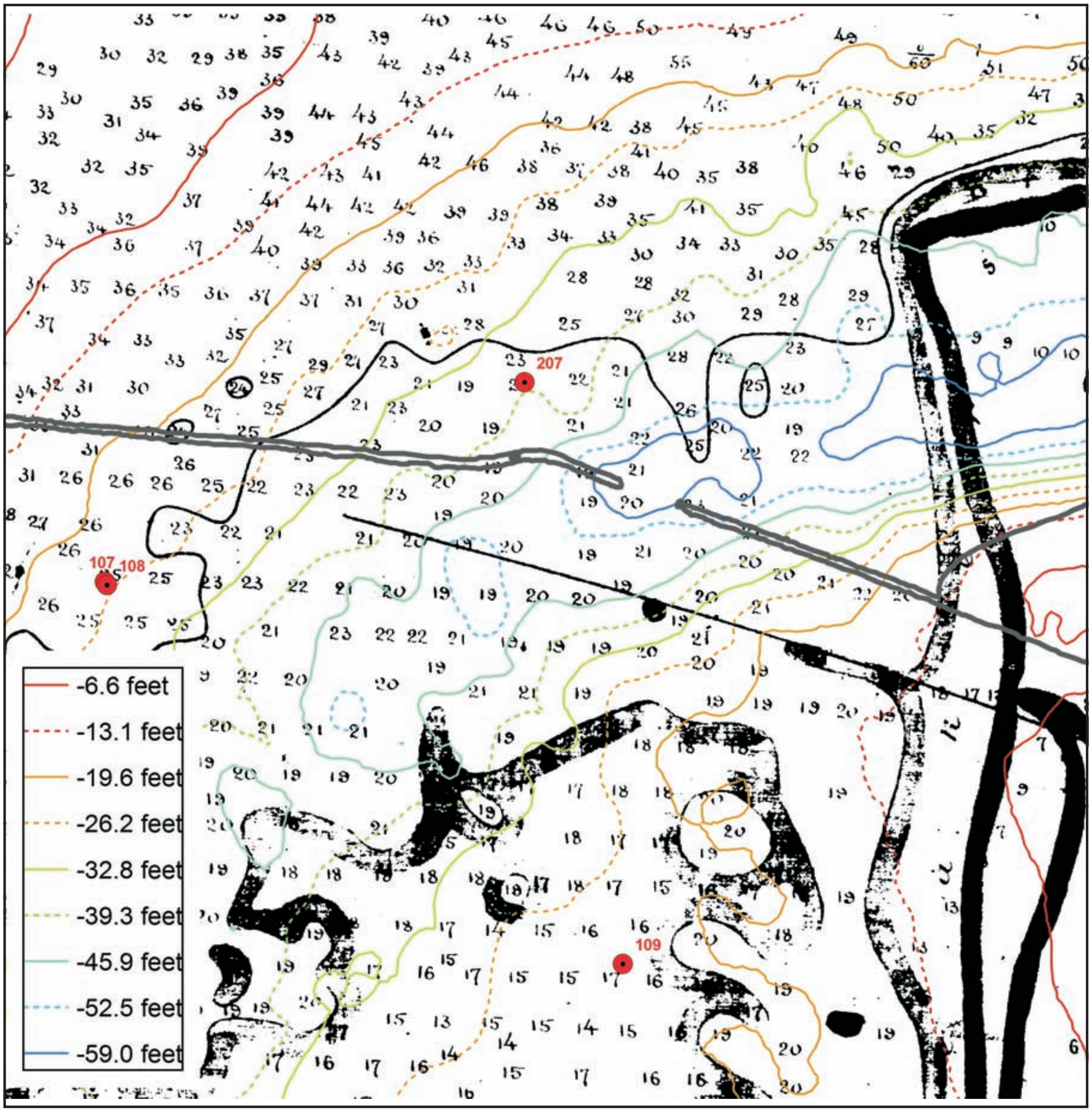

Fig. 43. 1868 bathymetric contours plotted on the 1883 survey along with the 1957 jetty. At the location of the subsequent jetty gap, the channel filled from 59 feet deep in 1868 to 20 feet deep in 1883.

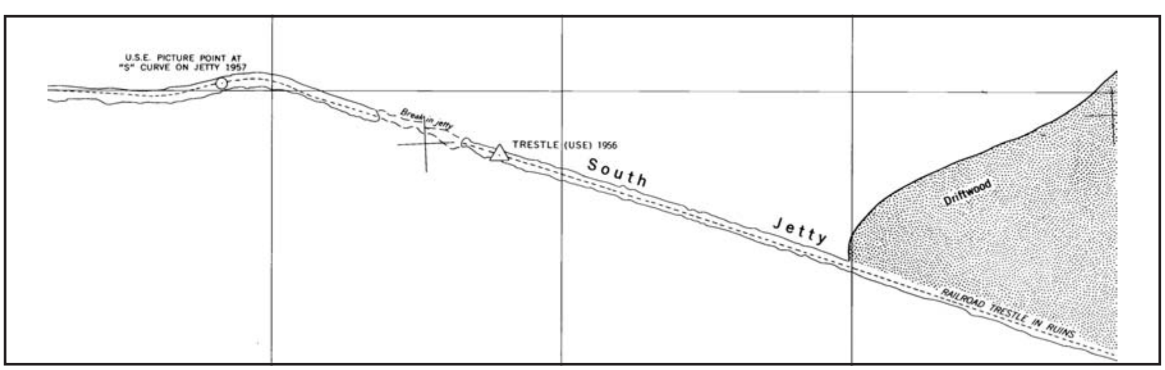

Fig. 44. Deteriorated section of the jetty east of the "knuckle" as mapped on the 1957 National Ocean Service Topographic Sheet (NOS T-Sheet) #10352.

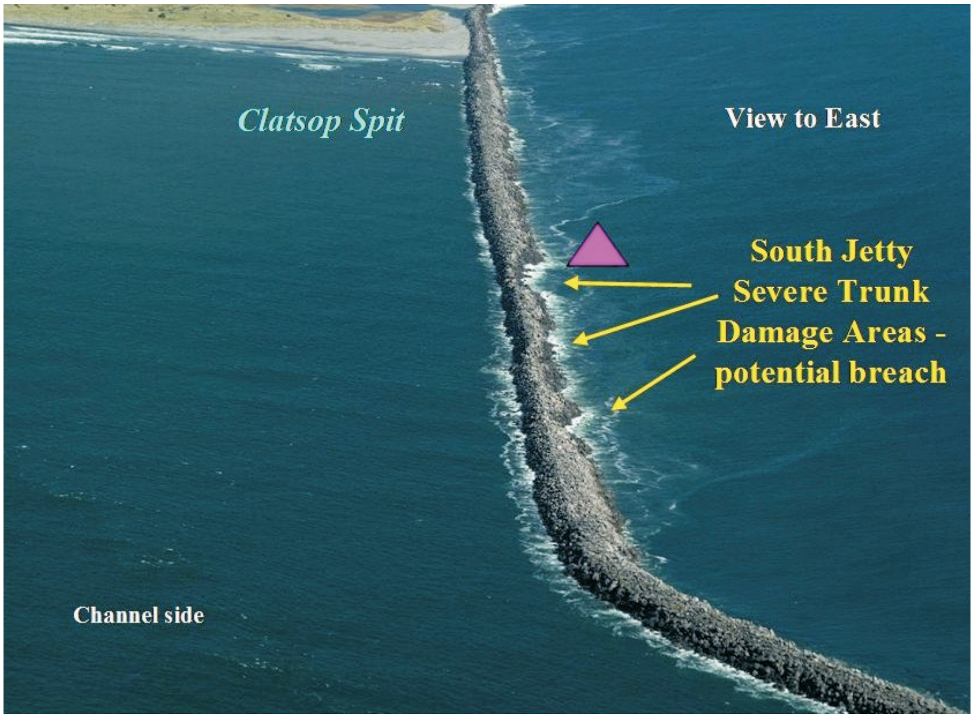

Fig. 45. Photograph of jetty section east of the "knuckle" taken September 11, 2002 (courtesy of Hans R. Moritz).

Sediment Budget

The vibracores provide evidence of erosion that support the analysis of historical bathymetric change. The implication of this result is the imperative to make the best use of sediment that is dredged from the MCR and estuary to reduce the impacts of erosion on the jetties and adjacent coasts. In order to develop a balanced and strategic approach to regional sediment management it is helpful to review the available sediment budget in context with dredging quantities.

The amount of erosion that has occurred in the vicinity of the MCR is on the same order of the amount dredged from MCR on an annual basis. The Corps of Engineers dredges approximately 3.4 million cubic meters per year (Mm^3/yr) from the MCR. Fig. 46 shows the bathymetric change data developed by Buijsman et al. (2003) for the period 1958-2000. They find the inner delta eroded at the rate of 1.15 Mm^3/yr, and Benson Beach eroded at the rate of 0.18 Mm^3/yr (above the Average High Water shoreline) during this interval. The inner delta area includes dredged material disposal site E, where an average of 1.13 Mm^3/yr was placed during this time. The Clatsop inner shelf eroded by 0.74 Mm^3/yr over this period. Therefore the total erosion rate of the inner delta, Benson Beach, and the Clatsop inner shelf is 1.15 + 0.18 + 1.13 + 0.74 = 3.2 Mm^3/yr. This does not consider the inlet between the jetties, which is known to have deepened (e.g., Table 5). In addition, the Clatsop shelf father offshore and to the south eroded by 0.63 Mm^3/yr during the same period.

In order to effectively counter the erosion of the shoals that provide the foundation to the jetties, and as well avoid further exposure to the jetties through shoreline retreat, it is essential to strategically place all sediment dredged from MCR and augment that quantity with sediment dredged from the navigation channel in the lower estuary. Without direct sediment nourishment to Clatsop and Peacock spits through the placement of dredged material, the jetties will continue to be compromised due to shoreline retreat and progressive deepening of both the inlet and adjacent shorefaces. As the foundation of the jetties become further undermined, the jetties weaken and maintenance requirements and costs increase. Jetty deterioration and maintenance costs can be effectively reduced though active feeding of the jetty foundation and the adjacent shoreface with dredged material.

More sand must be supplied to those areas subject to erosion than the measured volume change over a given period because sediment is transported outside the area of significant erosion. It is likely that the quantity required to avoid further erosion of the foundation to the jetties and shoals is on the order of 5 Mm^3/yr. In an analysis of shoreline change and dredged material placement scenarios, Kaminsky et al. (2003) estimated that approximately 3.25 Mm^3/yr would be required to maintain Peacock Spit as a sand source for the maintenance of Benson Beach adjacent to the north jetty. On the inlet side of the north jetty, approximately 0.38 Mm^3/yr is placed at the North Jetty Site (Fig. 46), yet outside this disposal site along the jetty the inlet continues to deepen (Table 5). On the Clatsop Spit and shelf there is net erosion of 0.74 + 0.63 = 1.37 Mm^3/yr. Therefore approximately 3.25 + 0.38 + 1.37 = 5.0 Mm^3/yr would be required to counter the ongoing erosion of the shorefaces, shoals, and beaches that support and protect the jetties. This quantity does not include the erosion occurring along the inlet side of the south jetty. A supply of 5 Mm^3/yr to maintain the jetty foundations and shoals implies the need for approximately 1.6 Mm^3/yr of dredged sand from the estuary (upstream of River Mile 3).

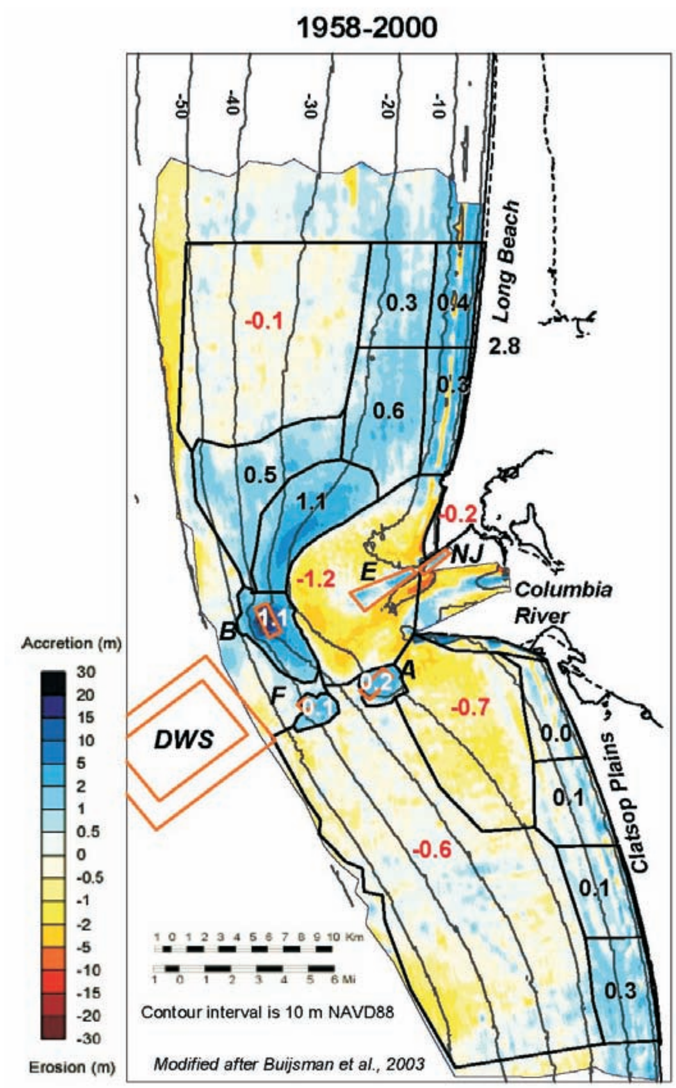

Fig. 46. Bathymetric change during 1958 to 2000 at the MCR. Numbers shown represent volumetric change rates within compartment boundaries in million cubic meters per year.

Conclusions

In summary, the vibracores provide a wealth of information to consider for the management of dredged material resources and jetty maintenance. A list of some of the major findings is provided below:

- The Clatsop inner shelf is sediment starved and undergoing broad, chronic erosion.
- Relict channel-margin deposits are present in most of the Clatsop shelf cores and are being exposed by surface erosion.
- Semi-consolidated mud deposits are more erosion resistant in the short-term, but they may limit shoreface sand supply and crab habitat.
- Radiocarbon ages from the Clatsop shelf cores as well as other features (e.g., relict mud deposits, coarse grain size, and rip-up clasts) are consistent with historical patterns of seafloor erosion.
- MCR cores indicate multiple depositional and erosional events and fluctuations in sedimentation on all time scales.
- MCR and Clatsop shelf cores have slightly coarser grain size than Long Beach shelf cores.
- Intervals of interbedded mud in the substrate near the north jetty are relatively thin and old.
- Massive and chronic shoreface erosion contributes to deterioration of both jetties.
- The substrate characteristics (e.g., thickness of mud units) are important to the jetty stability, and may govern the amount of subsidence that occurs due to loading.
- Annual quantities of dredged sediment from MCR are insufficient to counter ongoing erosion.
- All dredged sediment from MCR and the estuary must be used judiciously and strategically in order to reduce the impacts of erosion to the MCR jetties and adjacent coasts.

Recommendations

1. The placement of dredged material north of the north jetty and south of the south jetty would be prudent and helpful to maintaining the jetty foundation. An extensive layer of dredged sand (rather than very dense rocks in a restricted area to reinforce the jetty), could be more effective in reducing the erosion impacts and result in less localized loading of substrate under the jetties.
2. Historical shoreface and beach erosion patterns and volumetric losses should be taken into account in developing and implementing the alongshore and cross-shore placement and distribution of dredged material.

3. Further study: additional detailed analysis of historical shoreface change in the vicinity of the jetties is recommended to provide quantitative results on spatial and temporal changes of the shoreface and an estimation of equilibrium shoreface configurations. This analysis is needed to assess the need for and feasibility of maintaining the shoals and beaches that support the jetties.
4. No dredged material from the MCR or lower Columbia River should be placed in the Deep Water Site because the sediment budget requires more than is dredged for annual maintenance to counter the ongoing erosion that directly contributes to the deterioration of the jetties, and the net loss of ebb-tidal shoals (Peacock and Clatsop Spits), jetty foundation and adjacent beaches. The ebb-tidal shoals, jetties and beaches are key components to maintaining a safe navigation channel through the MCR. The present rapid erosion of Benson Beach, the vulnerability of the south jetty to a breach, and the high-cost of interim jetty repairs illustrates the critical and urgent need to rectify the present sediment deficit.
5. Dredged material with coarser-than-native mean grain size should be especially considered for placement immediately south of the south jetty and in areas where a shallower-than equilibrium shoreface profile is desired to be maintained, such as for the purpose of dissipating incident wave energy seaward of the jetties.
6. Consideration of sediment grain size relative to water depth and intended dispersal pathways is needed. Finer sediment is more appropriate for placement in dispersal areas like the Shallow Water Site and Benson Beach, where the objective is to supply sediment to the littoral drift to the north. Coarser sediment is more appropriate for Clatsop shoreface where the objective is to counter shoreface erosion and avoid sediment migration into the entrance channel.
7. Further study: Additional mapping and analysis of grain size variability within the entrance and lower Columbia River channels is warranted to better match dredged material source to the appropriate disposal location. The spatial variability in grain size can be assessed based on coring and surface sediment sampling within the dredged navigation channels.
8. Further study: modeling of sediment mobility based on waves, water depth and grain size is needed to better achieve Regional Sediment Management objectives of maintaining ebb-tidal shoals, avoiding excessive mounding and wave amplification, and supplying sediment to the littoral drift.

Acknowledgements

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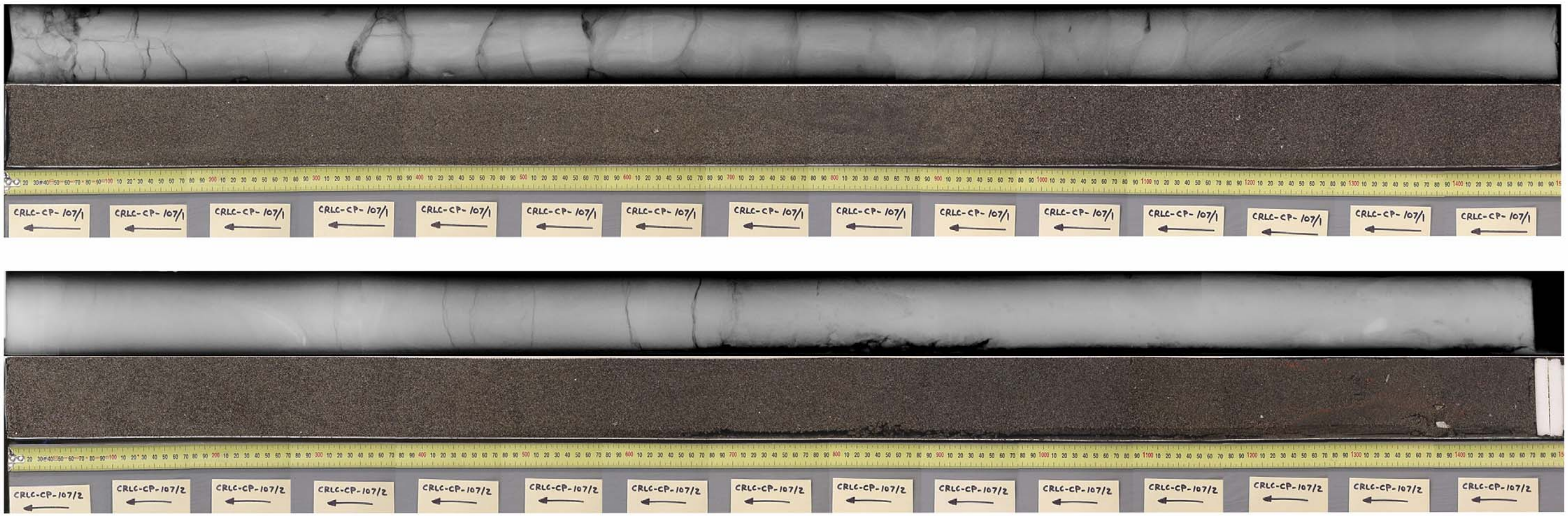
Appendix A: Core Photo and X-ray Mosaics



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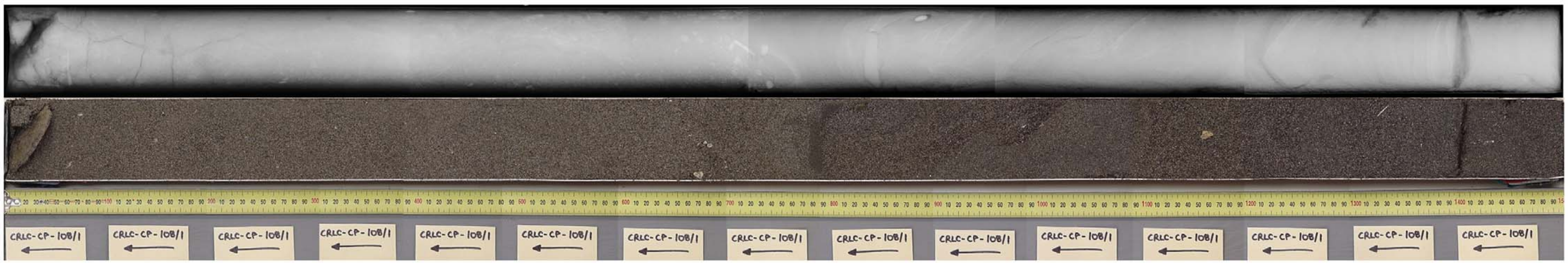

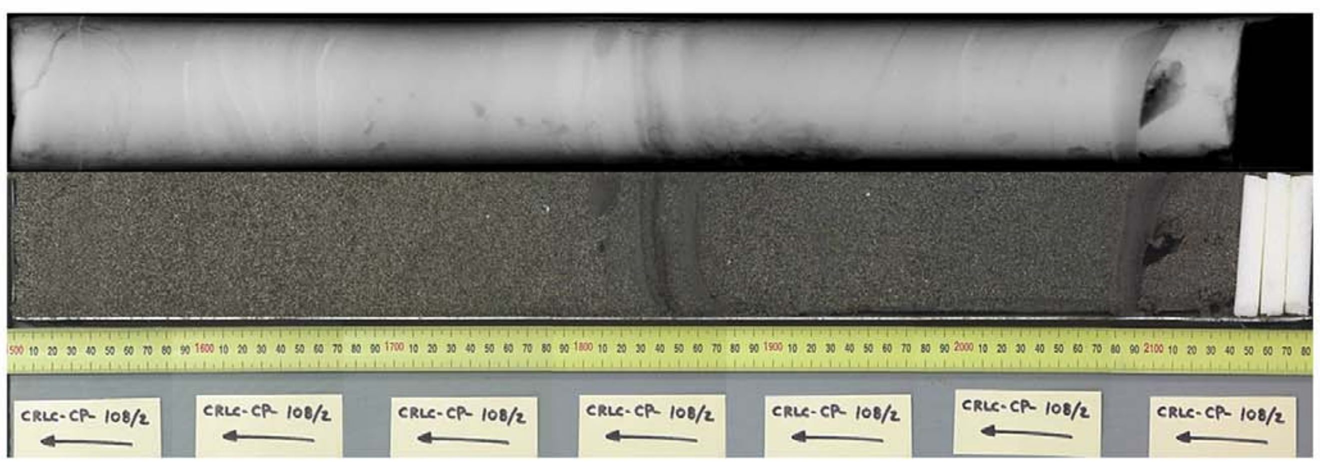

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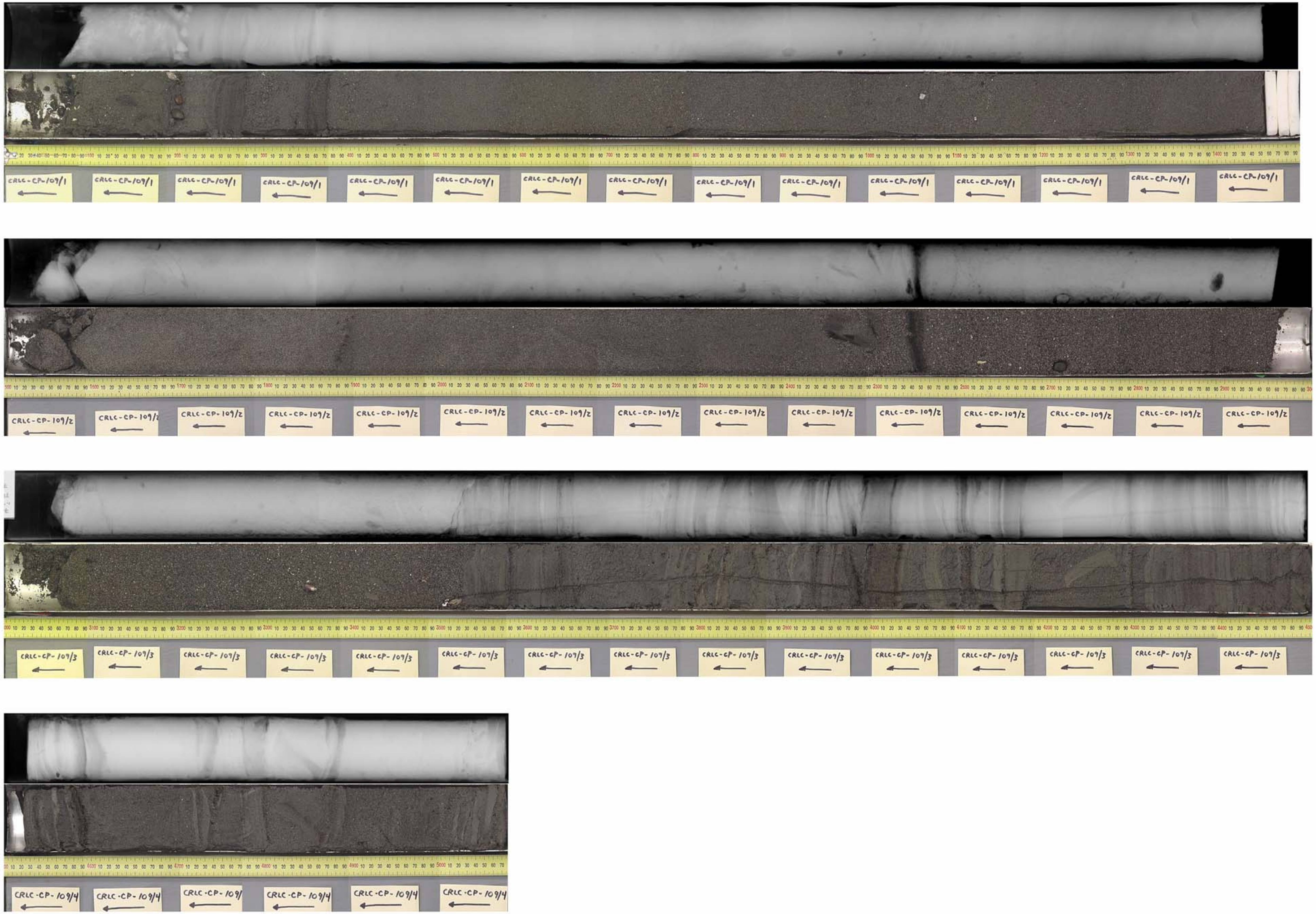

CP109


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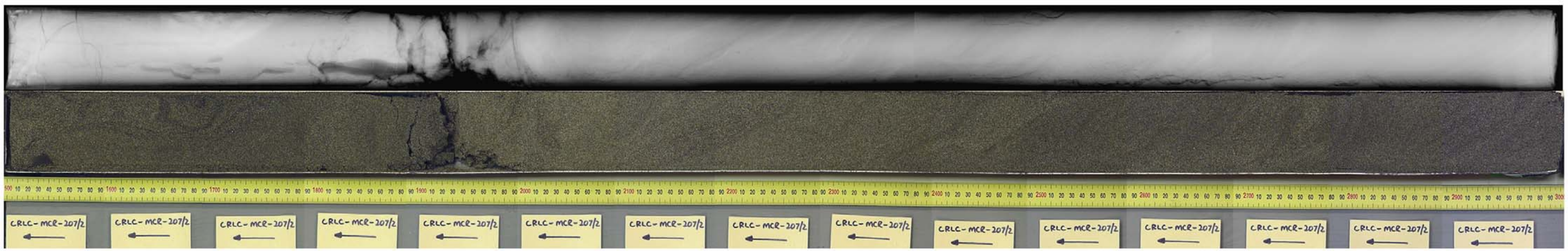
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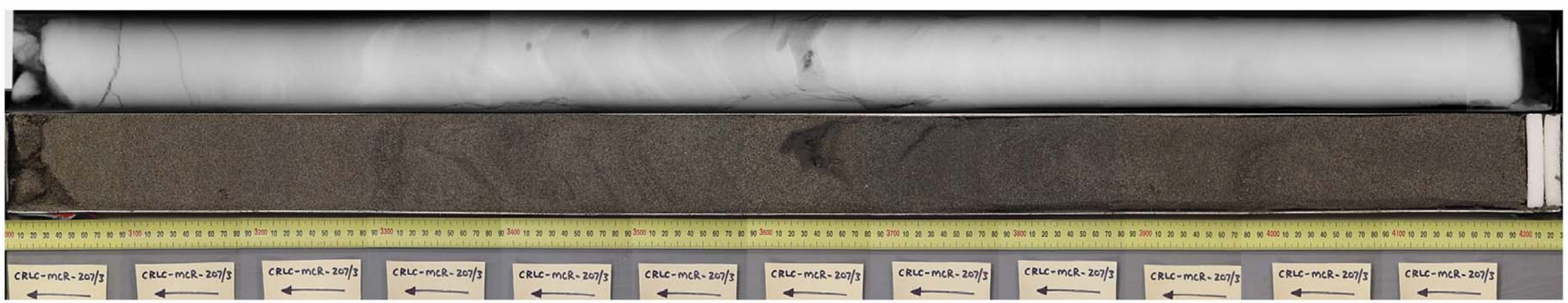
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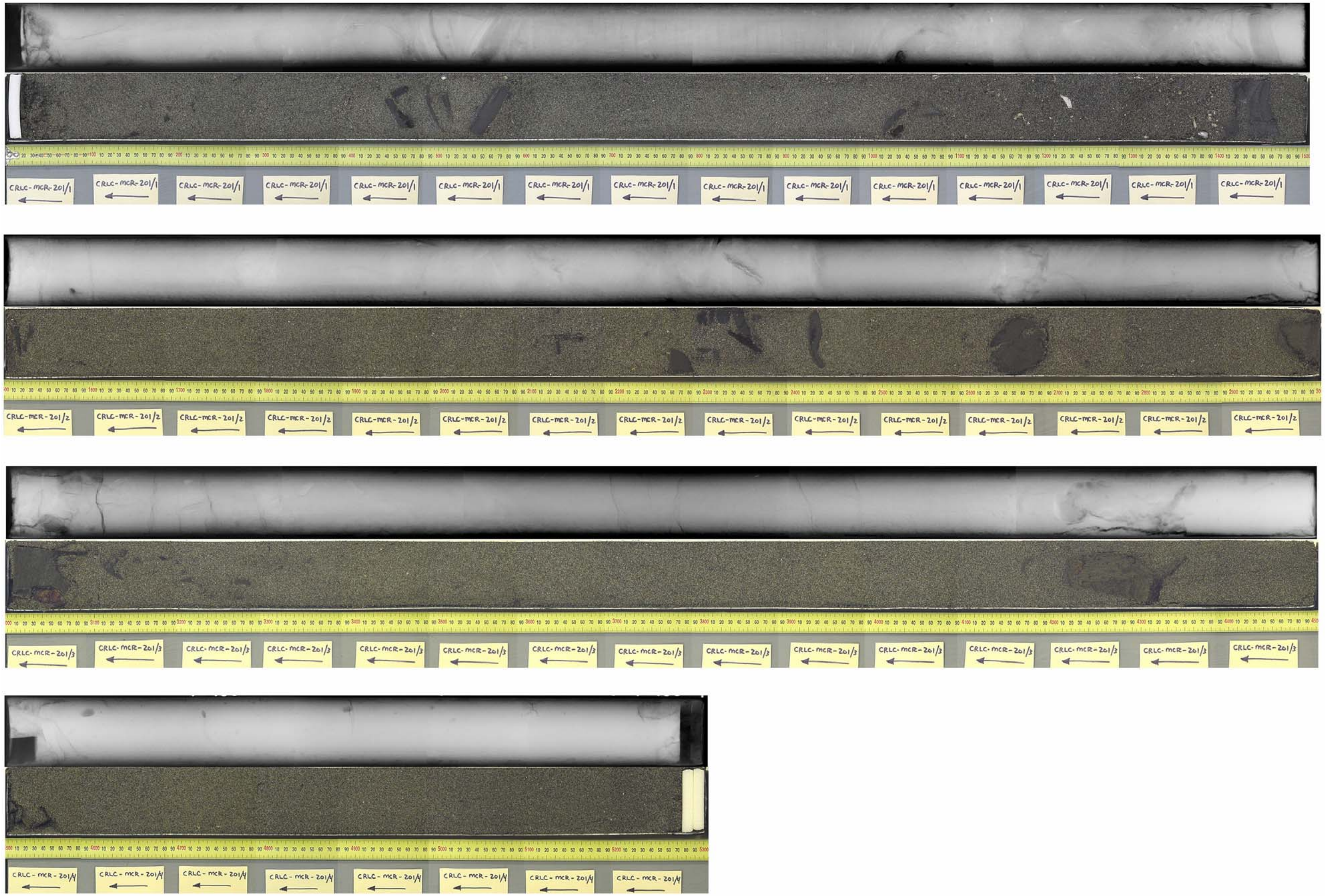
MCR207



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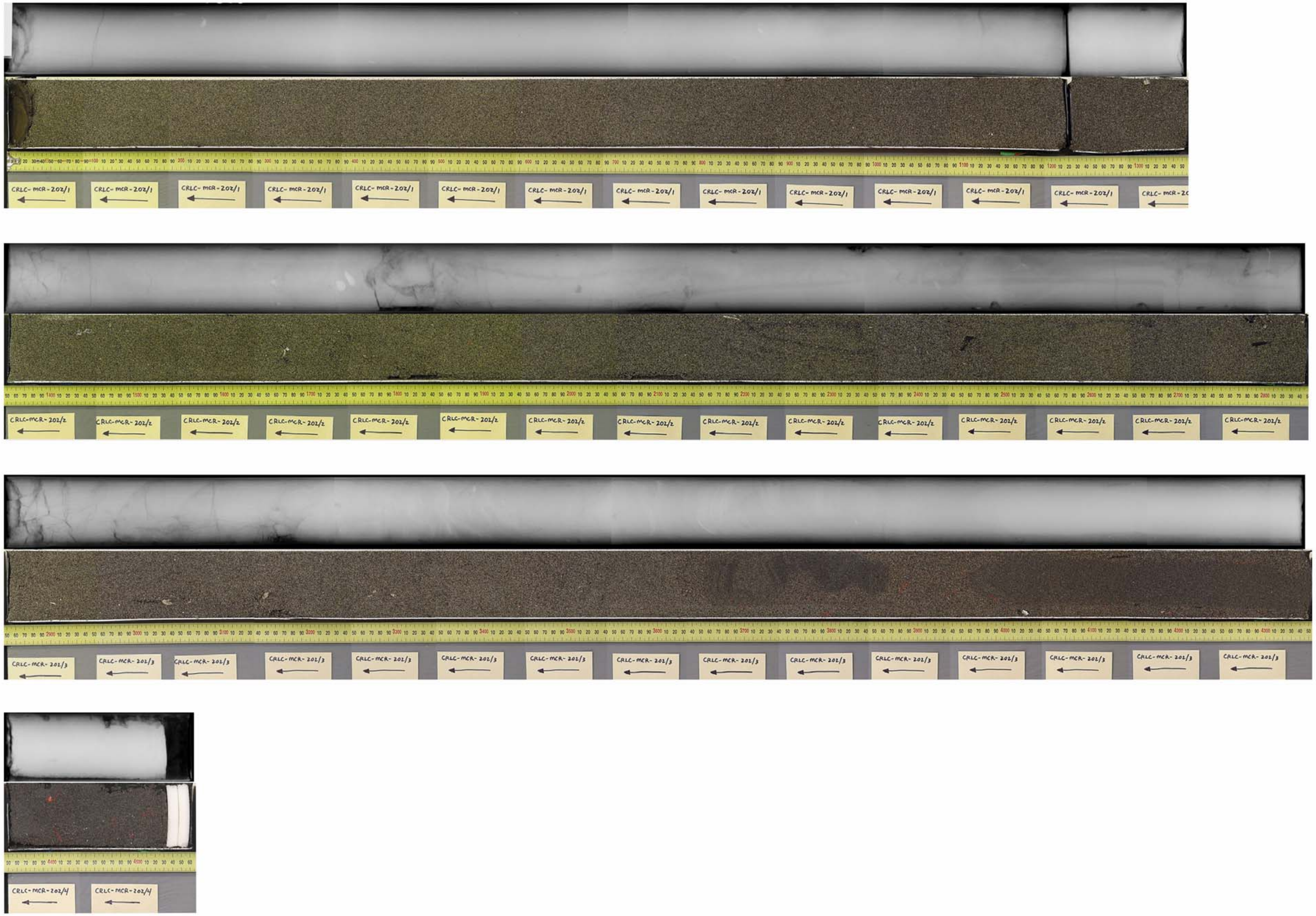

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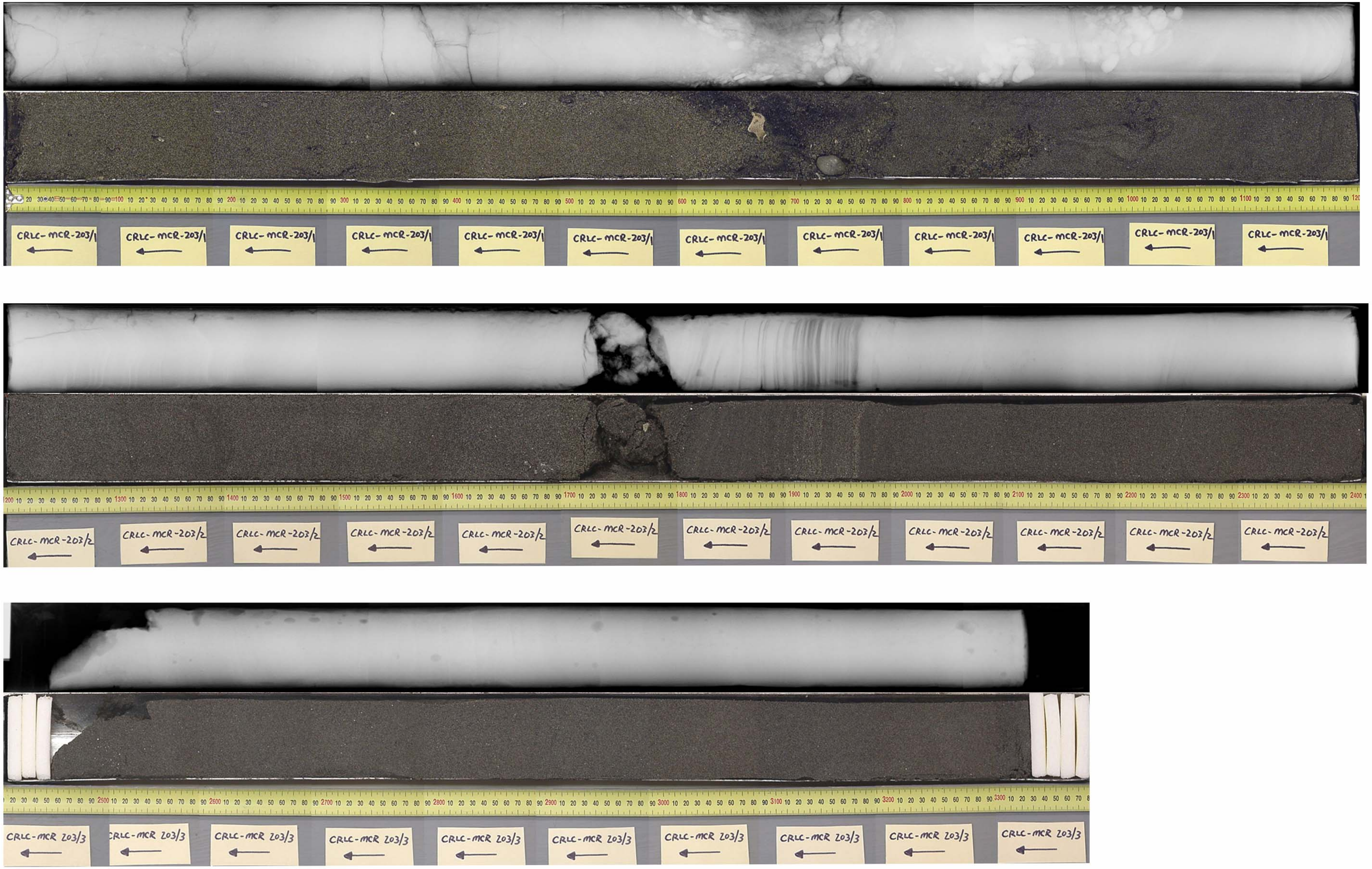

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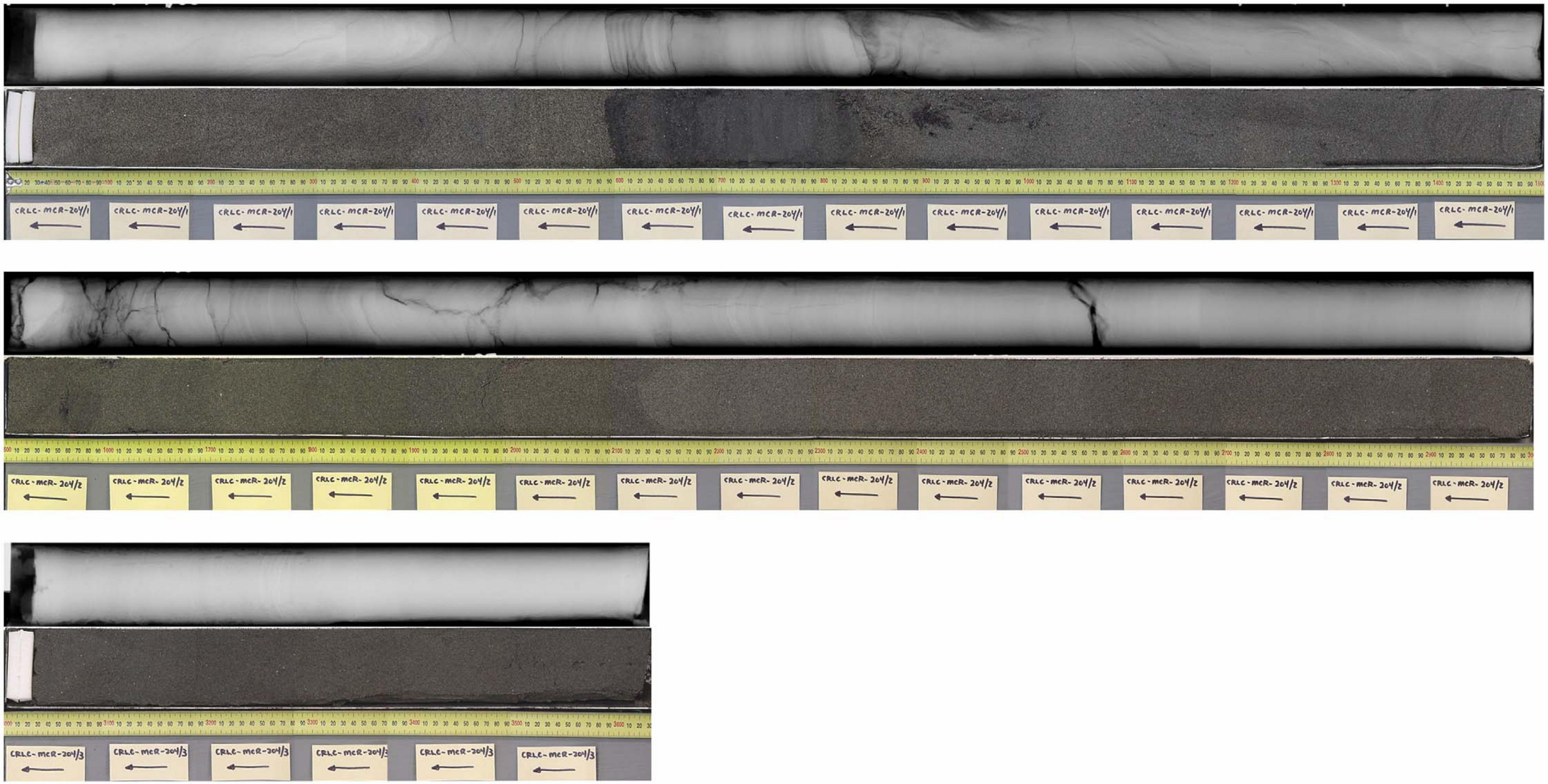
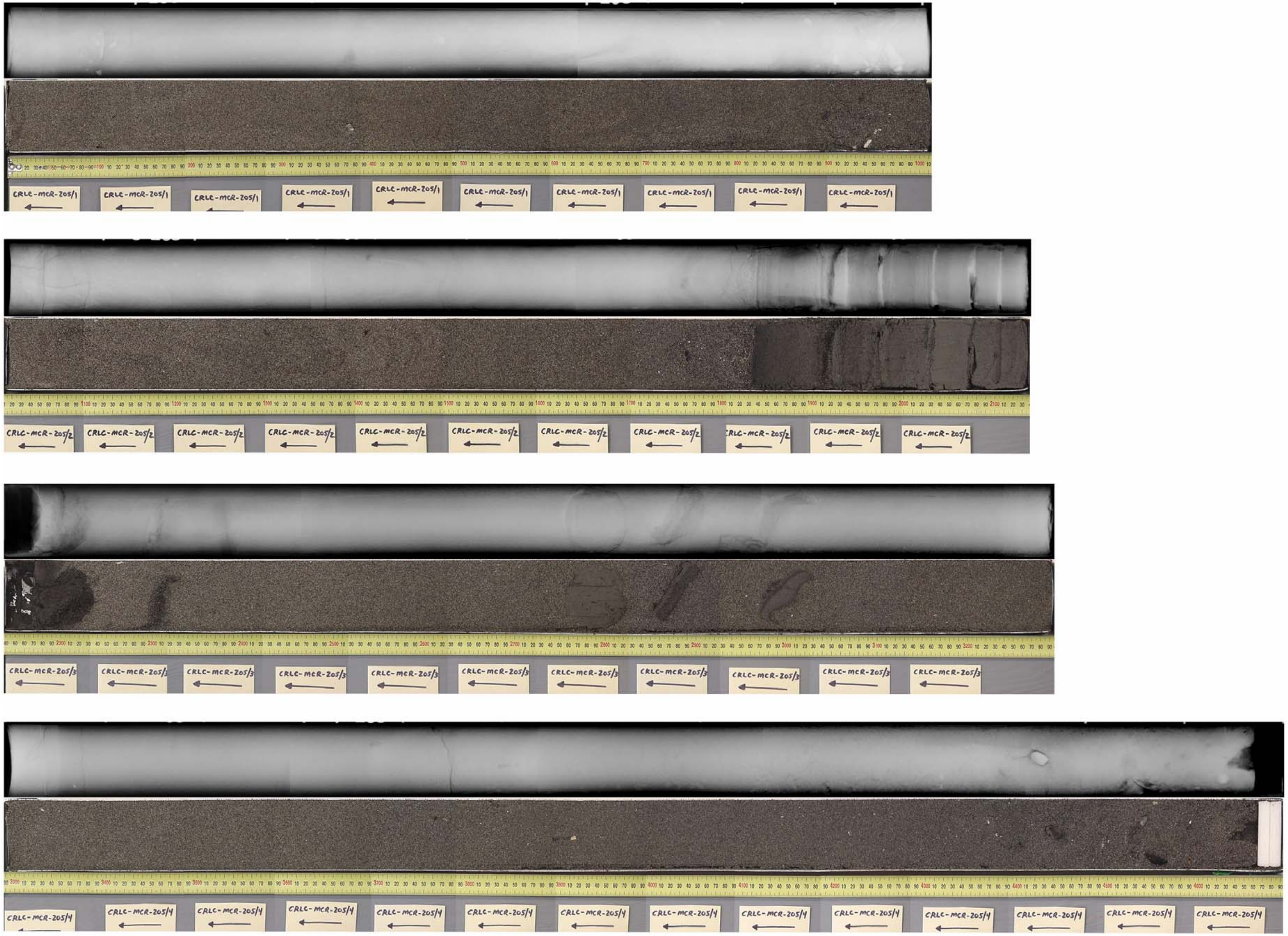
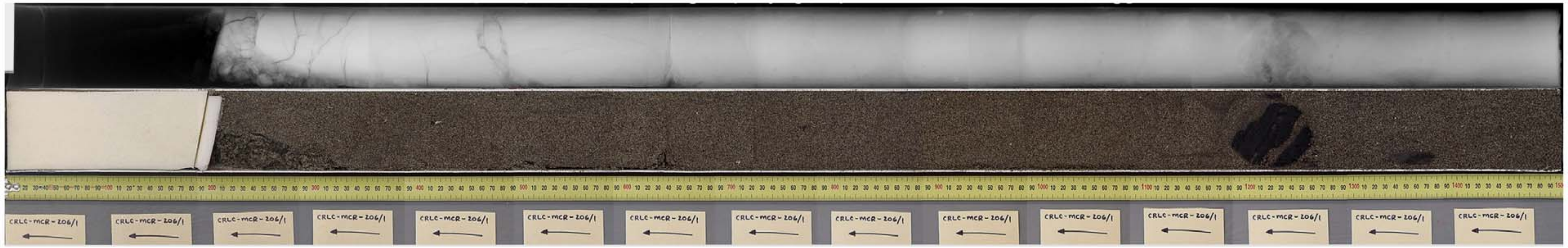
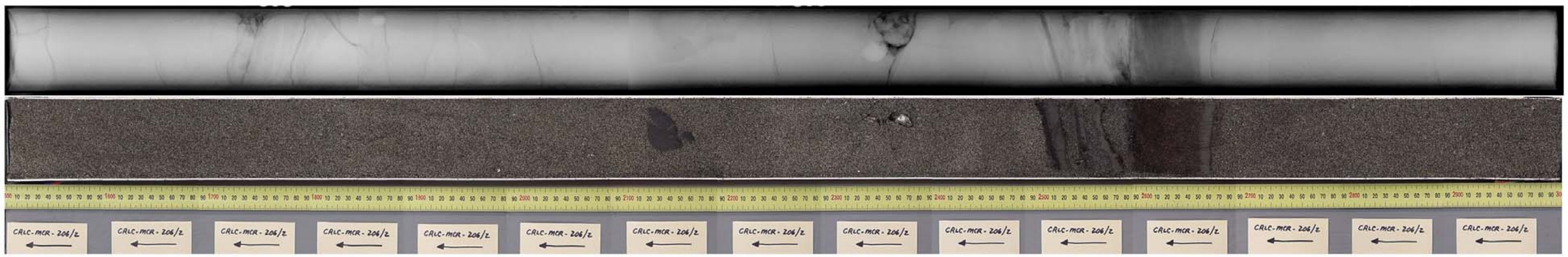


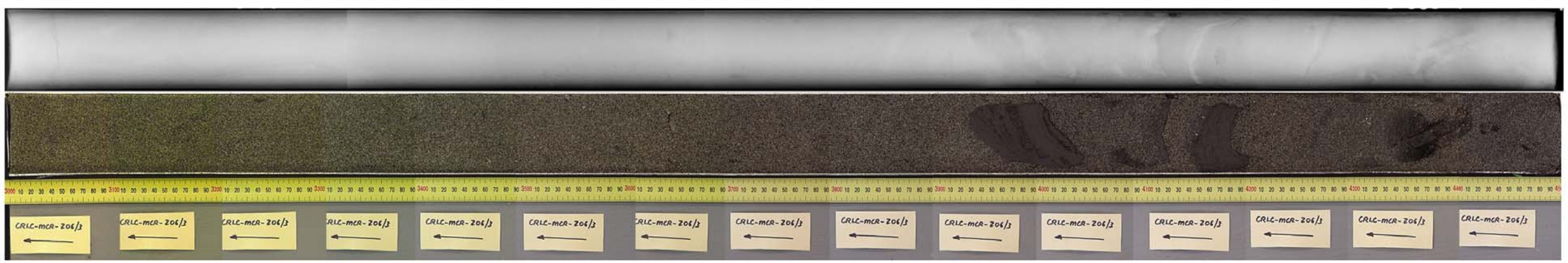
MCR204

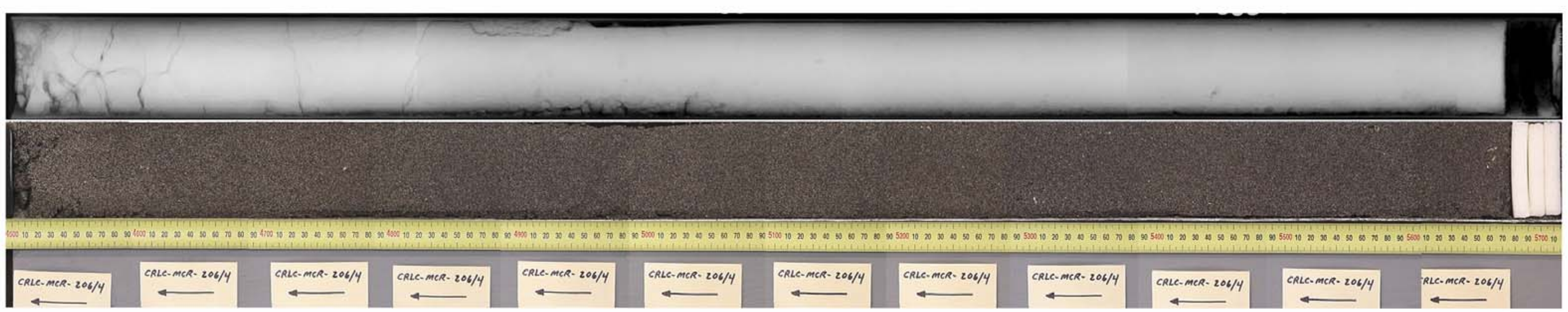


MCR205









MCR206