DEPOSITION AND PRESERVATION OF ESTUARINE SEDIMENT, TURNAGAIN ARM, COOK INLET, ALASKA

by

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Abstract

Turnagain Arm is the hypertidal (commonly exceeding 9 m) west-east trending extension of Cook Inlet in south-central Alaska. The inlet formed from a drowned glacial valley that was subsequently filled with tidal deposits of silt and fine sand. The tidal system is semidiurnal with a prominent diurnal inequality. There are also variations due to spring and neap tides. Turnagain Arm is home to a tidal bore generated during spring tides that can reach heights of up to 2 m and travel at speeds of up to 5 m/s. Current reversals can be dramatic with ebb tidal velocities of 6 m/s changing to flood velocities of 10 m/s over a period of a few minutes. During the initial flood tide, highly turbid water can rise as fast as 10 cm/min. This combination of elements results in a highly dynamic depositional setting. Measurements taken in the inner estuary during several neap-spring cycles in the summers of 2007-08 documented deposition upon mud bars of as much as 8.9 cm per tidal event. Conversely, erosion of up to 13.5 cm per tidal event has been measured. The highest rates of deposition and erosion occurred during the spring tides while much lower rates occur during the neap tides. Some portions of the inner estuary are only submerged during the extreme high tides. The magnitude of the high tide needed to cover each site increases with increasing distance into the upper estuary. Even if submerged, deposition does not always occur. Such a high percentage of non-depositional events has real implications when interpreting tidal cyclicity of the rhythmites found at these sites.

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Thank you all.

Dedication

For my wife, Angela.

CHAPTER 1 - Introduction

Turnagain Arm of Cook Inlet, Alaska (Figure 1-1), has the sixth highest tides of the world, and the third highest in North America (Archer and Hubbard, 2003). Turnagain Arm also offers a very compact system where glacial to open marine processes can be observed in a very short distance. As such, it provides an ideal location to study the sedimentology of a hypertidal estuary. A clear understanding of the sedimentology of this system is valuable because it is a potential modern analog for ancient incised valley fills. Turnagain Arm is presently in the process of filling its valley. Previous studies in Turnagain Arm noted an extremely dynamic system with high rates of tidally driven deposition and erosion. One purpose of this study is to measure these rates at several locations along the arm. Tidal rhythmites have also been identified in Turnagain Arm. Ancient rhythmites have been used in reconstructions of lunar parameters. A second purpose of this study was to identify sites where rhythmites form. For all sites a minimum height of the high tide that was needed to completely flood the site was determined. This value aids in determining the maximum number of tidal events that could potentially be preserved in rhythmites. Five localities (Figure 1-2) were chosen to study during three two-week long field visits during the summers of 2007 and 2008.

Study Area

Cook Inlet is located in south-central Alaska. At the location of present day Anchorage, the inlet splits into two estuaries. The south-north trending estuary is Kink Arm and the west-east trending estuary is Turnagain Arm (Figure 1-1).

Turnagain Arm stretches 73 km to the east-south-east from Anchorage and is 20 km wide at its mouth. At Chickaloon Bay, Turnagain Arm is its widest at 27 km. This study focuses on the 20 km long portion east of Bird Point, a bedrock point that protrudes into Turnagain Arm (Figure 1-2). At Bird Point the arm is 3.5 km wide.

From Anchorage the Seward Highway and the Alaska railroad follow the length of the north shore of the arm. At the easterly end of Turnagain Arm, the Seward highway turns south to Seward while the railroad continues east to the port city of Homer. These roads are the main arteries for both traffic and freight in this part of Alaska and provide easy access to study areas along the northern shore of the inlet.

Figure 1-1: Location map of Turnagain Arm and the surrounding area. The study area is outlined by the white box and is shown in more detail in Figure 1-2.

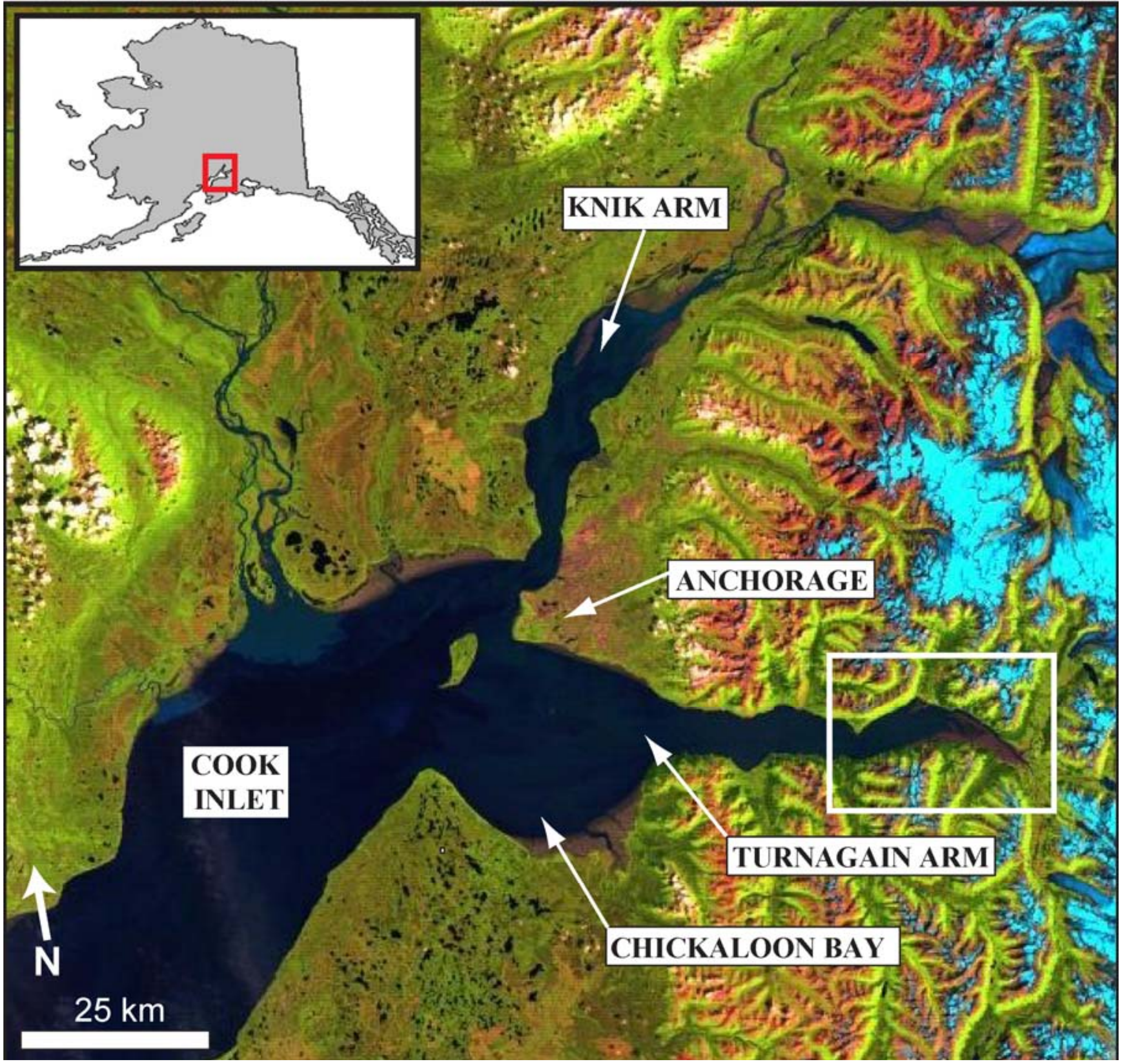
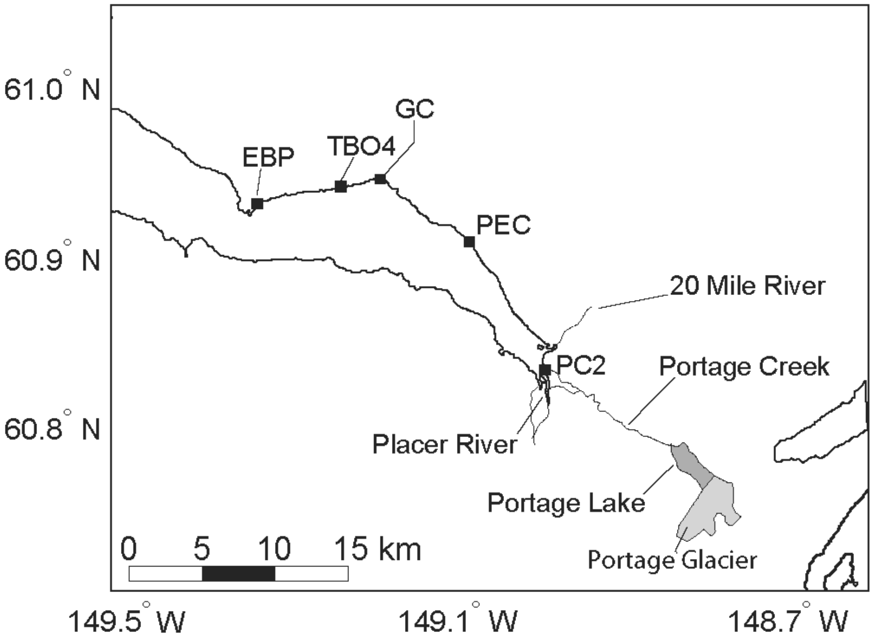


Figure 1-2: Location of major study sites within Turnagain Arm. Localities are: Bird Point (EBP), Tidal Bore Overlook #4 (TBO4), Glacier Creek (GC), Peterson Creek (PEC), and Portage Creek #2 (PC2).



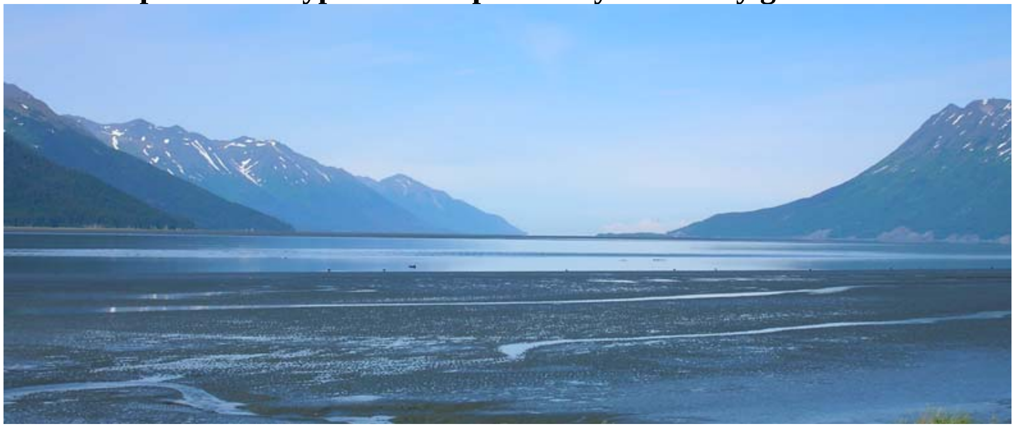
CHAPTER 2 - Background

Geography and Geology

The extremely deformed Cretaceous meta-sedimentary rocks of the Chugach range form the northern and southern boundaries of Turnagain Arm. These mountains rise steeply from sea level to 1200 m within 2 km of the tidal channels. Veins of quartz are common within the flysch and mélange of the Chugach Mountains (Burns et. al, 1991). Within close proximity of the study area several hard rock and placer gold mining operations are still functioning.

Turnagain Arm and the associated valleys were carved by glaciers that began their final retreat ca. 14,000 BP (Schroll et. al, 1972). Since that time approximately 300 meters of sediment has been deposited within the valley (Bartsch-Winkler et al., 1983).

Figure 2-1: View from Peterson Creek toward Bird Point.
Cross-profile is a typical U-shaped valley carved by glacial erosion.



Several small meandering and braided rivers empty into Turnagain Arm within the study area. Glacier Creek enters near the town of Girdwood, while Peterson Creek, 20 Mile River, Portage Creek, and Placer River all enter at the east end of the arm. These streams all reach their peak discharge during the mid to late summer when snow and glacial melt and rainfall are at their maximum. One of the major sources of melt water is

Portage Lake (Figure 2-2). Portage Lake is a glacial lake formed behind a moraine left by the retreat of Portage Glacier. During the summer months large ice bergs are common in the lake.

Figure 2-2 Portage Lake in May, 2007.
Portage Lake is located 9 km upstream from the PC2 study site and is a major source of melt water to Turnagain Arm.

On March 27, 1964, one of the strongest earthquakes in recorded history shook Anchorage and the surrounding area. Known as the “Good Friday” or “Great Alaskan Earthquake”, this earthquake had a moment magnitude of 9.2 (Kanamori, 1978). During and shortly after the earthquake, large portions of Turnagain Arm subsided. This combined with the liquefaction of the tidal sediment resulted in the flooding of low-lying areas during periods of high tides. To escape this frequent flooding, the town of Girdwood was moved to higher ground and the small village of Portage was abandoned (Figure 2-3). Within the next fifteen years, tidal silt and sand had buried the pre-earthquake landscape with as much as 1.5 m of sediment (Atwater et al., 2001).

Figure 2-3: The flooded village of Portage, shortly after the earthquake. The PC2 study site is located only a few hundred meters from the site in this photograph. From the USGS Photographic Library (libraryphoto.cr.usgs.gov)

Climate

The study area is located in one of the northern most rain forests in the world. The amount of annual precipitation increases dramatically eastward along the length of Turnagain Arm. Anchorage receives 41cm/yr of precipitation, while Girdwood receives 164 cm/yr, and 470 cm/yr falls at Portage Glacier. The greatest amount of rainfall occurs during August and September while the greatest amount of snow falls during December and January.

High winds are not uncommon along Turnagain Arm as the surrounding mountains work to confine air currents. Waves created by strong winds are a major cause of erosion along the tidal channels.

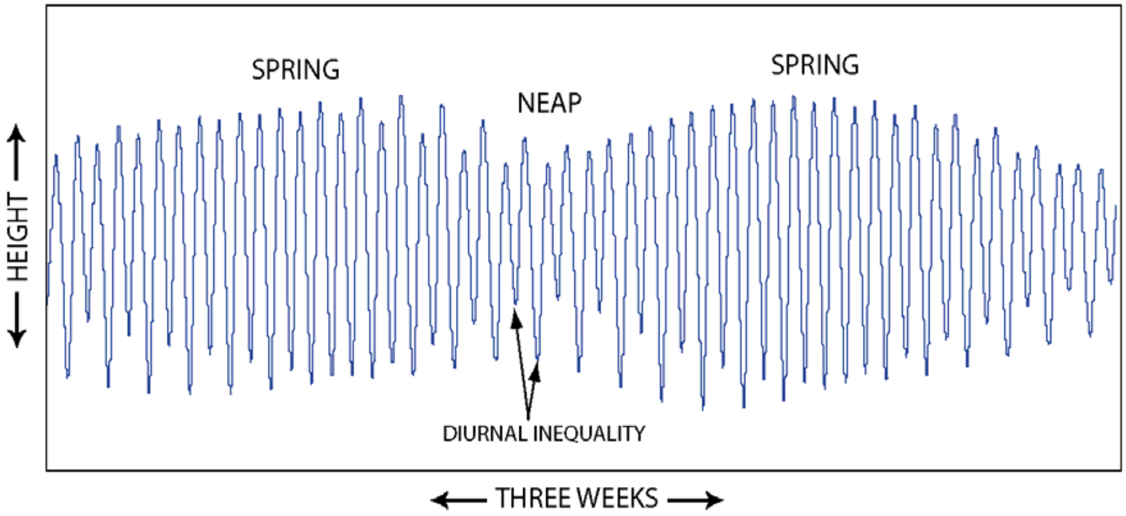
Typical weather during the three two-week field visits consisted of ten or more days of overcast, windy, or rainy conditions. Usually there were only one or two completely clear days per week.

Because of the northerly latitude of the study area, the amount of day light varies greatly with the season. During the July 2008 field season, an average of 20 hours of useable light per day was observed. This made it possible for two high or low tides to be observed in a single day.

Tidal Setting

Turnagain Arm is considered hypertidal with a range commonly exceeding 9 m and is home to the sixth highest tides in the world (Archer and Hubbard, 2003). In North America, Turnagain Arm is only exceeded by the Bay of Fundy and Ungava Bay in tidal range. This high tidal range is partially due to the funnel shape of the arm. The tidal system is semidiurnal (two high and two low tides per day) with a prominent diurnal inequality (one high tide is higher than the other) and shows variations due to spring and neap tides (Figure 2-4). Spring tides occur at new and full moons when the earth, moon, and sun are all aligned. During these periods, the gravitational pull of the sun adds to that of the moon, creating higher tides. When the moon is at a quarter phase, the sun and moon form a right angle to the earth, neap tides occur. During neap tides, the sun's gravitational force subtracts from that of the moon.

Figure 2-4: Generalized tidal curve for Turnagain Arm.
Note spring-neap-spring tidal cycle and the diurnal inequality.



During spring tides a tidal bore of up to 2 m in height traveling at speeds of up to 5 m/s is commonly generated **(**Figure 2-5**)**. This bore provides an extremely high energy source for the erosion and transportation of sediment. Immediately following the bore is a surge of extremely turbid water.

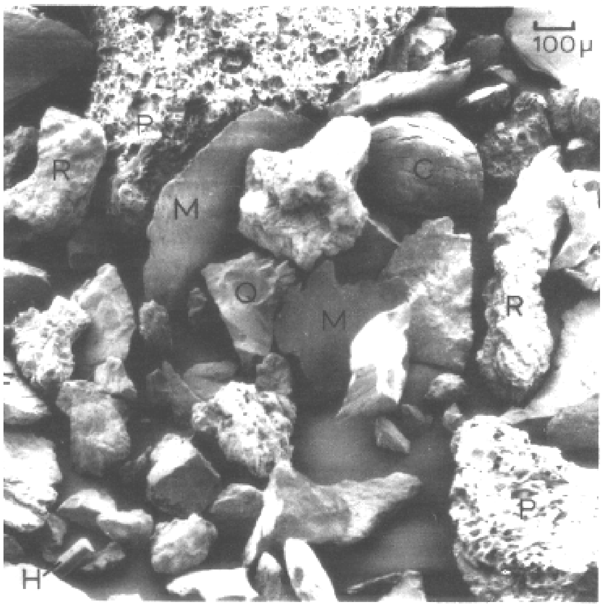
Figure 2-5: Tidal bore advancing up Turnagain Arm. Estimated height of 1.5 m. Note surfers for scale.

Sediment

The bulk of the sediment that makes up the tidal flats and bars is fine sand and silt (Figure 2-6). This fine grained sediment is mainly composed of fragments of pumice, bedrock, quartz, mica, silt, and plant debris. Any clay sized particles present tend to stay in suspension due to the high-energy nature of the tidal setting (Bartsch-Winkler and Ovenshine, 1984). The water in Turnagain Arm is extremely turbid because of this. In areas where streams join the estuary, deposits of poorly sorted, well rounded gravels are common. These gravels are composed of weathered, relatively soft meta-sedimentary bedrock and some extremely resistant quartz pebbles.

.

Figure 2-6: Microphotograph of fine grained Turnagain Arm tidal sediment. Individual grains are pumice (P), quartz (Q), feldspar (F), mica (M), hornblende (H), rock fragments (R), and coal (C).
From Bartsch-Winkler and Ovenshine, 1984, Fig. 7.



While some of the sediment found in Turnagain Arm is undoubtedly locally derived, present day stream flow is generally clear and free of glacial flour. Bartsch-Winker and others (1983) have found evidence that most of the sediment is actually derived from the Susitna River which empties into Knik Arm. This sediment is then transported out of Knik Arm and reworked by the tides into Turnagain Arm

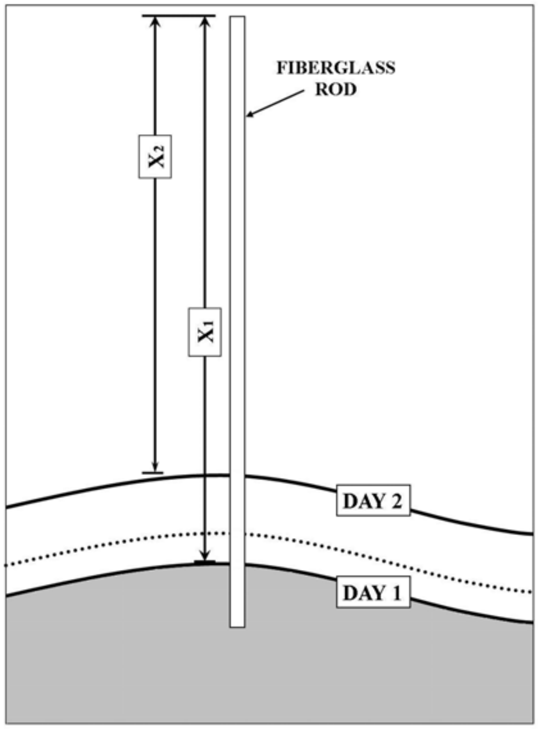
CHAPTER 3 - Methods

Three visits to the field area were planned for the summers of 2007 and 2008. These were planned around higher than normal spring tides using tidal predictions from the National Oceanic and Atmospheric Administration (NOAA). The first visit was in mid May, 2007. The second was at the end of July and beginning of August, 2007, and the third visit was at the beginning of July, 2008.

During the initial visit to the field area in May of 2007, several tasks were performed, the first of which was to identify multiple mud bars or flats that would be observed for the duration of the study. Bars with a variety of sizes and geometries were selected considering a balance between accessibility and remoteness. Each locality had to be readily accessible during times of low tide, but remote enough that it would remain undisturbed by the general public. Accessibility is generally not an issue as the Seward Highway and the Alaska Railroad run the length of and within a close proximity to the northern side of Turnagain Arm.

Once bars of interest were identified, each was photographed, described, and then staked with rods running along the axis of the bar and other areas of interest. These were numbered such that the lowest number of the set was in the downstream direction. The highest number of rod in the transect marked the upstream end. The rods used were 7 mm diameter 1.2 m tall fiberglass driveway markers with the reflector removed. When placed, a 32 mm diameter washer was slid over the rod and dropped onto the surface of the bar. The purpose of the washer was to provide a check to determine if the rods would gradually sink into the mud. The large surface area of the washer prevents it from sinking. Over each two-week period, the exposed portions of the rods were measured daily (every other tidal cycle) unless prevented by severe weather. The difference between these two measurements ($X_1 – X_2$ in Figure 3-1) is the amount of deposition or erosion resulting from the previous high tides. Once each two-week study was over, the washer was excavated and the amount of overlying sediment was measured. If that amount was equal to what was expected from measuring the rod, then no sinking of the rod had occurred. In all cases the actual amount of sediment above the washer equaled what was calculated from the daily measurements.

Figure 3-1: Schematic of rod system used to measure deposition/erosion. The difference between day 1 and day 2 represents two tidal events, as shown by the dashed line.



Photographs taken at set locations and orientations were used to document bar morphology over the entire duration of the study. Table 3-1 shows the coordinates and azimuths used to photograph the sites.

Daily descriptions of any sedimentary structures such as ripples, soft sediment deformation, scour marks or drag marks were made.

Another aspect that was documented was at what height (at Anchorage) the high tide fails to cover each locality. If there was no change at any of the rods, then other features such as tracks were examined. If the tracks left by the previous visit to the site were crisp and clear, then the surface had not flooded since the previous measurements were taken. This height is used to determine the maximum number of tidal events that could potentially result in deposition or erosion.

Table 3-1: Locations used to photograph sites over the course of the study.

Photo benchmark localities (WGS 84)		
Site	**Coords**	**Description**
PC2	N60 49.581 W148 58.679	Standing on top of post in parking lot on the south side of the creek that marks the end of the guard rail coming from the bridge. Facing 330°.
PEC	N60 52.985 W14902.735	Half way down rip-rap from "Avalanche Danger" sign on the east side of the bridge over Peterson Creek. Facing 303°.
GC	Original: N60 56.261 W149 10.573 New: N60 56.262 W149 10.567	From rebar benchmark on the vegetated bank, north side of Glacier Creek near the drowned trees. This benchmark was moved 5 meters north in Aug. 2007 to prevent loss due to cut bank erosion. Facing 125° (toward power poles).
TBO4	N60 56.318 W149 14.482	From the north-western most post of the sign "Trails, Rails, Blacktop & Beyond" Toward 267° (centered on spruce tree).
EBP	N60 55.791 W149 20.450	100 paces east of the railroad tunnel, just to the south side of the highway guard rail. Facing 225°.

CHAPTER 4 - Sedimentary Structures

At low tide, a variety of primary and secondary sedimentary structures are exposed on the surfaces of the mudflats and tidal bars. While deposition and erosion occur throughout the tidal cycle, it should be noted that most surface features are the result of late ebb-tide processes.

Depositional Structures

Single tidal events usually deposit thin laminae of fining-upward sediment. The initial high-energy flood of the rising tide erodes, transports, and deposits fine sand. As the tide continues to rise and eventually reaches high stand, energy decreases and finer particles settle out. In a setting with a diurnal inequality, the higher-high tide will deposit a thicker layer of sediment than the lower-high tide. This results in sequences of thick and thin lamination pairings. Spring tides with higher tidal range and more energy create relatively thick laminations while the lower range and less energetic neap tides create thinner laminations. Larger packages of these individual laminations create rhythmites (Figure 4-1). These rhythmites are observed at several study sites and contain records of previous tidal cycles. Figure 4-1 shows a rhythmite preserving a record of a neap-spring-neap cycle at the Glacier Creek study site. Rhythmites are most easily observed in natural cut banks due to the differential erosion of the fine sand-sized sediment particles over compacted silt gains. This causes the silt-grained portion of each individual lamination to stand out in relief. Higher flow velocities are needed to erode compacted silt grains than fine sand. This concept is illustrated by a Hjulström diagram (Figure 4-2). Because of the fining upward nature of each lamination, erosive events tend to remove whole laminations. Once the more resistant silt layer has been breached, the fine sand is easily eroded.

Figure 4-1: Rhythmite section from Glacier Creek. Scale is in cm/dm.

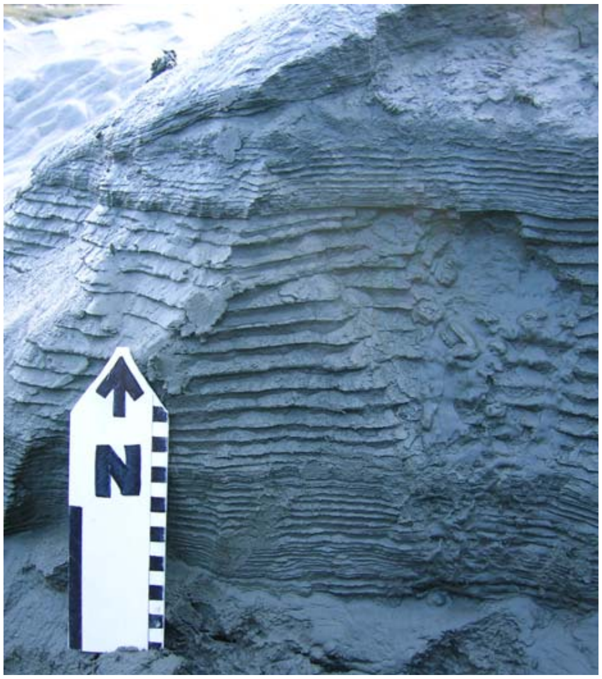
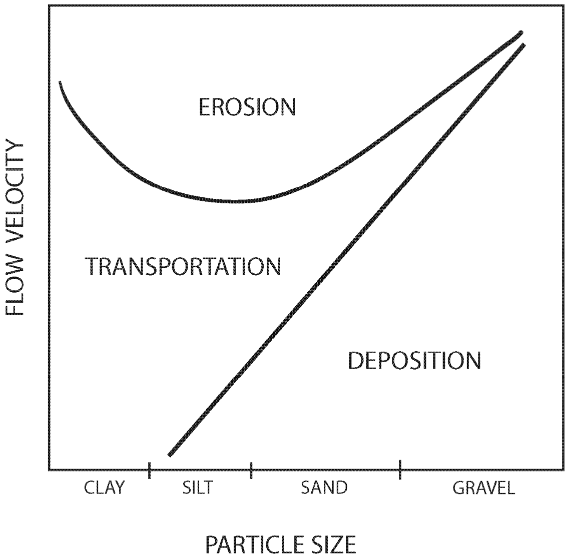


Figure 4-2: Simplified Hjulström diagram. Modified from Hjulström, 1935.



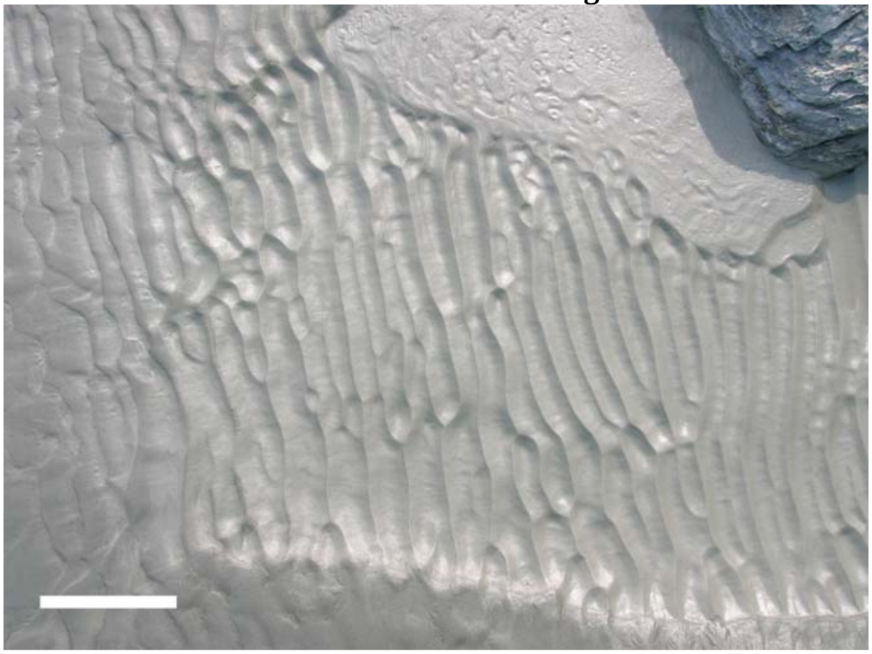
Because of the high-energy environment, sediment grains are deposited in random orientations, making the sediment very thixotrophic, and it will easily undergo liquefaction when disturbed. This poses a particular hazard when working on the mudflats as it is easy to become stuck in the "quicksand" if care is not taken. Because of this danger, safety was a major concern of this study. Locally there are many stories of lives lost and there are even signs posted to caution the unaware of the hazard.

A variety of different ripple types are observed throughout the study area. While sediment transport occurs during both the flood and ebb tides, ripples on the surfaces of mud bars are the result of only the late ebb flow. At the Bird Point study site only the flat upper portion of the bar showed rippling. This is most likely due to wave action reworking the sediment during the falling ebb tide.

Asymmetrical lingoid current ripples (Figure 4-3) and symmetrical branching ripples were observed at all localities. The current ripples form when the flow of the ebb tide is relatively high. These ripples are also formed by the direct actions of fluvial flow. The smaller scale symmetrical ripples form during relatively low energy periods or in locations on the bars that are protected from high flow velocities.

Figure 4-3: Asymmetrical lingoid current ripples.
Flow from left to right. Shovel blade is 20 cm wide.

Figure 4-4: Symmetrical branching ripples at EBP. Scale bar is 15 cm. Flow from right to left.



At Bird Point and TBO4 where there is often significant wave action, interference ripples are common (Figure 4-5). Interference ripples are also commonly referred to as ladder-back ripples. These ripples form with two sets of crests. The primary set is created by the ebb flow. Secondary crests form transverse to the primary crests from wave action.

Figure 4-5: Interference ripples (ladder-back ripples) at EBP.
Ebb flow from right to left, wave action from bottom of photo. Note boot for scale.

Climbing ripples can be seen in relief in places where cut-bank erosion has removed the fine sand but not the silt particles (Figure 4-6). This shows the downstream migration of ripples though several ebb cycles.

Figure 4-6: Climbing ripples on the upper surface of a cut bank at PC2. Ebb flow is from right to left.

Erosional Structures

Direct precipitation, run off from the surrounding areas, and wave action commonly create rills and gullies of various scales. While the smaller scale rills tend to only surface marks (Figure 4-7), the larger gullies can remove significant amounts of sediment from the bar (Figure 4-8). These gullies create roughness in the surface of the bar which contributes to even more erosion during the ensuing tides. In other localities large scours formed. These sours often contain ripple marks. This situation could be very confusing to interpret in the rock record as one set of ripples could be stratigraphically lower but be formed later than others that are stratigraphically higher.

Figure 4-7: Small scale rills at EBP.
Note boot for scale.

Figure 4-8: Large gully at EBP.
Run off from the surrounding area was concentrated by a small ditch which emptied onto this portion of the bar. Scale at center of photo is 1 m.

Figure 4-9: Large sour containing ripples at PEC. The ripples formed after the scour. Scale is 1 m.

During the July 2008 field season strong east winds were observed forming adhesion warts (Figure 4-10). Adhesion warts are formed when strong winds start dry particles rolling along a surface of damp sediment. As these particles roll and bounce, they adhere to the dry damp particles creating an irregular “warty” surface.

Figure 4-10: Adhesion warts at the EBP study site.
Winds blowing from the right to left. Scale is in cm/dm.

Deformation Structures

The frequent flooding and dewatering of the estuarine sediment can cause a variety of types of soft-sediment deformation to form (Figures 4-12 and 4-13). In the past these forms were interpreted to be created by seismic events, such as the 1964 earthquake. However, Greb and Archer (2007) documented that deformation can be caused by purely tidal processes. While present at all the study sites, the thickest and most extensively deformed zones were noted at Bird Point, TBO4, and Glacier Creek. These sites experience the greatest tidal flux. Soft-sediment deformation at Bird Point and TBO4 could also be caused by the frequent passage of the tidal bore during the spring tides.

Figure 4-11: Soft-sediment deformation in a cut bank at Glacier Creek. Flow rolls and flame structures overlying undeformed sediment. Scale is 16 cm long and is divided into cm/in.

Figure 4-12: Soft-sediment deformation as seen on the surface of the TBO4 bar. Scale is in cm/dm.

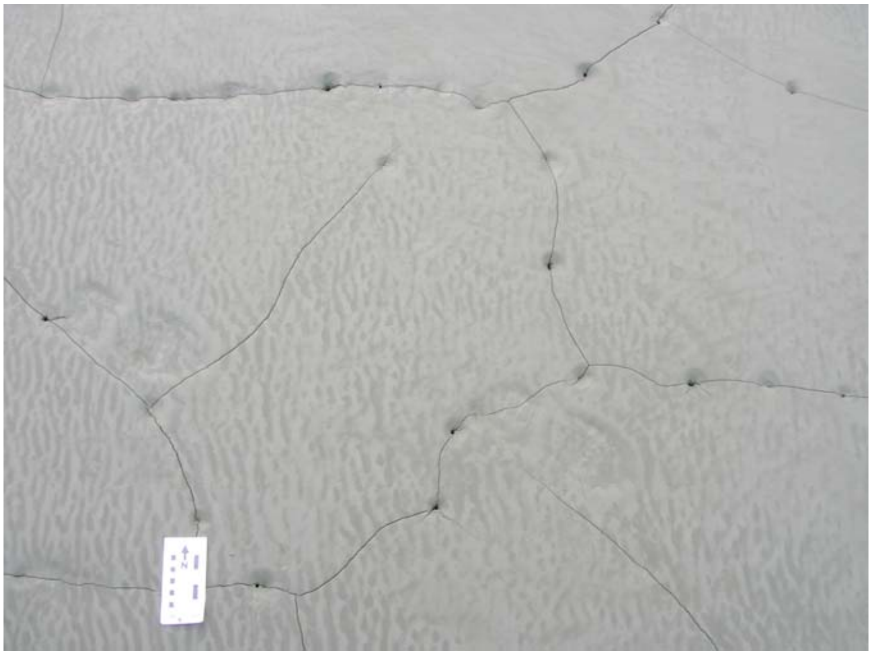
During periods of subarial exposure, water seeps from the sediment and mud volcanoes and dewatering pits are created. A mud volcano forms when water is forced out of the sediment by overlying weight. As the water spills out, it carries particles of sediment with it. This sediment builds up small volcano-like forms (Figure 4-13). Small mud volcanoes are commonly seen when walking across a mud bar that has only recently been exposed. The weight of a person walking adds to the weight of the sediment, helping to force the water out. These mud volcanoes are one of the signs that the bar may not be dry enough to safely work on. Dewatering pits form in much the same way as mud volcanoes. Instead of the sediment piling up to create a convex volcano form, the sediment is removed and a concave pit forms (Figure 4-14).

Figure 4-13: Small mud volcano on left and dewatering pit on right at the PEC site. Penny for scale.

Figure 4-14: Large dewatering pits at the PEC site. Scale is 1 m.

During the neap tides when some bars are not flooded for an extended time period, dessication cracks form. These cracks form paths or water to escape from when the bar is next flooded. Small dewatering pits are commonly found superimposed on mud cracks (Figure 4-15). Drag marks from wood debris and raindrop imprints are also common features.

Figure 4-15: Mud cracks with small dewatering pits at the GC site. Scale is 14 cm tall.



Biogenic Structures

The extremely high turbidity of the water and the high rates of deposition limit organisms from living in the intertidal. There are no shell fish that live in the mud flats. However, various types of tracks and trails can be seen on the surfaces of some of the tidal flats and bars. Tracks of moose, bears, raccoons, and gulls are common. During the salmon spawning season, fish travel from Cook Inlet, through Turnagain Arm to their spawning grounds in the melt-water-fed streams. Fish crossing a bar in shallow water can leave swim marks as their fins drag across the surface (Figure 4-16). These swim marks were frequently observed during early August, 2007, which coincided with the beginning of the local Coho salmon run. If a bar is not flooded for several days, small insects begin to burrow in the very upper silt lamination (Figure 4-17).

**Figure 4-16: Salmon fin drag marks (arrow), gull tracks and rain-drop prints at the GC site.
Scale bar is 20 cm.**

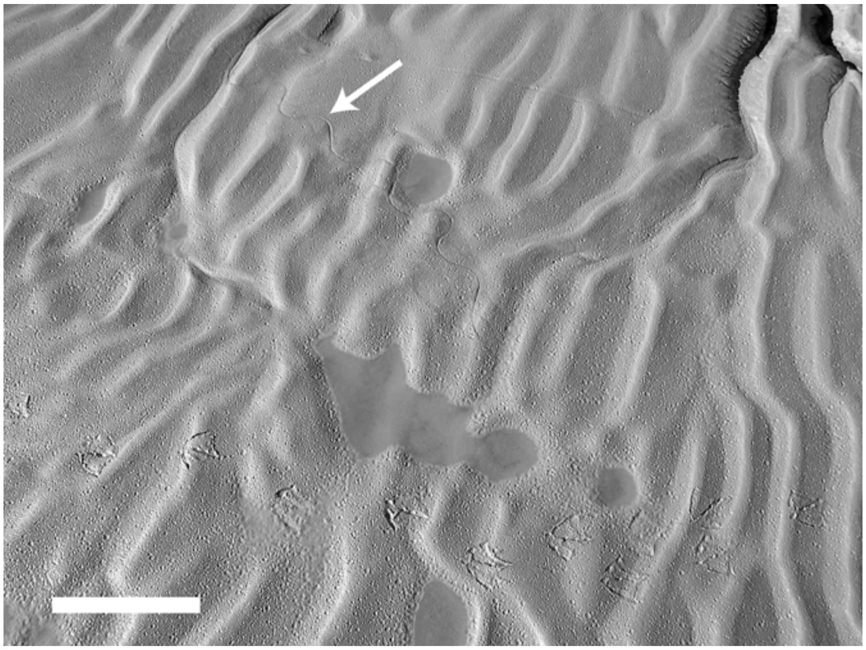
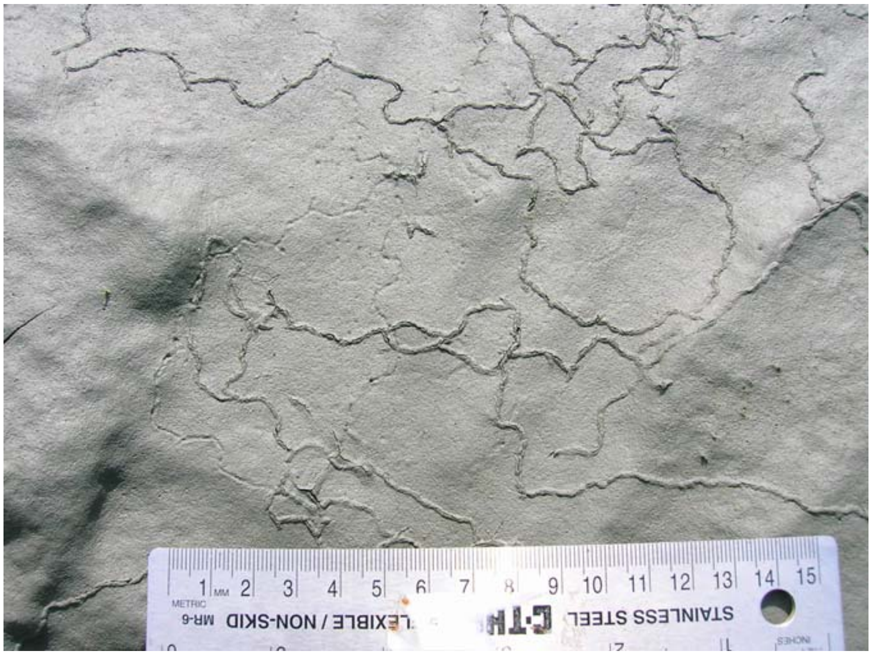


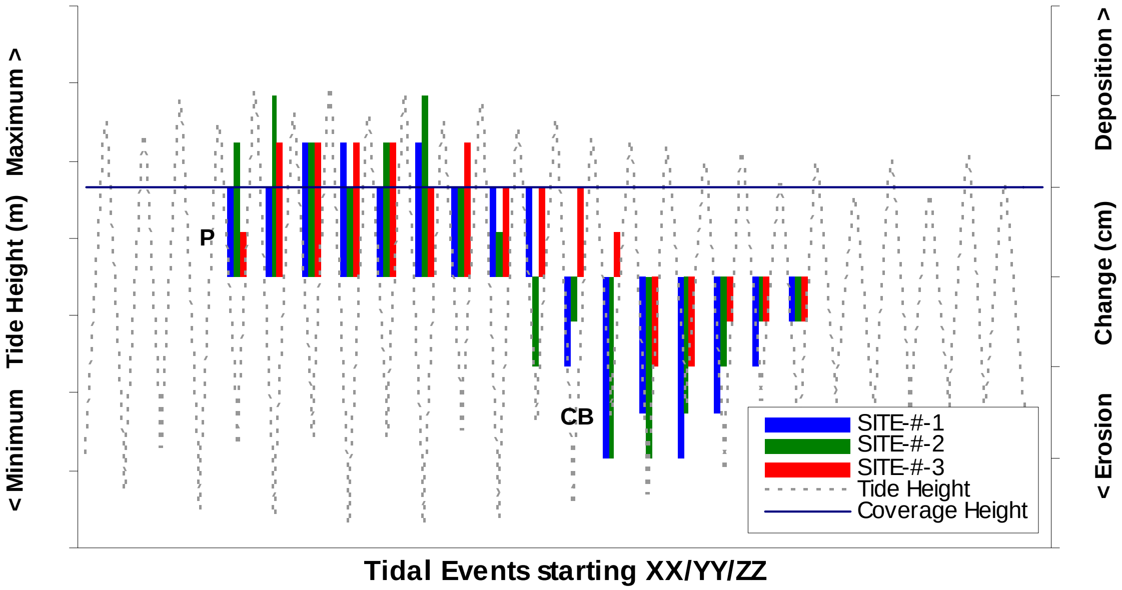
**Figure 4-17: Insect burrows at the GC site.
Scale is in cm.**



CHAPTER 5 - Observations

The data collected at the various study sites was plotted in a format similar to Figure 5-1. The tidal curve for the study period is overlain by the amount of single tide deposition or erosion (change) that was caused by the previous tidal event (high tide and following low tide). Each rod of each transect is plotted as a different color of bar and is identified by the following code: site abbreviation (EBP, TOB4, etc) – transect number (#) – rod number (1, 2, or 3). The calculation used to determine the value of each bar is outlined in the Methods section. If the bar points upward this indicates deposition. If a bar points downward this indicates that erosion has occurred. The amount of erosion or deposition is plotted after the high tide that is responsible for the change. One important thing to note is that the amount of deposition and erosion varied greatly from transect to transect. As such the scale of the "Change" axis differs from plot to plot. Some study sites are not covered by all high tides. If this is so then the value of high tide needed to completely cover the site is also plotted as "Coverage Height". The letter "P" indicates when the rods were placed and active monitoring of the site began. If the site underwent any cut bank erosion, this is signified by "CB".

Figure 5-1: Schematic of data plot.



Bird Point

The Bird Point (EBP) study site is the western-most locality in this study. EBP is located on the eastern side of a bedrock point that protrudes into Turnagain Arm (Figures 5-2 and 5-3). This point provides protective coves for bars and flats to develop on both the upstream and downstream sides. Bird Point State Park is located here and provides easy access to the study site. This bar seems to be semi-permanent as it is visible in many historical photos of the area. Throughout the study this bar accreted and eroded slightly, but still retained roughly the same size and shape. At its average size, this bar is 200 m long and 80 m wide. During the study, EBP was covered by every high tide. If there is a tidal bore, it is at Bird Point where it begins to develop significant height.

Over the course of the study, six transects were observed at Bird Point, two per visit. Transects 1, 4, and 6 were set along the margin of the bar closest to the channel. Transects 2, 3, and 5 were located higher up along the axis of the bar (Figure 5-2 inset). These transects had to be reset each visit as the previous ones were always missing.

Figure 5-2: Air photo and schematic of EBP study site.
Inset shows locations of transects and rods from all three visits. Image from GoogleEarth.

Figure 5-3: Photo of EBP taken on August 3, 2007.
View is to the southwest. Bird Point is in the right-central of the photo. Ebb tide flows from left to right. Bedrock protrusions and gullies formed from runoff were used as reference points throughout the study. Note the two people for scale.

When EBP was first observed in May, 2007 its surface was very smooth and featureless except for several small runoff gullies. Four measurements were taken at transect 1 (Figure 5-4) and transect 2 (Figure 5-5) on EBP. The first two sets of measurements showed deposition was dominant over the entire bar. The greatest amount of single tide deposition along transect 1 was 8.9 cm at rod 1-3 after high tides #3 and #4. Transect 2 experienced a maximum of 3.6 cm/tide at rod 2 following high tide #10. During this depositional period interference ripples were frequently found on the flatter portions of the bar. Except for these ripples this site was devoid of any depositional structures. Small rills formed during the ebb tide and deposits of extremely broken down organic debris were commonly found. After high tide #11 EBP began to be eroded by cut bank action (Figure 5-6). This immediately removed rods 1-1, 2-2, and 2-3. During this period a 2 m wide portion of the bar was observed being removed during one hour. Rod 2-1 remained until the next high when it was also missing. Erosion continued at rods 1-2 and 1-3 until they were lost following high tide #17 (Figure 5-7). At the end of this visit EBP had become extremely heavily eroded with large cut banks along the main channel and the runoff gullies had become deeply entrenched.

Figure 5-4: EBP transect 1, May 2007.

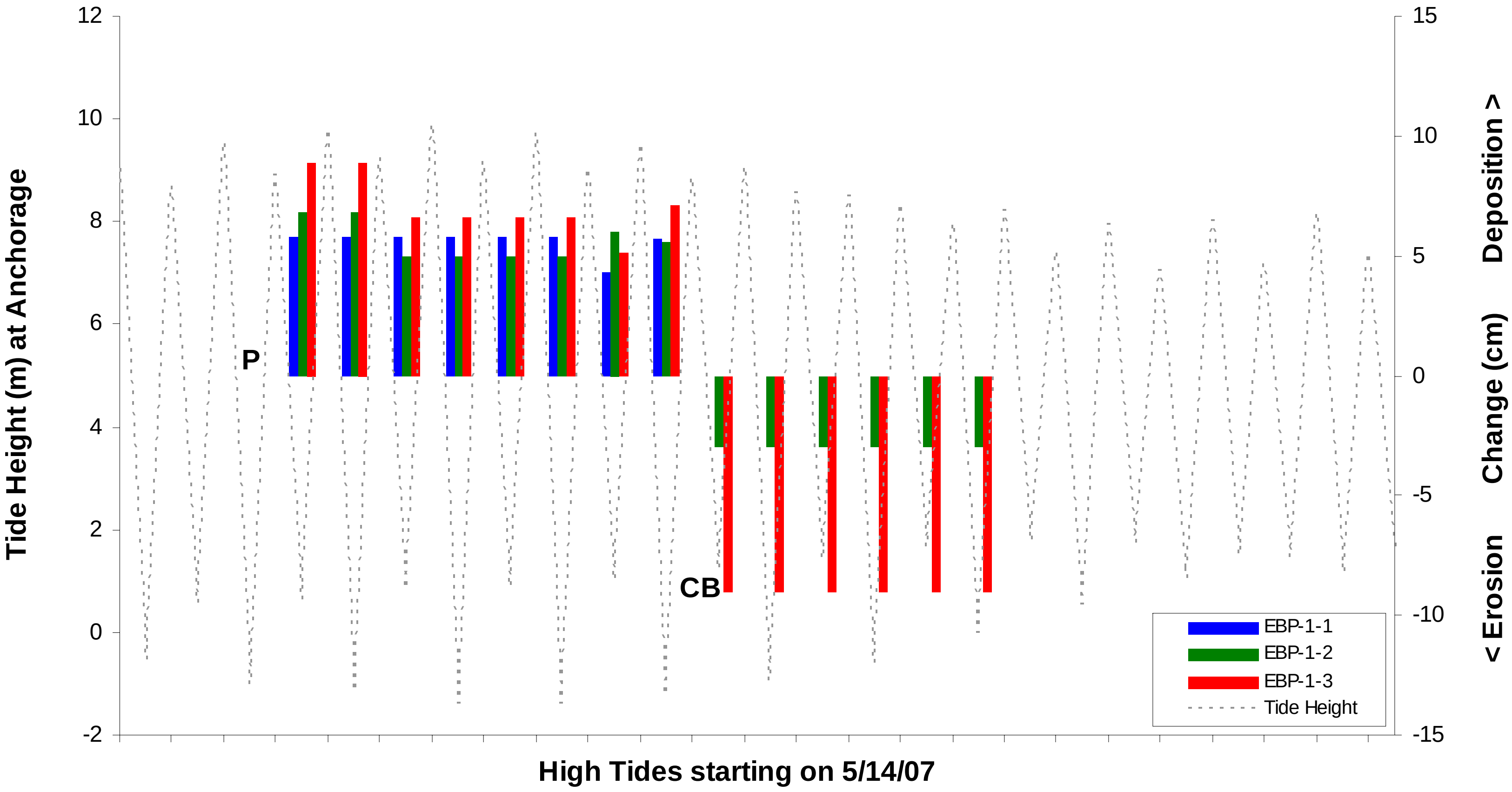


Figure 5-5: EBP transect 2, May 2007.

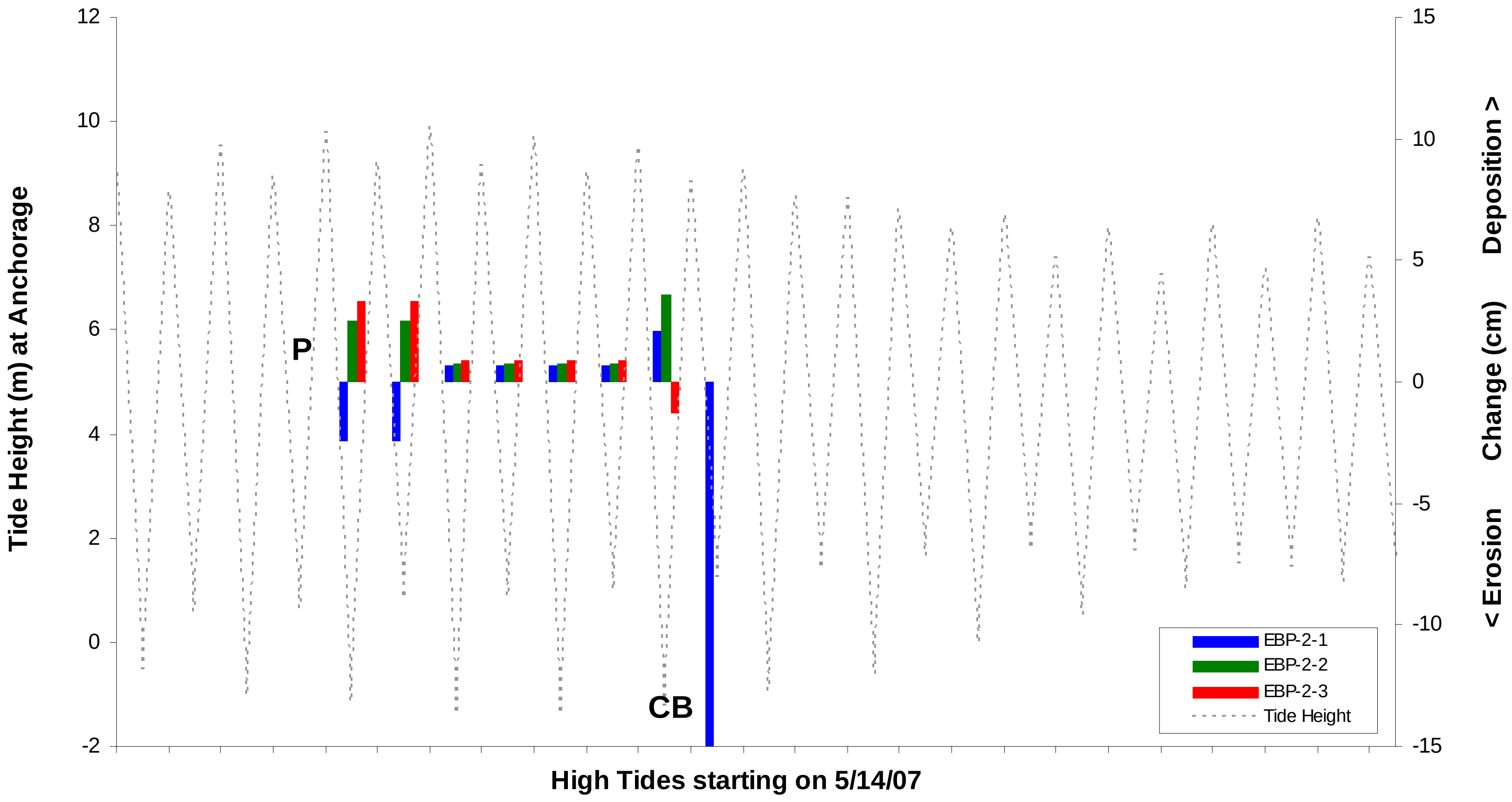


**Figure 5-6: EBP partially flooded on May 20, 2007, after high tide #12.
Cut bank erosion is hidden by the relatively high water level.**

Figure 5-7: EBP at low tide on May 23, 2007, after high #17.
The bar is now extensively eroded.

Upon the return to EBP in late July, 2007 the bar appeared much the same as it did at the beginning of the May, 2007 visit. Transect 3 (Figure 5-8) and transect 4 (Figure 5-9) were each measured 10 times during this visit. At the start of observation the surface of the bar was generally smooth except for small patches of interference ripples. Over the next few days substantial rainfall caused the small runoff gullies to become deeply entrenched (Figure 5-10). The upper portion of the bar along transect 3 was primarily depositional during this visit. After high tide #13 rod 3-3 did show up to 1.6 cm/tide of erosion. At the end of this visit this same rod recorded 2.5 cm/tide of deposition. Transect 4 along the lower portion of the bar showed mixed periods of deposition and erosion. Maximum deposition at all rods occurred after high tide #7. Rod 4-1 recorded 3.9 cm/tide of deposition at this time. Deposition occurred at all rods in transect 4 until high tide #11 when rods 4-2 and 4-3 recorded significant cut bank erosion (Figure 4-8). During this period rod 4-3 experienced up to 7.7 cm/tide of erosion. The upstream end of the bar began to become significantly eroded midway through the visit. Rod 4-3 was missing after high tide # 13 and rod 4-2 was missing after high tide #18. At the end of this visit EBP had developed a cut bank up to 2 m tall along the main channel and the upstream end of the bar had become extremely eroded (Figure 5-11). While erosion dominated the lower and upstream portions of EBP, the upper and downstream parts of the bar were primarily depositional throughout this visit.

Figure 5-8: EBP transect 3, July-August, 2007.

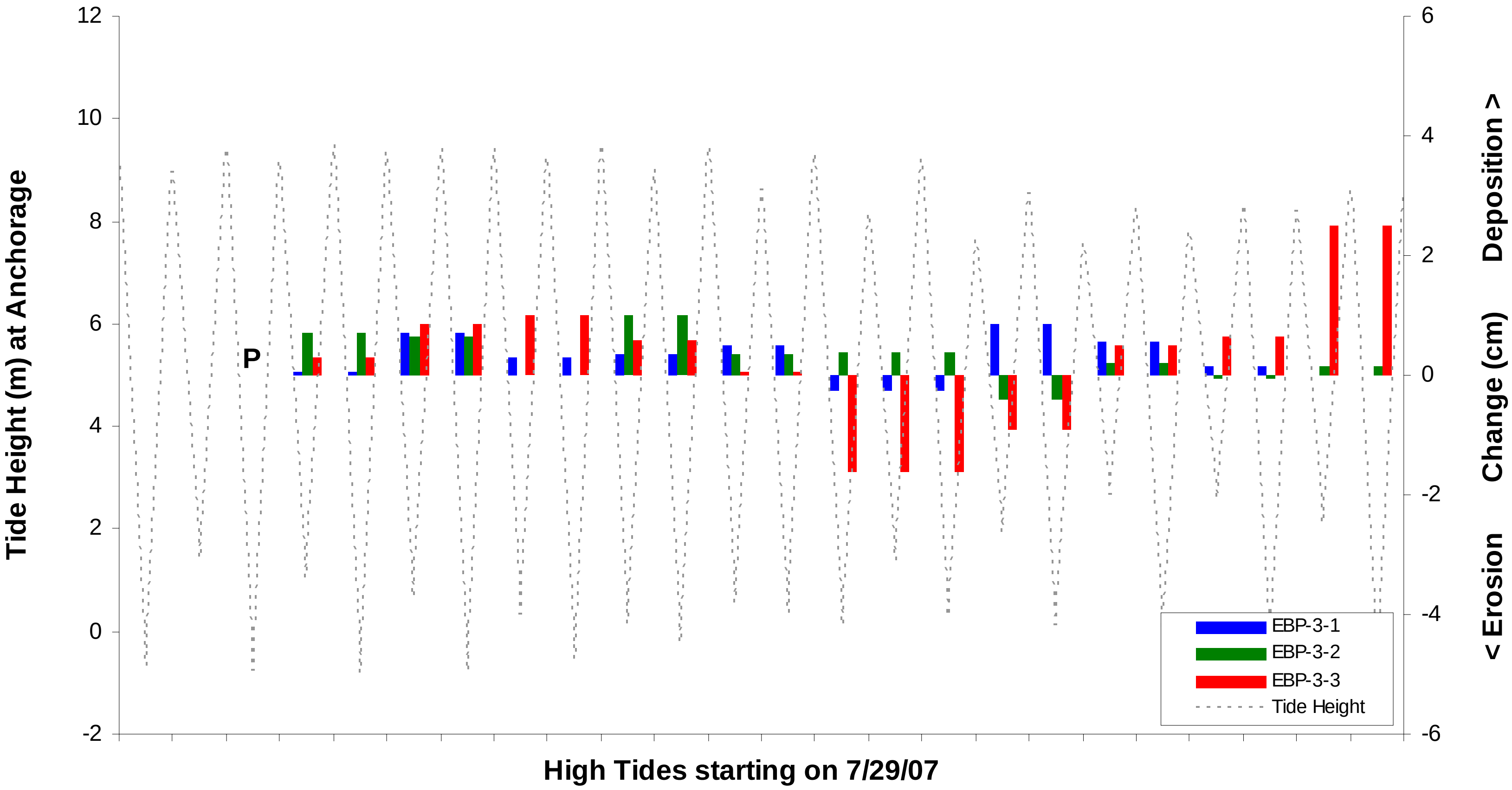


Figure 5-9: EBP transect 4, July-August, 2007.

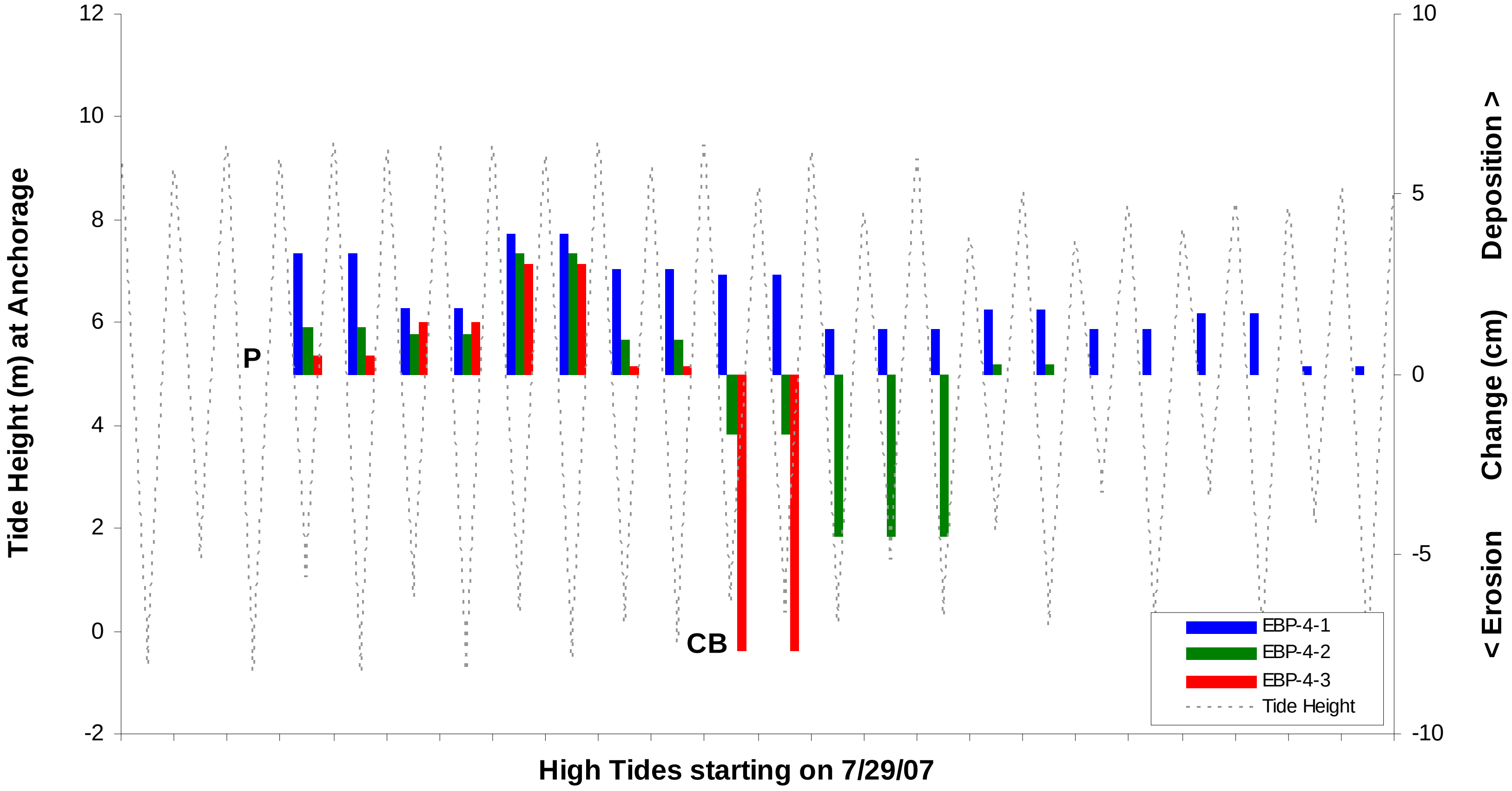


Figure 5-10: EBP on July 30, 2007, after high tide #2.
The surface of the bar is relatively smooth and the runoff gullies are entrenched.

Figure 5-11: EBP on August 10, 2007, after high tide #23.
The surface of the bar is rough, a 1 m tall cut bank has formed, and the upstream end of the bar has been eroded.

In July, 2008 transect 5 (Figure 5-12) and transect 6 (Figure 5-13) were each measured 12 times. This visit provided the most detailed observations of EBP. The bar had grown significantly eastward from the previous visit. As such a new perspective was needed to photograph the bar (Figure 5-14). The first observations of the bar revealed that the surface was nearly void of any type of ripples. The upper portion of the bar along transect 5 experienced two dramatic periods of sedimentation. The first period was entirely depositional with a maximum of 3.2 cm/tide recorded after high tide # 7. The second period from high tide #18 on was dominated by little to no deposition or erosion. Transect 6 along the lower portion of the bar recorded a similar dichotomy. The first 14 tides all resulted in deposition. A rate of deposition of 6 cm/tide occurred at rod 6-3 after high tide # 7. This is the highest rate of deposition recorded at any of the sites over the entire study. Conversely, the period of observation following high tide #16 was dominated by cut bank erosion. The same rod that recorded the highest rate of deposition also recorded the highest rate of erosion at 13.5 cm/tide. The rest of transect 6 was primarily non-depositional during this period. By the end of the July, 2008 visit, cut bank erosion had removed a significant amount of the lower and upstream portions of the bar (Figure 5-15). The higher and downstream parts of the bar experienced only accretion during this period.

Figure 5-12: EBP transect 5, July, 2008.

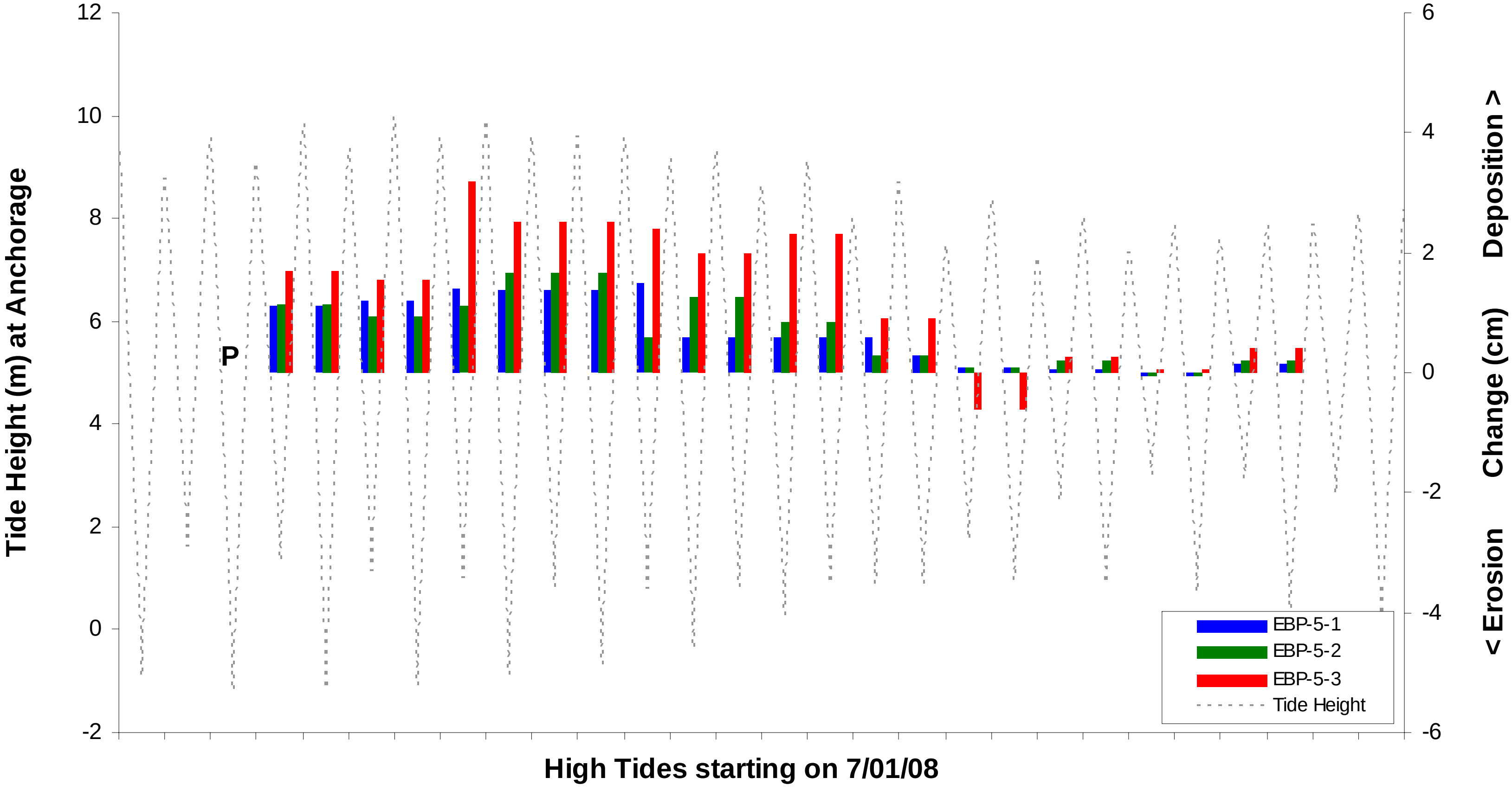


Figure 5-13: EBP transect 6, July, 2008.

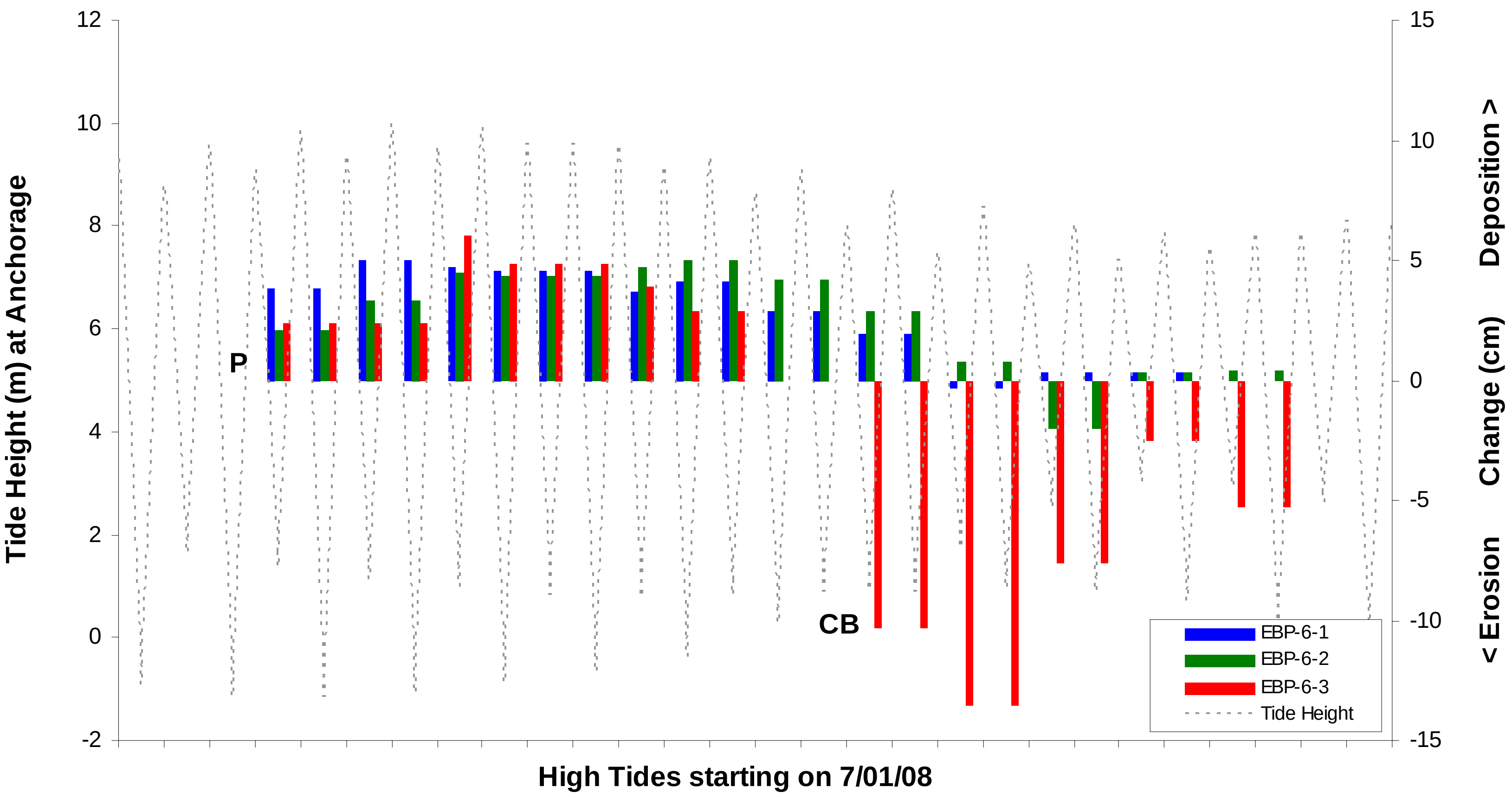


Figure 5-14: EBP on July 2, 2008, after high tide #2.
Note that this photo is taken from a different perspective than the previous photos.
The bar had grown significantly to the east (left in photo).

Figure 5-15: EBP on July 14, 2008, after high tide #25.
Cut bank erosion has decreased the width of the bar.

Tidal Bore Overlook #4

In the mid 1990's portions of the Seward Highway were widened and realigned. As part of this construction, five turnoffs on the south side of the highway were built between Bird Point and Girdwood. These turnoffs are informally called Tidal Bore Overlook #1 (the western most) through #5 (the eastern most) as they provide excellent viewing of the tidal bore as it advances eastward. A bar formed on the west side of Tidal Bore Overlook #4 (TBO4) was another locality of this study (Figure 5-16). This 200 m long and 40 m wide bar is formed in a protected area between the artificial turnoff and a small natural bedrock point. Over the course of the study, three transects were monitored at TBO4. Transect 1 was set along the axis of the bar. This transect had to be reset each visit as the rods went missing. This reset transect was named transect 2 during the July-August, 2007 visit and transect 3 during the July, 2008 visit. It is some what uncertain whether the rods were removed by erosion or if the site was vandalized between visits. Vandalism was a concern at this site as all of the rods were visible from the frequently populated parking area on clear days.

Figure 5-16: Air photo and schematic of the TBO4 study site.
Inset shows locations of transects and rods for all three visits. Image from GoogleEarth.

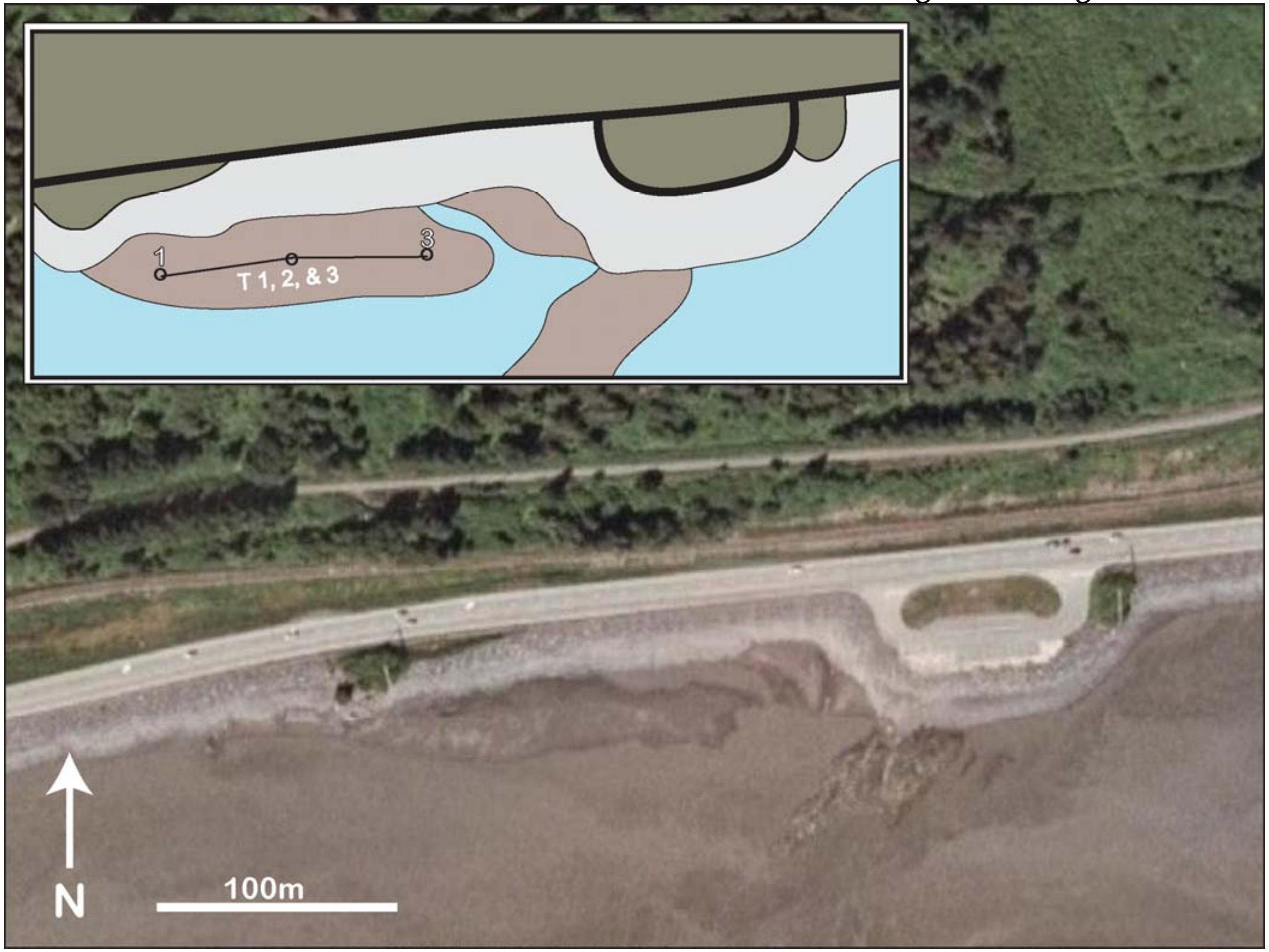


Figure 5-17: TBO4 as seen from the Tidal Bore Overlook #4.
View is to the west. Ebb tide flows from left to right. Rods 2-2 (far) and 2-3 (near) are visible in right central of photo.

During the May, 2007 observation, transect 1 (Figure 5-18) at TBO4 was measured four times. The first four high tides observed at TBO4 resulted dominantly in deposition. The maximum amount of sediment deposited was 1.5 cm/tide at rod 1-3. During this period of deposition the surface of the bar was covered in straight crested ripples and retained a very smooth appearance from a distance (Figure 5-19). After high tide #19 the surface of the bar became very scoured and diminished in size (Figure 5-20). Soft sediment deformation was uncovered by this souring (Figure 4-12). Rods 1-1 and 1-2 were missing and rod 1-3 documented erosion for the remainder of the visit. The bar at rod 3-1 eroded at an average of 0.36 cm/tide for several days. After high tide #20 this rate jumped to 4.5 cm of erosion per tide. This erosion is due to scouring only and not from cut bank action.

Figure 5-18: TBO4 transect 1, May, 2007.

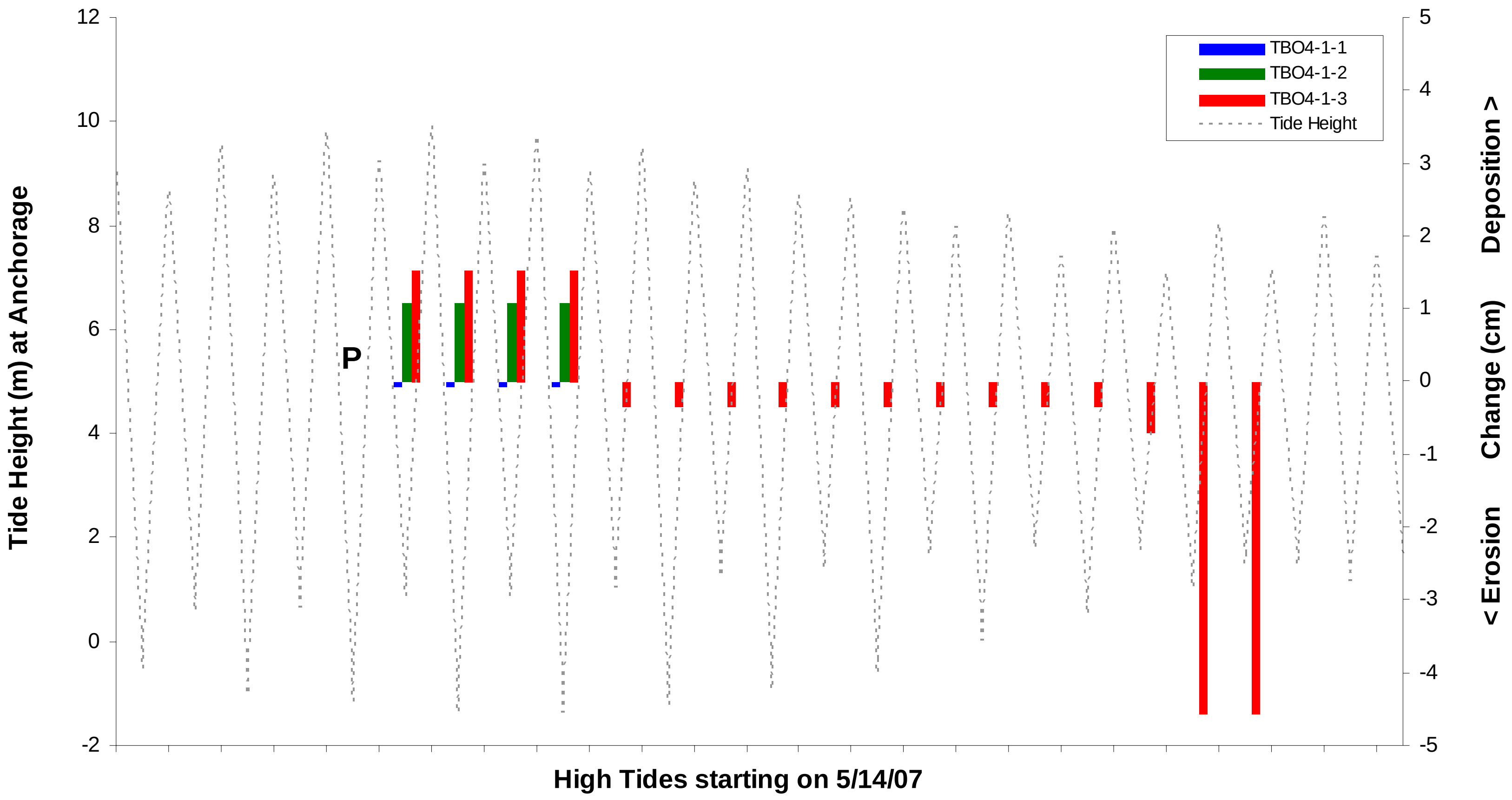


Figure 5-19: TBO4 on May 20, 2007, recently dewatered from high tide #12.

Figure 5-20: TBO4 on May 25, 2007, after high tide #22.
The bar has eroded significantly since May 20.

0

Upon the return to TBO4 in July, 2007, transect 2 (Figure 5-21) was set. Over the course of this visit, 10 measurements were taken at TBO4. At the start of this period of observation, TBO4 (Figure 5-22) had returned to much the same shape and size as it had been during the early portion of the May, 2007 visit (Figure 5-19). Deposition dominated the first 13 tides, with maximum of 1.9 cm/tide. During this period the surface of the bar was consistently covered with straight crested ebb directed ripples. Following this came a period of mixed deposition and erosion across the bar. During this time a maximum of 1.7 cm/tide was deposited and 2.0 cm/tide was eroded. Using a flowmeter, the velocity of the ebb flow just prior to the passing of the bore was recorded to be 6 m/s. Just after the passage of the bore, the velocity of the flood waters was recorded to be 10 m/s. During this initial surge of the flood tide, the water rose at a rate of 10 cm/min. Late in the study, even though the site was covered by every high tide, small mud cracks were observed forming on the very upper portions of the bar. Over this two week long period of observation the main tidal channel migrated farther to the south and flats developed immediately to the south and west of the study site (Figure 5-23).

Figure 5-21: TBO4 transect 2, July-August, 2007.

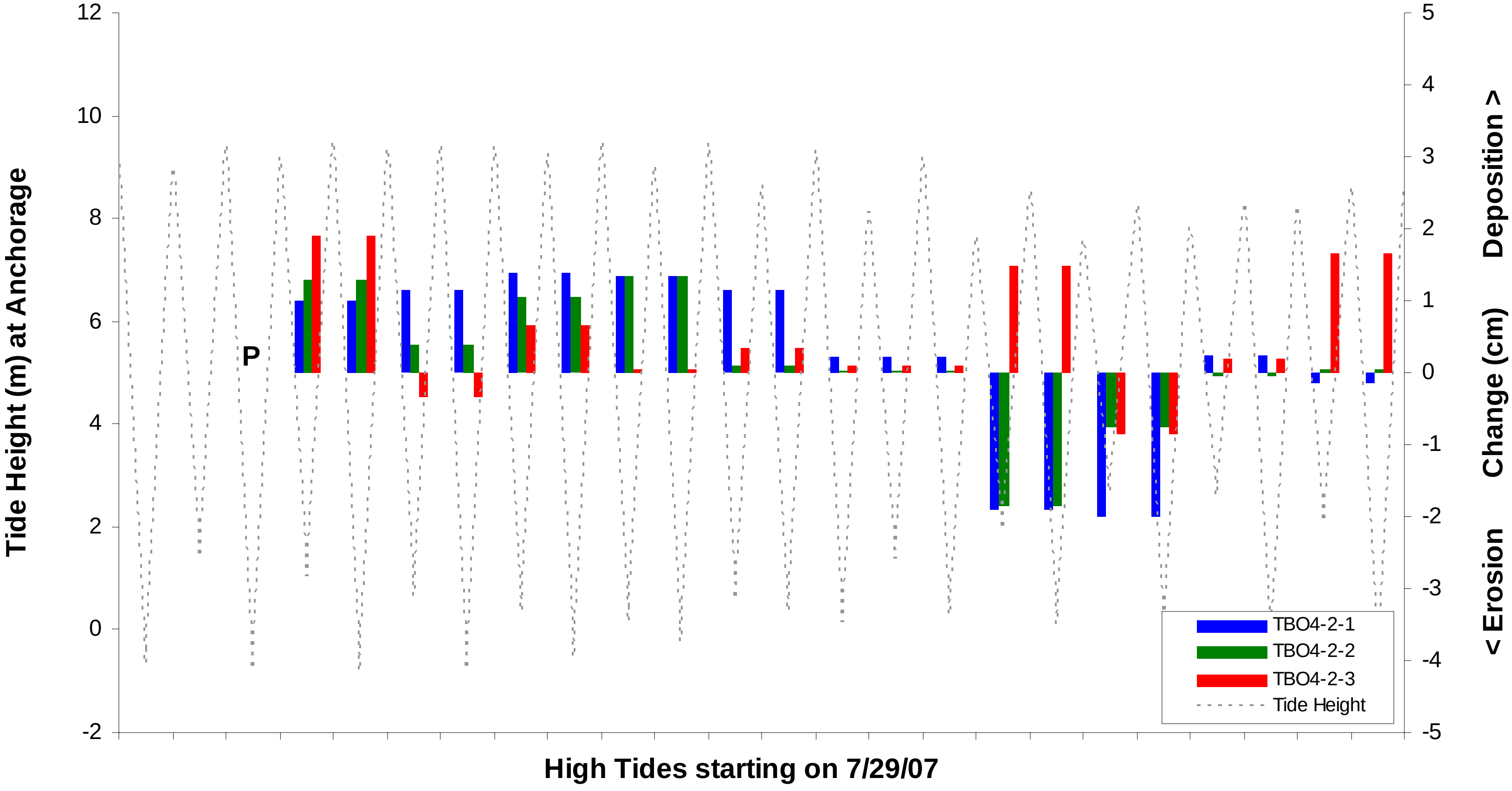


Figure 5-22: TBO4 on July 29, 2007, dewatering from high tide #0.

Figure 5-23: TBO4 on August 8, 2007, after high tide #23.
Flats have developed to the west and the main channel has shifted south. Rods 2-2 (far) and 2-3 (near) are visible.

In July, 2008, a third transect at TBO4 was set (Figure 5-24). Figure 5-25 shows the bar as it appeared at the beginning of this visit. Visually it was very similar to the way it looked at the end of the previous visit except that the main channel now was running along the southern margin of the bar. During the ebb tide this channel was cutting a very steep bank on the western end of the bar. Almost all of the twelve measurements taken at TBO4 during this visit documented that deposition was occurring over all portions of the bar. The maximum amount recorded was 3 cm/tide after high tides #7 and 8. With only one exception, the first thirteen tides resulted in deposition of amounts greater than 1 cm/tide at all the rod locations. During this time, straight crested, asymmetrical ripples of two orientations covered the bar. One orientation was perpendicular to the axis of the bar and was created by the flow of the ebb tide. Ripples of this orientation were common on the top of the bar. Ripples with an orientation parallel to the axis of the bar covered the flanks of the bar. These were created by gentle wave action during the ebb tide. Following the period of high rates of deposition came a period of slightly lower rates. The only significant amount of erosion came after high tide #24 when 2 cm/tide was removed from the area around rod 3-1. The margins of the bar became slightly scoured and were slightly erode during this period of deposition on the upper bar. Even though the bar was still being covered at high tide and deposition was occurring on the upper portions of the bar, large polygonal mud cracks developed on the upper surface on sunny, dry days. At the end of this visit, portions of the surface of the bar were pitted by small scours, revealing soft sediment deformation. Over the course of this visit, the tidal channel had migrated southward and flats had developed to the south and west of TBO4 (Figure 5-26).

Figure 5-24: TBO4 transect 3, July, 2008.

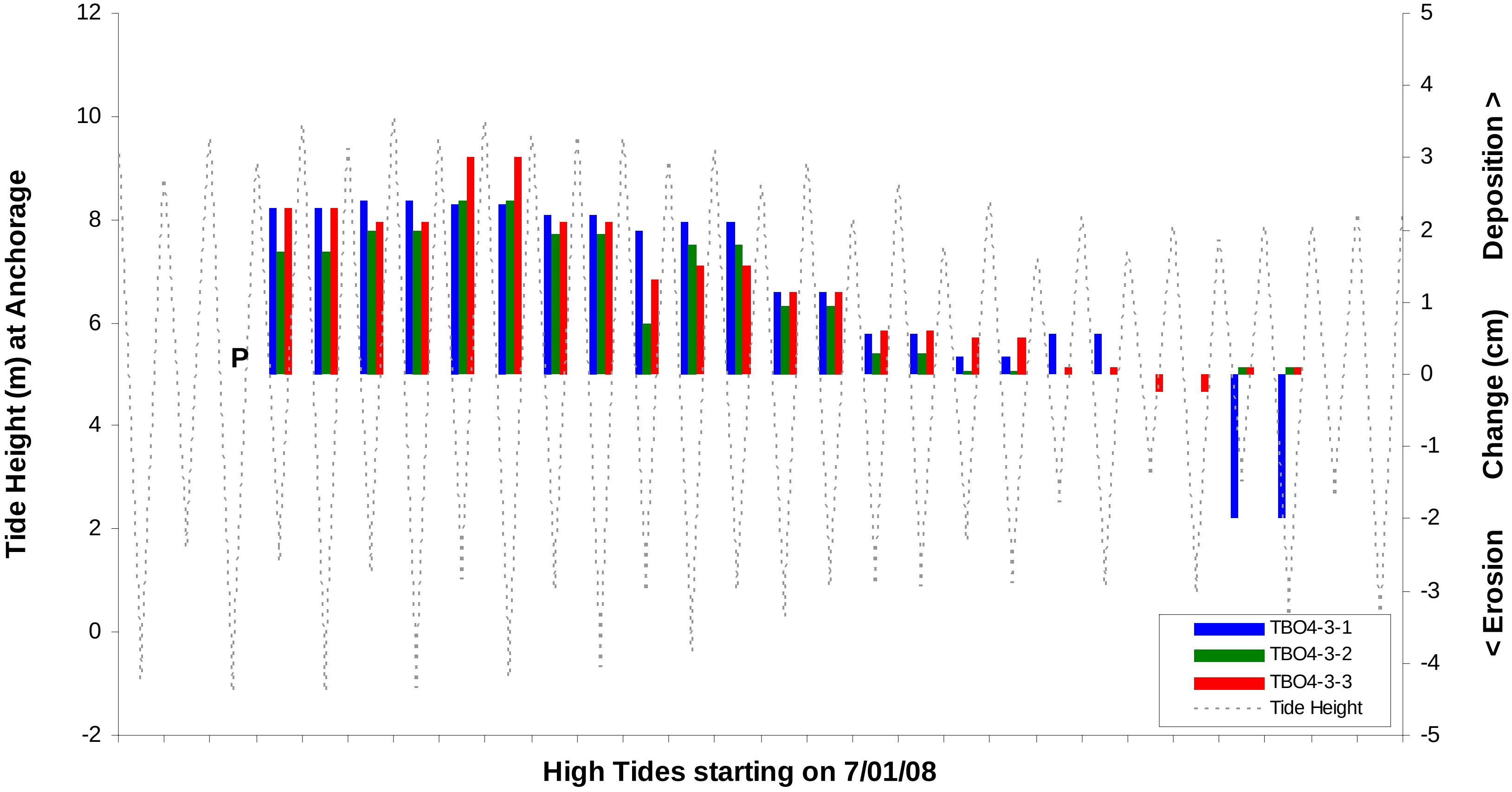


Figure 5-25: TBO4 at low tide on July 2, 2008, following high tide #2. The main tidal channel (left center of photo) forms the southern margin of the bar.

Figure 5-26: TBO4 on July 14, 2008, at low tide following high tide #25.
The main tidal channel has migrated to the south and flats have developed to the south of the bar.

Glacier Creek

The Glacier Creek (GC) study site is located at the confluence of Glacier Creek and the tidal channels of Turnagain Arm (Figure 5-27). Glacier Creek runs through the small town of Girdwood and is primarily fed by melt water from glaciers to the north and northeast. The surrounding salt marsh experienced approximately 1.5 m of subsidence during the 1964 earthquake. While the subsided area flooded frequently shortly after the earthquake, it has since been filled with tidal sediment (Atwater et al., 2001). Now the marsh is only flooded during the extreme spring tides. During the earthquake a small spruce forest was dropped down into the intertidal. These trees quickly died from the salt water, however many are still standing. The pre-earthquake surface is a peat layer that can be seen in many of the cut banks of Glacier Creek.

This study site consists of small tidal flats overlying fluvial gravel. These flats are dissected by tidal channels (Figure 5-27). This study site exhibited the greatest change from 2007 to 2008 (Figure 5-28) as Glacier Creek meandered, eroding and transporting the tidal deposits and gravel. Extensive flats are found farther to the south and west. As Glacier Creek meanders through these flats, the channel becomes extremely sinuous. These flats and the sinuosity of the creek channel minimize the effect of the passage of the bore at this site. While this site varied in size from season to season its average size was 140 m by 75 m. Over the course of the study, six transects were monitored at the GC site.

Figure 5-27: Air photo of the GC study site.
Glacier Creek runs through the center. Box corresponds to schematics in Figure 5-28.
Image from Google Earth.

Figure 5-28: Schematic showing the GC study site during the three field visits. A) May, 2007. B) July-August, 2007. C) July, 2008.

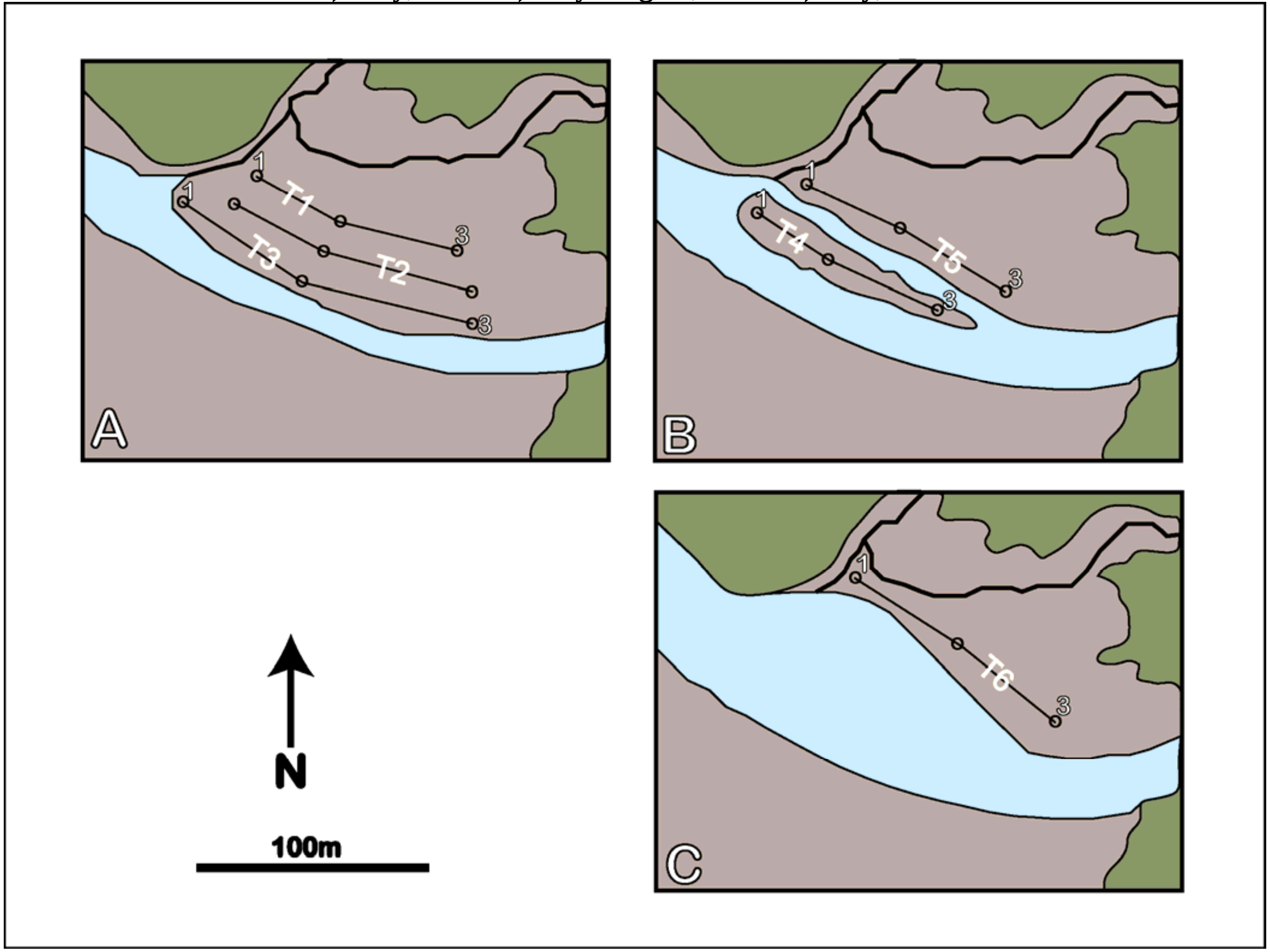


Figure 5-29: GC on July 31, 2007.
View is to the southeast. The two people are standing next to rod 4-1.

During the May, 2007 visit, three transects were monitored at GC (Figure 5-28 A). Transect 1 (Figure 5-30) was set along top of the flat, approximately half way between the main channel of Glacier Creek and a small tidal channel. Transect 2 (Figure 5-31) was set down the center of a small swale that cut through the flat. Transect 3 (Figure 5-32) was place along the top of the flat next to the creek channel. During this visit, each rod was measured twice before the high tides no longer covered the site. When these transects were first set the flat was being consistently flooded and portions were covered with ebb oriented straight crested ripples. For the nine high tides following when the rods were places, all stations documented an average of 0.5 to 0.8 cm/tide of deposition. During this visit, only ten high tides were high enough to completely cover the site. When the site was covered, small mud volcanoes and dewatering pits were common. Any high tides less than 8.54 m (at Anchorage) did not cover the site. Figure 5-33 shows the site after the last high tide high enough to cover it. After this the surface of the flat became extensively cracked and burrowed by insects. Rhythmites were observed at several points on the flat as they were eroded away by cut banks.

Figure 5-30: GC transect 1, May, 2007.

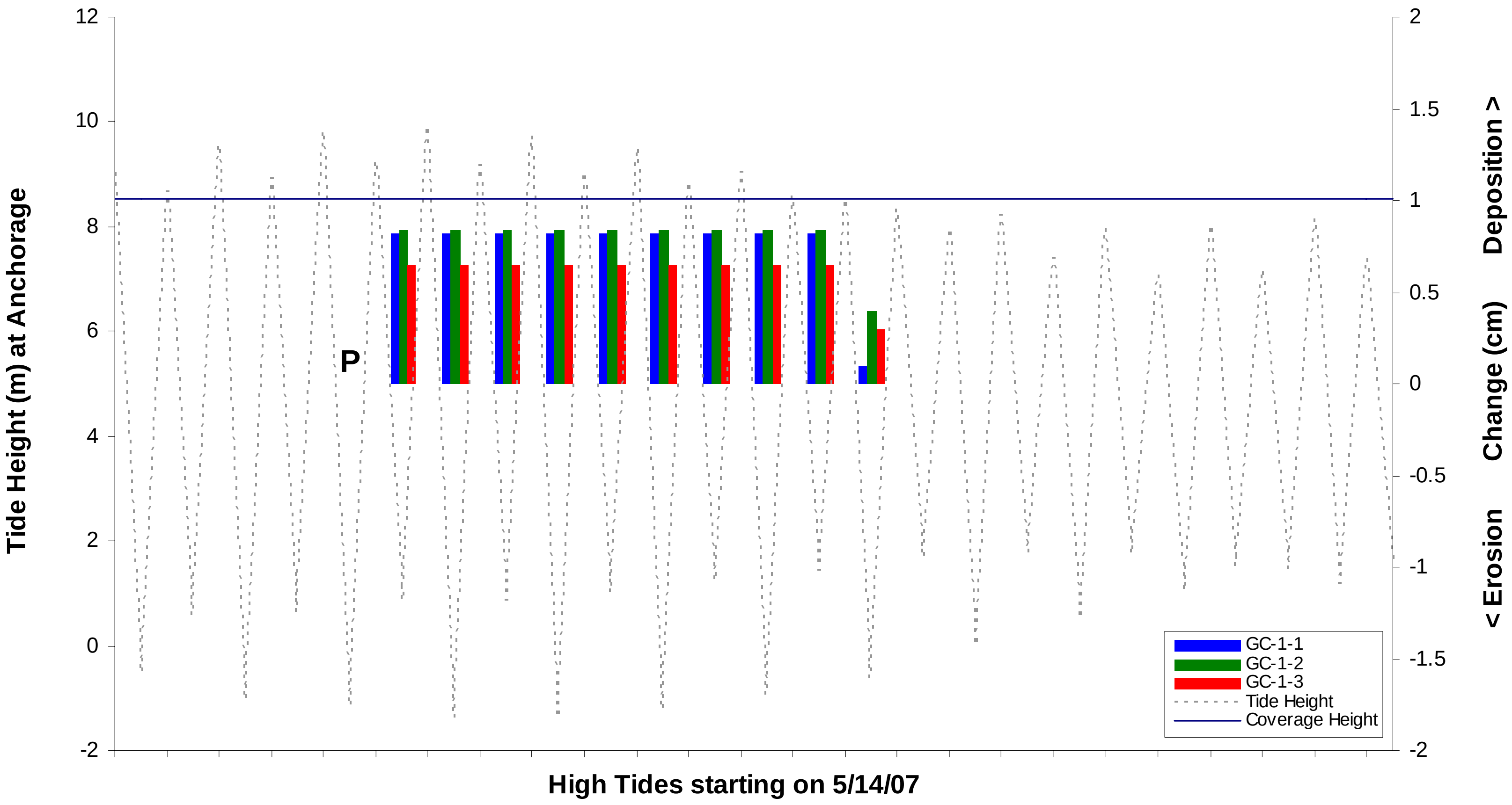


Figure 5-31: GC transect 2, May, 2007.

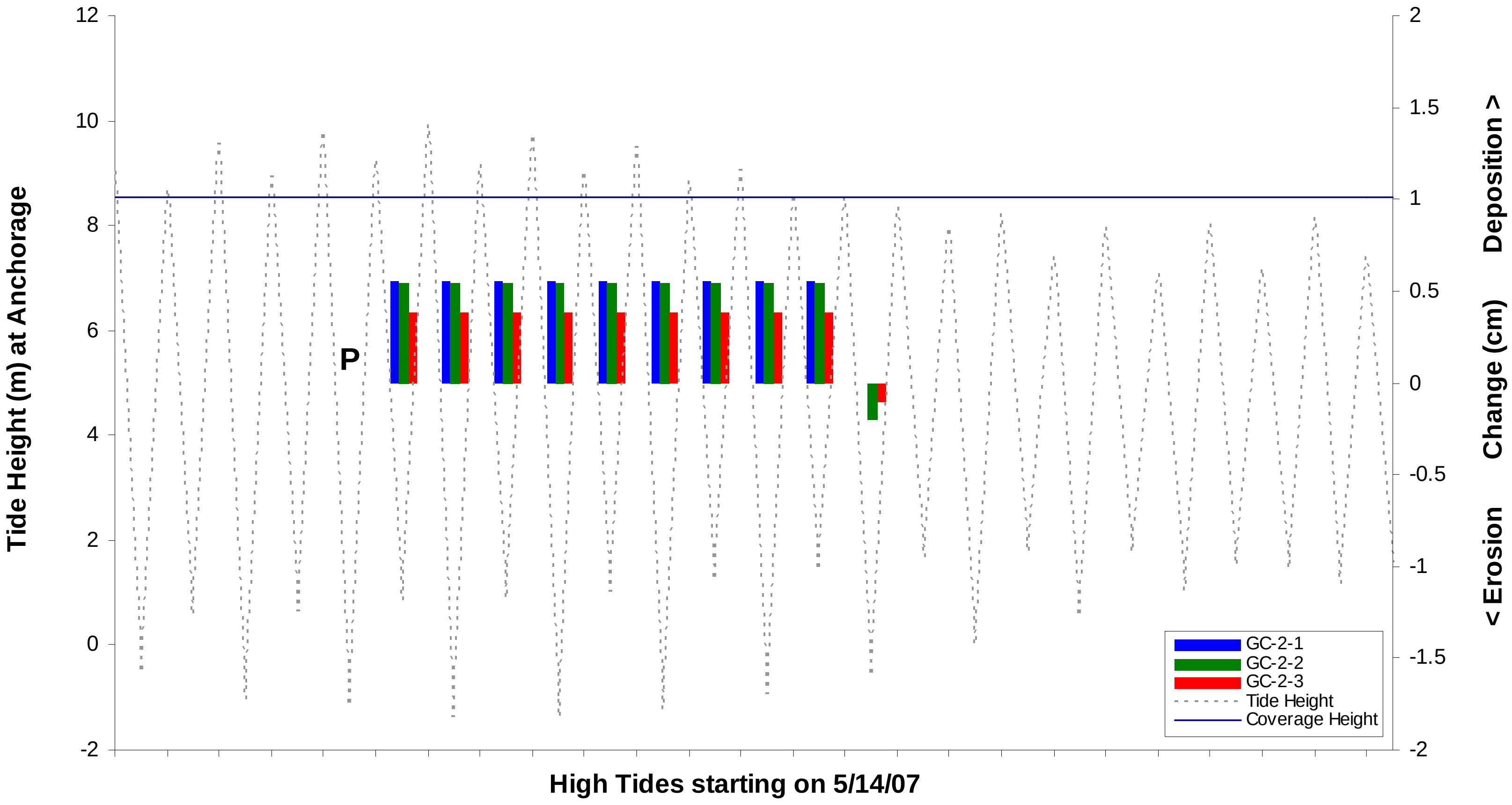


Figure 5-32: GC transect 3, May, 2007.

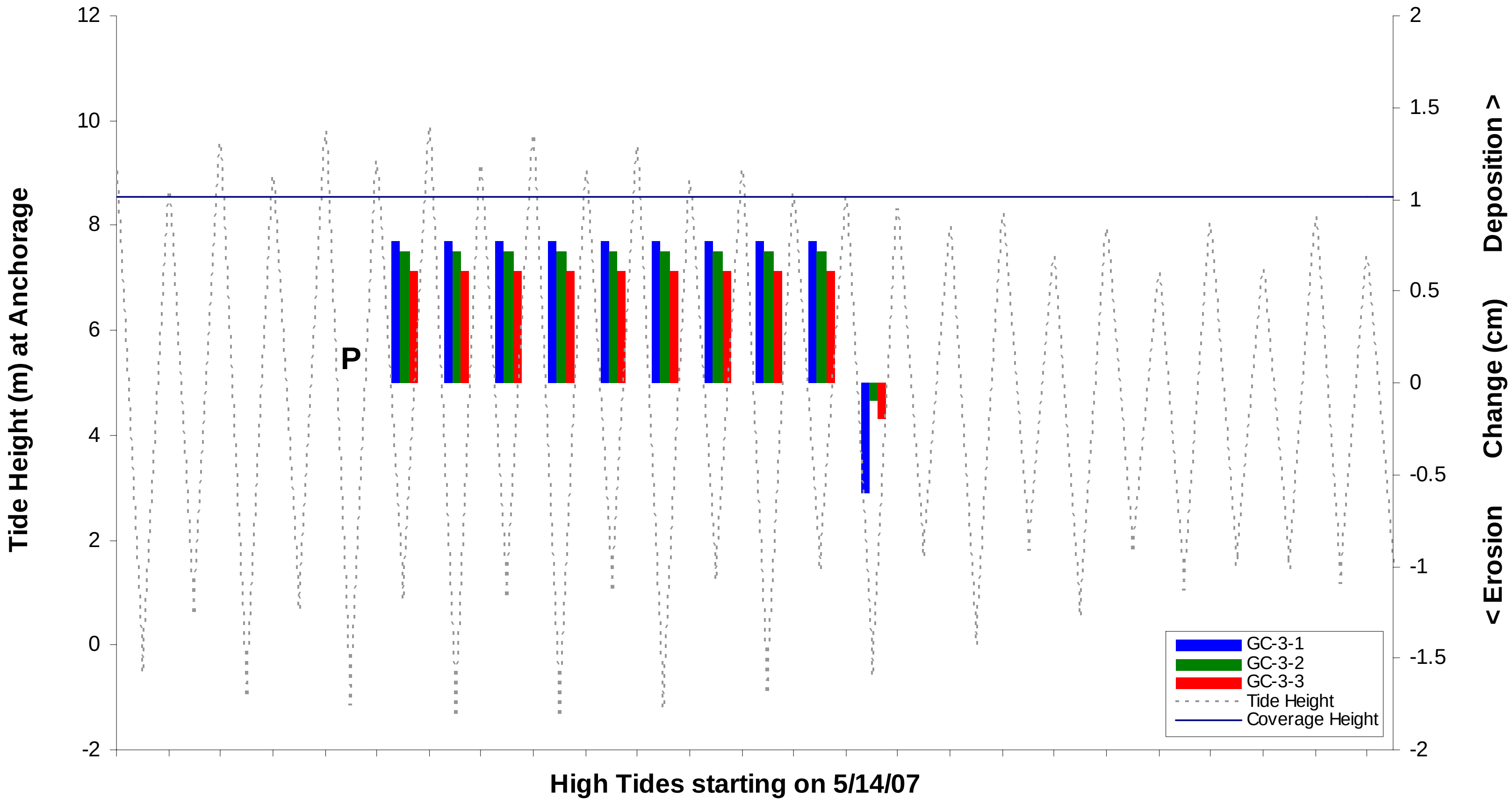


Figure 5-33: The GC study site on May 21, 2007, after high tide #14.

When the GC site was returned to at the end of July, 2007, two more transects were set. Transect 4 (Figure 5-34) was set in previous location of transect 3. Transect 5 (Figure 5-35) was placed in the same location as transect 1. Four sets of measurements were taken at each. The small swale where transect 2 was located was now a flowing channel of Glacier Creek (Figure 5-36). The erosive action of this small channel revealed an extensive section of tidal rhythmites. The first eleven high tides all deposited sediment along the transects. The maximum rate of deposition was 0.8 cm/tide at the rod 4-1 location. Both transects experienced a similar pattern of relatively constant rates of deposition followed by a period of little or no deposition or minor amounts of erosion. After high tide #17 the site was no longer submerged at high tide. During this time the surface of the flat became extensively covered with cracks and insect burrows. A tide of 8.55 m or greater was needed to cover the site. Of the nineteen observed high tides, only twelve were high enough to affect the study site. The overall morphology of the study site did not change significantly during this visit.

Figure 5-34: GC transect 4, July-August, 2007.

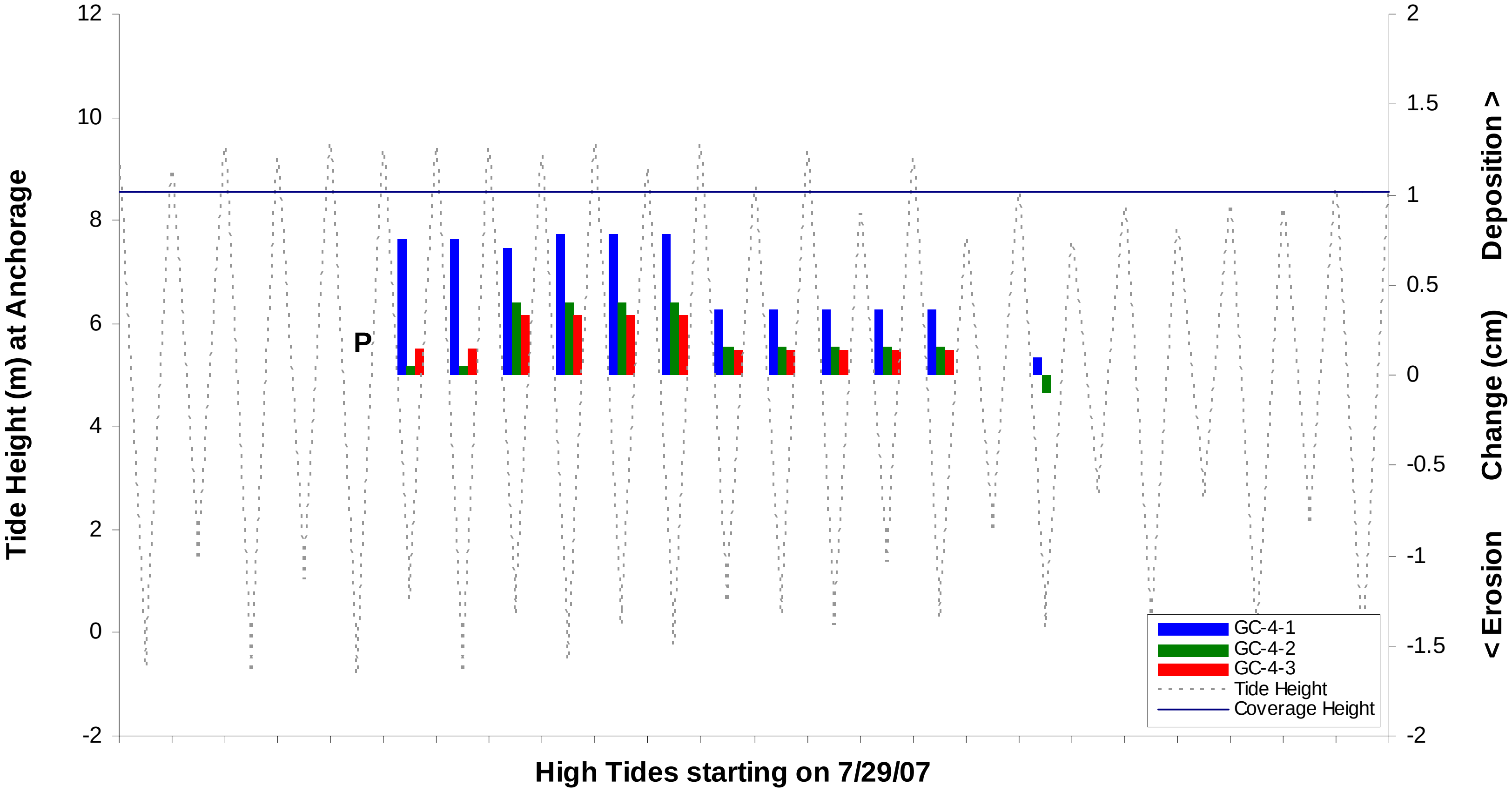


Figure 5-35: GC transect 5, July-August, 2007.

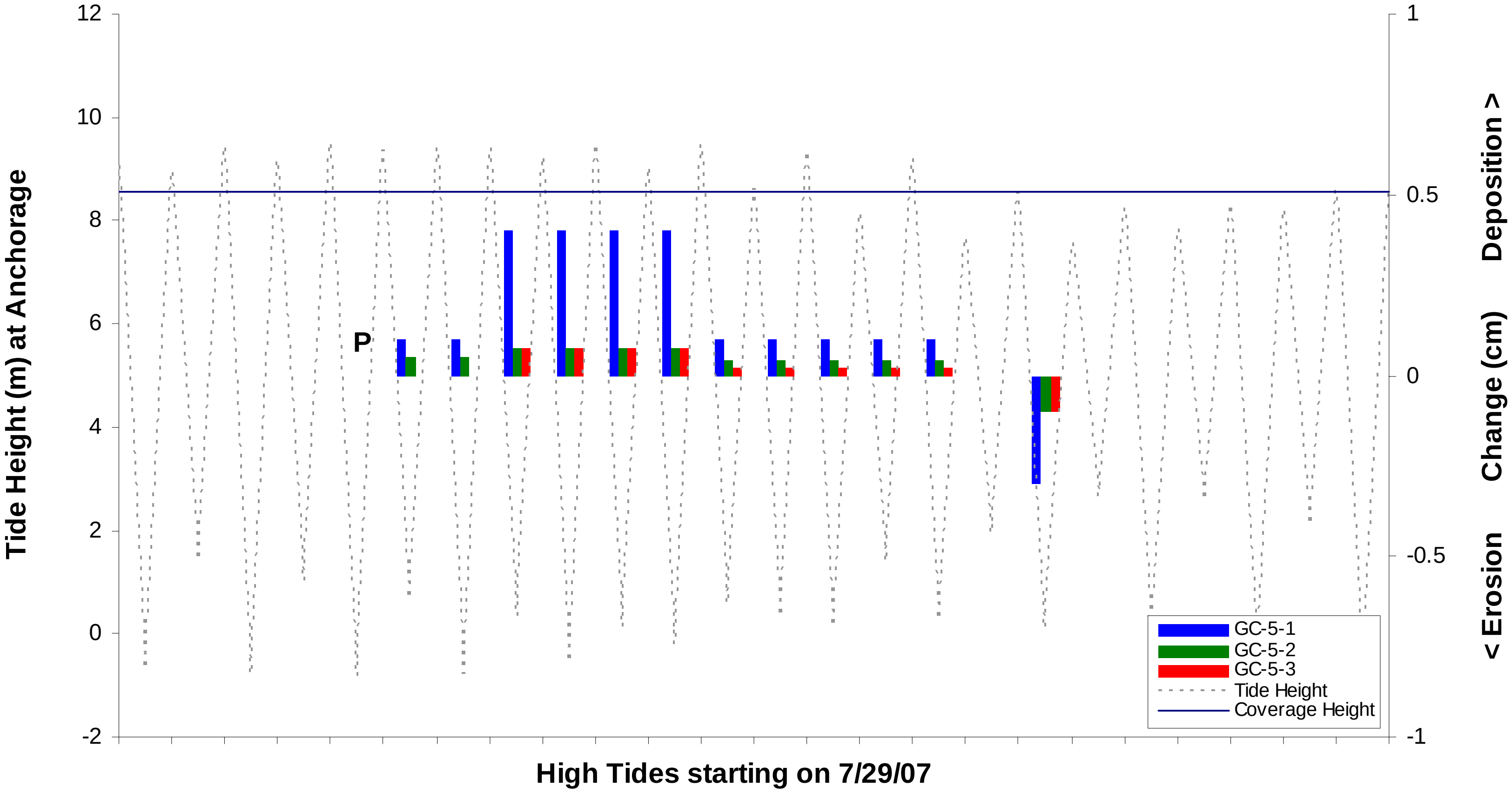


Figure 5-36: GC on July 29, 2007, following high tide #0.

Figure 5-37: GC on August 9, 2007, following high tide #21.

In July, 2009 only one transect was set at the GC site (Figure 5-38). This is because the portion of the flat that was studied the pervious summer had been completely eroded by the migration of Glacier Creek (Figure 5-39). The new transect was set along a portion of the flat just to the north of the previous transect locations (Figure 5-28 C). The cut bank exposed a continuous section of rhythmites several meters in length. Four sets of measurements were made during this visit. Deposition dominated this portion of the flat during this period. A maximum of 0.38 cm/tide of sediment was deposited during the highest of the spring tides. During this time the surface of the flat was consistently covered with straight crested ripples oriented parallel to the creek channel. Only one location experienced any erosion. Of the 25 high tides observed during this visit, only 13 were higher than the 8.72 m height needed to submerge the site. After high tide #17 the surface of the flat became covered with desiccation cracks and insect burrows. Over the two week period of observation the overall morphology of the bar did not significantly change (Figure 5-41).

Figure 5-38: GC transect 6, July, 2008.

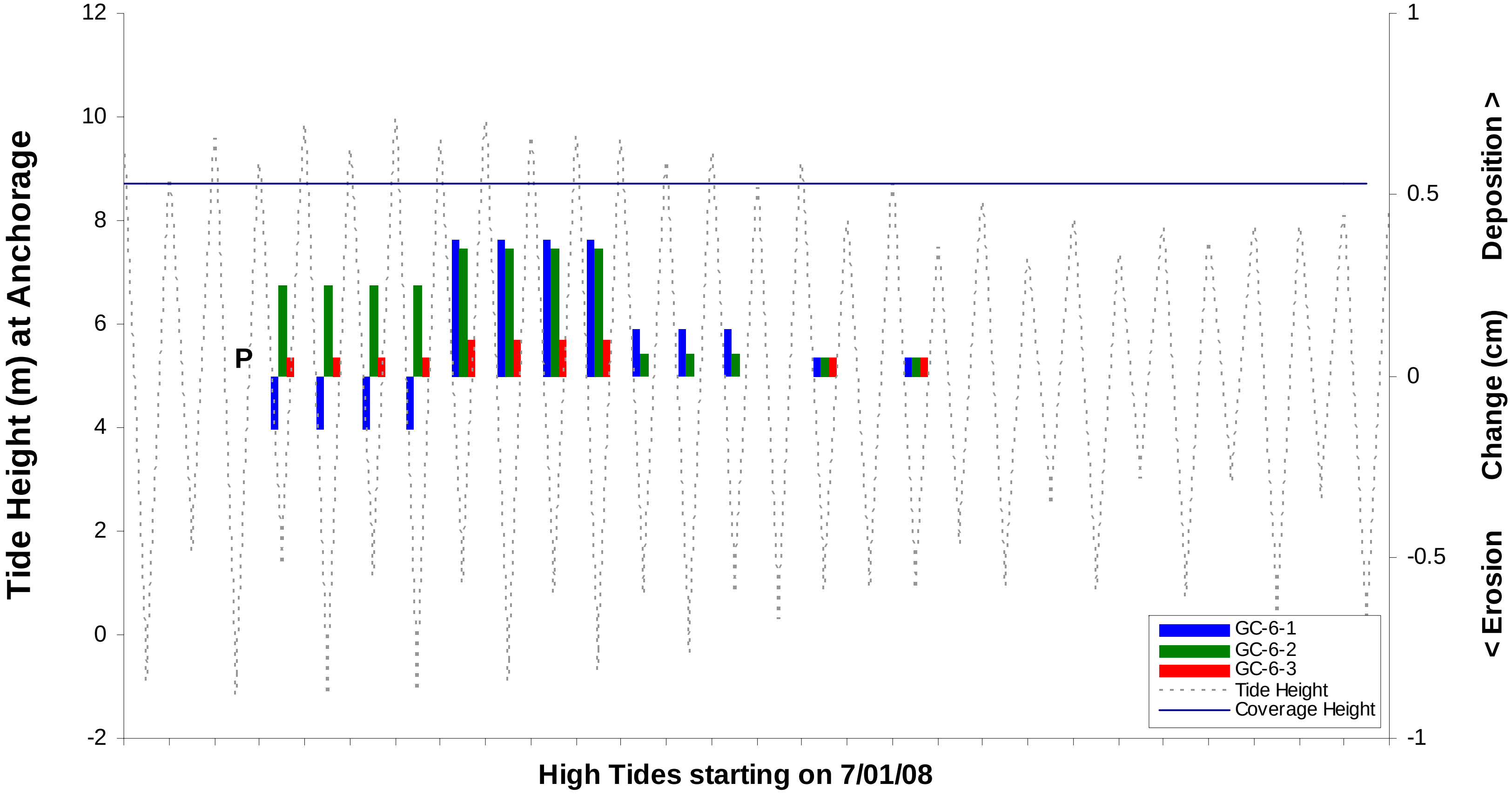


Figure 5-39: GC as it appeared on July 2, 2008.
The previously studied portion of the bar has been completely removed by the migration of Glacier Creek.

Figure 5-40: The portion of the GC site studied during July, 2008.
The person can be used as a reference with Figure 5-39 to orient the 2008 site to the 2007 site.

Figure 5-41 The GC study site on July 13, 2008, after high tide #23. The site had not flooded for a period of several days.

Peterson Creek

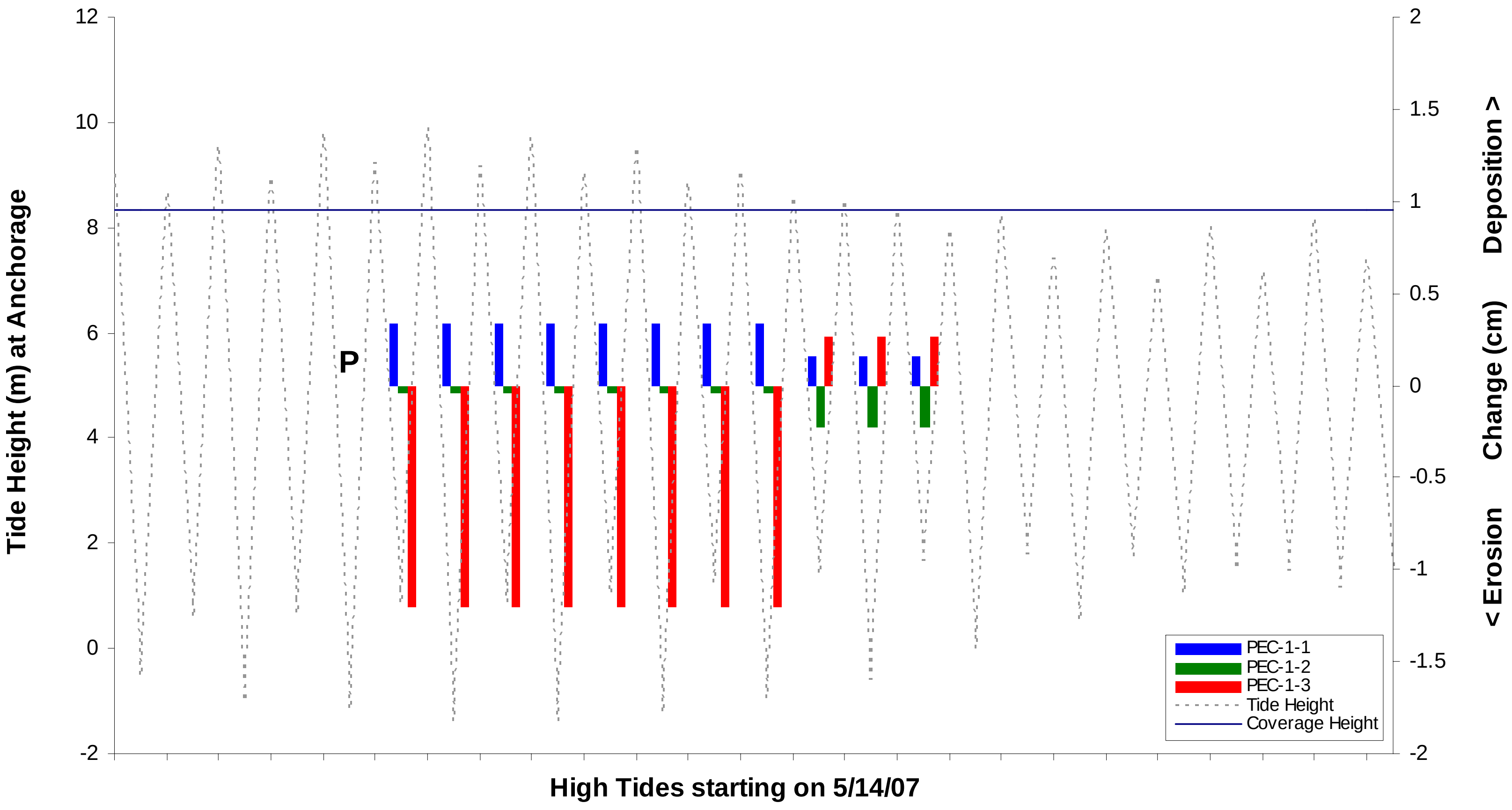
Peterson Creek is another melt water stream that flows into Turnagain Arm. As it enters the arm, it dissects a large mud flat. The braided stream transports gravel onto the tidal flat. This gravel can be transported up to 100 m out into the flat from the mouth of the creek. This flat is the largest of the study, comprising an area approximately 2000 m by 500 m. Portions of the flat on either side of the creek are the Peterson Creek (PEC) study sites (Figure 5-42). Because of the low relief of the site and the lack of easily accessible high ground, the PEC site was difficult to photograph. Figure 5-43 shows a portion of the PEC flat in May, 2007. Instead of photographing the entire site on a regular basis, individual features and changes in the morphology of the flat were described. Besides Peterson Creek, this flat is also cut by many tidal channels that meander and reshape the deposits.

Figure 5-42: Air photo and schematic of the PEC site.
Inset shows transect locations. Image from Google Earth.

**Figure 5-43 Photo of the PEC site taken on May 20, 2007.
View is to the west.**

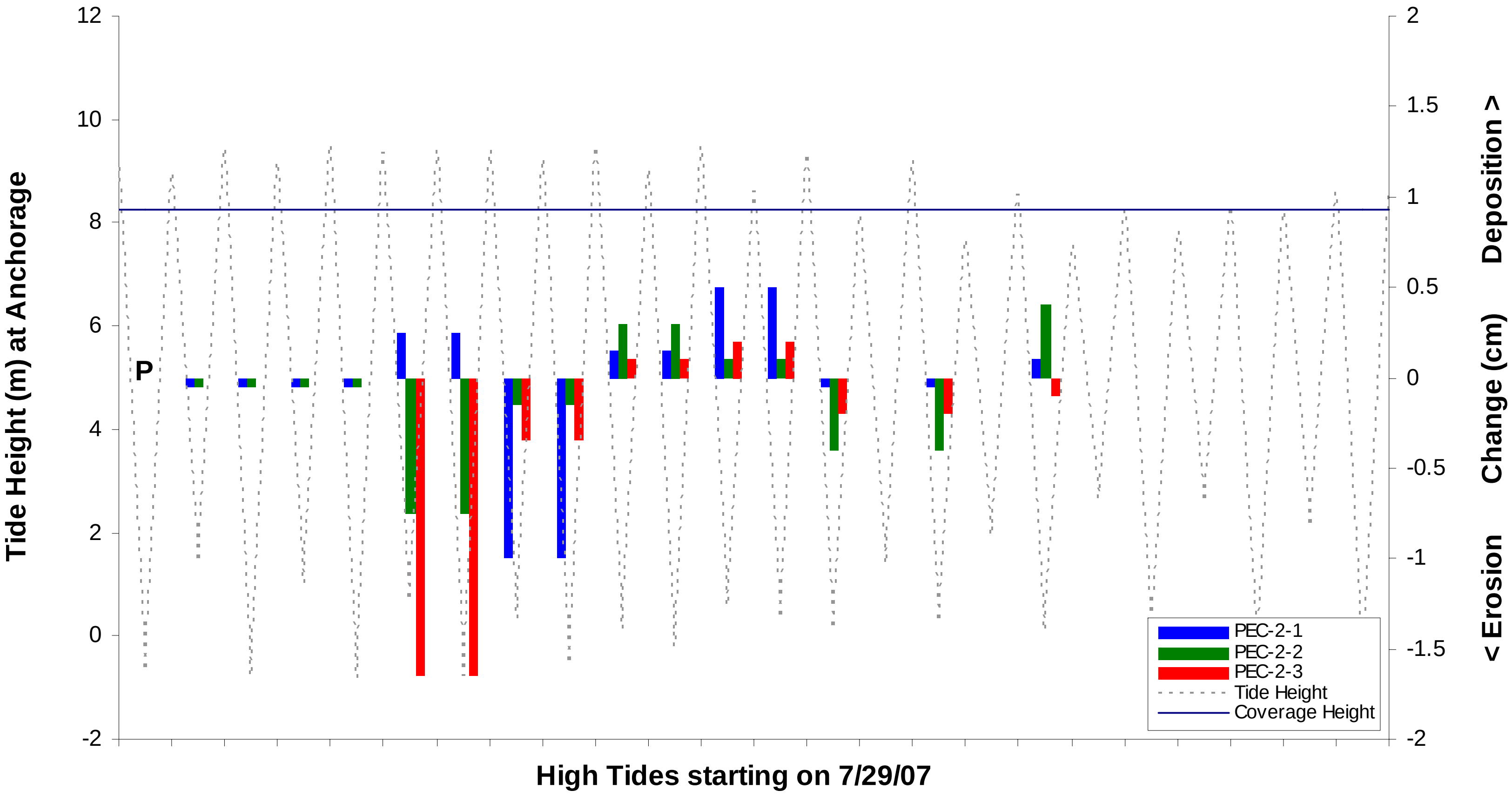
The first transect (Figure 5-44) set at PEC was set to the east of Peterson Creek, parallel to the shore line (Figure 5-42). Transect 1 was measured only twice before the tides were no longer high enough to cover the site. These measurements indicated a mixing of erosion and deposition across the bar. The greatest rate of deposition observed was 0.3 cm/tide. Erosion was measured at a rate of up to 1.2 cm/tide. Over the period of observation, large, meter-scale scours formed at the site. These often uncovered soft sediment deformation or previously rippled surfaces. Straight crested asymmetrical ripples were common. Only tides higher than 8.34 m covered the sight. During the period when the transect was being monitored, only eleven tides flooded the site.

Figure 5-44 PEC transect 1, May, 2007.



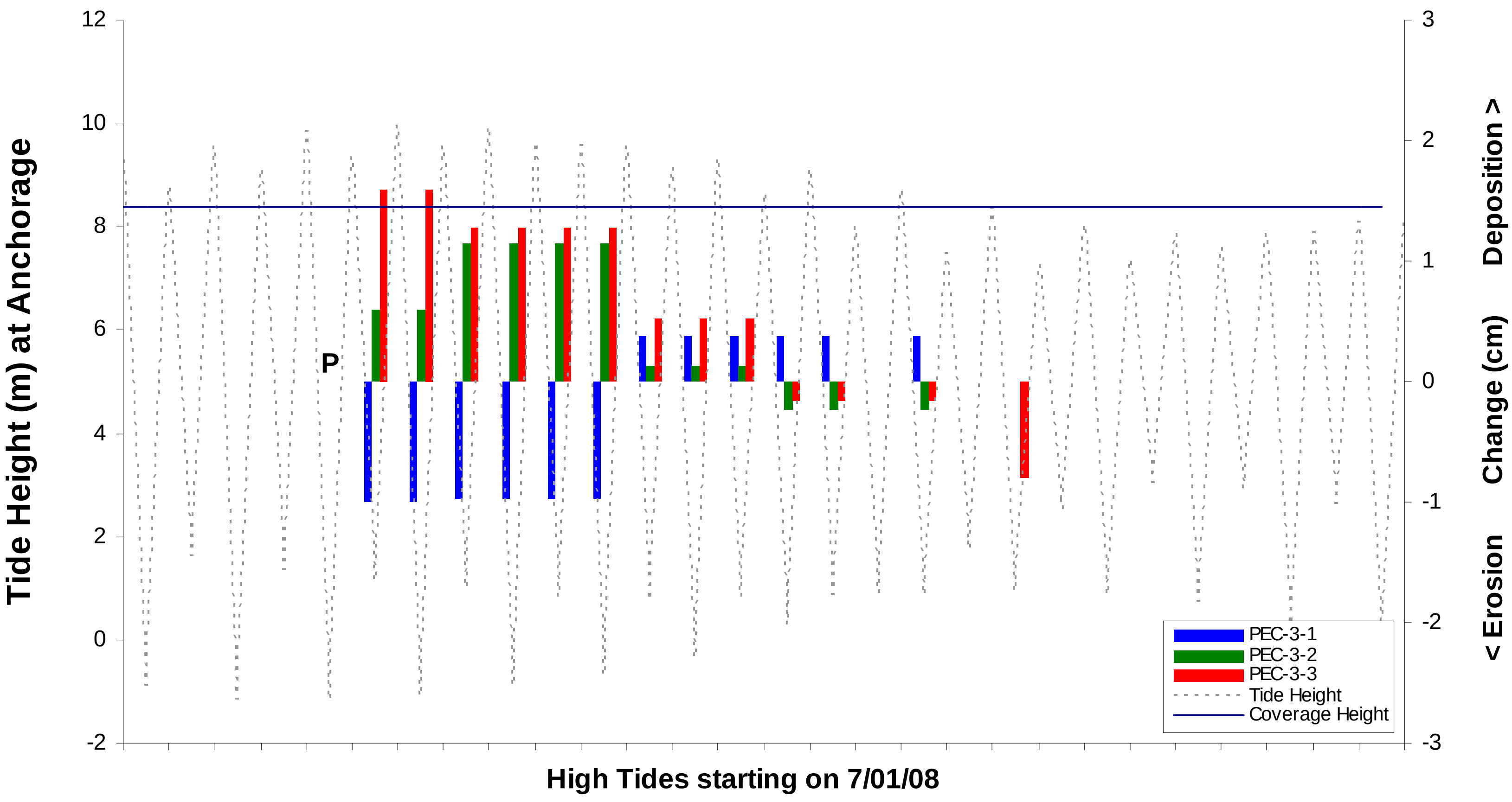
When PEC was returned to in July, 2007, the rods were reset as transect 3 (Figure 5-45). The flat was noticeably smoother than it had been in May. No large scours were present at the beginning of this visit. Over the period when the flat was being actively flooded, deposition and erosion was mixed across the flat. The maximum amount of deposition recorded was 0.3 cm/tide. The maximum amount of erosion was 0.2 cm/tide. Eleven high tides flooded the site while the transect was being monitored. Only tides greater than 9.02 m high submerged the site. While the flat was being flooded, large scours formed. These were often later filled with rippled sediment (Figure 4-9).

Figure 5-45 PEC transect 2, July-August, 2007.



Transect 3 (Figure 5-46) set in July, 2008, was set on the western side of Peterson Creek, parallel to the shore (Figure 5-42). At the beginning of observation, the flat was extensively rippled with ebb oriented interference and lingoid ripples. Large scours were also present. Four set of measurements were taken while the site was actively flooding. During this period, mud volcanoes and dewatering pits were observed forming in the small tidal channels that cut the flat. Small cut banks created by these tidal channels revealed climbing ripples and a variety of types of soft sediment deformation. Transect 3 documented mixed erosion and deposition across the flat. The maximum amount of deposition observed was 0.4 cm/tide. The maximum amount of erosion documented was 0.5 cm/tide. Only nine high tides were observed to cover the site. Tides less than 9.16 m were not high enough to flood the flat. During one low tide, Peterson Creek was meandering laterally through the tidal sediment cutting back the banks at a rate of 2 m/hr.

Figure 5-46 PEC transect 3, July, 2008.



Portage Creek #2

The eastern most study site is located at Portage Creek #2 (PC2). Portage Creek #2 is one branch of Portage Creek, a braided stream that flows from Portage Lake. Portage Lake is located 9 km to the southeast of the PC2 site. Portage Lake is a glacial lake formed behind a moraine left by the retreat of Portage Glacier. While the main sediment load of Portage Creek is gravel, fluvial gravel bars are sometimes overlain by tidal silt. This site is one of the furthest east locations where the tides have significant effects. The PC2 study site is a 350 m by 100 m bar located inside a meander bend of the creek (Figure 5-47). Figure 5-48 gives a general view of the PC2 site. Over the course of the study, six transects were monitored at this site. Transects 1, 3, and 5 were set along a small swale that meandered along the eastern edge of the bar. Transects 2, 4, and 6 were set along the highest points of the axis of the bar.

Figure 5-47: Air photo and schematic of the PC2 study site.
Portage Creek #2 flows from lower right to upper left. Image from Google Earth.

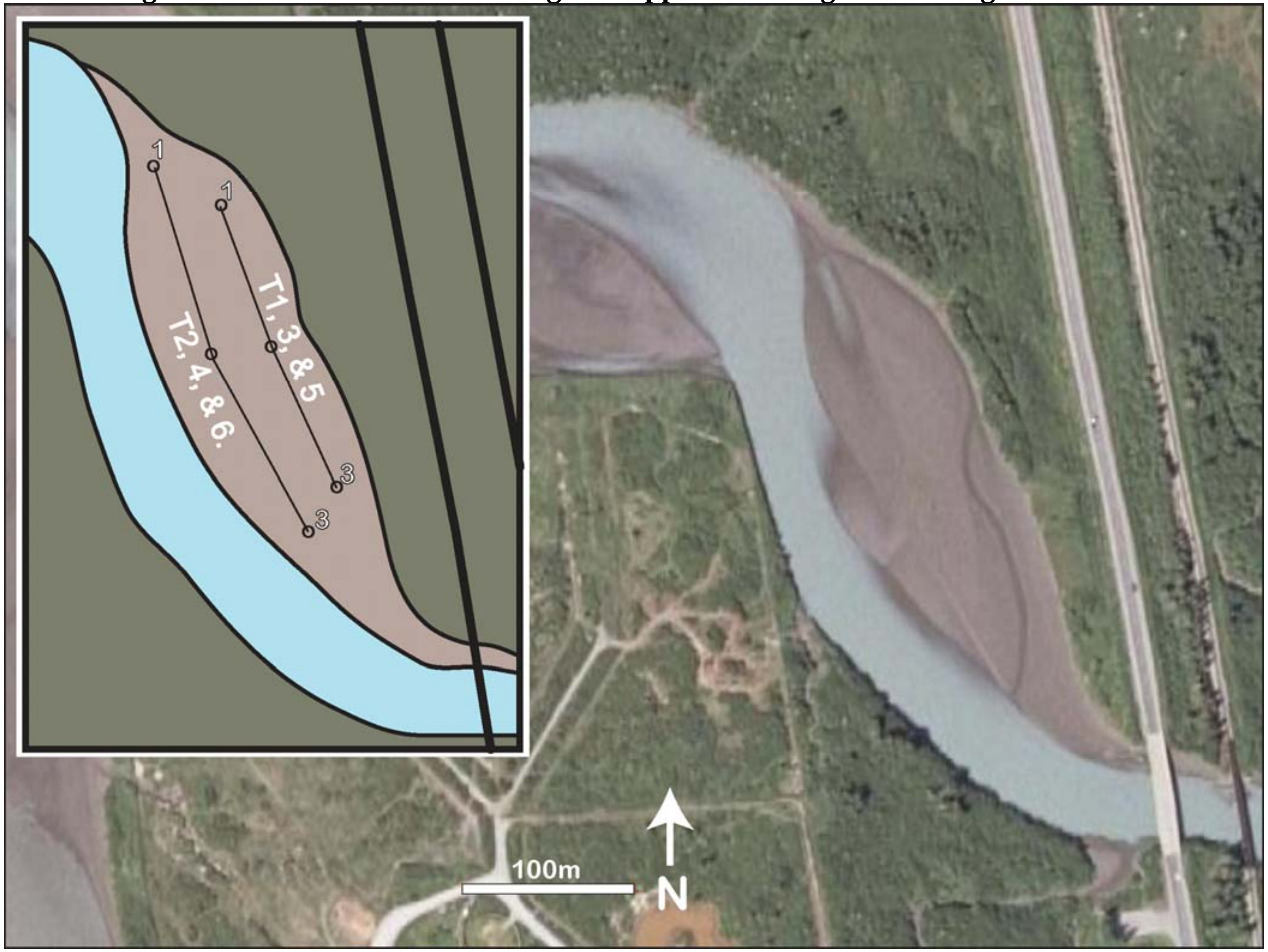


Figure 5-48: The PC2 study site on August 7, 2007.
View is to the west. Portage Creek 2 flows from right to left.

When transect 1 (Figure 5-49) and transect 2 (Figure 5-50) were set in May, 2007, the site was being actively flooded at high tide. The surface of the bar was covered with ebb oriented asymmetrical straight crested ripples. Large dewatering pits were also present on the upper portion of the bar. Over the course of observation, transect 1 recorded only deposition. The maximum rate of deposition along the swale was 1.6 cm/tide at the downstream end. This same location near rod 1-1 consistently showed the highest rates of deposition for the rest of the visit. Figure 5-51shows the site part way through the study. The small swale along transect 1 is now partially filled. At the end of this visit, water was no longer flowing through the swale at low tide. Transect 2 showed mixed erosion and deposition. The upstream end of the bar was consistently depositional with rates as high as 1.1 cm/tide at rod 2-3. The downstream portion of the bar experienced only erosion. Rod 2-1 recorded rates of erosion up to 1.2 cm/tide. After high tide #12 the site was not flooded. A high tide of 9.05 m or higher was needed to flood the site. Of the twenty two tides monitored at PC2, only nine were high enough to cover the site.

Figure 5-49: PC2 transect 1, May, 2007.

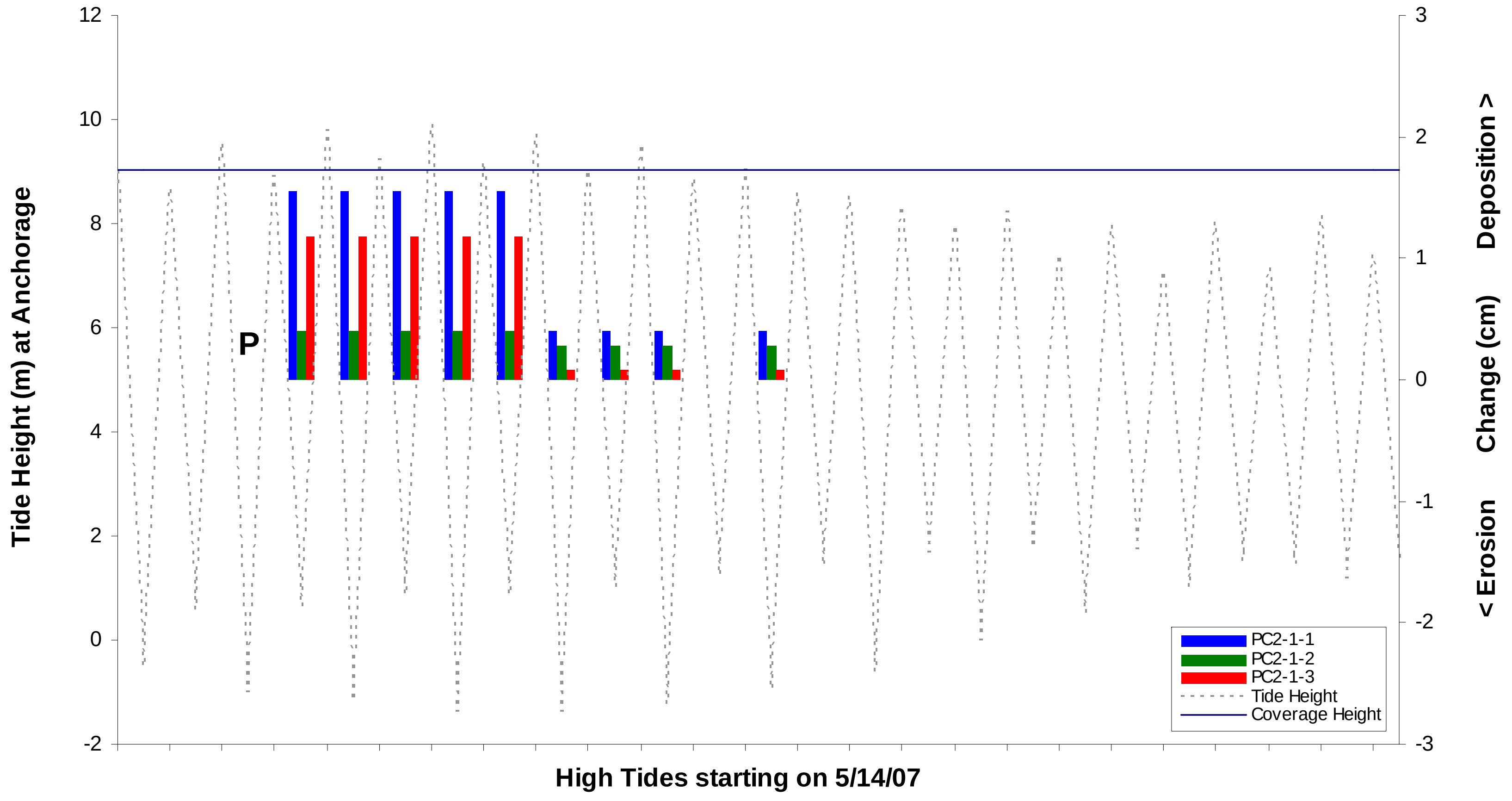


Figure 5-50: PC2 transect 2, May, 2007.

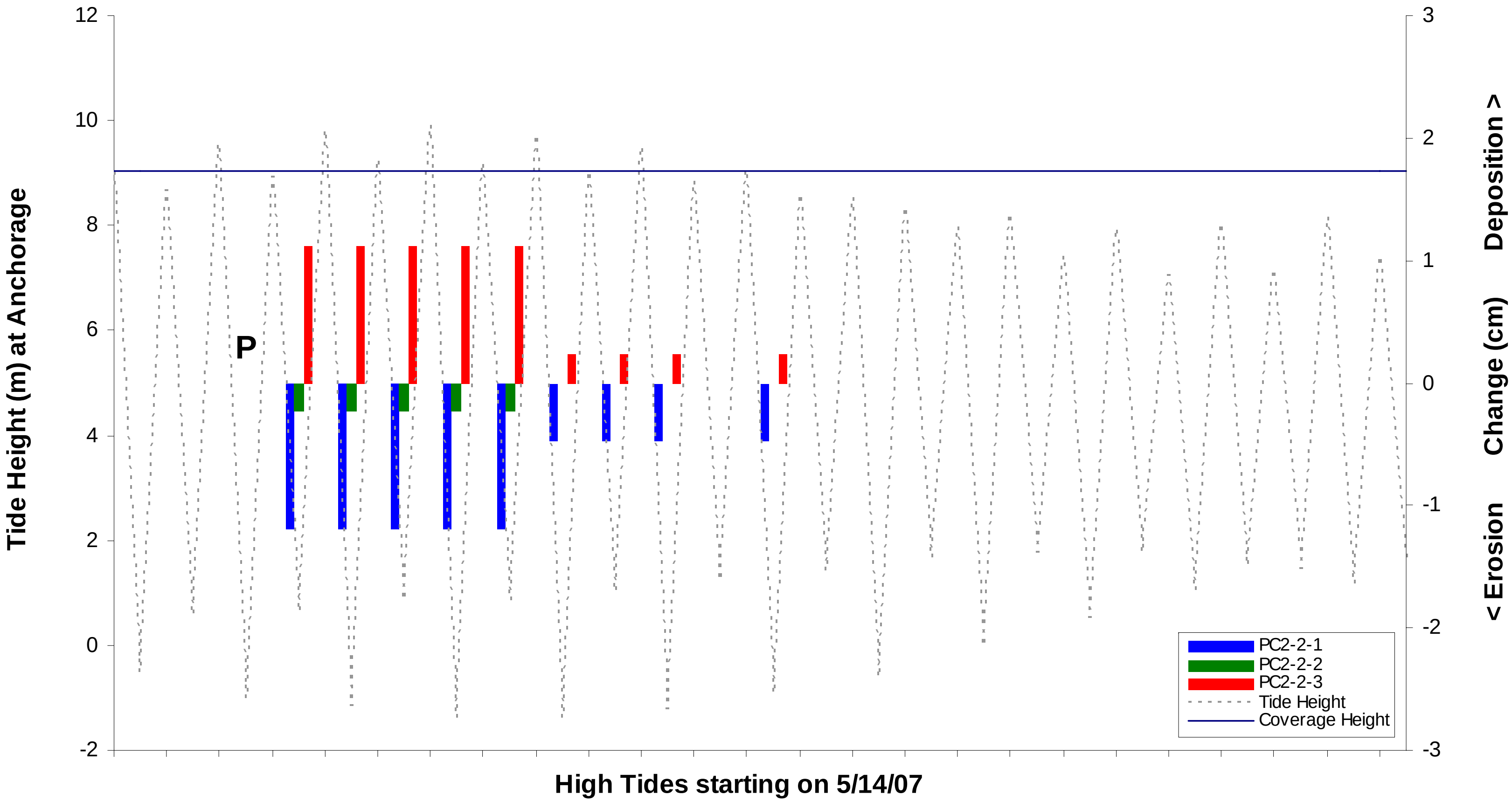


Figure 5-51: PC2 on May 20, 2007, following high tide #12.

When PC2 was revisited in late July, 2007, transect 3 (Figure 5-52) and transect 4 (Figure 5-53) were set. The overall shape and size of the bar was the same as the previous visit. The small swale along the eastern side was now a flowing channel at low tide (Figure 5-54). The surface of the bar was covered with asymmetrical straight crested ripples. Dewatering pits of various scales pock marked the upper portion of the bar. The highest point of the bar was now vegetated with grass. Over this visit, transect 3 recorded mixed deposition and erosion. Deposition was the greatest at the upstream end. Rod 3-3 recorded a maximum rate of 0.4 cm/tide here. Erosion occurred in minor amounts at all of the stations. Transect 4 on the top of the bar recorded similar rates of deposition and erosion. The maximum amount of deposition occurred at the downstream end near rod 4-1. Here a rate of 0.3 cm/tide was recorded. Minor amounts of erosion occurred at all of the rods in transect 4. After these transects were set, only eleven of the observed twenty one high tides covered them. A high tide of 9.02 m was needed to flood the site. Figure 5-55 shows the bar at the end of this period of observation. The site had not undergone any significant changes in morphology during this visit.

Figure 5-52: PC2 transect 3, July-August, 2007.

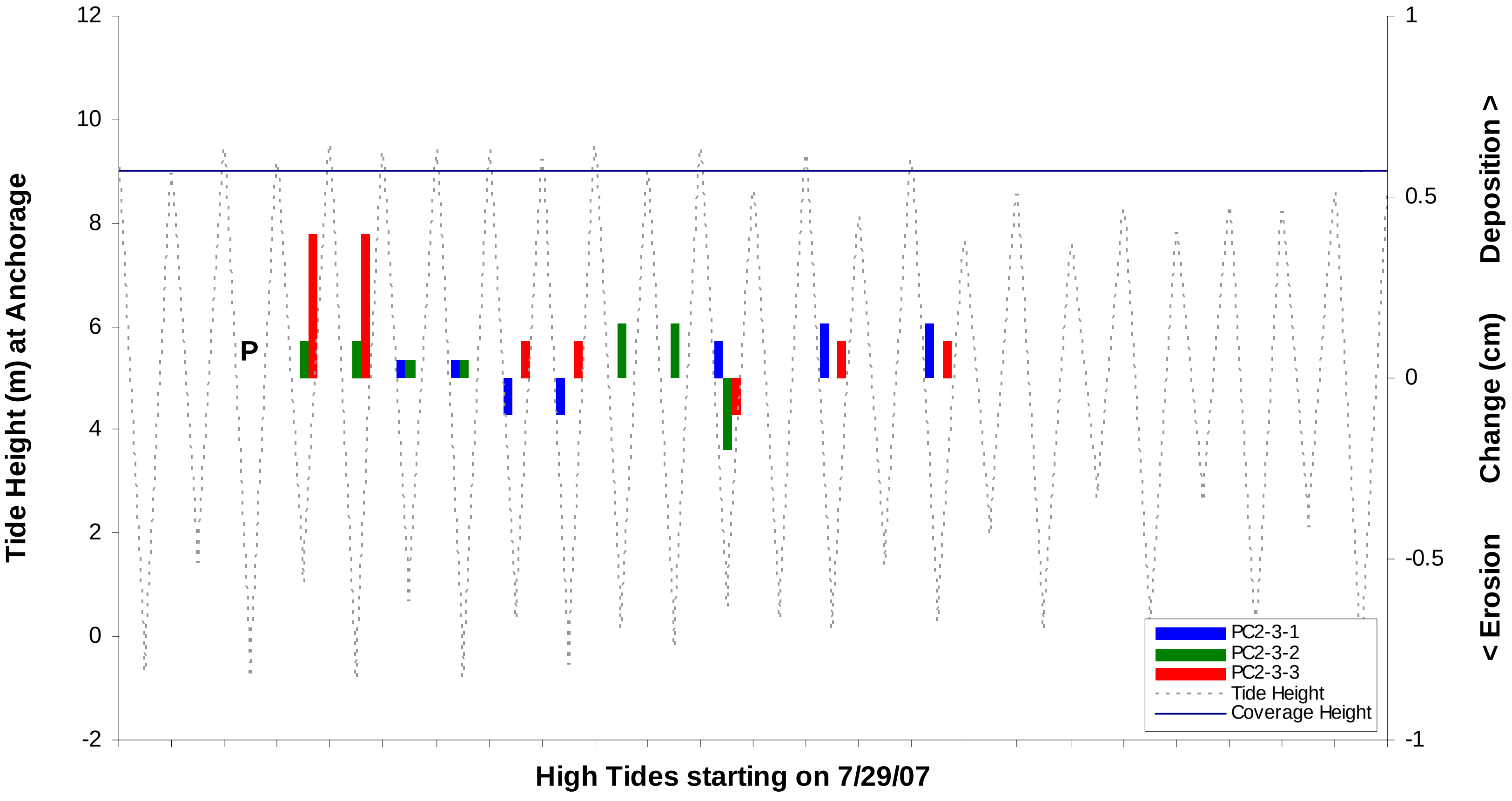


Figure 5-53: PC2 transect 4, July-August, 2007.

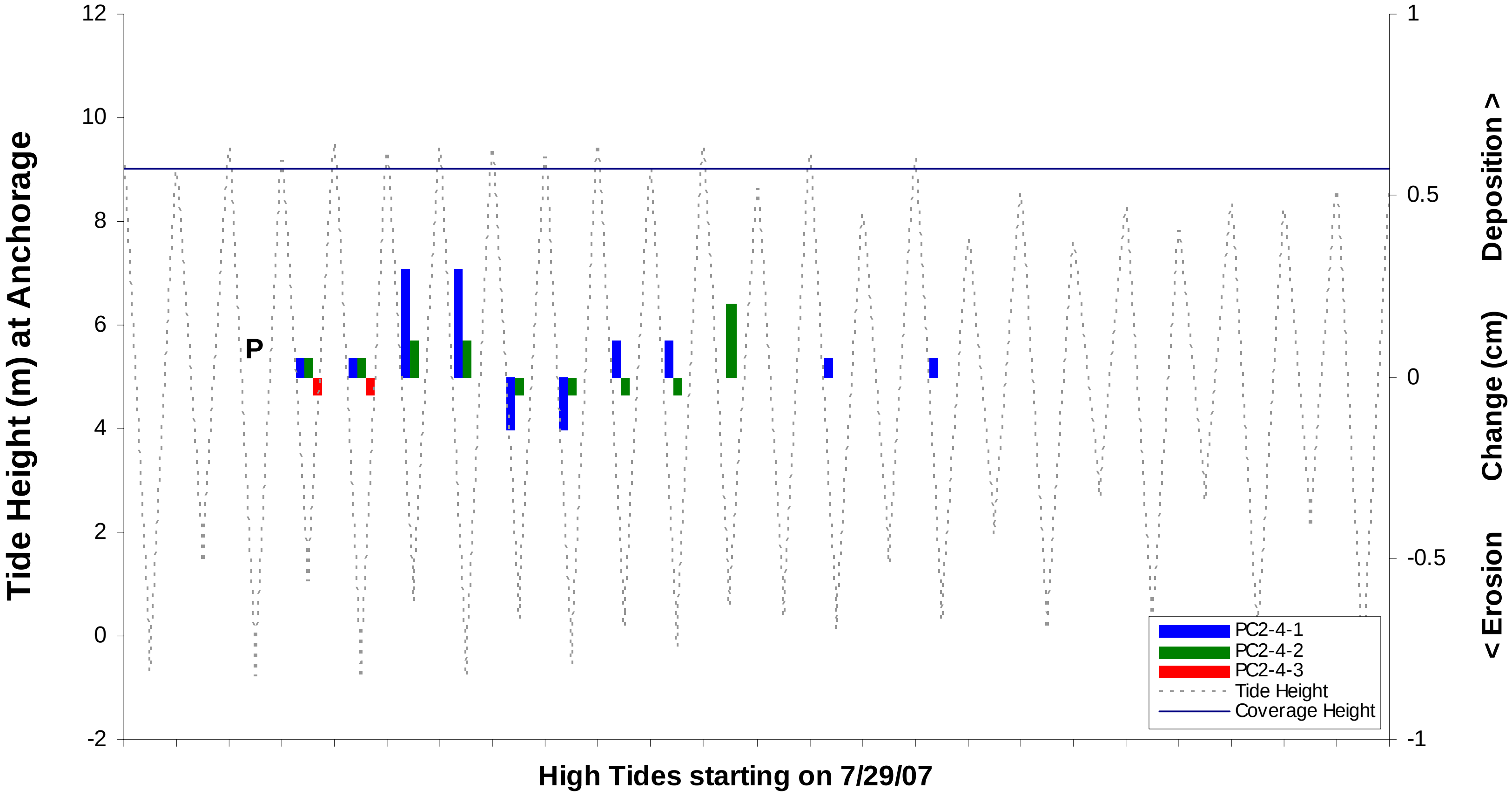


Figure 5-54: PC2 on July 29, 2007, following high tide #0.

Figure 5-55: PC2 on August 8, 2007, following high tide #23.

Transect 5 (Figure 5-56) and transect 6 (Figure 5-57) were set at PC2 in July, 2008. At the beginning of this visit, the small channel on the eastern edge of the bar was no longer flowing during low tide (Figure 5-58). The surface of the bar was covered observed with straight to slightly sinuous crested asymmetrical ripples. Large dewatering pits were also observed at various spots on the bar. The upper portion of the bar was more extensively vegetated than the previous summer. The portion of the bar along the swale was dominantly depositional as documented by transect 5. The maximum rates of deposition occurred at ends of the swale where it met the main channel of Portage Creek #2. The highest rate of deposition observed was 1.1 cm/tide at rod 5-1. The upper portion of the bar along transect 6 experienced mixed deposition and erosion during this same period. The maximum amount of deposition occurred at the downstream end of the bar near rod 6-1. Here 0.4 cm/tide of deposition was recorded. The maximum rate of erosion was documented at the highest point of the bar at rod 6-2. Here 0.5 cm/tide of sediment was eroded by the first two high tides after the rod was placed. Of the twenty three high tides observed at PC2, only nine were high enough to cover the site. A tide of 9.16 m or higher was needed to flood the study site during this visit. Figure 5-59 shows the PC2 site as it appeared at the end of the study. The only noticeable change to the bar over this period was that the swale on the easterly side of the bar became more filled.

Figure 5-56: PC2 transect 5, July, 2008.

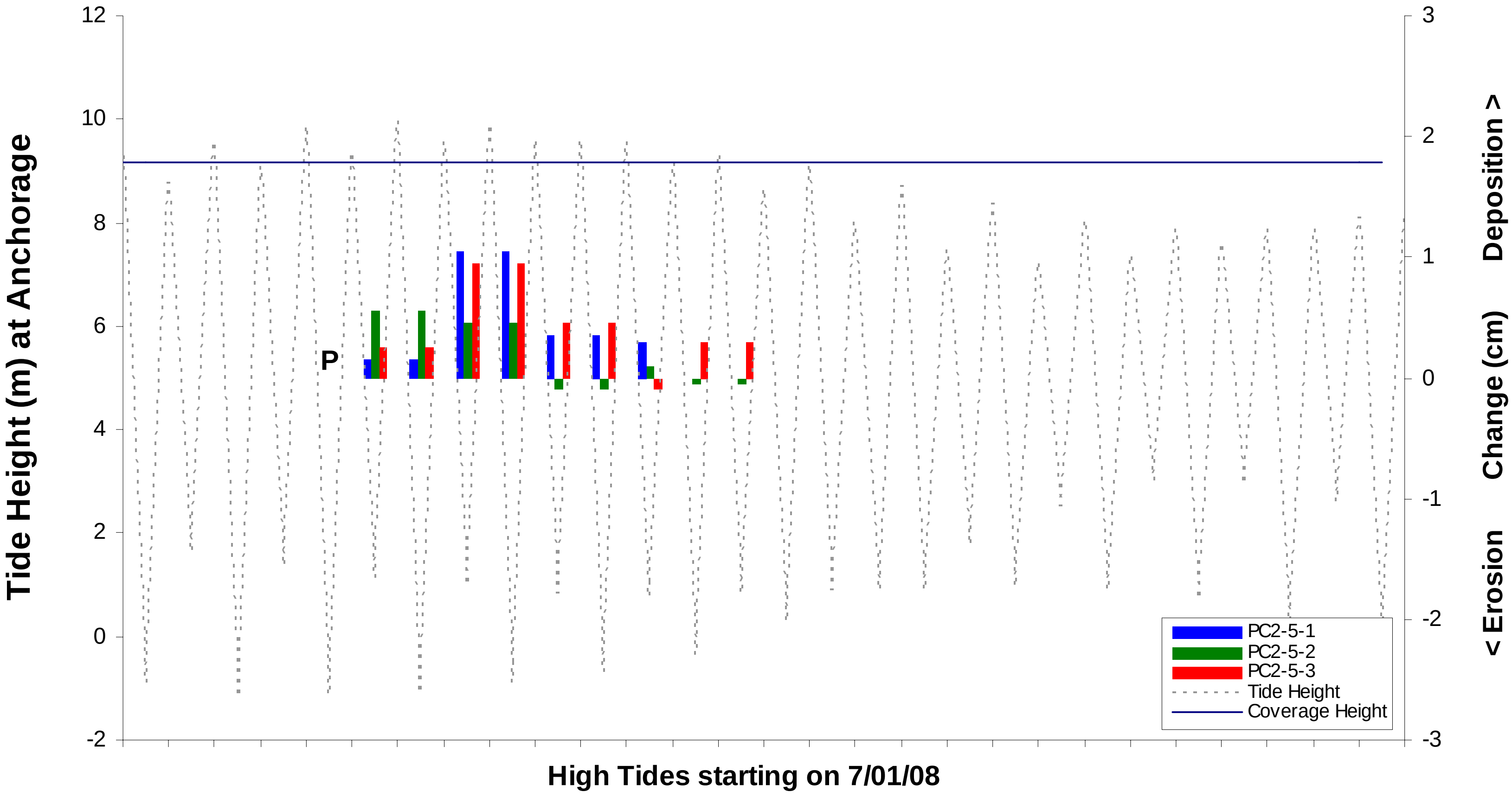


Figure 5-57: PC2 transect 6, July, 2008.

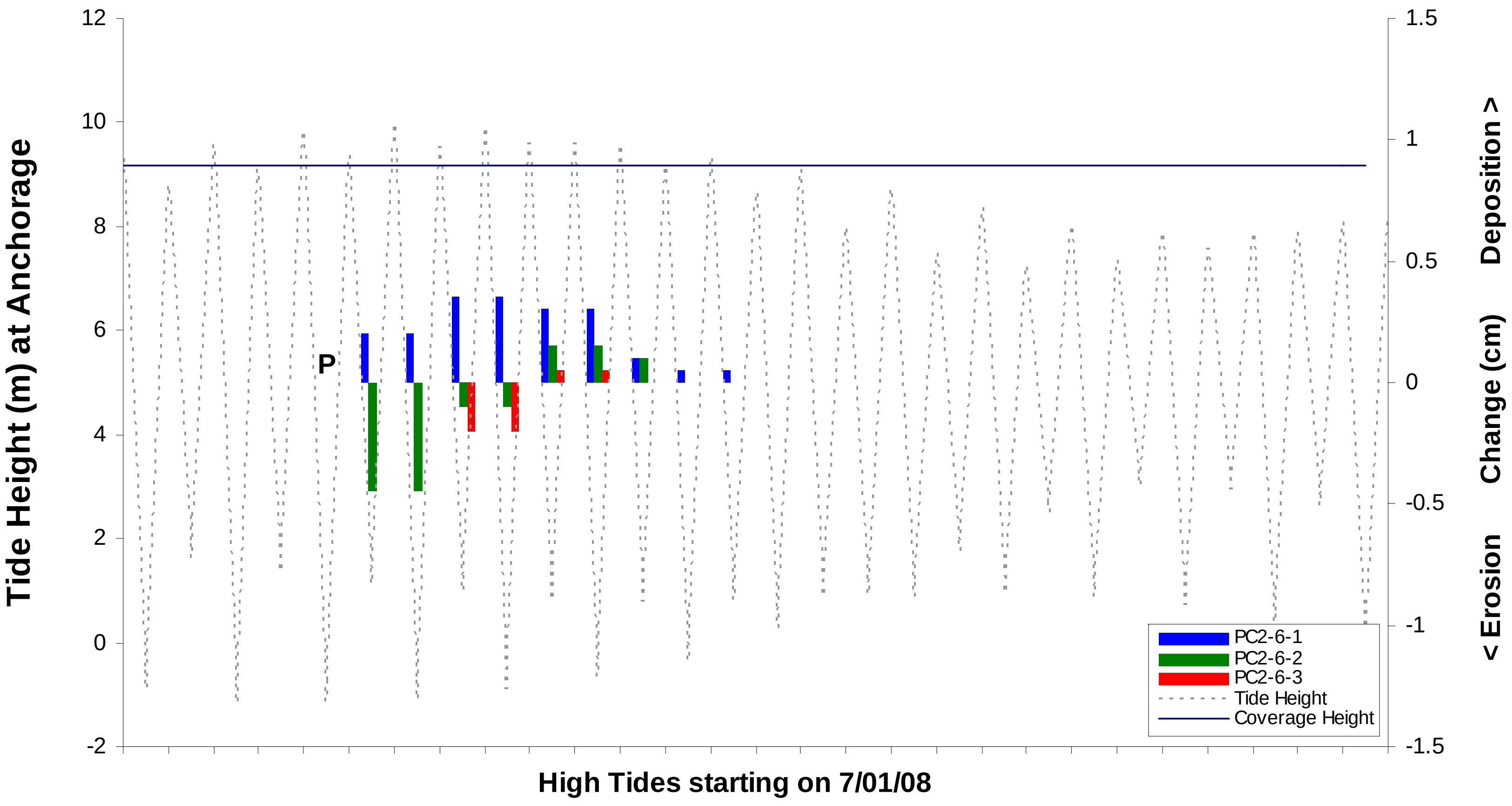


Figure 5-58: PC2 on July 4, 2008, following high tide #4.

Figure 5-59: PC2 on July 14, 2008, following high tide #25.

CHAPTER 6 - Summary of Observations

The study site at Bird Point consistently showed the highest rates of deposition and erosion over the course of the study. The highest single tide rates of deposition and erosion were recorded here. In May, 2007, 8.9 cm/tide of sediment was observed being deposited at EBP. 13.5 cm/tide of erosion was documented at EBP in July, 2008. EBP consistently underwent a period where high rates of deposition dominated during the spring tides. This was followed by a period of lower rates of deposition or erosion during the neap tides. A significant amount of erosion can be attributed to cut-bank action during the neap tides. No rhythmites were ever observed at EBP. This is probably due to the extremely high rates of deposition and erosion. These extreme rates are likely due to the location of the site within the estuary. This site experienced the highest tidal flux of any of the study sites. The impact of the tidal bore could also be a factor. The EBP site is a good candidate for further evaluation as it seems to be a semi-permanent feature.

The second highest rates of deposition and erosion were recorded at the Tidal Bore Overlook #4 site. The greatest rate of deposition observed here was 3.0 cm/tide, while the greatest rate of erosion documented was 4.5 cm/tide. An ebb tide velocity of 6 m/s and a flood tide velocity of 10 m/s were measured at this site. Although this site was flooded by all high tides, some the lowest of the neap high tides only briefly covered the site. Over the course of the study, soft-sediment deformation was consistently found at TBO4. The TBO4 site also seems to be semi-permanent as it is formed in an area protected from the migration of the main tidal channel. No rhythmites were observed at TBO4.

The lowest rates of deposition and erosion were consistently measured at the Glacier Creek site. Over the course of the study, only millimeter-scale rates of deposition and erosion were noted. Deposition dominated during the spring tides when the site was being actively flooded. Rhythmites were observed at this site during all three visits. The scale of per-tide deposition closely matches the thicknesses of the lamina in these rhythmites. Erosive events tended to remove multiples of entire laminations. The low rates of erosion are result of the location of this flat. The GC site is situated within a pocket of salt marsh that protects it from wave action. The channel of Glacier Creek is extremely sinuous as it meanders through the mud flats to join the main tidal channel. This addition of length decreases the effect of the bore as it migrates up the creek channel. Extensive tidal flats are located to the south of this site. When the tide rises and falls at this site, it does so in a very gentle manner. These factors combine to make the GC site ideal for the accretion and short term preservation of rhythmites. However, on average, only tides higher than 8.60 m will flood this site. Fluvial gravels underlie the tidal flats at this site. These gravels aid in the vertical movement of water through the tidal silt, creating soft sediment deformation and dewatering structures. The GC site experienced the greatest change in morphology over the course of the study. Between the summers of 2007 and 2008, Glacier Creek migrated and eroded a significant portion of the tidal flat. This migration over time creates accommodation space for the deposition of tidal sediment, but limits the amount of time that these deposits may be preserved.

The flats at the Peterson Creek site experienced mixed deposition and erosion throughout the study. The highest rates of both were seen during the highest of the spring tides. The maximum rate of deposition recorded was 0.4 cm/tide while the maximum rated of erosion observed was 1.2 cm/tide. No rhythmites were observed at the PEC site during this study. Meter-scale scours and extensive areas of soft sediment deformation were common during the study. The portions of the flat nearest the channels of Peterson Creek were underlain by fluvial gravels. In these areas dewatering structures frequently form. Areas along these channels are constantly being reworked by them migration of the creek and other tidal channels. Averaged over the duration of the study, a high tide with a minimum height of 8.84 m was needed to flood the flat.

The study site with the least tidal influence was the Portage Creek #2 site. During the study, on average, only high tides greater than 9.08 m flooded the site. This resulted in only a relatively small number of measurements of deposition or erosion. The maximum rate of deposition of tidal sediment measured was 1.6 cm/tide. The highest rate of erosion documented was 1.2 cm/tide. Deposition and erosion was mixed through out the tidal cycle, with the greatest rates of both coming during the highest of the spring tides. The greatest change to the overall morphology of the bar was the cyclical filling and eroding of the small channel on the eastern side of the bar. Over the course of the study, the upper, less frequently flooded portion of the bar became more vegetated. This will likely increase the stability of the bar and minimize any erosive action on that portion of the bar. This site is also underlain by fluvial gravels, making large dewatering structures common. During this study no rhythmites were observed at this site.

CHAPTER 7 - Conclusions

The rates of deposition and erosion of tidal sediments in Turnagain Arm are directly linked to two variables. The first of these variables is tide height. The highest rates of tidal deposition and erosion occur during the highest of the spring tides. The absolute highest rates of erosion documented were the result of cut-bank action shortly following the highest of these tides. The neap tides were dominated by much lower rates of deposition and erosion, if the site was covered at all. Erosive events tend to remove multiples of entire laminations. The second variable controlling sedimentation is the location of each site within the estuary. The sites farthest out into the estuary experienced the greatest tidal flux and were covered by all high tides. As a result, they were more dynamic, experiencing deposition and erosion throughout the entire neap-spring cycle. Moving farther up into the estuary, progressively higher high tides are needed to cover each site. Some localities at the extreme limits of tidal influence are only covered by the extreme high spring tides. If rhythmites were to be found at these localities, they would only preserve a limited portion of the tidal record.

Rhythmites are likely to be preserved for a short time in locations that are protected from wave impact and the passing of the bore. The Glacier Creek site is an example of this type of site. While rhythmites are preserved for a short time here, they only record the high tides that were high enough to submerge the site and those that resulted in deposition. This is why care should be taken when interpreting tidal rhythmites of ancient estuaries.

References

Archer, A.W., and Hubbard, M.S., 2003, Highest tides of the world. In: Chan, M.A., and Archer, A.W. (Eds.), Extreme depositional environments: mega end members in geologic time. Boulder, Colorado, Geological Society of America Special Paper 370, p. 151-173.

Atwater, B.F., Yamaguchi, D.K., Bondevik, S., Barnhardt, W.A., Amidon, L.J., Benson, B.E., Skjerdal, G., Shulene, J.A., and Nanayama, F., 2001, Rapid resetting of an estuarine record of the 1964 Alaska earthquake. Geological Society of America Bulletin 113, 1193-1204.

Bartsch-Winkler, S., and Ovenshine, A.T., 1984, Macrotidal subarctic environment of Turnagain and Knik Arms, Upper Cook Inlet, Alaska: Sedimentology of the intertidal zone. Journal of Sedimentary Petrology, v. 54, p. 1221-1238.

Burns, L.E., Pessel, G.H., Little, T.A., Pavlis, T.L., Newberry, R.J., Winkler, G.R., and Decker, J., 1991, Geology of the northern Chugach mountains, south-central Alaska: State of Alaska, Division of Geological and Geophysical Surveys Professional Report 94, p. 29-30.

Greb, S.F., and Archer, A.W., 2007, Soft-sediment deformation produced by tides in a mizoseismic area, Turnagain Arm, Alaska. Geology, v. 35, no. 5, 435-438.

Hjulström, F., 1935, Studies of the morphological activity of rivers as illustrated by the River Fyris: Geological Institute of University Uppsala Bulletin, v. 25, p. 221-527.

Kanamori, H., 1978, Quantification of great earthquakes. Tectonophysics, v. 49, p. 207-212.

Schroll, H.R., Szabo, B.J., Rubin, M., and Dobrodny, E., 1972, Radiocarbon dating of marine shells from the Bootlegger Cove Clay, Anchorage area, Alaska: Geological Society of America Bulletin,v. 83, p. 1107-1114.

Appendix A - EBP Photos

**Figure A-1: Cut bank formed in August 2007.
Shovel is 1 m tall.**

Figure A-2: 1 m tall cut bank dissected by runoff from the bar.

Figure A-3: Bands of organic debris left by the falling water level. Note boot for scale.

Figure A-4: Surface of the bar after erosion dominated period. Scale is in cm/dm.

Figure A-5: The 64 cm of sediment deposited at rod 6-1 by nineteen high tides in July, 2008.

Appendix B - TBO4 Photos

Figure B-1: Soft sediment deformation observed on eroded surface, May, 2007. Scale is in cm/dm.

Figure B-2: Soft sediment deformation exposed on the surface of the bar, May, 2007. Scale is in cm/in.

Figure B-3: Planed off ripples at TBO4.
Scale is in cm/dm.

Figure B-4: Starved ripples at TBO4.
Scale is in cm/dm.

Figure B-5: Polygonal mud cracks at TBO4.

Appendix C - GC Photos

Figure C-1: Section of rhythmites exposed in a cut bank in May, 2007. Scale is in cm/dm.

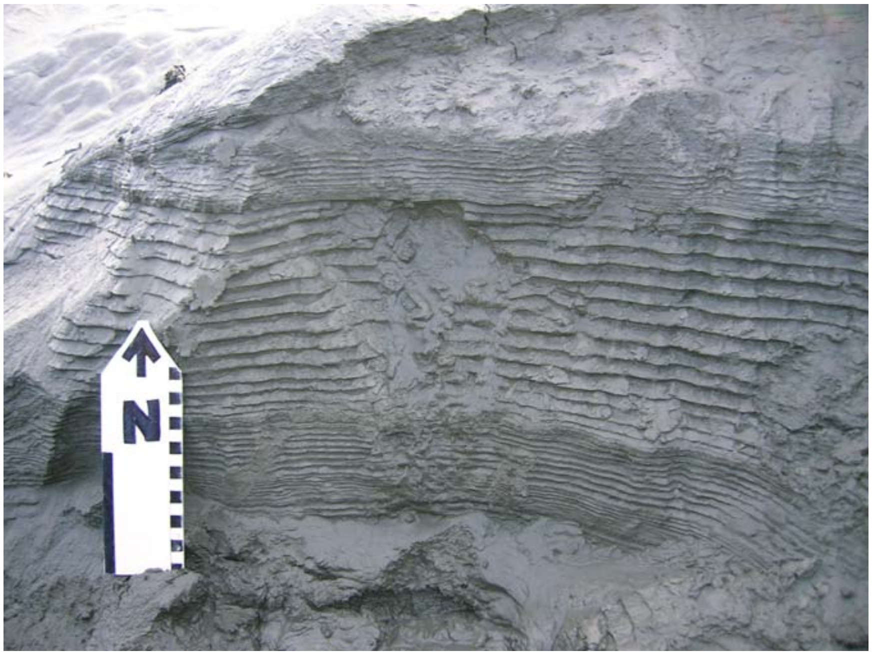


Figure C-2: Small scale laminations on upper surface of flat, July, 2008. Scale is in cm/in.

Figure C-3: Salt marsh and peat layer to the west of the GC site. The peat layer represents the pre-1964 earthquake land surface.

Figure C-4: Salmon fin drag marks on upper surface of the flat. Scale is in dm/in.

Figure C-5: Large dewatering pits observed in August, 2007. Shovel blade is 20 cm wide.

Appendix D - PEC Photos

Figure D-1: Scours covering the surface of the flat in May, 2007. Scale is 20 cm long.

Figure D-2: The multiple channels of Peterson Creek as it spreads out on the flat.

**Figure D-3: Erosion of rippled surfaces.
Scale is 50 cm.**

**Figure D-4: Soft sediment deformation eroded in cut bank.
Scale is in cm.**

Appendix E - PC2 Photos

Figure E-1: Large dewatering pits on highest vegetated point of the bar. Scale is 20 cm.

Figure E-2: The PC2 site at high tide on August 3, 2007.

Figure E-3: Ebb directed ripples typically found at PC2. Scale is in cm/dm.

Figure E-4: The vegetated upper portion of the bar in July, 2008.