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Open-File Report O-09-01

BEACH AND SHORELINE RESPONSE TO AN ARTIFICIAL LANDSLIDE AT ROCKY POINT, PORT ORFORD, ON THE SOUTHERN OREGON COAST

By

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NOTICE

The results and conclusions of this report are necessarily based on limited geologic and geophysical data. At any given site in any map area, site-specific data could give results that differ from those shown in this report. **This report cannot replace site-specific investigations.** The hazards of an individual site should be assessed through geotechnical or engineering geology investigation by qualified practitioners.

Cover photo: A moderate storm on January 9, 2008, impacts oceanfront homes and condominiums in the community of Neskowin. An earlier storm (January 5) destroyed portions of the riprap wall and came close to destroying one home. Photo by Jonathan Allan.

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EXECUTIVE SUMMARY

The failure of the Rocky Creek landslide south of Port Orford in January 2006 raised a number of important questions about the appropriate use of the public beach and intertidal region for the disposal of sediments (cobbles to sand and silt) excavated from the landslide that destroyed a portion of U.S. Highway 101. In particular, questions were raised about the likely impact of this sediment fill to the Hubbard Creek littoral system and to the marine biology immediately below Rocky Creek and adjacent to the landslide. To understand the former effects (i.e., sediment disposal), the Oregon Department of Geology and Mineral Industries (DOGAMI) was commissioned to monitor and assess the impacts of 53,000 m^3 (~69,300 yd^3) of sediment bulldozed onto the beach in April 2006.

Out of the original 53,000 m^3 (69,300 yd^3) of fill added to the beach, we estimate that about 19,700 m^3 (25,770 yd^3) of the fine sand to silt-size sediment fractions were removed and lost to deep water, while the remaining 33,000 m^3 (~39,000 yd^3) of coarser sediment were added to the beach sediment budget. Our monitoring surveys and analyses documented that by early to mid April 2006 only about 7,050 m^3 (9,220 yd^3) of the fill remained on the beach immediately below Rocky Creek, the bulk of the material having been eroded by the ocean's waves, transported into the intertidal zone offshore from Rocky Creek, and carried by the waves along the shore to the north where, consequently, the beach grew seaward. Furthermore, rapid erosion of the landslide fill was aided by the fact that the period during which the excavation work occurred coincided with a phase of heavy rainfall and hence high creek discharge so that the fill sediment added to the beach was composed of a mixture of water and sediment (i.e., a slurry). Had this mix of sediment and water not occurred, we suspect that the erosion process would have taken longer and that there would have been more sediment remaining below Rocky Creek when our monitoring began.

Monitoring revealed that the particles eroded from the fill were transported as far south as the Greg1 beach monitoring site (about 82 m [269 ft] south of the creek outlet) and as far north as the Greg6 profile site (about 830 m [2,723 ft] north of the creek). In response to the addition of the new sediment, the beach north of Rocky Creek prograded seaward, about 26 m (85 ft) at the Greg2 profile site and about 10 m (33 ft) at Greg3, initially as a cobble berm and then in response to a large influx of coarse sand and fine gravels. Within the time frame of this monitoring study, progradation of the shore extended to at least Greg6, located north of the landslide site. Volume change estimates of the beach between Greg1 and Greg5 revealed that the shore gained about 27,640 m^3 (36,153 yd^3) of sediment between March 2006 to February 2008 (i.e., a winter-to-winter comparison). This addition of new sediment to the beach helped provide enhanced protection to the shore from the unusually extreme winter storms that occurred in December 2007 and January 2008.

Sediment volume changes along the length of the Hubbard Creek littoral cell measured from the monitoring surveys indicated that the seasonal change in the profiles due to the high waves of the winter versus those of the summer ranged from a high of 195,000 m^3 (255,300 yd^3) of sediment in 2006 to 165,500 m^3 (216,474 yd^3) in 2007. Nevertheless, high wave energy levels, as observed over the 2007-2008 winter, can contribute to extensive erosion of the shore as the sediment is removed to the nearshore to form bars. For example, between November 2007 and February 2008 the beach lost 241,400 m^3 (315,751 yd^3) of sediment, which can be attributed to two major storms (December 2-3, 2007, and January 8-9, 2008). Furthermore, by February 2008 there was less sediment (-5,700 m^3 (7,456 yd^3) on the beach relative to our baseline survey in March 2006, indicating that the addition of new sediment from the landslide was relatively small when compared with the natural seasonal exchange of sand and/or the effects of an elevated winter storm season.

In summary, our monitoring efforts at Rocky Creek indicate that the placement of the fill material did not have an adverse effect on the beach within the Hubbard Creek littoral cell, having contributed cobbles, gravel, and sand to the sediment budget (analogous to naturally occurring landslides that take place on the coast), and has not had a lasting effect in terms of the morphodynamic response of the beach. Although the Rocky Creek sediment disposal onto the beach can be considered to have been a success from the standpoint of the beach, this approach may not necessarily be acceptable elsewhere. Thus, future projects will need to carefully consider the geology of the fill relative to what is supplying the beach to avoid introduction of contaminants and, in particular, the amount of fill volume that

might be added to a beach system. For example, had the volume of sediment input at Rocky Creek been much larger relative to the existing beach sediment budget and the sediment inputs from naturally occurring landslides, the effects would almost certainly have been more dramatic, with potentially greater consequences to the public beach and adjacent infrastructure.

INTRODUCTION

U.S. Highway 101, which spans the length of the Oregon coast, is a vital connecting link for the coastal communities. During the past decade, portions of the highway have been compromised due to landslides, a result of ongoing coastal erosion and geologic instabilities, leading to failure of sections of the highway. Two of the most significant landslides that affected road traffic and coastal communities were the Cape Cove landslide south of the Heceta Head lighthouse that failed in January 2000 and the Cape Foulweather landslide that occurred just north of Otter Rock in December 1999. Due to the scale and complexity of these landslides, remediation of the highway took several months and interrupted vehicular traffic between Yachats and Florence (Cape Cove landslide) and Newport and Depoe Bay (Cape Foulweather landslide). In both cases, sediments derived from the landslide failure were removed from the site and disposed of in upland sites.

On December 31, 2005, a large crack developed across a portion of U.S. Highway 101, at Rocky Creek, approximately 3.5 km (2.2 mi) south of the town of Port Orford on the southern Oregon coast (Figure 1, Figures 2A and 2B). Initial construction of this section of Highway 101 was carried out in the early 1940s. A culvert was constructed over Rocky Creek in 1949, and the creek valley was eventually filled with material that was locally derived from the excavation of Highway 101. The site has been subject to previous phases of slumping and, according to ODOT staff, was scheduled for repairs in ~2008. By January 4, 2006, the crack had developed into a major landslide (hereafter referred to as the Rocky Creek Landslide) and was classified by Oregon Department of Transportation (ODOT) geologists as a "fill/block failure." The landslide caused a portion of Highway 101 to slump seaward, and its western lane dropped vertically some 6 m (20 ft) (Figure 2C). Road traffic between Port Orford and Gold Beach was reduced to one lane, causing significant disruption along this portion of the highway. At the same time, additional cracking associated with another landslide feature developed about 230 m (760 ft) north of the Rocky Creek landslide (Figure 2D).

In response to the landslide at Rocky Creek, ODOT engineers and geologists concluded that the entire fill section overlying Rocky Creek would need to be excavated, disposed of elsewhere, and replaced with much coarser fill material. ODOT staff settled on two possible approaches for remediation:

- Removal of the fill material (estimated to be about 34,400 to 45,900 m^3 [45,000 to 60,000 yd^3]) and its disposal some 12.9 km (8 mi) to the south near Humbug Mountain, followed by rebuilding of the Rocky Creek culvert and Highway 101; or,
- Removal of the fill material and its disposal on the beach directly below the landslide, followed by rebuilding of the Rocky Creek culvert and Highway 101.

After consulting with state, federal, and local parties, a permit was granted by the Oregon Parks and Recreation Department (OPRD) enabling ODOT to proceed with the beach disposal option. An important component of the permit was the requirement that the effects of beach disposal be assessed for potential impacts to the beach littoral system and to the marine biology adjacent to the landslide. To understand the former (i.e., fill disposal on the littoral system), the Oregon Department of Geology and Mineral Industries (DOGAMI) was commissioned to implement a beach and shoreline monitoring program, including detailed studies of the sediments and morphologic responses of the beaches. The specific tasks of this study included:

1. Examinations of the sediment grain-size characteristics along the Hubbard Creek littoral cell, which extends from Pillar Point adjacent to the port of Port Orford to Rocky Point in the south. Because the shore length between Rocky Creek and Port Orford is approximately 3.9 km (2.4 mi), at least 10 to 12 sediment samples at intervals about 300 m (1,000 ft) alongshore were required to characterize the preexisting beach sediments.

Additional sediment samples were taken adjacent to the proposed fill placement site, to the north and south of the landslide, and from the landslide itself. Follow-up grain-size measurements were also undertaken in January 2007, several months after the fill sediment had been present on the beach;

2. Determination of the rate and dispersion patterns of the placed fill, using combination of approaches that included the following:
    - Large-scale topographic surveys that encompass the cross-shore extent of the subaerial beach and extend to the north and south of the landslide were periodically undertaken using Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) technology mounted on either an all-terrain vehicle (ATV) or on a backpack carried by an operator and undertaken as close as possible to low tide to maximize topographic measurements of exposed beach.
    - A beach profile monitoring network was established along the full length of the shore from the Port of Port Orford to Rocky Creek. Spacing between the profile sites was on the order of 250 m (820 ft). A total of 14 beach profile sites were initially installed; later, three other sites near the Port of Port Orford were installed.

This report summarizes the results of beach monitoring and grain-size and mineralogy analyses undertaken over a 2-year period between March 2006 and March 2008. A parallel report documenting the effects of the fill sediment on the marine biology was also produced by Gil Rilov, Department of Zoology, Oregon State University.

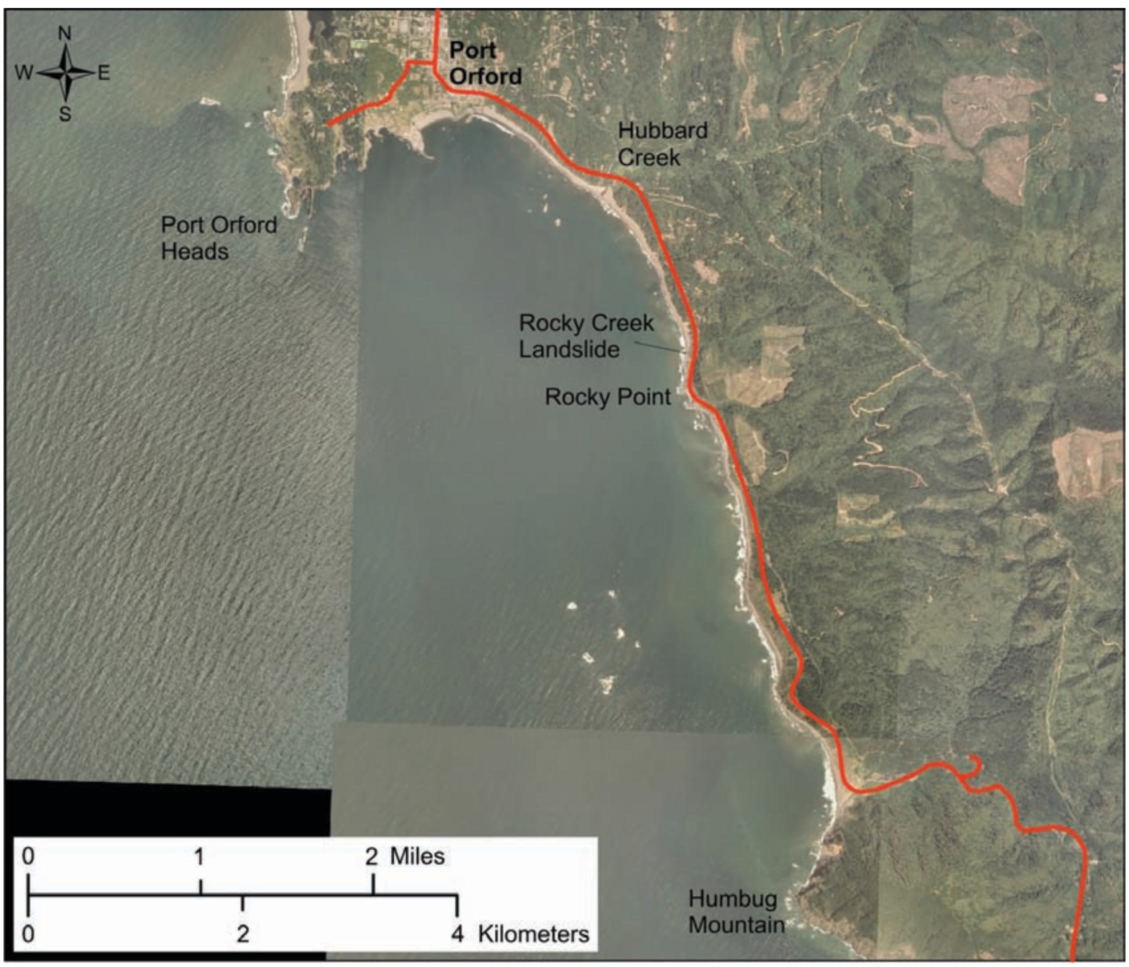

Figure 1. Map showing the location of the Rocky Creek landslide within the larger Humbug Mountain littoral cell that extends from Humbug Mountain in the south to Port Orford in the north.

STUDY AREA

The Oregon coast is approximately 560 km (360 miles) in length and can be broadly characterized as consisting of long stretches of sandy beaches that are bounded by resistant headlands. These types of systems are referred to as "littoral cells" and include both a cross-shore and a longshore extent. There are at least 18 major littoral cells on the Oregon coast, with the majority of the shoreline (72%) consisting of either dune- or bluff-backed sandy beaches, while the remaining 28% of shore is composed of a mixture of rocky shores, mixed sand and gravel beaches, and coarse-grained (gravel) beaches. For the purposes of this study, the term gravel beach refers to beaches containing sediments that range in size from granules (>2 mm) to cobbles (<256 mm). Most Oregon beaches are backed by sea cliffs that have eroded into Tertiary mudstones and siltstones, in places capped by Pleistocene terrace sands (million-year-old uplifted beaches and dunes), while along low-lying stretches of coast the beaches are backed by modern active sand dunes or are part of barrier spits that have developed across estuaries and bays.

Oregon's beaches generally have limited sand sources and simple sediment budgets. In a study of the beach-sand mineralogies along the coast, Clemens and Komar (1988) found that the sand on most beaches was derived from three sources, the Klamath Mountains in southern Oregon and northern California, the Coast Range mountains backing most of the coast, and the Columbia River to the north. It was concluded, however, that those sources cannot supply

Figure 2. A) The Rocky Creek landslide on December 31, 2005, with surface cracks extending across the western lane of U.S. Highway 101; **B)** the western lane of the highway is undermined due to a slump/block failure (note the head scarp running seaward near the top-right center of the photo); **C)** the main slump on January 12, 2006, which caused Highway 101 to drop by approximately 6 m (20 ft); **D)** surface cracking on January 12, 2006, some 230 m (760 ft) north of the main slump/block failure across Rocky Creek, indicating other movements in the area.

sand to the littoral cells at present due to the numerous headlands; instead, sand has been carried onshore by beach migration under rising sea levels over the last 3 to 5,000 years. Current observations of coastal shoreline and bluff changes suggest that only limited quantities of modern sand are being added to the beaches, and the quantity varies considerably from cell to cell. Erosion of the coastal bluffs, primarily those containing Pleistocene dune and beach sands, represents a major sand source for Oregon's "pocket beach" littoral cells. However, because many of the cliffs are eroding at rates typically less than 0.3 m/yr (0.1 ft/yr) (Priest and others, 1993), the volume of sand supplied to the littoral system is likely to be small. Little of the sediment transported down the major rivers reaches the ocean beaches, because most of the sediment is deposited in estuaries (Komar, 1997). It is more likely that the estuaries are sinks of beach sand, demonstrated by several studies of sediment accumulation in Oregon's bays and estuaries (e.g., Peterson and others (1991). Nearly all the sand presently derived from the Columbia River is transported northward to the Washington coast.

The Rocky Creek landslide is located within the Hubbard Creek littoral cell (Figure 3), which likely forms a subcell within the much larger Humbug Mountain cell. The southern boundary of the Humbug Mountain cell is at Humbug Mountain State Park, some 8.3 km (5.2 mi) south of Port Orford, and the northern boundary is the Port Orford Heads. The Rocky Creek landslide is located at the south end of the Hubbard Creek littoral cell, which extends from Rocky Point in the south to the Port Orford Heads in the north. The length of this subcell is 3.9 km (2.4 mi). Because Rocky Point does not appear to be an effective barrier to sediment transport, it is likely that the sand-sized beach sediments are able to be periodically exchanged with the shore south of Rocky Point and vice versa. In contrast, the movement of the coarser sediments (pebbles to cobbles) is probably confined to within the various subcells with little to no exchange between the adjacent subcells. In the north at Port Orford, the movement of sand-sized beach sediments probably did not "leak" around the "Heads" prior to the construction of the breakwater at the Port. Today, the breakwater structure now acts as an extremely effective sand trap, trapping the sand-sized beach sediments that are transported north along the Hubbard Creek cell, where they pass around Pillar Point and accumulate within the harbor.

The geomorphology of the Hubbard Creek littoral cell, broken into five sections from south the north, can be broadly classified into three contrasting beach types (shown in boldface below):

1. In the far south adjacent to the Rocky Creek culvert (i.e., south of Greg2) the beach is composed of large boulders and cobbles (i.e., a ***boulder beach***), which are locally derived from the erosion and mass wasting of coastal bluffs north of Rocky Point (Figure 4). Because much of the underlying rock lithology is highly fractured and friable and the highway is located in close proximity to the bluff face, slumping and landsliding present a high risk to the highway. For example, in the past few years a large slump feature has begun to develop west of the highway and south of the current landslide along a pullout area (which could fail at any time), while a second landslide is developing some 230 m (760 ft) north of the Rocky Creek slide;
2. Between Greg1 and Greg4, the beach can be broadly characterized as ***mixed sand and gravel, backed by a cobble berm*** (Figure 5). The beach is steep and narrow and is fronted in the north at Greg4 by a wide, gently sloping rocky intertidal terrace;
3. Boulders predominate the beach at Greg5, although this shore section is typically buried by mixed sand and gravel in response to the summer buildup of sand following the winter season;
4. From Greg5 to Greg13, the beach ranges from mixed sand and gravel to essentially a coarse to medium sand beach. In both areas, the beach foreshore is steep sloping. At the low tide line, the beach makes a transition to either a gently sloping sand beach or a rocky low tide terrace.
5. In the far north at Greg14 (and at Greg15, -16, and -17 adjacent to the port), the beach is composed of ***medium sand***. The subaerial beach is moderately steep, while the lower beach face/ nearshore region slopes gently seaward.

Due to the range of grain-sizes, the morphology of the beach along the Hubbard Creek cell broadly ranges from being steep and reflective to an intermediate category beach state using the classification of Wright and Short (1983). In general, the steep reflective state characterizes much of the southern half of the Hubbard Creek cell. This state is typified by a narrow surf zone so

Figure 3. Location map showing the distribution of beach profile stations established in the Hubbard Creek littoral cell, Global Positioning System (GPS) survey control sites, National Geodetic Survey (NGS) and Oregon Department of Transportation (ODOT) benchmarks, and the Rocky Creek landslide.

Figure 4. Mass wasting of the bluff face immediately south of the Rocky Creek landslide is occurring in response to winter rainfall and from toe erosion by ocean waves. The photo, taken in January 2007, shows the result of recent storm wave erosion — a 1 m (3 ft) high erosion scarp at the toe of the bluff. The mean elevation of the scarp toe is ~5.6 m (18 ft) and indicates that the wave swash is reaching and exceeding this elevation. Erosion of the bluff is naturally contributing a wide range of sediments to the Hubbard Creek littoral system.

Figure 5. Mixed sand and gravel beach backed by a cobble berm. Looking north from Greg2 (Figure 3) on April 4, 2006.

the waves tend to break close to shore, often on a plunge step, where they immediately develop into strong swash up the beach face. As a result, reflective beaches lose very little wave energy during shoaling; the bulk of their energy is expended during the breaking process and directly on the beach face. In contrast, dissipative beaches in the Wright and Short (1983) classification make up much of the Oregon coast and are characterized by low sloping morphologies and wide surf zones, so that most of the wave energy is dissipated across the surf prior to reaching the beach face. Intermediate beach states as occur at various sites in the Hubbard Creek cell have a range of morphologies, including the tendency to develop strong seaward-flowing rip currents that can locally erode back the beach to from an embayment.

Geologic Setting

Within the Hubbard Creek cell, beach-forming sediments are derived mainly from the erosion of bluffs that make up the bulk of this shoreline, and from the alongshore transport of sediments (primarily sand) from south of Rocky Point. As a result, in order to understand the relative sediment contributions (i.e., from inland formations and from Hubbard Creek) along the cell, geologic mapping of the backshore was undertaken. Figure 6 is a modified geologic map originally derived by Beaulieu and Hughes (1976). The geologic units that characterize the Hubbard Creek cell are (from north to south) the Late Jurassic Otter Point (Jop) Formation, the Upper Cretaceous Humbug Mountain Conglomerate (Kh), and the Upper Cretaceous Rocky Point Formation (Kr) (Figure 6). In general, these units have been subjected to low-grade metamorphism and, in the southern portion of the study area, deformed by shear zones separating massive landslide blocks (Figure 7).

The sequence appears to be a section of Mesozoic oceanic crust and sediments. Metabasalt of the Otter Point Formation represents paleo-oceanic volcanic crust at Battle Rock (site 1, Figure 6). Up section, to the south, deep-water rhythmic turbidite beds grade into shallow water meta-siltstones and slates with shallow marine bivalve fossils and coalified terrestrial plants, suggestive of a deltaic environment. Examination of selected rock samples indicated no evidence of metamorphic fabric or schistosity (although mica is common in the turbidites and meta-siltstones). Quartz veins are pervasive and in places brecciated by hydrothermal activity (fragments are pressure shattered and partially rounded). The matrix of veins is apparently silicified (Hart and others, 1986). Overall the metamorphism is metosomatic in nature with original igneous and sedimentary textures intact (except near the above-mentioned slide block shear zones). Silica metasomatism is common in ophiolites that have been subjected to the action of submarine hydrothermal activity (Hart and others, 1987). At site 2 (Figure 6) sedimentary and possibly volcanic rocks are metamorphic greenstones. At site 5 (Figure 6), turbidite sandstone has been altered to greenstone facies around joint systems, leaving spherical cores of relatively unmetamorphosed but silicified sandstone. In general, the pervasive silicification of the sequence might present problems distinguishing silicified sandstone and siltstone from basalt and quartzite in reflected light microscopy.

Lithologies of the Otter Point Formation (Jop)

The late Jurassic Otter Point Formation crops out from Battle Rock north to Port Orford Heads. The dominant lithology is submarine basalt altered to greenschist facies with multicolored thin-bedded chert deposits. The basalt displays fine, irregular jointing.

Lithologies of the Humbug Mountain Conglomerate (Kh)

The Early Cretaceous Humbug Mountain Conglomerate crops out between site 2 and site 9 (Figure 6) and may grade into the basalt of the underlying Otter Point Formation. The lowest outcrop of the section (site 2) is pervasively metamorphosed in the greenschist facies with typical secondary minerals such as chlorite, saponite, epidote, talc, and serpentine minerals obscuring the original mineralogy. Moderately thick beds of aphanitic greenstone could have been originally basalt or silicified greywacke siltstone. Other layers are made up of pebble conglomerates altered to greenschist facies with undeformed clasts.

Exposures of relatively unmetamorphosed, silicified, rhythmically bedded conglomerate, sandstone, siltstone, and shale crop out at site 4 (Figure 6). The repetition of moderately thick (approximately 1 m) graded beds are reminiscent of turbidites, although the clasts are unusually rounded for turbidites and may reflect redeposition of previously worked gravel beds (Figure 8A). The pebble-sized well rounded clasts in the basal conglomerate layers are poorly sorted mixtures of quartz diorite, chert, diorite, and volcanic and metamorphic lithic fragments. The conglomerate grades upward into poorly sorted gray sandstone with rounded clasts followed by siltstone and shale (Figure 8B). At site 5 (Figure 6), distinctive beds of pebbly sandstone have been partially altered by greenschist facies metamorphism that invaded along joint systems, leaving remnant cores of relatively unmetamorphosed sandstone (Figure 8C). The transition from metamorphic haloes to unaltered cores is abrupt with no indication of exfoliation. The sandstone is a poorly sorted greywacke assemblage with abundant clay minerals replacing original minerals.

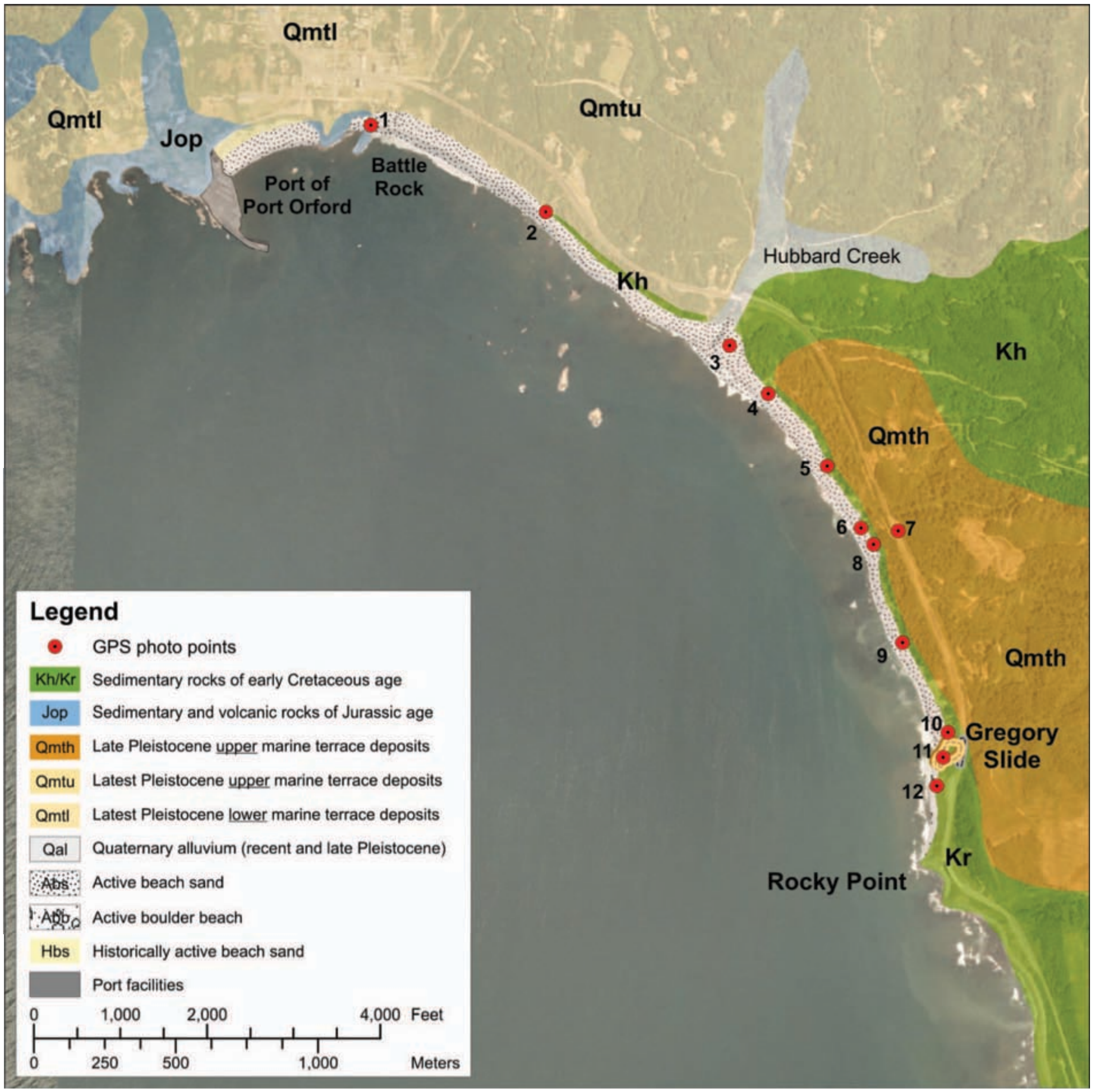

Figure 6. Geologic map of the southern Port Orford, Hubbard Creek, and Rocky Point region (after Beaulieu and Hughes, 1976). GPS photo points indicate the locations where photographs were taken of the backshore geology and were located using GPS.

Figure 7. View of the southern end of the Hubbard Creek littoral cell looking south toward Rocky Point. Locations of massive landslide blocks that dissect the bedrock geology are shown.

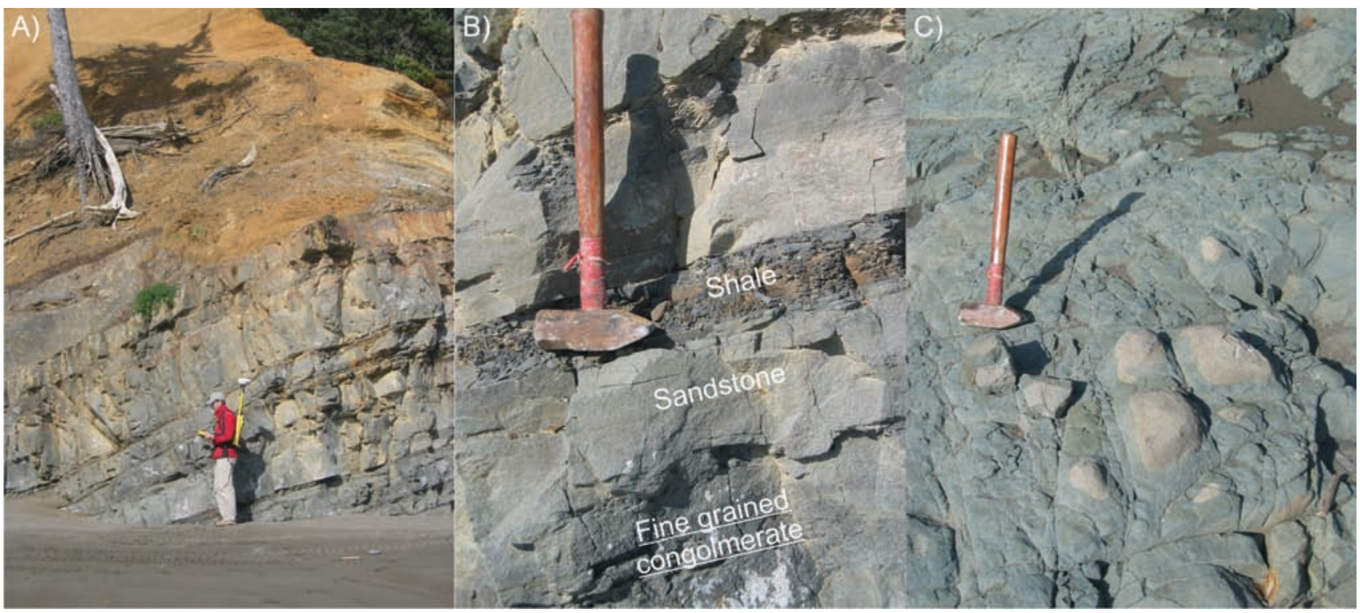

Figure 8. A) Rhythmic beds of the Humbug Mountain Conglomerate at site 4. The layers of gray bedrock (turbidites) are unconformably overlain by the distinctive red-orange fluvial sands and gravels of the Quaternary marine terrace deposits; **B)** Sequence of layers in graded bedding of the Humbug Mountain Conglomerate (Kh) at site 4 (Figure 6); **C)** Coarse-grained poorly sorted sandstone (greywacke) altered to greenstone along fracture systems at site 5 (Figure 6).

Lithologies of the Rocky Point Formation (Kr)

The Humbug Mountain Conglomerate grades into silicified sandstone (Figure 9A), siltstone, and shale (Figure 9B) of the Rocky Point Formation between sites 9 and 12 (Figure 6). Coalified fossils of plant fragments increase in abundance up section, suggesting shoaling of the sequence into a near-sea-level deltaic environment (Figure 9A). Mica is an abundant mineral even though schistosity is absent.

Surficial Deposit lithologies

Surficial deposits were investigated in three environments: stream-bed cobbles and boulders in the mouth of Hubbard creek (site 3, Figure 6), Quaternary marine deposits (Qmt) unconformably overlying the Mesozoic rock units (site 7, Figure 6), and landslide material pushed onto the beach by ODOT (site 11, Figure 6).

Boulders and cobbles in Hubbard Creek (site 3, Figure 6) are composed of a variety of igneous, metamorphic, and sedimentary rocks, reflecting compositional variety in inland sources. Silicified sandstones and conglomerates from the Humbug Mountain Conglomerate are most abundant along with minor dark gray siliceous siltstones and slates. A phenocrystic andesite present in the stream bed lithologies probably reflects a fine-grained equivalent of the Late Jurassic Pearse Peak Diorite. Relatively unsilicified brownish sandstones and conglomerates may have originated from local formations but seem more typical of the early Pliocene Empire formation that crops out north of Port Orford. Boulders composed of basal conglomerates from the Pleistocene fluvial terrace deposits are strongly cemented with iron sesquioxides. Rounded clasts in the Pleistocene basal conglomerate vary in size from pebbles to small cobbles.

Quaternary marine terrace deposits unconformably overlie the Mesozoic units the full length of the cell (Figure 10A). A sample taken at site 7 (Figure 6) is semi-consolidated, heterogeneous sand with characteristic mottling of orange, yellow, and black spherical shapes probably due to cementation processes involving iron and manganese oxides. The cobble-size clast component of landslide debris at site 11 (Figure 6) consists mainly of dark, hard angular clasts of siliceous dark gray siltstone and shale typical of the Early Cretaceous Rocky Point Formation (Figure 8B). Lesser amounts of poorly sorted siliceous sandstone (greywacke) fragments appear to be less indurated than the siltstone and shale.

Figure 9. A) Silicified siltstone with coalified plant fragments in the Rocky Point Formation (Kr) at site 9; **B)** Alternating beds of silicified siltstone and shale in the Rocky Point Formation (Kr) at site 10 (Figure 6).

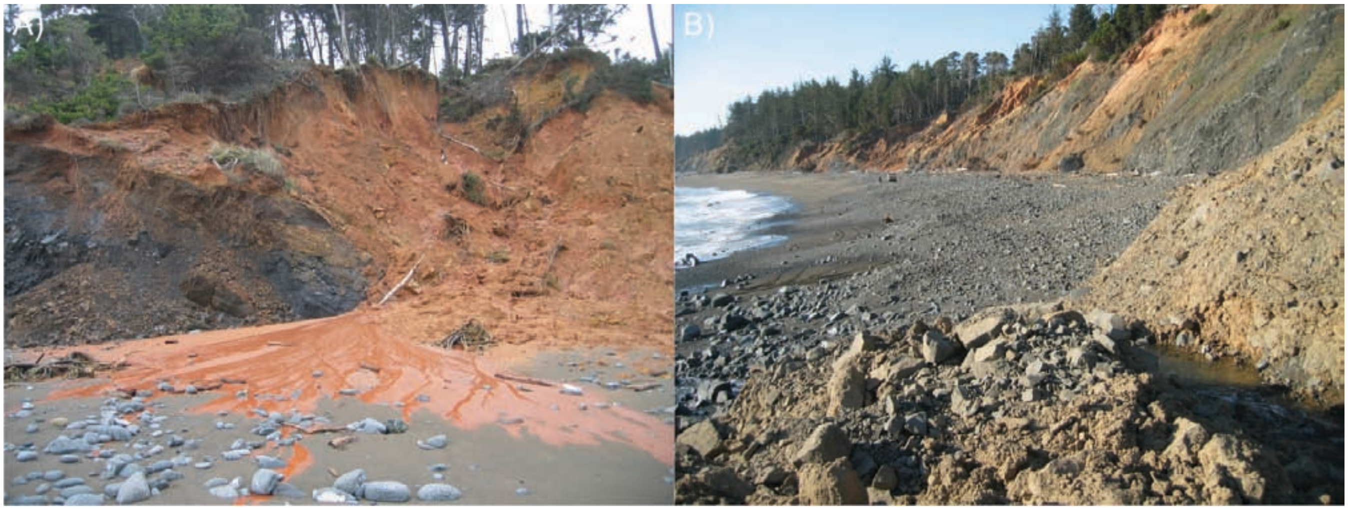

Figure 10. A) Marine terrace deposits undergoing mass wasting onto the beach near site 9; **B)** The coarse clast component of landslide material pushed onto the beach consists mainly of silicified unsorted sandstones and siltstones with some fragments of hard, coarse, unsilicified brown sandstone.

Oregon Beach Processes

Beaches composed of loose sediments are among the most dynamic and changeable of all landforms, responding to a myriad of complex variables that reflect the interaction of processes that drive coastal change (waves, currents, and tides), and the underlying geological and geomorphological characteristics of the beaches (sediment grain size, shoreline orientation, beach width, sand supply and losses, etc.). These multiple factors have a threefold role in contributing to the morphology and erosion versus the progradation of the beach:

1. Promoting the supply of sediments to the coast for beach construction;
2. Transferring sediments through the system; and ultimately,
3. Removing sediments through the process of erosion.

Beaches are composed of loose material, so they are able to adjust their morphology rapidly in intervals of time ranging from seconds to days to years in response to individual storm events, enhanced periods of storm activity, and increased water levels (e.g., the 1982-1983 and 1997-1998 El Niños).

Sediment transport

Sediment transport in the littoral zone can be divided between the movement of sediments that is directed in primarily onshore-offshore directions (*cross-shore sediment transport*), and the movement of sediments parallel to the beach (*longshore transport*). The latter is especially significant when waves approach the shore at an angle as they then generate stronger currents confined to a narrow zone landward of the breaker zone and can be responsible for the movement of substantial volumes of sand along the shore, including significant quantities of gravels and cobbles.

Along the Oregon coast the role of longshore currents is especially important due to a seasonal variation in the direction of wave approach between the summer and winter (Figure 11A). During a "normal year," summer waves, driven by north to northwesterly winds, approach the coast from the northwest, transporting large volumes of sand and fine gravel toward the southern ends of the cells and also landward, causing the dry part of the beach to build out. In contrast, the arrival of large waves from the southwest during the winter results in a reversal in the net sediment transport direction, which is now directed toward the north, as well as cutting back the dry summer beach by moving the sand back offshore. Over several normal years there can be an equilibrium balance such that the net sediment transport is close to zero (i.e., there

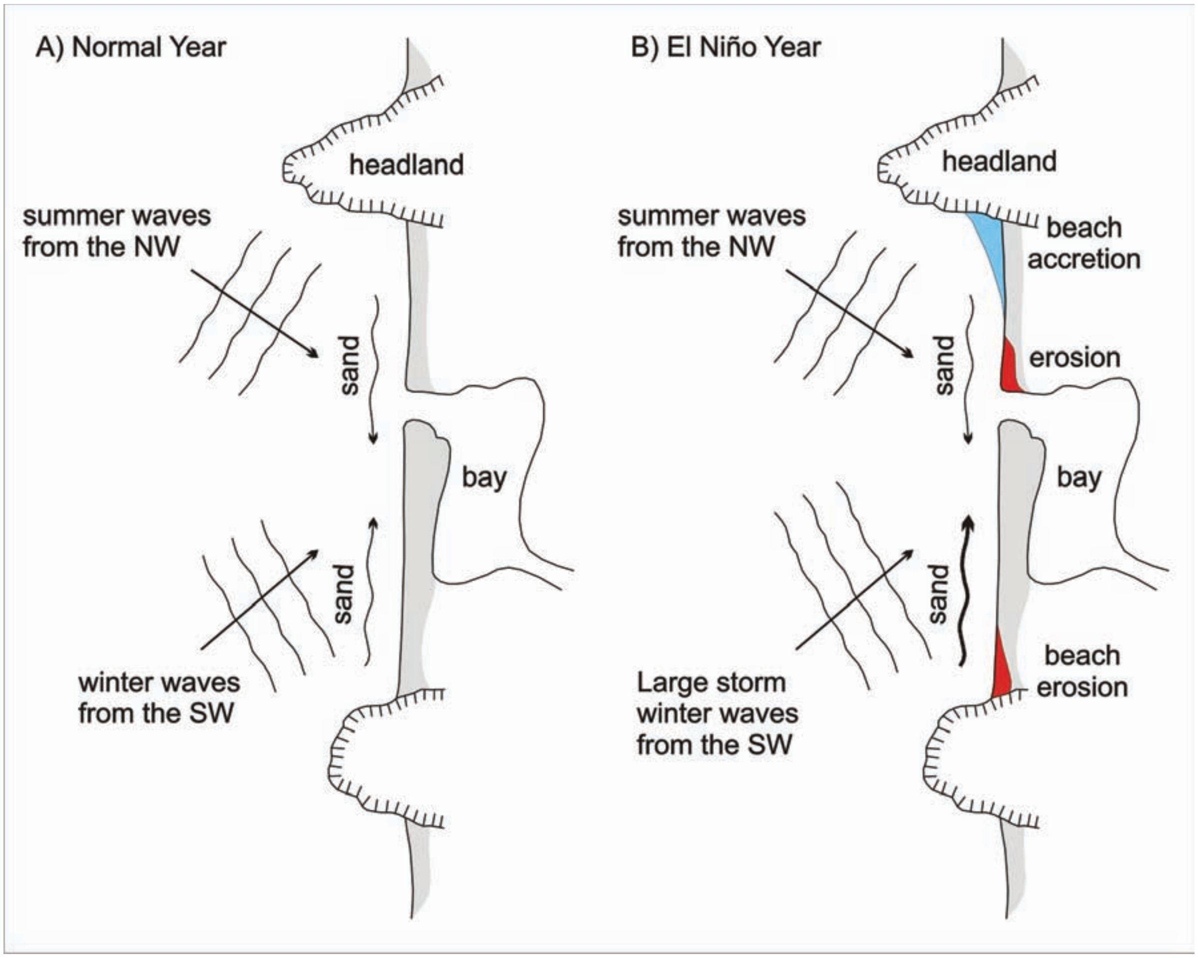

Figure 11. The alongshore-seasonal movement of beach sediments on the Oregon coast for **A)** a typical year and **B)** an El Niño year (Komar, 1998). Red areas signify beach (hotspot) erosion; blue area signifies beach accretion.

is no net long-term buildup (accretion) of sediment at either end of the littoral cells) (Komar, 1986). However, although the net balance of longshore sediment transport for sand-size particles is thought to be zero within a “pocket beach” littoral cell, this is unlikely to be the case for gravels. This is because the energy flux required to transport gravels and cobbles is significantly greater and because the waves may reach the cobbles at the back of the beach only during the winter. As a result, it can be expected that on the Oregon coast coarse sediments (gravels and cobbles) may preferentially move north during the winter months but tend not to return to the south during the summer months.

The volume and direction of sand and gravel transported along Oregon’s littoral cells may be augmented due to the periodic occurrence of an El Niño. El Niños typically occur at intervals of 5 to 6 years but may recur on 2- to 7-year cycles. In the past two decades there have been seven El Niños, with the 1982-1983 and 1997-1998 events the strongest on record, while the period between 1990 and 1995 was characterized by persistent El Niño conditions, the longest on record (Trenberth, 1999). The 1982-1983 and 1997-1998 El Niños were particularly significant events, producing some of the most extreme erosion occurrences on the Oregon coast, including along Agate Beach north of The Heads in Port Orford (Komar, 1986, 1998; Allan and Komar, 2002; Revell and others, 2002; Allan and others, 2003).

El Niños impact Oregon’s beaches in a variety of ways, most notably by elevating the mean water levels that cause the measured tides to be much higher than usual. Under normal conditions, the Oregon coast experiences a seasonal variation in its monthly mean water levels. During the summer, water levels tend to be lowest, a result of coastal upwelling that produces cold, dense water, which depresses water levels along the coast. With the onset of winter, the upwelling process breaks down: ocean temperatures are much warmer and thermal expansion causes the level of the ocean to be elevated by some 0.2 m (0.6 ft), with the highest water levels achieved in December and January (Allan and others, 2003). During an El Niño, however, ocean temperatures are further enhanced due to the release of a warm pool of ocean water that emanates from the tropics. The arrival of this warm pool along the Oregon coast during the winter elevates the ocean surface by an additional 0.3 m (1 ft). Thus, an El Niño may produce an increase in winter water levels by as much as 0.5 m (1.6 ft), greatly enhancing the capacity of waves to erode beaches and backshore properties during those months.

Aside from changes to mean water levels along the coast, during an El Niño there is also a southward displacement of the storm tracks so they mainly cross the coast of central California (Seymour, 1996). As a result, storm waves reach the Oregon coast from a more southwesterly quadrant, creating an abnormally large northward transport of sand within its littoral cells. This creates "hotspot" erosion at the southern ends of the cells, north of the bounding headlands and also north of migrating inlets, shown conceptually in Figure 11B. The opposite response is found south of the headlands, where the northward displaced sand accumulates, causing the coast there to advance seaward (Figure 11B).

Pacific Northwest wave climate

The wave climate offshore from the Oregon coast is one of the most extreme in the world, with winter storm waves regularly reaching heights in excess of several meters. This is because the storm systems emanating from the North Pacific travel over fetches that are typically a few thousand miles in length and are also characterized by strong winds, the two factors that account for the development of large wave heights and long wave periods (Tillotson and Komar, 1997). These storm systems originate near Japan or off the Kamchatka Peninsula in Russia and typically travel in a southeasterly direction across the North Pacific toward the Gulf of Alaska, eventually crossing the coasts of Oregon and Washington or the shores of British Columbia in Canada.

Wave statistics (heights and periods) have been measured in the North Pacific using wave buoys and sensor arrays since the mid 1970s. These data have been collected by the National Oceanic and Atmospheric Administration (NOAA), which operates the National Data Buoy Center (NDBC), and by the Coastal Data Information Program (CDIP) of Scripps Institution of Oceanography. The buoys cover the region between the Gulf of Alaska and Southern California and are located in both deep and shallow water. The NDBC operates some 30 stations along the West Coast of North America, while CDIP has at various times carried out wave measurements at 80 stations. Presently, there is one CDIP buoy operating offshore from Coos Bay, and there are three NDBC buoys (Columbia River, Newport, and Port Orford) located offshore from the Oregon coast. Wave measurements by NDBC are obtained hourly (CDIP provides measurements every 30 minutes) and are transmitted via satellite to the laboratory for analysis of the wave energy spectra, significant wave heights, and peak spectral wave periods. These data can be obtained directly from the NDBC through their website (http://seaboard.ndbc.noaa.gov/Maps/Northwest.shtml).

For the purposes of this study, long-term wave information (1987–2007) has been derived from the Newport NDBC buoy (#46050), while short-term wave records (2006–2008 period) are based on wave data measured at the Port Orford buoy (#46015) (Figure 12A). In contrast, information on wave directions is based on the CDIP (#139) buoy located north of Coos Bay (Figure 12). Previous analyses of the significant wave heights along the central and southern Oregon coast have revealed that there is little difference in the measured wave heights between the Newport and Port Orford buoys (Allan, 2004), with a slight decrease in the wave heights by the time one reaches the Columbia River buoy in the north (Allan and Komar, 2000). As a result, using the long-term record from Newport to describe the broad conditions near Port Orford is justified.

There is a strong seasonality to the wave climate along the Oregon coast, with the strongest storms and largest generated waves occurring in the winter months. Figures 12B and 12C present the monthly average deepwater significant wave heights (H_S) and peak spectral wave periods (T_P) for the Newport buoy. The graphs clearly show a prominent cycle in the mean monthly wave heights and peak wave periods, both increasing

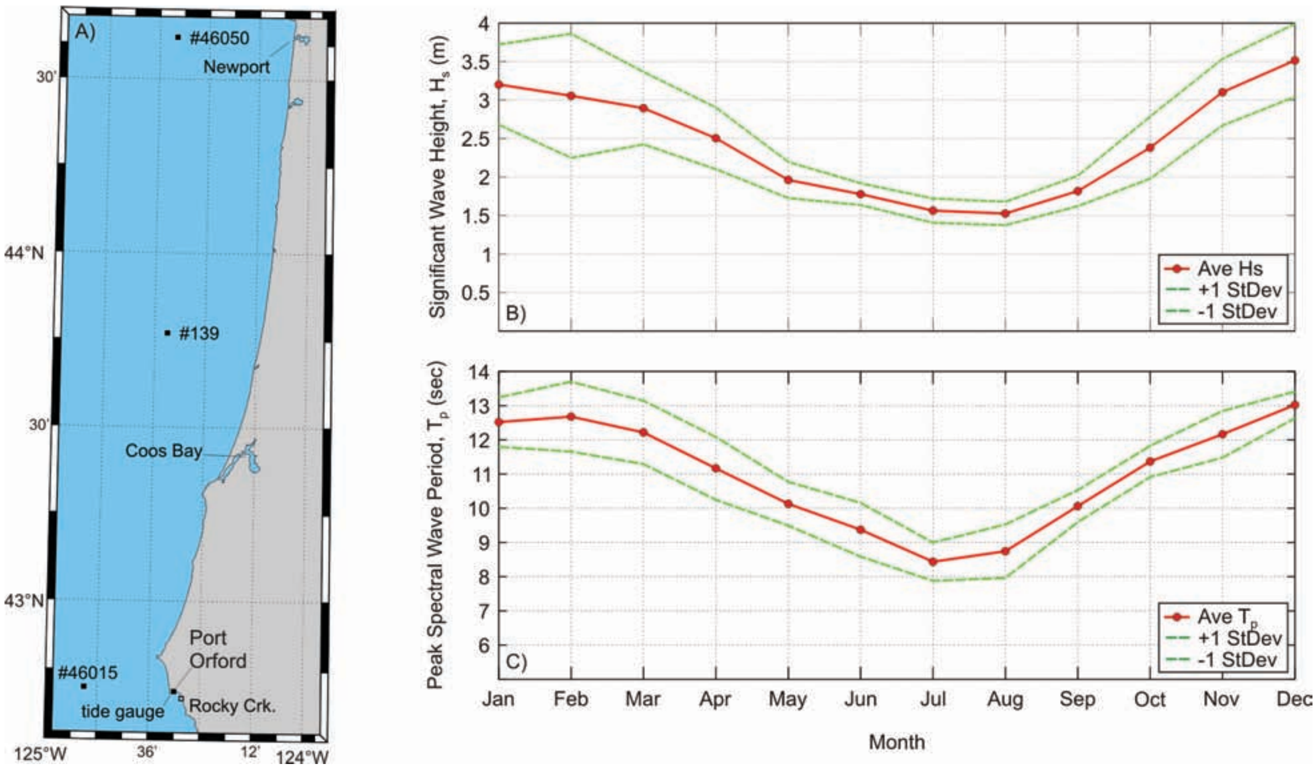

Figure 12. A) Location map of National Data Buoy Center (NDBC), Coastal Data Information Program (CDIP) wave buoys, and National Ocean Service tide gauge. The graphs show **B)** average monthly significant wave heights (1987–2007) and **C)** peak spectral wave periods, including their range (±1 standard deviation) for each month.

during the winter months of severest storms. Waves are characteristically smallest (<2.0 m [6.6 ft]) between May and September, reaching a minimum in August (Figure 12B). The range (±1 standard deviation) of wave heights during July and August is approximately 0.15 m (0.5 ft). This suggests that during the summer the West Coast is characterized by relatively similar conditions for wave generation, likely by local winds that blow over short fetches. During the winter, wave heights typically range from 3 to 4 m (9.8 to 13.1 ft). However, during major winter storms, wave heights in excess of 7 m (23 ft) are not uncommon, with the most extreme storms producing deep-water significant wave heights on the order of 14 to 15 m (45.9 to 49.2 ft) (Allan and Komar, 2002). A similar pattern can be seen for the peak wave periods (Figure 12C), such that during the summer the periods are typically less than ~10 sec, reaching a minimum of 8.3 sec in July. Wave periods tend to be longest in December and January and range from 12 to 14 sec on average and may reach as much as 25 sec during major storms.

We are less confident about the characteristics of wave direction offshore from Oregon, mainly because these data have only recently begun to be compiled, but also because of a dearth in instrumentation sites along the U.S. West Coast. Nevertheless, as a general rule, during the winter, waves typically arrive from the west or southwest, while in the summer the predominant wave direction is from the northwest (Komar, 1997). This pattern is shown in Figure 13, which is based on an analysis of both summer and winter directional data measured over a 2-year period by the CDIP buoy (#139, Figure 12A) located offshore of the Umpqua River. To better highlight the predominant wave directions for the winter months, wave heights less than 6 m (18 ft) have been eliminated from the analysis. As can be seen in Figure 13, summer months are characterized by waves arriving from mainly the westerly (46%) to northwesterly quadrant (43%), with few waves out of the southwest quadrant. The bulk of these reflect waves with amplitudes that are predominantly less than 3 m (9.8 ft). In contrast, the winter months are dominated

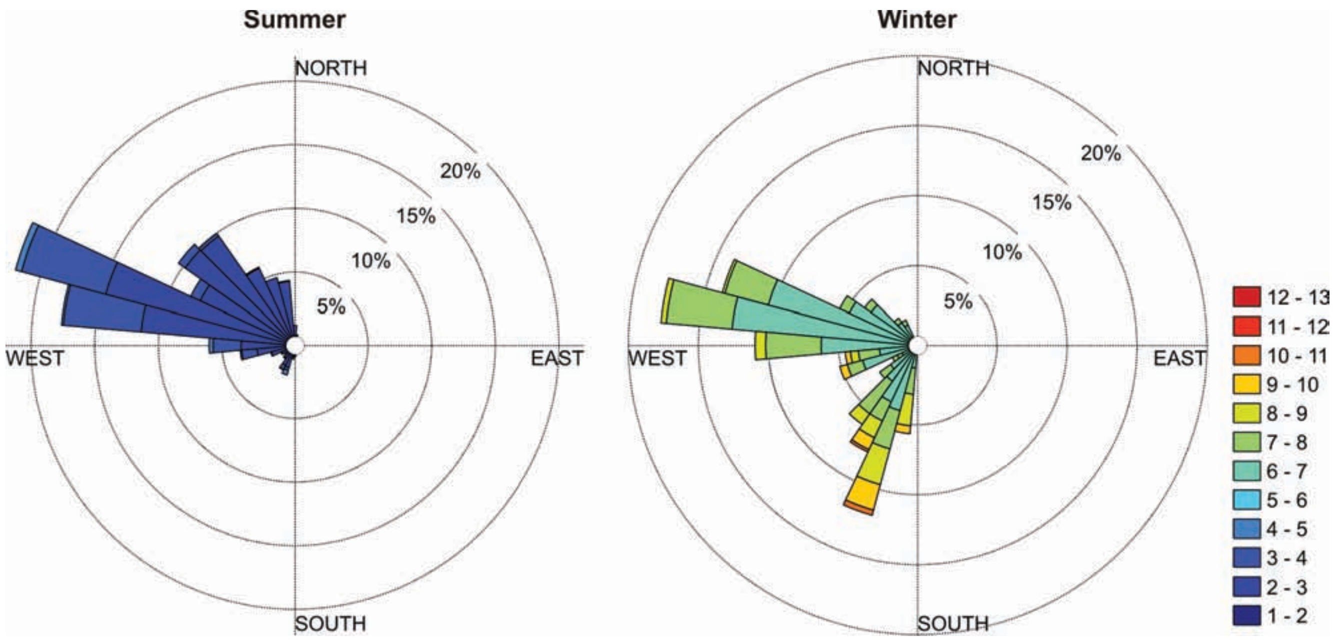

Figure 13. Wave direction information derived from the Umpqua River buoy (CDIP #139) for the period August 1, 2006, to March 18, 2008. Colored scale indicates the significant wave height in meters.

by much larger wave heights (up to 12 m [39.4 ft]) out of the southwest, which make up about 25% of the wave spectrum. Waves from the west are also important in the winter.

Tides

Measurements of tides on the Oregon coast are available from gauges located at four locations: the Columbia River (Astoria), Yaquina Bay (Newport), Charleston (Coos Bay), and Port Orford. The long-term record from Crescent City, California, is also useful in analyses of tides on the southern Oregon coast. Tides along the Oregon coast are classified as moderate, with a maximum range of up to 4.3 m (14 ft) and an average range of about 1.8 m (6 ft) (Komar, 1997). There are two highs and two lows each day, with successive highs (or lows) usually having markedly different levels (Figure 14). Tidal elevations are given in reference to the mean of the lower low water levels (MLLW). As a result, most tidal elevations are positive numbers with only the most extreme lower lows having negative values. Figure 14 shows the daily tidal elevations derived from the Port Orford tide gauge (#9431647). Tides at Port Orford have a mean range of 1.6 m (5.21 ft) and a diurnal range of 2.2 m (7.28 ft). The highest tide measured at Port Orford reached 3.5 m (11.49 ft), recorded in February 1978 during the peak of the strong 1977-1978 El Niño.

The actual level of the measured tide can be considerably higher than the predicted level provided in standard tide tables and is a function of a variety of atmospheric and oceanographic forces, which ultimately combine to raise the mean elevation of the sea. These latter processes also vary over a wide range of time scales and may have quite different effects on the coastal environment. For example, strong onshore winds coupled with the extreme low atmospheric pressures associated with a major storm can cause the water surface to be raised along the shore as a storm surge, and have been found in tide-gauge measurements to be on the order of 1.5 m (4.9 ft) (Allan and Komar, 2002). However, during the summer months these processes can be essentially ignored due to the absence of major storms systems.

On the Oregon coast, tides tend to be enhanced during the winter months due to warmer water temperatures and the presence of northward flowing ocean currents that raise water levels along the shore, persisting throughout the winter rather than lasting for only a couple of days as is the case for a storm surge. This effect can be seen in the monthly averaged water levels (Figure 15), derived from the Port Orford tide gauge, but where

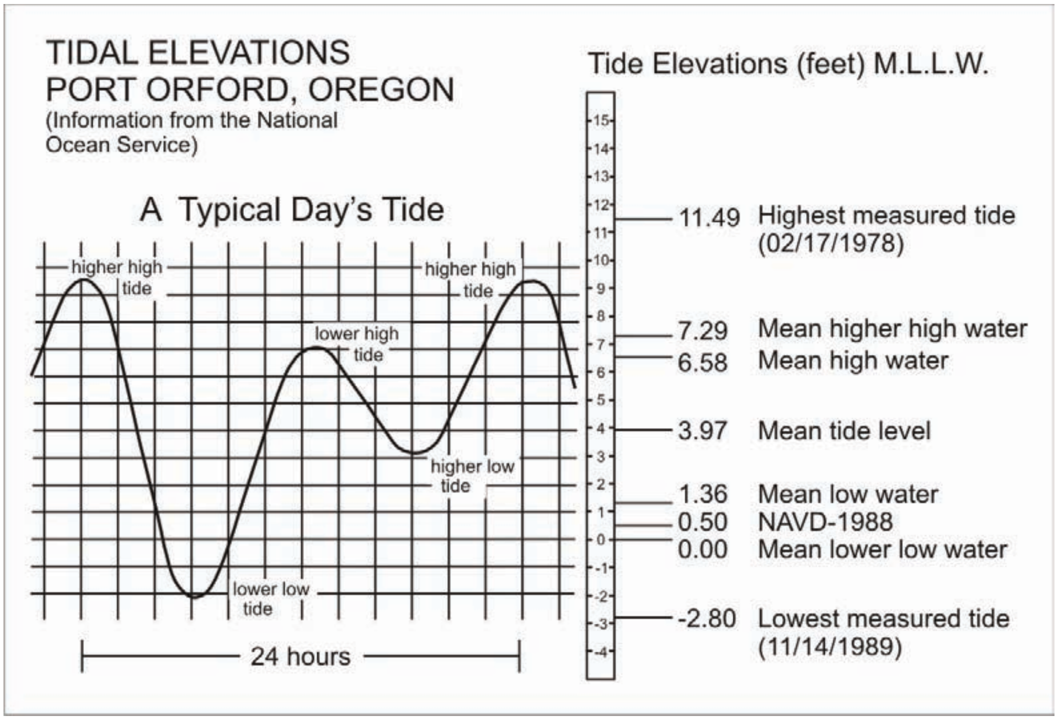

Figure 14. Daily tidal elevations measured at the Port Orford tide gauge (#9431647) on the southern Oregon coast. Data from the National Ocean Service (http://www.co-ops.nos.noaa.gov/).

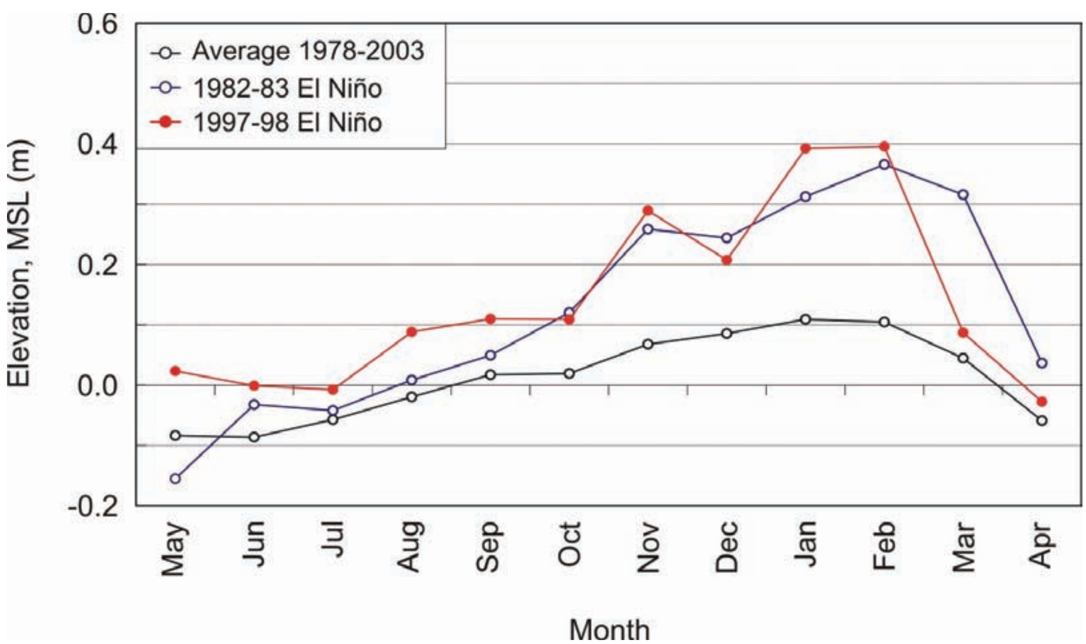

Figure 15. Mean monthly tides determined from the Port Orford, Oregon, tide gauge (#9431647), expressed as a long-term average and as monthly averages for the 1982-1983 and 1997-1998 El Niños. MSL is mean sea level.

the averaging process has removed the water-level variations of the tides, yielding a mean water level for the entire month. Based on 26 years of data, the results in Figure 15 show that on average monthly-mean water levels during the winter are nearly 20 cm (0.7 ft) higher than in the summer. Water levels are most extreme during El Niño events, due to an intensification of the processes, largely enhanced ocean sea surface temperatures offshore from the Oregon coast. This occurred particularly during the unusually strong 1982-1983 and 1997-1998 El Niños; as seen in Figure 15, water levels during those climate events were approximately 40 to 50 cm (1.3 to 1.6 ft) higher in the winter than during the preceding summer, enabling wave swash processes to reach much higher elevations on the beach.

METHODOLOGY

Hubbard Creek beach monitoring

Beach profile surveys

The monitoring of two-dimensional beach profiles (cross-sections) over time provides an important means of understanding the morphodynamics of beaches and the processes that influence the net volumetric gains or losses of sediment (Morton and others, 1993; Ruggiero and Voigt, 2000). Beach monitoring is capable of revealing information concerning short-term trends in beach stability, such as the seasonal response of a beach to the prevailing wave energy, responses due to individual storms, or hotspot erosion associated with rip current embayments. Over sufficiently long periods, periodic beach surveys can reveal important insights as to the long-term response of a particular coast, such as its progradation (seaward advance of the mean shoreline) or recession (landward retreat), attributed to variations in sediment supply, storminess, human impacts, and, in the longer term, the progressive global rise in mean sea level.

Beach profiles that are oriented perpendicular to the shoreline (Figure 3) can be surveyed using a variety of approaches, including a simple graduated rod and chain, surveying level and staff, Total Station theodolite and reflective prism, light detection and ranging (lidar) airborne altimetry, and Real-Time Kinematic Differential Global Positioning System (RTK-DGPS) technology. Traditional techniques such as leveling instruments and Total Stations are capable of providing accurate representations of the morphology of a beach but are demanding in terms of time and effort. For example, typical surveys of a single profile line undertaken with a Total Station theodolite may take anywhere from 30 to 60 minutes to complete, which reduces the capacity of the surveyor to develop a spatially dense profile network along a stretch of shore. At the other end of the spectrum, high-resolution topographic surveys of the beach derived from lidar are ideal for capturing the three-dimensional state of the beach over an extended length of coast within a matter of hours; other forms of lidar technology are now being used to measure nearshore bathymetry out to moderate depths but are dependent on water clarity. However, lidar technology remains expensive and is impractical along small segments of shore and, more importantly, the high cost effectively limits the temporal resolution of the surveys and hence the ability of the end-user to understand short-term changes in the beach morphology (Bernstein and others, 2003).

Within the range of surveying technologies, the application of RTK-DGPS for surveying the morphology of both the subaerial and subaqueous portions of the beach has effectively become the accepted standard (Morton and others, 1993; Ruggiero and Voigt, 2000; Bernstein and others, 2003; Ruggiero and others, 2005) and is the surveying technique used in this study. The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations, originally developed by the U.S. Department of Defense. In its simplest form, GPS can be thought of as triangulation with the GPS satellites acting as reference points, enabling users to calculate their position to within several meters (e.g., by using off-the-shelf hand-held units), while survey-grade GPS units are capable of providing positional and elevation measurements that are accurate to a centimeter. At least four satellites are needed mathematically to determine an exact position, although more satellites are generally available. The process is complicated because all GPS receivers are subject to error, which can significantly degrade the accuracy of the derived position. These errors include GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere and multipath effects (where signals bounce off features and create spurious data). For example, hand-held autonomous receivers have positional accuracies that are typically less than about 10 m (<~30 ft), but can be improved to less than 5 m (<~15 ft) using the Wide Area Augmentation System (WAAS). This latter system is essentially a form of differential correction that accounts for the above errors, which is then broadcast through one of two geostationary satellites to WAAS-enabled GPS receivers.

Greater survey accuracies are achieved with differential GPS (DGPS) using two or more GPS receivers to simultaneously track the same satellites, thus enabling comparisons to be made between two sets of observations. One receiver is typically located over a known reference point, and the position of an unknown point is determined relative to that reference point. With the more sophisticated 24-channel dual-frequency RTK-DGPS receivers, positional accuracies can be improved to the subcentimeter level when operating in static mode and to within a few centimeters when in RTK mode (i.e., as the rover GPS is moved about). In this study we used a Trimble® 5700/5800 GPS Total Station®, which consists of a GPS base station (5700 unit), Zephyr Geodetic™ antenna, TRIMTALK™ 3 radio, and 5800 "rover."

In order to establish a dense GPS beach monitoring network along the Hubbard Creek littoral cell (Figure 3), we initially identified the approximate locations of the 17 profile sites used in this study in a geographical information system (GIS). This step also included an assessment of potential GPS "survey control" monuments established by the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA) and by ODOT. For the purposes of this study, we were able to identify two survey monuments characterized by horizontal order "A" and "first-order" vertical control; these included "BLCO," located about 6.4 km north of Port Orford, and "943 Tidal L," located adjacent to the port of Port Orford. Additional control was provided by three other monuments: "943 Tidal 4," a first-order vertical control site operated by the NGS; "Y757," a first-order vertical control site operated by ODOT; and "Battle," a control site established by DOGAMI (PK-nail) adjacent to a drinking fountain overlooking Battle Rock in the town of Port Orford. Coordinate information for each of the benchmarks were expressed in the Oregon State Plane (southern zone, meters) coordinate system, and the elevations were measured relative to the North American Vertical Datum of 1988 (NAVD88).

On March 3-4, 2006, we obtained our first survey of the beach. The objective of this initial phase of monitoring was to:

- Finalize the locations of the beach profile survey network and identify the locations of the survey control sites that would be used for calibration of the GPS survey;
- Document the "initial" conditions along the beach prior to the disposal of fill material on the beach by surveying in the morphology of the beach; and,
- Obtain sediment samples of the beach, from which various grain-size statistics could be derived along with an assessment of the mineralogy of the sediments (the purpose of the latter was to see if it would be feasible to identify any potential natural tracers in the sediments).

Precise coordinates and elevations were determined for the Hubbard Creek beach and shoreline monitoring network using the 5700 GPS base station, mounted on a fixed-height (2.0 m) tripod. Because of security concerns, the 5700 base station was typically located adjacent to the Castaway By The Sea motel overlooking the harbor. As a result, it was not possible to locate the base over a known geodetic survey monument. Nevertheless, survey control was provided by undertaking 180 GPS epoch measurements on each of the "control" monuments, enabling us to perform a GPS site calibration, which brought the survey into a local coordinate system. This step is critical in order to eliminate various survey errors. For example, Trimble reports that the 5700/5800 GPS system has horizontal errors of approximately ±1 cm + 1 ppm (parts per million × the baseline length) and a vertical error of ±2 cm (TrimbleNavigationSystem, 2005). These errors may be compounded by other factors such as poor satellite geometry, multipath, and poor atmospheric conditions, combining to increase the total error to several centimeters. Thus, the site calibration process is fundamental in order to minimize these uncertainties (Ruggiero and others, 2005).

After local site calibration had been completed, cross-shore beach profiles were surveyed with the 5800 GPS rover unit mounted on a backpack, worn by a surveyor (Figure 16). This was typically undertaken during periods of low tide. The general approach was to walk from the landward edge of the primary dune or bluff edge, down the beach face, and out into the ocean to approximately wading depth. A straight line perpendicular to the shore was achieved by navigating along a predetermined line displayed on a hand-held Trimble TSCe computer connected to the 5800 rover. The computer shows the position of the operator relative to the survey line and indicates the deviation of the GPS operator from the line. The horizontal variability during and between subsequent surveys is generally minor, approximately 1 m (3 ft) (i.e., about ±0.5 m either side of the line) and typically results in negligible vertical uncertainties due to the relatively uniform nature of beaches characteristic of much of the Oregon coast (Ruggiero and others, 2005). Surveys were repeated two weeks after the initial survey and then bimonthly and/or after major storms (Table 1). From our previous research at numerous sites along the Oregon coast, this method of surveying can reliably detect elevation changes on the order of 4-5 cm, that is, well below normal seasonal changes in beach elevation, which typically varies by 1 to 2 m (3 to 6 ft) (Shih and Komar, 1994; Ruggiero and others, 2005).

The collected GPS data were subsequently processed using the Trimble Geomatics Office™ suite of software. The first stage involves a re-examination of the site calibration undertaken on the TSCe™ computer. A three-parameter least-squares fit was then applied to adjust all data points collected during the survey to the local coordinate system established for the Port Orford area and to reduce any errors that may have occurred as a result of the GPS units. The reduced profile data were then exported for subsequent analysis.

Additional beach morphology information was derived from a light detection and ranging (lidar) survey of the Oregon coast (including the Hubbard Creek littoral cell) in September 2002. These data have been used to supplement the GPS beach monitoring and topographic surveys undertaken at Port Orford. The advantage of this comparison with the lidar data is that it provides another measure of the response of the

Figure 16. Beach surveys were undertaken by walking lines perpendicular to the water's edge, navigating along a predetermined line identified on a hand-held TSCe Trimble computer connected to the Trimble 5800 GPS rover. The example here is of R. Hart undertaking a topographic survey of the landslide toe adjacent to the Rocky Creek culvert on January 26, 2007. Note the accumulation of gravel associated with the southward transport of some of the fill.

Table 1. Beach profile and topographic survey dates.

Year	Beach Profile Survey	Topographic Survey
2006	March 15	—
	April 3	April 4-5
	April 27	April 27-28
	July 11	July 14
	September 21	September 21-22
	November 21	—
2007	January 25	January 25-26
	April 20	April 18–20
	July 20	July 18-19
	August 31	August 30-31
	November 28	November 27-28
2008	February 5	February 5–8

beach, in this case at the end of the 2002 summer, which extends our knowledge of the longer-term morphology and beach volume changes that have taken place in the Hubbard Creek littoral cell over the past several years.

Analysis of the beach survey data involved several stages. The data were first imported into MathWorks MATLAB®[i] using a customized script. A least-squares linear regression was then fit to the profile data. The purpose of this script was to examine the reduced data in order to eliminate data points that exceed a ±0.5-m threshold either side of the predetermined profile line. The data were then exported to a Microsoft® Excel® database for archiving purposes. A second MATLAB script was used to export values from the Excel profile database, plot the latest survey data (relative to the earlier surveys), and output the generated figure as a Portable Network Graphics (PNG) file. A third script examined the profile data and quantified the changes that occurred at selected contour elevations; for this study, temporal trends were developed for all contours between the 1-m and 6-m elevations and for all available data. Finally, the reduced contour data were plotted against time and exported as a PNG file for additional analysis.

Topographic surveys at Rocky Creek

While beach profiles provide important information about the cross-shore and, to some degree, the longshore response of the beach as a result of variations in the incident wave energy, nearshore currents, tides, and sediment supply, it is also necessary to understand the alongshore variability in shoreline response that may reflect the development of large morphodynamic features such as rip embayments, beach cusps, and the alongshore transport of sediment. To complement the beach profile surveys initiated along the Hubbard Creek littoral cell, large-scale topographic surveys were undertaken to better document the movement of sediment adjacent to the landslide disposal site and farther north and south along the beach. Aside from identifying large-scale morphodynamic responses along the shore, topographic surveys also enable the user to extrapolate other important information such as shoreline contours and volumetric changes derived between successive inter-survey periods.

In order to undertake the topographic mapping, a 5800 GPS rover unit was mounted on top of a six-wheel ARGO ATV (Figure 17). The height of the rover unit was measured relative to the ground and input into the TSCe computer so that ground elevations could be determined along the survey tracks. The ATV vehicle was then driven along the beach at a rate that enabled point samples to be measured roughly every 1 to 5 m. Because of the variable nature of the slope of the beach, the spacing between the ATV transects varied from 5 to 10 m, with the wider tract lines generally being confined to the lower beach slopes and narrower lines to the upper beach face. In areas consisting of more complex terrain, such as the area around Rocky Creek, the GPS rover unit was transferred to a backpack worn by a surveyor (Figure 16). This combined approach yielded anywhere from 12,000 to 18,000 data points per survey, with an average point density of ~3 to 5 m^2. The spatial extent of the ATV topographic survey ranged from the landward edge of the beach, typically the bluff face or bluff toe, seaward to the low tide line. The southern extent of the survey commenced just south of Greg1 (Figure 3) and extended northward to Hubbard Creek. Accordingly, the focus here was the response of the beach and shore in the southern half of the littoral cell. Unfortunately, we were unable to undertake a topographic survey of the beach prior to the commencement of excavation of the Rocky Creek landslide. The first complete survey was undertaken on April 4-5, 2006 (Table 1) and was repeated on nine other occasions, the last on February 5-8, 2008.

Analysis of the topographic data was carried out using MapInfo Professional®, Vertical Mapper™, which was used to develop the digital elevation models of the

i. Computer programming languages.

beach, including extrapolating elevation contours of interest (e.g., the 3 m (9 ft) and 5 m (16 ft) contours as shown in Figure 18) that may be used to track the erosion of the fill sediment over time. Volume calculations between successive surveys were also undertaken using Surfer® spatial analysis and gridding software.

Sediment analysis

To develop a baseline of the pre-existing sediment grain-size characteristics and mineralogy along the Hubbard Creek littoral cell, a total of 17 sediment samples were obtained on March 14, 2006, prior to the commencement of remediation work on the Rocky Creek landslide. Twelve samples were derived from the lower beach face (Greg2 to Greg13), with each sample taken from the beach "reference line," which equates to approximately the mid-tide (~1.4-m NAVD88 elevation) level at the shore. No sample was taken from the Greg1 site as the beach was characterized mainly by boulders and cobbles. Sediment samples were also obtained from Hubbard Creek (one sample taken landward of the bridge), the bluff face near Greg5, and the landslide itself (three samples).

The grain-size and mineralogy analyses were performed by Robert Lee (Ph.D. candidate) in the Geosciences Department sediment laboratory at Oregon State University, Corvallis. The sediments were sieved using U.S. Standard Sieve Series sieves and a model RX-24 portable sieve shaker manufactured by W. S. Tyler Company, Cleveland, Ohio. The samples were first washed and dried using a conventional oven at 65°C

Figure 17. Topographic mapping of the beach was undertaken using a Trimble 5800 GPS unit mounted on top of a six-wheel ARGO ATV. Photo shows the presence of survey tracklines undertaken on the lower beach face, which are spaced roughly 5 to 10 m apart.

Figure 18. The toe of the artificial landslide on July 14, 2006, showing the presence of an erosion scarp that formed over the latter part of the 2005-2006 winter. To capture the change in position of the landslide toe, various elevation contours (e.g., the 3-m [9 ft] and 5-m [16 ft] contours) are tracked over time. (See Figure 21.)

for at least 4-5 hours (some were dried overnight). The samples were then randomly split, and 500 ml of each sample was weighed and poured onto a stack of U.S. Standard sieves, ranging in size from −6.0ϕ[ii] to −2.0ϕ (64 to 4 mm) at 1ϕ intervals for the coarse fraction (pebble size range) and −2.0ϕ to 4.0ϕ (4 to 0.06 mm) at ¼ϕ intervals for the sand to finer grain size fractions. The sieves were placed in the portable sieve shaker for approximately ten minutes. Each phi (ϕ) step was then weighed using an electronic scale precise to ±1 mg.

ii. The phi (ϕ) scale is derived from $\phi = -\log_2 (D/D_0)$, where D represents the grain diameter and D_0 represents a "standard" grain-size of 1 mm.

The individual weights of the sieve fractions were plotted using Excel on cumulative percent graphs, and the graphic mean, sorting, skewness, and kurtosis were determined using the equations of Folk and Ward (1957). The sediments were also classified using the sediment classification scheme of Folk (1957).

The mineralogy of the samples was determined using a binocular microscope to count individual grains. Grain shape and type were identified using the coarse size fractions as a rough proxy for the finer grain size. For consistency, point counts were conducted on the 1.0ϕ size fraction for all samples, with approximately 150 to 450 counts on each sample.

RESULTS

Reconstruction of the Rocky Creek culvert and Highway 101 commenced on March 14, 2006. Initial efforts by the contractor were directed at constructing a bypass to allow traffic to detour around the work site. Actual fill removal and the placement of a small volume of the material on the beach below did not occur until March 22. A concerted effort to begin pushing the fill onto the beach did not commence until around April 1, 2006. Figure 19 shows the early efforts undertaken by ODOT and their contractor to remove the fill material. At the conclusion of the fill removal process in mid-April, the contractor had removed approximately 53,000 m^3 of fill (~69,300 yd^3), all of which was deposited on the beach below Rocky Creek (J. Lonie, Oregon Department of Transportation, personal communication, June 28, 2007).

To understand the impact of the Rocky Creek landslide to the beach system, this section is broadly divided into two parts. The first focuses on the initial baseline conditions of the beach below Rocky Creek, including documentation of the initial erosion of the fill sediment, the general distribution of the sediments about Rocky Creek (i.e., within about 100 m (300 ft) north and south of the creek outlet), the timing of the erosion, and the processes driving the changes. The second section examines the larger-scale beach morphodynamic responses measured along the entire Hubbard Creek littoral cell. This includes discussions of the measured beach profile changes, the alongshore distribution of sediment, beach volume changes that occurred, and changes to the sediment fractions identified prior to and after the fill was placed on the beach.

Artificial landslide changes and beach response at Rocky Creek

Landslide fill grain-size statistics and sediment input volumes

Grain-size statistics were derived from the fill material by ODOT staff in March 2006 prior to the excavation work (Garwood, 2006). Their results are depicted graphically in Figure 20 and are compared with independent grain-size analyses preformed by R. Lee (2007, Appendix A) on sediment samples obtained by the authors. As can be seen in Figure 20, the fill material was characterized by grain sizes that ranged from silts to cobbles. Although the boulder fraction is not depicted in the grain-size curves, our field-based observations indicated the presence of numerous boulders in the fill sediment. As these larger clasts were eroded, the boulders tended to form a lag deposit below the creek, essentially armoring it, providing some additional protection to the reconstructed Rocky Creek culvert.

In general, the ODOT grain-size curves are consistent with the DOGAMI samples for the coarser fractions (i.e., -7ϕ to -4ϕ [128 to 4 mm]), with some difference in the quantities of the finer particle sizes (i.e., the sand-size particles); the DOGAMI-1 and DOGAMI-2 samples indicate a greater quantity of coarse sand and granules. In contrast, the ODOT samples indicate a much higher concentration (~37%) of fine sand and silt size particles. The ODOT samples are likely to be a better indicator of the actual grain-size statistics obtained from the fill, as those samples were much larger in volume. Hence, our volume estimates of the various grain-size fractions described below are based on the ODOT sample results.

In terms of sediment supply to the beach, the medium range of sizes (gravels to medium sand) make the greatest contribution to the beach sediment budget, whereas the finer particles (fine sand to silt) are removed offshore where they will be lost to deep water. Given the initial volume of sediment available for transport (53,000 m^3 of fill [~69,300 yd^3]), we estimate that about 19,700 m^3 (~25,770 yd^3) of the fine sand to silt size sediment fractions would be removed to deep water, where they would be permanently lost from the nearshore, while 33,000 m^3 (~43,160 yd^3) of sand and gravel would be added to the beach sediment budget and would contribute directly to beach building.

Out of the 33,000 m^3 (39,000 yd^3) of material, we estimate that about 800 m^3 (1045 yd^3) of the cobble fractions ($> -6\phi < -8\phi$ [> 64 < 256 mm]) would probably be added directly to the beach, where the cobbles have accumulated at the crest of the beach. Due to their larger size and greater threshold of motion and because of the asymmetry of wave swash velocities on the beach face (Allan and others, 2006; Allan and Hart, 2007) these particles have remained on the subaerial beach and over time have been slowly migrating to the north.

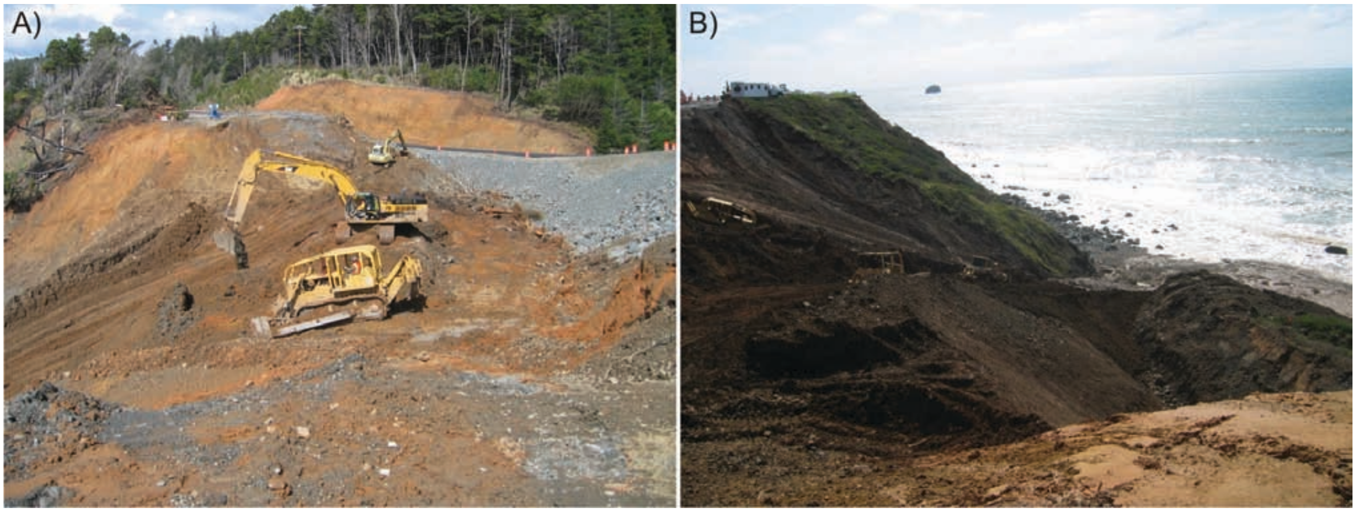

Figure 19. A) Excavation work began at Rocky Creek by removing the portion of U.S. Highway 101 that failed (road in the top right-hand section of the photo reflects the constructed detour used to circumnavigate the work site); **B)** Removed fill material were bulldozed seaward out onto the beach.

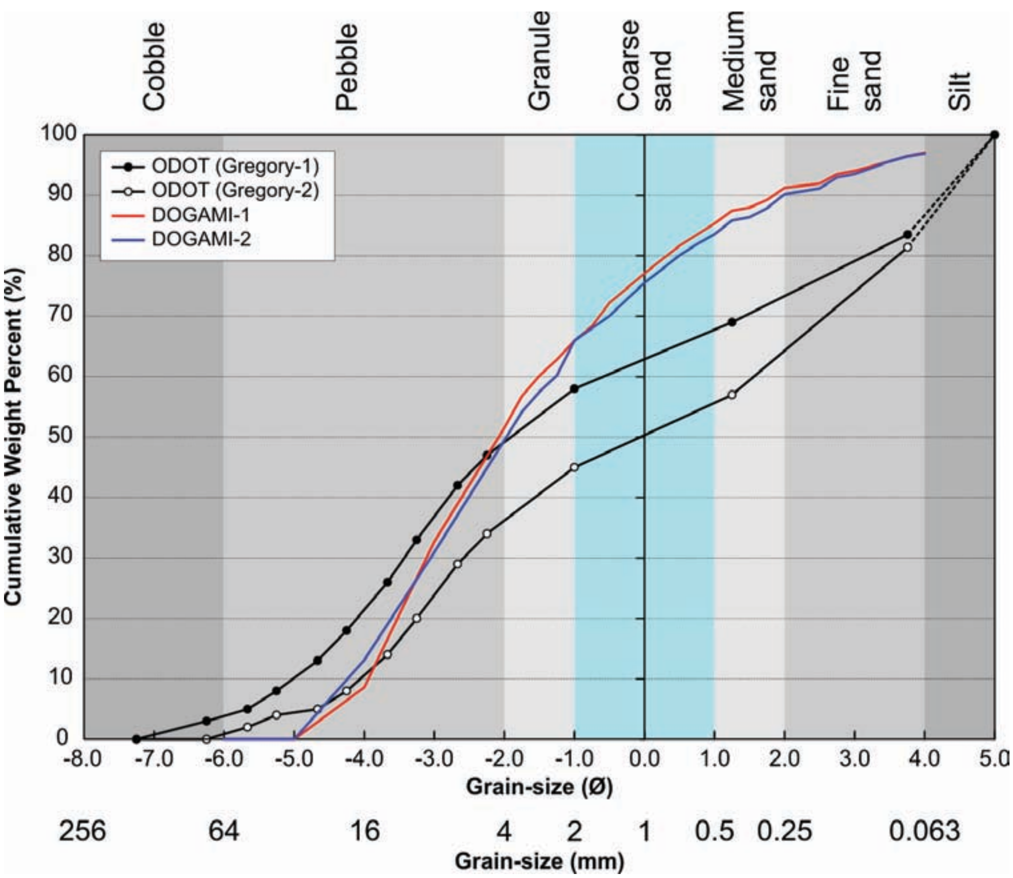

Figure 20. Grain-size curves generated for two ODOT and two DOGAMI sediment samples obtained from the Rocky Creek fill.

Accumulations of the cobble fractions near the crest of the beach have in effect created a type of dynamic revetment or cobble beach, which is now providing some protection to the bluffs that back the beach and to some degree to a small section of Highway 101 immediately north of Rocky Creek. About 6,100 m^3 (7,980 yd^3) of the coarser pebbles ($> -4\phi < -6\phi$ [> 16 < 64 mm]) would probably also remain within the wave swash zone. In contrast, the remaining 26,600 m^3 (34,790 yd^3) of the finer pebbles and coarse to medium sand fractions ($> 2\phi < -4\phi$ [> 0.25 < 16 mm]) would be subject to both cross-shore and longshore sediment transport. That is, the particles would tend to be removed from the beach face during the winter when wave energies are elevated, accumulating in the nearshore as bars, and returning to the beach face in the summer with the transition to lower swell waves, and/or transported farther along the beach.

Beach response at Rocky Creek

As indicated in Table 1, initial baseline beach profile surveys were carried out on March 15, 2006, while topographic surveys did not commence until April 4, shortly after the contractor began to push significant quantities of the fill onto the beach. Additional baseline information has been derived from an analysis of 2002 lidar data (flown in September) measured by the U.S. Geological Survey and NOAA. Because this latter survey was carried out at the end of the summer season, following the post-summer buildup of sand, the lidar survey captured the beach in its most accreted state. Figure 21 shows the initial response of the beach to the north of the culvert (cross-section 1) and to its south (cross-sections 2, 3, and 4). Included in the figure map are topographic contours (bold colors) derived from an RTK-DGPS survey of the beach on April 27, 2006, four weeks after excavation work commenced. For reference, the location of Rocky Creek is identified near the top center of the photo. Furthermore, the locations of the 3-m (9 ft) and 5-m (16 ft) contours identified in Figure 21 are shown schematically on Figure 18 along the face and toe of the bulldozed fill, which essentially formed the toe of the artificial landslide.

The April 4, 2006, cross-section (green line) reveals the immediate response to the fill placement — the beach elevation has been raised vertically by as much as 4 m near the top of the beach, with the degree of vertical change decreasing seaward. These changes were initially confined to an area extending from just north of cross-section 1 to cross-section 3 in the south (i.e., spatially covered about 45 m (150 ft) of linear shoreline length). As a result, the beach face prograded seaward by up to 25 m (82 ft) relative to its original position in 2002. In the north at the cross-section 1 profile site, part of this seaward progradation of the beach face (about 10 m [~30 ft]) is associated with the movement of the landslide block to the immediate north of Rocky Creek. The block movement was confined entirely to the area north of cross-section 2 (determined from the RTK-DGPS ground survey and photos of the area) and did not extend south of cross-section 2.

Figure 22 shows the initial impact of fill placement on the beach. The period prior to commencing excavation work had been characterized by significant amounts of rainfall. As a result, flow discharge from Rocky Creek during early April 2006 was elevated, which contributed to fluidization of the sediment as it was being bulldozed down onto the beach. By the time the sediment reached the beach, the material consisted of slurry, composed of a mixture of water and sediment. This probably enabled waves and currents to more easily entrain the sediments, particularly the fine grain-size fractions (i.e., the fine sand and silt). As can be seen in Figure 22, the finer sediments were rapidly entrained in the water column and dispersed offshore and alongshore. As noted above, a conservative estimate of the volume of the finer sediment fractions removed to deep water is about 19,700 m^3 (~25,770 yd^3) of material, much of which was moved in a matter of a few weeks.

The removal of the fines and its rapid dispersal offshore from Rocky Creek was aided by the presence of a strong rip current that develops just north of Rocky Creek (Figure 22). The formation of this rip current is probably due to the interaction of oblique wave approach near Rocky Point, which generates a northward flowing longshore current within the breaker zone and landward of it. North of the Greg3 beach profile site (Figure 3), wave approach tends to be predominantly normal (parallel) to the shore, which results in the development of longshore currents flowing north (i.e., toward Greg4 and farther north) and south toward the creek. Convergence of the currents (Figure 22, middle) results in the formation of a strong seaward flowing rip current capable of transporting large amounts of fine sediments offshore, where the rip current is subsequently dispersed by surface wind driven

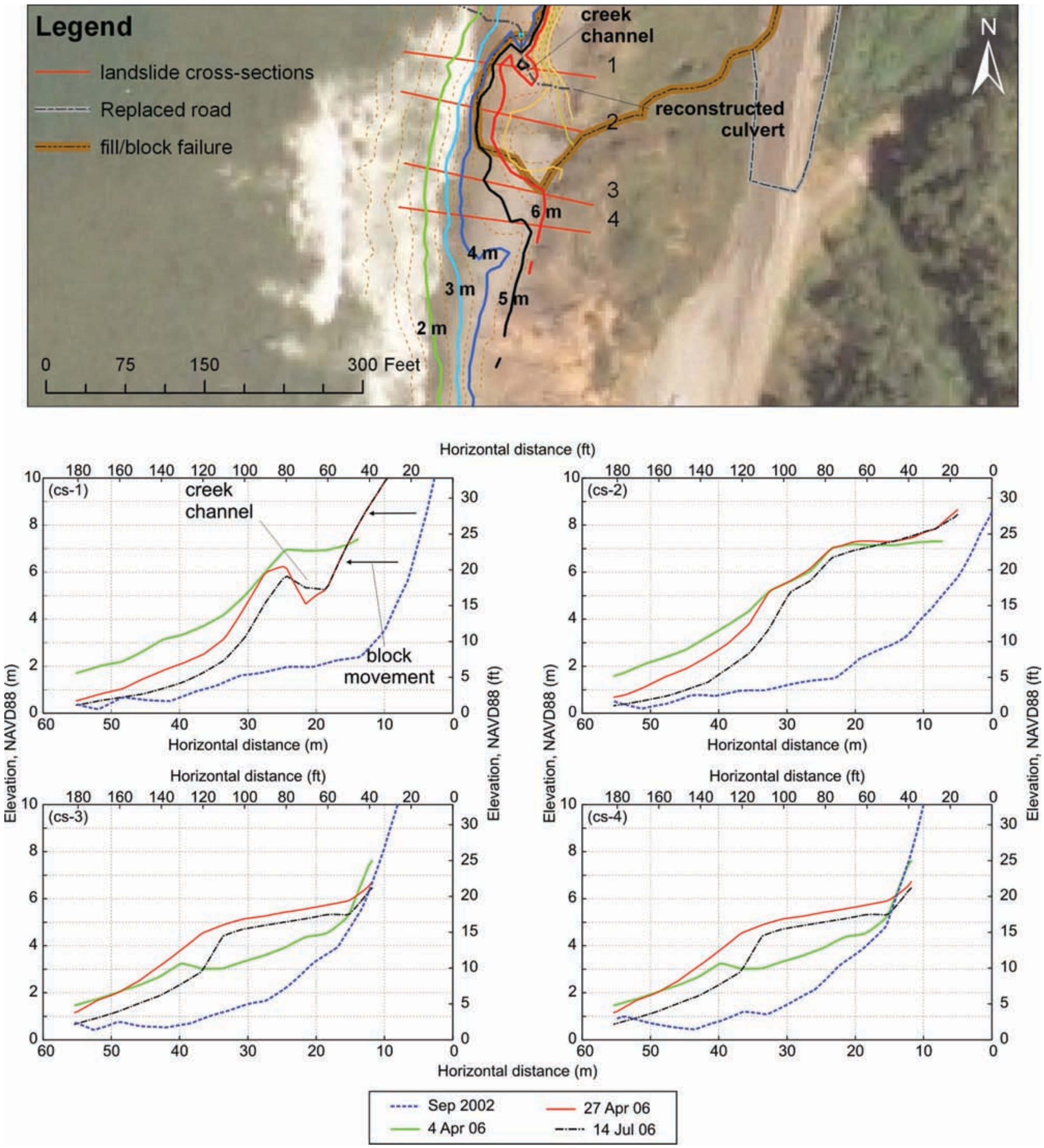

Figure 21. Initial beach profile responses measured adjacent to the Rocky Creek culvert both prior to (based on 2002 lidar data**)** and four months after fill material was pushed onto the beach. Map (top) shows locations of cross-sections (red lines), beach contour elevations (0.5-m increment) as of April 27, 2006, and spatial extent of landslide area. Profiles are shown for cross-sections (cs) 1–4.

Figure 22. A rip current on April 3, 2006, carries fine-grained sediments (silts and clays) offshore, where the rip current is broadly dispersed by surface wind driven currents.

currents. Over time, the finer particles settle out of the water column and accumulate on the ocean bottom. Since visiting the Rocky Creek site in January 2006, we have repeatedly observed the presence of a rip current at this same location.

By April 5, the coarser sediments (medium sand to gravel fractions) had begun to be distributed to the north and south, relative to their initial placement below Rocky Creek (Figure 23). As a result, the beach face aggraded vertically as well as seaward, shifting the mean shoreline position toward the ocean (Figure 21). By April 6, the contractor had exposed the original culvert (Figure 24A), A large plume of fine sediments had developed on the ocean west of Rocky Creek and extended north to Port Orford (Figure 24B). In fact, the sediment plume that developed covered a broad swath of the ocean and was observed as far south as Humbug Mountain. Follow-up photos taken a few weeks later on April 27 show the transformation of the beach face and ocean four weeks after the excavation had commenced (Figure 25). By this stage, all the fill material had been removed from Rocky Creek and was effectively now on the beach or had been dispersed by ocean currents. As can be seen in Figure 25, a small sediment plume still remained adjacent to Rocky Creek. North of the creek, an extensive gravel (predominantly small to large cobbles) berm had formed, caused the mean shoreline to be pushed seaward by up to 50 m (~164 ft).

The inter-survey period April 4–7, 2006, was characterized by only one significant storm, which occurred on April 16 (Figure 26). Figure 26A graphs the hourly significant wave heights measured by the National Data Buoy Center (NDBC) wave buoy (#46015), located 29 km (18 mi) offshore from Port Orford. These data cover the period from January 1, 2006, to February 29, 2008, and provide a measure of the relative intensity of the storm waves during the period when the fill material was being placed on the beach, and the subsequent conditions that would have contributed to its erosion. Figure 26B shows the calculated hourly total water levels (T_{WL}), which include the measured tidal elevation plus the calculated wave runup for the same period. Figure 26B provides an insight as to the range of elevations where the wave swash was affecting the beach and landslide toe. The wave runup ($R_{2\%}$) was calculated using the Stockdon and others (2006) wave runup model:

Figure 23. Beach conditions on April 5, 2006, showing the dispersal of the coarser sediments (medium sand to gravel fractions) to the north and south of the creek outlet, while the finer particles continue to be removed offshore.

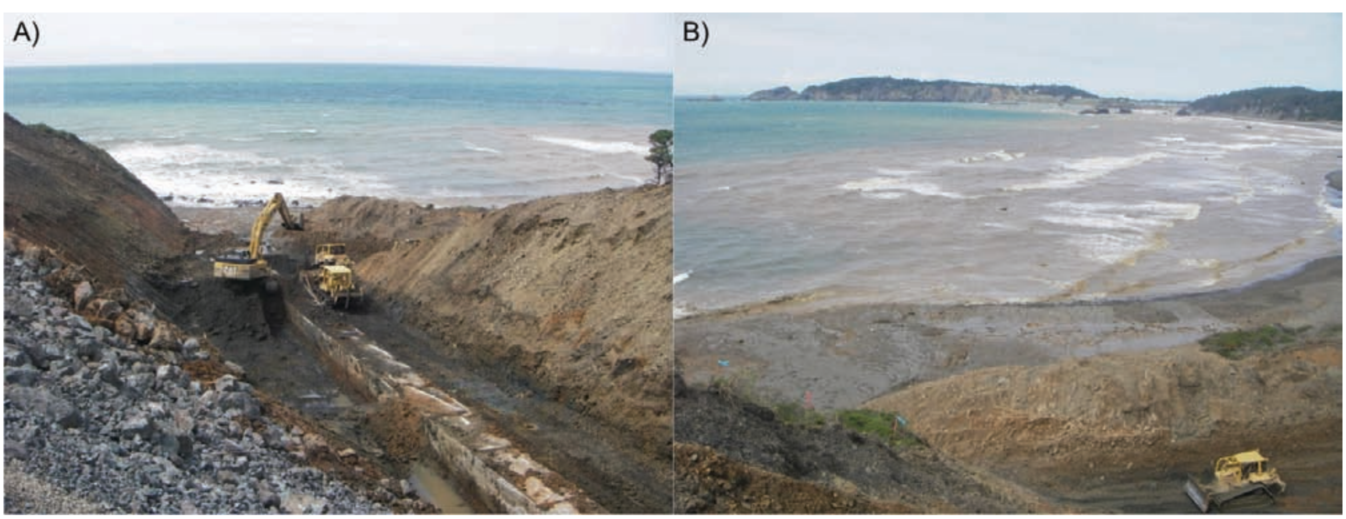

Figure 24. A) Excavation at Rocky Creek exposes the broken culvert on April 6, 2006. **B)** Erosion and dispersal of the finer sediments between April 5 and 6 resulted in the development of an large sediment plume that extended north to Port Orford. A similar plume developed to the south and almost reached Humbug Mountain.

Figure 25. Photograph of Rocky Creek beach on April 27, 2006, four weeks after excavation of the landslide had begun. Red dots, center right, are jackets worn by ODOT contractors.

$$R_2 = 1.1 \left\{ (0.35 \beta_f (H_o L_o)^{1/2} + \frac{H_o L_o (0.563 \beta_f + 0.004)]^{1/2}}{2} \right\} \tag{1}$$

where β_f is the foreshore beach slope, H_o is the deepwater wave height, and L_o is the deepwater wave length calculated from $L_o = (gT^2)/(2\pi)$ in which g is acceleration due to gravity, and T is the wave period.

As can be seen in equation 1, the wave runup is dependent on the deepwater wave height, wave period, and mean beach slope. For the purposes of this study, a beach slope (β) of 0.124 was used in equation 1. The calculated hourly wave runup was then added to the tidal component measured at Port Orford, with the resulting levels related to the NAVD88 vertical datum. Because the beach profile and topographic surveys were originally surveyed using the NAVD88 vertical datum, the calculated total water levels can be compared directly to the measured changes observed on the beach and along the toe of Rocky Creek. Shown in red is the daily average total water level, which provides an average measure of the range of total water levels at the shore, effectively smoothing the signal (Figure 26B).

Although April 2006 was characterized by the one storm, the total water level elevations (the calculated wave runup plus the tide level) during that event remained relatively high, enabling waves to erode the fill placed on the beach. Because the fill was already highly fluidized due to mixing with the water discharged from Rocky Creek, the sediments were rapidly entrained and redistributed along the beach (north and south), as shown in Figures 23 and 25, as well as

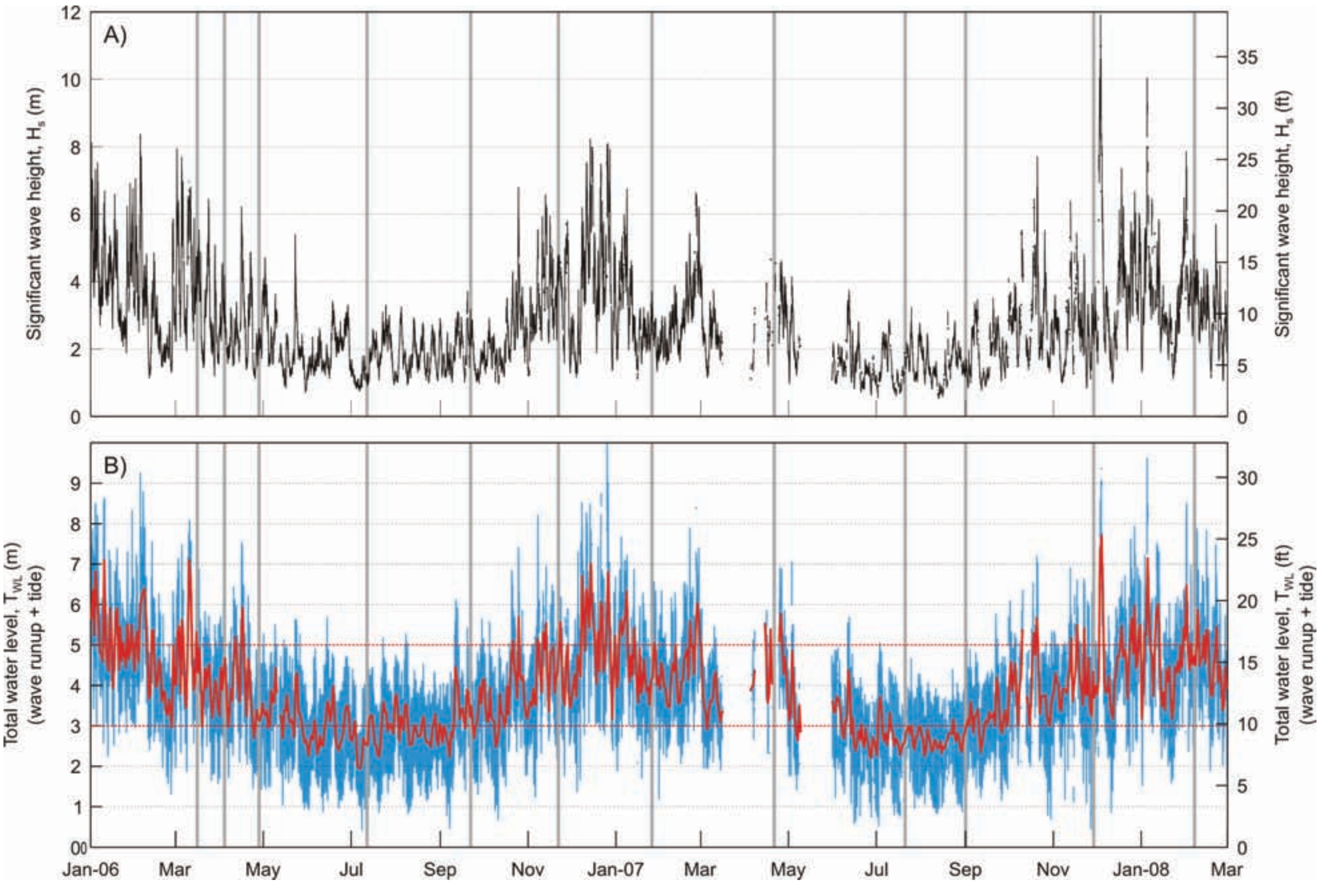

Figure 26. A) Time history plot of hourly measured significant wave heights derived from the Port Orford wave buoy (National Data Buoy Center buoy #46015); **B)** Estimates of the hourly total water levels (calculated wave runup plus tides, T_{WL}) determined at Rocky Creek. The total water levels were estimated using the Stockdon and others (2006) wave runup model, which is based on measured deepwater wave statistics (wave height and period), measured tidal elevations (Port Orford gauge), and the beach slope (tan β = 0.124). The heavy red line reflects the average daily T_{WL}, effectively smoothing the hourly data. Vertical lines indicate beach survey dates. The locations of the 3-m (9 ft) and 5-m (16 ft) contour elevations are also depicted.

removed offshore. These latter changes are captured in the topographic survey of the beach near Rocky Creek (Figure 21) and in the plan view map of elevation contour changes identified between April and July 2006 (Figure 27). For example, it is apparent that the beach aggraded vertically at cs-3 and cs-4 (Figure 21) between April 4 and April 27 as a small volume of the sediments was transported south of the creek (note the volume changes in Table 2 described for the same period later in this report). As can be seen in Figure 27A, erosion was concentrated in the area adjacent to the creek outlet (approximately −11 m [−36 ft]), while the shoreline to the south and north of the creek prograded seaward as the sediments were redistributed away from their initial placement. The greatest erosion occurred immediately adjacent to the landslide face and lower down on the beach face (Figures 27A and 25A). Nevertheless, movement of sediments below Rocky Creek probably also reflects some new fill material that was placed on the south side of the creek between April 5 and April 27, as indicated by the seaward progradation of the 5-m contour (+9 m [+30 ft]) south of the creek and the positive gain in beach volume during this initial period (Figure 27B and Table 2).

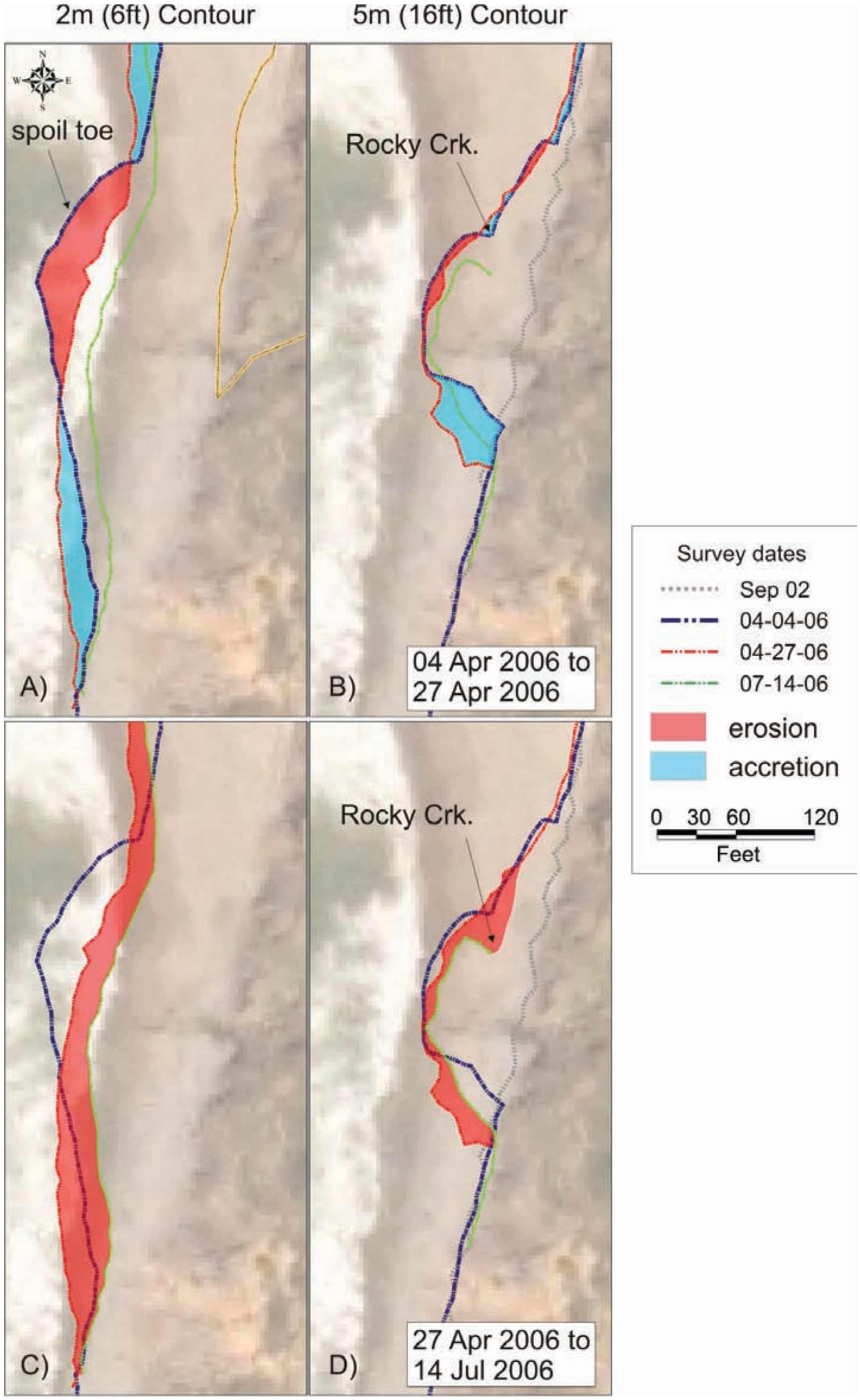

Figure 27. Plan view of beach contour changes measured by the RTK-DGPS topographic surveys. Contours shown are for the 2-m (6 ft) (left panels) and 5-m (16 ft) (right panels) elevations and for two time periods: March to April 2006 (upper panels) and April to July 2006 (lower panels). Note the red polygon denotes erosion, while the blue polygon indicates accretion. Grey dashed line indicates the position of the 5-m contour in September 2002.

Table 2. Rocky Creek beach volume change estimates.

Time	Net Change (m^3)	Net Change (yd^3)	Cumulative Change (m^3)	Cumulative Change (yd^3)
Apr. 5, 2006	7,050	9,220	7,050*	9,220
Apr. 27, 2006	60	80	7,110	9,300
July 14, 2006	−2,090	−2,730	5,020	6,570
Sept. 21, 2006	1,140	1,500	6,160	8,060
Jan. 25, 2007	−2,250	−2,950	3,910	5,110
Apr. 20, 2007	−800	−1,045	3,110	4,065
July 18, 2007	360	470	3,470	4,535
Aug. 31, 2007	3,630	4,750	7,100	9,285
Nov. 27, 2007	−1,770	−2,310	5,330	6,975
Feb. 5, 2008	−2,970	−3,890	2,360	3,085

Note: * denotes the net beach volume change between September 2002 and April 2006. Volumes have been rounded to the nearest 10 m^3 or 10 yd^3. Red lettering denotes periods in which the beach eroded.

The southward transport of sediments eroded from the toe of the landslide was removed as far south as Greg1 (Figure 3), located approximately 82 m (269 ft) south of the creek outlet. At Greg1, the beach aggraded vertically by approximately 0.2 m (0.7 ft) during the same period (Figure 28), mostly due to infilling by gravels and sands. Sand and gravel movement from the Rocky Creek slide did not extend farther south than the Greg1 site.

Erosion of the fill material at Rocky Creek continued to occur through July 2006 (Figures 21, 27C, and 27D), due to the occurrence of several other small storm events. Two storms occurred in May (9 and 23), and a third event occurred in mid June. Of these, the May 23 event was the more significant, generating total water levels on the order of 4.6 m (15 ft), allowing waves to directly attack the toe of the landslide material. As a result, all four cross-sections reveal evidence of beach retreat as material was eroded and removed from below the Rocky Creek site (Figure 21). Figure 27 shows the overall alongshore response to the same storm events. As indicated in Figure 27, the lower beach face (2-m [6 ft] contour) eroded landward by about 4 to 11 m (13 to 36 ft), while the upper beach face eroded by about 2 to 6 m (6.5 to 20 ft).

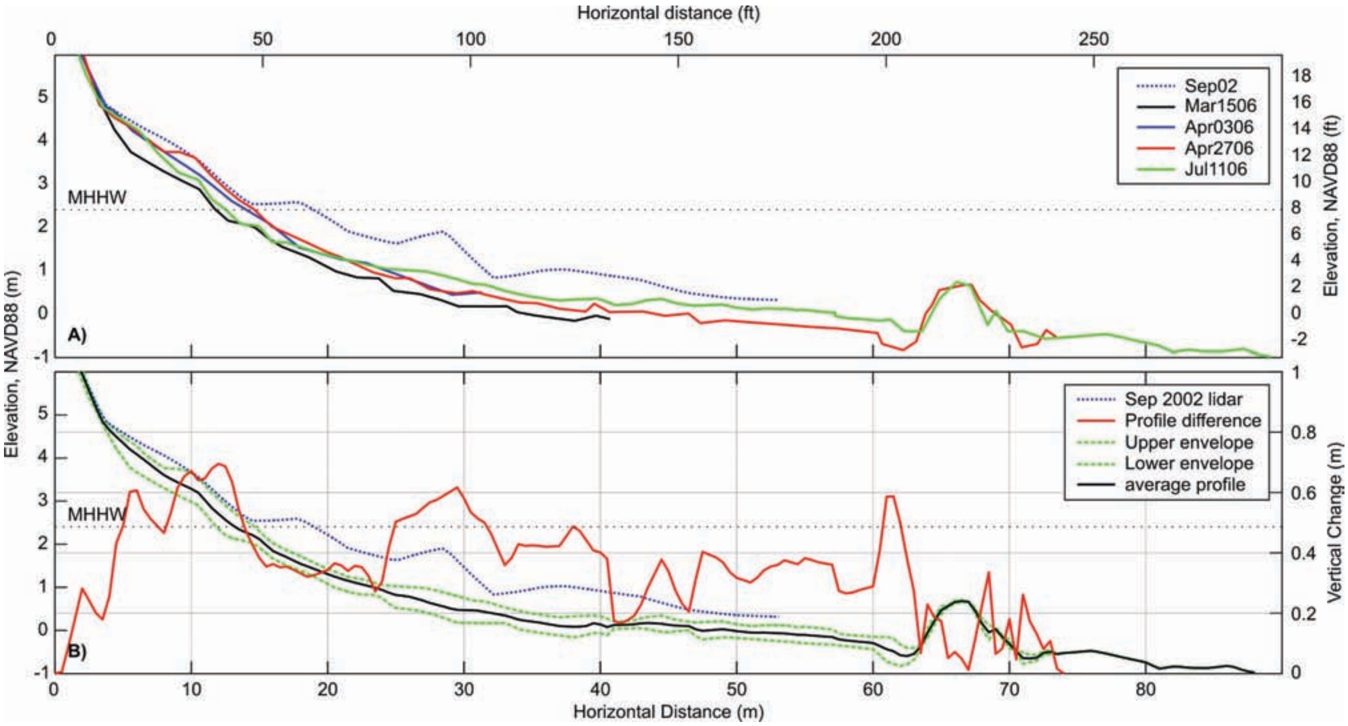

Figure 28. A) Beach profile measurements obtained at Greg1 between March and July 2006. A measurement of the beach morphology in 2002 that was derived from lidar is included. **B)** Plot showing the average profile, the maximum and minimum beach elevation changes (envelope of variability), and difference line that captures the vertical change between the maximum and minimum beach elevation changes.

Figure 29 shows the plan form response of the beach contours for the period July 2006 to January 2007, while Figure 30 presents the same measured response but for the period January 2007 to February 2008. The summer period from July to September 2006 was characterized by relatively little beach change at Rocky Creek due to the low wave heights and total water levels during this period (Figure 26). However, with the transition to winter around November 2006, erosion of the fill material resumed, with the greatest changes having been captured in our January 2007 survey. The bulk of the erosion probably occurred December 2006 due to the occurrence of two major storms (mid and late December), which generated daily average total water levels that reached elevations of 6 to 7 m (19 to 23 ft) at the shore, allowing the wave swash to directly attack and erode the face of the remaining fill. As can be seen in Figure 29, the lower beach face retreated landward in response to the storms. However, the greatest response occurred on the upper beach face, which saw the 5-m (16 ft) contour retreat landward by about 8 m (26 ft).

Additional beach retreat occurred between January and April 2007, although most of this was concentrated on the lower beach face. As can be seen in Figure 30, the beach experienced only minor changes over the early part of the 2007 summer, with the lower beachface gaining material. Again, this response is entirely due to the transition to lower wave heights typical of the summer months and highlighted in Figure 26. In fact, it turns out that the beach below Rocky Creek gained about 3,600 m^3 (4,700 yd^3) of sediment, predominantly sand-size particles, that were transported back onto the beach due to the predominance of swell wave conditions during July and August 2007. With the return of winter in November 2007, the fill was once again attacked by ocean waves. According to Figure 26, the 2007-2008 winter was characterized by two major storms: the first on December 2-3, 2007, that generated significant wave heights that reached 12 m (39 ft), and a second storm on January 8-9, 2008. As can be seen in Figure 29, the entire section of beach below the creek retreated by about 2 to 4 m (6 to 13 ft). However, the overall response at Rocky Creek was somewhat muted,

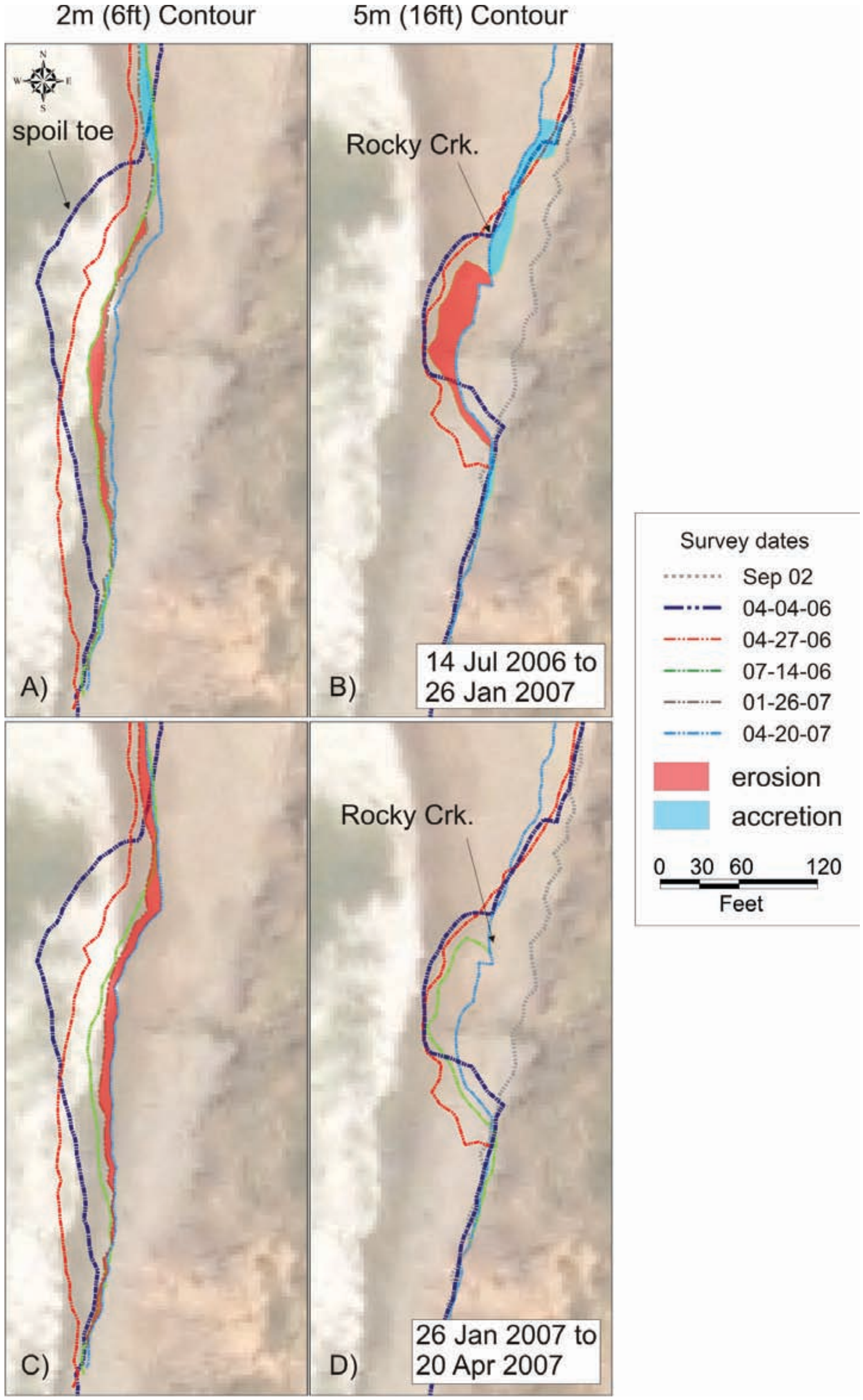

Figure 29. Plan view of beach contour changes measured by the RTK-DGPS topographic surveys. Contours shown are for the 2-m (6 ft) (left panels) and 5-m (16 ft) (right panels) elevations and for two time periods: July 2006 to January 2007 (upper panels) and January to April 2007 (lower panels). Note the red polygon denotes erosion, while the blue polygon indicates accretion. Grey dashed line indicates the position of the 5-m contour in September 2002.

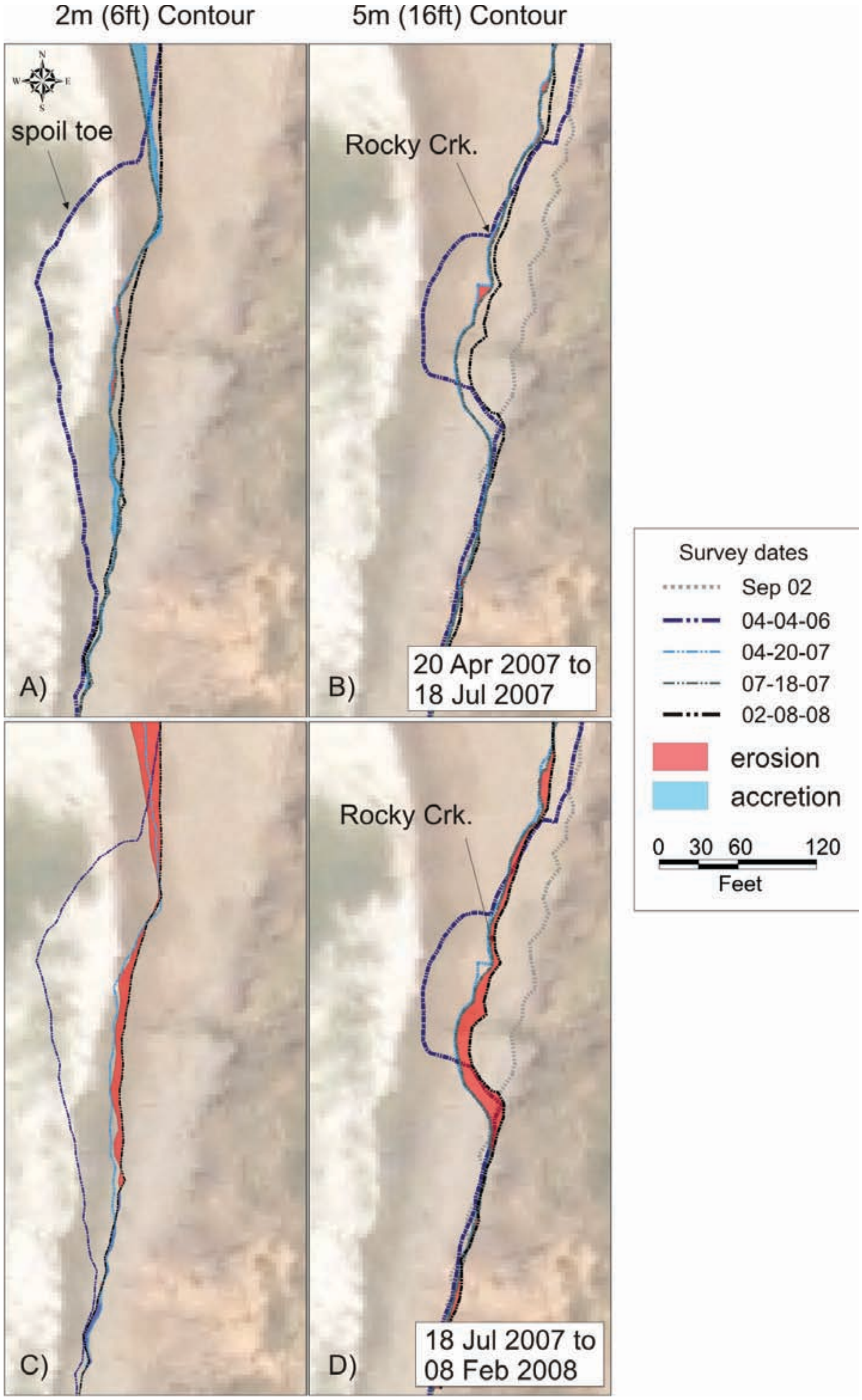

Figure 30. Plan view of beach contour changes measured by the RTK-DGPS topographic surveys. Contours shown are for the 2-m (6 ft) (left panels) and 5-m (16 ft) (right panels) elevations and for two different time periods: April to July 2007 (upper panels) and July 2007 to February 2008 (lower panels). Note the red polygon denotes erosion, while the blue polygon indicates accretion. Grey dashed line indicates the position of the 5-m contour in September 2002.

probably because the bulk of the fill had already been eroded, and because the accumulation of the coarser sediment fractions below the creek had by now formed an armored layer, capable of providing protection to the remaining fill.

Fill volume changes at Rocky Creek

Estimates of the volume of fill present at Rocky Creek on April 5, 2006, and from subsequent surveys of the same area are provided in Table 2. Figure 31 shows a difference plot for three time periods: April 6 to July 14, 2006; July 14, 2006, to April 20, 2007; and April 20, 2007, to February 5, 2008. The difference plots were derived by subtracting a digital terrain model (DTM) derived from the RTK-DGPS topographic survey data (say, April 6, 2006) from a second DTM measured at some later date (say, the July 14, 2006, survey). The focus of this effort is approximately 90 m (300 ft) of shoreline adjacent to Rocky Creek and broadly highlights the three-dimensional (morphodynamic) response of the beach to waves and nearshore currents as the sediments were eroded and transported elsewhere. Initial baseline conditions were established using lidar data measured in September 2002 at the end of the summer season. However, because the 2002 lidar data capture the beach topography in its most accreted state, those data were adjusted by lowering the portion of the beach below 6 m (19 ft), which approximates the toe of the bluff and hence the crest of the beach, by 1 m (3 ft); the 1-m vertical drop in the beach profile is a typical seasonal response observed on the sand beaches of the north coast and is close to the measured responses identified at Greg1 and Greg5 near Rocky Creek (i.e., sites protected by a wide, low sloping rocky intertidal nearshore shelf).

As indicated in Table 2, the volume of material present on the beach on April 5 shortly after the excavation work commenced, reflected a net gain of approximately 7,050 m^3 (~ +9,220 yd^3) of new material, well short of the estimated 33,000 m^3 (39,000 yd^3) we had expected to see on the beach. Despite erosion of the area near cs-1 and cs-2 (Figure 21), the beach gained an additional 60 m^3 of material between April 5 and April 27, 2006 (Table 2). This response in part reflects the redistribution of sediments to the south and probably some additional material from the excavation of the landslide; fill material continued to be pushed seaward onto the beach well after April 6.

By July 2006 the beach along Rocky Creek had lost about 2,090 m^3 (−2,730 yd^3) of the original fill, most of which came from the erosion of the toe of the fill as depicted in Figure 18. This pattern of response is reinforced in Figure 31A, which shows that the erosion was concentrated along the seaward face of the fill (i.e., the toe of the landslide) and along its southern extent, with the beach having been lowered by as much as 2 m (6 ft) during the inter-survey period. Erosion was also greatest adjacent to the channel of Rocky Creek. The degree of vertical lowering decreases asymptotically with distance offshore from the landslide. Nevertheless, as can be seen in the Figure 31, the area subject to large-scale erosion remained spatially large, extending offshore some 70 m (230 ft) from the landslide. Figure 31A also shows some sediment gain, concentrated near the central portion of the area and likely due to the arrival of new sediments placed on the site following our initial survey on April 5, 2006.

One year later, the remaining landslide fill volume had decreased by an additional 3,050 m^3 (~ −4,000 yd^3), the bulk of which had been removed by January 2007 (i.e., during the 2006-2007 winter). As can be seen in Figure 31B, erosion of the fill remained concentrated along its seaward face and along its southern margin, which was lowered by as much as 3.0 m (9 ft) in some places. Furthermore, it is evident from Figure 31B that the beach also continued to be lowered well seaward of the fill. This ongoing change is likely due to the winnowing out of sediments that had accumulated among the boulders and in the rocky intertidal region below Rocky Creek.

By August 2007 a large volume of sediment (~4,000 m^3 [5,220 yd^3]) had migrated back onto the beach at Rocky Creek (Figure 32). As noted previously, this response reflects the post-summer buildup of sand typical of the Oregon coast.

With the return to winter wave conditions over the 2007-2008 period, the beach at Rocky Creek lost an additional 4,740 m^3 (~ −6,200 yd^3) of sediment. Much of this sediment loss probably reflects the removal of sand that had accumulated during the previous summer season (Table 2, Figure 32). Figure 31C indicates that the erosion remained concentrated along the retreating landslide face. Seaward of the landslide, vertical lowering of the intertidal region appears to have slowed, suggesting that this portion of the beach may have been approaching equilibrium. Nevertheless, it is likely that

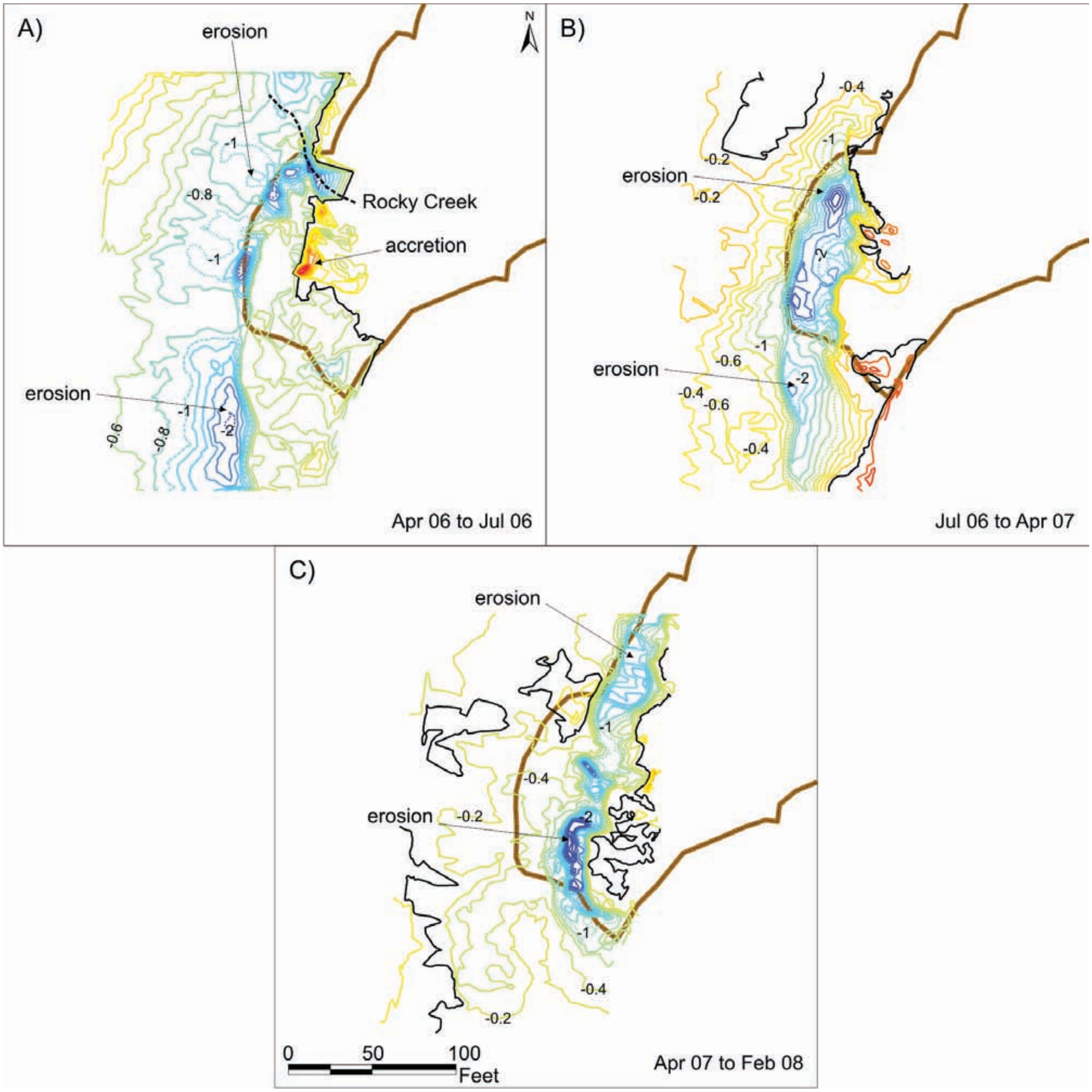

Figure 31. Digital terrain model difference plots derived for three time periods: **A)** April 6 to July 14, 2006; **B)** July 14, 2006, to April 20, 2007; and **C)** April 20, 2007, to February 5, 2008. Contour lines indicate the measured change (difference) between the two time periods. Cold colors (blue/cyan) denote erosion of the beach face, while hot colors (red/orange) indicate accretion. Black contour lines denote areas that experienced no change, or identify transition zones from erosion to accretion. Brown line denotes the approximate extent of the landslide, including the fill material deposited below Rocky Creek.

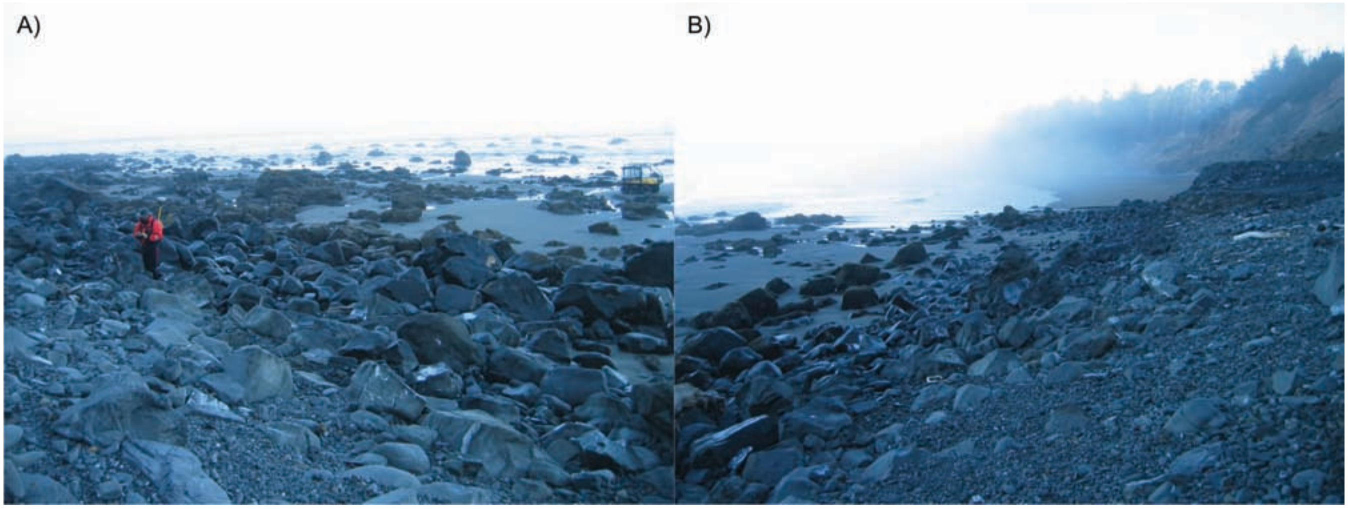

Figure 32. A) Post-summer sand accretion south of Rocky Creek on August 31, 2007. **B)** Accretion of sand against the landslide toe on August 31, 2007 (view is to the north) inundating the portion of the boulder beach within the intertidal zone.

the intertidal boulder beach seaward of Rocky Creek will continue to see an influx of sand during subsequent post-summer accretion phases.

As of February 2008, the remaining volume of material on the beach relative to the 2002 lidar survey was about 2,360 m^3 (~3,080 yd^3). These results indicate that the bulk of the material (~86%) bulldozed onto the beach in early April 2006 had been transported offshore or redistributed along the beach north of Rocky Creek, leaving only about 14% of the original volume on the subaerial beach below Rocky Creek. These measured responses highlight the rapid speed in which the landslide material was integrated into the littoral system (in a matter of a few weeks).

Beach morphodynamic responses along the Hubbard Creek littoral cell

The previous section examined the response of the beach immediately adjacent to the Rocky Creek landslide, documenting the overall changes to the landslide toe and beach following the placement of approximately 53,000 m^3 (~69,300 yd^3) of fill material. The objective of this section is to extend the analysis to document the larger-scale beach and shoreline responses measured along the entire Hubbard Creek littoral cell. The goal here is to assess the effect of the addition of approximately 33,000 m^3 (~39,000 yd^3) of new sediment on the morphology of the beach (e.g., shoreline progradation or recession), relative to its natural background level of variability, and in terms of changes to the predominant beach sediments.

As discussed previously, we estimated that about 6,900 m^3 (~9,025 yd^3) of the coarsest sediment fractions would be added to the beach as a result of the erosion of the landslide material, while some 26,600 m^3 (34,790 yd^3) of the medium sand to fine pebble sediment fractions would be subjected to both cross-shore and longshore sediment transport. Given that very little of the sediment was transported south of Greg1 (Figure 3) and that a relatively small volume (~20%) of fill remained on the beach on April 27, 2006, the bulk of the sand to pebble fractions must have been transported offshore, where the sediment was subsequently redistributed by nearshore currents, and/or must have been transported north from the landslide, where the sediment accumulated on the beach.

Figures 33 and 34 present results of the repeated RTK-DGPS beach surveys measured at the Greg2 and Greg3 sites located north of Rocky Creek (Figure 3). Included in the plots are the 2002 lidar data, measured in September at the end of the summer season and hence capturing the beach in its most accreted state. For the purpose of these comparisons the 2002 elevation data have not been adjusted as described for the previous section. Once again, the 2002 lidar data provided the baseline information from which subsequent measurements were compared. However, in this case we were interested in the addition of new material that would likely contribute to seaward growth (progradation) of the beach over and above the profiles in 2002.

The top halves of Figures 33 and 34 show selected profile surveys undertaken between March 2006 and February 2008; we have limited the number of surveys shown in the figures to avoid confusion. The bottom halves of the plots contain a variety of information including the September 2002 lidar profile, an average profile that is derived from all profile surveys excluding the lidar survey, the maximum and minimum beach elevation changes (also known as the envelope of variability), and a difference line that captures the vertical change between the maximum and minimum beach elevations. Also included in the figures are areas of yellow shading, which highlight the portions of beach that gained new material relative to the 2002 lidar plot. This last feature is a conservative estimate of the degree of net gain for this section of beach taken at comparable times of the year (i.e., at the end of the summer season).

As can be seen in Figures 34 and 35, our initial survey carried out on March 15, 2006, shows the state of the beach at the end of the 2005-2006 winter season, essentially with the beach in its most eroded state. By early April, the beach had prograded (migrated) seaward by several meters. However, most of the growth occurred over the next few weeks — by late April the beach face had migrated about 26 m (85 ft) seaward of its original position at the Greg2 profile site and about 10 m (33 ft) seaward at Greg3. At both sites, the net gain of material reflected the formation of a prominent berm, which initially was almost entirely made up of the coarser gravel fractions (i.e., cobbles). However, by late April the cobble berm was fronted by coarse sand and fine gravels. Sand continued to accumulate on the beach face throughout the summer. By late September 2006 the beach near MHHW had built seaward by as much as 40 m (131 ft) at Greg2 and about 30 m (98 ft) at Greg3 (Figure 17).

The quandary presented here, however, is that it is difficult to distinguish the effect of the new sediments added to the beach sediment budget (i.e., as a direct morphological response), relative to the natural seasonal variability of beach response typical along the Hubbard Creek littoral cell. The reason is simple: we have no a priori beach survey information documenting the degree of natural variability at the site. Hence, the best we can realistically achieve is to compare the changes to the 2002 lidar data, acknowledging that even here we may be underestimating (or overestimating) the actual beach volume and morphological changes. Additional evidence documenting the effect of the new fill on the beach sediment budget is based on comparisons of the pre- and post-sediment samples acquired along the shore described in more detail below. Taken together, these results have helped guide our interpretation of the responses shown in the figures. With these points in mind, it can be seen that both Greg2 and Greg3 gained new material (yellow shading, Figures 33 and 34). Our estimate of the volume change for the area between Greg2 and Greg3 reflects a net gain of about +3,900 m^3 (5,100 yd^3). Recall that by July 2006 there were about 5,000 m^3 (6,500 yd^3) of fill material still present near Rocky Creek, so that the bulk of the material (28,000 m^3 [36,600 yd^3]) had been dispersed by this stage.

Apparent from Figure 35 is that by September 21, 2006, shore progradation (and hence aggradation) had occurred as far north as Greg6. The bulk of this material accumulated around mid-beach (~ <4 m [12 ft] >1 m [3 ft]), with some aggradation occurring at the higher beach elevations near Greg3 (Figure 35). From these changes, a conservative estimate of the total volume of new material added between Greg2 and Greg6 is about 14,000 m^3 (18,300 yd^3). This suggests that as of September 2006, about 9,000 m^3 (11,700 yd^3) of material could not be accounted for. In all likelihood, much of the "missing" sediment was probably stored within the nearshore zone beyond our ability to safely survey and will eventually migrate back onto the beach at some later date. As can be seen in Figure 35, some aggradation also occurred north of Hubbard Creek, adjacent to Greg10 and north of Greg13. This response probably reflects the natural seasonal return of sand eroded from the beach during the previous winter, as opposed to the arrival of new sand from the Rocky Creek site. This is because waves generated during the summer arrive at the shore from predominantly west to northwesterly directions, which tend to drive sand landward onto the beach and toward the south (Figure 13).

Similar analyses of the alongshore response of the beach for surveys undertaken in April and August 2007 and in February 2008 are shown in Figure 36. The general pattern of change indicates that sediments that had accumulated between Greg1 and Greg6 eroded during the 2006-2007 winter. However, by late August 2007 the beach north of Rocky Creek had regained some of the

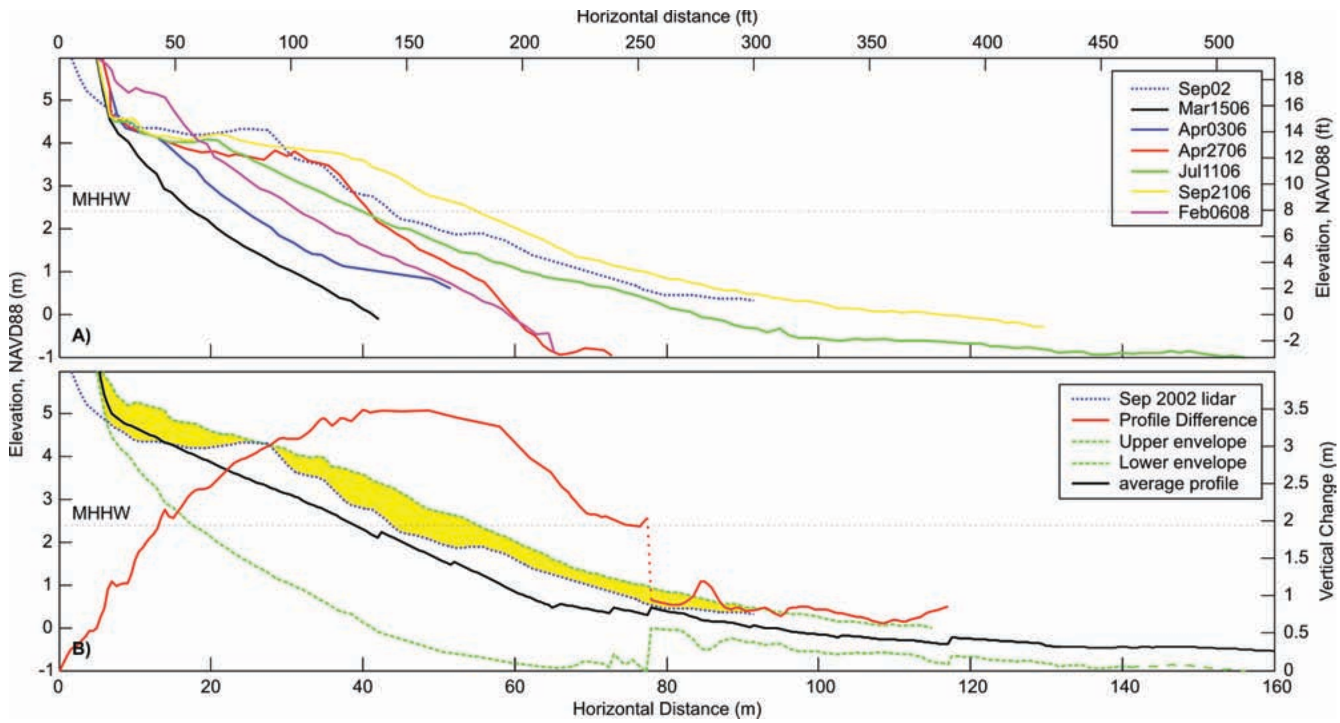

Figure 33. A) Measured beach profile responses at Greg2 for selected time periods. **B)** Bottom plot depicts the September 2002 lidar profile, an average profile (derived from all profile surveys excluding the lidar survey), the maximum and minimum beach elevation changes (envelope of variability), and a difference line which captures the vertical change between the maximum and minimum beach elevation changes.

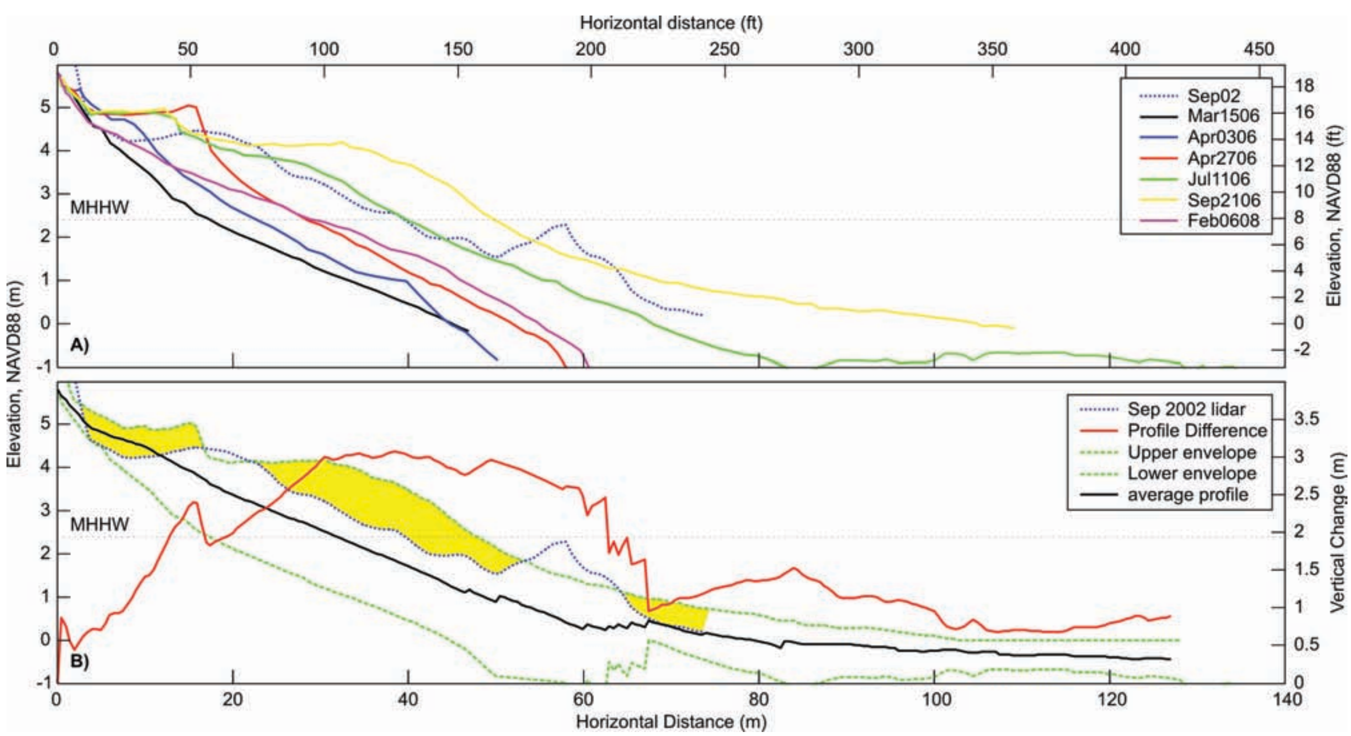

Figure 34. A) Measured beach profile responses at Greg3 for selected time periods. **B)** Bottom plot depicts the September 2002 lidar profile, an average profile (derived from all profile surveys excluding the lidar survey), the maximum and minimum beach elevation changes (envelope of variability), and a difference line which captures the vertical change between the maximum and minimum beach elevation changes.

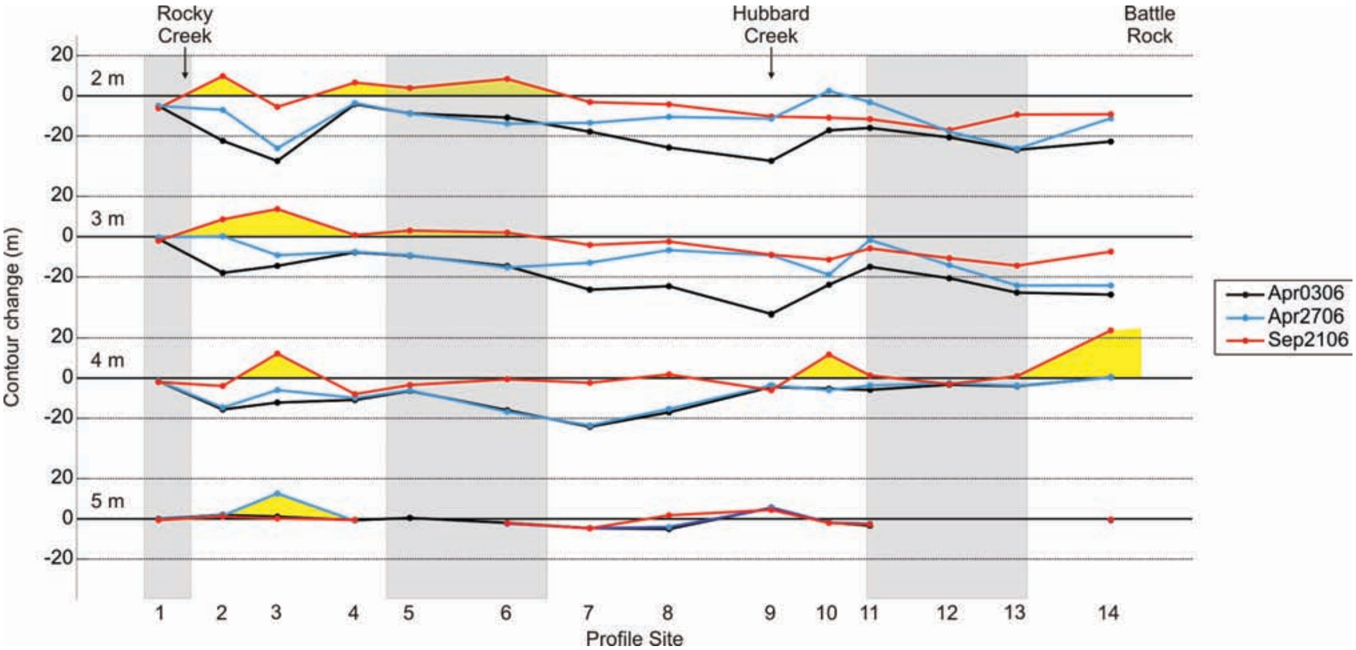

Figure 35. Alongshore responses of four beach contour elevations (2 m [6 ft], 3 m [9 ft], 4 m [12 ft], and 5 m [16 ft]) measured between April and September 2006 along the full length of the Hubbard Creek littoral cell. All data are relative to the 2002 baseline data set. Positive values indicate progradation (seaward advance) of the shore (yellow shading), while negative values indicate erosion (shore recession). Grey shading identifies those areas characterized by a broad rocky intertidal region.

previously eroded sediment. For example, the beach at Greg2 reached its most accreted state by August 31, 2007. Yet, by far the greatest response occurred north of Hubbard Creek, where the beach prograded seaward by as much as 25 m (82 ft), when a large pulse of sand had migrated onto the beach face between Greg9 and Greg13; this section of shore alone gained about 42,000 m^3 (54,936 yd^3) of material. While it is possible that some of this sediment may have originated from the Rocky Creek site, the bulk of the net volume gain is likely to have been due to the natural seasonal response of this beach (see below for more discussion on volume changes). The extreme winter storms experienced in early December 2007 and again in January 2008 resulted in extensive beach erosion along the entire Hubbard Creek cell. In fact, our measurements of the beach topography in February 2008 indicated that the beach was generally in its most eroded state, compared with our initial survey undertaken in March 2006. The erosion was particularly severe between Greg6 and Greg9 and also at Greg14 (Figure 36). In contrast, the shore between Greg1 to Greg6 did not experience as much erosion, probably because the beach was wider than normal, the product of new sediment from the landslide, which essentially provided a greater buffering capacity against the higher wave energy levels.

One last feature worth noting about both Figures 35 and 36 is that the response of the beach to waves and currents tended to be more muted in areas dominated by a wide, rocky intertidal nearshore (grey shading in Figures 35 and 36), while areas without the rocky substrate tended to exhibit greater cross-shore variability. These differences highlight the important role of wave-energy dissipation in the rocky intertidal areas, which effectively mitigates the wave impacts before they can reach the subaerial beach.

Sediment grain-size changes

Figure 37 shows the alongshore variation in mean grain-sizes derived from the DOGAMI sediment samples obtained prior to the excavation work, and from a resample undertaken in January 2007. In both cases, the sediments were sampled from the beach "reference point" located near mid-tide level at each of the profile sites. However, samples obtained in January 2007 were confined to those transect sites south of Greg11.

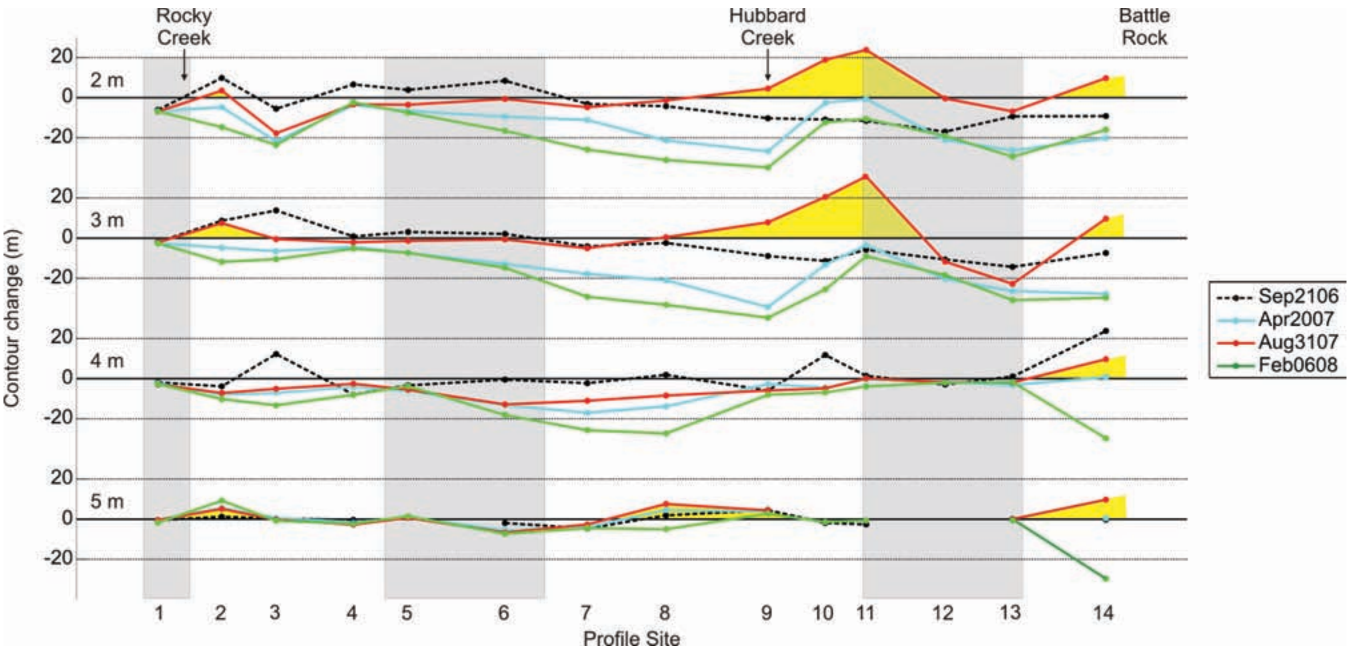

Figure 36. Alongshore beach response in the Hubbard Creek littoral cell for selected beach contour elevations for the period September 2006 to February 2008. Negative values indicate erosion (recession) of the contour, while positive values indicate accretion (progradation) of the shore. All data are relative to the 2002 baseline data. Yellow shading denotes accretion of the shore, while the grey shading identifies those areas characterized by a broad rocky intertidal region.

In both years, the sediment samples were obtained in the winter, enabling direct comparisons of the samples. The derived plots shown in Figure 37 reflect composite averages, which were obtained by aggregating the sample weights from each profile site and then averaging them. Furthermore, the composite averages have been generated for three different shore sections in the Hubbard Creek cell (south, central, and north), which closely follow the contrasting coastal geomorphology described previously in the study area section.

As depicted in Figure 37, the Hubbard Creek littoral cell is broadly characterized by two contrasting sediment populations. Between Greg1 and Greg6 at the south end of the cell the baseline conditions indicate a bimodal sediment population dominated by a long tail of coarse sediments, with one mode at −2.25ϕ (fine pebbles) and a second mode at 0.5ϕ (coarse sand). A similar bimodal spread has been identified between Greg12 and Greg13; however, along this shore, although the coarse sediments are comparable to the grain-size statistics identified between Greg1 and Greg6, the sand population is characterized by a dominant mode at 1.25ϕ, medium-size sand. In both regions, erosion of the bluffs that back the beach is probably largely responsible for the introduction of such a wide range of grain sizes, while Hubbard Creek likely also contributes to some of the coarser sediment fractions observed between Greg12 and Greg13. In contrast, the beach between Greg7 and Greg11 and in the north at Greg14 is characterized by a unimodal sediment population, dominated by medium to fine sand. It is probable that these finer sediments reflect the alongshore transport and hence winnowing out of the finer sediment fractions originally derived in the south from the erosion of the bluffs (i.e., northward transport). As a result, the presence of medium sand between Greg12 and Greg13 is likely due to the mixing of fine sediments transported from the south and those fines eroded from the bluffs that back this section of shore.

By January 2007 the average grain-size distribution curve for the shore between Greg1 and Greg6 had changed. While the shore was still characterized by a long tail of coarse sediments, the coarse sediment mode had been reduced and was now somewhat muted. At the other end of the distribution curve, the coarse sand mode originally present in the baseline samples had

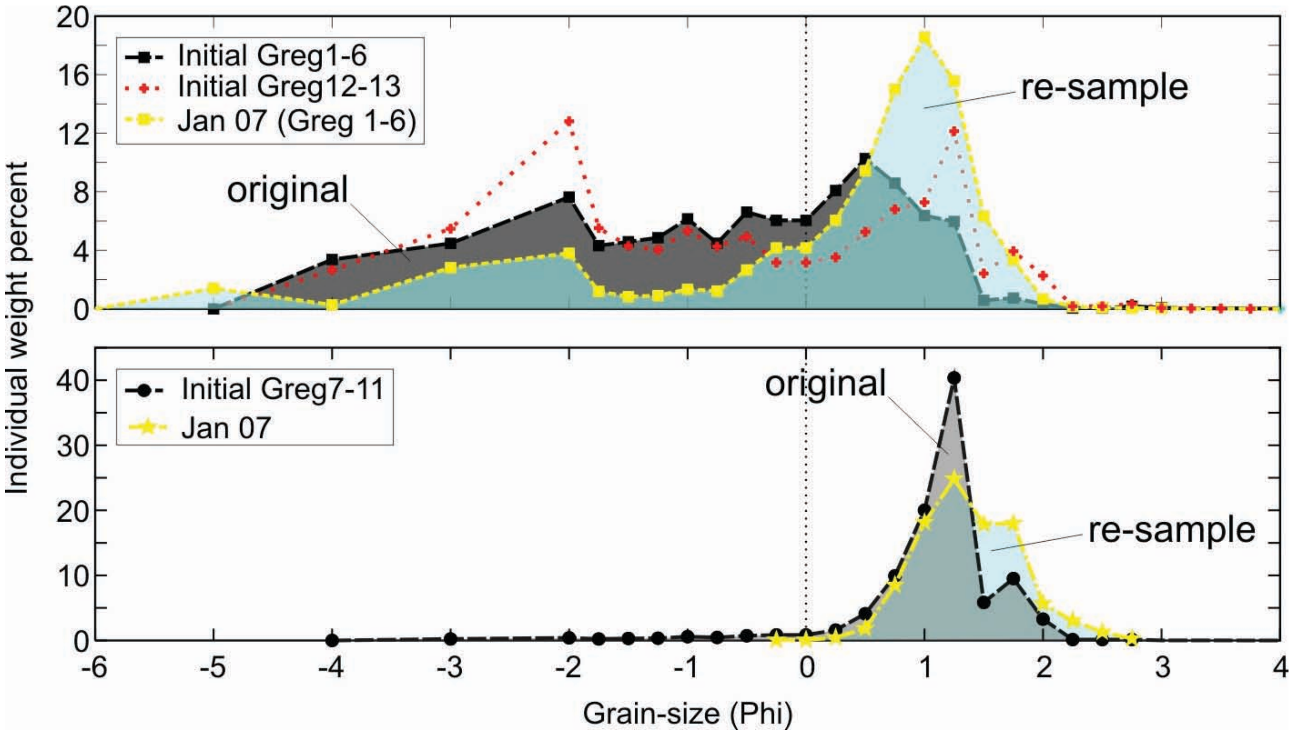

Figure 37. Grain-size distribution curves obtained along the Hubbard Creek littoral cell prior to the commencement of excavation work at Rocky Creek. Curves presented here reflect a composite average derived from the individually analyzed samples and highlight differences in the grain-size statistics (and hence beach morphology) for three different shore sections.

been shifted to a more dominant mode that spanned the coarse and medium sand boundary. In addition, it is very apparent that the beach in general had become much finer, with significantly greater quantities of sand present in 2007 when compared with the pre-excavation sediment samples. The changes identified south of Greg6 contrast with those measured between Greg7 and Greg11, where the beach was still characterized by a dominant medium sand mode (Figure 37). Nevertheless, the updated results also suggest some additional fining, possibly in response to the arrival of fine sediments from Rocky Creek in the south. Given these results and the findings of the alongshore profile responses presented in Figures 35 and 36, the combined results strongly indicate the occurrence of a northward transport of the fill sediments to at least Greg6 by January 2007.

Beach volume changes: 2002–2008

Beach volumes were estimated from the profile surveys using a custom script developed in MATLAB. The results of the analyses are presented in Table 3, rounded to the nearest 100 m^3 or 100 yd^3. Volumes were calculated for each individual profile site. Volumes span the beach from the toe of the bluff (equivalent to the beach crest) down to an elevation of 0.5 m (1.6 ft) and therefore include only the subaerial beach. This approach yields a volume estimate per linear meter of shore. Thus, to derive the alongshore volume within each profile compartment, the volumes were multiplied by the distance of shore between the profile sites. Results of these calculations are presented in Table 3 as gross volume changes and as the net volume change for each intersurvey period. Both data sets are plotted in Figure 38 for comparison.

As indicated in Table 3, the volume of sand present in the Hubbard Creek cell in September 2002 was estimated to be about 646,000 m^3 (845,753 yd^3) of material. At the beginning of our survey campaign on March

Table 3. Beach volume change estimates derived from the Hubbard Creek beach monitoring network.

Time	Gross Volume (m^3)	Net Change (m^3)	Gross Volume (yd^3)	Net Change (yd^3)
Sept. 18, 2002	646,600	—	845,753	—
Mar. 15, 2006	394,000	−252,600	515,352	−330,401
Apr. 5, 2006	424,000	30,000	554,592	39,240
Apr. 27, 2006	464,200	40,200	607,174	52,582
July 14, 2006	522,000	57,800	682,776	75,602
Sept. 21, 2006	589,200	67,200	770,674	87,898
Nov. 21, 2006	473,800	−115,400	619,730	−150,943
Jan. 25, 2007	464,200	−9,600	607,174	−12,557
Apr. 20, 2007	487,700	23,500	637,912	30,738
July 18, 2007	591,600	103,900	773,813	135,901
Aug. 31, 2007	629,700	38,100	823,648	49,835
Nov. 27, 2007	536,100	−93,600	701,219	−122,429
Feb. 06, 2008	388,300	−147,800	507,896	−193,322
Total Change[1]		−258,300		−337,856
Total Change[2]		−5,700		−7,456

Net volume changes are based on the difference between two successive surveys. Blue denotes accretion (sand volume gain), red indicates erosion (loss of sand volume). Total Change[1] reflects the volume change between September 2002 and February 2008; Total Change[2] is based on the period between March 2006 and February 2008.

15, 2006, the volume of sediment was in a deficit state, having experienced a decrease in volume of about 252,000 m^3 (330,000 yd^3) between 2002 and 2006, which is within the expected range of seasonal beach volume changes identified along this shore. With progress into the 2006 summer period, the beach gained about 195,000 m^3 (255,300 yd^3) of sediment (Table 3, Figure 38) as sand that had eroded from the beach during the preceding winter was transported back onto the beach. With the transition into the 2006-2007 winter, erosion of the beach resulted in the removal of approximately 125,000 m^3 (163,500 yd^3) of sediment. However, the net volume change for the period March 2006 to January 2007 (winter to winter comparison) reflects a net gain of about 70,200 m^3 (91,821 yd^3) of sediment.

By late August 2007, beaches along the Hubbard Creek cell effectively regained much of what had been lost. In fact, the beach volume in August 2007 was about 16,900 m^3 (22,100 yd^3) less than what had been present on the beach in September 2002. Given the uncertainties in the volume estimates, the difference between 2002 and 2007 is basically negligible. With the return to higher wave energies during the 2007-2008 winter, the beach experienced significant erosion and by February 2008 had lost 241,400 m^3 (315,751 yd^3) of sediment. Consequently, by early February 2008 there was less sediment (−5,700 m^3 (7,456 yd^3), Table 3) on the beach when compared with our initial survey undertaken in March 2006. This result clearly highlights the overwhelming role of major storms in contributing to widespread and rapid erosion of the shore, well exceeding the input of new sediment from the Rocky Creek landslide. Of interest is whether the winter 2007-2008 erosion was observed everywhere along the shore. To that end, Figure 39 documents the net volume changes within the littoral cell for the period March 2006 to February 2008. Such a comparison is reasonable as we are essentially comparing beach volumes at or near the end of the respective winter seasons. These data are presented for each section of shore in which a profile is present and hence provide a measure of the alongshore beach.

Figure 39 clearly indicates that the 2007-2008 winter storms did not erode everywhere in the Hubbard Creek littoral cell, with the southern portion of the cell having experienced less erosion compared with the central and northern portions (Figure 36). In fact, there was a net gain of sediment by volume between Greg1 and Greg5 of about 27,640 m^3 (36,150 yd^3), close to the estimated 33,000 m^3 (~39,000 yd^3) of sediment thought to have been injected into the littoral system by erosion of the landslide fill sediment. While it is impossible to say for certain that this gain is entirely from the erosion of the fill, given the morphological response of the shore and the identified sediment changes at the southern end of the cell, it is highly likely that the bulk of this material was derived from erosion of the fill. The results shown in Figure 39 for the southern end of the cell contrast with the response observed along the rest of the Hubbard Creek shore (north of Greg5), where the net volume change for the 2-year period was one of erosion, with the beach having lost about 33,600 m^3 (43,950 yd^3) of sediment. Thus, despite the addition of about 33,000 m^3 (~39,000 yd^3) of new material from the placement of the fill on the beach in April 2006, the state of the beach in 2008 reflected an overall net loss of 5,700 m^3 (7,456 yd^3) of sediment.

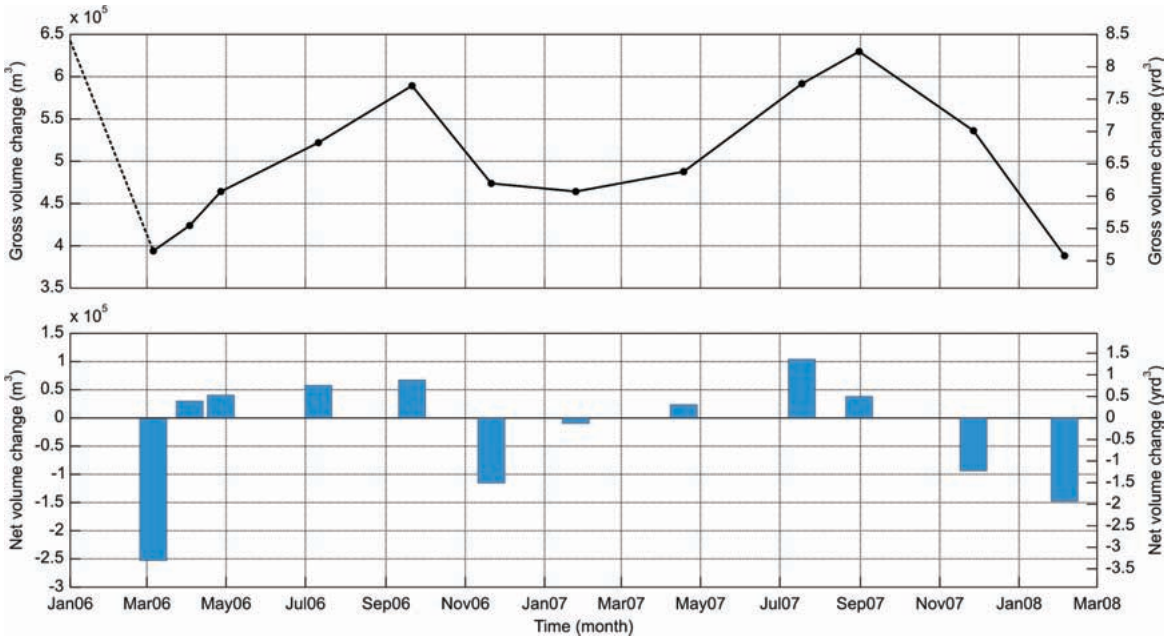

Figure 38. Gross volume changes for the entire period of study (top) and expressed as net changes for each inter survey period (bottom).

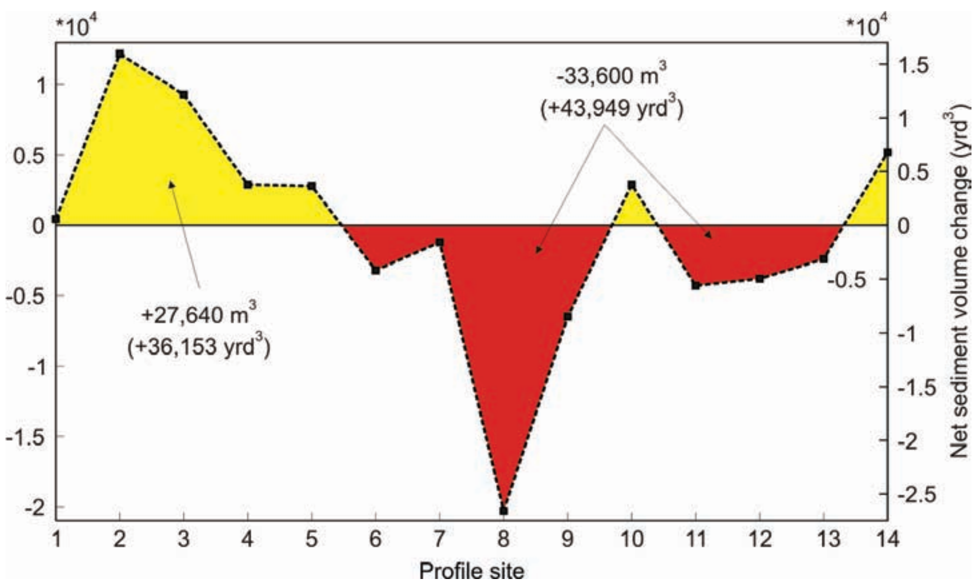

Figure 39. Net volume change estimates for the period March 2006 to February 2008 determined for each profile section. Note: the southern portion of the littoral cell (between Greg1 to Greg5) gained ~27,600 m^3 (~36,000 yrd^3) of sand, while the northern portion of the cell lost ~33,600 m^3 (~44,000 yrd^3). Yellow shading denotes accretion; red shading denotes erosion.

DISCUSSION AND SUMMARY

The failure of the Rocky Creek landslide south of Port Orford in January 2006 raised a number of important questions about the appropriate use of the public beach and intertidal region for fill placement following the excavation of the landslide and highway. In particular, questions were raised about the likely impact of the fill to the Hubbard Creek littoral system and to the marine biology immediately below Rocky Creek and adjacent to the landslide. To understand the former effects (i.e., fill disposal on the littoral system), the Oregon Department of Geology and Mineral Industries (DOGAMI) was commissioned to monitor and assess the impact of the addition of 53,000 m^3 (~69,300 yd^3) of fill material, bulldozed on to the beach in April 2006. Three key tasks were identified to examine and address this issue:

1. Document changes to the grain-size statistics and sediment fractions along the Hubbard Creek littoral cell, which extends from Battle Rock adjacent to Port Orford to Rocky Point in the south;
2. Establish a beach profile monitoring network along the full length of the shore and undertake repeated (approximately bimonthly) surveys of the beach to document the cross-shore and alongshore response of the beach to the introduction of the fill; and,
3. Undertake large-scale topographic surveys of the shore, particularly adjacent to the landslide, to document the morphodynamic response of the beach and fill material adjacent to Rocky Creek.

The results of this study revealed the following:

- Out of the original 53,000 m^3 (~69,300 yd^3) of fill added to the beach, we estimate that about 19,700 m^3 (~25,770 yd^3) of the sediment composed of fine sand to silt was removed and lost to deep water, while the remaining 33,000 m^3 (~39,000 yd^3) of coarser sediment was added to the beach sediment budget.
- Out of the 33,000 m^3 (~39,000 yd^3) of fill supplied to the beach, an estimated:
  - i. 800 m^3 (1,045 yd^3) consists of cobbles (> $-6\phi < -8\phi$ [> 64 < 256 mm]) and would be absorbed directly onto the beach;
  - ii. 6,100 m^3 (7,980 yd^3) consists of coarse pebbles (> $-4\phi < -6\phi$ [> 16 < 64 mm]). These particles would probably remain either close to or directly on the beach face, within the wave swash zone; and,
  - iii. 26,600 m^3 (34,790 yd^3) consists of fine pebbles and coarse to medium sand fractions (> $2\phi < -4\phi$ [> 0.25 <16 mm]). These latter sediments would be subject to both cross-shore and longshore sediment transport and hence may be removed to the nearshore or redistributed farther along the beach.
- As of 2008 the volume of new material remaining on the beach attributed to the excavation of Highway 101 at Rocky Creek was estimated to be only 7,050 m^3 (~9,220 yd^3), significantly less than the estimated 33,000 m^3 (~39,000 yd^3) bulldozed onto the beach (excluding the fine sediments that would have been lost to deep water).
- Heavy rainfall and elevated creek discharge levels at the time of excavation likely helped fluidize the sediment as it was bulldozed down onto the beach. By the time the sediment reached the beach, the material consisted of a slurry composed of water and sediment. Compounded by high surf action and high total water levels (wave runup plus the tidal elevation) during April, the slurry was rapidly eroded, with some of the sediment removed to the nearshore and to the north, where the sediment accumulated on the beach between Greg2 and Greg3.
- Removal of the fines to the offshore was aided by a strong rip current that is commonly present below Rocky Creek. This rip current likely helped transport the finer particles (clay and silt) beyond the wave breaker zone where it was subsequently disbursed by ocean and wind-driven currents.
- Between April and July 2006, the remaining fill experienced erosion along its toe and seaward on the lower beach face (−2,090 m^3 (−2,730 yd^3). This erosion is likely related to two storms that occurred in May 2006, with one storm having generated relatively high total water levels that reached about 4.6 m (15 ft) elevation, allowing the waves to erode the face of the fill.
- Sediments eroded from Rocky Creek were transported as far south as Greg1, where accretion raised the beach elevation by about 0.2 m (0.7 ft). Sediments transported toward Greg1 essentially

filled the interstices between the larger boulder clasts, inundating the tide pools and marine life. From our observations we do not believe the gravel fractions will be transported any farther south, because wave breaking along this section of shore typically results in oblique wave breaking, which tends to drive the gravels mainly to the north.

- Apart from an early phase of erosion between April and July 2006, the bulk of the fill erosion occurred during the winter months when wave energy levels and measured tide levels are highest. Wave energy levels during the 2007-2008 winter were particular significant and resulted in the loss of about 4,740 m^3 (~ −6,200 yd^3) of sediment from the beach at Rocky Creek. However, it should be noted that much of the sediment removed during this erosion phase was sand that had accumulated during the previous summer period, while erosion of the remaining fill was relatively minor. Given the severity of the 2007-2008 winter, it is possible that previous erosion events had helped armor the beach below Rocky Creek, providing additional protection to the remaining fill.
- As of February 2008 the volume of fill material estimated to remain on the beach was about 2,360 m^3 (~ 3,080 yd^3).
- Analyses of the response of the beach north of Rocky Creek revealed that the most significant morphological and sedimentary changes occurred between Greg2 and Greg3, eventually extending as far north as Greg6.
- Cobbles eroded from the landslide were dispersed mainly to the north of Rocky Creek. Some of the cobbles were also dispersed directly below Rocky Creek. The northward movement of the cobbles was not unexpected, because wave breaking along this shore typically occurs oblique to the shore, which sets up a northward flowing longshore current. Initially, the cobbles accumulated as a berm near the Greg2 profile site, but eventually migrated as far north as Greg3. Much of this response occurred during the first few weeks after the material had arrived on the beach. By late April the entire beach face had prograded seaward by about 26 m (85 ft) at the Greg2 profile site and about 10 m (33 ft) at Greg3 due to an influx of coarse sand and fine gravels.
- Comparisons of the response of the beach along the entire Hubbard Creek littoral cell revealed that by September 2006 the beach face had built seaward as far north as the Greg6 profile site due to aggradation of sand along this section of shore. Furthermore, comparisons of pre- (March 2006) and post- (January 2007) excavation grain-size analyses indicated a general fining of the sediment fractions south of Greg6. Taken together, these changes suggest that transport of the fill material had extended as far north as Greg6 by early January 2007.
- Volume change estimates of the beach between Greg1 and Greg5 revealed that the shore gained about 27,640 m^3 (36,153 yd^3) of sediment between March 2006 and February 2008 (i.e., a winter-to-winter comparison). The addition of new sediment to the beach helped provide some protection to the shore from extreme winter storms in December 2007 and January 2008. As a result, this shore section did not erode as much as the beach north of Greg6.
- Significant shore progradation was also identified north of Hubbard Creek in late August 2007, causing the beach face to progradeded seaward by up to 25 m (82 ft), with the accumulation involving only the arrival of sand. Overall, the section of shore between Greg10 and Greg12 gained about 42,000 m^3 (54,936 yd^3) of sand. Although it is possible that part of this volume gain may be related to sediments transported to the north from Rocky Creek, it is more likely that the response reflects the natural seasonal growth of the beach over the summer season as sand migrates back onto the subaerial beach. For example, estimates of the seasonal sediment volume change in the Hubbard Creek cell for the summer period ranged from a high of 195,000 m^3 (255,300 yd^3) in 2006 to 165,500 m^3 (216,474 yd^3) in 2007. In contrast, high wave energy levels over the 2007-2008 winter resulted in the loss of about 241,400 m^3 (315,751 yd^3) of sediment, which can be attributed to two major storms (December 2-3, 2007, and January 8-9, 2008).
- By February 2008 there was less sediment (−5,700 m^3 (7,456 yd^3) on the beach relative to when we first began surveying in March 2006.

- The relatively large volume changes identified within this small littoral cell are primarily a function of the dominant seasonal exchange of sediment, characteristic of summer/winter beach morphodynamics on the Oregon coast. These changes clearly exceed the effect of the new sediment added to the littoral cell. It is important to note that it is of course the occurrence of natural landslides in the long term that ultimately determines the volume and buffering capacity of the beaches in the Hubbard Creek littoral cell. Thus, introducing the fill sediment was in many respects similar to a natural landslide, whereby new sediments are rapidly dispersed and, ultimately, contribute to the beach sediment budget.

In summary, the placement of a relatively small quantity of fill material on the beach at Rocky Creek did not have an adverse effect on the adjacent beach below or elsewhere within the Hubbard Creek cell. This undoubtedly was helped by the fact that the fill used to construct Highway 101 at Rocky Creek had been locally sourced from the surrounding hills. As a result, the geologic characteristics of the fill (including the grain-size fractions) were directly comparable to what is presently supplying the beach system from the natural landslides and sea-cliff erosion. Also of importance, ODOT staff and the contractor undertook a concerted effort to remove "foreign" materials (asphalt, metals, electrical conduit, etc.) prior to disposal of the fill, to avoid introduction of contaminants on the beach. In this regard, the process at Rocky Creek can be considered a success.

Over time it can be expected that the sand contributed to the beach by the landslide will continue to be dispersed throughout the littoral system, eventually reaching Battle Rock and the Port of Port Orford in the north. An important consideration for any future work would need to consider this potential transport of sand into the port and its contribution to shoaling. The U.S. Army Corps of Engineers (USACE) and the Port of Port Orford recently dredged (July 2007) approximately 26,000 m^3 (34,000 yd^3) of sand from the turning basin adjacent to the port's dock. However, by winter 2007 the area that had been dredged had been filled with new sand, raising questions about where the sand had come from. In July 2007 DOGAMI established a monitoring network adjacent to the port to better understand the response of the beach at the very north end of the cell. While our monitoring of the beach adjacent to the port did indicate significant changes to the beach between August 2007 and February 2008 (i.e., spanning the extreme 2007-2008 winter), those changes reflected the erosion of about 29,400 m^3 (38,450 yd^3) of sediment from the subaerial beach, which were transported into offshore bars. It is our interpretation that the deepening of the turning basin adjacent to the port essentially created a "sink" for the sand removed from the beach so that it accumulated against the port dock affecting port operations. Because this sand had been present at the north end of the cell prior to July 2007 (i.e., the beach morphology and sand volumes in 2007 were comparable to 2002), we can conclude with certainty that the addition of the new material from the Rocky Creek landslide did not contribute to the recent problem experienced in the port.

Although the placement of fill sediment on the beach below Rocky Creek worked well, it cannot be expected to work everywhere. Future efforts will need to consider carefully the potential impact to both the beach and the marine biology. In particular, both the underlying geology (grain-size fractions and lithologic units) and the volume of material that might be added to the beach will need to be considered. For example, had the volume of material been much larger at Rocky Creek, the morphodynamic response of the beaches might have been more dramatic, possibly resulting in significant beach progradation, as well as more extensive cross-shore and longshore sediment transport, affecting both the biology and public use of the beach and ocean.

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APPENDIX A:
GRAIN-SIZE AND MINERAL ANALYSIS REPORT OF SEDIMENTS ALONG THE HUBBARD CREEK LITTORAL CELL AND GREGORY POINT LANDSLIDE

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Initial Work Statement

On January 4, 2006, a fill/block failure occurred on U.S. Highway 101 adjacent to Rocky Creek, located approximately 3 miles south of Port Orford on the southern Oregon coast. The landslide caused a 20-ft depression to develop along a portion of Highway 101, significantly affecting traffic in the region. To remediate the fill/block failure, the Oregon Department of Transportation (ODOT) concluded that the entire fill section overlying Rocky Creek would need to be excavated, moved elsewhere, and replaced with new coarser fill material. After consultation with several agencies, including the Oregon Department of Geology and Mineral Industries (DOGAMI), ODOT was granted a permit by Oregon State Parks and Recreation Department (OPRD) to push approximately 45,000–60,000 cubic yards of “fill” material, seaward onto the beach below.

Grain-size and mineral analysis

Analytical assessment of 17 samples from the field site were conducted by Robert Lee, a Ph.D. candidate in the Oregon State University Department of Geosciences. Approximately 10 kilograms of each sample were provided by Jonathan Allan of DOGAMI. All analyses were conducted at the Oregon State University Department of Geosciences sedimentology laboratories.

Methodology

Grain-size analyses were determined using U.S. Standard Sieves Sereis sieves and a Model RX-24 portable sieve shaker manufactured by W. S. Tyler Company Cleveland, Ohio. The samples were dried using a conventional oven at 65°C for at least 4-5 hours; some were dried overnight. The samples were then randomly split, and 500 ml of each sample was weighed and poured into the U.S. Standard sieves. The sieves were cleaned prior to each use. material was seived at -6.0ϕ to -2.0ϕ at 1ϕ intervals for the coarse fraction and -2.0ϕ to $+4.0\phi$ at $¼\phi$ intervals for the sand to finer grain size fractions. The sieves were placed in the portable sieve shaker for approximately ten minutes. Each ϕ step was then weighed using an electronic scale precise to ±1 mg.

The individual weight fractions were plotted using Microsoft Excel on cumulative percent graphs, and the graphic mean, sorting, skewness, and kurtosis were determined using the equations of Folk and Ward (1957). The sediments were also classified using the sediment classification scheme of Folk (1954).

The mineralogy of the samples was determined using a binocular microscope to count individual grains. Grain shape and type were identified using the coarse size fractions as a rough proxy for the finer grain size. For consistency, point counts were conducted on the 1.0ϕ size fraction for all samples with approximately 150 to 450 counts on each sample.

Results

All data were compiled in the Excel spreadsheet "Lee_DogamiFiles_pre-excavation" with the list of sediment classification, mean, median, sorting, skewness, kurtosis, and a sheet for the mineralogy point counts. Results for each sample are listed below. Additional grain-size analyses were performed on samples taken in January 2007. These data are summarized in a separate Excel spreadsheet "Lee_DogamiFiles_post-excavation."

Samples Greg2 through Greg13 (see Figure 3 of main text for sample locations) were collected along the main beach and varied from sandy gravel to sand with consistent mineralogy except for sample Greg2.

Greg2: Sample is poorly sorted sandy gravel. Grains are rounded to subrounded with the majority of the coarse fraction consisting of basalt, quartz, shell fragments with accessory granite?, sandstone, and metamorphics. Mineralogy point counts yielded 38% basalt, 27% quartz grains (consisting of transparent, smoky, and orange-yellow agate silica), 14% other (grains of possible granites, mixtures of varying clasts, and unidentified), 11% metamorphics (grains of green and red metamorphics possibly slate or quartzites), 5% sandstone (fragments of fine-grained sandstone clay particles), 2% shell fragments, and 2% feldspar grains (mainly plagioclase, most altered with clay rinds). The point-count grains were rounded to subangular. The sample differed from the other beach samples with a higher percentage of basalt clasts and the appearance of sandstone fragments. The location of this sample to the landslide suggests that the material in the Greg2 sample may contain landslide material. Clasts found in the landslide samples support this suggestion.

Greg3: The sample is poorly sorted sandy gravel. Grains are rounded to subangular, roller to spheroidal. Coarse fragments consist of basalt, quartz, metamorphics, and shell fragments. Point counts yielded 68% quartz (consisting of transparent, smoky, and orange-yellow agate silica), 15% basalt, 7% metamorphics (quartzite, red and green slate?), 7% other (unidentified, granites?, mixtures), 1% shell fragments, and 1% feldspar.

Greg4: The sample is poorly sorted gravelly sand. Grains are rounded to subangular, roller to spheroidal. Coarse fragments consist of quartz, metamorphics, basalt, and possible granite. Point counts yielded 52% quartz (consisting of transparent, smoky, and orange-yellow agate silica), 17% other (grain mixtures, unidentified, possible granite), 15% basalt, 10% metamorphics, 4% shell fragments, 3% feldspar.

Greg5: The sample is poorly sorted sandy gravel. Grains are rounded to angular, flat to spheroidal. Coarse fragments contained a higher amount of basalt than Greg3 and Greg4 along with quartz, metamorphics, and shell fragments. Point counts yielded 51% quartz, 19% other, 17% basalt, 7% metamorphics, 3% feldspar, and 3% shell fragments.

Greg6: The sample is poorly sorted gravelly sand. The grains are rounded to subrounded, roller to spheroidal. Coarse fraction consists of basalt and metamorphics with quartz and possible granite. Point counts yielded 54% quartz, 17% other, 17% basalt, 8% metamorphics, 2% feldspar, 1% shell fragments.

Greg7: The sample is moderately sorted gravelly sand. The grains are rounded to subangular, roller to spheroidal. Coarse fraction consists mainly of basalt, metamorphics, shell fragments, and minor quartz and granites. Point counts yielded 55% quartz, 15% basalt, 15% other, 14% metamorphics, ½% shell fragments, and ½% feldspar.

Greg8: The sample is well sorted sand. The grains are rounded to subrounded, roller to spheroidal. Coarse fraction consists of quartz, basalt, and shell fragments. Point counts yielded 47% quartz, 19% other, 17% metamorphics, 12% basalt, 4% feldspar, and 1% shell fragments. The finer-grained fraction is rounded to subangular.

Greg9: The sample is very well sorted sand. The grains are rounded to subrounded, roller to spheroidal. Coarse fraction consists or quartz, basalt, metamorphics and shell fragments. Point counts yielded 52% quartz, 17% metamorphics, 14% basalt, 11% other, 3% feldspar, and 2% shell fragments. The finer-grained fraction is rounded to subangular.

Greg10: The sample is well sorted sand. The grains are rounded to subrounded, roller to spheroidal. Coarse fraction consists of basalt, quartz, metamorphics and shell fragments. Point counts yielded 56% quartz, 14 % basalt, 13% metamorphics, 11% other, 3% feldspar, and 2% shell fragments. The finer-grained fraction is rounded to subangular.

Greg11: The sample is well sorted sand. The grains are rounded to subrounded, roller to spheroidal. Coarse fraction consists of basalt, quartz, metamorphics and shell fragments. Point counts yielded 61% quartz, 14% metamorphics, 14% other, 8% basalt, 2% feldspar, and 1% shell fragments. The finer-grained fraction is rounded to subangular.

Greg12: The sample is poorly sorted sandy gravel. The grains are rounded to subangular, flat, roller, and spheroidal. Coarse fraction consists of basalt, quartz, metamorphics, and shell fragments. Point counts yielded 39% quartz, 18% basalt, 16% other, 14% metamorphics, 7% shell fragments, and 5% feldspar.

Greg13: The sample is poorly sorted sandy gravel. The grains are rounded to subangular, flat, roller, and spheroidal. Coarse fraction consists of basalt, quartz, metamorphics, and shell fragments. Point counts yielded 47% quartz, 20% basalt, 18% metamorphics, 11% other, 2% feldspar, and 2% shell fragments.

The sorting of the beach samples improved toward the center of the beach pocket as did the roundness in shape of the grains, consistent with field observations of the area (Jonathan Allan, personal communication). From the mineralogical analysis, quartz dominates the beach sand with varying amounts of basalt, metamorphics, and other clasts. The basalt grains contained plagioclase phenocrysts, while limonite staining was observed on some of the clasts. The source of the basalt is unknown, but is clearly abundant within this section of the beach deposits. The samples were checked with a magnet; none of the beach samples appeared to contain a magnetic fraction.

The other five samples included Hubbard Creek, and deposits along the landslide face and cliff face. The mineralogy of these samples was clearly distinctive from those along the beach.

Hubbard Creek: The sample is poorly sorted gravel. The grains are rounded to subangular, roller and flat. Coarse fragments consist of basalt, sandstone, and quartz grains. Point counts yielded 22% quartz (clear to smoky variety of silica, minor yellowish orange agate), 19% basalt (grains round to flat with limonite staining), 15% other (unidentified coarse mixtures, possible sandstone or granites), 10% mica (schistoic micas, biotite? or phyllite? most likely from a metamorphic source), 9% metamorphics (green, red, and brown grains of metamorphic origin possibly slates), 9% sandstone fragments (fine-grained sandstone fragments consisting of quartz and feldspar grains), 7% feldspar (white to pink grains of feldspar, most appear to be plagioclase; minor alteration associated with most grains), 6% organic material (includes small twigs, seeds, and charcoal), 2% clay clumps (clumps of material consisting of clay, mica, and other unidentified material possibly organic soil), and less than 1% shell fragments.

Landslide Face 1: The sample is poorly sorted gravelly silty sand. The grains are subrounded to angular. Coarse fragments consist of quartz, clay-rich clumps, and organic material. Grains reacted to acid, suggesting some calcite mineralization. Point counts yielded 31% quartz (transparent, smoky, and light orange-yellow silica), 29% feldspar (mainly altered plagioclase), 17% organic material (consisting of charcoal and twigs), 8% mica (muscovite with possible other micas including phyllite), 7% mafics (not apparent as to the type of mafic, probably basalt or biotite; grains were soft and probably include both), 4% clay clumps (grains that consisted primarily of clay, mica, and feldspar), 3% other (unidentified grains mainly mixtures, possibly granite).

Landslide Face 2: Sample is very poorly sorted sandy gravel. Grains are subangular to angular. Coarse fragments contain sandstone and basalt. Some of the fragments reacted with acid, suggesting calcite mineralization within the sample. Point counts yielded 77% clay clumps (grains consisting of clay, mica, and feldspar clumped together), 18% mica (schistoic mica, dark colored, most likely from a metamorphic terrane), 3% feldspar (white to pink altered feldspar), 1% quartz (clear to smoky), and 1% organic material (twigs). The finer-grained fraction reacted to magnets, suggesting possible illite/magnetite in the clay fraction as larger grains of these minerals were not evident.

Landslide Face 3: The sample is very poorly sorted sandy gravel. Grains are angular to subangular. The coarse fraction contained sandstone and basalt; calcite rind/cementation was evident along the grains. Point counts yielded 82% clay clumps (grains consisting of clay, mica, and feldspar clumped together), 12% mafics (mixture of schistoic mica and basalt fragments; difficult to clearly define the two), 3% feldspar (white to pink altered feldspar), 1% quartz (clear to smoky), and 1% organic material (organic soil).

Cliff Face: The sample is poorly sorted gravelly silty sand. Grains are rounded to subrounded, spheroidal. The coarse fraction consists mainly of sandstone grains. Point counts yielded 81% clay clumps (grains consisting of clay, mica, and feldspar clumped together), 12% organic material (twigs and charcoal, seeds, and organic soil), 11% mafics (dark colored mica and basalt chips), 8% feldspar (white to pink altered feldspar grains), 5% quartz (smoky variety of silica), and 2% metamorphics (dark red metamorphic grains).

Conclusions

The beach samples clearly vary mineralogically from the other samples. For tracing purposes the landslide material contains micas and sandstone fragments not seen in the beach samples except in sample Greg2 located near the landslide locality. Along the active beach front the micas would be broken down and transported along with any clay material away from the area. The sandstone fragments are more robust and may provide a good marker for the landslide material.