Assessing Coastal Landscape Change for Archaeological Purposes: Integrating Shallow Geophysics, Historical Archives and Geomorphology at Port Angeles, Washington, USA

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ABSTRACT To mitigate saltwater flooding, the waterfront and downtown areas of Port Angeles, Washington were built-up with up to 8 m of anthropogenic fill beginning in 1913. Shoreline modification continued into the present as this important natural deep-water harbour along the Strait of Juan de Fuca was developed for maritime industries. This and other historical activities obscured at least two historically occupied villages and burial sites of the indigenous Coast Salish Klallam people. Since these archaeological sites remain buried beneath the modern Port Angeles waterfront knowledge of the distribution of buried landforms, coastal zone processes, and estimates of site preservation and modern disturbance potential is needed for archaeological identification and preservation efforts. We created a model of the fill thickness by combining data from: (i) field observations, where the thickness of the fill could be observed directly in the landscape; (ii) topographic differences between pre-fill sounding maps and present-day LIDAR-determined elevations; and (iii) ground-penetrating radar (GPR) surveys. The GPR surveys also helped to reconstruct the now buried palaeoenvironment by identifying tidal lagoons, beach berms and stream channel features beneath the fill layer. The history of post-glacial sea-level change, here impacted by global eustasy, glacio-isostatic and tectonic factors is the first control on the development of quasi-stable coastal landforms suitable for long-term human occupation. Knowledge of past landscapes is a critical component in the development of future archaeological site catchment ‘predictive’ models based upon the spatial distribution and stability of landforms and resource accessibility prior to the Euro-American historic period of intensive shoreline modification. The geophysical and geomorphic identification and spatial reconstruction of buried landforms also provides needed insight into the geology of the subsurface and its control on the flow of groundwater and contaminants across the nearshore environment. Copyright © 2012 John Wiley & Sons, Ltd.

Key words: Geoarchaeology; Tse-whit-zen; ground-penetrating radar; LIDAR; boreholes; carbon-14

Introduction

Marine shorelines are dynamic geologic and human environments that are an important focus of modern and ancient settlements. Shorelines are an interface between seafaring and terrestrial transportation corridors
and offer access for exploiting food and other types of resources. Human modification of the shoreline environment is not a new phenomenon (e.g. Morrison and Hunt, 2007; Stanley et al., 2007; Chalari et al., 2009), and the long-term natural preservation potential of low-elevation coastal archaeological sites is diminished along coastlines that are susceptible to erosion due to sea-level rise (Ranasinghe and Stive, 2009). However, an inadvertent benefit to the common practice of mechanical in-filling of low-lying near coastal environments is the increased preservation potential for archaeological sites buried by fill emplacement (e.g. Palacios-Fest et al., 2006; Homburg et al., 2012). Identifying archaeological sites is difficult where more recent fill material has been placed above it because, in many instances, the geomorphology of the pre-fill shoreline landscape is obliterated. Increased cultural and legal sensitivity to the identification and preservation of archaeological sites unearthed during present and future construction and development activities at in-filled coastal and nearshore sites necessitates the ability to reconstruct the pre-modification landscape and landforms as a first step toward developing buried archaeological site predictive models (e.g. Tiffany and Abbot, 1982; Strasser et al., 2010) as a tool for finding archaeological sites preserved beneath the detritus of modern coastal cities.

We report the results of a geomorphic and shallow geophysical investigation along the waterfront of the city of Port Angeles, Washington, USA (Figure 1), for the purpose of: (i) documenting, delineating and modelling the extent of artificial fill within the City’s waterfront development area; (ii) differentiating mechanical deposits from the underlying natural soils; (iii) evaluating the effects that natural geologic processes and historic mechanical earth-moving alterations have had on the evolution of waterfront landforms; and (iv) qualitatively assessing the potential for buried landforms that may contain preserved archaeological sites as part of a cultural resource management approach toward avoiding and/or conditioning future development projects in a high probability zone (the entire shoreline of the city). The City of Port Angeles contracted this project as part of their responsibility for archaeological management and planning along the urban waterfront. As such, this research focused specifically upon quantifying the thickness of artificial fill placed on top of the historic shoreline environment and the spatial and temporal distribution of landforms.

Figure 1. 2006 ortho-photograph of Port Angeles Harbour, Washington, showing the approximate location of historic Klallam Indian village sites, focused GPR survey areas (A to C), geotechnical boring, hand auger and radiocarbon sample locations. Inset map locates Port Angeles with respect to the Strait of Juan de Fuca (SJF), Puget Sound (PS) and Vancouver Island (VI). The eastern third of Ediz Hook Spit is occupied by the US Coast Guard’s Port Angeles Air Station (USCG – PAAS). This figure is available in colour online at wileyonlinelibrary.com/journal/arp
now buried beneath this fill. The identification and characterization of potentially buried sites of archaeological and historic-period significance is beyond the scope of this study.

Research motivation

The shoreline of the Strait of Juan de Fuca has been home to indigenous Native American peoples since deglaciation at the end of the Pleistocene (e.g. Fladmark, 1975; Gustafson et al., 1979; Carlson, 1990; Mitchell, 1990; Waters et al., 2011). In the vicinity of modern day Port Angeles, Klallam villages and earlier Native American sites are well documented in archaeological, historical-period and ethnographic records from the North Olympic Peninsula (e.g. Gunther, 1927; Lane, 1975; Bergland, 1983; Suttles, 1990; Wray, 2003; Larson, 2006; Figure 2). A substantial portion of the Port Angeles waterfront was in-filled during the first half of the twentieth century. The likelihood of the existence of buried archaeological sites beneath the City’s waterfront was underscored by the 2003 ‘rediscovery’ of cultural deposits associated with the Klallam village Tse-whit-zen (‘Tcīwī’tsen’) in an area proposed for construction of a graving (dry) dock by the Washington State Department of Transportation (e.g. Larson, 2006; Lenz, 2007; Mapes, 2009). The high-profile litigious outcome of the rediscovery of the Tse-whit-zen village (King, 2009; Stapp and Longenecker, 2009) highlights the importance of archaeological management during early stages of development planning. The ability to define fill depth and model buried prehistoric and historic landforms is an integral component of the City’s ability to plan and manage archaeological and environmental components during future development and construction projects within the urban waterfront corridor. Beyond the city of Port Angeles, local governments of coastal cities, regional permitting agencies, archaeologists and geotechnical engineering geologists will benefit from better knowledge regarding historic fill thickness and distribution and the spatial positions of pre-fill landforms (e.g. beach above the high-tide line) within their jurisdictions. Such knowledge complements future geotechnical, archaeological and municipal planning projects.

Geomorphic setting

Along the north flank of the Olympic Peninsula, late Quaternary sediments deposited by marine, glacial and fluvial processes discontinuously drape the foothills of the Olympic Mountains and reach local thicknesses of 100 m beneath the coastal plain (Washington Department of Ecology, 1978; Schasse, 2003). In addition to local sediment transport and deposition from streams draining the Olympic Mountains, sediments eroded from Vancouver Island and the Canadian Coast Ranges accumulated in the Port Angeles vicinity due to glacial
transport during late Wisconsin (Marine Isotope Stage; MIS 2) and earlier glaciations (Polenz et al., 2004; Schasse et al., 2004). The entire north flank of the Olympic Peninsula was covered by the Juan de Fuca lobe of the Cordilleran Ice Sheet, which retreated east of the Port Angeles area sometime between 14 460 ± 200 and 12 600 ± 200 14C yr BP (Heusser, 1973; Petersen et al., 1983). Late Pleistocene glacial drift and outwash sequences comprise the coastal bluffs above the Port Angeles waterfront (Schasse et al., 2004). Coastal deposits and landforms along the central North Olympic Peninsula reflect complex interactions between glacial, fluvial, hillslope and littoral processes that are dominated by bluff erosion. The formation and erosion of the coastal bluffs is a consequence of the interplay between vertical changes in sea level, a function of global eustasy, overprinted by a local glacio-isostatic signal, and tectonic vertical land-level changes.

**Ediz Hook Spit and the Port Angeles coastline**

The naturally protected deep-water harbour of Port Angeles was formed by the northward growth of Ediz Hook Spit as early as the middle Holocene (Figure 3; Galster, 1989; Galster and Schwartz, 1990; Warrick et al., 2008). Sand-to-gravel fluvial sediments discharged from the Elwha River, combined with landslide debris from the coastal bluffs to the east, formed the sediment source for the spit. A proto-spit formed when a beach ridge detached from the Elwha River delta around 8000 yr BP; when sea level was about 35 m below modern (Galster, 1989; Polenz et al., 2004). Continued local sea-level rise and sediment transport caused eastward spit migration to about its current location between 8000 and 5000 yr BP, at which point the spit’s basal junction ceased moving, concomitant with the reduction in the rate of local sea-level rise. Since about 5000 yr BP, and prior to damming of the Elwha River in 1913 for hydropower, the spit was a pseudo-stable landform that grew in length out into the Strait of Juan de Fuca. According to Lenz (2007), the tidal lagoon now present at the base of Ediz Hook probably formed sometime between 5000 and 2500 yr BP (Figures 2 and 3).

The establishment of Ediz Hook spit at its present position enhanced the long-term preservation and seaward (north) expansion of the pre-Euro-American shoreline in the study area (Lenz, 2007). Today, the spit protects the shoreline and coastal bluffs to the east from storm and ocean swell-driven wave energy approaching from the west along the axis of the Strait of Juan de Fuca. With the anchoring of Ediz Hook near its present location around 5000 yr BP the rate of coastal bluff erosion to the east between the base of the spit and Lees Creek almost certainly diminished (Figure 1). This reduction in local longshore sediment transport allowed for natural shoreline progradation at stream mouths and the creation of a substantial subaerial nearshore beach above the highest high-water level; a prerequisite for the long-term human habitation, and increased preservation potential for said habitation of the Port Angeles waterfront area. During the first US Coast Survey investigation of
the Port Angeles harbour (Alden, 1853), three extant Native American villages were identified, one each on the deltas of Tumwater and Ennis creeks with a third, known as Tse-whit-zen, near the base of Ediz Hook and the salt water lagoon (Figure 2); however, the entire shoreline and valley bottoms that now underlie the waterfront portion of the city of Port Angeles has high probability for archaeological sites and was surely used in some capacity by the Central Coast Salish in the past.

**Historic coastal modification**

The first Port Angeles business opened in 1861. Prior to the 1880s, when the first wharf was constructed, there is little evidence for Euro-American earthmoving modification of the waterfront (Figure 4). By 1890, when the city was incorporated, it had a population of 3000 residents. Development of the waterfront in the years prior to 1914 occurred directly on the beach above the elevation of the high-water line as well as on pilings and docks straddling the historical-period beach and tidal zone.

In 1914, a large-scale topographic regrading project was begun to infill and raise city streets in order to eliminate tidal flooding of the waterfront (Figure 4 – inset). Hydraulic mining and sluicing techniques were used to wash Late Pleistocene glacial sediments from the adjoining bluffs. The sluiced sediment was used to raise waterfront streets around downtown businesses one full story (up to 3.7 m) above the pre-1914 level, with the thickness of infilling over the intertidal zone locally exceeding 5.5 m. Over the next eight decades, additional beach and intertidal areas along the City of Port Angeles waterfront were infilled in a fragmentary fashion. Major areas of the waterfront affected included construction of Port Terminal 1 in 1926, the creation of the east and west bays of Boathaven Marina (1947 and 1958), industrial infilling at the base of Ediz Hook and near Ennis Creek (1913 onward); and additional expansions of the downtown waterfront north of the 1914 vintage railroad trestle after 1940 (Martin, 1983; Larson, 2006). The last major portion of tidelands along the City’s waterfront at Valley Creek was filled in 1998.

**Methods for assessing shoreline change**

**Landform mapping**

Surficial deposits were mapped at 1:2000 scale in the field and from interpretations of a 1.8 m horizontal resolution LIDAR-derived digital elevation model
Ground-penetrating radar

Ground-penetrating radar (GPR) is a non-invasive geophysical technique that utilizes an electromagnetic pulse directed into the ground. When this energy encounters a subsurface object or stratigraphic layer with different electrical properties, the signal is reflected upward and recorded by a receiving antenna at the surface. The travel time of the reflected signal indicates the depth to the reflector, and the amplitude of the reflection is proportional to the contrast in electrical properties across the interface. In this study GPR is used to delineate fill thickness and constrain the palaeogeomorphic setting. This is accomplished primarily by digitizing the depth of the reflector associated with the now buried pre-fill land surface and inferring ancient depositional environments based on stratigraphic indicators. Our objective was not to identify or characterize any specific archaeological target (cf. Conyers and Leckebusch, 2010).

In May 2010, more than 21 linear kilometres of GPR survey data were collected across the study area. We used a Sensor’s and Software Pulse Ekko Pro system equipped with 250 and 100 MHz antennae deployed on a four-wheeled cart, with fixed transmitter and receiver separations of 0.4 and 0.5 m, respectively. Received radar signals were stacked with a 16× ratio applied to each trace, with an along-track trace interval of 0.05 to 0.15 m for profiles collected with the 250 and 100 MHz antennae, respectively. Precise positioning information was collected using a Wide Area Augmentation System-enabled GPS, and along-track distance was measured using a calibrated cart-mounted odometer. Prior to data interpretation, we applied both a dewow (high-pass) filter to the stacked trace data to remove the low-frequency-noise component and a spreading and exponentially compensating gain function to compensate for attenuation and geometric spreading (Conyers, 2004; Annan, 2005).

Radiocarbon geochronology

Detrital charcoal samples were extracted from 1-cm-thick layers of fluvial sediment collected from natural exposures along the banks of Tumwater and Valley creeks (Figure 1 and Table 1). These sediments were placed in a sonic bath and sieved to 250 μm. Individual charcoal pieces were collected with the aid of a binocular microscope. Samples were then pretreated with 1 N HCl and NaOH according to the Acid-Base-Acid (ABA) radiocarbon pretreatment procedure (Olsson, 1986) in order to remove contaminants acquired, for example, during storage in soils. Sample Accelerator Mass Spectrometry (AMS) analyses were performed at AEON Laboratories in Tucson, Arizona. Radiocarbon results are reported with one-sigma (68%) standard errors following the recommendations of Stuiver and Polach (1977) and van der Plicht and Hogg (2006), and converted to calendar age (AD/BC) using the CalPal 2007 Hulu calibration curve with version 1.5 of the online quickcal2007 calculator (Weninger and Jöris, 2008).

Determination of fill thickness

We used four methods to measure fill thickness within the study area: (i) field observations, where the thickness of the fill could be observed directly in subsurface exposures; (ii) topographic differences between the 1892 Port Angeles Harbour sounding map (Gilbert, 1892) and present-day elevation; (iii) interpretations of depths of the palaeo-landsurface extracted from geotechnical drilling logs; and (iv) GPR surveys.

Direct observations

We measured the thickness of artificial fill directly, and where observable we made interpretations about the sedimentologic and geomorphic environments of native subfill deposits. We then incorporated measurements of fill thickness from direct observation into the model of fill thickness. Because of the urban–industrial nature of the Port Angeles waterfront and the dense vegetation on steeper bluff slopes, subsurface exposures are few in number and of limited lateral continuity.

Topographic analysis

The Port Angeles waterfront and harbour were surveyed in April and May of 1892 (Gilbert, 1892),
Table 1. Summary of Radiocarbon Dating Results.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>IDb</th>
<th>Yieldc (%)</th>
<th>Mass C (mg)d</th>
<th>d13C (%)e</th>
<th>F14Cf1</th>
<th>14C age (yr BP)g</th>
<th>Calibrated age (cal yr BP)h</th>
<th>Calendric age (cal AD/BC)i</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1: Tumwater Creek terrace</td>
<td>48.109527</td>
<td>123.456784</td>
<td>Aeon-560</td>
<td>58.7</td>
<td>1.077</td>
<td>−22.7</td>
<td>0.9863 ± 0.002</td>
<td>110 ± 20</td>
<td>145 ± 95</td>
<td>AD 1805 ± 95</td>
</tr>
<tr>
<td>Ab horizon; 20–35 cmbs</td>
<td></td>
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<tr>
<td>C-1: Tumwater Creek terrace</td>
<td>48.109527</td>
<td>123.456784</td>
<td>Aeon-550</td>
<td>54.2</td>
<td>1.206</td>
<td>−23.7</td>
<td>0.7801 ± 0.0018</td>
<td>1,995 ± 20</td>
<td>1,950 ± 30</td>
<td>BC/AD 0 ± 30</td>
</tr>
<tr>
<td>C4 horizon; 105–120 cmbs</td>
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<tr>
<td>C-1: Tumwater Creek terrace</td>
<td>48.109527</td>
<td>123.456784</td>
<td>Aeon-551</td>
<td>52.0</td>
<td>1.089</td>
<td>−23.4</td>
<td>0.5938 ± 0.0015</td>
<td>4,185 ± 20</td>
<td>4,750 ± 70</td>
<td>BC 2800 ± 70</td>
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<td>C5 horizon; 120–135 cmbs</td>
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<tr>
<td>C-2: Valley Creek terrace</td>
<td>48.116450</td>
<td>123.444112</td>
<td>Aeon-549</td>
<td>40.6</td>
<td>1.049</td>
<td>−24.4</td>
<td>0.5556 ± 0.0018</td>
<td>4,720 ± 25</td>
<td>5,460 ± 105</td>
<td>BC 3510 ± 105</td>
</tr>
<tr>
<td>Ab horizon; 90 cmbs</td>
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<tr>
<td>C-2: Valley Creek terrace</td>
<td>48.116450</td>
<td>123.444112</td>
<td>Aeon-553</td>
<td>57.8</td>
<td>1.185</td>
<td>−23.5</td>
<td>0.7489 ± 0.0016</td>
<td>2,325 ± 15</td>
<td>2,345 ± 10</td>
<td>BC 400 ± 10</td>
</tr>
<tr>
<td>3CS horizon; 120–130 cmbs</td>
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<tr>
<td>C-3: Lower Valley Creek fluvial silt buried by fill; 75 cmbs</td>
<td>48.116469</td>
<td>123.444087</td>
<td>Aeon-554</td>
<td>55.4</td>
<td>1.157</td>
<td>−23.9</td>
<td>0.8214 ± 0.0018</td>
<td>1,580 ± 15</td>
<td>1,470 ± 40</td>
<td>AD 480 ± 40</td>
</tr>
<tr>
<td>C-4: Valley Creek Estuary tidal muds buried by fill; 41 cmbs</td>
<td>48.122188</td>
<td>123.436573</td>
<td>Aeon-552</td>
<td>40.2</td>
<td>1.188</td>
<td>−22.3</td>
<td>0.9880 ± 0.0028</td>
<td>95 ± 25</td>
<td>145 ± 95</td>
<td>AD 1805 ± 95</td>
</tr>
</tbody>
</table>

aSample location, soil horizon and depth (cm) of radiocarbon sample beneath modern surface (cmbs) from Wegmann et al. (2010).
bThe unique identifier for each radiocarbon analysis performed by Aeon.
cThe percentage of carbon in the subsample (selected from the total sample submitted, as representative of what should be dated) analysed by Aeon.
dThe mass of the carbon subjected to AMS analysis; does not include any portion used for stable isotope analysis.
eThe relative difference between the 13C/12C ratio of the test sample (the test sample consists of the carbon extracted from the subsample) and that of the VPDB standard, expressed in per mille.
fThe 14C activity ratio (relative to ‘Modern’ as defined by the Oxalic Acid I standard) (corrected for isotopic fractionation and background activity) and reported with 1-sigma (68%) uncertainty.
gThe conventional radiocarbon age, normalized to −25‰, based on a 5568-year half-life and 1-sigma (68%) uncertainty (Stuiver and Polach, 1977; van der Plicht and Hogg, 2006).
hThe calibrated and calendar age using the CalPal_2007_HULU calibration curve with quickcal2007, v. 1.5, with reported 1-sigma uncertainties (Weninger and Jöris, 2008).
approximately 22 yr before significant portions of the downtown area were filled, in 1914. This map was constructed for the Washington State Harbour Line by the US Coast and Geodetic Survey and consisted of 4755 depth soundings, expressed in feet and reduced to the lowest of the low waterline. To correct these readings to mean sea level, 1.4 m was added to each sounding elevation, which is half the elevation change between the lowest (0 m) and highest (2.7 m) waterlines shown on the map. We cannot account for elevation changes resulting from variations in the nearshore morphology (either natural or anthropogenic) of the Port Angeles waterfront during the 22-yr interval between when the soundings were collected and when the first significant fill material was placed over the beach and tidal zone, and this may be a local source of error in the depth-of-fill dataset. But because of the protected nature of the Port Angeles harbour and the minimal amount of eustatic sea-level rise (ca. 1.9 cm; Douglas, 1997) that occurred during these two decades, significant variations in nearshore elevations are not expected.

We derived estimates of fill thickness across the project area by determining differences in elevation between a georeferenced version of the 1892 map (Wengler, 2007) and the 2002 airborne-LIDAR-derived DEM for Port Angeles (Puget Sound LIDAR Consortium, 2002). The harbour map included both point elevation measurements and contour lines identifying the low (−1.4 m relative MSL) and high (+1.4 m relative MSL) water lines; both were digitized. Given inaccuracies with the input datasets, we conservatively estimate that the palaeoelevation values are accurate to within 0.6 to 0.9 m for most locations. In a few areas, the modern DEM clearly contained artefacts associated with LIDAR returns from transient log-yard stockpiles (Survey area A), buildings and piers. The differencing technique was not used in these areas. We forced the difference between the georeferenced 1892 map and 2002 LIDAR datasets, and our fill thickness model (see later) to zero at the base of the coastal bluff.

Geotechnical borings and hand augering
We compiled data from 159 existing geotechnical borings, ultimately using only 25 that were deemed reliable enough for inclusion in the model of fill thickness for the Port Angeles waterfront (Wegmann et al., 2010). Previously reported geotechnical information was most abundant for the developed downtown areas, but less than 5% of the boreholes identified native beach material in their logs. Because the quality of the description and level of detail provided by different loggers varied greatly, we used only those where a reliable interpretation of native beach deposits existed. To supplement these data, we logged six additional hand-auger borings. The distribution of hand-auger sites includes two on Ediz Hook and four in the downtown area (Figure 1).

GPR surveys
The surface elevations at each GPR sampling point were extracted from a LIDAR-derived bare-earth DEM with a vertical resolution of about 0.3 m (Puget Sound LIDAR Consortium, 2002). Before merging these topographic profiles with the radar data, short-wavelength artefacts in the DEM were removed using a third-order low-pass Butterworth filter (f_c = 0.05 m s^{-1}). Buried point and line reflectors (e.g. pipes, railroad ties and pilings) are common in this environment. By fitting the shapes of their GPR reflection hyperbolas, we calculated a mean radar velocity of 0.1 m ns^{-1} for the survey area, from which we estimate reflector depths (e.g. Annan, 2005). The effective depth or radar penetration was typically in the order of 2.5 to 3 m. As a result, in areas where the fill thickness was greater than 3 m, the GPR technique could constrain the minimum thickness only.

We identified basement reflectors, indicating the interface between anthropogenic fill and the buried palaeoland surface, based on the strength and continuity of each reflector, together with the local dip angle and interface relief, as compared with modern beach analogues (e.g. Engels and Roberts, 2005; Dickson et al., 2009; Nielsen and Clemmensen, 2009). Where possible, we verified reflector depth against nearby estimates taken from geotechnical well logs and field observations, where vertical errors were found to be ≤ 0.5 m. We obtained greater than 5600 individual georeferenced point measurements of the basement reflector elevation by digitizing the interpreted fill–pre-fill reflector directly within the GPR processing software. The thickness of fill material from radar measurements was determined by subtracting the elevation of the interpreted basal fill interface from the overlying DEM-derived modern surface elevation.

Results

Coastal landscape evolution
Here we present our interpretation of the pre-Euro-American distribution of geologic units and landforms within the study area based on detailed field mapping, new radiocarbon results, and analysis of available geologic and geotechnical investigations. The post-glacial
geomorphic evolution of the Port Angeles waterfront is a product of the interplay between eustatic sea-level changes and crustal isostatic rebound (uplift) following glacial retreat and can be separated into two intervals: (i) latest Pleistocene to mid-Holocene (about 17 to 6 ka), and (ii) the mid-Holocene to present (Figure 5). The former immediately followed regional deglaciation and was characterized by substantial local relative sea-level fluctuations, ephemeral coastal landforms, significant coastal bluff erosion, and reduced potential for the preservation of nearshore archaeological sites. In comparison, the interval from about 6 ka to present is defined by local relative sea-level stability, the establishment of more-persistent coastal landforms, reduced bluff erosion and increased preservation potential for nearshore archaeological sites.

Late Pleistocene to middle Holocene

The Juan de Fuca lobe of the Cordilleran Ice Sheet readvanced into the study area at approximately 20 ka (Blunt et al., 1987). It reached a thickness of about 1100 m over the coastal plain and persisted until around 17 ka (Figure 5). The load of the ice sheet isostatically depressed the crust along the axis of the Strait of Juan de Fuca to such an extent that local sea level was greater than 40 m above modern sea level (MSL) at 13.3 ka (Dethier et al., 1995). Despite global sea-level rise due to deglaciation, the study area emerged above sea level between 12.8 and 11.4 ka because of rapid glacio-isostatic rebound (about 3 cm yr\(^{-1}\)) of the lithosphere following the north and eastward retreat of the ice sheet (Clague et al., 1982; Mathews et al., 1970; Schasse et al., 2004). Ultimately, local sea level fell to about 60 m below MSL at 10.7 ka (Figure 5; Mosher and Hewitt, 2004). This dramatic fall in the base level of erosion along the north-central Olympic Peninsula resulted in rapid incision of streams and the establishment of the modern drainage pattern, where steep-walled post-glacial valleys were cut down into sediments deposited during previous glacial and interglacial intervals, and in some cases, into underlying Tertiary bedrock (Schasse et al., 2004). Most of the crustal glacio-isostatic rebound was probably complete by about 10.7 ka (Thorson, 1989), after which local sea level began to rise at a rate of about 1 cm yr\(^{-1}\) (Figure 5). As local sea level rose in the early Holocene, coastal reaches of streams began to aggrade. Rising sea level caused nearshore landforms to be unstable and transient, and coastal bluffs increased in height as shoreline erosion caused them to retreat landward (south).

The formation of a proto-Ediz Hook as a detachment spit from the Elwha River delta is believed to have

![Figure 5. Relative sea level and time line of geologic and geomorphic events affecting the central North Olympic Peninsula from the late Wisconsin glacialiation to the present, modified from Schasse et al. (2004). The post-glacial sea level curve is primarily from Mosher and Hewitt (2004). Age control, based on previously published radiocarbon dates, was converted from \(^{14}\)C years BP into calendar years BP with the CALIB v. 5.0 calibration software (Stuiver and Reimer, 1993) using the calibration dataset of Hughen et al. (2004). Note that the top axis is labelled in \(^{14}\)C years BP and is nonlinear, whereas the lower axis is labelled in ka and is linear, within the limits of radiocarbon data calibration. This figure is available in colour online at wileyonlinelibrary.com/journal/arp](wileyonlinelibrary.com/journal/arp)
occurred at about 8 ka (Galster, 1989; Galster and Schwartz, 1990) when sea level was about 37 m below modern (Figure 3). The spit migrated about 7 km to the east at an average rate of 3 m yr\(^{-1}\) during the ongoing interval of sea-level rise. With the approach of local relative sea level to near-modern elevation at 6.2 ka (Mosher and Hewitt, 2004), it is estimated that the eastward migration of the base of Ediz Hook slowed, and that by 5.5 ka it was established as a quasi-stable landform at its present position (Figure 3).

**Middle Holocene to present**

Although global sea level was 3 to 3.6 m lower at 6 ka than at present (Lambeck and Chappell, 2001), the near-stable local sea level for the North Olympic Peninsula since that time suggests that eustatic rise has been balanced by crustal uplift of about 0.5 mm yr\(^{-1}\) (Mosher and Hewitt, 2004). With Ediz Hook as a stationary spit no longer migrating eastward with rising sea level, and blocking the dominant wave energy from the west, erosion of coastal bluffs along the south shore of the Port Angeles harbour slowed. Quasi-stable beaches within the confines of the protected harbour began to prograde seaward from the coastal bluffs beginning about 5.5 ka, concomitant with the extension of subaerial-to-tidal deltas at stream mouths (Figure 5).

Radiocarbon dating of detrital charcoal fragments collected from alluvial deposits exposed along the lower reaches of Tumwater and Valley Creeks indicates that both these streams experienced small amounts of net aggradation (±2 m) beginning as early as 5.5 ka, probably in concert with the establishment of near-modern local sea level (Figures 1 and 5; Table 1). The late Holocene fluvial sediments unconformably overlie MIS 2 glacial diamicton (till), into which the local streams have incised. From Tumwater Creek, four radiocarbon samples bracket the timing of aggradation of 1.7 m of alluvium on top of till to between 5460 ± 105 cal yr BP (calendar years before present) at the bottom of the deposit to only 145 ± 105 cal yr BP at the top (Table 1). An additional three radiocarbon samples collected from analogous deposits along Valley Creek demonstrate that aggradation occurred there at least between 2345 ± 10 cal yr BP and 135 ± 100 cal yr BP, and probably for a longer interval as the older radiocarbon date was collected from a midpoint within the alluvial channel deposit (Figures 1 and 6; Table 1). Fine-grained, tidally laminated sediments, preserved 150 m north of the 1892 shore just above the modern mean high-water level at the Valley Creek estuary, date to 145 ± 95 cal yr BP, a result that is indistinguishable from the youngest dates of aggradation recovered from upstream in both Valley and Tumwater Creeks (Table 1).

**Geophysical investigation of the pre-fill landscape**

Within the Port Angeles harbour, significant historic-period beaches existed above the highest high
waterline, where today they are almost entirely obscured by subsequent development and placement of fill material. From an archaeological perspective, the geomorphology of landscapes strongly influenced the availability of water and other resources in the natural environment. Consequently, knowledge of past landscapes, which may vary substantially from the modern environment, is critical in developing future predictive models aimed at evaluating the probability of settlement patterning based in part on the distribution and availability of resources. Knowledge of past environments also allows for insight into the geology of the subsurface and its control on the flow of groundwater and contaminants in modern settings. Below, we discuss applications of GPR techniques in identifying stream channels, beach berms, and tidal lagoons buried beneath mechanical fill.

**Buried shoreline and tidal lagoon at the base of Ediz Hook**

We collected GPR data near the intersection of the main coastline and the base of Ediz Hook along roughly shore-normal profiles, primarily within the active log yards that lie to the east and west of the Tse-whit-zen village site (Figure 7; GPR Survey Area A). This area has been used as a heavy industrial zone for more than a century, and the site has been marked by several generations of construction that have modified both the fill and the native land surface...
(Larson, 2006; Lenz, 2007). Despite these modifications, the profiles show a laterally continuous dominant reflector, which we interpret as the interface between the native land surface and anthropogenic fill (Figure 8). Our GPR results and topographic differences are the main constraints on fill thickness in Area A (Figure 7).

Figure 8. Examples of interpreted beach and lagoon features identified in radar data from GPR Survey Area A (see Figure 7 for profile locations). Shallow point and line reflection hyperbolas, many of which are probably buried pipes crossed by GPR surveys, are marked as white circles. The GPR data are consistent with the georeferenced historical position of the high water line from Gilbert’s 1892 map of the Port Angeles Harbour. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

The GPR results also show a number of stratigraphic markers that are useful for reconstructing the palaeoenvironment and validating the locations of geomorphic features identifiable on Gilbert’s 1892 Port Angeles Harbour map (Figures 7 and 8). For example, Profile A–A’ is a 100-MHz record collected to the west of Tse-whit-zen, along a paved log-yard roadway. The profile crosses several shallow line reflectors, probably pipes that generate hyperbolic reflections in cross-section. Beneath these features, a gently dipping (5–8°) shore-facing reflector is observable. Further inland (southwest), pockets of shore-facing reflectors with slightly greater dips (8–12°) are resolvable, consistent with foreset bedding associated with seaward propagation of the beach. Comparing the location of these data with the 1892 map, shallow shoreface reflectors are in close proximity to the 1892 high waterline (profiles A–A’, B–B’, and D–D’), and we interpret the up-dip extension of this feature as the native pre-fill beach berm. Similarly inclined reflectors further inland are therefore interpreted as older foreset beds that demarcate northward progradation of the shoreface over time. The observed dips for these features are consistent with local modern analogues (Engels and Roberts, 2005). Similar beach berm and foreset-bedding-like features are observed in the high-resolution profile C–C’, collected with a 250 MHz antenna (Figure 8).

As observed in modern settings, the palaeo-land surface slopes away from the height of land defined by the beach berm (Profiles D–D’ and F–F’; Figure 8). Evidence for preserved tidal channels beneath the fill that covers the eastern portion of the natural, but modified, lagoon at the base of Ediz Hook is apparent in Profile F–F’. This lagoon is clearly identified on the earliest map of Port Angeles Harbour (Alden, 1853), and the tidal channel that we interpret in the GPR data appears on Gilbert’s 1892 shoreline map. On the 1892 map, the tidal-lagoon area is shown to extend further to the east than at present, and our interpretation of the radar results supports the accuracy of this earlier shoreline mapping.

Buried tidal delta and palaeochannel of lower Tumwater Creek

A grid of 100- and 250-MHz GPR lines was collected at a former industrial site near the intersection of West Third Street and Marine Drive. We surveyed eight lines in the east–west direction and six lines in the north–south direction within this approximately 3800 m² site. The line spacing was approximately 5 and 20 m, respectively (Figure 9). The present-day landscape is characterized by nearly flat topography covered by sparse, grassy vegetation. These conditions were optimal for operating the cart-mounted GPR system.

Survey results indicate a prominent subsurface reflector at 0.6 to 2.7 m beneath the present-day land surface. For lines running in the northeast direction, this reflector dips from each end toward the centre, defining a channel-like landform, with reflectors disappearing below the depth of our imaging capabilities on Lines 3 and 4. We created a DEM of the pre-fill land surface by combining all digitized reflector elevations (Figure 10). By subtracting these elevations from the present-day land surface, we generated a high-resolution localized (or nested) model of the fill thickness (Figure 9). Our model results highlight the channel feature that closely matches the 1892 georeferenced location of a distributary channel on the Tumwater Creek Delta prior to straightening and channelization (Figure 9). In map view, the trace of the channel axis follows the sinuous path shown on the 1892 line drawing remarkably well. Modern coastal streams in the greater Port Angeles area are perennial freshwater drainages of similar depth and
morphology. Assuming a relatively stable climate over the past several-hundred years, this stream would have provided a reliable freshwater source. Not surprisingly, the location of the buried channel indicated by GPR generally coincides with the location of an unnamed ethnohistoric village situated on the delta of Tumwater Creek in 1853 (Alden, 1853; Figure 2); however, it is important to note that we did not look for, or observe, direct evidence of buried cultural features at the Tumwater Delta survey area or at any of the other GPR survey locations.

Model of anthropogenic fill emplacement across the historic shoreline

Fill thickness from topographic differencing

In total, we incorporated 808 sounding differences into the model of fill thickness that represent a best-estimate of the change in land-surface elevation between Gilbert’s 1892 Port Angeles Harbour survey map and the 2002 Puget Sound LIDAR Consortium dataset. Historical 1892 data points located seaward of the present shoreline were excluded, as were locations
in which the modern LIDAR dataset contained improbable elevation estimates associated with laser returns from log-yard stockpiles, buildings and piers. We find that areas seaward of the 1892 high waterline typically have the thickest fill and are not well constrained by either shallow geophysical or geotechnical observations.

Geotechnical borings and hand auger data

We combined data from geotechnical borings in unpublished company reports with limited hand augering to augment and verify our estimates of anthropogenic fill thickness for the Port Angeles waterfront based upon geophysical and topographic differencing techniques. We completed two hand auger investigations on Ediz Hook (Figure 1). Native beach materials were encountered in both at depths of 0.4 to 0.9 m, which is consistent with field observations for the thickness of fill overlying and protecting native beach deposits along the length of the natural spit between the Nippon paper mill and US Coast Guard’s Port Angeles Air Station. The mechanical fill placed along Ediz Hook is primarily roadbed material for the service road. Boulder-sized rip-rap 3 to 5 m thick has been placed along the northern edge of Ediz Hook to protect it from wave erosion; its placement is primarily on top of tidelands rather than over the historic beach deposits located above the mean high-water line.

Three of the downtown hand-auger sites (GPR Survey Area C; Figure 1) were in locations not covered by fill materials during the 1914 regrade project. We identified native beach material in these auger holes between 0.25 and 0.5 m below the modern surface. These sites include Auger Holes A-4 and A-5 where buried beach deposits were found 3.9 m beneath the post-1914 regrade elevation of First Street, and Auger Hole A-6, located in the basement (former street level prior to 1914) of what is presently a bike and kayak retail store along Front Street, where the native beach deposits were encountered 4.2 m beneath the 1914 fill elevation of Front Street (Figure 11).

Our assessment of available geotechnical boring logs shows that the identification of native beach within the study area based on a single drill hole can be difficult and that any interpretations recorded in individual logs should be viewed with skepticism. For example, we consider a set of five geotechnical borings completed by Landau Associates in support of the Port Angeles International Gateway project (Heavey, 2005). The borings (labelled B-5 and B-101 to 104) are oriented along a roughly shore-normal profile between West Front Street and West Railroad Avenue (Figure 11). Subfill native beach material is clearly identified in each of the five boring logs, but unexpectedly, the logs show the fill thickness decreasing by 50% as they move seaward from the 1892 high waterline. When these depths are converted to elevations with respect to MSL, four of the five logs locate the beach deposits 1.5 to 2.4 m above the elevation of the 1892 shore profile (Gilbert, 1892; Wengler, 2007). Native beach deposits were identified beneath fill materials in the boring log for B-101, at a depth of 5.5 m beneath the modern ground surface, correlating with the 1892 palaeo-landsurface at a well-constrained point near the high waterline (Figure 11). Projection of the 1892 land surface inland to the south at constant gradient results in its passage just beneath the elevation of the dirt-floored basement augured into at location A-6 at a depth of 0.5 m below the basement floor, or 4.2 m below the modern level of West Front Street (Figure 11). Our interpretation is that a sand deposit within the fill unit was incorrectly interpreted as native beach in four of these five geotechnical logs. Reliability tests such as this were performed whenever possible to identify potential inconsistencies in the reported thickness of fill material and depth to native subfill deposits in the available geotechnical boring logs. Ultimately, out of 159 geotechnical-boring log observations made available by the City of Port Angeles, only 25 were considered reliable enough for inclusion in the final model of fill thickness for the waterfront study area (Figure 1). This result was unexpected. Contractors may have been unaware of the area’s anthropogenic history and/or may have viewed distinction between fill and native material as of secondary importance to their geotechnical and engineering goals.

Pre-1890 landform reconstruction

We incorporated geomorphic interpretation of near-shore landforms visible in historic ground-based photographs of the Port Angeles harbour area as a means of cross-validating past shoreline position determinations (Wengler, 2007), geotechnical boring logs (e.g. Figure 11) and our geophysical survey results (e.g. Figures 8 and 10). Landform interpretation from historic photographs housed in the Bert Kellogg collections of the North Olympic Library System provided verification of the distribution of study site topography and environments prior to the 1914 Port Angeles downtown regrade project. For example, it is apparent that only a narrow supra-tidal beach was present between the high tide line and the coastal bluff in the vicinity of Hollywood Beach prior to about 1890 (Figure 12). The presence of Klallam tents and canoes, depicted on this and other historic photographs along
this section of coastline provides evidence for resource extraction and processing sites in addition to the village sites noted elsewhere on Alden’s 1853 map.

Stream mouth locations have been altered from pre-European American conditions. For example, as part of the 1914 regrade project, the lower 350 m of Peabody Creek was rerouted from its late Holocene delta position into a subgrade culvert, after the hydraulic mining and removal of the coastal bluffs separating the mouth of Peabody Creek and the beach. Peabody Creek was rerouted in 1914 beneath the northward extension of Lincoln Street to the waterfront (Figure 12a). In contrast to the narrow Hollywood Beach, a broad (150 to 200 m wide) supratidal beach existed near the historic mouth of Valley Creek between the high tide line and flanking coastal bluffs (Figure 13). Historic beach sediments were recovered in hand augers 3.9 m beneath the elevation of the 1914 regrade of West First Street. Analysis of the historic photographs helps to establish places where earlier historic and potentially prehistoric
landforms are more and less likely to be preserved beneath post-European American fill materials (i.e. above and below the supra-tidal beach to tide-land transition, respectively; Figures 12 and 13).

Discussion

Coastal geomorphology and the potential for site preservation

The establishment and persistence of a stable local sea level along the north-central Olympic Peninsula around 6 ka (Mosher and Hewitt, 2004) ushered in a change in the preservation potential of near-coastal landforms (Figure 5). As a result, the opportunity for preservation of a coastal archaeological record increased dramatically here. Specifically for the Port Angeles study area, a reduction in the eastward migration of the basal junction of Ediz Hook spit at about 5000 yr BP (Figure 3) favoured the long-term preservation and seaward (north) expansion of the pre-Euro-American shoreline position as the natural spit protected beach and coastal bluffs to the east from the erosive impacts of the dominant storm and ocean swell-driven wave energy coming from the west-northwest along the axis of the Strait of
Juan de Fuca. Quasi-stable beaches began to prograde seaward from the coastal bluffs fronting the Port Angeles harbour beginning about 5.5 ka, nourished both by the deposition of fluvial sediments in subaerial-to-tidal deltas at stream mouths within the confines of the wave protected harbour, and from mass-wasting of the backing bluffs. Rising local sea levels create the opportunity to both alter and preserve coastal archaeological sites (e.g. Gaffney et al., 2007). Based upon our understanding of the evolution of Ediz Hook spit and the erosion that dominated the coastal bluffs of the study area, we doubt that substantial archaeological sites older than about 5000 yr BP exist beneath the waters of Port Angeles harbour. However, it is possible that archaeological sites younger than the middle-Holocene establishment of Ediz Hook as a quasi-stable landform exist beneath either relatively shallow water or thick fill placed seaward of the 1892 shoreline. To our knowledge, the submarine archaeological record of the Port Angeles harbour has not been investigated in detail. The energetic nature of the littoral zone, even within the confines of the harbour, diminishes the potential for preservation of fine-grained deposits associated with such sites, as the nearshore substrate is dominated by cobbles and boulders with interstitial sands (e.g. Warrick et al., 2008; Wegmann et al., 2010).

**Models of mechanical fill thickness and subfill landforms**

We present an interpretation of the historical-period distribution of surficial geologic units and geomorphic landforms in the study area about AD 1890 in Figure 14. With the exception of Late Pleistocene glacial deposits...
underlying the uplands, we interpret the age of the near coastal deposits presented in Figure 14 as being mid-Holocene or younger. The establishment of a locally stable sea level at about 6 ka allowed the streams draining to the harbour to prograde deltas across the shoreface, as the rate of longshore sediment transport decreased concomitantly with the blockage of waves and swells by Ediz Hook. Utilizing historic maps and photographs, subsurface borings, GPR survey results and geomorphic observations we interpret the existence of significant historical-period beaches above the highest high waterline along: (i) the outer 1.6 km of Ediz Hook; (ii) east from the tidal lagoon inlet at the base of Ediz Hook spit for about a kilometre; (iii) a 1.6 km long swath encompassing the tidal deltas of Tumwater, Valley and Peabody creeks; and (iv) a span of about 1.1 km centred on the Ennis Creek delta (Figure 14). We present a model of the thickness of fill overlying these supratidal beaches in Figure 15. The modelled thickness of fill materials overlying the three mapped historic Klallam village sites is ≤ 4 m, and most probably closer to 2 m. Thick fill deposits are not a requirement for archaeological site preservation beneath this heavily industrial port city, as exemplified by the rediscovery of portions of the amazingly well-preserved Tse-wit-zen village site beneath only several metres of fill (Larson, 2006; Lenz, 2007). Resource extraction and processing sites and the known historic villages near the former mouths of Tumwater and Ennis Creeks may similarly be preserved beneath post-1890 anthropogenic fill deposits.

Radiocarbon results suggest that the lower reaches of Tumwater and Valley Creek were loci of net aggradation, inset into deeply-incised valleys carved through glacial deposits, beginning as early as 5.5 ka (Table 1); perhaps in concert with the establishment of near-modern local sea level and stabilization of the regional base level of erosion. This phase of net aggradation appears to have persisted until recently, as available radiocarbon data indicate that stream re-incision into these late Holocene alluvial deposits occurred only after 110 ± 20 14C yr BP, or between AD 1700 to 1900. If this interpretation is correct, it implies that cultural deposits might be preserved within natural alluvial deposits ≤ 2 m below the modern ground surface along reaches upstream of the limit of anthropogenic infilling of the Port Angeles waterfront (Figures 14 and 15). Laminated intertidal sediments, preserved 160 m north of the 1892 mouth of Valley Creek (beneath modern fill) were dated to 95 ± 25 14C yr BP (Figure 1 and Table 1). When calibrated, this date is indistinguishable from the youngest dates of aggradation recovered from upstream in both Valley and Tumwater Creeks, suggesting that the historical-period tidal delta of Valley Creek was prograding seaward and aggrading at about the same time that the upstream portion of the creek was incising into sediments aggraded along the floodplain during the late Holocene. It is possible that stream valley
aggradation and incision cycles were driven entirely by external causes such as climate change, but it appears more likely that the shift from stream aggradation to incision resulted from the alteration of upstream hydrology caused by land-use modifications (e.g. deforestation) associated with the arrival of Euro-Americans to the area in the late 1800s.

In addition to the importance for modelling the potential of buried archaeological sites in near-coastal settings, the combined techniques used in this study, GPR, geomorphology and historical dataset assessment, are useful for assessing subsurface flow of water and contaminants. For example, the identification of the now-buried tidal delta distributary channel of Tumwater Creek, visible in Figures 9 and 10, may prove important for shallow hazardous waste cleanup. This buried channel underlies the site of a former petroleum-products batch plant, where soil and groundwater contamination is known to have occurred (Wyll, 2008), and where contaminants may be concentrated along the axis of the now-buried channel at the contact between native and fill material.

Similarly, geotechnical investigations of near-coastal sites often rely extensively upon borings to provide constraint of subsurface conditions, palaeosurface elevations and the thickness of anthropogenic fill deposits. We found that a failure to incorporate elevation data from historic maps can lead to erroneous interpretations of fill depth and subfill geomorphic and depositional environments (Figure 11). Our finding that four out of five geotechnical borings from a recent engineering project in downtown Port Angeles incorrectly identified the depth to the pre-1914 land surface by as much as 3.5 m has implications for derivative use of the data presented in such reports, for example to estimate the allowable depth of disturbance at construction sites before penetration of pre-fill (native) deposits might be expected, or even what buried landforms (e.g. intertidal or supra-tidal beach) might be encountered during subsequent site development. While monetary costs are often the determining factor in the amount of subsurface geotechnical work done on coastal (re)development projects, to the extent possible, cultural resource managers should, in our opinion, seek to obtain information on the thickness of mechanical fill and subsurface landform position and distribution via integrated approaches; these could include the combination of historic elevation data from coastal zone surveys, archived historic photographs, existing geotechnical borings and non-invasive geophysical techniques such as GPR, electrical resistivity, or shallow refraction seismology. Too often the overreliance on geotechnical borings alone may result in mischaracterization of the subsurface (fill) conditions in heavily modified and extensively infilled coastal settings.

**Study results as a guide for future planning purposes**

The main purpose of this work was to present a methodology for defining potential cultural resource management areas within the heavily modified waterfront district of the city of Port Angeles. The identification of individual buried archaeological sites was beyond the scope of this work. As such, we have not
presented a site-predictive model in the strict sense of the term (e.g. Tiffany and Abbot, 1982). Rather, we have developed a model of the thickness of mechanical fill and of subfill landforms beneath an area that must be considered to have a high probability of hosting buried archaeological sites – based upon historic data (e.g. Alden, 1853) and recent re-discoveries (Larson, 2006; Lenz, 2007).

The application of GPR, geotechnical logs and historical sounding data in developing the fill thickness model has been assessed by evaluating the consistency between these techniques (see above), and the use of GPR data in delineating subfill landforms has been assessed by comparisons with historic maps (see above). However, in order to truly ‘test’ the models of fill thickness and buried landform reconstruction, one would need to excavate large areas of the largely developed waterfront corridor of the City of Port Angeles. Obviously this is not feasible. Tests of the fill thickness model will occur gradually, as individual development projects are permitted and excavations occur on a site-by-site basis.

In utilizing the constraints provided by our geomorphic investigations, the City has adopted an assessment framework that initially assumes that in the past much of the waterfront region was used in some capacity by the Central Coast Salish and therefore has a high probability of hosting archaeological sites. The City archaeologist then uses the fill thicknesses, shorelines locations and buried landform assessment provided by this study, and incorporating other environmental factors (e.g. topographic slope, distance to freshwater and winter sunshine hours) an assessment is made regarding the likelihood that a site may exist at any given location. By knowing what the landforms looked like before mechanical manipulation, a decision can be made about what has been created, raised, razed, or potentially preserved. Prior to any excavation, this information is used to assess the potential of encountering archaeological sites in certain areas and at certain depths beneath the modern fill surface. In the two years since our fill thickness and buried landform model was completed (Wegmann et al., 2010), the City has undertaken a couple of major subsurface projects. By limiting ground disturbance to areas and depth horizons with reduced modelled risk, the City has not encountered any archaeological sites during these activities. This is an admittedly weak test from a statistical perspective, but perhaps demonstrates the utility of such investigations from an operational point-of-view in which the city of Port Angeles must manage the development of its shoreline in the fallout from the Graving Dock project that unearthed the village of Tse-wit-zen.

Conclusions

The geomorphology of landscapes strongly influenced the availability of water and other resources to humans in the past, and as such exerts a strong control on the patterns of settlement transportation, and resource extraction and utilization. Consequently, knowledge of past landscapes, which may bear little similarity to those of the modern environment, is critical in developing future predictive models of buried archaeological sites. Knowledge of past environments (especially in urbanized settings) also allows for insight into the geology of the subsurface and its control on the flow of shallow groundwater and contaminants in modern settings. Geologic reconstructions of the heavily modified or urbanized areas such as exists along the Port Angeles waterfront may be of broad interest to city planners, cultural resource managers, archaeologists and environmental scientists who work in coastal settings where the placement of fill material has covered the surface and potentially preserved archaeological sites. Our research combining GPR, a non-invasive shallow geophysical technique, with data obtained from historic topographic and bathymetric maps, photographs, radiocarbon geochronology and geomorphic reconstruction, provided an effective interdisciplinary approach for reconstructing the palaeolandscape. Each technique has its own strengths and weaknesses, but by integrating and critically evaluating each one, we were able to build models of fill thickness and the spatial distribution of now-buried coastal landforms that together may be utilized in future archaeological site prediction models. Perhaps the true utility of the fill thickness and landform models are as management tools intended to assist in avoiding disturbance to potentially buried sites of cultural significance during development activities, and for aiding in the solving of archaeological, geological and environmental problems.

Like the now famous Tse-wit-zen village site, other prehistoric and ethnohistoric historic-period archaeological sites may yet be buried beneath fill used to build-out the Port Angeles waterfront during the twentieth century. Specifically, we identify buried landforms that correspond with the ethnohistoric village sites located near the former deltas of Tumwater and Ennis Creeks. These locations may yet contain archaeological components that are preserved beneath several metres of fill observable with GPR and recorded in geotechnical borings. A consistent match between the trace of Tumwater Creek from Gilbert’s 1892 map to the channel form observed in our GPR survey indicates that the stream existed in this particular location.
Assuming a relatively stable climate over the last several-hundred years, this stream, now buried beneath a former petroleum processing facility, would have provided a reliable freshwater source. Modern coastal streams in the greater Port Angeles area of similar depth and morphology carry freshwater throughout the year. Not surprisingly, the location of the now-buried stream channel indicated by GPR coincides with the location of an unnamed ethnographic village situated on the supra-tidal delta of Tumwater Creek in 1853. The City of Port Angeles waterfront is certainly one of numerous examples where fill emplacement above the coastal zone may have inadvertently preserved older cultural sites.

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