Massive submarine sand dunes in the eastern Juan de Fuca Strait, British Columbia

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Abstract

A field of very large submarine sand dunes in the eastern Strait of Juan de Fuca, British Columbia, has been surveyed with seismic reflection, sidescan sonar and multibeam bathymetric systems. The field is comprised of approximately 2.6×10^7 m^3 of sand and fine gravel (mean size > 0.5 mm). The largest of these dunes measures 25 m in height, 300 m in wavelength and 1200 m in width, comprising 9×10^6 m^3 of material. Its wavelength to water depth ratio (L/h) is 3.3 (typical for intertidal dunes) and height to water depth ratio (H/h) is 0.28 (larger than typical in any environment). Its vertical form index (L/H) is 12 indicating a steep dune, a dimension that is atypical for large dunes. Its modified symmetry index (MSI = [(stoss-side length/lee-side length)-1]) is 0.6, indicating only slight asymmetry. The lee slope is about 20° and stoss slope is 12° . The larger dunes in this field are classified as linear, slightly asymmetrical, stoss-erosional, lee-deposition, two-dimensional, very large dunes. They show net zero climb. A subsidiary set of sand waves exists on the larger dunes at an oblique angle.

Whether the dunes are modern or relict is unconfirmed, but conditions do exist today that could construct these features. Currents in excess of 100 cm/s can be expected at depth in the Strait. These currents have the potential of eroding and transporting material up to granule size. It is likely that deep flood tides and estuarine circulation during summer months construct the dunes. Most of the time the flow transports material only near the crest of the bedforms, giving them a concave-up appearance. The estuarine circulation may reverse during winter months, though less strong, resulting in reworking of the dunes and causing the near-symmetrical profile more typical of tidal bedforms. Clinoform bedding suggests net eastward migration. This combination of estuarine circulation, tidal forcing, bathymetric control accelerating currents, source material and size of the source material has resulted in the construction of some of the highest and steepest submarine bedforms documented in the literature. The question of dune age and stability remains unanswered but is of critical engineering importance with the presence of pipelines, sewage outfall and fibre optic cables in the area.

1 Introduction

High resolution seismic reflection profiles collected as part of a program of regional seafloor geophysical mapping in the eastern Juan de Fuca Strait have shown the ubiquitous presence of bedforms at a variety of scales. Most significant were a series of large-scale (10-25 m high and 300 m wavelength) submarine sand dunes observed in an isolated region just south of the junction of Haro Strait and Juan de Fuca Strait, within 10 km of the water front of the city of

Victoria, British Columbia. Sidescan sonar data were acquired over these features and sediment samples were taken. In 1998, these features were surveyed with multibeam (swath) sonar. These data document what are believed to be some of the largest features of their kind yet observed in a marine environment. Their presence impacts on the routing of submarine cables and has implications to the effects of sewage outfall in the area.

Geologic Setting

The eastern Juan de Fuca Strait is an estuarine body of water between southern Vancouver Island, British Columbia, and northern Washington State (Fig. 1). Mid-strait water depths range from less than 60 m over shallow sills to more than 250 m at the entrance to the open Pacific Ocean. The local Quaternary geology and seafloor morphology most strongly reflects various episodes of Pleistocene glaciations; in particular the latest Wisconsinan phase, known locally as the Fraser Stade. The area is very close to the terminus of this glacial epoch. Thick (up to tens of metres) deposits of sand and gravel are present in various locations in the region, resulting from outwash during the Fraser advance. This unit is referred to as the Quadra Formation. Till and other forms of diamict deposited directly by the ice are present almost everywhere, but at varying thickness. This unit is known as the Vashon Formation. Within the strait, a number of drumlins, and terminal and side moraines of this formation form shallow banks, occasionally reaching to the sea surface. During ice recession (between 17,000 and 14,500 years ago), thick deposits of glacial-marine sediment accumulated almost everywhere. These sediments are referred to locally as the Capilano Formation. They range in lithology from silty clay to gravel, depending on the proximity of the outwash to the receding glacier. A large outwash delta, known as the Colwood delta, formed at this time near Victoria. The distal portion of this former delta is now submerged along the Victoria waterfront. Onshore, this delta is mined for its aggregate. Since deglaciation there has been little sediment input to the area as there are no major rivers flowing into the strait. Most recent Holocene sediments, known as the Salish Formation, largely consist of reworked Capilano and Quadra material. These sediments are variable in location and thickness, usually less than a few metres thick.

Relative sea level within the region changed rapidly during deglaciation, from a high of at least 90 m above present at 14,500 years ago, to possibly 50 m below present about 9,000 years ago (Clague et al., 1982; Linden and Schurer, 1988; Hewitt and Mosher, 1999). Sea level initially rose quite rapidly following this low until about 5,000 years ago. Since this time, sea level has risen at about the rate of eustatic rise, which is on the order of 10 cm/100 years. The region lies in an active subduction zone setting, so in addition to these eustatic and glacio-static sea level changes, there may be sudden, yet short-term elevation changes having resulted from tectonic displacements (see Thomson and Crawford, 1998).

Physical Oceanography

Haro and Juan de Fuca Straits form the principal waterway connecting the marine basins of the Strait of Georgia and Puget Sound with the Pacific Ocean. Currents in eastern Juan de Fuca Strait are dominated by daily tidal currents with typical speeds of 75 to 100 cm/s through the water column. Two ebb and two flood currents each day have unequal speeds because the tidal currents are principally a combination of diurnal (1 cycle per 25 hours) and semi-diurnal (2 cycles per 25 hours) constituents. These currents, in turn, undergo a marked fortnightly variation of around 25 cm/s associated with the spring-neap cycle in the tides.

Superimposed on the rapidly varying tidal currents are more persistent estuarine currents driven by the hydraulic head of the Fraser River as it enters the Strait of Georgia near Vancouver. As this freshwater moves seaward through Haro Strait, it undergoes strong vertical mixing and entrainment with the underlying oceanic water. The result is a net seaward flow of brackish riverine water in the upper layer of the strait and a net inward flow of salty oceanic water at depth. During May through September, the reversal in direction of the estuarine component of the flow is found around 60-m water depth. Maximum outflow currents of around 25-30 cm/s occur at the surface while maximum inflow currents of around 15-20 cm/s occur at about 90 m depth. The estuarine pattern can be reversed during times of strong westerly winds in Juan de Fuca Strait (October through March). This reversal results in intense inflow currents of 25 cm/s appearing in the upper 20 m of the water column and strong outflow currents of around 15 cm/s in the lower portion of the water column. In summer, therefore, combined bottom currents can readily exceed 100 cm/s during each tidal cycle with a bias toward the east-northeast. In winter, the bottom currents will be less intense and have a bias toward the west. In shallow water, direct wind-forced currents and orbital wave currents also can effect transport of bottom sediments.

2 Methods

Regional seismic reflection data were acquired with a Huntec Hydrosone DTS. This system utilizes a boomer source mounted within a deeply towed "fish". The boomer emits an impulse source wavelet, with significant energy spanning frequencies from 500 to 5000 Hz. Data were received on a single element, internally mounted hydrophone array and on an external array. These data were digitized at a rate of 25 kHz. Data acquired using this system resulted in relatively good profile imaging through the sand dunes. A single line of sidescan sonar data over the sand dunes was acquired with a Simrad 992 system. This system operates with two frequencies, 120 and 330 kHz. These data were slant-range and beam-pattern gain corrected.

Regional bathymetric data were acquired from Canadian Hydrographic Service field sheets, which were generated from single beam echo-sounding lines. The Victoria water front, including the sand dune field, was surveyed in September of 1998 with a Simrad EM3000 multibeam echosounder, hull mounted on the M/V Revisor. The EM3000 is a 300 kHz, 120-beam sonar system, spanning 120° of swath. It is capable of operating in water depths ranging from 5 to about 100 m. The system is integrated with differential global positioning and a POS-MV inertial navigation system. Accuracy is a function of positioning errors, water depth and the water sound velocity profile, but is on the order of 0.1 m vertically, and 0.5 m horizontally in this environment. Data were rigourously edited for errors and, in the final mosaicing, smoothed and gridded to a 2-m interval.

Numerous attempts at sampling the sand dunes with a vibro-core system failed due to the steep angles of the dunes; the system simply toppled over. One stratigraphic sample to 1.53-m depth was acquired and several surface samples were collected. Subsamples of these cores were analyzed for grain size distribution with sieve and settling tower techniques. Grain size are reported according to the Wentworth scale and statistics were calculated using the method of moments (Folk, 1980). Median grain size data were used to derive the critical shear velocity to transport this material according to algorithms presented by Miller et al. (1977). The observed bedforms, with their relative dimensions and cross-bedding patterns were numerically simulated with modeling software documented in Rubin (1987).

3 Results

$$u/u_{in} = a_{in}/a = \frac{w_{in} \times h_{in}}{w \times h}$$

Multibeam bathymetry data were acquired from the coastline of the Victoria waterfront and offshore to a water depth of about 70 m (Fig. 1). These multibeam data have been superimposed within field sheet data to provide the general morphologic framework of the region (Fig. 1) as well as details of the dunes. The submarine sand dune field can be observed at the easternmost extent of the multibeam data set, just south of Discovery Island near the opening to Haro Strait. The field lies within a seafloor depression at 60-90 m water depth. This depression is funnel-shaped, narrowing to the east-northeast. Based on simple volume transport continuity, flow acceleration up the channel can be estimated:

, where u is the depth averaged current velocity, the subscript *in* refers to the entrance to the funnel, a is area, w width and h height.

Assuming a constant flow depth, the ratio of flow velocities is simply the ratio of the width of the channel at the entrance to its width where the sand dunes occur. These values are approximately 4 and 1.2 km respectively, so the flow velocities may increase on the order of 3.3:1

The dunes range in size from one to 25 m in height, increasing in amplitude towards the east-northeast. At the southwestern extent, the dunes are on the order of 100-200 m in length and are cuspate-shaped towards the east-northeast. In the main dune field there are linear dunes, up to 1.2 km along the crest, spanning the width of the depression. They are up to 25 m in height and with wavelengths on the order of 300 m (Figs. 2-4) (500 m between the two largest dunes with an interdune flat area). The easternmost dune supports a 400 m-long spur off its eastern end. The total volume of sediment comprising these bedforms is estimated to be 2.6 x 10^7 m^3. Sidescan sonar images over these dunes show a subsidiary set of bedforms, too small to be noted by the multibeam data, aligned oblique to the main dunes (Fig. 4). These super-positioned sand waves are on the order of 10 m in wavelength.

Seismic reflection images across the main dunes show only a slight asymmetry with a steep lee side to the east as well as subbottom clinoforms on their eastern flanks (Fig. 4). These dunes rest on a highly reflective surface under which there is little subbottom penetration. This surface forms the seafloor in the trough between dunes. There are no apparent buried dunes or complex cross-bedding patterns within the dunes.

Grain size analysis show the dunes to be composed of coarse sand and granule, with mean sizes ranging between -0.7 and -0.92f (about 0.5 to 0.6 mm) (Fig. 5). Calculations of critical shear velocity for each sample are shown in Table 1. These values are for a flat seabed. Given the roughness of the bed at a number of scales, it is likely that critical shear velocity could be as little as half of the value reported due to the initiation of turbulence, especially since the median size used in the calculation is much larger than the mean size.

Sample - depth	**Med. size (mm)**	**J_{cr} (dynes/cm^2)**	**U_{cr} (cm/s)**	**$U_{cr\ 100}$ (cm/s)**
97B025-15cm	2.11	10.90	3.30	79
97B025-64cm	1.34	6.35	2.52	68
97B025-120cm	1.65	8.12	2.85	73

Table 1: Critical shear stress for erosion calculations assuming a flat-bed situation (using Miller

et al., 1977). J_{cr} is the critical shear stress, U_{cr} is the critical shear velocity at the bed and U_{cr100} is the critical shear velocity at 1m above the bed. A flow density of 1 was assumed in the critical shear stress calculation.

Discussion

Numerical simulations of bedforms approximating the form and relative dimensions of the observed sand dunes are shown in Figure 6. Based on the geophysical imagery and these models, the main set of large bedforms are classified as linear, slightly asymmetrical, stoss-erosional, lee-deposition, two-dimensional, very large dunes (classification nomenclature of Rubin (1987) and Ashley (1990)). These dunes show net zero climb with interdune flats. Bedform steepness is about $^{1}/_{12}$ (height/wavelength) for each of the larger dunes, yielding slopes of 12° of the stoss side and near 20° on the lee. The presence of smaller, superimposed dunes on the large ones (Fig. 4) indicates some complexity in flow pattern. The height of these subsidiary dunes cannot be measured from sidescan records. They occur at oblique angles to the main dunes and appear to be on the order of 10 m in wavelength (Fig. 4). The superposition of smaller dunes on larger ones is widespread in the tide-dominated, outer portion of estuaries. Their process of formation is believed to be related to the development of an internal boundary layer on the stoss side of the larger dunes (Dalrymple, 1984).

The size (wavelength and height) of dunes is a complex function of many variables, the most important of these being water depth (or boundary-layer thickness), current speed, and grain size. Tabulations of the height and wavelength of dunes from many environments show that dune size generally increases as water depth increases (Yalin, 1964, 1977, 1987; Allen, 1982, Ashley, 1990; Southard and Boguchwal, 1990; Dalrymple and Rhodes, 1995). Yalin (1964, 1977, 1987) suggests that dune wavelength (L_D) should be approximately six times the water depth (h), while dune height (H_D) should be approximately 17% of the water depth.

$L_D = 6h$

$H_D = 0.167h$

The presence of stratification in the flow (such as in a salt wedge or estuarine flow) does not appear to cause a detectable decrease in the scale of the dunes (Dalrymple and Rhodes, 1995). Dune height, therefore, is more closely related to total water depth, rather than flow depth. In the case of the dunes described herein, the ratio of dune length to water depth plots within the mean scatter presented in Allen (1980), with an L/h of 3.3. The dune height to present water depth ratio plots on the upper margins of the scatter of data shown in Allen (1980) with an H/h of 0.28 (*cf.* 0.167 of Yalin, 1964, 1977, 1987). If the flow depth was used as opposed to the total water depth, the ratios would plot well outside the bounds established by empirical data described in Allen (1980).

One measure of dune shape is the ratio of wavelength to height, known as the ripple index or vertical form index (Allen, 1968). Low values (10-30) indicate steep dunes and high values (100-400) flat dunes. Dalrymple and Rhodes (1995) show that large dunes generally have an RI > 30 and commonly greater than 100. In the case of the larger dunes shown here, the RI is 300/25 m or 12 indicating steep dunes, a dimension that is atypical for large dunes. A measure of the asymmetry of bedforms is the "modified symmetry index' (MSI = [(stoss-side length/lee-side length)-1]; Allen, 1968). A MSI of 16 is typical for dunes formed by unidirectional currents. Large tidal dunes rarely exceed 4. The dunes in this study have a MSI=0.6, indicating they are only slightly asymmetric (0 would be perfectly symmetrical).

The influence of grain size on dune shape is complex. In general, dune height increases as the grain size increases until about 0.5 mm, after which dune height decreases as grain size continues to increase (Rubin and McCulloch, 1980; Allen, 1982; Southard and Boguchwal, 1990; Dalrymple and Rhodes, 1995). In the case of this study, the mean size is just above 0.5 mm, although the median is somewhat higher. This distribution would seem to be about optimal for dune height construction.

The angle of repose for unconsolidated sand is between 32° and 35° . Dalrymple and Rhodes (1995) report that average lee slopes are typically less than 10° and may be as low as 1-2° . It is a general observation that larger dunes have lower-angle lee faces than smaller ones. Stoss-side slopes of large and very large dunes average 2-3° . Figure 3 shows that one of the larger dunes in this study has a lee slope of about 20° and a stoss-side angle of about 12° . These angles are atypical for very large dunes. The slight concave-up form of dunes, as observed in the dunes in this study (Fig. 3), are common in areas where the threshold of sediment motion may not be exceeded for long periods. Normal tidal currents may be capable of moving sand only on the dune crest. Sand in the troughs can become stabilized. This stabilization of sand in the trough may produce a flat-troughed form, mimicking the situation where dunes are migrating over a non-erodible substrate (Aliotta and Perillo, 1987).

The most critical questions with respect to the presence of these submarine sand dunes of the magnitude documented herein, and in the environment shown, is whether or not they are relict or active, and if active, how stable are they? Grain size data of these dunes show they are composed of coarse sand and gravel, requiring currents on the order of 70 cm/s (at 1 m above bed and for a flat bed) to generate a critical shear force to erode (Table 1). This velocity may be halved, given bed roughness causing turbulence. The general oceanographic setting suggests that flow during certain tidal flood cycles combined with estuarine circulation during summer months can generate currents of this magnitude. In addition, the presence of a funnel-shaped bedrock trench at the depth of maximum Pacific water inflow (90 m) during summer months, within which the dune field exists, could serve to accelerate currents in excess of 3x.

The second component to addressing the issue of relict vs. modern is whether or not there is enough cohesionless sediment to form the dunes at present. There are no present-day rivers supplying sediment to the marine environment near Victoria but large quantities of sediment were deposited in the Juan de Fuca Strait during Wisconsinan deglaciation. This material ranges in size classes from clay to boulder (glacial marine clay to diamict). The Colwood delta, just west of Victoria (Fig. 1), was deposited as a result of glacial-marine outwash during a period of higher sea level. It consists largely of sand and gravel and forms a significant aggregate resource. Its eastern extent is not much beyond the mouth of Victoria Harbour, but material could have been transported to the east in the past. A significant sea level low (-50 m) at about 9,000 years B.P. appears to have caused significant erosion of the seafloor, leaving a regionally extensive unconformity at the top of the glacial/glacial-marine succession (Linden and Schurer, 1982, Mosher and Bornhold, 1994, Hewitt and Mosher, 1999). This erosive period could have supplied abundant material in the past, but water depths would have been only 40 m above the base of the trough.

Clearly, source material existed in the past, but much of the glacial and early post-glacial deposits offshore of the Victoria waterfront now underlie a gravel lag that armour them from further erosion. The sea bluffs, which form the Victoria waterfront, are composed of this till and glacial-outwash material. They have been subjected to pervasive erosion until recent engineering shoreline protection measures were taken. It is feasible that this material is or was transported offshore during winter storms. Further winnowing would leave a gravel surface lag and transport the portion of material granule-size and smaller to the east. The sand and granule material could be moved as traction or bedload within the funnel-shaped depression, eventually to form the dunes. Material finer than fine sand could be transported in suspension away from the area. Another, less likely potential modern source area for sediment is outcrop of Quadra sand to the north and east of the dune field in the San Juan and Gulf Islands. This material would first have to be transported west, perhaps during the winter when estuarine circulation is reversed.

The stability of the dune field remains unanswered. Repetitive observations and long term monitoring are required. Dune stability is critical to the impact on sea floor cables and pipelines (see Whitney et al., 1979, for example). The dunes are large and steep enough that a cable laid across them could cause suspension of the cable from crest to crest. Turbulence and detachment of flow can induce vibration and sand movement can cause erosion of cable and pipeline casings, scouring around these structures or movement of the structure itself, inducing strain and possible breakage. Figure 1 shows the route of a recently laid (1999) fibre optic cable and two sewage outfall pipes from Victoria. The cable route was chosen before the benefit of multibeam bathymetry but after the seismic surveys identified the presence of this dune field. The route wisely avoids the dunes but the multibeam bathymetry shows that a better or more efficient route might have been chosen with the benefit of these data. The knowledge of the presence of currents that are capable of constructing these large dunes may also assist in assessing the effectiveness of allowing sewage from Victoria to outfall in this area.

5. Conclusions

The presence of very large (25 m high, 300 m wavelength) submarine sand dunes, some of the largest yet documented in the literature, in the eastern Juan de Fuca Strait, British Columbia, is the result of a unique combination of factors. These variables include diurnal tides, estuarine circulation, seafloor morphology, water depth and availability of sediment of a specific grain size range. Whether the dunes are modern or relict is unconfirmed, but conditions do exist at present that could construct these features. Although the Strait is a relatively large body of water, its circulation is estuarine due to strong diurnal tides and large freshwater outflow from the Fraser River in the neighbouring Strait of Georgia. Currents in excess of 100 cm/s can be expected at depth in the Strait as a result. These currents have the potential for eroding and transporting material up to granule size. The observed sand dune field occurs at the head of a funnel-shaped bathymetric depression, which could serve to accelerate bottom currents.

The sediments comprising these dunes, which contain about 2.6×10^7 m^3 of sand and fine gravel, is available along cliff exposures off Victoria. This source may now be unavailable due to engineered shore protection along the Victoria waterfront. Other source areas may be cliff exposures of sand and gravel in the San Juan and Gulf Islands. The dune field shows no net deposition. The grain size of source material appears to be optimal for constructing these massive features, with respect to their height. As for the process of their construction, their steepness and near symmetry is expected from tidal environments, but their size is more indicative of uni-directional flow. It is possible that deep flood tides and estuarine circulation during summer months construct them. Most of the time the flow transports material only near the crest of the bedforms, giving them a concave-up appearance. The estuarine circulation may reverse during winter months, though less strong, resulting in reworking of the dunes in the opposite direction and causing the near-symmetrical profile more typical of tidal bedforms. Sub-bottom profiles of these features show clinoform reflectors and the lee side of the bedform facing towards the east, suggesting net eastward migration. The stability of the dune field remains unanswered. Repetitive multibeam bathymetric surveys and long term current flow monitoring are required to answer this question. These questions of dune construction and stability are relevant to the presence of sewage outfall and sea floor cables in the region.

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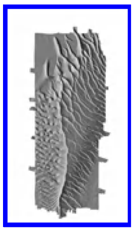
Sommaire: 

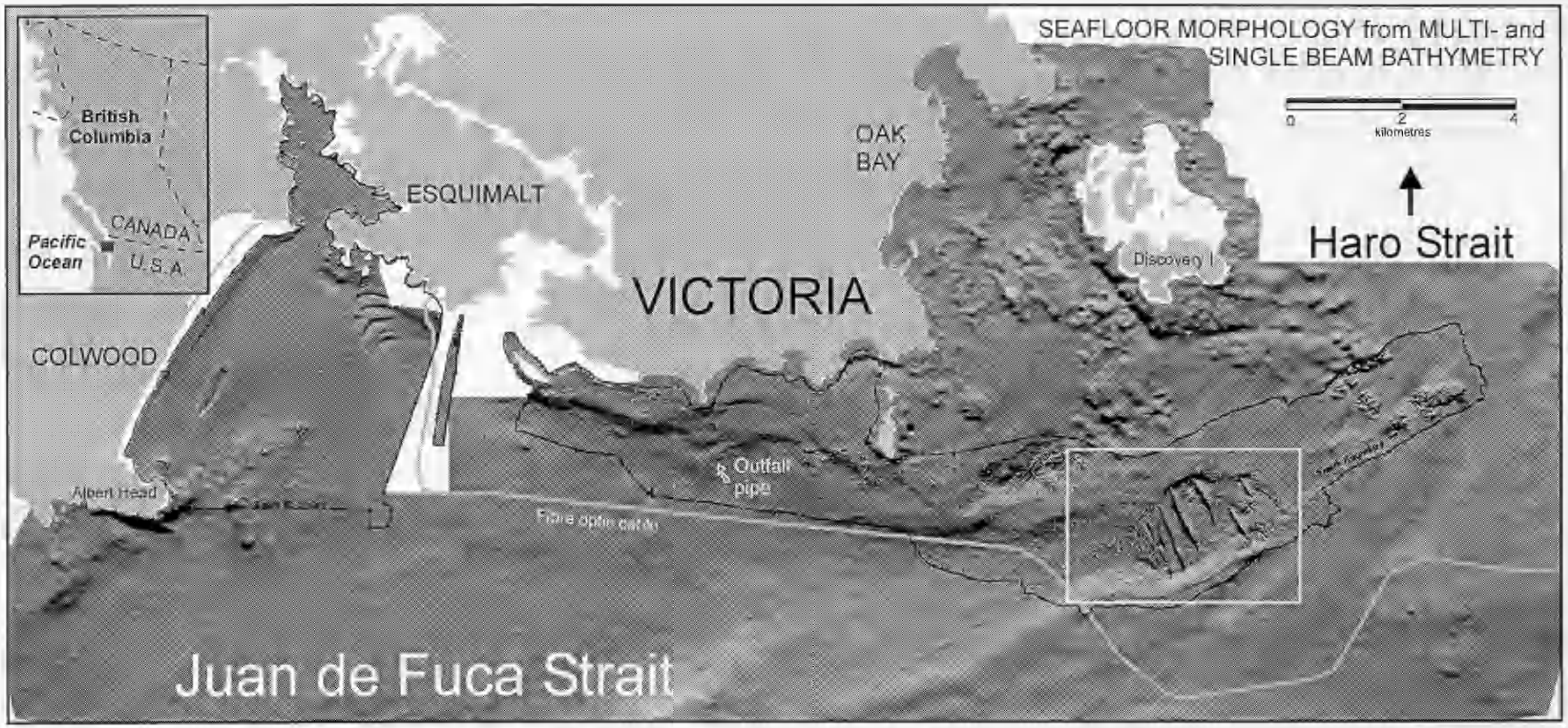


Figure 1: Location diagram for study area off of Victoria, British Columbia. The sun-illuminated image is a result of a

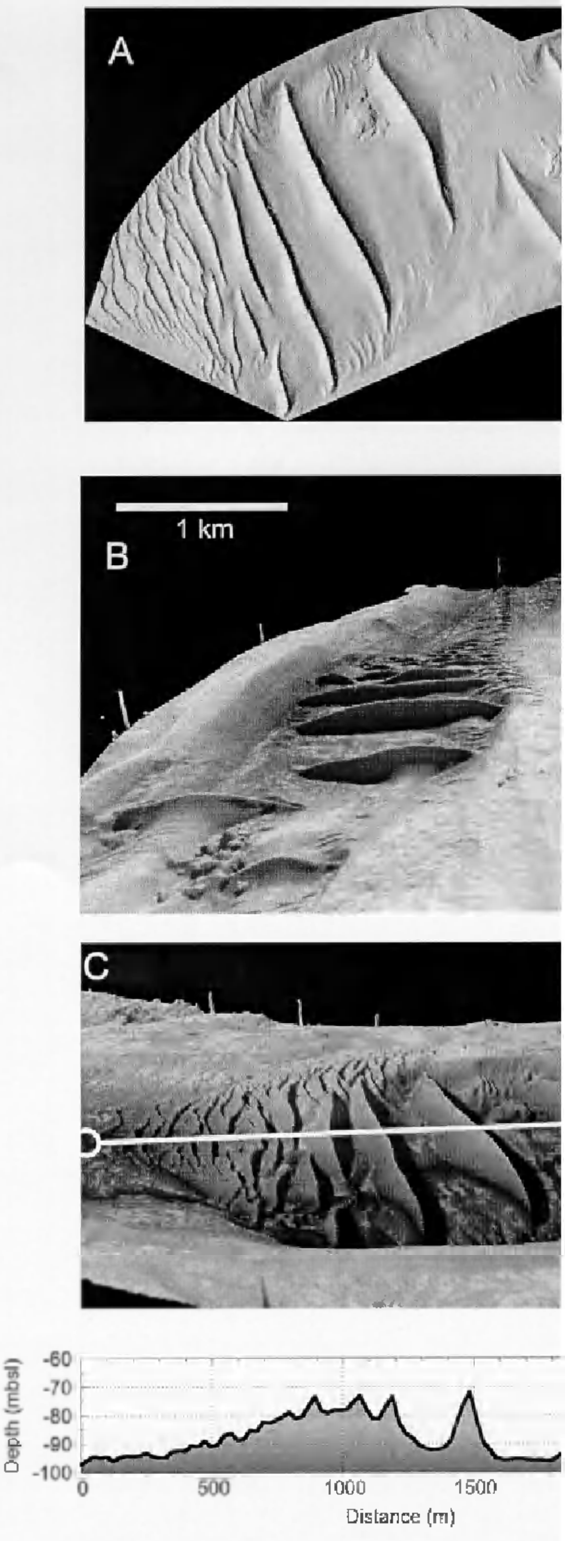
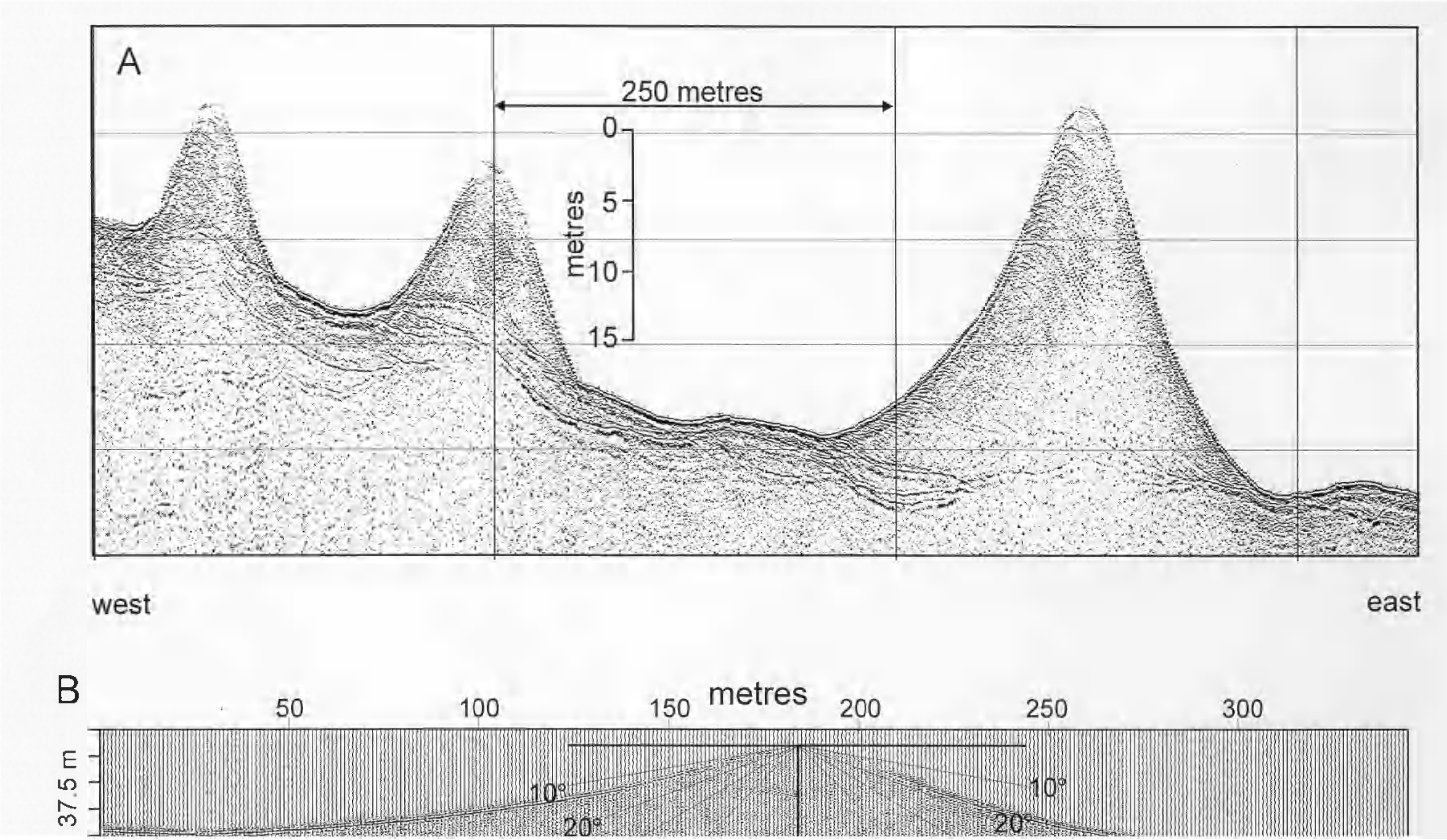


Figure 2: Plan and perspective views of sun-illumi
dune field. Vertical exaggeration is 6x.
looking west, C) view looking north.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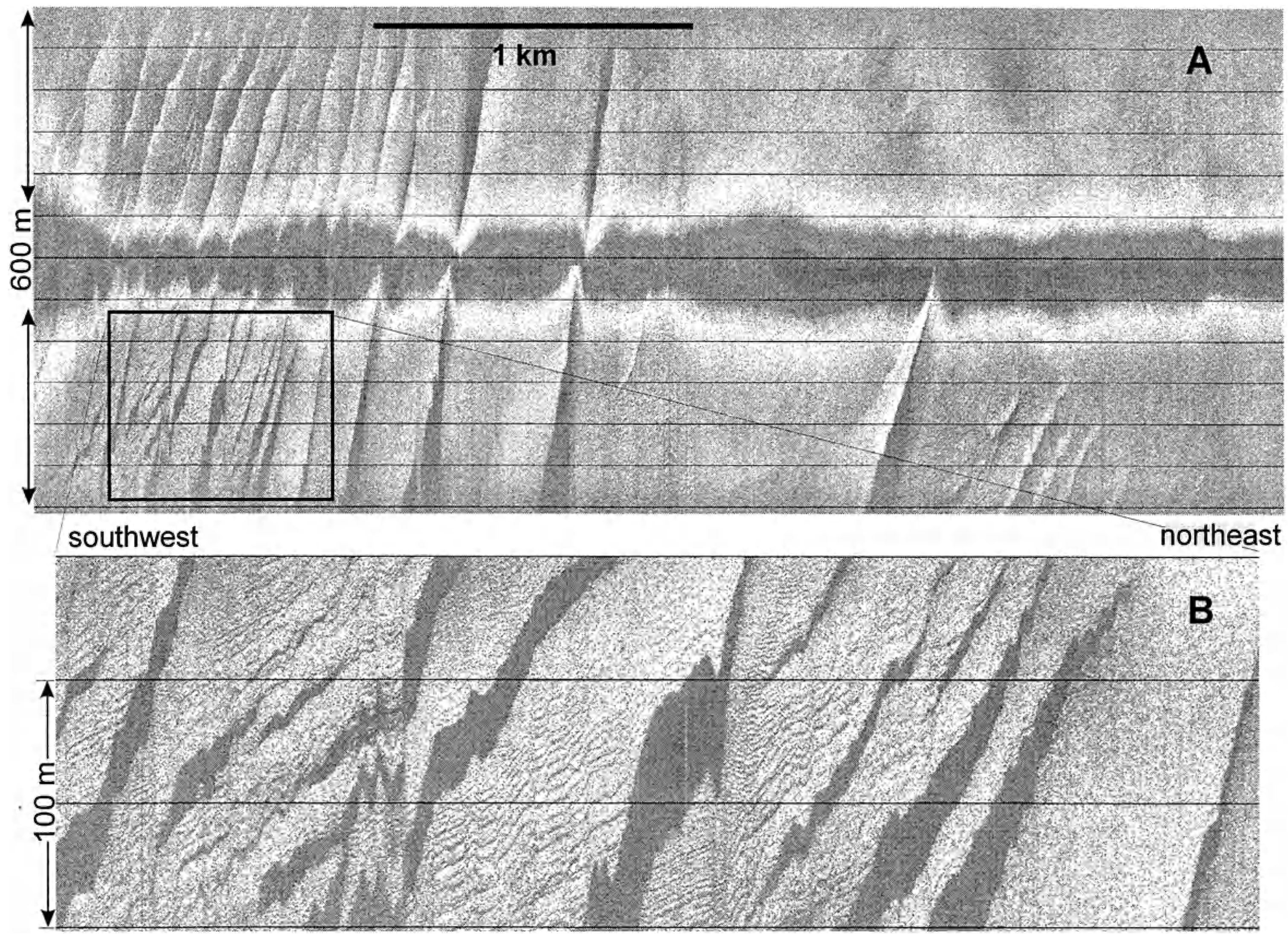
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100 m

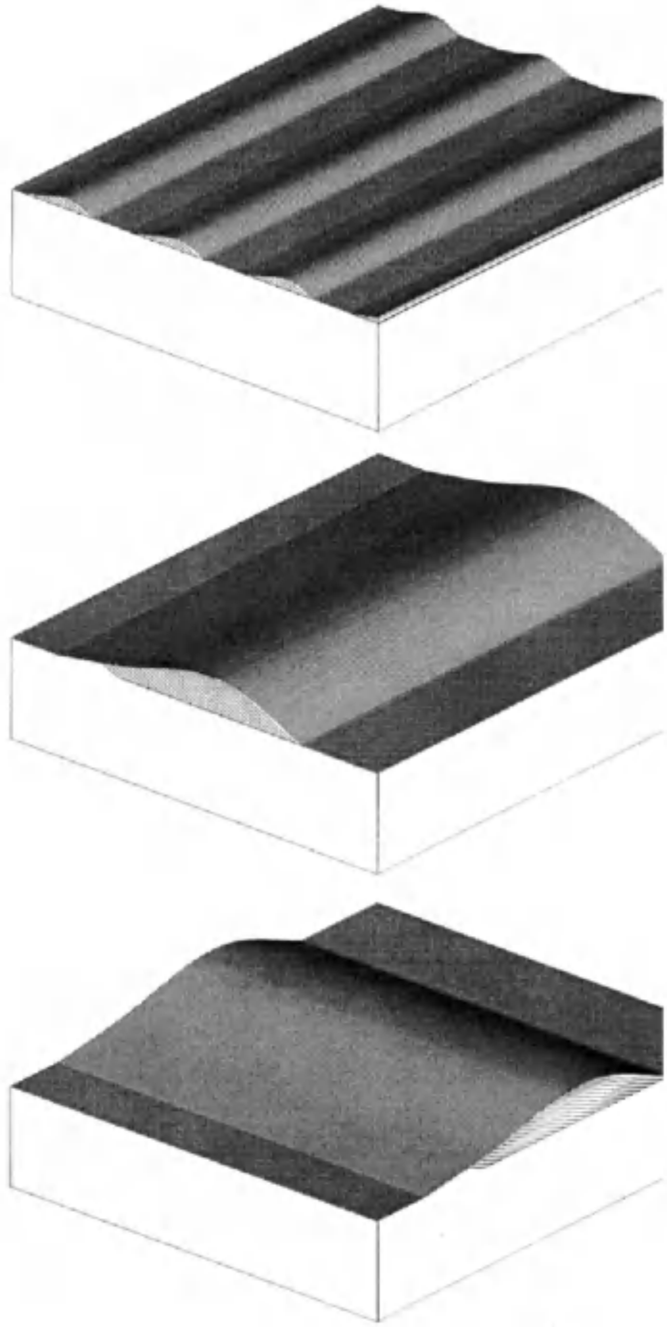

Figure 6: Models resulting from numerical simulation of the observed bedforms using Bedform 1.0 (Rubin, 1987). These models, designed to simulate the field observations, assist in quantification and classification of the dune field. These forms are classified as linear, 2D, stoss erosional, lee depositional, slightly asymmetrical, very large dunes. They show net zero climb with interdune flats.