

MARINE BENTHIC HABITAT MAPPING OF THE SAN JUAN ISLAND NATIONAL HISTORICAL PARK

H. Gary Greene^{1,2}, Sandy Wyllie-Echeverria¹, Jerald Weaver³, Norman Maher⁴, and Joseph Bizzarro¹

¹Friday Harbor Labs, University of Washington, Friday Harbor, WA, email: green3@u.washington.edu

²Tombolo, Orcas Island, WA

³National Park Service, San Juan National Historical Park, Friday Harbor, WA

⁴Center for Habitat Studies, Moss Landing Marine Labs, Moss Landing, CA & Tombolo, Orcas Island, WA

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INTRODUCTION

In response to the U.S. National Park Service's (NPS) interest to map the submerged lands within park boundaries and to understand the aquatic processes that play a role in the formation, distribution and disturbance of coastal and submarine resources in and around park boundaries, research scientists at the Friday Harbor Laboratories (FHL), University of Washington (UW), constructed a series of thematic maps for the use of San Juan Island National Historical Park (SAJH) personnel to evaluate and manage nearshore and offshore resources. To accomplish this task we: (1) compiled all available seafloor mapping data in and around the SAJH including multibeam echosounder (MBES) bathymetry and backscatter data, terrestrial LiDAR and photographic data, and sediment sample information, (2) analyzed and interpreted new data collected in spring, summer and fall 2010, and (3) constructed site specific habitat maps.

GOALS

The objective of this project was to compile available regional seafloor mapping data for both American and English camps of SAJH and to interpret newly collected data provided through a cooperative program with the Geological Survey of Canada to construct benthic habitat maps of the Salish Sea. The habitat maps were constructed using the same habitat classification scheme and mapping code presently being used for the

development of the California State Mapping Project habitat maps ([Greene et al., 1999, 2005, 2007a](#); also see code in [Appendix I](#)). The maps comprise an integration of previous seafloor maps such as those constructed for the deep-water parts of the San Juan Archipelago and southern Georgia Basin ([Greene and Barrie, 2011](#)).

The purpose of this investigation was to provide up-to-date seafloor maps that characterize potential benthic habitats, substrate types and submerged vegetation within and adjacent to the Park. This will facilitate effective management of the watershed and in-water activity within park boundaries, and provide direction for other federal, state and county authorities charged with natural resources management in the San Juan Archipelago. Valuable marine resources are present on the seafloor within and adjoining the submerged lands of the SAJH. These resources include rockfish (*Sebastes* spp.) and Dungeness crab (*Cancer magister*) habitat and eelgrass (*Zostera marina*), an important recruitment habitat. SAJH. However, maps delineating the specific location and interconnectedness of these resources did not exist prior to this work.

Based on the fact that shallow-water nearshore and intertidal areas are difficult to map using conventional boat-based acoustic instruments, another goal was to investigate and develop a shoreline mapping protocol that could be used at other NPS shoreline parks. The technique is based on (1) extending onshore mapping units offshore through the use of existing geologic maps and field checking of onshore mapping, (2) the use of terrestrial LiDAR and geo-referenced air photographs (collected during low tides) to fill in the “white zone” (data gap area), and (3) the collection of bottom sediment grab samples and nearshore underwater video (collected during high tides) to validate interpretations. The outcome was the construction of shallow-water benthic habitat and geologic maps using a combination of these methods and techniques.

REGIONAL GEOLOGIC SETTING

The marine benthic habitats of the San Juan Archipelago result from the past and present regional geological processes. In this section we provide a geological framework and brief history of the tectonic and glacial activity that formed the landscape and seascape of

the region. The following is a condensation of the many studies that have addressed regional tectonics.

The San Juan Archipelago is composed of the western part of a series of metamorphic nappes (thrust sheets) that construct the Northwest Cascades orogen of [Bergh \(2002\)](#), which is synonymous with the San Juan-Cascade Nappes of [Brandon et al. \(1988\)](#) and the Northwest Cascade System of [Brown \(1987\)](#). The Northwest Cascades orogen represents the boundary between the Insular Superterrane – a fault-bounded package of multiple smaller tectonostratigraphic terranes – on the west and the Intermontane Superterrane on the east. The Insular and Intermontane superterranes represent the two largest allochthonous blocks in North America (Fig. 1). The Intermontane Superterrane was accreted or sutured to the North America during Mid-Jurassic, and represents the western margin of the continent during the Cretaceous ([Monger et al., 1982](#)). The Insular Superterrane includes the Wrangellia tectonostratigraphic terrane, which lies parallel to and west of the Intermontane Superterrane. The entire superterrane boundary extends for ~1200 km from southern Alaska to northern Washington State. The San Juan Archipelago is also associated with the Coast Plutonic Complex, which represents Mid-Cretaceous to Eocene subduction volcanism and can be divided into two main blocks separated by the Haro Fault (Fig. 1). The highly metamorphosed rocks of the San Juan thrust system are exposed south of the fault, while the primarily un-metamorphosed rock units external to the San Juan thrust system are found north of the fault (Fig. 2).

The tectonic origin of the San Juan Archipelago is an unresolved scientific issue. The idea that the Archipelago underwent a fairly rapid period of thrusting and uplift 100 Ma and 84 Ma ([Brandon et al., 1988](#)) is broadly accepted, however, there is widespread disagreement as to the direction and mechanism by which the Archipelago was amalgamated, as well as the paleo-latitude of this region during the mid-Late Cretaceous.

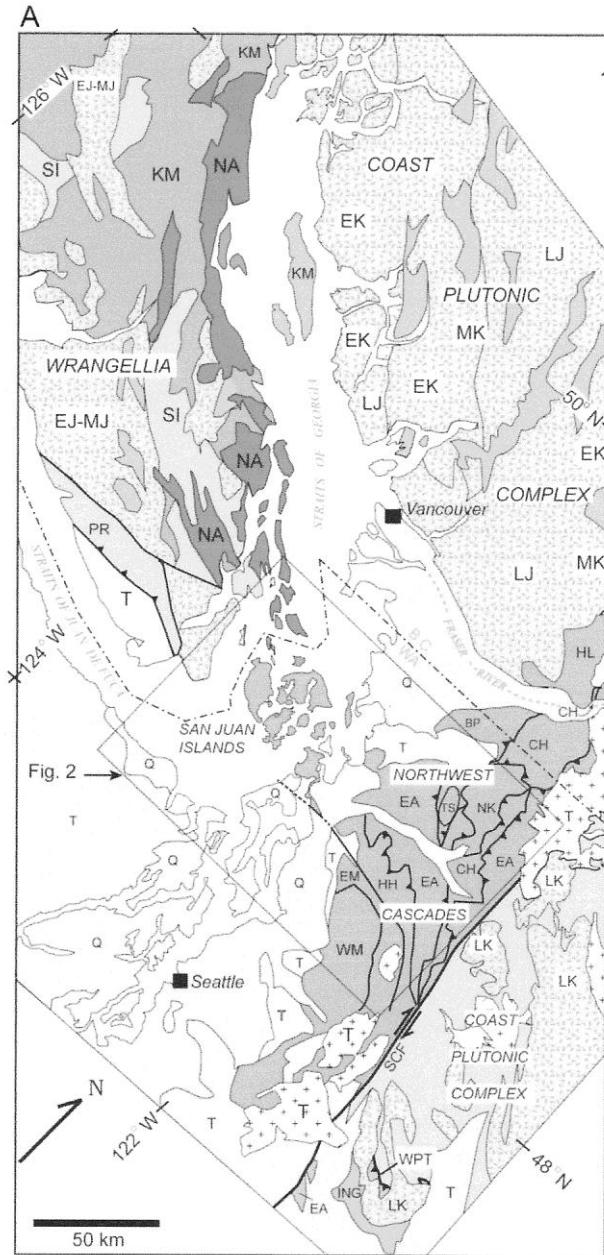


Figure 1. Geologic setting of the San Juan Islands – northwest Cascades thrust system; regional geologic map. Plutons: EJ-MU, Early to Middle Jurassic; LJ, Late Jurassic, EK, Early Cretaceous; MK, mid-Cretaceous; LK, Late Cretaceous. Terranes of the northwest Cascades thrust system: BP, Bell Pass mélangé; CH, Chilliwack composite terrane; EA, Easton terrane; EM, Eastern mélangé; HH, Helena-Haystack mélangé; HL, Harrison Lake stratigraphic sequence; ING, Ingalls tectonic complex; NK, Nooksack terrane; TS, Twin Sisters Dunite; WM, Western mélangé. Other rock units and structures: SI, Sicker Group, KM, Karmutsen Formation and related sedimentary rocks; NA, Nanaimo Group; PR, Pacific Rim terrane; Q, Quaternary deposits; SCF, Straight Creek fault; T, Tertiary rocks; WPT, Windy Pass thrust. After [Brown \(2012\)](#).

The existing theories on the direction and mechanism of mid-Late Cretaceous thrusting can be summarized by three models: 1) the “*contractual*” model in which the San Juan Islands formed due to SW-NE accretion in a zone of shortening between Wrangellia and North America (Brandon et al., 1983, 1988, 1993; Rubin et al., 1990; McGroder, 1991; Feehan and Brandon, 1999), 2) the “*northward transported model*” in which a dextral transform fault zone along the North American subduction margin transports accreted terranes and clastic sequences northward until reaching a bend in the coastline where northwest-directed thrusting commences (Vance, 1977; Vance et al., 1980; Maekawa and Brown, 1991, 1993), and 3) the “*combination model*” in which early SW-NE contraction is followed by northwest directed thrusting and sinistral coast-parallel transport as suggested by a left-lateral fault zone in the Lopez Structural Complex (Bergh, 2002). Paleomagnetic data suggests there has been between 1,000 km to 3,000 km of northward transport of the Insular Superterrane, the Coast Plutonic Complex, and by association the San Juan Archipelago since 90 Ma with minimal tilting (Irving, 1985; Housen and Beck, 1999; Bogue et al., 1989). In addition, Burmester et al. (2000) recognized widespread remagnetizations were consistently dipping steeply down to the southeast, suggesting a combination of tilting and clockwise rotation since terrane accretion. Some geologists argue that <1,000 km of northward translation has occurred within the boundary between the Insular and Intermontane supertarranes, based primarily on the absence of evidence of a fault system that could have accommodated more than 1,000 km of slip (Price and Charmichael, 1986; Mahoney et al., 1999).

At present the regional tectonic setting of northwestern Washington involves the oblique convergence of the North American and Juan de Fuca plates. Currently, the Juan de Fuca Plate is moving northeastward in a reference frame fixed to North America and is being subducted at a rate of ~45 mm/yr (Wilson, 2002). The Cascadia subduction zone defines this active plate boundary. According to GPS velocity data along the Cascadia subduction zone, the northwestern Washington/southwestern British Columbia region is currently shortening in a N-S direction at ~3-3.5 mm/yr, with long term shortening estimated at 5-6 mm/yr (Mazzotti et al., 2002). According to Wells et al. (2002), this shortening is linked to the dextral translation of the Sierra Nevada block of California. The convergence of

the Sierra Nevada block with the Oregon forearc near the Mendocino triple junction has resulted in the clockwise rotation of the Oregon forearc, which in turn drives the Washington forearc northward against the Canadian Coast Mountains ([Wells et al., 2002](#)).

Seismicity

The San Juan Archipelago is located within the seismically active Puget Lowland. Earthquakes that occur in the region can be divided into crustal earthquakes that occur within the upper 37 km of the crust ([Ramachandran, 2003](#)), subduction earthquakes that occur at the interface between the North American and the subducting Juan de Fuca plates at intermediate depths, and deep focused earthquakes within the Juan de Fuca Plate. Our interest is on the shallow crustal earthquakes because these events are the most likely to result in surface ruptures near or within the SAJH. Crustal earthquakes in the greater Puget Sound region occur primarily as a result of N-S compressive stresses along the northern Washington forearc. While large earthquakes with magnitudes greater than 4 are rare in the San Juan Islands, smaller earthquakes are prevalent. Paleoseismologic studies have shown that at least five to seven Holocene ground-rupturing earthquakes have occurred ([Bucknam et al., 1992](#); [Sherrod et al., 2000](#); [Nelson et al., 2003](#); [Kelsey et al., 2004](#); [Johnson et al., 2004](#)). Evidence exists that show that earthquake associated deformation of the seafloor or associated landsliding has produced tsunamis ([Atwater and Moore, 1992](#); [Bourgeois and Johnson, 2001](#); [Williams and Hutchinson, 2000](#); [Williams et al., 2005](#)).

Faults

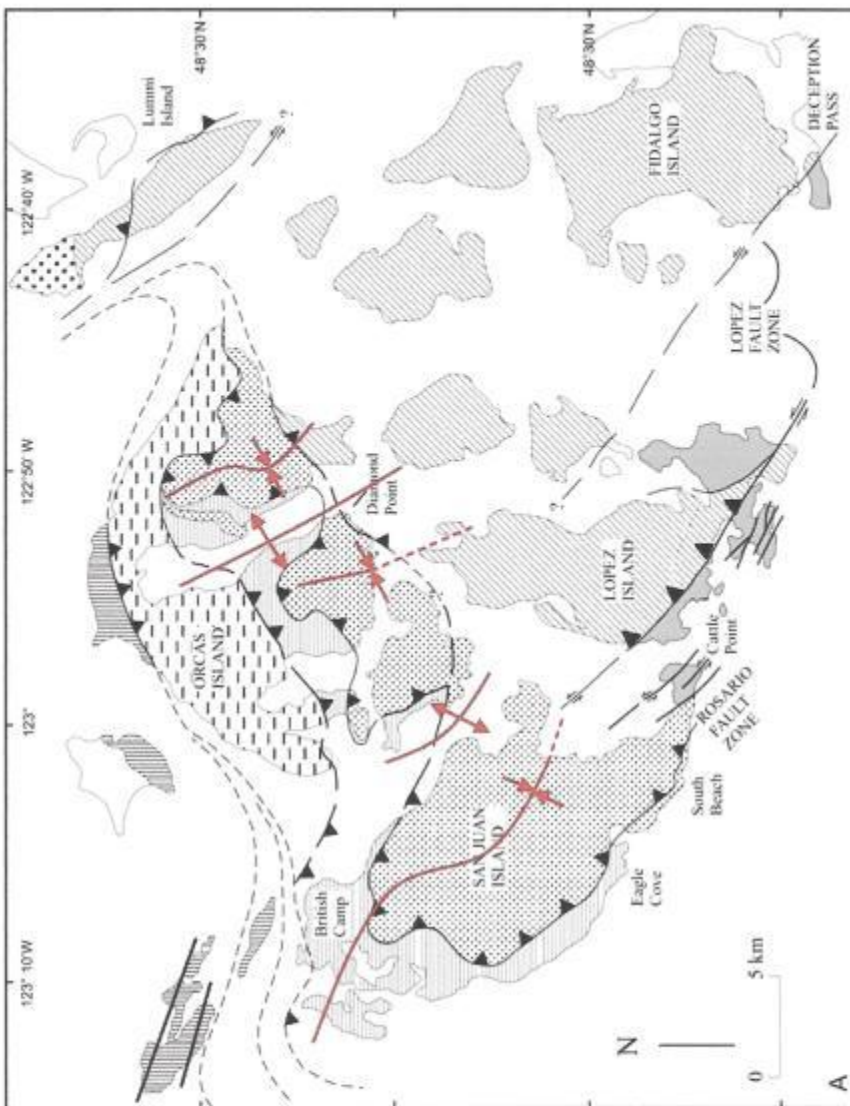
Faults within the San Juan Archipelago have been previously mapped from exposures on the islands. A study by [Tilden \(2004\)](#) revealed fault expressions on the seafloor between islands. Two of the most prominent fault zones mapped on the islands, the NW-SE trending Lopez Fault zone (Lopez Structural Complex of [Brandon, 1980](#)) and the Rosario Fault Zone, juxtapose a mixture of deformed igneous, sedimentary, and metamorphic rocks that were emplaced during the Late Cretaceous terrane accretion of the San Juan

thrust system (Figs. 2 and 3). Based on the detailed microscopic structure analyses on rocks within these two fault zones [Berg \(2002\)](#) concluded that the structural fabrics are related to two Late Cretaceous deformation events; 1) SW-NE shortening that occurred during the initial subduction-related accretion of the nappes, and 2) a combined orogen-parallel strike-slip motion and NW-directed thrusting associated with oblique convergence.

The Lopez Fault Zone is a 3 km wide system of steep to sub-vertical en echelon sinistral strike-slip faults bounded by the Decatur Terrane, an upper Mesozoic (middle Jurassic-early Cretaceous) ophiolite, volcanic arc, and clastic rock sequence to the north, and the Constitution Formation, an upper Mesozoic (Jurassic-early Cretaceous) sequence of volcanoclastic sandstone, black mudstone, ribbon chert, green tuff, and minor pillow lava, to the south (Fig. 3). [Berg \(2002\)](#) speculated that the high-angle Lopez Fault Zone was located above a thrust detachment represented by the Rosario Fault Zone that allowed for orogen-parallel translation

The Rosario Fault zone can be traced from the southern tip of San Juan Island, and just south of American Camp, north, and eastward across Orcas Island (Fig. 3). This 1 km wide, gently dipping fault zone juxtaposes strongly foliated mudstone mélangé containing ribbon chert, schist, and metavolcanic rocks derived from the footwall composed of the Deadman Bay terrane, a rock sequence of early Permian to early Triassic volcanic pillow basalts and breccias interbedded with massive limestone and ribbon chert, and metasandstone from the headwall Constitution Formation.

Another fault that may be significant is the Buck Bay Fault, a low angle thrust that juxtaposes the Lopez Structural complex and Decatur terrane with the Constitution Formation and older terranes (Fig. 2). A small segment of this fault was mapped on Orcas Island by [Bradon \(1980\)](#), but much of its length is inferred to extend offshore to the southwest based on the need for a fault to explain the truncation of the Lopez Structural complex in southern San Juan Channel. This fault is thought to be part of the Mid-Cretaceous San Juan Thrust system ([Brandon, 1980](#)). The faults of the Lopez Structural



Legend

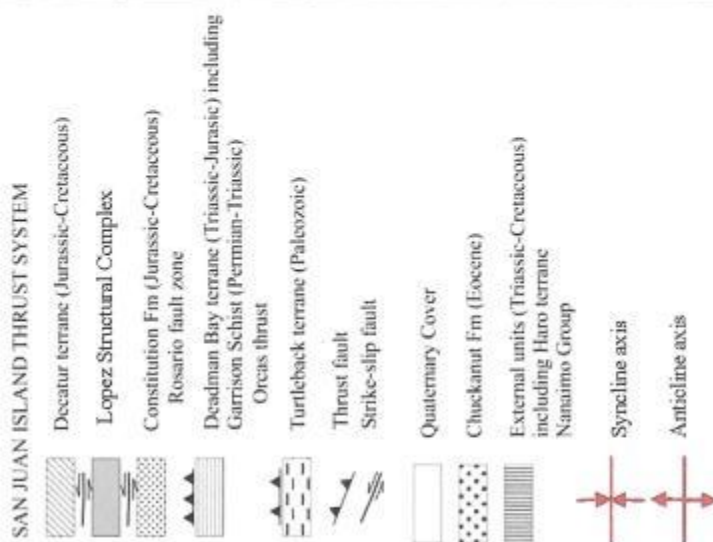


Figure 3. Overview of the San Juan thrust system showing the different terranes, clastic-linking sequence, and structural complex of [Brandon et al. \(1988\)](#) and the terrane bounding fault zones according to [Bergh \(2002\)](#). Note that [Berg \(2002\)](#) shows the Lopez Structural Complex as a strike-slip fault zone as opposed to an imbricate thrust fault zone, as described by [Brandon et al. \(1988\)](#). Also, the Garrison Schist is included in the Deadman Bay terrane according the [Bergh \(2002\)](#). The units external to the San Juan thrust system include the Chuckanut Formation, the Haro terrane, and the Nanaimo Group. Faults modified after [Bergh \(2002\)](#) and [Brandon et al. \(1988\)](#). Folds (red) after [Vance \(1977\)](#). After [Brown et al. \(2007\)](#).

Complex are not exposed along the shoreline of Griffin Bay near American Camp, and therefore [Brandon \(1980\)](#) drew the fault through San Juan Channel and across the glacial deposits of Mt. Finlayson (Fig. 2; [Tilden, 2004](#)).

A major fault zone of considerable concern lies primarily offshore immediately south of the San Juan Islands, and just south of American Camp, in the northern Strait of Juan de Fuca and is known as the Devils Mountain Fault Zone (Fig. 3). This is a W-NW-striking 125 km long oblique-slip transpressional deformation zone that extends westward from the Cascade Range foothills across the eastern Strait of Juan de Fuca to Vancouver Island ([Johnson et al., 2001](#)) to where it may join the Leech River Fault and/or San Juan fault (Fig. 3). The oldest rocks offset by the Devils Mountain Fault Zone are Oligocene in age, which gives an older age limit for fault movement. Onshore and offshore geophysical and geologic data indicate left-lateral and/or vertical displacement of Quaternary sediments at numerous locations along the 125 km long zone, indicating high seismic potential ([Oldow, 2000; Johnson et al., 2001, 2004](#)). Possible additional segments to this fault zone were recognized east of Whidbey Island in Skagit Bay and south of the southeastern part of San Juan Island, near American Camp (Fig. 3). Based on seismic reflection profiles the dip of the Devils Mountain Fault Zone is estimated to be $61^{\circ} \pm 10^{\circ}$ to the north with the steepest dips in the east near the western shore of Whidbey Islands ([Johnson et al., 2001](#)). The plan view geometry of the fault zone and its associated structure is similar to left-lateral, oblique-slip wrench fault zones ([Wilcox et al., 1973](#)) with the more continuous fault segments acting as the “master fault” within a wide zone of deformation ([Johnson et al., 2001](#)).

Glaciation

The northern Puget Lowland, where the San Juan Archipelago is located, is an extensive topographic N-S trough bounded in the west by Vancouver Island and in the east by the Cascade Mountain Range. The Cordilleran Ice Sheet advanced into and retreated from or stagnated in western Washington six times or more during the Pleistocene ([Easterbrook, 1992, 1994](#); Fig. 4). In the central and northern Puget Lowland only deposits of the three youngest glaciations are exposed: the Double Bluff, the Possession, and the Fraser glaciations ([Easterbrook, 1992](#)). Of these, only the Fraser Glaciation has been divided into two distinct stades, or periods of ice advance and retreat and one interstade ([Kovanene and Easterbrook, 2001](#)). From the oldest to the youngest, they are the Vashon Stade, the Everson Interstade, and the Sumas Stade. The Vashon Stade represents the maximum advance of the Cordilleran Ice Sheet. It began around 18 ka and can be identified by the presence of sand and gravel sediment called the Esperance Sand in Puget Lowland. This sediment was deposited by melt water in front of the advancing glacier, and is therefore termed advance outwash sediment. In the San Juan Islands, the largest volume of Esperance Sand can be found on Lopez Island, and both American and English camps are partially covered with these deposits. When Fraser ice reached the Strait of Juan de Fuca, the ice margin split into two lobes: the Juan de Fuca, which spread westward, and the Puget, which continued south. Based on radiocarbon age constraints, [Porter and Swanson \(1998\)](#) estimated that the Cordilleran ice reached its southernmost limit just south of Olympia by ~16,950 years ago, and after only about 100 years began to retreat northward. Maximum ice thickness in the San Juan Islands was around 1500 m, based on the maximum elevations of glacial erratics ([Thorson, 1980](#); [Easterbrook, 1992](#); [Kovanen and Easterbrook, 2001](#)). Glacial erratics are prominent within both American and English camps park boundaries.

During retreat of the Fraser ice, rapid glacio-isostatic rebound commenced ([Thorson, 1989](#)). According to [Dethier et al. \(1995\)](#), the local uplift rate in the San Juan Islands was 10 cm/yr. As the ice retreated, marine water poured into the area from the Strait of Juan de Fuca eventually creating calving margins on both lobes in northern Puget Sound.

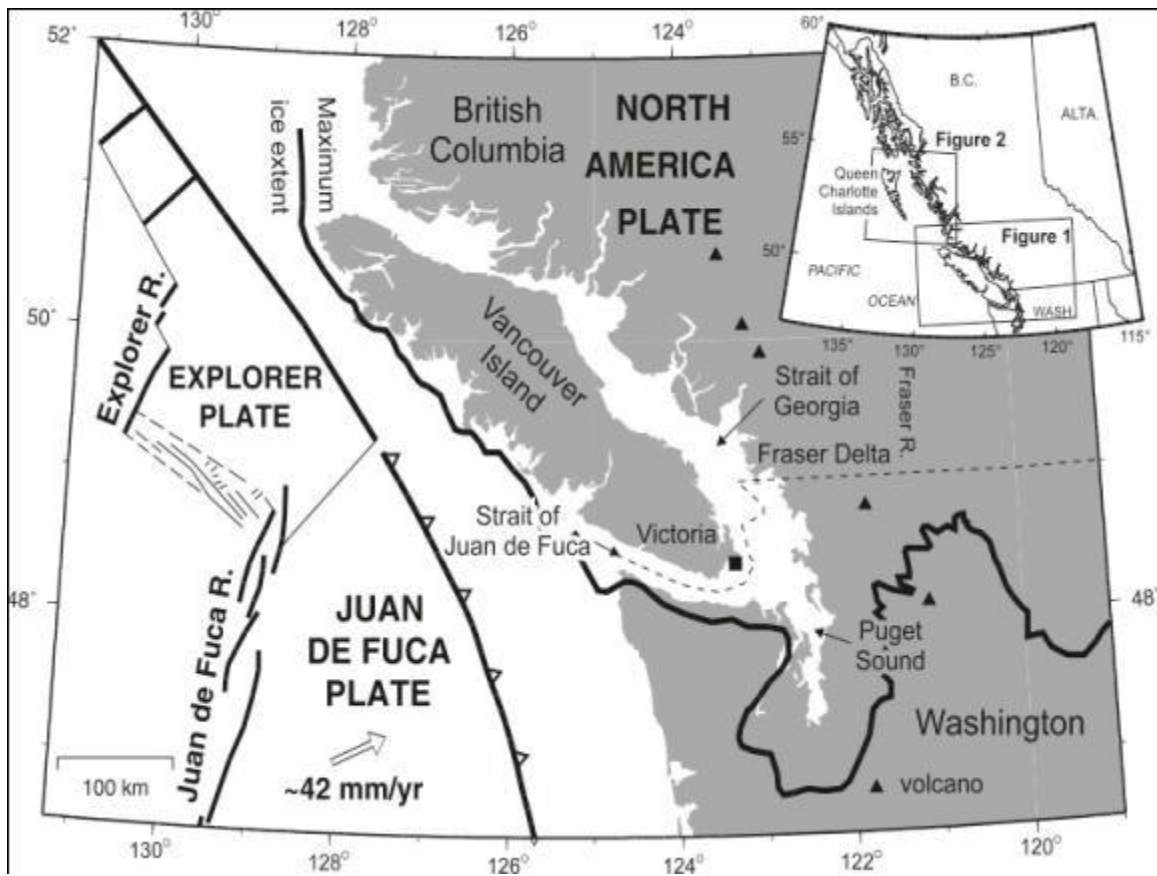


Figure 4. The regional and tectonic setting of Georgia Basin. The heavy line shows the maximum extent of the late Wisconsin ice (after [James et al., 2000](#)). After [Barrie et al. \(2009\)](#).

According to [Dethier et al. \(1995\)](#), the marine incursion began before 13.6 ka and ended with emergence before 11 ka. The maximum marine limit within the San Juan Archipelago was between 90 m in the south and 125 m in the north. This period of partial ice retreat resulted in the deposition of glaciomarine sediments called the Everson Glaciomarine Drift. The numerous emerged glaciomarine fans, deltas and submerged banks in the eastern Strait of Juan de Fuca, just south of American Camp, mark grounding line positions of the ice during calving at the time of retreat ([Dethier et al., 1995](#)). The ice likely stalled near these deposit due to topographic highs in underlying bedrock, such as were imaged offshore of American Camp, at Salmon Bank by [Hirshfield \(1996\)](#) using seismic reflection profiles.

METHODOLOGY

New data collected by the Canadian Hydrographic Service under mapping efforts of the Tombolo/SeaDoc Society-Geological Survey of Canada cooperative was used to update the compiled data and any previously constructed maps. The FHL team (1) interpreted data using the classification scheme of [Greene et al. \(1999, 2005, 2007a; Appendix I\)](#), and (2) collected data to characterize previously un-sampled benthic habitats, using underwater video ([Norris et al., 1997](#)) and a bottom sediment grab sampler. The Greene et al. classification scheme has been incorporated into NOAA's Coastal and Marine Ecological Classification Standard (CMECS), and also used in the mapping of marine benthic habitats of the San Juan Archipelago, the California State Mapping Program and for the construction of the Golden Gate National Recreational Area (GOGA) and Point Reyes National Seashore (PORE) benthic habitat maps. In addition, this team worked in close cooperation with the U.S. Geological Survey's Coastal and Marine Team in Santa Cruz, California to coordinate data sharing and mapping activities as they related to the SAJH mapping effort.

Multibeam Echosounder Data

The MBES coverage was undertaken to obtain contiguous full seafloor coverage of the SAJH. For areas >50 m water depth data were collected with a hull-mounted Kongsberg-Simrad EM1002® system, which operates at a frequency of 95 kHz and uses 127 beams. For areas <50 m water depth, a hull-mounted Kongsberg-Simrad EM3002® system was used; this system operates at a frequency of 300 kHz and uses 121-135 beams. In most areas, the tracks were positioned so as to insonify 100% of the seafloor with 100% overlap, providing 200% coverage.

Positioning was accomplished using a broadcast Differential Global Positioning System (DGPS) and MBES data were corrected for sound speed variations in the stratified water column using frequent sound speed casts. This provided an overall accuracy of 2 m horizontal and 0.2 m vertical.

Acoustic backscatter intensities were used to identify substrate type and sedimentary textures on the seafloor. Generally, higher backscatter intensities represent larger grain sizes so larger grain clasts such as pebbles, cobbles, and small boulders were identified by high backscatter intensities and groundtruthed by a towed video sled. Rock outcrops were identified using both the bathymetry and high backscatter intensity data. Potential habitat types were then identified and mapped.

The newly collected MBES data in Garrison Bay (English Camp), in Griffin Bay and in nearshore western San Juan Island (American Camp) were processed to a gridded horizontal resolution of one to two meters and backscatter intensities processed at one-meter resolution, similar to what has been done for other San Juan Archipelago shallow water mapping work ([Greene et al., 2011](#)). All data were compiled and displayed for interpretation using ESRI ArcGIS® software, ArcMap® v.9.3. This process required the editing of a shapefile within ArcMap to delineate benthic features. A feature is an area with common characteristics that can be mapped as a single potential habitat or geologic unit. The boundary and extent of these features were determined from the bathymetric data. Generally, interpretations were done at a scale of 1:1,000 or larger and mapped at 1:5,200 or 1:2,200. In addition, MBES data already collected and interpreted were compiled and incorporated within the map products.

USGS Data

Sediment sample information, single channel bathymetry and other data collected and interpreted by the USGS were used to extend the maps at English Camp into deep-water Westcott Bay complex ([Grossman et al., 2007](#)). The combination of acoustic data and sediment samples was used to delineate seafloor substrate and habitat types within areas identified as "soft (s)" induration. Initially, "groundtruthed" data, in the form of sediment grab sample descriptions were categorized into four basic grain sizes: mud (m), muddy sand (s/m), sand (s), and sandy gravel (s/g).

LiDAR and Air Photos

LiDAR data were interpreted in the same fashion as MBES data. This process provided the same results as if these data were collected acoustically. After analysis these data were incorporated into a GIS platform as a digital dataset and constructed into seamless acoustic-optical maps.

To fill in the white zones (Fig. 5) air photos collected using a small fixed-wing, single engine aircraft were geo-reference and merged into the nearshore parts of the maps. These were collected during low-tide conditions and provided good substrate and vegetation information, but were not useful for obtaining “z” (depth/elevation) values. These images collected for this project were obtained by flying the coast along several parallel transects.

Aerial Photography of Shorelines

An inexpensive system was developed by Greg Ridder to acquire shoreline aerial images using a small private plane with a remotely controlled camera mounted under the wing (see Fig. 6). The camera (Canon G10) was mounted to point downward vertically during flight. All images were taken within 30 minutes of lowest tides. The airplane (a Cessna 177RG Cardinal) was flown at 2,500 feet (762 m) at 100 knots along the entire shoreline while taking pictures at an interval of approximately every 4 seconds using a remote, radio-controlled trigger (Optika®) to provide overlap between successive images. The wings were kept as level as possible for all photographs. The camera was set at a fixed exposure time of 1/500 sec, a resolution of 14 megapixels, which provided for the highest quality of JPEG compression, image stabilization, and fixed focus (infinity). Complete details of the photographic parameters were recorded in the EXIF information within each image (Fig.7).

The GPS track of the plane’s flight was recorded (Garmin 396™), downloaded (Garmin Basecamp™), and each photo was geo-tagged (Geotagalog™) with the time, coordinates, altitude, direction and speed information from the GPS track. A time

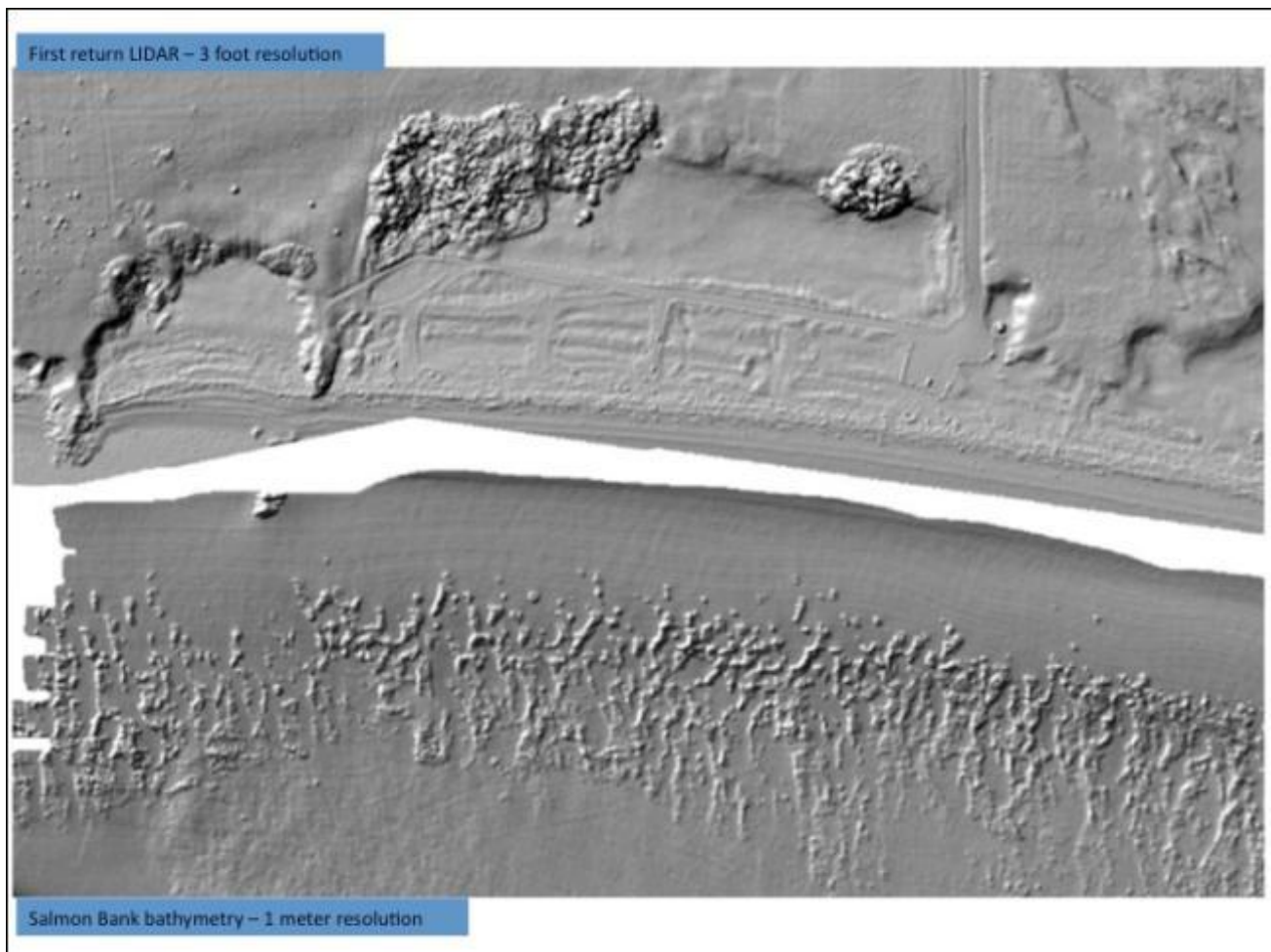


Figure 5. MBES bathymetry offshore and LiDAR images onshore showing “white zone” (data gap) between the land and ocean data.

correction factor was used to synchronize the GPS’s and camera’s clocks thereby allowing the linkage of the GPS information with the photo. Several times in the flight a single image was taken at the beginning of a rapid tight turn or over a known geographically distinct site to help determine the time correction factor. All the positioning data were stored in the GPS section of the photo information. The geo-tagged images were mapped using the iPhoto™ Map option to allow photograph selection based on position. Selected photos were exported in TIFF format from iPhoto for further processing.



Figure 6. Aerial Camera at 2,500 feet (762 m)

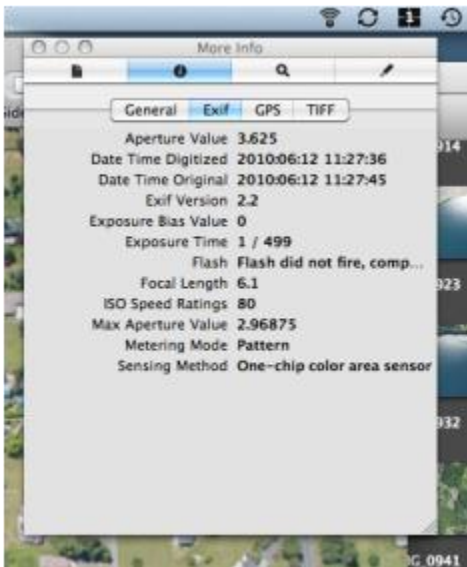


Figure 7. Photo Details

Spatial Analyses of Aerial Photos Using GIS

The images were geo-referenced with the airplane's GPS information imbedded in the picture information (using the Garmin BaseCamp™ and Geotagalog™ programs to do this after the flights). Originally all pictures were put into iPhoto, which will map the position of each photo, then exported as individual JPEG files. The exported files were opened in the Mac™ Preview program with the GPS coordinates and altitude

accessible. A GPS tab is located in the info section for each picture. This geo-reference information was then placed in ArcGIS™ with the information contained in each picture file. This places the picture in the correct location; adding it to a map required rotating, translating, sizing and adding fiduciary points manually. An example of a resultant image is shown in Figure 8.

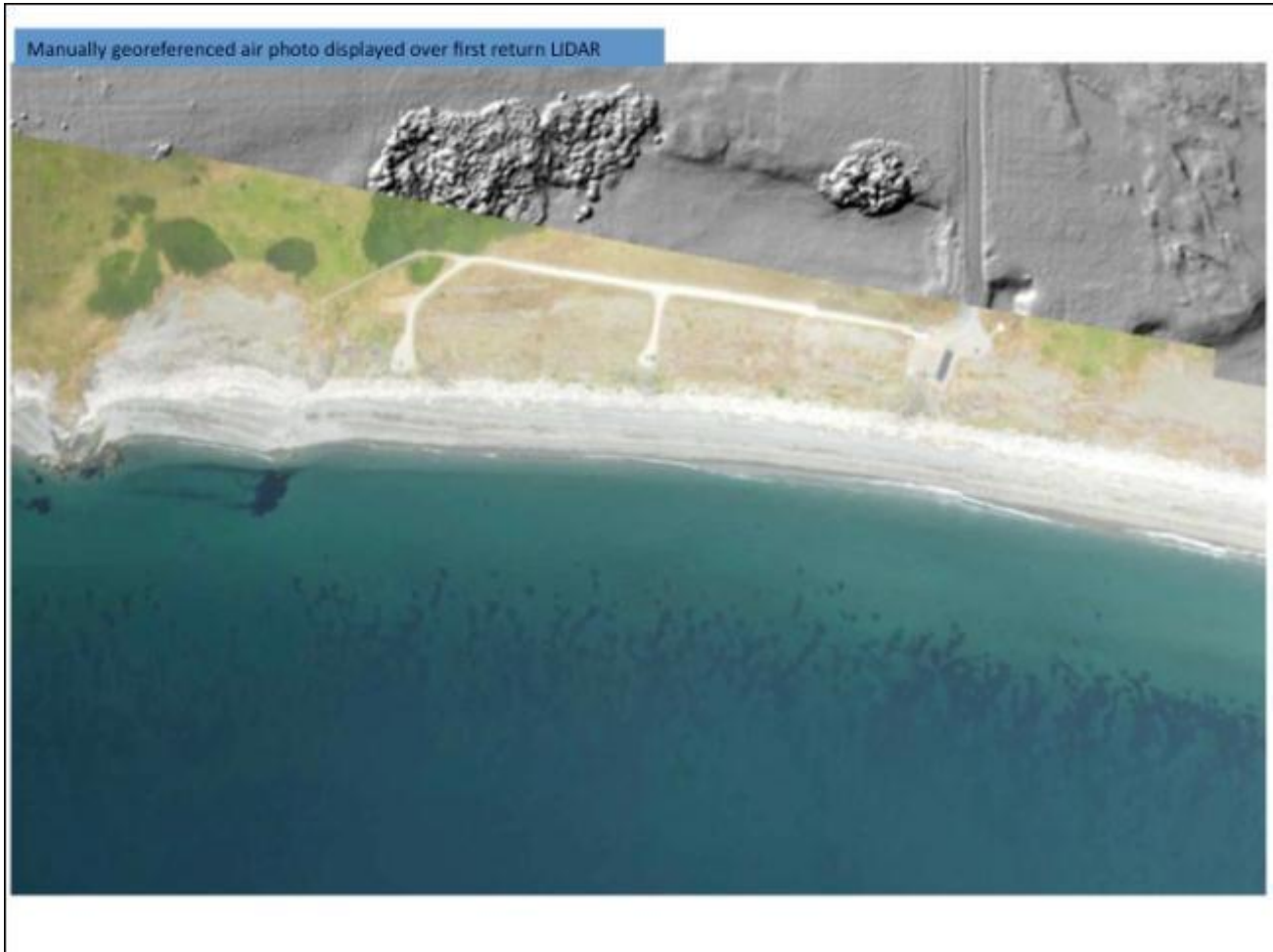


Figure 8. Aerial photo taken along shore parallel transect showing nearshore area during low tide and eelgrass beds underwater.

Video Validation

The eelgrass beds were validated using a Deep Blue Underwater video Camera mounted on a PVC sled operated from a 27 ft. (8.23 m) long PacCat motor boat, the R/V *Tombolo*. The video was projected in real time on two screens in the cabin of the boat and simultaneously recorded on a VHS tape. The GPS coordinates were recorded manually when the bottom sediment or vegetation changed and also at intervals along transect, so

that the path traveled could be plotted. Transects were made perpendicular to shore. Visual observation was used as a secondary method. This involved looking over the side of a boat while moving slowly parallel or perpendicular to the shore.

Underwater Video Transects

In Westcott and Garrison bays (adjacent to English Camp) and Griffin Bay, and along the southwestern coast of San Juan Island (adjacent to American Camp), we mapped the presence of *Zostera marina* (eelgrass), macroalgae, and surface sediment grain sizes using a Splash-Cam® underwater camera and digital recording system by following the procedures of [Norris et al. \(1997\)](#), and a benthic grab (e.g., see [Appendix II](#)). Transect spacing depended upon the homogeneity of the seafloor and the presence of localized data gaps. Positioning was recorded using differential GPS. Along these transects surface sediment samples (all mud in Garrison Bay) were collected using a small Ponar grab sampler to validate the video observations and provided data to interpret substrate types. After sampling, underwater video images were processed and surface sediment grain size analyses were conducted using a Ro-Tap® sieving machine at FHL.

Additional video was collected around the Pier at English Camp to determine eelgrass presence and abundance, as well as to determine substrate type. Dr. Sandy Wyllie-Echeverria describes the results of this survey in a report to the SAJH and the survey is shown in [Appendix III](#).

Environmental Monitoring

The SAJH contracted with FHL to provide data that characterizes: (1) seasonal changes in the water column environment in Garrison Bay (adjacent to English Camp), (2) potential changes to water column properties within Garrison Bay during the summer boating season, and (3) seasonal changes in water quality properties in the larger American Camp lagoons. These data can be included as a layer in the GIS format

(provided to SAJH), which can then be compared with the benthic habitat types (See separate report provided by Dr. Sandy Wyllie-Echeverria).

INTERPRETATIONS

High-resolution multibeam sonar data in the form of bathymetric depth grids (seafloor digital elevation models, referred to as the “bathymetry”) were used for the interpretation of offshore deep-water (in depths greater than 5 m) benthic habitat types. Shaded relief imagery (“hillshade”) allowed for visualization of the terrain and interpretation of submarine landforms. Based on analyses of these hillshades, areas of rock were identified by their often sharply defined edges and high relative relief; these may be contiguous outcrops, isolated parts of rock subcrops (outcrops) protruding through sediment cover (pinnacles), or isolated boulders. Although these features can be confidently characterized as exposed rock, it is not uncommon to find areas within or around the rocky feature that appear to be covered by a thin layer of sediment. These areas were mapped as “mixed” induration, containing both rock and sediment. Broad areas of the seafloor lacking sharp and angular characteristics were considered to be sediment. Sedimentary features may contain erosional or depositional characteristics recognizable in the bathymetry, such as dynamic bedforms (sand waves and ripples). General morphologic features such as scours, mounds, and depressions were also mapped using the hillshade relief imagery. Terrestrial LiDAR and air photos were used to map the intertidal (to ~1 m depth) areas and underwater video transects and sediment grab samples were collected to add data and detail for shallow water areas (1-7 m depth), as explained above.

Particular emphases were on nearshore shallow water areas. We evaluated mapping results to assess the distribution of sediment in the offshore region that may act as a source for beach sediment replenishment and evaluated coastal seafloor processes that may result in coastal erosion. Substrate type, stability and ruggedness were identified on habitat maps. Submerged vegetation (e.g., *Z. marina* and macroalgae) beds were

identified and mapped using the air photos, underwater photos, LiDAR and MBES data and particular emphases was placed on offshore anchorage sites where sensitive bottom habitats may be impacted by recreational boating. All of this mapping effort was undertaken in full cooperation with scientists and staff of the SAJH as a joint scientific venture in marine benthic habitat mapping.

RESULTS

HABITAT MAPPING AND EVALUATION

Fractured bedrock outcrops and areas of stacked boulders are considered optimal bottomfish habitat in the San Juan Archipelago ([Pacunski and Palsson 2001](#)). To distinguish potential marine benthic habitat types, acoustic multibeam echosounder (MBES) techniques were employed to map the seafloor in San Juan County. Habitat maps were constructed using wide-swath digital MBES bathymetry and backscatter data and locally groundtruthed using sediment samples and a video drop camera.

The use of the air photos allowed us to fill in the white zone with information that could be used for marine benthic habitat characterization. By accurately georeferencing and combining marine multibeam bathymetry, terrestrial LiDAR and air photos, we were able to fill in the white zone with information that can be used to produce habitat maps (Fig. 9).

Areas of seafloor roughness were extracted from the bathymetry data using a ratio of surface area to planar area (Fig. 10). The area of roughness represents the eelgrass beds, which allows the abundance of eelgrass to be calculated. We were able to confirm the eelgrass beds from the air photos and underwater video.

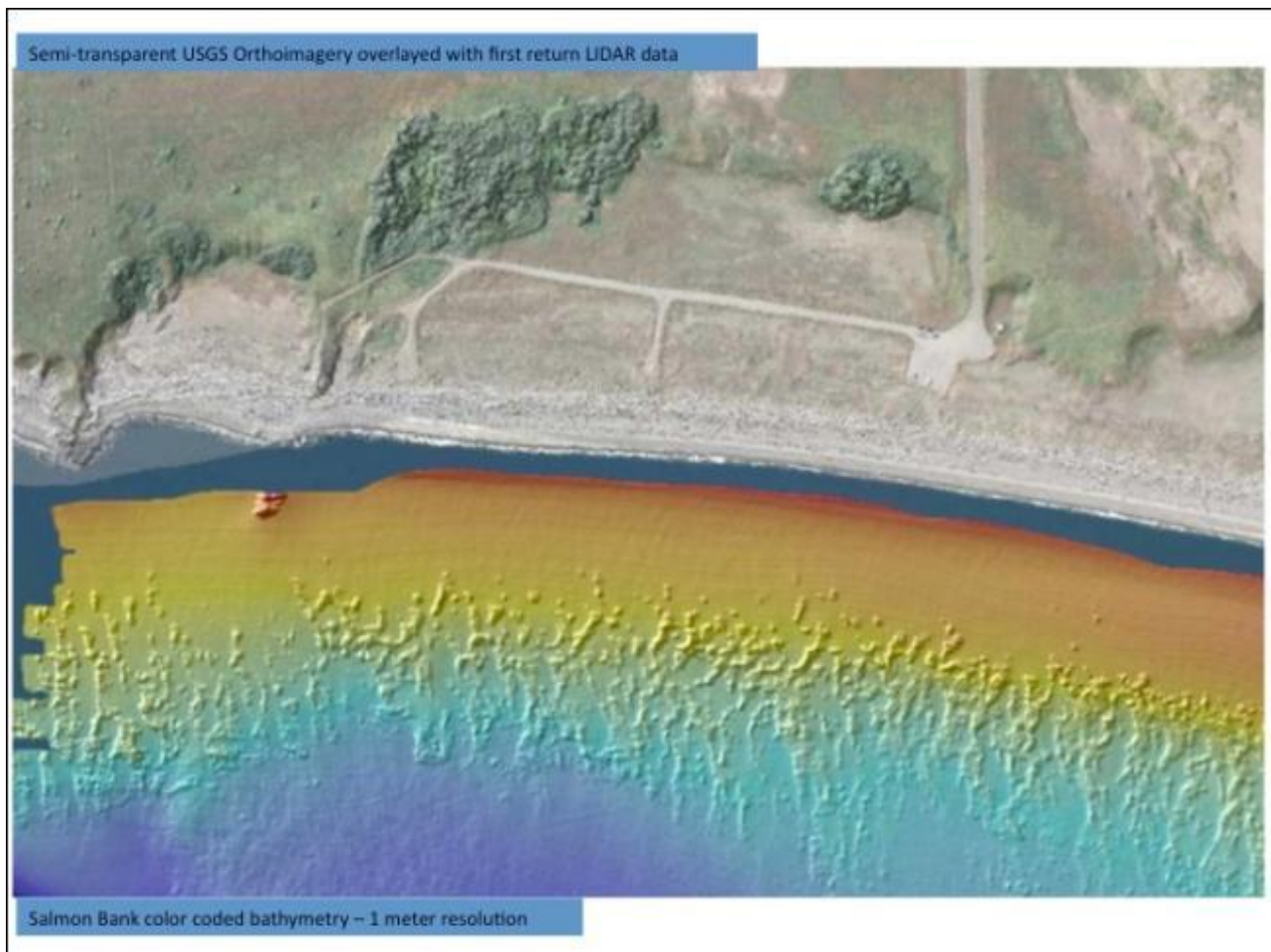


Figure 9. Marine multibeam bathymetry, terrestrial LiDAR and air photos georeferenced and sutured together to produce a seamless seafloor/land image.

Foraging Habitats

Sand wave fields may provide important foraging habitat for demersal fishes. Diet of juvenile lingcod in the San Juan Channel of the San Juan Islands region of Washington State was found to be 100% Pacific sand lance (PSL, *Ammodytes hexapterus*; [Beaudreau, 2005](#)). [Greene et al. \(2007b\)](#) observed the presence of juvenile lingcod on the sand wave fields of the San Juan Channel. This observation suggested that perhaps the sand wave field is a foraging habitat for juvenile lingcod and the source for much of their early feeding, which led to an extensive study of the field. Similar schooling forage fish may be using the dynamic bedforms near or in the SAJH for refuge and could be preyed on by lingcod, rockfish, salmon and birds, similar to the patterns observed in the San Juan

Channel. During a previous investigation (Greene, et al., 2011) PSL were found burrowing in the fine-grain sands of Salmon Bank (see Appendix II for sample locations).

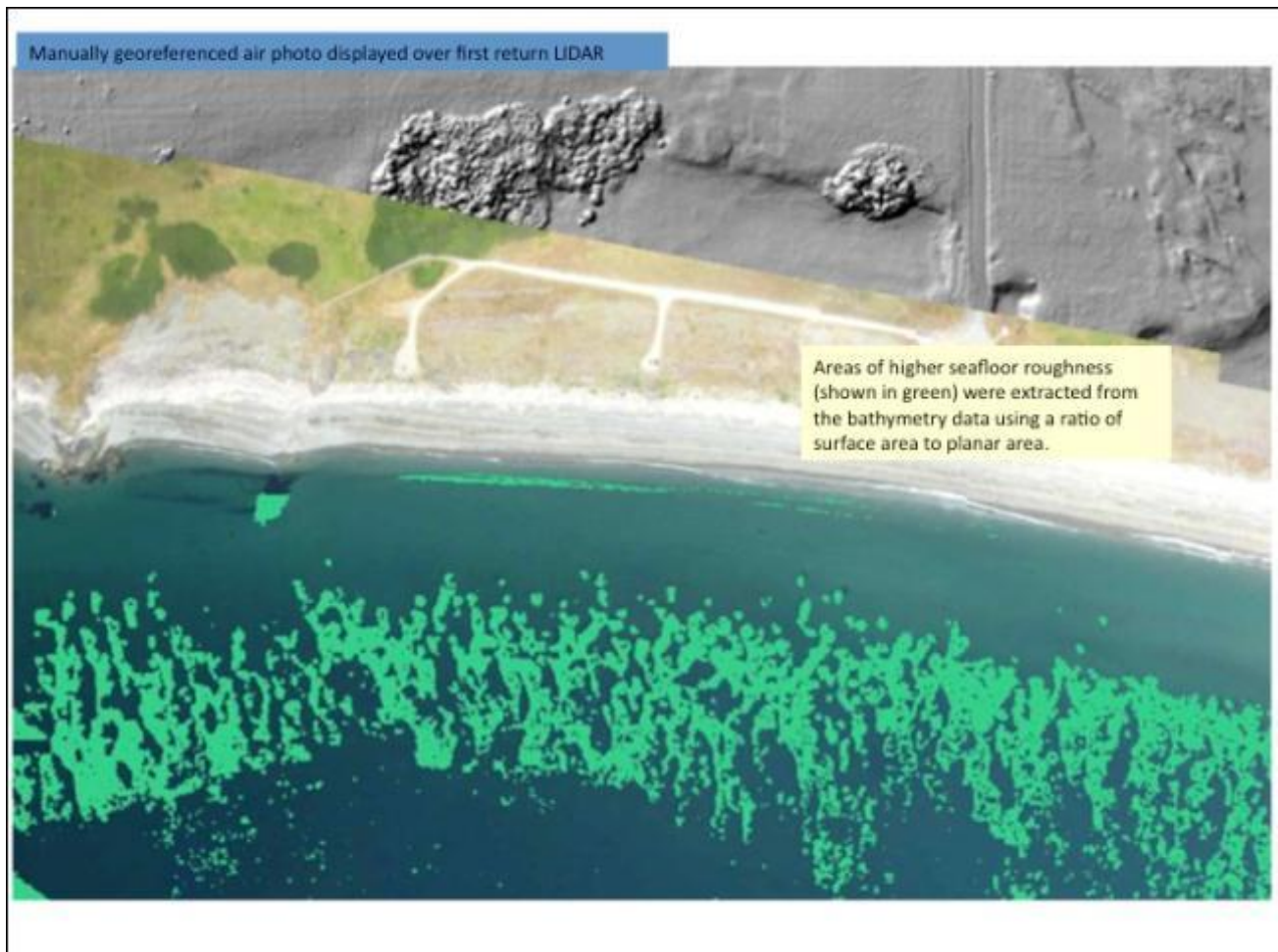


Figure 10. Areas shown in bright green represent eelgrass beds whose abundances can be calculated using the ratio of surface area to planar area in GIS.

In Garrison Bay all sediment samples were of mud and most had heavy concentrations of hydrogen sulfide (H_2S ; not measured but detected by its black color and rotten egg odor). Seafloor images and observations of dense concentrations of boats in Garrison Bay during our surveys, along with the presence of H_2S odor, suggested that the bottom was continuously being disturbed, most likely from anchors. In shallow enclosed water bodies such as Garrison Bay little circulation of water allows for fine-grain (mud) sedimentation and the burial of organic matter. Once buried the organic matter decomposes into H_2S gas and is trapped beneath the mud. Anchors dragged along the seafloor surface breaks this

mud seal and allows for the gases to escape into the aquatic and atmospheric environment.

Products (Maps)

The primary goal and results of this work was the construction of a series of nearshore and shoreline maps for the SAJH that include MBES bathymetric seafloor relief images or digital elevation models (DEM), acoustic backscatter, and interpretive potential marine benthic habitat, including the distribution of submerged vegetation at the time of the surveys. We constructed three 1:5,200 scale maps for American Camp and three 1:2,200 scale maps for English Camp that show the deep-water and nearshore bathymetry, backscatter and potential marine benthic habitats (see map sheets for habitat maps, [Appendix V](#) for data sources and metadata), as listed below:

- Multibeam echosounder artificially illuminated bathymetric map (with LiDAR and air photo mosaics included), constructed in ArcGIS; 1:5,200 scale (American Camp) and 1:2,200 scale (English Camp)
- Multibeam echosounder backscatter map constructed in ArcGIS; 1:5,200 scale (American Camp) and 1:2,200 scale (English Camp)
- Potential marine benthic habitat and submerged vegetation map constructed in ArcGIS using habitat mapping scheme and attribute code of [Greene et al. \(1999, 2005, 2007a\)](#); 1:5,200 scale (American Camp) and 1:2,200 scale (English Camp)
- Perspective view maps for both American and English camps

Citations for Map Sheets are as follows:

- Sheet 1. Maher, N. 2012. Sun-illuminated Bathymetry and LIDAR Map. *In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, English Camp, Map 1 of 3, Final Report to NPS/SAJH, Scale 1:2,200.
- Sheet 2. Maher, N, 2012. Multibeam Backscatter and Aerial Imagery Map. *Camp. In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, Map, English Camp, Map 2 of 3, Final Report to NPS/SAJH, English Camp, Scale 1:2,200.

- Sheet 3. Maher, N, 2012. Habitat Classification Map. *In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, English Camp, Map 3 of 3, Final Report to NPS/SAJH, Scale 1:2,200.
- Sheet 4. Maher, N., 2012. Sun-illuminated Bathymetry and LIDAR Map. *In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, American Camp, Map 1 of 3, Final Report to NPS/SAJH, American Camp, Scale 1:5,200.
- Sheet 5. Maher, N, 2012. Multibeam Backscatter and LIDAR Imagery Map. *In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, American Camp, Map 2 of 3, Final Report to NPS/SAJH, English Camp, Scale 1:5,200.
- Sheet 6. Maher, N, 2012. Habitats Classification Map. *In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, American Camp, Map 3 of 3, Final Report to NPS/SAJH, English Camp, Scale 1:5,200.
- Sheet 7. Maher, N, 2012. Perspective views of potential marine benthic habitat classifications (inset maps). *In* Greene, H.G., and Wyllie-Echeverria, S. (Eds.), Seabed Classification Map Series, Final Report to NPS/SAJH.

HABITAT MAPS

Tectonic and glacial processes shaped the habitats of the SAJH so that rock outcrops interspersed with glacial sediments result in diverse substrate types. Rockfish (*Sebastes* spp.) and other bottomfish, such as greenlings and lingcod, prefer the hard rocky areas while flatfish and crustaceans can be found on the relatively flat unconsolidated sediment floors. The diversity of habitat types is higher near rocky points than in the restricted bays. The bays are primarily dominated by soft unconsolidated sediment (mainly sand and mud, both of glacial and marine origin), with local areas of hard bedrock outcrops found near the heads (points) of bays and surrounding areas (see [Appendix IV](#) for percentage of habitat types). The habitat maps were constructed primarily using MBES bathymetry and backscatter data and validated using underwater video and grab sample observations, as explained in the Methodology section above (see [Appendix V](#) for data sources, metadata).

BATHYMETRY

From 2001 through 2008 the Canadian Coast Guard vessels *Otter Bay*, *Revisor*, *Young* and *Vector*, under the direction of the Canadian Hydrographic Service (CHS) and in cooperation with the Geological Survey of Canada (GSC) and MLML's Center for Habitat Studies/Tombolo/SeaDoc Society, acquired extensive high-resolution bathymetric datasets of the waterways surrounding the Southern Gulf Islands and the San Juan Archipelago. The MBES Simrad EM 1002 (95kHz frequency) and EM 3000-3002 (300 kHz frequency) systems were used for deep (>80 m) and shallow (<80 m) waters respectively. The dataset resolutions were 5 and 2 m respectively.

The bathymetric data were carefully processed by CHS with CARIS Hydrographic Information Processing Software (HIPS®). The outlying navigation and attitude sensor data were rejected, the gaps restored using linear interpolation, and the filtered data were then merged with DGPS and POS/MV (positioning and movement) input. Subsequently, automatic coarse filters were applied to swath data (+/- 60° swath angle). Spurious data points were removed manually in the SwathEdit module of HIPS on a line-by-line basis, and tidal corrections were applied (predicted, or observed, if available). After merging the depths/tides/navigation data, HIPS Subset module cleaning was completed, a beam-weighted-mean base surface (grid) was generated and the gridded data were exported to an ASCII format as XYZ triplets and transferred to the GSC for further processing.

BACKSCATTER

Backscatter intensity is a measure of sound that is scattered back toward the transmitter by acoustic reflection and scattering, both at the sediment-water interface and within the sediment (volume scattering). Many factors influence the intensity value, including the angle of incidence of the beam, the volume scattered, the seabed slope and the surficial sediment type and roughness. With these factors in mind, backscatter strength datasets were used to determine relative sediment differences within one or many datasets, and aided the interpretation of the benthic habitat types. To assure the best interpretation, backscatter images were used in conjunction with other multibeam echosounder bathymetry derivative datasets, such as seafloor shaded relief, slope analysis and

bathymetric contours. The multibeam echosounder bathymetry and backscatter raster datasets, as well as the benthic habitat layer, were processed using ESRI™ ArcGIS tools.

High backscatter intensities (darker areas in mosaic) represent bedrock, hard rocks and coarse-grain sediment, and low intensities (lighter areas) represent fine-grain sediment (sand and mud). Medium to low intensities of backscatter represent dynamic bedforms and other sediment deposits in the Haro and Juan de Fuca straits area. Bedrock in this area is comprised predominantly of metamorphic or volcanic bedrock or basement.

DESIGNATION OF MARINE BENTHIC HABITATS

The habitat maps show potential marine habitats, representing substrate types, geomorphology, seafloor process or other attributes that may be used as a habitat by a specific species or assemblage of organisms. The seafloor imagery interpretation and habitat type delineation were based on knowledge of the geology of the seafloor and seafloor processes in the study area ([Thompson, 1981](#), [Mosher et al., 2000](#); [Barrie et al., 2005](#); [2009](#)). Resolution of the seafloor interpretation varied with the type of MBES systems that were used in the various surveys. However, for most of the area, seafloor features such as bedrock types (e.g., sedimentary, metamorphic, volcanic, and granitic rocks), structures (e.g., faults, folds, scours, and landslides), and bedforms of unconsolidated sediments were easily distinguished. To differentiate pinnacle and/or boulders (Ih(b)/p) habitat from simple bedrock habitat, a specific rule was assigned where any known bedrock polygons with a surface area smaller than 500 m² became identified with “Ih(b)/p”.

Habitat types of the SAJH are predominantly comprised of hard faulted and fractured metamorphic rocks, boulders and dynamic bedforms. Strong currents in Haro Strait sweep the bedrock clean and produce sediment waves and dune fields.

American Camp

Twenty-eight distinct potential benthic habitat types were defined from the interpreted data sets with 19 consisting of unconsolidated sediments, three as mixed soft over hard substrate, five as hard substrate and one as vegetated substrate (*Zostera marina*, eelgrass) in an Inland Sea megahabitat covering a total of 12,346,213 m² (100% of the mapped area). These potential habitats ranged from hard basement and bedrock seafloor outcrops and pinnacles, primarily restricted to the coastal nearshore, shallow bays and current scoured channels, to soft, unconsolidated beach sand and silty marine sediment with boulders, cobbles, and pebbles locally covering bedrock (Fig. 11, [Appendix IV](#)). The dominant potential habitat type in the area mapped is soft unconsolidated sediment, which covers 8,838,279 m² (89.87% of the mapped area). Hard rock exposures mapped in the area cover 1,211,416 m² (9.81% of total mapped area), while hard pinnacles and boulders cover 15,345 m² (0.12% of total mapped area) for a total of hard ground covering 1,226,761 m² (9.94% of the mapped area). The mixed habitat (soft, unconsolidated sediment overlying hard substrate or bedrock) covers 23,826 m² (0.19% of the mapped area). The highly fractured and differentially eroded bedrock, pinnacles and boulders can provide excellent habitat for rockfish (*Sebastes* spp.) and the sandy part of the beaches can be recruitment habitat for the PSL with the sandy substrate of Salmon Bank being a burrowing habitat of PSL. Eelgrass is well imaged and mapped along the southwestern shoreline of American Camp. These marine flowering plants represent ideal foraging and refuge habitat for fish and waterfowl, and stabilize the sediment, both of which increase nearshore biodiversity and productivity ([Wyllie-Echeverria and Ackerman, 2003](#)).

The eastern part of American Camp is subjected to storm surges from the Strait of Juan de Fuca, which tends to erode the unconsolidated glacial deposits that form the southwestern part of San Juan Island. While the erosion is beneficial to supplying sand to the beach of the SAJH and offshore areas, such as Salmon Bank (a good forage fish habitat for PSL), it is detrimental to the road infrastructure of the Park, which is being undermined in some places. Offshore of the northeastern part of American Camp a linear

to circuitous strip of sand, mud, and gravel (labeled “Is(s/m)s_u”) represents a paleo-shoreline formed during the last low stand of sea level (see Sheet 6, Map 3 of 3).

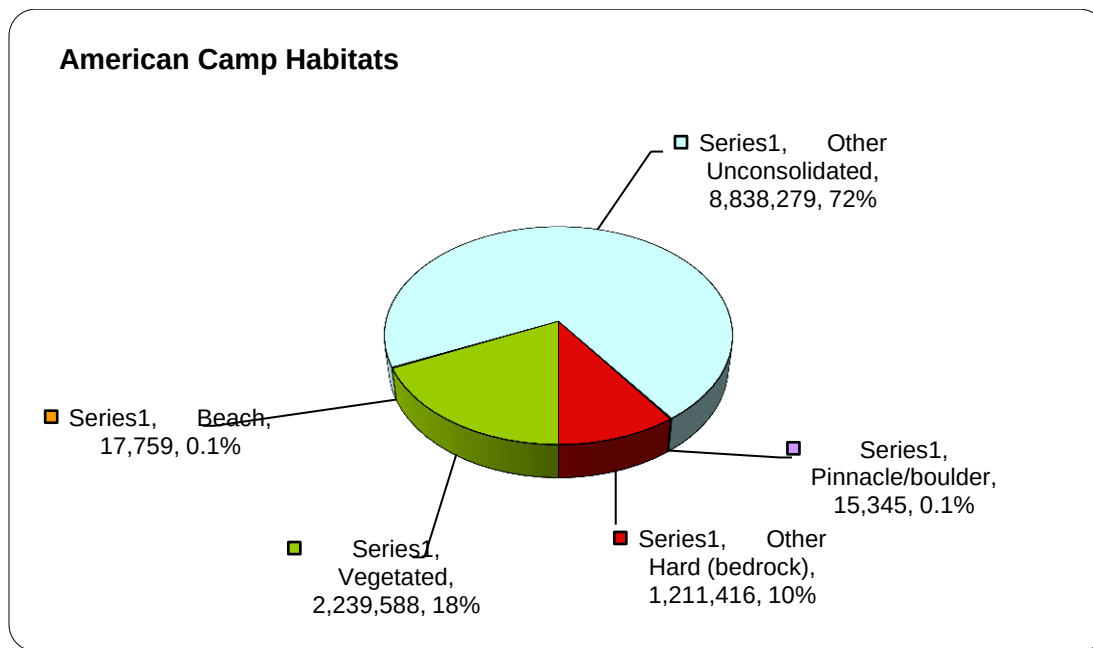


Figure 11. Pie chart showing percentages of different habitat types found in the American Camp offshore area. See [Appendix IV](#).

English Camp

Fifteen distinct potential benthic habitat types were defined from the interpreted data sets, with seven consisting of soft, unconsolidated sediment, three of vegetated unconsolidated substrate of eelgrass (*Zostera marina*) and sea lettuce (*Ulva lactuca*), and one of sand with unidentified vegetation. Two habitat types are of mixed soft over hard substrate, and five are hard substrate, two of which are anthropogenic. All habitat types are located in an Inland Sea megahabitat covering a total area of 1,289,896 m² (100% of the total area mapped). These potential habitats range from hard basement and bedrock seafloor outcrops restricted to the coastal nearshore and pinnacles, to shallow bays and current-scoured channels of mud and sand, to soft, unconsolidated beach sand and intertidal mud

flats, and channels with boulders, cobbles, and pebbles locally covering bedrock (Fig. 12, [Appendix IV](#)). The dominant potential habitat type in the English Camp

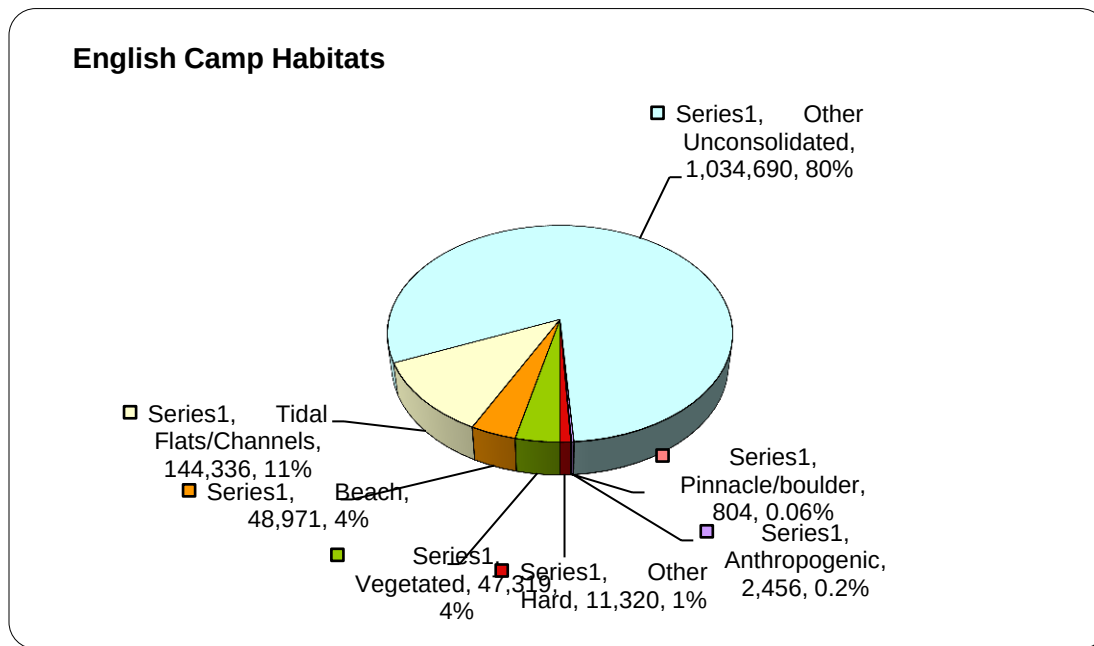


Figure 12. Pie chart showing percentage of various habitat types found in the American Camp offshore area. See [Appendix IV](#).

area is soft, unconsolidated sediment, which covers an area of 1,274,489 m² (90.80% of the area mapped), including beach sediment and sand, gravel, pebbles, and cobbles, which cover an additional 48,971 m² (3.80% of the mapped area), vegetated sediment of primarily eelgrass and sea lettuce, which cover 47,319 m² (3.6% of the mapped area), intertidal mud flats and channels, which cover 144,336 m² (11.19% of all the mapped area), and other unconsolidated sediment, which cover 1,034,690 m² (80.23% of the mapped area).

Hard rock exposures mapped in the English Camp offshore area cover 14,580 m² (1.13% of the mapped area) with hard pinnacles and boulders covering 804 m² (0.06%) of the mapped area), anthropogenic features covering 2,456 m² (0.19% of the mapped area) and other hard substrate covering 11,320 m² (0.88% of the area mapped). Pinnacles and boulders can provide habitat for rockfish and the sandy parts of the beaches can act as recruitment habitat for forage fish such as PSA. Vegetated substrate, comprised of

eelgrass and sea lettuce identified in the aerial photos and video transects, fringe most of English Camps boundary, providing the same benefits as described for American Camp.

CONCLUSIONS

The SAJH has a diverse and resources-rich submerged land area. Both hard, glaciated rock outcrops and soft Quaternary (glacial and marine) sediment filled bays (Garrison and Griffin bays) exists within or adjacent to the Park. These substrates provide habitat for rockfish, crustaceans, and forage fish. Eelgrass beds present in both American and English camps provide refugia for a multitude of biological organisms and acts as recruitment habitat for many fishes. The potential marine benthic habitat maps produced for this study illustrate the types and distribution of habitats, and are useful in planning and managing the environment and resources of SAJH's submerged land.

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APPENDIX I

Key to Habitat Code

System – Marine

Subsystem – Tropical

An attribute code was written to easily distinguish each habitat type and to facilitate ease of use and queries in GIS (e.g., ArcGIS). This code is based on the deep-water habitat characterization scheme developed by [Greene et al. \(1999\)](#) and modified for use in mapping habitats offshore of California ([Greene et al., 2005, 2007a](#)) and here has been expanded to address habitats in a Tropical environment (0-1000 m water depth and 0-23° North and South Latitude). The code is designed so that the first character in the code, a capital letter, indicates one of nine Megahabitat types. These general Megahabitat types with suggested depth ranges in parentheses¹ are as follows:

- A = Aprons, continental rise, deep fans and bajadas (3000-4000 m)
- B = Basin floors, borderland types (floors at 1000-2500 m)
- D = Demarcation, shelf edge or shelf break (100-200 m)
- E = Estuary, (0-100 m)
- F = Flanks, continental slope, basin/island flanks (200-3000 m)
- I = Inland seas, fiords, and narrow inlets or passages (0-200 m)
- M = Submarine mesa or plateau (200-1000 m)
- P = Plains, abyssal (4000-6000+ m)
- R = Ridges and seamounts (crests at 200-2500 m)
- S = Shelf, continental and island shelves (0-200 m)
- T = Trench, represents subduction, or paleo-subduction zones (3000-7000 m)
- Z = Zone of fractures (3000-5000 m) or fracture zones associated with spreading ridges

The second character in the code, a lower case letter, indicates bottom induration (hardness) and consists of the following:

- h = hard bottom (e.g., rock outcrop or sediment pavement)
 - m = mixed hard and soft bottom (e.g., local sediment cover of bedrock)
 - s = soft bottom, sediment cover
- Sediment types (for above indurations) – Use parentheses.
- (b) = boulder
 - (c) = cobble
 - (p) = pebble
 - (g) = gravel
 - (s) = sand
 - (m) = mud, silt, clay

¹ Depths found in parentheses are estimations and can be changed to fit depth ranges known to occur for the mapping project at hand.

(h) = halimeda sediment, carbonate
(r) = rubble, coral
(f) = fragments, shell hash
(y) = barnacle plates

When inferred, use question mark; i.e., (m?). This part of the code is not always used so is not considered as a character in the code.

The third character in the code, another lower case letter, not always used, indicates the Meso- or Macrohabitat type (based on scale). These types consist of the following:

a = atoll
b = beach, relic (submerged) or shoreline
c = canyon
 c(b) = bar within thalweg
 c(c) = curve or meander within the thalweg
 c(f) = fall or chute within the thalweg
 c(h) = canyon head
 c(m) = canyon mouth
 c(t) = thalweg
 c(w) = canyon wall
d = deformed, tilted and folded bedrock, overhangs
e = exposure, bedrock
f = flats, floors
g = gully, channel
 g(b) = bar or lobe within thalweg
 g(c) = curve or meander
 g(f) = fall or chute within the thalweg
 g(h) = gully head
 g(m) = gully mouth
 g(t) = thalweg
 g(w) = gully wall
h = hole, depression
i = ice-formed feature or deposit, moraine, drop-stone depression
j = platform
k = karst, solution pit, sink
l = landslide, mass movement, rubble
m = mound; includes linear ridges
n = enclosed waters, lagoon
o = overbank deposit (levee)
p = pinnacle, cone (Note: Pinnacles are often difficult to distinguish from boulders. Therefore, these features may be used in conjunction [as (b)/p] to designate the meso/macrohabitat)
q = bay, embayment, bights, sounds

r = rill (subterranean winnowing of sediments forming linear depressions on surface)
 s = scarp, cliff, fault or slump scar
 t = terrace
 u = underwater tidal lands, tidepools
 v = vegetative sediment or rock (grass or algae covered)
 v(a) = algae
 v(e) = eelgrass
 v(r) = rhodoliths
 v(u) = ulva
 w = dynamic bedforms
 w(d) = sediment dunes (10s of m in amplitude, 100s m in period)
 w(s) = sediment sheet
 w(w) = sediment waves (10 cm to <m amplitude, 10s m in period) and dunes
 x = seamount
 x(b) = seamount base
 x(c) = seamount crest, top
 x/f = flat-topped seamount, guyot
 y = delta, fan
 z = zooxanthellae hosting structure, carbonate reef
 z(br) = barrier reef
 z(fr) = fringing reef
 z(h/b) = head, bommie
 z(pr) = patch reef
 z(rr) = rear or back reef
 z(rf) = reef flat
 z(rc) = reef crest
 z(fr) = fore reef

The fourth character in the code, preceded by an underline (i.e., a), is a modifier that describes the texture, bedform, biology or rock type and consists of the following:

a = anthropogenic (artificial reef/breakwall/shipwreck/disturbances)
 (a-c) = cable
 (a-dd) = dredge disturbances
 (a-dg) = dredge grooves or channels
 (a-dp) = dredge potholes
 (a-dm) = dredge mounds (disposal)
 (a-f) = ferry or other vessel prop wash scour or scar
 (a-td) = trawl disturbances
 (a-g) = groins, jetties, rip-rap
 (a-m) = marina, harbor
 (a-p) = pipelines
 (a-s) = supports; dock pilings, dolphins, platform legs/pipes
 (a-w) = wreck, ship, barge or plane
b = bimodal (conglomeratic, mixed [includes gravel, cobbles and pebbles])

_c = consolidated sediment (includes claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
 _d = differentially eroded
 _e = effusive pit, pockmark
 _f = fracture, joint; faulted
 _g = granite, intrusive
 _h = hummocky, irregular relief
 _i = interface, lithologic contact
 _k = kelp
 _l = limestone or carbonate rock or structure
 _l(a) = alive reef
 _l(d) = dead reef
 _l(l) = linear reef
 _l(s-g) = spur and groove
 _l(p) = patch reef
 _l(pr-i) = individual patch reef
 _l(pr-a) = aggregated patch reef® _l(r) = reef rubble
 _m = massive sedimentary bedrock
 _n = numerous
 _o = outwash
 _p = pavement
 _r = ripples (>10 cm in amplitude)
 _s = scour (current or ice, direction noted)
 _t = tar flow or asphalt
 _u = unconsolidated sediment
 _v = volcanic rock, tuff
 _w = wall

Seafloor - Slope - Use category numbers, which is the fifth character in the code. Typically calculated for survey area from x-y-z multibeam data.

- | | |
|---|--------------------------|
| 1 | Flat (0-5°) ² |
| 2 | Sloping (5-30°) |
| 3 | Steeply Sloping (30-45°) |
| 4 | Vertical (45-90°) |
| 5 | Overhang (>90°) |
| 6 | Unknown |

Seafloor –rugosity - Use category letters (in caps), the sixth character in the code. Typically calculated for survey area from gridded x-y-z multibeam data using neighborhood statistics and reported as the ratio of surface area to planar (flat) area for a particular grid cell.

² Numbers in parentheses are suggestions only and can be tailored to meet objectives of the habitat mapping exercise at hand.

- A Very Low Rugosity (1.00 to 1.25)
- B Low Rugosity (1.25 to 1.50)
- C Moderate Rugosity (1.50 to 1.75)
- D High Rugosity (1.75 to 2.00)
- E Very High Rugosity (> 2.00)

An example of how this code for remotely sensed data can be used is given below:

Ssc_u4 = Canyon head indenting shelf with smooth, soft, gentle-sloping sedimentary walls that locally crop out as steep (near vertical) scarps (10-100 m).

Ssf_u = Flat to gently sloping shelf with soft, unconsolidated sediment (10-150 m).

Fhe_m/cC = Continental slope with hard sedimentary (sandstone) bedrock that locally crops out and has smooth to moderately irregular relief (<1-3 m high); m means exposures often covered with sediment (200-2500 m).

Shz/t_l/h1D = Reef terrace at shelf depth, carbonate, flat with hummocky (high rugosity) surface

Geologic Unit – When possible, the associated geologic unit is identified for each habitat type and follows the habitat designation in parentheses. Examples given below:

Shp_1D(Q/R) - Continental shelf megahabitat; flat, highly complex hard seafloor with pinnacles differentially eroded. Geologic unit = Quaternary/Recent.

Fhd_d-C (Tmm) - Continental slope megahabitat; sloping hard seafloor of deformed (tilted, faulted, folded), differentially eroded bedrock exposure forming overhangs and caves. Geologic unit = Tertiary Miocene Monterey Formation.

Determined from video, still photos, or direct observation. Macro/Microhabitat – preceded by an asterisk. Use parentheses for geologic attributes, brackets for biologic attributes. Based on observed large-scale seafloor features.

Geologic attributes (note percent grain sizes when possible)

- (a) = anthropogenic (e.g., cables, pipelines, disturbances)
 - (a-t) = trawl trails or grooves
 - (a-d) = dredge tracks, pits or mounds
- (b) = boulder (sm=small size, m=medium size, lg=large size)
 - (b-d) = dropstone (kelp @ice)
- (c) = cobble
- (d) = deformed, faulted, or folded

- (e) = exposure, bedrock (sedimentary, igneous, or metamorphic)
 - (e-s) = smooth bedrock surface
 - (e-r) = rough bedrock surface
- (f) = fans or aprons
- (g) = gravel
- (h) = halimeda sediment, carbonate slabs or mound
- (i) = interface
- (j) = joints, cracks, crevices, and overhang (differentially eroded)
- (k) = knob or ridge
- (l) = limestone, carbonate deposit
- (m) = mud, silt, or clay
- (n) = notch, groove
- (p) = pebble
- (q) = coquina (@ll hash)
- (r) = rubble
- (s) = sand
- (t) = flat terrace-like seafloor including sedimentary pavements
- (u) = Undulating surface, hummocky
 - (u-r) = ripples
 - (u-s) = scours
 - (u-w) = sediment wave
- (w) = wall, scarp, or cliff
- (y) = barnacles or plates

Biologic attributes

- [a] = algae
 - [a-b] = red algae
 - [a-c] = coralline algae
 - [a-g] = green algae
 - [a-m] = macroalgae
 - [a-r] = rhodoliths
 - [a-t] = turf algae
- [b] = bryozoans
- [c] = corals
 - [ca-s/h] = alive hard coral (stony, hydrocorals)
 - [ca-g/b] = alive soft coral (gorgonians, black)
 - [c-d] = dead coral
- [d] = detritus, drift algae
- [e] = eelgrass and other seagrasses
- [g] = gorgonians
- [h] = holothorians
- [k] = kelp
- [n] = anemones
- [o] = other sessile organisms
 - [o-c] = crinoids, segmented worms, and cnidarians
- [s] = sponges

- [t] = tracks, trails, or trace fossils (bioturbation)
 - [t-b] = burrows
 - [t-m] = mounds
- [u] = unusual organisms, or chemosynthetic communities
- [w] = worm tubes
 - [w-s] = spoon worms
- [v] = vegetation
 - [v-e] = emergent vegetation
- [x] = uncolonized

Seafloor Slope - Use category numbers. Estimated from video, still photos, or direct observation.

- 1 Flat (0-5°)
- 2 Sloping (5-30°)
- 3 Steeply Sloping (30-45°)
- Vertical (45 - 90°)
- 5 Overhang (90°+)

Seafloor Rugosity - Use category numbers. Estimated from video, still photos, or measured in situ. Numbers represent seafloor rugosity values calculated as the ratio of surface area to linear area along a measured transect or patch.

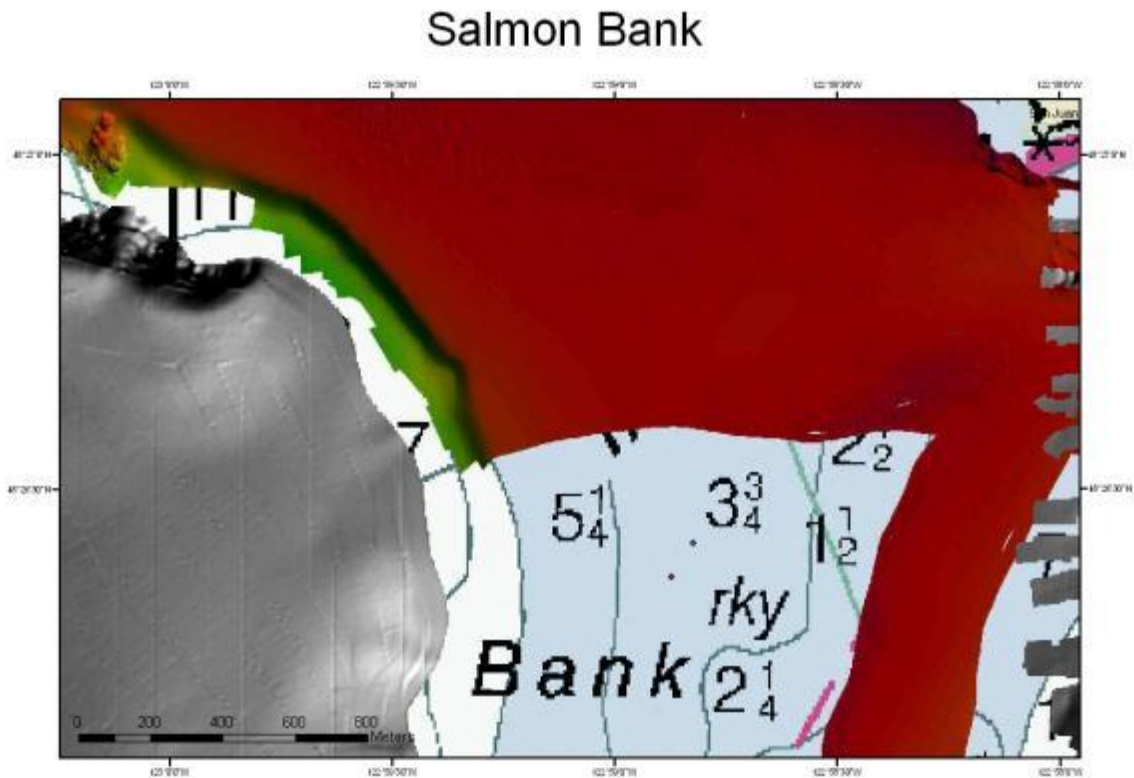
- A Very Low Rugosity (1.00 to 1.25)
- B Low Rugosity (1.25 to 1.50)
- C Moderate Rugosity (1.50 to 1.75)
- D High Rugosity (1.75 to 2.00)
- E Very High Rugosity (> 2.00)

Example—: *(m)[w]1C - Flat or nearly flat mud (100% cover) bottom with worm tubes; moderate rugosity.
 *(s/c)1A - Sand bottom (>50% cover) with cobbles. Flat or nearly flat with very low rugosity.
 *(h)[c]1E - Coral reef on flat bottom with halimeda sediment. Very high rugosity.
 *(l/r)[ca-s/h] – limestone (carbonate) rubble with alive stony coral (<50% cover) and hydrocoral (>50% cover).

Shp_d1D–Q/R)*(m)[w]1C - *Large-scale habitat type*: Continental shelf megahabitat; flat, highly complex hard seafloor with pinnacles, differentially eroded. Geologic unit = Quaternary/Recent. *Small-scale habitat type*: Flat or nearly flat mud (100% cover) bottom with worm tubes: moderate rugosity

APPENDIX II

Sample Locations on Salmon Bank (Offshore American Camp)

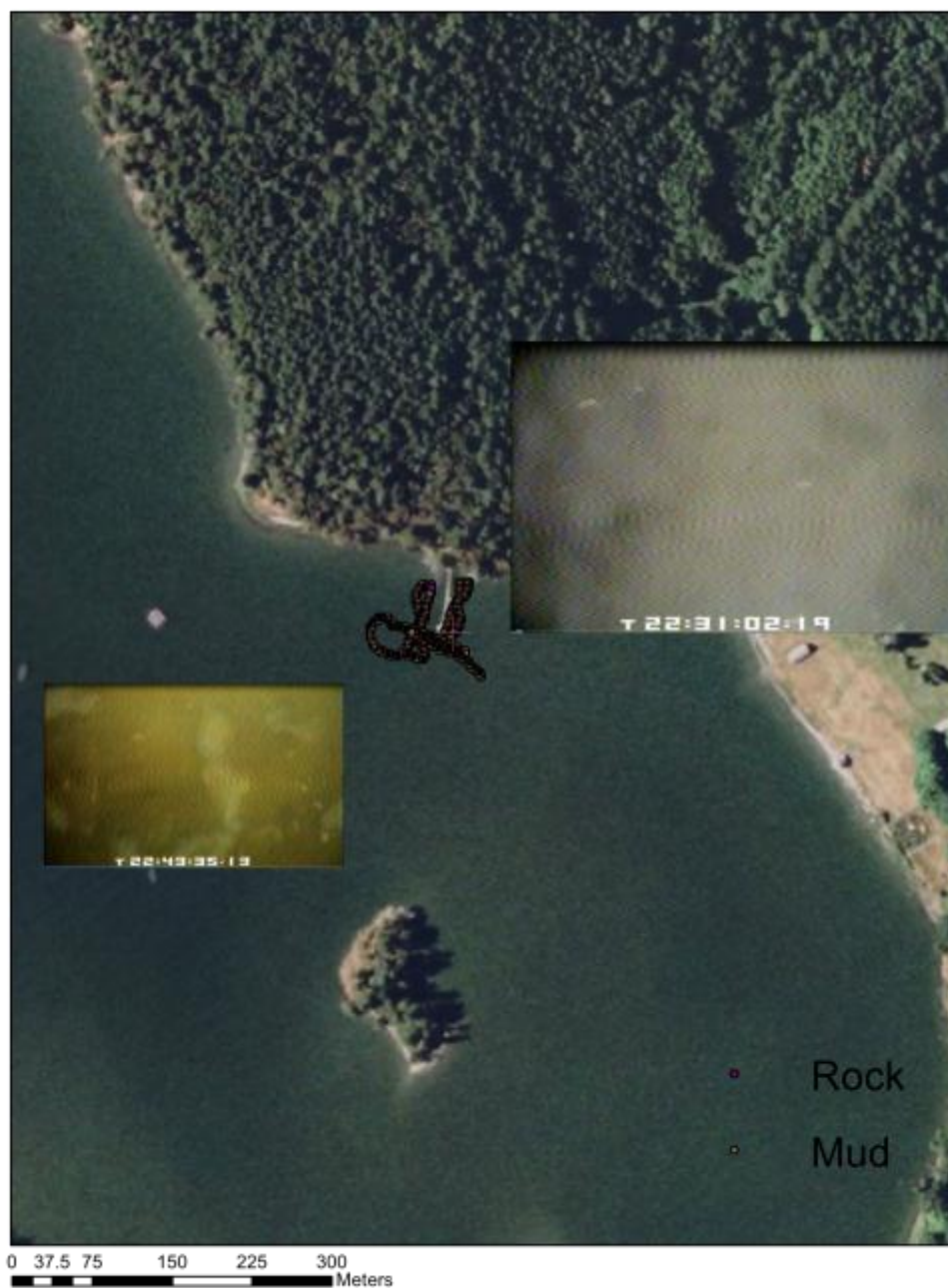


Colored dots in blue area of bank are the grab sample locations.

Sample ID	Latitude	Longitude	Depth	Grain Size	Comments
C-10-3	48°26.420'	122°58.825'	9.6 m	Fine-grain sand	1 PSA
C-10-4	48°26.369	122°58.874	10.2 m	Fine-grain sand	1 PSA

APPENDIX III

Location of video transects around pier at English Camp with selected frame grabs of seafloor on either side of pier.



APPENDIX IV

Tables of Percentages of Potential Habitat Coverage

American Camp

Habitat Type	Area (m2)	Percent
Soft - Total	11,095,626	89.87%
Vegetated	2,239,588	18.14%
Beach	17,759	0.14%
Other Unconsolidated	8,838,279	71.59%
Hard - Total	1,226,761	9.94%
Pinnacle/boulder	15,345	0.12%
Other Hard (bedrock)	1,211,416	9.81%
Mixed - Total	23,826	0.19%
Total Mapped Area	12,346,213	100.00%

English Camp

Habitat Type	Area (m2)	Percent
Soft - Total	1,274,489	98.80%
Vegetated	47,319	3.67%
Beach	48,971	3.80%
Intertidal Flats & Channels	144,336	11.19%
Other Unconsolidated	1,034,690	80.23%
Hard - Total	14,580	1.13%
Anthropogenic	2,456	0.19%
Pinnacle/boulder	804	0.06%
Other Hard	11,320	0.88%
Total Mapped Area	1,289,896	100.00%

APPENDIX V

Data Sources – Metadata

Air Photos:

Source: Greg Ridder

Resolution: 0.2-0.3 meters

Collection Date: July 24, 2010; February 21, 2011; September 27, 2011

Notes: Photos collected during calm, clear, and low-tide conditions to optimize imaging nearshore areas.

Photo mosaics were created by manually georeferencing using control points selected from USGS orthoimagery. Where possible, sets of ~3-10 photos were first stitched together using Microsoft Image Composite Editor software before georeferencing with the ArcGIS georeferencing tool. As many ground control points as possible were used for each photo, usually at least 10 points. A spline transformation method was used for “rubber sheeting” photos. Photo mosaics were not corrected for topographic variations (orthorectification) and uncertainty increases with distance from shore, as there are no control points in the water areas.

Photos were layered so as to position the sun glint portions beneath adjacent overlapping images. Most of the individual photos only contain a small portion of un-glintoned area but with large overlaps and by properly “shingling” the photos it was possible to create mosaics with minimal sun glint.

Separate photo mosaics were assembled for each of the three flight dates. There were three flights over the English Camp area and two over the American Camp area. Dates and number of photos mosaicked are summarized as follows:

English Camp: July 24, 2010 (61 photos); February 21, 2011 (6 photos);
September 27, 2011 (27 photos)

American Camp: July 24, 2010 (67 photos); September 27, 2011 (79 photos)

None of the mosaics covered all of the desired areas, so in some cases more than one mosaic was used for habitat interpretation in a given area. In some cases the higher quality images have minimal land area resulting in decreased positional certainty. A good example of this is in the northeast portion of the English Camp map, where the February 2011 photos show an area of oyster strings very well, but the positioning is less certain than the September 2011 photos which do not image the oyster strings nearly as well.

Orthoimagery – 2008

Source: U.S. Geological Survey and MJ Harden Associates, Inc.

Resolution: 0.5 foot

Collection Date: June 12-16, 2008

Spatial Reference: NAD_1983_StatePlane_Washington_North_FIPS_4601_Feet

Linear Unit: Foot_US (0.304801)

Spheroid: GRS_1980

Notes: High quality, high-resolution imagery, but water areas are dodged to eliminate sun glint so while this imagery is very useful for shoreline delineation and imaging land areas, it could not be used for shallow water habitat interpretation.

"Digital Orthophotographs are orthorectified aerial photographs. In this data set San Juan County, WA was flown at an altitude of 4800' AMT and orthorectified with a resolution of 0.5 feet." An orthoimage is remotely sensed image data in which displacement of features in the image caused by terrain relief and sensor orientation have been mathematically removed. Orthoimagery combines the image characteristics of a photograph with the geometric qualities of a map.

Orthoimagery - 2006

Source: U.S. Geological Survey

Resolution: 0.5 meter

Collection Date: 2006

Spatial Reference: NAD83_UTM_zone_10N

Linear Unit: Meter (1.000000)

Spheroid: GRS_1980

Notes: No metadata was included with imagery download. Lower resolution than the 2006 data but water area is not dodged out.

LIDAR

Source: Puget Sound LiDAR Consortium

Resolution: 3 feet

Collection Date: February 13-17 and April 30, 2009

Spatial Reference: NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601_Feet

Linear Unit: Foot_US (0.304801)

Spheroid: GRS_1980

Vertical Datum: NavD88 Geoid03

Notes: Collected by Watershed Sciences for the Puget Sound Regional Council using a Leica ALS50 Phase II laser system.

American Camp Bathymetry/Backscatter

Survey Area Name: Salmon Bank 2010

Source: Tombolo/SeaDoc Society

Resolution: 1 meter (bathymetry)/2 meters (backscatter)

Vertical Datum: Chart Datum – Mean Lower Low Water (MLLW)

Collection Date: September 18-22, 2010

Notes: Collected by Fisheries and Oceans Canada Canadian Hydrographic Service. Acquisition Vessel - CCGS Otter Bay fitted with a Kongsberg-Simrad EM3002 MBES.

Survey Area Name: Salmon Bank 2005

Source: Tombolo/SeaDoc Society

Resolution: 2 meters (bathymetry)/2 meters (backscatter)
Vertical Datum: Chart Datum – Mean Lower Low Water (MLLW)
Collection Date: 2005
Notes: Collected by Fisheries and Oceans Canada Canadian Hydrographic Service. Acquisition Vessel - CCGS Otter Bay fitted with a Kongsberg-Simrad EM3002 MBES.

Survey Area Name: Griffin Bay
Source: Tombolo/SeaDoc Society
Resolution: 1 meter (bathymetry)/2 meters (backscatter)
Vertical Datum: Chart Datum – Mean Lower Low Water (MLLW)
Collection Date: September 20, 2010
Notes: Collected by Fisheries and Oceans Canada Canadian Hydrographic Service. Acquisition Vessel - CCGS Otter Bay fitted with a Kongsberg-Simrad EM3002 MBES.

Survey Area Name: San Juan Channel
Source: Tombolo/SeaDoc Society
Resolution: 2 meter (bathymetry)/2 meters (backscatter)
Vertical Datum: Chart Datum – Mean Lower Low Water (MLLW)
Collection Date: 2007, 2008
Notes:

Survey Area Name: Haro Strait
Source: Tombolo/SeaDoc Society
Resolution: 5 meters (bathymetry)/2 meters (backscatter)
Vertical Datum: Chart Datum – Mean Lower Low Water (MLLW)
Collection Date: 2008
Notes:

English Camp Bathymetry/Backscatter

Survey Area Name: Garrison Bay
Source: Tombolo/SeaDoc Society
Resolution: 1 meter (bathymetry)/2 meters (backscatter)
Vertical Datum: Chart Datum – Mean Lower Low Water (MLLW)
Collection September 16-24, 2010
Notes: Collected by Fisheries and Oceans Canada Canadian Hydrographic Service. Acquisition Vessel - CCGS Otter Bay fitted with a Kongsberg-Simrad EM3002 MBES

Explanation of “High Water Line” shown on maps

The “High Water Line” shown on the maps is based on shoreline features visible on the USGS high-resolution orthoimagery collected in 2008. Locations were chosen that clearly show where highest high water typically reaches, based mostly on morphology, vegetation lines, and driftwood piles. Elevations from representative locations were extracted from the LIDAR data and then averaged. A contour line, representing the

average high-water elevations was then derived from the LIDAR elevation data. This line is not based on a tidal measurement, but rather is based on a natural line that is apparent in the orthoimagery.

The high water line, being derived from the LIDAR data is given as meters above sea level, using the North American Vertical Datum of 1988 (NAVD88).

The average high water line was found to be higher in the American Camp area than in the English Camp (2.4 m vs. 1.4 m). This may be due to American Camp's greater exposure to storm surges.

The high water line is an average so may not be accurate at all locations.

Below are examples from each of the camps, of the how the line matches up with the orthoimagery:



English Camp (above)



American Camp