Geomorphic Units in the Strait of Georgia and Southern Shelf Bioregions

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GEOMORPHIC UNITS IN THE STRAIT OF GEORGIA AND SOUTHERN SHELF BIOREGIONS

by

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Abstract

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The Pacific Marine Ecological Classification System (PMECS) was developed in 2016 to categorize species, habitats, and ecosystems into ecological classes at varying spatial scales in Canada's Pacific Region to support Marine Spatial Planning (MSP) activities and Marine Protected Area (MPA) network development. Geomorphic units are one level of the hierarchical PMECS that is suitable for informing ecosystem-based management decisions. At the scale of 100s of km, geomorphic units are areas with similar benthic features that are often associated with distinct biota. Spatial data developed to populate the PMECS geomorphic units focused on the Northern Shelf Bioregion and the continental slope portion of the Southern Shelf Bioregion. In this paper, we fill previously identified data gaps by classifying the continental shelf portion of the Strait of Georgia and Southern Shelf Bioregions into geomorphic units. The geomorphic units were produced following the PMECS methods using bathymetric data and the Benthic Terrain Modeler (BTM) toolbox. The results of this work, when combined with previous geomorphic unit analyses, produce a continuous spatial data product representing geomorphic units for the Canadian Pacific continental shelf and slope. These data will support MSP efforts in the Pacific South Coast planning region, including MPA monitoring, and future analyses to assess species assemblages associated with each geomorphic unit.

Résumé

Proudfoot, B. and Robb, C. 2022. Geomorphic units in the Strait of Georgia and Southern Shelf bioregions. Can. Tech. Rep. Fish. Aquat. Sci. 3459: vi + 23 p.

Le Système de classification écologique marine du Pacifique (PMECS) a été élaboré en 2016 pour classer les espèces, les habitats et les écosystèmes en catégories écologiques à diverses échelles spatiales dans la région du Pacifique du Canada afin d'appuyer les activités de planification spatiale marine (PSM) et la mise en place d'un réseau d'aires marines protégées (AMP). Les unités géomorphologiques constituent un niveau du PMECS hiérarchique qui peut éclairer les décisions de gestion écosystémique. À l'échelle de 100 km, les unités géomorphologiques sont des zones ayant des caractéristiques benthiques semblables qui sont souvent associées à un biote distinct. Les données spatiales produites pour constituer les unités géomorphologiques du PMECS étaient axées sur la biorégion du plateau Nord et la partie de la pente continentale de la biorégion du plateau Sud. Dans le présent document, nous comblons les lacunes en matière de données qui ont été cernées en classant la partie du plateau continental des biorégions du détroit de Georgia et du plateau Sud en unités géomorphologiques. Les unités géomorphologiques ont été produites selon les méthodes du PMECS à l'aide de données bathymétriques détaillées et de la boîte à outils de modélisation du terrain benthique (BTM). Les résultats de ce travail, combinés aux analyses d'unités géomorphologiques antérieures effectuées dans le cadre du processus du PMECS, ont permis d'obtenir un produit de données spatiales continues représentant les unités géomorphologiques pour le plateau et la pente continentaux de la région du Pacifique du Canada. Ces données appuieront les efforts de PSM dans la région de planification de la côte sud du Pacifique, y compris la surveillance des AMP, et les analyses futures pour évaluer les assemblages d'espèces associés à chaque unité géomorphologique.

1 Introduction

In Canada's Pacific Region, spatial data on species, habitats, and ecosystems are needed to inform Marine Spatial Planning (MSP) efforts, including Marine Protected Area (MPA) network development and MPA monitoring. MSP is a process that brings federal, provincial, territorial and indigenous partners, organizations, and stakeholders together to coordinate how we collectively use marine spaces to achieve ecological, economic, cultural, and social objectives (Ehler and Douvere 2009). In the Pacific Region, MSP efforts are underway in the Pacific North Coast, comprised of the Northern Shelf Bioregion (NSB), and the Pacific South Coast, comprised of the Southern Shelf and the Strait of Georgia Bioregions (Figure 1).

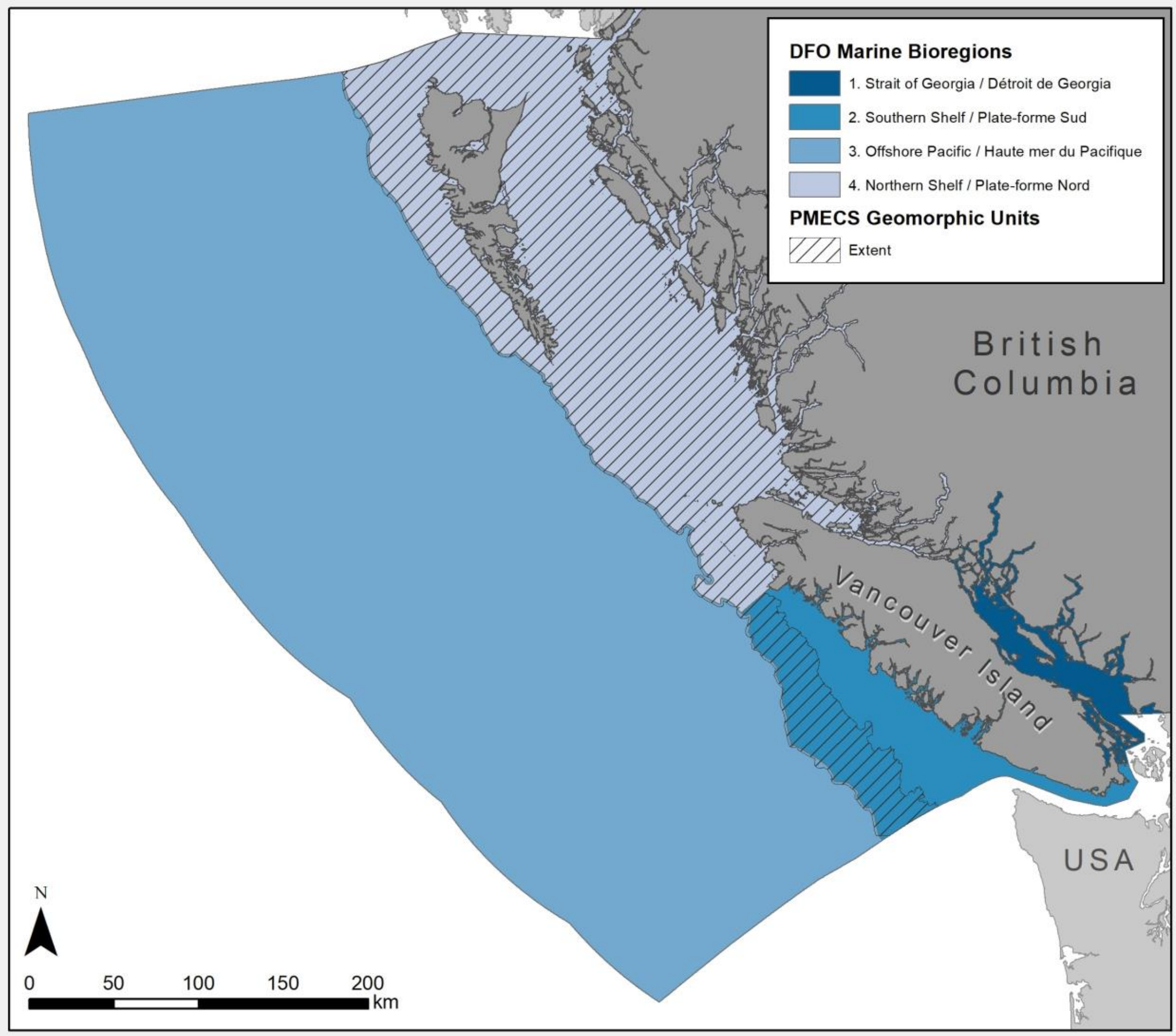

Figure 1. Marine bioregions in Canada's Pacific Region (DFO 2009). The extent of the geomorphic units produced as part of the Pacific Marine Ecological Classification System (PMECS) process in 2016 (Rubidge et al. 2016) are shown by diagonal hatch marks.

Marine ecological classification systems are a means of contextualizing spatial data for species, habitats, and ecosystems at varying spatial scales. Continuous spatial data representing physical features can function as important surrogates for biological communities and habitats, and are central to marine conservation and MSP activities (Rubidge et al. 2016; Lacharité and Brown 2019). For example, design guidelines developed to support MPA network planning in the NSB state that the network should "represent and replicate targets for each class in at least one broad-scale comprehensive classification system across the planning area" (Lieberknecht et al. 2016) to help meet the network objective of representing marine habitats. Ecological classifications have been selected as inputs into site selection analyses supporting MPA network design (DFO 2017, 2018; Martone et al. 2021) and, following implementation of an MPA or MPA network, can be used to inform assessments of design features, including representation, replication, and connectivity (Balbar et al. 2020; Proudfoot et al. 2020). Additionally, ecological classifications can support future research to assess species assemblages associated with each class and investigate potential relationships (Rubidge et al. 2016).

In 2016, the Pacific Marine Ecological Classification System (PMECS) was developed and spatial data for benthic ecosystems was classified for most of the continental shelf and slope in Canada's Pacific Region (Rubidge et al. 2016). PMECS follows a hierarchical framework with a series of levels with nested spatial extents, ranging from broad-scale realms to fine-scale micro-assemblages (Table 1). At the scale of 100s of km, geomorphic units represent areas with similar benthic characteristics that are often associated with distinct biological assemblages and describe the terrain of the seafloor (depressions, slopes, flats, and ridges). As part of Rubidge et al. (2016), spatial data for the geomorphic units in the NSB and the continental slope portion of the Southern Shelf Bioregion were produced using the Benthic Terrain Modeler (BTM) toolbox (Walbridge et al. 2018b, 2018a). These areas were prioritized because the immediate focus was on spatial data to support ongoing MPA network planning within the NSB. The Strait of Georgia Bioregion and continental shelf portion of the Southern Shelf Bioregion (which comprise the majority of the planning region for MSP in the Pacific South Coast) were not included in the 2016 analyses. As such, additional work was required to develop a dataset that covers the entire Pacific continental shelf. Here, we address this gap by producing geomorphic units to support MSP activities underway in the Pacific South Coast, following the methods developed for PMECS by Rubidge et al. (2016).

Table 1: Levels, spatial extents, definitions, and output units of the hierarchical Pacific Marine Ecological Classification System framework (adapted from Rubidge et al. (2016)).

PMECS Level	Spatial extent	Framework definition	Output Unit in the Pacific Region
1. Realms	>10000s of km	Ocean basin.	Temperate North Pacific
2. Province	1000s of km	Based on large-scale patterns of endemism.	Oregonian & Aleutian transition zone.
3. Bioregion	1000s of km	Distinctive recurring and smaller-scale physical oceanographic processes (e.g., separation between California and Alaska current regions).	See Figure 1
4. Biophysical units	100s – 1000s of km	Distinct physiographic and oceanographic conditions/processes related to biotic composition.	Dogfish Bank, Other Banks, Shelf, Troughs, Slope
5. *Geomorphic units*	*100s of km*	*Discrete geomorphological structures assumed to have distinctive biological assemblages; Individually defined by shape, size, and topographic variation.*	*Ridge, Canyon, Gentle Slope, Steep Slope, Mound*
6. Biotopes (habitats and communities)	100s of m – 100s of km	Discrete taxonomic assemblages characterized by associated substrate and environmental factors.	Major abiotic units that act as surrogates for assemblages living on or in these substrates.
7. Biological facies	100s of m	Groups of biogenic or foundation species identified by one or more indicator species. They are patchy and nested within biotopes.	E.g., sponge reefs, kelp forest, eelgrass beds
8. Micro-assemblages	1 cm – 10s of m	Small scale assemblages of often highly specialized species. Will be associated with biotope but may or may not be associated with biological facies.	E.g., kelp holdfast assemblages

2 Methodology and Application

2.1 Summary of Methods

The methodology described in Rubidge et al. (2016) was followed and adapted to reflect the scale of features within the current study area. The major steps in the analysis are as follows:

1. Divide study area (Strait of Georgia and Southern Shelf Bioregions) into smaller areas such that each area contains seascape features of roughly the same scale (Section 2.2)
2. For each of the smaller areas, use the tools within the BTM toolbox (BTM 3.0; Walbridge et al. 2018b) and high resolution bathymetric data to produce classified maps of benthic terrain (Section 2.3)
3. Post-process the raster output to simplify boundaries, remove slivers, and join geomorphic units at the boundaries of the smaller analysis areas (Section 2.4)
4. Attach names to features from the gazetteer of undersea feature names, as appropriate, and write metadata for final files (Section 2.5).

2.2 Study Area

The study area included the Strait of Georgia Bioregion and the continental shelf portion of the Southern Shelf Bioregion (Table 1; DFO 2009) extending from the high water coastline developed by the Canadian Hydrographic Service (CHS)[1] to the shelf break line defined in Rubidge et al. (2016; Figure 2). The study area was divided into four analysis areas due to differences in the sizes of features within each analysis area and differences in the resolutions of bathymetry data used (Figure 2; Table 2). The four analysis areas were: the Strait of Georgia/Strait of Juan de Fuca (SOG/SJDF), Mainland Inlets and Fjords, the West Coast Vancouver Island (WCVI) Shelf, and WCVI Inlets/Fjords. The boundary between the SOG/SJDF and the WCVI Shelf was delineated using the Southern Shelf and Strait of Georgia Marine Bioregions (DFO 2009) and adjusted to match the extent of regional boundaries utilized for species distribution and habitat suitability modelling analyses (Fields and Nephin 2020). British Columbia Marine Ecological Classification (BCMEC) ecosections (Ministry of Sustainable Resource Management (MSRM) Decision Support Services Branch 2002) were used to delineate the WCVI Inlets and Fjords (Low Flow Nearshore ecosection) and Mainland Inlets and Fjords (Mainland Inlets and Fjords and Johnstone Strait ecosections). The WCVI Inlets and Fjords analysis area was extended to 5 km seaward of 50 m depth contour to allow for overlap with the WCVI shelf analysis area and to facilitate the delineation of geomorphic units along the border between the WCVI Shelf and WCVI Inlets and Fjords analysis areas, particularly in the larger sounds such as Barkley, Clayoquot, and Nootka Sounds where the shared boundary is long. This was not necessary for the Mainland Inlets and Fjords analysis area because the scale of features of interest within the mainland fjords were consistent with those in the SOG/SJDF, and the shared boundaries between the two regions were small. Clipping was done using the Mask function in the Raster R package (version 3.5-2; Hijmans et al. 2020)

Table 2. Bathymetry data used to derive geomorphic units for each analysis area.

Analysis Area	**Resolution**	**Source**
Strait of Georgia/Strait of Juan de Fuca (SOG/SJDF)	10 m	Kung 2021
Mainland Fjords	10 m	Kung 2021
West Coast Vancouver Island (WCVI) Shelf	75 m	Natural Resources Canada 2014
West Coast Vancouver Island (WCVI) Inlets and Fjords	75 m	Natural Resources Canada 2014

[1] Canadian Hydrographic Service - [Data products and surveys (charts.gc.ca)](charts.gc.ca)

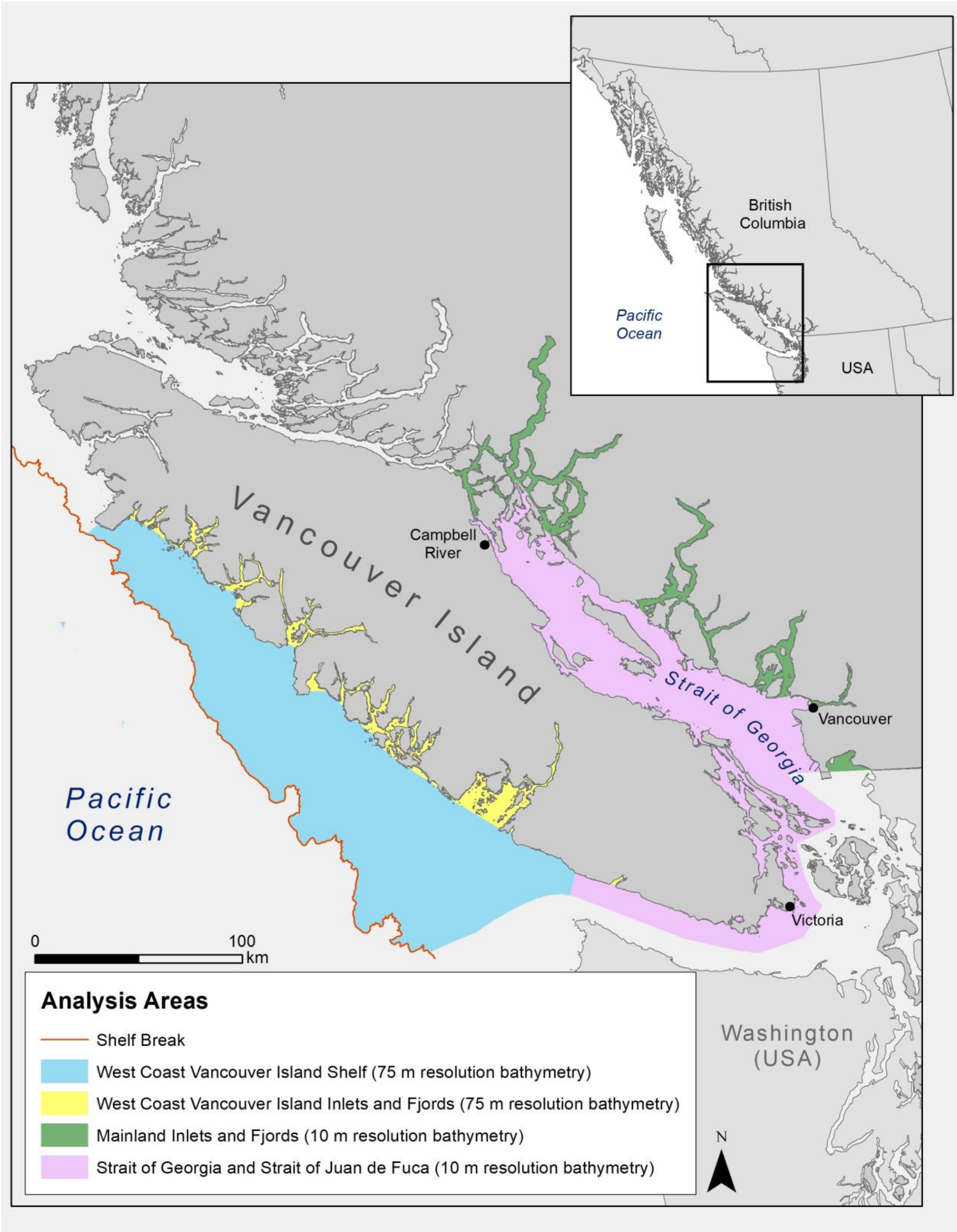

Figure 2. Study area for the geomorphic unit analysis showing analysis areas and resolutions of bathymetry data.

2.3 Benthic Terrain Modeler Toolbox

2.3.1 Inputs

Bathymetry, slope, bathymetric position index (BPI) data and a set of classification rules (Section 2.3.2) are required inputs for delineating geomorphic units using the BTM toolbox[2] (Walbridge et al. 2018b). The data for this analysis are described in detail below.

2.3.1.1 Bathymetry and Slope

The 10 m bathymetry layer used in the SOG/SJDF and Mainland Inlets and Fjords analysis areas was created by Robert Kung at Natural Resources Canada (NRCAN) to support MSP (Kung 2021). The data was produced by compiling the best available bathymetry data from multiple government agencies.

The 75 m bathymetry layer that covers the WCVI Shelf and WCVI Inlets and Fjords analysis areas was developed and made available by Robert Kung of NRCAN (Natural Resources Canada 2014) using data from the CHS.

Ten-meter resolution bathymetry data were also available for the WCVI Inlets and Fjords analysis area (Kung 2021). Tests were conducted to determine if geomorphic units derived for the WCVI Inlets and Fjords analysis area using 10 m bathymetry data could be merged with geomorphic units derived for the WCVI Shelf using 75 m resolution bathymetry. Merging the geomorphic units along the extensive boundary of the two study areas resulted in artifacts and spatial patterns that were not representative of the seascape. As such, it was determined that the 75 m resolution bathymetry layer would be used for both the WCVI Shelf and WCVI Inlets and Fjords analysis areas to facilitate merging the geomorphic units at the boundary of the two analysis areas and to maintain continuity between the PMECS geomorphic units that cover the continental slope and majority of the continental shelf. Further, tests also showed that the outputs derived from the 10 m and 75 m bathymetry were not substantially different given the scale of features being delineated.

For each analysis area, slope (i.e., change in depth) was calculated in degrees using the chosen bathymetry dataset and the Slope tool in ArcGIS 10.7.1 (ESRI Inc. 2019).

2.3.1.2 Bathymetric Position Index (BPI)

The BPI is a second order bathymetric derivative (slope is the first order derivative) that identifies depressions, crests, ridges, and flat areas by quantifying the relative position of a location on a bathymetric surface (Walbridge et al. 2018a). The BPI algorithm in the BTM toolbox employs a user-defined annulus (inner and outer radii of a search neighbourhood) to compare a raster cell's depth to the mean depth of surrounding cells. The resulting BPI raster cell values represent depressions (negative values), crests or ridges (positive values), and flats or areas of constant slope (near-zero values) (Lundblad et al. 2006). Rubidge et al. (2016) developed guidance on appropriate scale factors for setting BPI radii. To determine appropriate BPI parameters for the three analysis areas in this study, the size range of features targeted for delineation were recorded and broad scale BPI layers were developed using scale factors that are approximately half the dimension of the features of interest (Rubidge et al. 2016; Table 33). The broad and fine scale BPI rasters were created and standardized using the 'build BPI' and 'standardize BPI' tools in the BTM toolbox.

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[2] https://coast.noaa.gov/digitalcoast/tools/btm.html

Table 3. Features measured in each analysis area, range of sizes, and final scale factors.

Analysis Area	Features targeted for delineation	Size range (width)	Broad scale BPI factor (m)	Inner radius (cells)	Outer radius (cells)
Strait of Georgia/Strait of Juan de Fuca (SOG/SJDF)	Troughs, banks, fjords, channels, inlets	2–8 km	4000	20	200
Mainland Inlets and Fjords	Fjords, channels, inlets	2–7 km	3400	5	170
West Coast Vancouver Island (WCVI) Shelf	Troughs, banks	10–20 km	10000	10	100
West Coast Vancouver Island (WCVI) Inlets and Fjords	Fjords, channels, inlets	2–7 km	3375	5	45
Trough Walls (SOG/SJDF; WCVI Shelf)	Trough walls	1.5–4 km	Trough walls defined using slope, not BPI		

2.3.2 Classification Rules

In addition to the bathymetry, slope, and BPI data, delineating geomorphic units using the BTM toolbox requires a classification table that specifies rules to define each class or feature (i.e., geomorphic unit). Rubidge et al. (2016) developed a list of features they anticipated delineating in each analysis area in the PMECS study area (e.g., crest, depressions, mounds, walls; Table 4), and then iteratively tested various parameters in the classification tables until the features targeted for delineation best matched the analysis results. Classification tables based on the broad scale BPI and slope were found to be most appropriate for delineating features at the scale of geomorphic units (Rubidge et al. 2016). The same features were targeted in this analysis and the same classification tables and names of geomorphic units were applied and input into the 'Classify Benthic Terrain' tool from the BTM toolbox (Table 3 and Table 5). Following the approach developed by Rubidge et al. (2016), trough walls were delineated using slope thresholds.

Table 4: General definitions of features delineated in each analysis area. Descriptions were sourced from Rubidge et al. (2016), which used the Greene et al. (2008) classification and definitions found in Harris and Baker (2012).

Feature	Description
Crest	Flat areas with extreme positive relief
Depression	Relatively flat areas with negative relief and gentle negative slope (less than 1 degree)
Depression floor	Flat areas with extreme negative relief
Mound	Relatively flat areas with positive relief and gentle positive slope (less than 1 degree)
Wall, sloping	Areas with slope values greater than 1 (degree) that capture sloped areas between depressions and mounds (continental shelf only)
Wall, steeply sloping	Areas of constant, steep slope with slope values greater than 2.86 (degrees; inlets and fjords only)

2.3.2.1 West Coast Vancouver Island Inlets and Fjords and Mainland Inlets and Fjords

Features of interest in fjords and inlets included steep slopes of fjord walls, depressions of fjord and channel floors, flat regions at the heads of inlets and mounds or sill features in regions where fjords and inlets meet the continental shelf. Extreme BPI values of ± more than 1 SD from the mean defined fjord walls (crests) and fjord or channel bottoms (depression floors). Depressions and mounds were delineated using the mean BPI values as a threshold. Steeply sloping walls were defined as areas with constant, steep slopes using the threshold used to define the slope break (Table 5).

2.3.2.2 Strait of Georgia and Strait of Juan de Fuca

Features to be delineated in the SOG/SJDF included mounds, crests, depressions, depression floors and slopes. Crests and depression floors were defined by extreme BPI values of ± more than one SD from the mean. Mounds and depressions were delineated using the same approach as the WCVI Inlets and Fjords and Mainland Inlets and Fjords analysis areas. All flats with slope values greater than one were defined as sloping walls to capture sloped areas between depressions and mounds (Table 5).

2.3.2.3 West Coast Vancouver Island Shelf

Features to be delineated in the WCVI Shelf analysis area included mounds, crests, depressions, depression floors and slopes and were defined using the same approach as the SOG/SJDF analysis area (Table 5).

Table 5. Classification table for the four analysis areas.

Analysis Area	Class	Zone	Broad BPI Lower	Broad BPI Upper	Fine BPI Lower	Fine BPI Upper	Slope Lower	Slope Upper	Depth Lower	Depth Upper
West Coast Vancouver Island Inlets and Fjords	1	Crest	100							
	2	Depression Floor		-100						
	3	Depression	-100	0.46				2.86		
	4	Mound	0.46	100				2.86		
	5	Wall, steeply sloping	-100	100			2.86			
Strait of Georgia and Strait of Juan de Fuca	1	Crest	100							
	2	Depression Floor		-100						
	3	Depression	-100	0.57				1		
	4	Mound	0.57	100				1		
	5	Wall, sloping	-100	100			1			
Mainland Inlets and Fjords	1	Crest	100							
	2	Depression Floor		-100						
	3	Depression	-100	0.61				2.86		
	4	Mound	0.61	100				2.86		
	5	Wall, sloping	-100	100			2.86			
West Coast Vancouver Island Shelf	1	Crest	100							
	2	Depression Floor		-100						
	3	Depression	-100	0.33				1		
	4	Mound	0.33	100				1		
	5	Wall, sloping	-100	100			1			

2.4 Post-processing of Classified Geomorphic Units

The following post-processing steps were undertaken separately for each analysis area based on guidance in Rubidge et al. (2016). Classified rasters (the output of the Classify Benthic Terrain BTM tool) were converted to polygon feature classes using the Raster to Polygon tool in ArcMap 10.7.1 (ESRI Inc. 2019) with the “simplify polygons” option selected to produce smoother polygons. Sliver polygons were merged with neighbouring polygons with which they shared the longest border using the Eliminate tool

(ESRI Inc. 2019). Sliver polygons were defined as fragments smaller than 0.5 km^2 for the WCVI Shelf and 0.2 km^2 for the WCVI Inlets and Fjords, SOG/SJDF and Mainland Inlets and Fjords analysis areas (Rubidge et al. 2016). A smaller threshold is required for the WCVI Inlets and Fjords, SOG/SJDF and Mainland Inlets and Fjords analysis areas to ensure that narrow features found in the channels, inlets, and fjords (e.g., fjord sills, fjord walls with steep slopes, narrow channels between islands) are not eliminated. The Eliminate process was repeated a second time to ensure all sliver polygons were removed. The three analysis area files were then merged into a single file. Small gaps between the analysis areas (resulting from the simplification procedure when the classified rasters were converted to polygon feature classes) were removed by creating topology and performing edge matching.

Along the western edge of the WCVI Shelf analysis area, between the continental shelf geomorphic units created in this analysis and the continental slope geomorphic units created for the PMECS (Rubidge et al. 2016), were several long, narrow ridge and depression floor units that were deemed as artifacts created by the presence of the analysis area edge. Within the dataset for the newly created geomorphic units for the WCVI Shelf analysis area, these units were reclassified to "Wall, sloping" to align with continental slope geomorphic units.

2.5 Comparisons with Undersea Features and BCMCA Benthic Classes

The geomorphic units were compared to the point locations of gazetted undersea features, using the Canadian Gazetteer of Undersea Feature Names[3]. The Canadian Gazetteer of Undersea Feature Names includes the most complete set of the locations of marine features in our study area. A field was added to the geomorphic units attribute table to record the names of associated gazetted features.

A visual comparison of the geomorphic units and Northeast Pacific Ocean Undersea Features (Manson 2009) produced using BPI and slope surface analyses was also done to assess how well the two datasets agree on the location of troughs, valleys, and basins on the continental shelf.

The geomorphic units were also visually compared to Benthic Classes produced for the British Columbia Marine Conservation Atlas (BCMCA; British Columbia Marine Conservation Atlas 2010). The Benthic Classes combined landscape features, depth, and substrate information to identify areas of similar benthic characteristics and were used in past planning exercises (e.g., the Marine Plan Partnership), prior to the development of the PMECS geomorphic units (Rubidge et al. 2016).

The level of agreement between the geomorphic units, gazetted undersea features, Northeast Pacific Ocean Undersea Features (Manson 2009), and Benthic Classes (British Columbia Marine Conservation Atlas 2010) can help assess uncertainty in the geomorphic units, and identify differences resulting from the various methods used to identify seafloor terrain features at broad spatial scales.

3 Geomorphic Units Results

Figure 3 illustrates the geomorphic units for the Strait of Georgia Bioregion and the continental shelf portion of the Southern Shelf Bioregion that extends from the high water coastline to the Shelf Break defined in Rubidge et al. (2016). These results, when merged with the PMECS geomorphic units, form a continuous spatial layer representing geomorphic units in the Canadian Pacific continental shelf and slope (Figure 4).

Also displayed are the point locations of gazetted undersea features that align spatially with a geomorphic unit that likely represents the feature. Of the 55 gazetted undersea features that are within the study area, 29 features had an associated geomorphic unit (Table 6). The majority of the point locations of gazetted undersea features were within the boundaries of the polygon that likely represented the feature (e.g., Halibut Bank, Sooke Basin, Achilles Bank). Point locations of other features such as Ajax Bank, Comox

[3] BC Gazetteer - BC GAZETTEER 22JUL2020 - Open Government Portal (canada.ca)

Bar, and Constance Bank were in close proximity (<1 km) to the geomorphic unit that likely represents the feature and it has been previously noted that some of the gazette locations may be offset spatially (Rubidge et al. 2016). Some gazetted undersea features are represented by multipart geomorphic unit (e.g., Sargison Bank and Swiftsure Bank). These are typically cases where adjacent crest and mound geomorphic units together represent a bank feature. The point location of La Perouse Bank was not located within a distinct geomorphic mound or crest feature, but rather located within the large mound geomorphic unit that extends across the majority of the WCVI Shelf analysis area. A portion of La Perouse Bank is represented by a crest geomorphic unit located approximately 30 km southwest of the entrance of Barkley Sound. Gazetted undersea features that did not have an associated geomorphic unit are listed in Appendix 2.

Table 6: Gazetted undersea features and their associated geomorphic units

Gazetted Feature Name	Associated Geomorphic Unit	Proximity to Geomorphic Unit Polygon Feature	Additional Information
Achilles Bank	Crest	Within polygon	
Ajax Bank	Crest	<1 km from polygon boundary	
Ballenas Trough	Depression	Within polygon	
Bjerre Shoal	Crest	<200 m from polygon boundary	
Boundary Bay	Depression	Within polygon	
Comox Bar	Mound	<1 km from polygon boundary	
Constance Bank	Mound	<100 m from polygon boundary	
Exeter Shoal	Crest	<200 m from polygon boundary	
Halibut Bank	Crest	Within polygon	
Hidden Basin	Mound	Within polygon	
La Perouse Bank (partial)	Crest	N/A	Crest geomorphic unit represents a portion of La Perouse Bank. The gazetted point is located within a large mound geomorphic unit that covers an extensive area beyond the location of La Perouse Bank. Only a portion of the bank (crest) is assigned to a geomorphic unit.
Malaspina Strait	Depression floor	Within polygon	
Mary Basin	Depression	Within polygon	
McCall Bank	Crest	~2 km from polygon boundary	
Montgomery Bank / Sentry Shoal	Crest	~1.5 km from polygon boundary	Sentry Shoal point is located within a crest geomorphic unit. Montgomery Bank point is located ~ 1.5 km from polygon boundary.
Nash Bank	Mound	Within polygon	
Roberts Bank	Crest/Mound/ Depression	Within polygon	Multipart feature.
Rocket Shoal	Mound	~250 m from polygon boundary	
Sargison Bank	Crest/Mound	Within polygon	Multipart feature.

Sinclair Bank	Crest	Within polygon	
Sooke Basin	Depression	Within polygon	
Spanish Bank	Mound	<150 m from polygon boundary	
Sturgeon Bank	Crest/Mound/ Depression	Within polygon	Multipart feature.
Swiftsure Bank	Crest/Wall, sloping	<500 m from polygon boundary	Multipart feature.
Thames Shoal	Mound	<300 m from polygon boundary	
Victoria Shoal	Mound	<400 m from polygon boundary	
Yaculta Bank	Mound	<250 m from polygon boundary	
Yellow Bank	Mound	Within polygon	

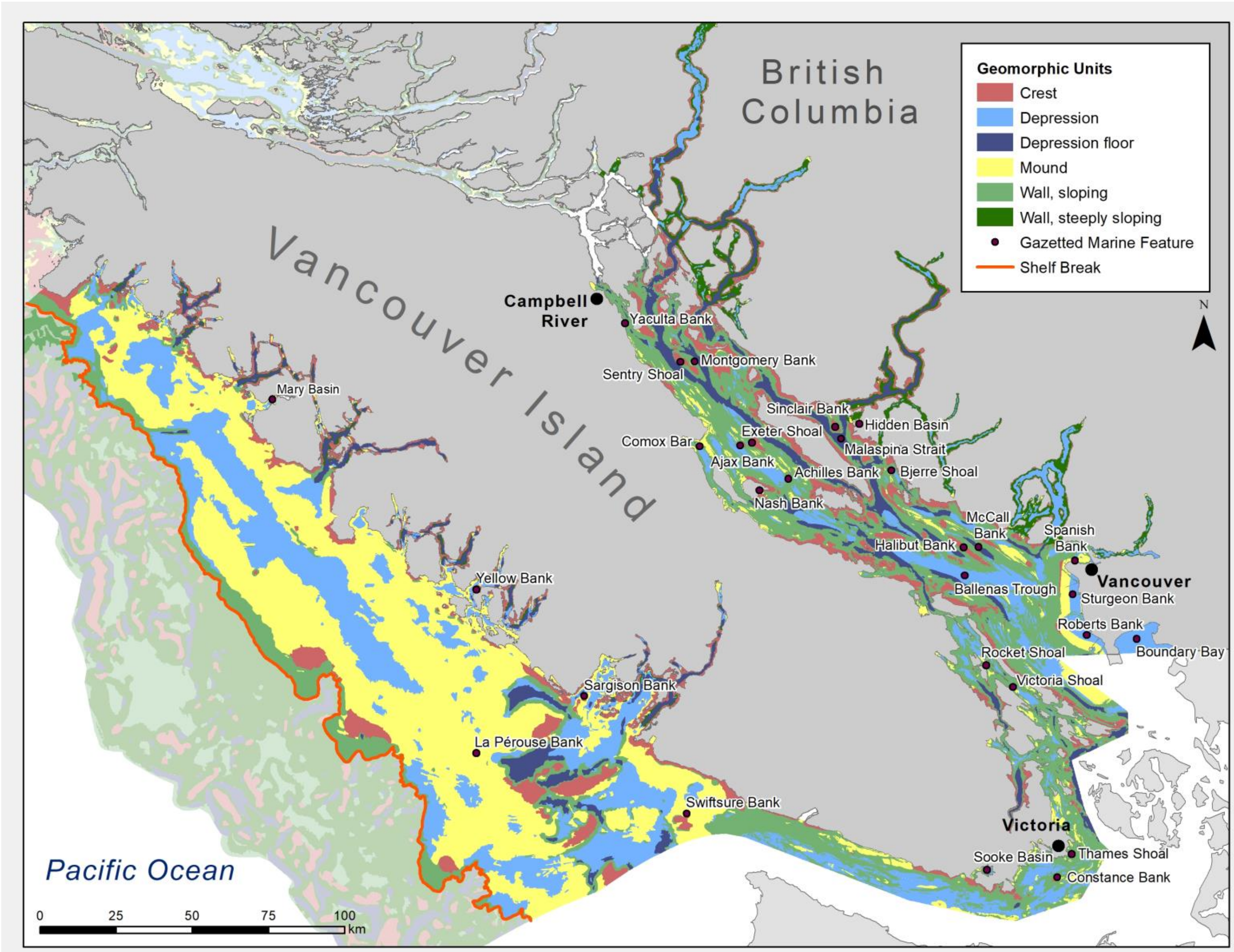

Figure 3. Merged geomorphic units for the four analysis areas. The adjacent geomorphic units produced as part of the Pacific Marine Ecological Classification System (PMECS) process (Rubidge et al. 2016) are displayed semi-transparently and have the same colour symbology as the units in this analysis.

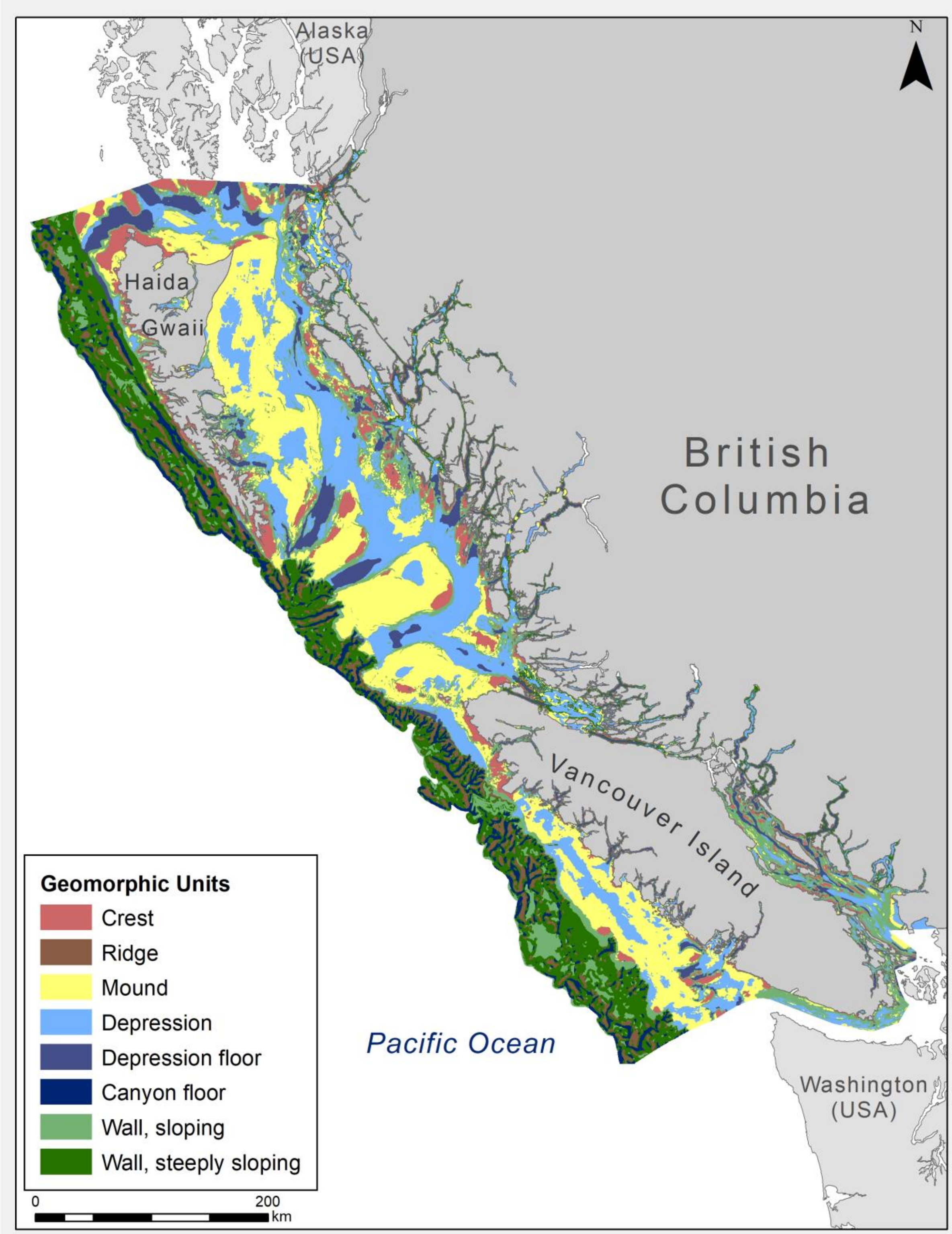

Figure 4: Geomorphic units in the Canadian Pacific continental shelf and slope produced by merging the results from this analysis with the geomorphic units generated as part of the Pacific Marine Ecological Classification System process (Rubidge et al. 2016).

The visual assessment of the degree of overlap between the new geomorphic units and the Northeast Pacific Ocean Undersea Features (Manson 2009) indicates agreement between the location of Ballenas Trough, Malaspina Strait as well as unnamed troughs and basins southeast of the entrance to Barkley Sound and in the northern Strait of Georgia. The geomorphic units representing these features are narrower than the Undersea Features, and capture finer scale features within the troughs, such as small crest and mound features that are not represented in the Undersea Features.

The visual assessment to compare the BCMCA Benthic Classes[4] with the geomorphic units shows that there is some agreement, particularly with the locations of depression and ridge features. However in the SOG/SJDF, the BCMCA Benthic Classes seem to be less able to capture the transition between depression and ridge/crest features as evidenced by the relative lack of slope features. The BCMCA Benthic Class depression features are also narrower than the trough features in the Manson (2009) dataset and align well with the geomorphic unit depression and depression floor features.

4 Discussion

This analysis addressed an identified spatial data gap by classifying the continental shelf portion of the Strait of Georgia and Southern Shelf Bioregions into geomorphic units, which were then merged with existing geomorphic units for the Northern Shelf Bioregion and BC Continental slope to produce a continuous geomorphic units layer for the continental shelf and slope regions of Canada's Pacific coast (Figure 4). These data support MSP efforts in the Pacific South Coast planning region, including MPA monitoring, as well as future analyses to investigate the relationships between species assemblages and geomorphic units.

4.1 Uncertainty

For the SOG/SJDF and Mainland Inlets and Fjords analysis areas, finer scale bathymetric data (10 m resolution) was used than the PMECS geomorphic unit analyses (Rubidge et al. 2016). This was done because 10 m bathymetry data was more appropriate given the smaller scale of features of interest within these analysis areas. This decision did however pose some challenges when adjacent SOG/SJDF and WCVI Shelf geomorphic units were merged because the resolution was not consistent across the two analysis areas, affecting the resolution and complexity of the polygon edges. However, the boundary between the WCVI Shelf and SOG/SJDF analysis areas was relatively small (~ 10 km) and only five polygons were merged from the two analysis areas, so the impact of this mismatched resolution was minor.

Generally there was good alignment between gazetted features and geomorphic units (Table 6), suggesting that the geomorphic units represent known seafloor features. However, small shoals and banks near the coastline seemed to be the most common gazetted features that did not have associated geomorphic units (e.g., Holland Bank, Collins Shoal; Appendix 2). This suggests that the geomorphic unit approach is less able to discern small, shallow nearshore features and that shoals, mounds, and ridges may be underrepresented. As such, it may be necessary to use an alternative method to identify nearshore features. This could potentially include using areas of high rugosity (Du Preez 2015) as recommended in Rubidge et al. (2016) to complement the geomorphic unit approach and identify more complex features in nearshore areas. Another option could be to use higher resolution bathymetry data (e.g., LIDAR; Walbridge et al. 2018a) and an alternative set of BPI parameters to identify finer scale features in nearshore areas.

A limitation of this approach that was highlighted in Rubidge et al. (2016) and persists in this analysis is the importance of identifying features of interest prior to running the BTM tool. This is important because the tool does not easily identify complex features such as fjords and canyons with steep slope walls and

[4] https://bcmca.ca/datafeatures/eco_physical_benthicclasses/

flat depressions. As such, some understanding of the terrain of the seafloor and features of interest is required to ensure the BPI classification parameters produce geomorphic units that are meaningful for the particular area of interest.

4.2 Future Considerations

In addition to supporting MSP activities within Pacific South Coast, the continuous geomorphic units layer for the BC Coast can be used for broader coast-wide analyses, as well as investigations to assess the species assemblages associated with each geomorphic unit.

There is substantial evidence of the relationship between biological assemblages and physiographic units and abiotic factors and that physical features such as geomorphic units can function as proxies for ecological structures and assemblages (Brown et al. 2012; Harris and Baker 2019; Lacharité et al. 2020; Proudfoot et al. 2020). However, the relationship between geomorphic units and species assemblages at coastwide and regional scales is not well understood. Further examination into potential correlations between geomorphic units and species assemblages could support a variety of spatial programs and initiatives, including MSP. One possible analytical route could be to utilize the DFO Synoptic Trawl dataset (Sinclair et al. 2003; Anderson et al. 2019) to assess correlations between groundfish assemblages and geomorphic units to determine whether geomorphic units could serve as proxies for species assemblages. This could be particularly valuable in areas where spatially comprehensive species and habitat data are lacking. This information could have multiple uses, including potentially informing MPA monitoring by helping to understand and minimize confounding habitat effects (Lacharité and Brown 2019) on benthic and epibenthic biota patterns. However, it is not recommended that the geomorphic units be used for mapping and analyses at a local scale or to represent fine scale seafloor patterns. The geomorphic units were produced and should be interpreted as areas with similar benthic features at the scale of 100s of km. This is particularly relevant for more confined areas such as the Strait of Georgia or within inlets and fjords, where the scale of features is comparatively finer than that of the outer shelf and slope. Additionally, the lower levels in the PMECS hierarchy (e.g., biotopes, biological facies; Table 1) could be more appropriate for identifying fine scale features to meet more localized needs.

Additionally, the results of this work could be used to validate and compare against existing substrate models by providing overlapping spatial data that represents seafloor features. For example, it is unlikely that steeply sloping geomorphic units would be in areas with muddy substrates. Furthermore, the geomorphic units and coast-wide predicted substrate layers (Gregr et al. 2013, 2021) could be combined to assign the most likely substrate to each geomorphic unit. This is similar to what was done to produce Benthic Classes (British Columbia Marine Conservation Atlas 2010), which combined landscape features, depth, and substrate information to identify areas of similar benthic characteristics. However it is unclear how the landscape features were derived and the specific BTM settings applied in the BCMCA Benthic Classes analysis. As such, the geomorphic units produced here and the recently published substrate model (Gregr et al. 2021) could potentially be used to update the Benthic Classes dataset. There was a moderate level of agreement between the geomorphic units and the BCMCA Benthic Classes[5], particularly with the locations of depression and ridge features. However, the relative lack of slope features in the BCMCA Benthic Classes in the SOG/SJDF suggests that the classification table applied in the BCMCA analysis had different thresholds for delineating the various landscape features and are thus capturing slightly different features. The BCMCA Benthic Classes were used in past planning exercises that focused on the full BC Coast (e.g., Ban et al. 2013) or large bioregions (e.g., the Marine Plan Partnership), which may have influenced the scale at which the features were identified (i.e., broad scale, coast-wide) and the slope thresholds applied.

Geomorphic units are one example of the spatially comprehensive data products representing benthic characteristics that are essential to MSP and conservation prioritization activities. The geomorphic units

[5] https://bcmca.ca/datafeatures/eco_physical_benthicclasses/

produced in this analysis, when coupled with the existing geomorphic units produced as part of the PMECS process, can be included in assessments of existing and proposed conservation networks across the BC coast to evaluate the degree of geomorphic unit representativity and replication. These assessments will be particularly valuable if combined with further work on the degree to which geomorphic units are associated with species assemblages and/or species of conservation concern.

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Appendix 1 – Geomorphic Unit Attributes

Table 7. Attributes included for each polygon in the spatial dataset of geomorphic units.

Attribute	Type	Description
Id	Long	Unique numeric identifier for each polygon. Values range from 1 – 2991 (n polygons)
Geomorph	String	Original geomorphic unit name
GeoGreene	String	Geomorphic unit class described using the classification developed by Greene et al. (2008). Values are: Fjord, Crest Fjord, Depression Fjord, Depression floor Fjord, Mound Fjord, Wall, steeply sloping Shelf, Crest Shelf, Depression Shelf, Depression floor Shelf, Mound Shelf, Wall, sloping
Zone	String	Generalized Geomorphic unit class described using the classification developed by Greene et al. (2008). This field does not differentiate features by their location on the continental shelf. This field may be useful for mapping and visualization purposes. Values are: Crest Depression Depression floor Mound Wall, sloping Wall, steeply sloping
Area	String	Broad geological classification to differentiate fjords and inlets from continental shelf. Values are: Continental Shelf Continental Shelf (inlets and fjords)
Label	String	Map label (used in Rubidge et al. 2016). Retained to prevent errors when merging with PMECS geomorphic units
FeatureGazette	String	Name of feature found in the Canadian Gazetteer of Undersea Feature Names, if applicable
Year_Created	String	Year that the analysis was done. This is to differentiate geomorphic units produced as part of the PMECS process (2016) and geomorphic units produced in this analysis.
AnalysisArea	String	Analysis Areas used to divide the study area (Strait of Georgia and Southern Shelf Bioregions) into smaller areas such that each area contains seascape features of roughly the same scale. The three analysis areas are: Strait of Georgia and Strait of Juan de Fuca West Coast Vancouver Island Inlets and Fjords West Coast Vancouver Island Shelf
Shape_Length	Double	Length of polygon perimeter (units = meters)
Shape_Area	Double	Areal measurement of polygon (units = square meters)

Appendix 2 – Alignment Gazetted Undersea Features with Geomorphic Units

Table 8. Gazetted Undersea Features that do not align spatially with the geomorphic units.

Gazetted Feature Name	Geomorphic unit* the point feature falls within
Alan Bank	Located within large wall (sloping) geomorphic unit. No crest or mound geomorphic unit present.
Barnsley Shoal	Located within large wall (sloping) geomorphic unit. No crest geomorphic unit present.
Beaumont Shoal	Located within large wall (sloping) geomorphic unit. No crest geomorphic unit present.
Black Shoal	Located within depression geomorphic unit. No crest geomorphic unit present.
Collins Shoal	Located within large wall (sloping) geomorphic unit. No crest geomorphic unit present.
Coomes Bank	Located within large mound geomorphic unit that covers an extensive area beyond the location of the bank feature.
D’Arcy Shoals	Located within large wall (sloping) geomorphic unit. No crest geomorphic units present.
Edgell Banks	Located within large crest geomorphic unit that covers an extensive area beyond the location of the bank feature.
Elbow Bank	Located within large mound geomorphic unit that covers an extensive area beyond the location of the bank feature.
Entrance Bank	Located within large wall (sloping) geomorphic unit. No mound geomorphic unit present.
Fairway Bank	Located within large wall (sloping) geomorphic unit. No mound geomorphic unit present. .
Four Mile Shoal	Located within depression geomorphic unit.
Ganges Shoal	Located within large mound geomorphic unit that covers an extensive area beyond the location of the shoal feature.
Gossip Shoals	Located within large wall (sloping) geomorphic unit adjacent to a large crest geomorphic unit that covers an extensive area beyond the location of the shoal features.
Grant Knoll	Outside study area.
Gumboot Bank	Located within large wall (steeply sloping) geomorphic unit. No mound geomorphic unit present.
Hesquiat Bar	Located within large mound geomorphic unit that covers an extensive area beyond the location of the bar feature.
Holland bank	Located within large wall (sloping) geomorphic unit. No mound geomorphic unit present.
Horda Shoals	Located within large wall (sloping) geomorphic unit. No crest or mound geomorphic units present.
Josephine Flat	Located within large wall (sloping) geomorphic unit that covers an extensive area beyond the location of the flat feature. No depression geomorphic unit present.
Loch Katrine Bank	Located within depression geomorphic unit. No crest or mound geomorphic unit present.
Neptune Bank	Located within depression geomorphic unit. No crest or mound unit present.
Oswald Bank	Located within large crest geomorphic unit that covers an extensive area beyond the location of the bank feature.
Snug Basin	Located within crest geomorphic unit. Gazetted point feature is on the edge of the study area boundary and the basin is likely outside the boundaries of the study area.
Soquel Bank	Located within depression geomorphic unit. No crest or mound geomorphic unit present.

Gazetted Feature Name	Geomorphic unit* the point feature falls within
Wilby Shoals	Located within large crest geomorphic unit that covers an extensive area beyond the location of the shoal features.

*Greene et al. (2008) classification