Small Scale Delineation of Northeast Pacific Ocean Undersea Features Using Benthic Position Index

M.M. Manson

Oceans, Habitat and Enhancement Branch
Fisheries and Oceans Canada
100 Annacis Parkway, Annacis Island
Delta, British Columbia
V3M 6A2

2009

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 2864

Fisheries and Oceans Canada   Pêches et Océans Canada

Canada

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of the Department of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in *Aquatic Sciences and Fisheries Abstracts* and indexed in the Department's annual index to scientific and technical publications.

Numbers 1–900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 901–1425 were issued as Manuscript Reports of the Fisheries Research Board of Canada. Numbers 1426–1550 were issued as Department of Fisheries and the Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page. Out-of-stock reports will be supplied for a fee by commercial agents.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux or régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au suject; de fait, la série reflète la vaste gamme des intérêts et des politiques du ministère des Pêches et des Océans, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications complètes. Le titre exact paraît au-dessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la revue *Résumés des sciences aquatiques et halieutiques*, et ils sont classes dans l'index annuel des publications scientifiques et techniques du Ministère.

Les numéros 1 à 900 de cette série ont été publiés à titre de manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre. Les rapports épuisés seront fournis contre rétribution par des agents commerciaux.

Canadian Manuscript Report of
Fisheries and Aquatic Sciences 2864

2009

SMALL SCALE DELINEATION OF NORTHEAST PACIFIC OCEAN UNDERSEA FEATURES USING BENTHIC POSITION INDEX

by

M.M. Manson

Oceans, Habitat and Enhancement Branch
Fisheries and Oceans Canada
100 Annacis Parkway, Annacis Island
Delta, British Columbia
V3M 6A2

Cat. No. Fs 97-4/2864E ISSN 0706-6473

Correct citation for this publication:

Manson, M.M. 2009. Small scale delineation of northeast Pacific Ocean undersea features using benthic position index. Can. Manuscr. Rep. Fish. Aquat. Sci. 2864: iv + 16 p.

TABLE OF CONTENTS

ABSTRACT

Manson, M.M. 2009. Small scale delineation of northeast Pacific Ocean undersea features using benthic position index. Can. Manuscr. Rep. Fish. Aquat. Sci. 2864: iv + 16 p.

A spatial inventory of large undersea features in the northeast Pacific Ocean was created through the analysis of small scale bathymetric data using benthic position index and slope surface analyses. Names recorded in the Canadian Gazetteer of Undersea Feature Names were applied to the resultant data set. 175 seamount, hill, and ridge features were identified, 39 of which were named in the gazetteer. 57 canyon and valley features (13 named) were also identified on the continental slope, as were 25 trough, basin, and canyon features (10 named) on the continental shelf, and 48 trough, basin and canyon features (16 named) on the continental rise. The biophysical association between large undersea features and ocean productivity should render the results valuable in Integrated Management planning activities in Fisheries and Oceans Canada's Pacific Region.

RÉSUMÉ

Manson, M.M. 2009. Small scale delineation of northeast Pacific Ocean undersea features using benthic position index. Can. Manuscr. Rep. Fish. Aquat. Sci. 2864: iv + 16 p.

Un inventaire spatial des formes principales du relief sous-marin dans l'océan Pacifique nord-est a été créé grâce à l'analyse de données bathymétriques à petite échelle, utilisant l'indice de position de benthic et l'analyse de la surface de pente. Les noms enregistrés dans le répertoire des noms d'entités sous-marines du Canada ont été appliqué à la série de données résultante. 175 monts, collines et dorsales ont été identifiés, dont 39 ont été inscrits au répertoire. 57 canyons et vallées sous-marins (dont 13 nommés) ont été également identifiés sur la pente continentale, tout comme 25 dépressions, bassins, et canyons (dont 10 ont été nommés) sur la plate-forme continentale, et 48 dépressions, bassins et canyons (dont 16 nommés) sur le glacis continental. L'association biophysique entre les grandes formes du relief sous-marin et la productivité océanique, devrait rendre les résultats intéressants pour la direction intégrée planifiant dans la région Pacifique de Pêches et Oceans Canada.

1.0 INTRODUCTION

Canada's Ocean Strategy, adopted in response to the Oceans Act, commits Fisheries and Oceans Canada to develop and implement a program of Integrated Management for ocean activities. A key to the success of this commitment, identified as one of the objectives of the Strategy, is to advance the understanding of the marine environment. The delineation of ecosystem boundaries and identification of key ecosystem functions will be an important consideration during the development of Integrated Management plans and provides a valuable area to focus research effort.

Much of the study of the large undersea features such as canyons, seamounts, and troughs in Canada's territorial waters of the Pacific Ocean has concentrated on single features which have previously been identified for special management (e.g. Bowie Seamount). The contribution of major undersea feature types to the ecological function of the region as whole has not been addressed. For example, it has been demonstrated that canyons enhance deep ocean water upwelling (Hickey 1997, Allen et al. 2001), potentially playing a significant role in shelf productivity. The configuration of the canyons has also been associated with aggregations of zooplankton and fish (Mackas et al. 1997, Allen et al. 2001). Yet in northeast Pacific waters there is no inventory of the configuration, number, or size of canyons along the edge of the continental shelf. Before the role of canyons in shelf production can be understood, it is important to characterize them, place them into context relative to the general configuration of the continental slope, and examine the current understanding of their ecological role.

Similar contributions to ecological function may be present for other types of undersea features, such as seamounts, hills, basins, troughs, valleys, and banks. As a first step, these need to be identified, quantified and linked to ecosystem function, so that they can be understood in terms of ocean management. This study attempts to characterize and quantify the major undersea features below 30 m within the Canadian Economic Exclusion zone in the Pacific Ocean through Geographic Information System (GIS) analysis of existing digital bathymetric data.

2.0 METHODS

STUDY AREA

The study area was confined to the geographic extent of the Natural Resource Map (NRM) bathymetric mapping series, which roughly corresponds to the Canadian Economic Exclusion Zone (EEZ). The approximate geographic coordinates of this area are 46.9935° N, 141.06902° W to 55.2199° N, 128.094949° W. Preliminary stages of the analysis were also carried out south of this study area (using 1:1 million scale bathymetry from California, Oregon and Washington), but the work has yet to be completed for this area.

INPUT DATA SETS

NRM Bathymetry

The NRM bathymetry contours were created from 10 kilometre line spacing depth sounding surveys of the Canadian EEZ that took place in the 1980's. The data are available as digital vector lines in 46 tiles. The scale is variable, though generally accepted to be 1:250,000. For the purpose of this analysis, a bathymetric surface was created in a two step process. 1) A TIN was created using the NRM contour lines as mass points, with a 1:50,000 scale coastline as hard replace lines of 0 elevation, 2) the TIN was converted to a 50 metre resolution raster using natural neighbours interpolation.

Canadian Gazetteer of Undersea Feature Names

The Canadian Gazetteer of Undersea Feature Names is maintained by the Geographical Names Board of Canada, originally published by the Canadian Hydrographic Service (Advisory Committee on Names for Undersea and Maritime Features, CPCGN. 1987). It contains 3605 named features located within Canada's territorial oceans. The name, designation and geographic point location (to the nearest minute) are included. A digital spreadsheet was obtained from the Canadian Geographic Names Database, and converted to decimal degrees for use in the GIS.

ANALYSIS

The Benthic Position Index (BPI) is a position based measure, calculated to provide an indication of the convexity of a surface at any given point. The index was originally developed as the Topographic Position Index (Weiss, 2001), modified for bathymetric application as BPI. Areas of consistent slope will have BPI values approaching 0, whereas convex areas will be highly positive and concave areas highly negative (Figure 1). BPI is derived using a standard algorithm involving a neighbourhood analysis function:

BPI = int((bathymetry-focalmean(bathymetry, annulus, irad, orad)) + .5)

bathymetry = input bathymetric data set
irad = inner radius of the annulus shape defining the analysis neighbourhood
orad = outer radius of the annulus shape

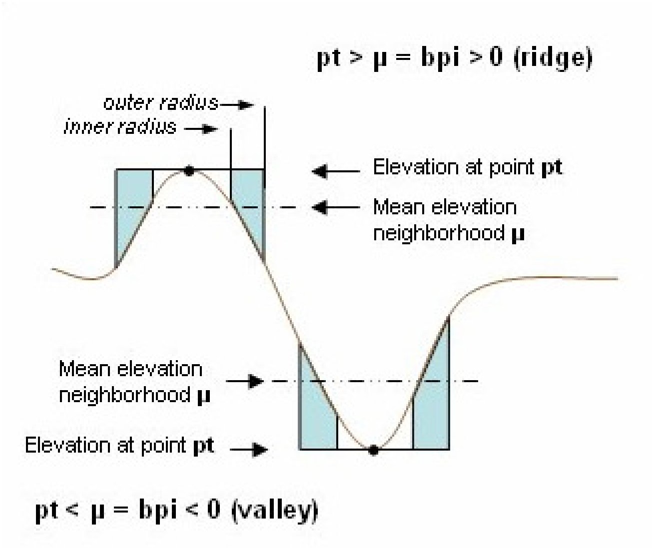

Figure 1. Areas of positive (e.g. ridges) and negative (e.g. valleys) BPI derivation (from Murphy and Wright, 2005)

The size and shape of the neighbourhood analysis window can be varied to distinguish features of different scale, depending on the purpose of the analysis. For use in the ESRI ArcGIS analysis environment, the Benthic Terrain Modeller (BTM) Tool extension has been developed by Oregon State University Department of Geosciences and NOAA Coastal Services Center (Rinehart et al., 2004) to calculate BPI surfaces and provide tools to aid in the identification of undersea features. The BPI surface used in this analysis was calculated from the derived NRM Grid, using the BTM extension (resampling the surface to 500 metres, specifying an outer cell radius of 10, and a scale factor of 10 kilometres). A 500 metre resolution slope surface was also created from the NRM Grid. To delineate the preliminary boundaries of undersea features, the slope and BPI surfaces were combined in a series of surface analyses (not using the BTM extension), identifying features of the 4 groups described below.

Seamounts, Hills, Ridges on the Continental Rise

Areas of slope greater than 3° (including areas surrounded by slope greater than 3°) and BPI value exceeding 100 were extracted to a raster grid. This grid was converted to a polygon shapefile and manually edited to 1) smooth edges, 2) snap to the deepest depth contour where possible, 3) separate joined features, 4) join broken features.
Following manual edits, the shapefile was converted back to a raster with unique ID as the value. The zonal maximum and zonal range were calculated for each feature using the NRM surface. These values were used to populate the Depth and Height attributes for the polygon features.
The polygons were spatially joined to the point locations of the Canadian Gazetteer of Undersea Feature Names, and where possible, overlapping

gazetted names were assigned to the polygon features. An attribute field was created in the resultant GIS Shapefile to store the Gazetted name. This field remains blank for unnamed features. An additional “Alias” attribute field was created to record known feature names that are not recorded in the Canadian Gazetteer for Undersea Feature Names.

Canyons and Valleys on the Continental Slope

For the purposes of this analysis, canyons are defined as “A relatively narrow, deep depression with steep sides, the bottom of which generally deepens continuously, developed characteristically on some continental slopes” (Intergovernmental Oceanographic Commission 2001). To match this definition, the following criteria were assessed for each feature: 1) depression: areas of the continental slope with BPI value less than -50 were extracted to a separate grid and converted to polygon shapefile; 2) steep sided: a visual comparison to the slope grid indicates a slope greater than 4 on a significant portion of the canyon sides; 3) narrow: a visual assessment of the width of the feature indicates approximately 50% of the overall width is steep sides; 4) deep: a visual comparison to the bathymetry contours indicates the height of sides is approximately 20% of width. Features with a bottom of generally continuous gradient were coded as valleys, the rest are canyons.

The BPI value of areas at the top of the slope tended to be high, and at the bottom of the slope tended to be low, so manual edits were performed to 1) extend features to the shelf break, and 2) remove areas of low BPI following the toe of the slope. 3) Joined features were separated, and 4) broken features were joined.

Gazetted names were transferred to the features using the same methodology as that used for the seamounts.

Troughs, Valleys and Basins on the Continental Shelf

Inlets, passages and channels were excluded from the analysis. These features all share the common criteria of “depression” and “continuous low gradient” in their definition. As such, they have been distinguished from canyons based primarily on their flat bottom. The following criteria were assessed: 1) depression: area of the continental shelf with BPI value less than 0; 2) bottom of low gradient: no major breaks in gradient and slope less than 2.

Gazetted names were transferred to the features using the same methodology as that used for the seamounts.

Troughs, Valleys and Basins on the Continental Rise

The same criteria as above were applied, but the extent of the features was limited to the continental rise, deeper than the toe of slope.

Gazetted names were transferred to the features using the same methodology as that used for the seamounts.

3.0 RESULTS

Seamounts, Hills, Ridges on the Continental Rise

The analysis identified a total of 175 isolated, steep sided, convex features. Table 1 lists the count for each feature type, classified according to height > 1000m and general shape (i.e. distinguishing ridges from the others). It was found that the "seamount" feature type designation in the gazetteer was not limited to features greater than 1000 metres in height. For example Seminole Seamount was found to be only 600 metres in height. For this reason, the features in the output shapefile were coded as "seamount" if they exceeded 600 metres in height (Figure 2). Further distinction between related feature types such as guyot, peak, knoll, caldera, cone, plateau, or pinnacle, were not attempted, except where the gazetteer had made the distinction (Table 2).

Table 1. Number of named and unnamed features of each type. Seamounts defined as uniform features greater than 1000 metres in elevation, ridges generally several times longer in length than width, and hills uniform features less than 1000 metres in elevation.

Feature Type	Named	Unnamed	Total
Seamount (height > 1000 m)	25	14	39
Ridge	9	4	14
Hill	5	118	123
Total	39	136	175

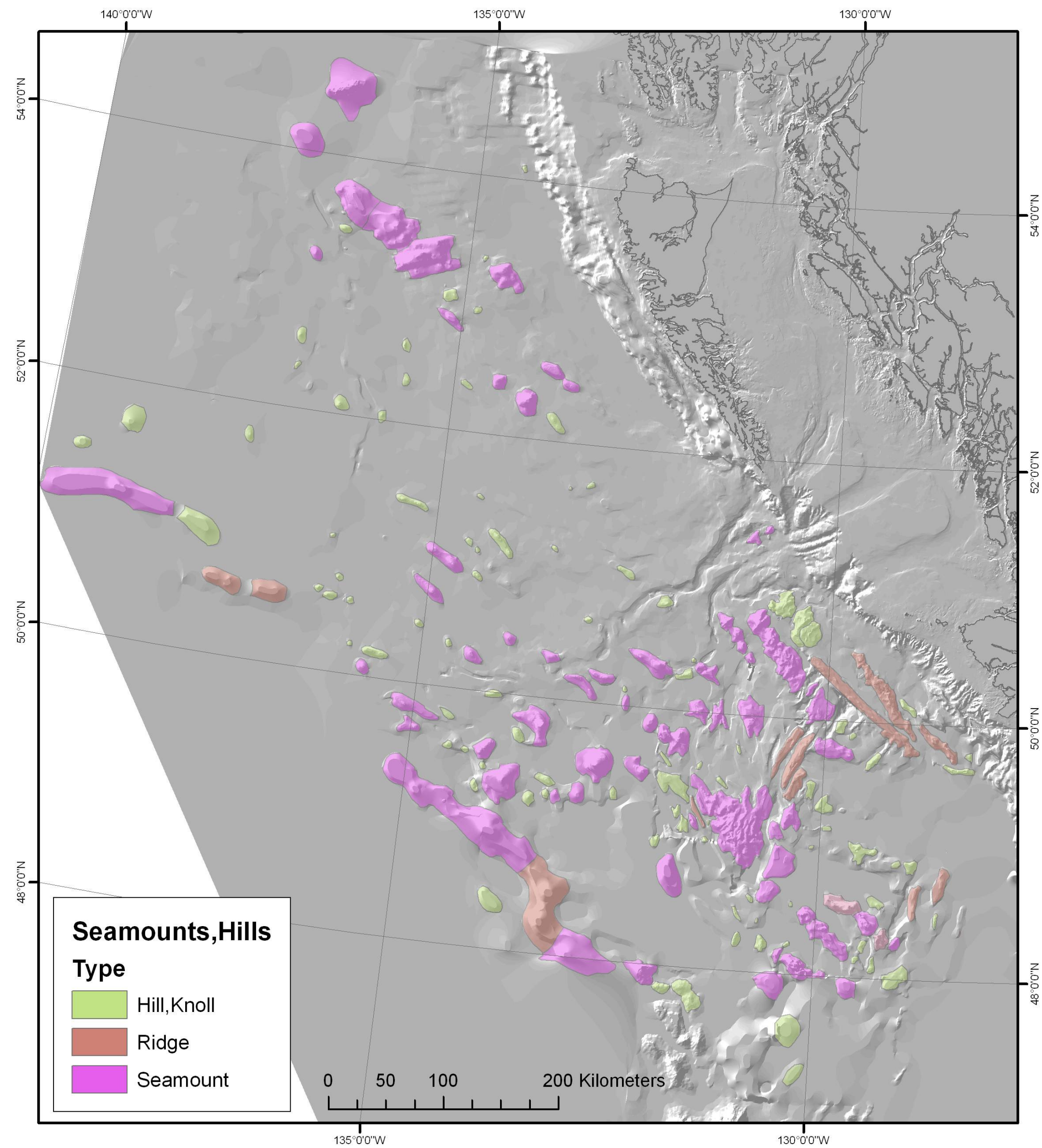

Figure 2. Seamount, hill and ridge features identified by BPI and slope analysis.

Only one feature of the Seamount, Ridge or Hill type from the Canadian Gazetteer of Undersea Feature Names database did not spatially join to the location of a feature identified in this analysis. The location of Stirni Seamount as recorded in the gazetteer (49° 07.00" N, 132° 16.00" W) was found to be 25 kilometres from any identified feature. Based on similarity to the morphology depicted in the Seamount Biogeosciences Network catalog (SBN, 2004), the NRM bathymetry indicates Stirni Seamount is located 100 kilometres west and 20 kilometres north, at (49° 18.00" N, 133° 50.00" W). The Stirni Seamount name was therefore applied to the feature identified by this analysis at that location, and the Geographical Names Board of Canada has been notified of the discrepancy.

Table 2. Features recorded in the Canadian Gazetteer of Undersea Feature Names identified by this analysis as seamount, hill, and ridge type. Values for depth and height were calculated by this analysis, and are approximate only.

Feature Name	Designation Type	Depth	Height
Bowie Seamount	Seamount - Mont	-65	3292
Union Seamount	Seamount - Mont	-498	2750
Forster Seamount	Seamount - Mont	-998	2648
Dickins Seamount	Seamount - Mont	-498	2504
Eickelberg Ridge	Ridge - Dorsale	-999	2502
Explorer Seamount	Seamount - Mont	-900	2400
Warwick Seamount	Seamount - Mont	-999	2400
Hodgkins Seamount	Seamount - Mont	-999	2302
Dellwood Seamount Chain	Seamount Chain - Ch	-598	2002
Oshawa Seamount	Seamount - Mont	-998	1838
Springfield Seamount	Seamount - Mont	-1000	1818
Tucker Seamount	Seamount - Mont	-1599	1734
Davidson Seamount	Seamount - Mont	-1499	1710
Stirni Seamount	Seamount – Mont	-1599	1704
Scott Seamount Chain	Seamount Chain - Ch	-1200	1640
Schoppe Ridge	Seamount Chain - Ch	-1998	1603
Chelan Seamount	Seamount - Mont	-1498	1602
Heck Seamount	Seamount - Mont	-1099	1588
West Peak	Peak - Pic	-1198	1502
Graham Seamount	Seamount - Mont	-1300	1422
Oglala Seamount	Seamount - Mont	-1599	1414
Heckle Seamount	Seamount - Mont	-1400	1380
East Peak	Peak - Pic	-1186	1316
Dellwood Knolls	Knolls - Dômes	-1848	1203
Heckle Seamount Chain	Seamount Chain - Ch	-1598	1201
Paul Revere Ridge	Ridge - Dorsale	-1399	1028
Denson Seamount	Seamount - Mont	-1998	1006
Northwest Dellwood Knol	Knoll - Dôme	-1497	952
Endeavour Seamount	Seamount - Mont	-1699	901
Haida Ridge	Ridge - Dorsale	-1398	805
West Ridge	Ridge - Dorsale	-2099	800
Winona Ridge	Ridge - Dorsale	-1498	702
Tuzo Wilson Seamounts	Seamounts - Monts s	-1399	657
Peters Ridge	Ridge - Dorsale	-2998	607
Seminole Seamount	Seamount - Mont	-1699	600
Southeast Dellwood Knol	Knoll - Dôme	-1498	518
Tuzo Wilson Seamounts	Seamounts - Monts s	-1969	486
Middle Ridge	Ridge - Dorsale	-2099	303
East Ridge	Ridge - Dorsale	-2400	101

Canyons and Valleys on the Continental Slope

A total of 57 canyon and valley features were identified on the continental slope. The spatial distribution of canyon and valley features was strongly predicted by location. Only one canyon was found on the Queen Charlotte Slope (north of Cape St. James), where the major steep sided, narrow, depressions were consistently oriented parallel to the slope and classified as valleys (Figure 3). In contrast, 35 canyons were found south of Cape St. James.

None of the valleys were named in the Canadian Gazetteer of Undersea Feature Names database, whereas 13 named canyons were delineated (Table 3). The boundaries of Crowther, Kyuquot, and Esperanza Canyons were difficult to distinguish, as the terrain was very complex in these areas. Higher resolution bathymetric surveys of this area may provide further clarity to the configuration of these features should they be carried out in the future.

Table 3. Number of named and unnamed canyon and valley features of each type.

Feature Type	Named	Unnamed	Total
Canyon	13	36	49
Valley	0	8	8
Total	13	44	57

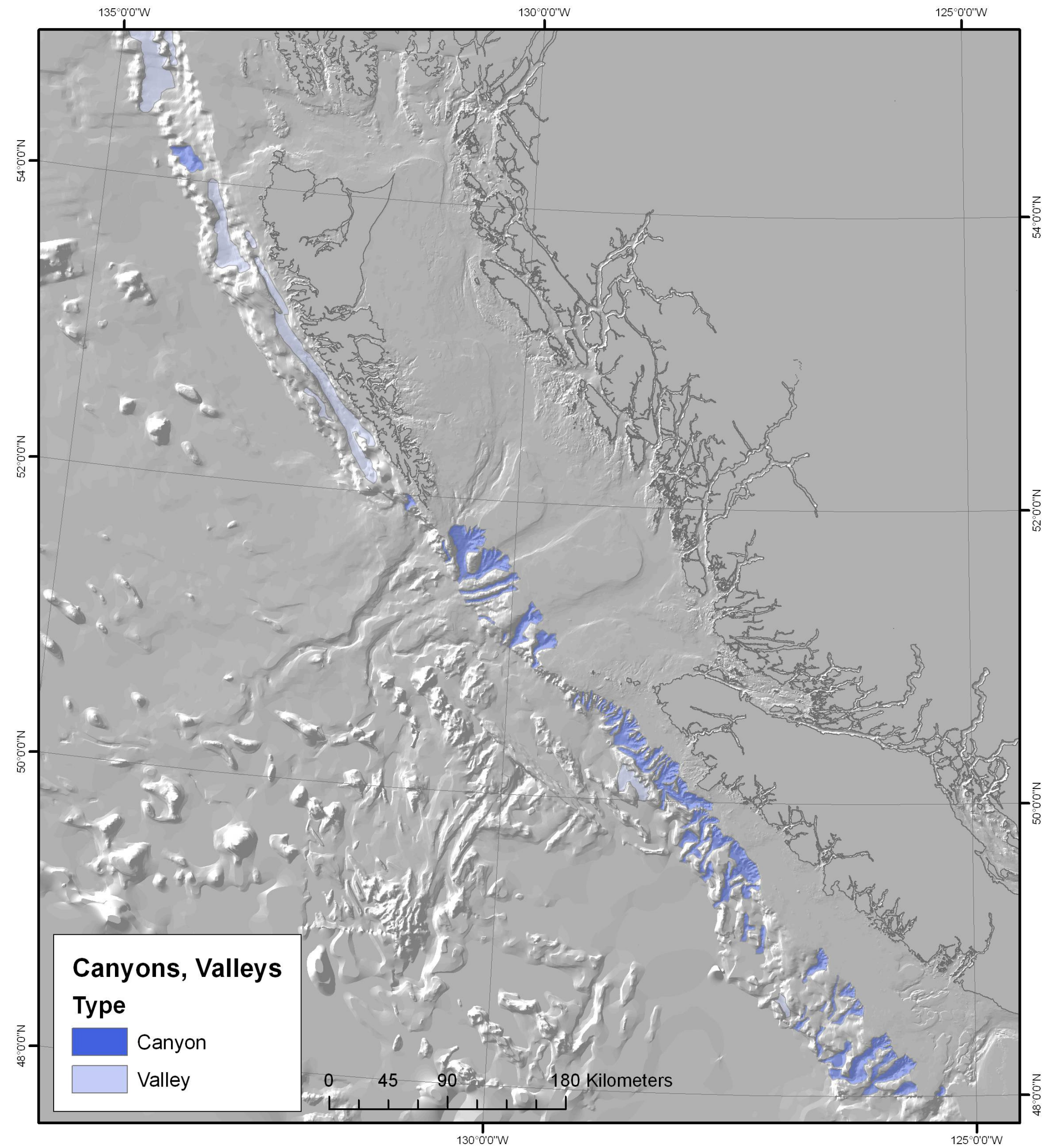

Figure 3. Canyon and valley features on the continental slope identified by BPI and slope analysis.

Troughs, Valleys and Basins on the Continental Shelf

On the continental shelf, excluding features which are defined by the shoreline (i.e. passages, inlets, and channels), there were a total of 25 large undersea features identified (Figure 4). Features were classified as trough, basin, and canyon types, 60% of which were unnamed (Table 4). The major features named in the Gazetteer included the large troughs in Hecate Strait: Morseby, Reed, Sea Otter, and Cook Troughs; as well as Dixon Trough; and Malaspina and Ballenas

Troughs in the Strait of Georgia. Also named in the Gazetteer were Sechelt and Boundary Basin, and Tully Canyon on the Vancouver Island shelf.

Table 4. Number of named and unnamed trough, basin and canyon features identified on the continental shelf.

Feature Type	Named	Unnamed	Total
Trough	7	12	19
Basin	2	2	4
Canyon	1	1	2
Total	10	15	25

Troughs, Valleys and Basins on the Continental Rise

A total of 48 features were identified on the continental rise (Figure 4). Features were classified as trough, basin, valley, median valley and gap (Table 5). The major named features included Queen Charlotte Trough, Moresby and Scott Channels; Dellwood, Winona and Tofino Basins; and the Explorer Median Valleys.

A feature named “Haida Channel”, classified in the Gazetteer as a trough at the geographic coordinates 49° 15.00” N, 129° W, was found to fall in the middle of a large basin with no trough-like feature in the vicinity. Local knowledge of an undersea trough named Haida Channel could not be obtained during this exercise, and therefore no feature has been assigned the name Haida Channel. The Geographical Names Board of Canada has been advised of the error in the coordinates for this record in the Canadian Gazetteer for Undersea Features, though corrected values for the coordinates were not proposed. The Gazetteer contains feature named “Haida Ridge” approximately 75 km to the northeast, and it is suspected that the intended location of Haida Channel lies in this vicinity.

The large basin identified in this analysis as Tofino Basin has no record in the Canadian Gazetteer for Undersea Feature Names database. The name was sourced from a map in Thomson (1981). It is counted in Table 4 as a named basin.

Table 5. Number of named and unnamed trough, basin and canyon features identified on the continental rise.

Feature Type	Named	Unnamed	Total
Trough	4	17	21
Basin	3	1	4
Valley	4	14	18
Median Valley	3	0	3
Gap	1	0	1
Abyssal Plain	1	0	1
Total	16	32	48

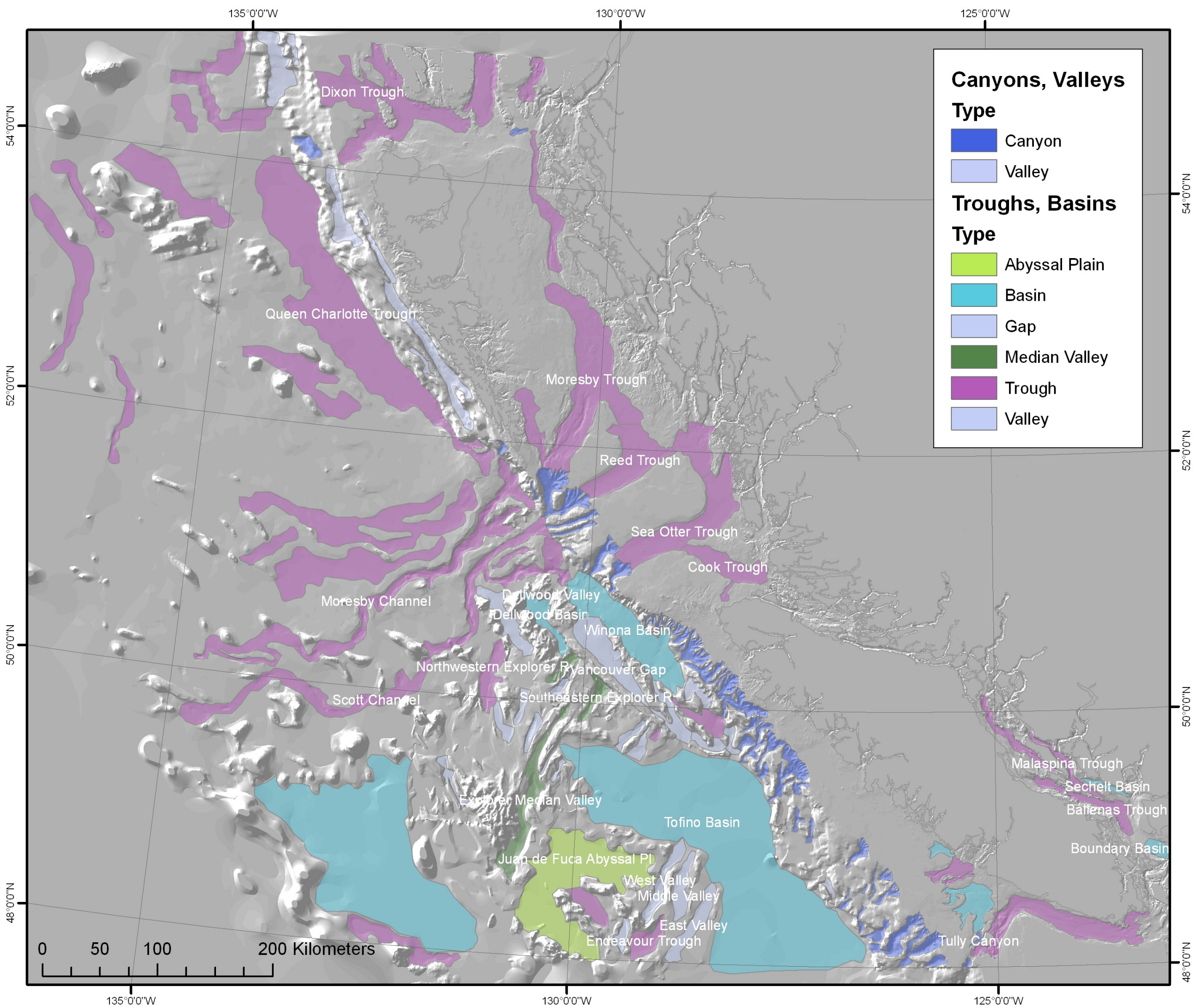

Figure 4. Troughs, basins, valleys, and canyons identified in the study area.

Output Data Sets

Copies of the GIS data sets produced from this analysis may be obtained in ESRI Shapefile format by contacting:

GIS Unit
Oceans, Habitat and Enhancement Branch
DFO – Pacific Region
200-401 Burrard Street
Vancouver, British Columbia
V6C 3S4
email: dwight.mccullough@dfo-mpo.gc.ca

4.0 DISCUSSION

Differences in the general physical characteristics of the geographic regions (e.g. continental rise, continental slope, continental shelf) and the varied topography encompassed by the broad geographic extent of the study area led to difficulty in identifying a single set of parameters to use for the definition of the output features by the BTM extension. For example, the generally high slope characterizing the continental slope tended to influence the BPI scores for cells in its vicinity. Defining a single range of BPI values to define a feature type that would also apply to areas in generally flat areas was therefore not possible. Results were generally improved by analysing subsets of the BPI surface corresponding to the broad geographic areas of the continental rise, continental slope, and continental shelf as separate data sets, in combination with the slope. This was more efficiently done outside of the BTM extension, using the GIS raster calculator.

Difficulty was also encountered with the tendency of the BPI algorithm to assign negative BPI values to flat areas located at the bottom of a slope. This results in a “moat effect”, where a trough erroneously appears at the base of seamounts or ridges. The reverse effect was also found at the shelf break. This effect could not be entirely eliminated by modifying the parameters for the algorithm. Attempts to combine a “fine scale” BPI surface through the BTM extension were not completely successful in resolving the issue. Some manual editing of the resultant data was therefore necessary to distinguish real troughs from the artefacts resulting from this “moat effect”.

In general, the analysis was most successful at identifying seamounts and shelf break canyons, due to the relatively well defined nature of the features.

The real value of this analysis will ultimately be determined by its utility in Integrated Management planning activities in the Pacific Region. Preliminary spatial overlays of the shelf break canyons with catch per unit effort data from the sablefish trap fishery reveal a strong spatial correlation (Figure 5). The correlation between shelf break canyons and fish concentrations has been observed elsewhere (Genin 2004) and can be explained by the biophysical interactions which lead to increased areas of productivity at canyon heads (Allen et al. 2001, Genin 2004). It has been demonstrated that canyons enhance deep ocean water upwelling (Hickey 1997, Allen et al. 2001, Sobarzo and Djurfeldt 2004, Mirshak and Allen 2005) which leads to aggregations of zooplankton and fish forming at the canyon heads (Mackas et al. 1997, Allen et al. 2001). Similar areas of high productivity are observed over seamounts and can also be explained through biophysical interactions (Genin 2004). Recognizing the potential importance of undersea features to biological productivity in the northeast Pacific Ocean, consideration of their distribution in Integrated Management planning activities should be important.

This inventory enables the consideration of the spatial distribution of large undersea features in future planning activities in Fisheries and Oceans Canada's Pacific Region. Current Integrated Management planning activities have been varied, and will continue to involve many stakeholders. The spatial data sets created through this analysis are freely available for download, and should contribute to these processes, in this way helping to fulfill Fisheries and Oceans Canada's commitment to implementing Canada's Ocean Strategy.

5.0 ACKNOWLEDGEMENTS

The author wishes to thank Dwight McCullough for his valuable assistance in coordinating the review and completion of the project, and to Kim Conway, Robert Kung, Terry Curran, Jack Mathias, Rob Hare, and George Schlagintweit for their review of the manuscript and results.

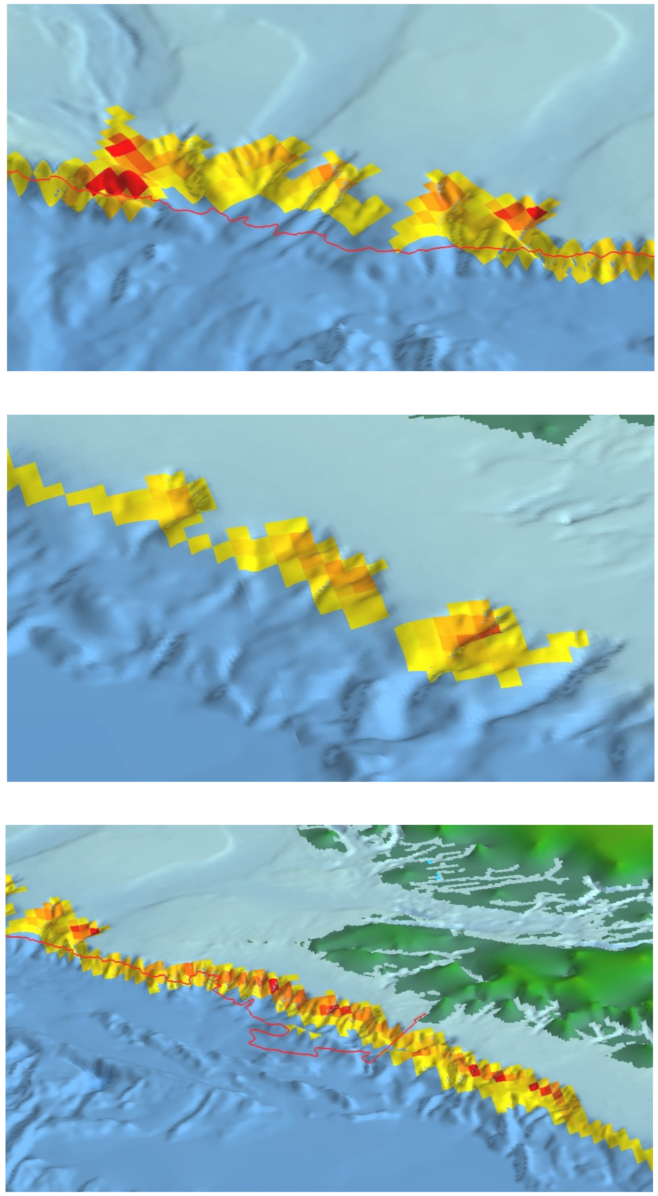

Figure 5. Perspective 3 dimensional views of spatial overlays of sable fish catch per unit effort (by trap fishery) on the bathymetric surface used during this analysis. High values are spatially associated with a) Moresby, Reed, and Sea Otter Canyons; b) Barkley and Clayoquot Canyons; and c) various canyons at the northern Vancouver Island shelf break (Pacific North Coast Integrated Management Area boundary shown in red).

6.0 REFERENCES

Allen, S.E., Vindeirinho, C., Thomson, R.E., Foreman, M.G., and Mackas, D.L. 2001. Physical and biological processes over a submarine canyon during an upwelling event. Can. J. Fish. Aquat. Sci. 58: 671-684.

Advisory Committee on Names for Undersea and Maritime Features, CPCGN. 1987. Gazetteer of Undersea Feature Names 1987. Department of Fisheries and Oceans, Canadian Hydrographic Service, Ottawa, Ont. 155p.

Ferdana, Z. 2005. Case Study: Pacific northwest coast (PNWC) ecoregion offshore classification methodology. TNC-NOAA CSC Partnership Project.

Genin, A. 2004. Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. J. Mar. Systems 50:3-20.

Hickey, B.M. 1997. The response of a steep-sided narrow canyon to time-variable wind forcing. J. Phys. Oceanogr. 27: 697-726.

Intergovernmental Oceanographic Commission, 2001. Standardization of Undersea Feature Names. Guidelines Proposal Form Terminology. Bathymetric Publication No. 6. International Hydrographic Bureau, Monaco. 29 pp.

Mackas, D.L., Kieser, R., Saunders, M., Yelland, D.R., Brown, R.M., and Moore, D.F. 1997. Aggregation of euphausiids and Pacific hake (Merluccius productus) along the outer continental shelf of Vancouver Island. Can. J. Fish. Aquat. Sci. 58: 685-702.

Mirshak, R., and Allen, S.E. 2005. Spin-up and the effects of a submarine canyon: Applications to upwelling in Astoria Canyon. J. Geophys. Res. 110, C02013, doi:10.1029/2004JC002578

Murphy, J, and Wright, D.J. 2005. Benthic Terrain Modeller Version 1.0 Help Documentation.

Rinehart, R.W., Wright, D.J., Lundblad, E.R., Larkin, E.M., Murphy, J., and Cary-Kothera, L. 2004. ArcGIS 8.x Benthic Terrain Modeller: Analysis in American Samoa. Proceedings of the 24th Annual ESRI User Conference, San Diego, CA, Paper 1433, 2004.

Sobarzo, M. and Djurfeldt, L. 2004. Coastal upwelling process on a continental shelf limited by submarine canyons, Concepcion, central Chile. J. Geophys. Res. 109, C12012, doi:10.1029/2004JC002350.

Thomson, R.E. 1981. Oceanography of the British Columbia coast. Can. Spec. Publ. Fish. Aquat. Sci. 56: 291 p.

Wiess, A.D. 2001. Topographic positions and landforms analysis, Proceedings of the 21st Annual ESRI User Converence (Map Gallery Poster), San Diego, CA.