

# Undersea Feature Discovery Project (UFDP) Report on SCUFN 32

## Introduction / Background

Fisheries and Oceans Canada (DFO), is a member of the Geographical Names Board of Canada (GNBC). As Canada's national naming authority, the GNBC has a sub-committee dedicated to undersea feature naming - the Advisory Committee for Undersea Feature Names (ACUFN). The Canadian Hydrographic Service of DFO, leads this Committee and maintains the Canadian Gazetteer of Undersea Feature Names.

With the availability of new and finer quality bathymetric data, ACUFN wanted to discover new undersea features in Canadian waters, in order to generate new name submissions. Thus began the Undersea Feature Discovery Project (UFDP). There is no technological investment cost attached to this project, other than the human resource. The analysis is based on open bathymetric data and GIS.

The methodology for discovery was derived from the definitions of the generic terms in the B-6. These definitions were used as the IHO standard from which to base the analysis. The project explored how features could be detected in bathymetric data, and how that detection could be automated. The initial research findings for the discovery of Seamounts and Basins were shared at SCUFN31. Great interest was generated as it pertained to:

1. **the potential for automating the discovery of undersea features.**
2. **standardizing the settings and thresholds used to discover different features (different generic terms) with a desire to build consistency in the result of the analysis.**

## Project Plan Overview

The Undersea Feature Detection Project (UFDP) emerged through a series of leadership and research opportunities related to the national and international commitments of DFO's Canadian Hydrographic Service (CHS)

By the time this document was written, a team of intern university students (Shenghao Shi (lead), Oliver Farwell, Erin Turnbull and Samir Sellars) had accomplished the following.

1. Completed the discovery methods for abyssal plains and slope
2. Fully automated the discovery of seamounts, guyot, and basins
3. Developed Python script based tools that help to improve the efficiency and effectiveness of the undersea feature discovery (see full list below)
4. Discovery methods for canyons and escarpments have been preliminary established.

The Undersea Feature Detection Project Plan covers the stakeholders involved, the history of UFDP, strategic objectives and detailed discovery workflow for each objective.

To summarize, the strategic objectives of the UFDP are **to create automated tools for the discovery of all undersea features listed in the B6, storing the newly discovered features in a reliable database, and provide feedback, when applicable, to the Generic Terms Working Group at SCUFN to consider for improvement of the generic term definitions in B6.**

Figure 1. briefly explains the steps that are followed during the development of the undersea feature discovery tools.

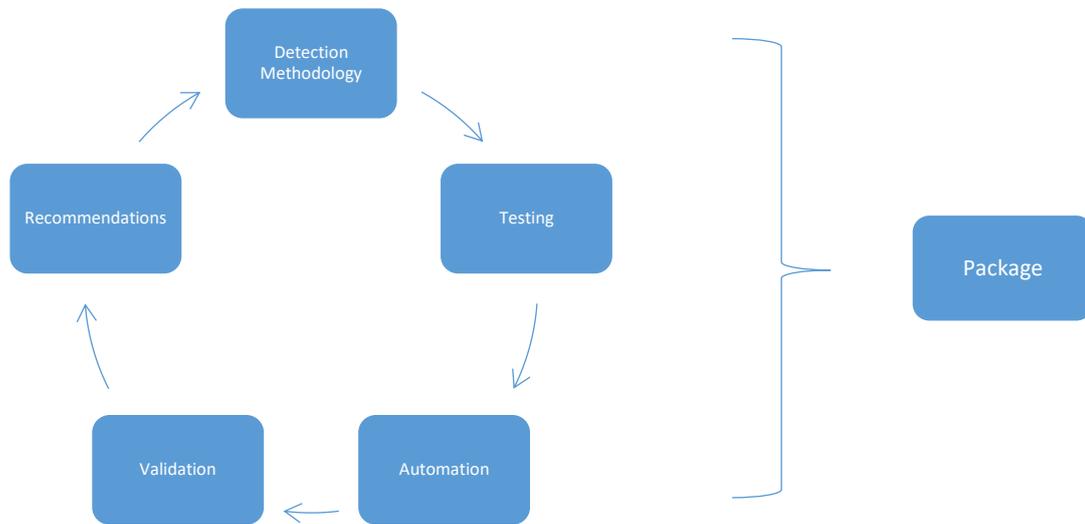


Figure 1 Undersea Feature Detection Cycle

For more information regarding the project plan, please see [Appendix I](#).

## Outcome

Currently, the research taking place at UFDP, is well aligned with one of SCUFN's many mandates, in this case being, the revision of definitions in B-6. The progress since SCUFN31 includes:

- Discovery methods that have been automated as a toolbox for ArcMap:
  - [Basins](#),
  - Seamounts,
  - Guyot (flat-top seamount, as a sub-category of seamount)
- Other discovery methods have been completed, but have not been automated yet:
  - [Ridges](#),
  - [Abyssal Plains](#)
  - [Sea Channels](#)
  - [Shelf](#)
  - [Slope](#)
- Discovery methods in progress: Canyon, Escarpment
- Python script based tools that help to improve the efficiency and effectiveness of the undersea feature discovery have been developed for:
  - Concave Hull,
  - Directional Buffer,
  - Topographic Position Index,
  - TPI-Slope Classification,
  - Dual-TPI Slope Classification,
  - Filter Elliptical Cones,
  - Identify Pelagic Zones,

- Identify Point Nearest Centroid,
- Identify Zonal Maximum Cells,
- Local Topography,
- Nice Raster to Polygons

For more information regarding the discovery methodologies and automation, please see [Appendix II to VI](#).

### Issues about the Current B6 Generic Terms

During the automation process of Seamounts we experienced the advantages of automating the discovery of generic terms in B-6 that contain clear quantitative information. A Seamount is described as “A distinct generally equidimensional elevation **greater than 1000m** above the surrounding relief as measured from the deepest isobath that surrounds most of the feature.” That 1000m played an important role as the threshold for deciding whether the elevations can be identified as seamounts or not. However, the definition of seamount is not perfect since its many aspects are still qualitative, which will be further explained in the following paragraphs. In addition, 37 Out of 43 of the generic terms in B-6 do not have a quantitative figure, associated with the criteria defined in the B-6 definitions (Figure 2).



Figure 2. List of common criteria in the B-6 generic terms definitions.

For instance, B-6 defines basin as “A depression more or less equidimensional in plan and of variable extent”. However, there is no explanation about what is considered to be a depression. In our discovery method for basin, the analysts used their own interpretation of the word “depression”. The resulting method included 1) dividing the entire area of interest into multiple potential basins, using a flow accumulation method. 2) Identifying the edge and the centre of each polygon. 3) Comparing the average depth of the centre to the edge area. 4) Comparing the average slope value of the centre to the edge area. Although we were able to automate the identification, we still made plenty of assumptions in our methodology such as what was considered to be flat.

These assumptions will need to be verified, against a standardized understanding of how to identify a “depression”. Otherwise, it would be difficult to expect that a different team of analysts would reach the same result. It is required that for consistency, all analysts (or automated scripts) apply the same interpretation of the criteria defined in the B-6 definitions (Figure 1). For this outcome to be successful, the associated quantitative settings and thresholds will need to be defined.

This is an example of a definition of “depression”, that could be applied consistently and that could be successfully automated:

**The deepest point of a depression, should be no less than 500m, when compared to its surrounding isobath, and the steepness of the descending slope should be greater than 5 degrees on average. The flat central area should have a relief variance of less than 75m and occupy no less than 66% of the total area considered to be a depression.**

*Please note that this is just an example, the number is not validated and should not be considered as a reference in any ways. In addition, drawn from the experience of our GIS technicians, the definition does not always need to be a fixed value, it should allow fluctuation by giving a margin of error and/or have localized parameters.*

For more reliable examples of improved definitions, please see the drafted the definitions for abyssal plains and sea channels, which have detailed explanations and justifications in Appendix II and V respectively. The new quantitative definitions will be created base on 1) existing literatures 2) B6 generic terms definition 3) methodology parameters 4) data measured from named features from GEBCO database 5) data measured from newly discovered features using our discovery methodology (with high level of confidence).

The team is currently continue developing quantitative definitions for undersea features that already have their discovery method completed.

## Conclusions

In our efforts to discover new undersea features in Canadian waters in order to generate new name submissions, we have encounter challenges. Applying the definitions of the generic terms in B-6, to derive methodologies for analysis and then automation, required that we made some assumptions of the quantitative aspect of some descriptions such as “depression”, “steepness” or “slope”. To have the assurance that we have followed, and will continue to follow the international standards for identifying generic terms, the assumptions that we have made, would need to be checked, and revised quantitative information for all generic terms, would be useful to define. This will be necessary to standardize the consistent interpretation of each generic term, and the successful automation of the discovery and identification of more undersea features.

## Recommendations

1. Summarize the list of common terms that may cause ambiguity. *E.g. sloping, equal-dimensional, shallow, deep, elongated...*
2. Define common terms such as “flat” and “near” with quantitative description such as “elevation variation less than 100m” and “no further than 50km away from...”
  - Wording needs to be quantified and standardized. For example, slope equal or less than 0.5 degree shall be called **flat**; slope greater or equal to 0.5 but less than 2 degree shall be called **gently sloping**; slope greater or equal to 2 degree but less than 5 degree shall be called **slope**; slope greater than 5 degree shall be called **steep slope**...
3. Quantify and standardize the usage of modal verb and frequency related adjectives, such as *must, should, usually, seldom, etc.*
4. Decide the category of numerical value needed to be standardized for each generic term. *E.g. basin needs quantitative description for its descending slope minimum in degree, center area size to total area proportion in percentage, minimum size in square kilometres.*
5. Consolidate the new definitions for the generic terms that have been revised, and make them available to test in the development of automation scripts to aid the discovery of undersea features, from bathymetric data.

The UFDP has developed a few updated, quantitative generic term definitions based on credible sources. They are:

- **Abysal Plain:**  
An extensive area larger than 850 km<sup>2</sup>, that overlies a flat or gently sloping area with 0 - 50 m of local relief, and is found at a depth between 4000 and 6000 meters.
- **Shelf Break:**  
A line defined by the shoreward boundary of an area which deepens at a rate of at least 400 m per 30,000 m away from shore or has a localized slope of at least 1°. It may include adjacent areas which deepen at a rate of 350 m per 30,000 m or have a localized slope of at least 0.5°. It must span depths from 250 m to 1,000 m.
- **Shelf:**  
The flat or gently sloping region adjacent to a continent or around an island that extends from the low water line to the shelf-break.
- **Sea Channel:**  
A meandering linear depression with sinuosity typically greater than 1.3, at least no less than 1.15. Feature need to be no shorter than 150 km, usually occurring on a gently sloping plain or FAN where local slope standard deviation is typically less than 0.5 degree, at least no more than 0.65 degree.

The UFDP team will continue working on definition recommendations and make adjustments base on the feedback we receive after the SCUFN 32.

### **Justification and Impacts**

Standardizing the definitions of generic terms, fits into the objective of SCUFN and benefits our understanding about the seafloor.

### **Action Required of SCUFN32**

We are willing to have more in-depth presentation of our work to anyone who is interested, either for showing or for discussion and updating.

The UFDP will highly appreciate support and feedback from SCUFN members, we are expecting expertise, suggestions, and feedbacks include but not limited to the following fields of study:

- GIS
- Topography
- Oceanography
- Geology
- Earth science

Topics we would like to discuss include:

- General discussion about discovery methodology, automation, and/or validation
- Information about undersea feature development, formation, and transformation
- Undersea feature categorization
- Definition improvement
- etc.

## Appendix I

# Undersea Feature Detection – Project Plan

Canadian Hydrographic Service – Fisheries and Oceans

April 1<sup>st</sup>, 2019

Andrew Roberts

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## Contacts

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## Overview

The Undersea Feature Detection Project (UFDP) emerged through a series of leadership and research opportunities related to the Canadian Hydrographic Service's (CHS) national and international commitments. To understand those opportunities and the 'why' of the UFDP, some context is required.

### Stakeholders

Representing DFO, CHS is an official federal member of the Geographical Names Board of Canada (GNBC) whose board consists of Federal, Provincial, and Appointed members. As Canada's national naming authority, the GNBC has a sub-committee dedicated to undersea feature naming - the Advisory Committee for Undersea Feature Names (ACUFN). CHS chairs ACUFN, houses the secretariat, and maintains the ACUFN website. ACUFN is composed of members from the GNBC secretariat, CHS, private industry, and academia. It reports annually to the GNBC, and handles all naming requests or inquiries related to undersea features.

On the international level, undersea feature naming is handled through the Standing Committee of Undersea Feature Names (SCUFN) at the International Hydrographic Organization (IHO). CHS represents Canada as a member at SCUFN, and serves as an observer and advocate for Canadian interests and submissions. The IHO jointly supports the General Bathymetric Chart of the Oceans (GEBCO), which has as a project Seabed 2030 – the goal of mapping all ocean floors by 2030.

## History

All of these organizations and sub-committees have a common shared goal of data standardization and interoperability. ACUFN aims to harmonize all generic terms (official names for undersea feature types) with the IHO. The IHO aims for an improved data structure for GIS web map services and the addition of all generic terms to the IHO Geographic Information Registry. National hydrographic organizations (i.e. Canada) are creating and contributing more bathymetric data for projects like Seabed 2030, requiring an international standard for categorization, naming, and sharing. In September 2016 at SCUFN's 29<sup>th</sup> meeting (SCFUN29), the Undersea Feature Name Project Team (UFNPT) was created to address these issues. Along with exploring the creation of an S-100 compliant data model which would set a new and flexible international standard for undersea feature names (UFNs), the UFNPT would work closely with the Generic Term Working Group (GTWG) to harmonize generic terms.

The UFDP began in the context of these moving parts. In light of new and finer quality bathymetric data, ACUFN wanted to investigate whether new undersea features could be discovered in Canadian waters in order to generate new name submissions. CHS headed that research and began the UFDP as a co-op project. As one of ACUFN's priorities was harmonizing with IHO generic terms, the B6 Generic Terms list (IHO standard) was applied to the research. Using characteristics defined in the B6 definitions, the project explored how features could be detected in bathymetric data, and how that detection could be automated. CHS' position on SCUFN allowed the opportunity to bring the research findings to an international level at SCUFN30. Great interest was generated from the UFDP presentation as it pertained to 1) benefits of automation in terms of international standardization, and 2) issues with the ambiguity of generic terms and challenges that presents to automation and standardization. The research of the UFDP exposed the weakness of the current generic terms as they apply to standardization, and in order to achieve the goal of an international data model standard for UFNs, the UFNPT must incorporate the required changes of the generic terms into the new data model (changes the GTWG must confirm). After SCUFN30 interest in the UFDP was strong in both the UFNPT and the GTWG.

As described here, the interests of ACUFN and SCUFN are well aligned and continue to generate demand for the UFDP research. The following sections will outline the main areas of focus, strategic objectives, and deliverables.

## Strategic Objectives

The strategic purpose of the UFDP is to create methodologies to automate the discovery of undersea features from bathymetric data. This will provide ACUFN with the possibility for new name submissions, as well as increase efficiency in data processing. The UFDP research has broader interest from SCUFN and the UFNPT, and so objectives can be aligned. The strategic objectives of the project are as follows;

- 1) Create reliable tools for the discovery of undersea features listed in the B6 Generic Term list;
- 2) Create a bank of newly discovered, unnamed undersea features;
- 3) Provide feedback on B6 generic terms to the GTWG regarding their applicability to standardization and automation;

- 4) Provide feedback to the UFNPT regarding generic term definitions and impacts or modifications that could be applied to the new S-100 Undersea Feature product specification.

### Objective 1. Reliable Tools

Objective 1 is the core research goal of the project. In order to confidently identify undersea features in current and future bathymetric data sets, reliable, validated tools must be developed. This development can follow a similar cycle for the various undersea feature. Figure 1 below illustrates the recommended development cycle.

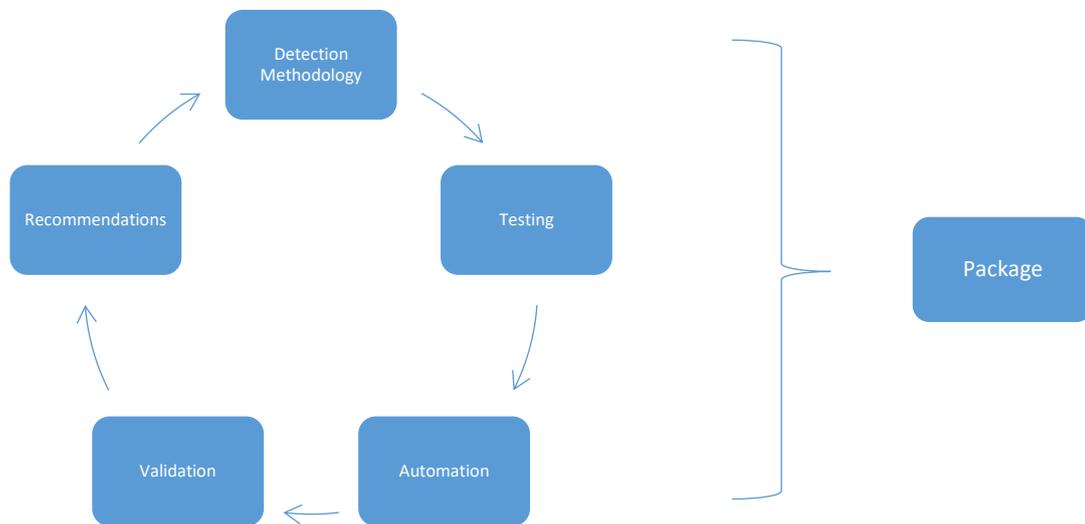


Figure 2 Undersea Feature Detection Cycle

#### Step 1. Detection Methodology

Several examples of this already exist thanks to prior research done on Seamounts, Guyots, Basins, Ridges, and Channels. Methodologies will change from feature to feature as unique specs are accounted for using the B6 definitions. Some definitions have quantifiable qualities that make them easily measured, i.e. seamounts must be at a depth of at least 2000m. However, some definitions have vague and qualitative descriptions. Interpretation of these and the translation of them into measured detection methods requires creativity and testing.

*Deliverable: Preliminary detection methodology for a new undersea feature*

#### Step 2. Testing

Once a methodology is developed it must be tested and refined. Visual validation can be performed to check results. For this purpose training data should be identified though visual check should suffice.

The main goal is to confirm that the methodology is identifying the correct features, and that small fragments and residual features are removed.

*Deliverable: Tested methodology and relatively accurate output features*

### Step 3. Automation

With a methodology working, it should be compiled into an automated environment such as ArcGIS Model Builder, or a python script. Automating will force qualitative questions to be answered and recorded, as well as remove variability in analysis decisions common in a user controlled workflow. Output should be a workable raster or polygon feature layer of identified features.

*Deliverable: Automated script or model of the new undersea feature detection methodology*

### Step 4. Validation

This step is crucial in order to report with confidence the validity of the automated output. A methodology must be developed that will determine the statistical confidence of the outputs, and which can be applied to all the models. Training data must be identified or created for this purpose. This will be an iterative process and, will be the final refining of the model in order to generate accurate results. Should validation expose flaws in the methodology, Step 1 should be revisited. Accuracy of the models must be recorded, and should be tested with differing data and parameter modifications.

*Deliverable: Final automated detection model/script, statistically tested and validated*

### Step 5. Recommendations

With the completion of a detection methodology, recommendations should be made, if applicable, on how to improve the B6 Generic Term definition of the feature. Definitions are notoriously vague and qualitative, leaving arguably too much room for interpretation and subjectivity. Hard numbers generated for the models or discovered in the research can be recommended. Lessons learned from the research and the interpretation of the current term can be added. Any information that can be useful for the improvement and increased specificity of the B6 Term should be included in a recommendation.

*Deliverable: short document outlining recommendations that can be passed on to the GTWG and UFNPT*

### Step 6. Packaging

As a final step the completed automation script must be wrapped in a shareable/transferable package. This must include two main portions; supporting documentation and tools.

Supporting documentation should include a final report outlining methodology, validation output, and a how-to-guide for running the tool itself and interpreting the outputs.

The tool should be a simplified interface to the automation process. If it's a script, requests for path changes and optional parameters should be clear and kept to a minimum (parameters that effect output quality should be hardcoded). If the tool is a model, again, clear and minimal steps must be outlined. Variability in output is counter to standardization (as well as multiple runs by the same user).

## **Objective 2. Discovered Features Database**

The ultimate goal of the UFDP is to generate newly discovered undersea features to name in Canadian waters. The newly discovered features from Objective 1 will therefore need to be stored in a database that facilitates their sharing and access. Submission of these features to GEBCO requires specific attribute data and correct feature geometries.

### **Step 1. Project and Database Creation**

An ArcMap project and geodatabase should be created to store and standardize the unnamed features. The B6 document specifies the accepted geometry of submitted features, as well as required attribute data. The geodatabase should be created using these requirements in order to populate with accepted standards. The project should facilitate the discovery and selection of undersea features.

*Deliverable: standardized geodatabase created for various undersea feature geometries.*

### **Step 2. Populate Database**

Although the scripts will be refined and the outputs will be validated, the features added to this database should be thoroughly vetted as they are theoretically ready for submission. However the naming process looks, the point, lines, and polygons in this database are the authoritative source for the unnamed features. Script outputs for the varied features must be validated, then imported to the db under the correct geometries, and the required attribute data either entered or calculated for each feature. The db must be formatted in a way to facilitate submissions. A simple export of features should meet all GEBCO submission requirements.

*Deliverable: database populated with all discovered undersea features, accessed via an organized map project.*

## **Objective 3. GTWG Feedback**

This objective should be covered through Step 5 in objective 1. The Generic Term Working Group is actively reviewing B6 Definitions and has already taken much interest in the UFDP. Findings from research and development should be composed in a document and submitted to the group as recommendations that can improve automation and standardization. Both goals go hand in hand as standardization leans towards quantifiable characteristics (min height, max width, etc), which apply well to automation and scripting. The recommendation feedback can be submitted as new features are identified, though the format should be standardized for submissions.

*Deliverable: A single report or series of reports outlining improvement recommendations to the B6 Definitions.*

#### **Objective 4. UFNPT Feedback**

The development of a new S-100 Undersea Feature product specification is underway. A primary goal in moving to a new product spec is data interoperability and flexibility. The new spec allows for additional attributes which will meet the requirements of various user types (mariners, scientists, etc). As research is underway for both the B6 Definitions and the Undersea Feature model itself, it only makes sense to provide feedback between both. Any research findings or modifications/enhancements to the data model that could result in improvements to standardization or automation should be included in a report to the UFNPT.

*Deliverable: A single report outlining improvement recommendations to the UFN Data Model for new S-100 Spec.*

#### **Wish List**

Packaging – Once all automation scripts are developed and finalized, the creation of a single interface for UFN discovery would be favorable. This could come in the form of an Arc Toolbox. All automation scripts could be merged into a single tool where users select the feature to discover, parameters are entered, outputs are chosen, and with one click the automation begins.

#### **Conclusion**

This project plan should serve as a thorough, high level understanding/vision for the UFD. Timeline and task lists must be developed according to current work availability and skills. Development will be variable as work resources are subject to change. For any questions, please consult the contacts listed at the beginning of the documents.



## Appendix II

# Abyssal Plains Report

By: Samir Sellars

**IHO definition:** An extensive, flat or gently sloping region, usually found at depths greater than 4000m.

- IHO also defines abyssal hills as an isolated elevation within the abyssal plains
  - Abyssal hill: An isolated small elevation on the deep seafloor.

# Interpreting the IHO (B6) definition:

\*Green is a recommendation\*

**An extensive, flat or gently sloping region, usually found at depths greater than 4000m.**

- **“An extensive”**: Extensive is a difficult and broad word to apply when there is an extreme variability in the size of established abyssal plains. There is documentation in the literature of plains that are hundreds of thousands km<sup>2</sup>, while some only cover an area of 850 km<sup>2</sup> (Weaver et al. 1987). It was decided the smallest GEBCO established abyssal plain should be used as a minimum size to qualify. **Although, a much larger minimum size of 50,000 km<sup>2</sup> could be used to simplify the data. A minimum size should be created to clear up any confusion on the accepted size as there is a large variability in the literature.**
- **“flat or gently sloping region”**: Abyssal hills are talked about in the B6 and are defined above as small elevations in the seafloor. It was assumed gently sloping regions could be considered abyssal hill areas. The definition of abyssal hills was non-specific and to further understand, the literature was consulted and revealed sources stating that an abyssal hill could typically rise from 300 to 1000 meters (Harris et al. 2014). However, in many examples of GEBCO established abyssal plains, there is no clear indication that plains were established with a maximum amount of relief allowed. Therefore, it is difficult to strictly classify abyssal areas and how you classify abyssal areas based on the local relief can drastically change the size of identified areas. **Flat or gently sloping regions should be defined further within the IHO definitions and local relief ranges (Roughness levels) should be stated for different types of abyssal areas.**
- **“usually found at depths greater than 4000m”**: The word “usually” in this part of the definition allows for too much subjectivity. The literature and examples tend to state abyssal plains can only be found below 4000 m as a general rule. Some examples in GEBCO, such as the Canadian Abyssal Plain in the north, do not contain any areas of depth below 4000 m. Furthermore, one study states that there are major differences between areas of depth at 4000 meters that differentiate true abyssal plains from other shallower areas. These major differences are attributed to varying hydrodynamic energy between the different depths. Generally shallower depths (Continental slopes) are found to contain increased movement of sediments (Hannides et al. 2003). The literature states areas deeper than 6000 meters are not considered to be part of the abyssal plain. However, this is not specified at all within the IHO definition despite 6000 meters of depth being an agreed upon depth limit in the literature. **Therefore, a defined parameter should be given within the definition that states the minimum and maximum depths.**

# Methodology in ArcMap:

\*Blue = Assumption made to aid detection\*

1. Assign a coordinate system to the working layer (WGS\_1984\_Web\_Mercator\_Auxiliary\_Sphere was used).
2. Raster calculator: Used to eliminate all areas that are too shallow or too deep to be an abyssal plain.
  - a. Assumption: The shallowest depth considered to be part of the abyssal area was 4000 meters and the deepest depth was considered to be 6000 meters. The 6000 meters value was taken from various literature that all agreed on 6000 meters is the deepest part of abyssal plains with anything below 6000 meters being classified as the Hadal zone (Harris et al. 2014)
3. Buffer the outcome of the previous step by 5 cells from the area that was identified to be at abyssal plains depth. This will generalize the data and remove any peaks within the raster. 5 cells is 9 kilometers. This parameter was chosen as most points of elevation in abyssal plains are considered abyssal hills (Abyssal hill: An isolated small elevation on the deep seafloor), with some seamounts included. The buffer removes the peaks (A conical or pointed elevation at the summit of a larger feature according to the B6 definition) of seamounts that usually rise above 4000 meters of depth. Additionally, 9 kilometers is large enough to smooth out the edges of the plain.
  - a. Assumption: 9 kilometers is small enough of a value to smooth out the data and eliminate peaks. This number was chosen through trial and error and was not based on any literature.
4. Use the reclassify tool and render all parts of the buffered raster that do not lie on approved depth to have their values changed to NoData.
5. Use the Extract by Mask tool to input the bathymetric data into the buffered raster that was reclassified. In other words, the raster mask inputs the data from the bathymetry into the remaining buffered raster (Viable raster).
6. Use the focal statistics tool and input the bathymetry from the buffered raster to measure roughness of surface. The sample size should be 25 by 25 cells. This means the area tested was 2025 km<sup>2</sup>. Standard deviation will be used to detect differences in elevation in the local area. The output will be classified with breaks at 50, 300, and 300+. The first classification is between 0 - 50 meters and is set to identify areas that are most likely abyssal plains. Areas that are classified between 50 and 300 meters can be considered to contain abyssal hills and may or may not fit into the IHO definition. The next classification is a standard deviation of over 300 meters and are areas that contain larger hills or seamounts.
  - a. Assumption: These ranges of classification are more conservative than other papers that attempted to also classify abyssal areas using a similar method. The methodology was created in an attempt to follow the IHO definition as closely as possible while also ensuring abyssal plains established by GEBCO are located. The existing GEBCO undersea feature database was used to test the methodology. GEBCO data does not differentiate between abyssal plains, abyssal hills and abyssal mountains. Therefore, a conservative abyssal plains range was selected in an attempt to be as accurate as possible in respect to the data the methodology was

based on. The abyssal zone classifications from other studies can be found in the literature (Harris et al. 2014 ; Dekavalla and Demtre. 2017)

7. Use raster calculator to divide the three regions into three separate fields based on the three classifications between plains, hills and mounts.
  - a. The raster hills area requires this statement: `output = ("Ex.Raster" >=50) & ("Ex.raster" <=300)`
8. Reclassify the newly cut out raster calculator output for each abyssal level
9. Use the raster to polygon tool to convert the raster layers to polygons.
10. Create new fields that contains area in km<sup>2</sup> for each polygon. Ensure the new field is a double.
11. Delete the polygon sizes that are too small. The current minimums tested were 850 km<sup>2</sup> as a small scale and 50,000 km<sup>2</sup> as a large scale test. These deletions were only performed to the hills and mount zones. The deletion was done by editing and selecting all the polygons that do not meet the minimum size threshold and then deleting them. A smaller minimum size detects many more new plains and is capable of finding the smallest GEBCO abyssal plains. The 50,000 km<sup>2</sup> restricts itself to only finding larger abyssal plains, but it also removes a lot of possible "noise" from the plains found.
  - a. Assumption: The 50,000 km<sup>2</sup> minimum size was chosen originally through trial and error to fit the methodology. A final parameter for this detection methodology will require the IHO to have a quantitative definition used to define how extensive a plain must be. 850 km<sup>2</sup> was eventually chosen as it was the smallest GEBCO established abyssal plain size.
12. Use the union tool with the parameter "Gaps allowed" unchecked. This will fill in the remaining holes within the polygons. Then use the dissolve tool to combine the fill polygons with the larger polygon.
13. The resultant layers represent the three abyssal areas as plains, hills and mounts. It is likely that the plains area fits the IHO definition and less likely the other areas fit the IHO definition.

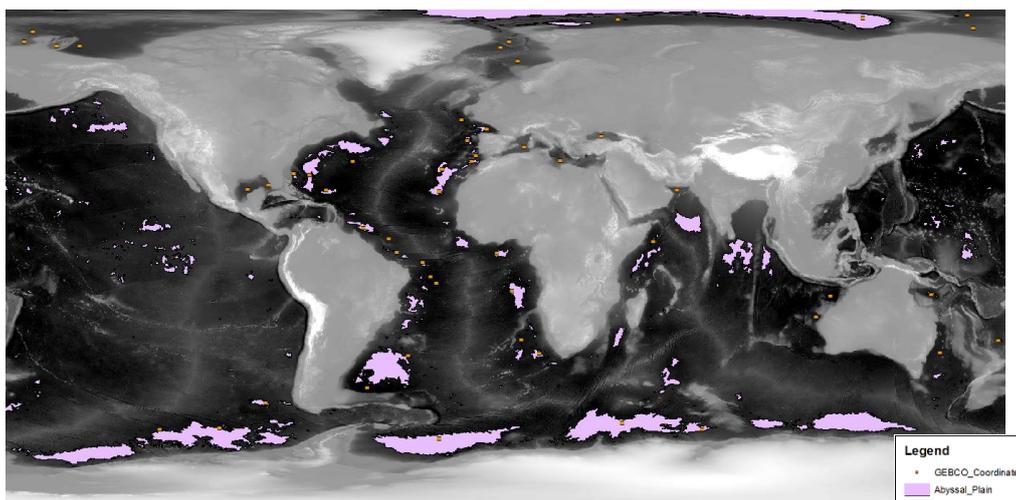
## Results of the Methodology

Running the methodology at a world scale with a minimum area threshold of 850 km<sup>2</sup> yields 831 separate abyssal plains. Some of these separate abyssal plains are very close together and may be

considered a single plain when visually assessed. 17 abyssal plains from the GEBCO database were located and had an overlap between the point and the plains polygon generated. 12 GEBCO abyssal plain points were slightly off the plains polygon generated by under 100 km. 9 GEBCO abyssal plains areas were overlaying hills or mounts relief zones that were at least 100 km away from the closest plain. 14 abyssal plains from the GEBCO database were not identified by the methodology due to the plains not being deep enough. A visualization of the results can be seen in Figure 1.

Running the methodology at a world scale with a minimum area threshold of 50,000 km<sup>2</sup> yields 65 separate abyssal plains. 12 abyssal plains from the GEBCO database were located and had an overlap between the point and the plains polygon generated. 5 GEBCO abyssal plains points were slightly off the plains polygon generated by under 100 km. 18 GEBCO abyssal plains areas were overlaying hills or mounts relief zones that were at least 100 km away from the closest plain. 17 abyssal plains from the GEBCO database were not identified by the methodology due to the plains not being deep enough.

These tests were performed on the NOAA ETOPO1 Global Relief Model which is 1 arc-minute. A cell-registered georeferenced tiff was used that was assigned the “WGS\_1984\_Web\_Mercator\_Auxiliary\_Sphere”. The data can be found: <https://www.ngdc.noaa.gov/mgg/global/global.html>



**Figure 1.** These polygons were generated from running the methodology on a world bathymetry dataset. 831 separate abyssal plains were identified, 17 GEBCO established abyssal plains had direct overlap between the generated polygon and established point, 12 GEBCO points were under 100 km away from the nearest generated polygon, 9 GEBCO points overlaid regions that may or may not be classified as an abyssal plain (too much local relief) and 14 points were not detected as they overlaid areas that were typically too shallow

## Discussion of Methodology and Current Issues

The 850 km<sup>2</sup> minimum size was able to detect an increased amount of GEBCO abyssal plains than the 50,000 km<sup>2</sup>. The smaller threshold was more accurate than the larger threshold as more GEBCO abyssal plains were found, along with identifying GEBCO abyssal plains within 100 km of a generated polygon. The smaller size threshold may potentially allow for the naming of many new smaller abyssal plains. Alternatively, many of the smaller abyssal plains detected are closer to larger abyssal

plains and a decision would have to be made on when to associate two separate plains. A larger agreed size would present many less new abyssal plains, but would also contradict current GEBCO recognized abyssal plains.

The largest issue in the current methodology is the minimum size needed to be considered an abyssal plain. Abyssal plains have been identified to be as small as 870 km such as the Barents abyssal plain. This plain is mentioned in the literature and is in the GEBCO Gazetteer (Weaver et al. 1987). Plains have also been identified to be as large as 1,000,000 km<sup>2</sup> such as Angola abyssal plain which is also in the literature and the GEBCO Gazetteer (Weaver et al. 1987). An example of using a smaller minimum threshold can be seen in Figure 3 which uses a minimum of 850 km<sup>2</sup>. The lower minimum allows for the detection of previously too small to detect abyssal plains such as the Blake abyssal plain. A lower minimum also permits for “noise” within the identified plains. For example, “A” on Figure 3 is not an identified abyssal plain and could potentially be a new abyssal plain, or part of either Blake or Hatteras.

Three areas of the abyssopelagic zone are identified when using the methodology. The three areas are plains (0-50 m standard deviation of relief), hills (50 – 300 m standard deviation of relief) and mountains (300+ m of standard deviation). Each of these areas could be considered part of the abyssopelagic zone depending on the interpretation of the current definition. Therefore, the size of abyssal plains can drastically change depending on the interpreters subjectivity and this presents a problem concerning the accuracy of the methodology. An example of this can be seen in Figure 2 as there is a discrepancy between the size of the plains detected by the methodology verse the size stated in the literature. Although, the author had stated that the size estimates in the paper have a large margin of error (Weaver et al. 1987). Based on testing the methodology from the GEBCO database, it is most likely that the first classification of 0 – 50 meters will be the most accurate and useful range. The 0 – 50 m classification is the range that will be used to classify proposed abyssal plains.

Currently, the B6 definition includes the phrase “Gently Sloping” inferring that a specific slope can be associated to this term. The average slope was taken from each of the GEBCO identified abyssal plains. Polygons that overlapped with GEBCO points and polygons that were less than 100km away from a GEBCO point were used to calculate average slopes of each abyssal plain. Please refer to abyssal statistics spreadsheet to see the average slope of each plain. The average slope between 29 GEBCO established plains was found to be 2.667857° with a standard deviation of 2.111188°. The minimum value reached was 0.655418° and the maximum average slope reached was 8.024422°. A large difference can be noted between these values and therefore a specific slope value was excluded from the final definition and the methodology. These slope values were calculated based on the 850 km<sup>2</sup> minimum area threshold.

The choice to sample roughness at a scale of 2025 km<sup>2</sup> was not specifically chosen according to literature as it was a value selected due to trial and error. Sample area size for roughness is directly related to the agreed upon minimum size. A smaller minimum size would use a smaller area to sample roughness. A new definition with a minimum size will allow for this parameter to be assigned an appropriate value. If a testing size of 850 km<sup>2</sup> is eventually agreed upon, it may be beneficial to decrease the sampling of the roughness area.

A clear and quantitative definition must be agreed upon to remove subjectivity from the detection of undersea features.

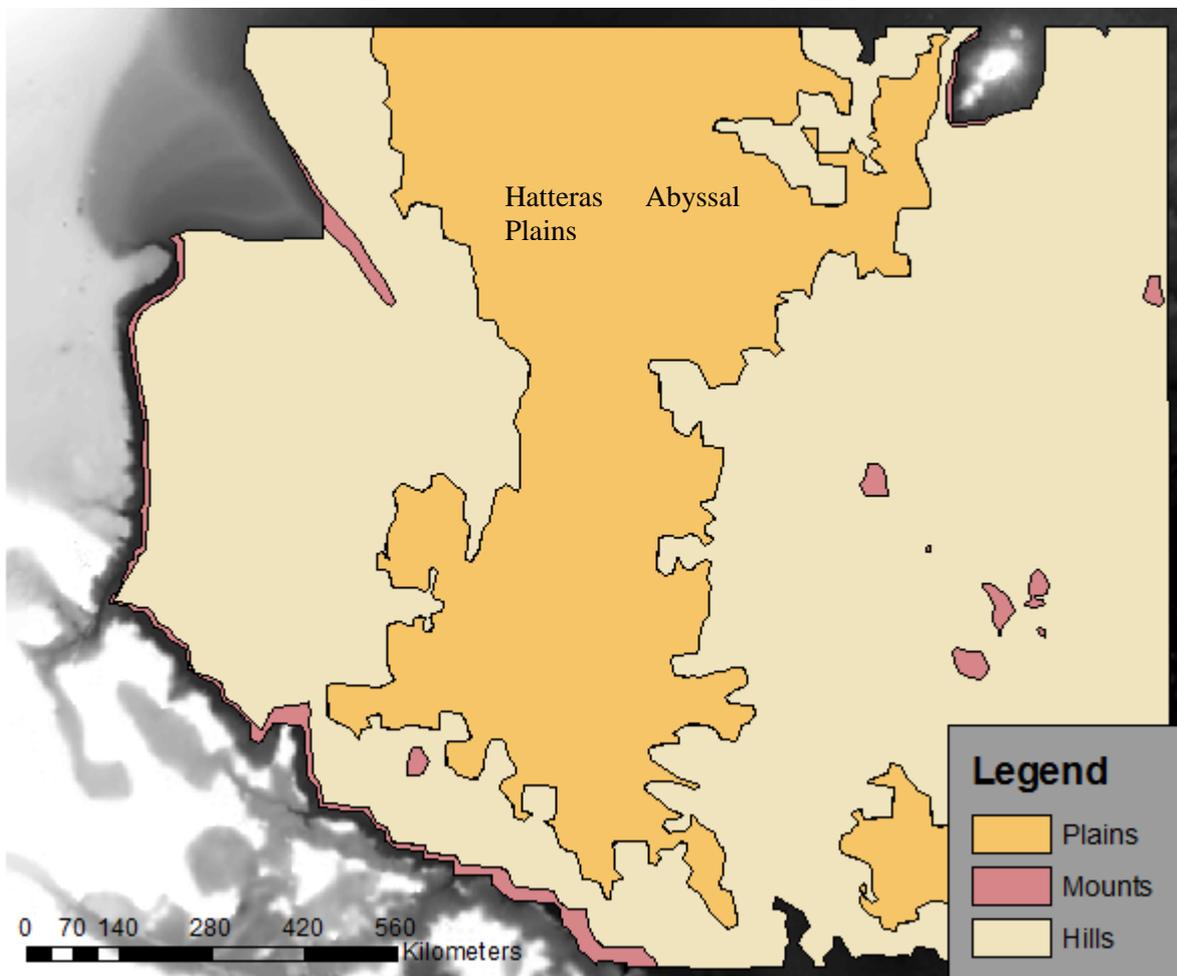


Figure 2. Hatteras Abyssal Plain is visualized above and has an area in the literature of 460,000 km<sup>2</sup> and versus the methodology which calculated the area to be 594,000 km<sup>2</sup>. (Performed with a minimum abyssal plains size of 50,000 km<sup>2</sup>)

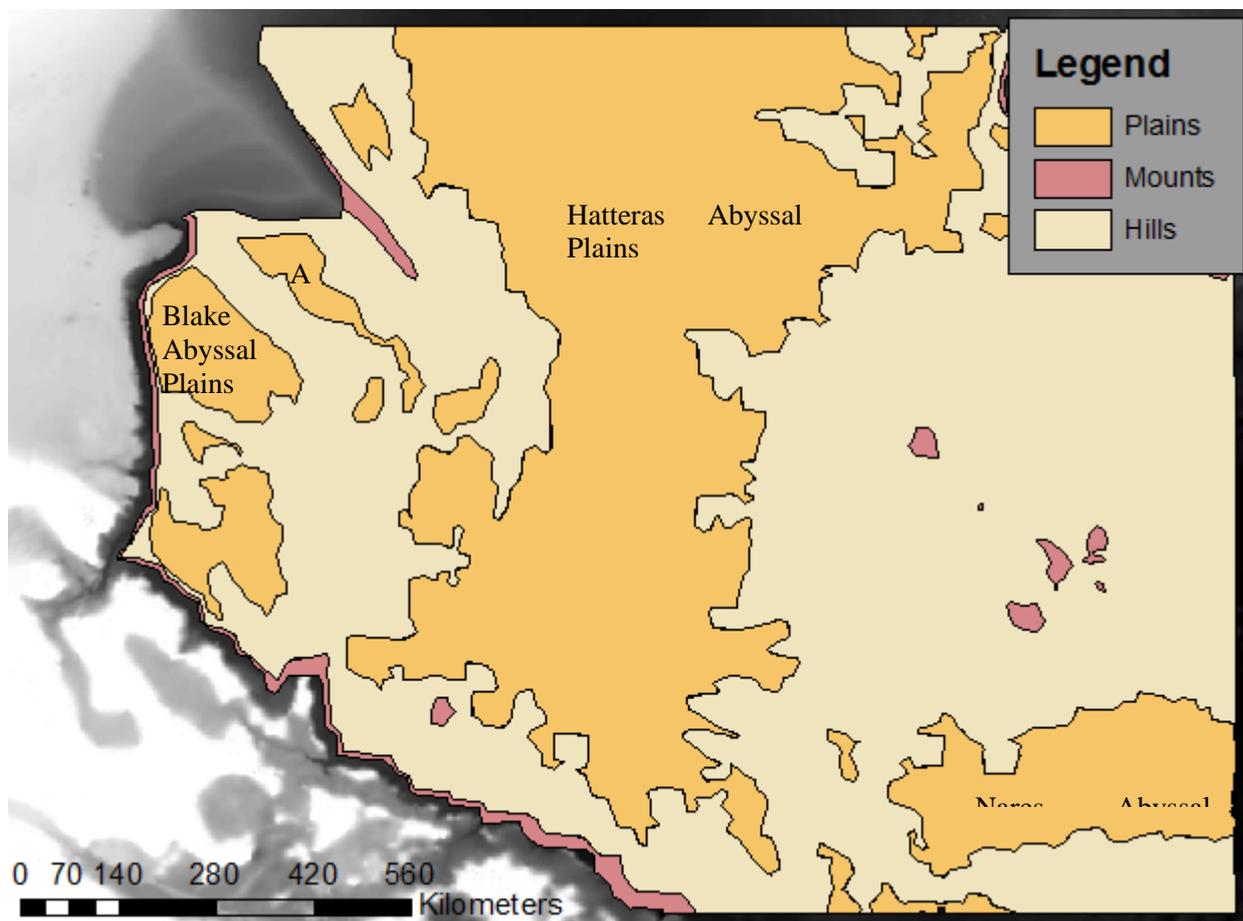


Figure 3. Hatteras, Blake and Nares abyssal plains are visualized above. All three plains are present in GEBCO and literature. "A" is an example of a new abyssal plain. (Performed with a minimum abyssal plains size of 850 km<sup>2</sup>)

## Revised Definitions:

A revised definition is suggested to allow for an effective method to discover new abyssal plains and to ensure that all currently identified abyssal plains are *actually* abyssal plains. The most effective definition will define all parameters of the undersea feature and will leave no phrases up for subjective interpretation. A revised definition should be quantitative and have exact parameters for each attribute of the feature.

Ideally, all IHO definitions would undergo a change and become increasingly quantitative to facilitate the validation of current features and the discovery of new ones. The goal to map the ocean floor will arguably only be achieved if the features being mapped are easily identifiable and have no overlapping attributes with another feature. Overlapping attributes will cause confusion and discrepancy between groups attempting to classify undersea features, which will ultimately slow the discovery process. It can also be noted that papers that attempt to classify undersea feature have a specific set of defined attributes assigned to each feature to allow for easy classification and overlap (Harris et al. 2014 ; Dekavalla and Demtre. 2017).

The following definitions are examples that are suggested to increase the quantitative values within the IHO abyssal plains definition. Suggestion #1 includes the quantitative values within the definition, while suggestion #2 almost completely retains the initial definition while only defining specific keywords below.

**Current Definition:** An extensive, flat or gently sloping region, usually found at depths greater than 4000m.

### Suggested Definition Option #1:

An extensive area larger than 850 km<sup>2</sup>, that overlies a flat or gently sloping area with 0 - 50 m of local relief, and is found at a depth between 4000 and 6000 meters

### Suggested Definition Option #2:

An extensive, flat or gently sloping region, usually found at depths between 4000 and 6000m.

Extensive: 850 km<sup>2</sup> or larger

Flat or gently sloping area: (0 - 50 m of local relief)

### Justifications:

- 850 km<sup>2</sup> was chosen as the minimum size as it is the smallest abyssal plain identified in the literature and is present in the GEBCO undersea feature database (Weaver et al. 1987). A larger size will detect less new abyssal plains, but, will detect less false positives. A smaller minimum size will detect new abyssal plains and may detect false positives. Ultimately, 850 km<sup>2</sup> was chosen as it was shown to be more accurate when identifying already established abyssal plains.
- No value was given for slope as the current minimum slope, maximum slope and average slope does not help identify abyssal plains.
- 0 – 50 meters of local relief or relative surface roughness was chosen to be the parameters for flat or gently sloping which is based on other papers that have attempted to perform

similar undersea classifications. A more conservative roughness scale was chosen than other papers as trial and error revealed 0 – 50 meters to be accurate concerning GEBCO data (Harris et al. 2014 ; Dekavalla and Demtre. 2017).

- A depth of 4000 – 6000 meters was chosen partly based on the 4000 meter parameter given by the B6 and partly chosen based on the literature that agreed abyssal plains can only be found at a maximum of 6000 meters (Angel. 1997).

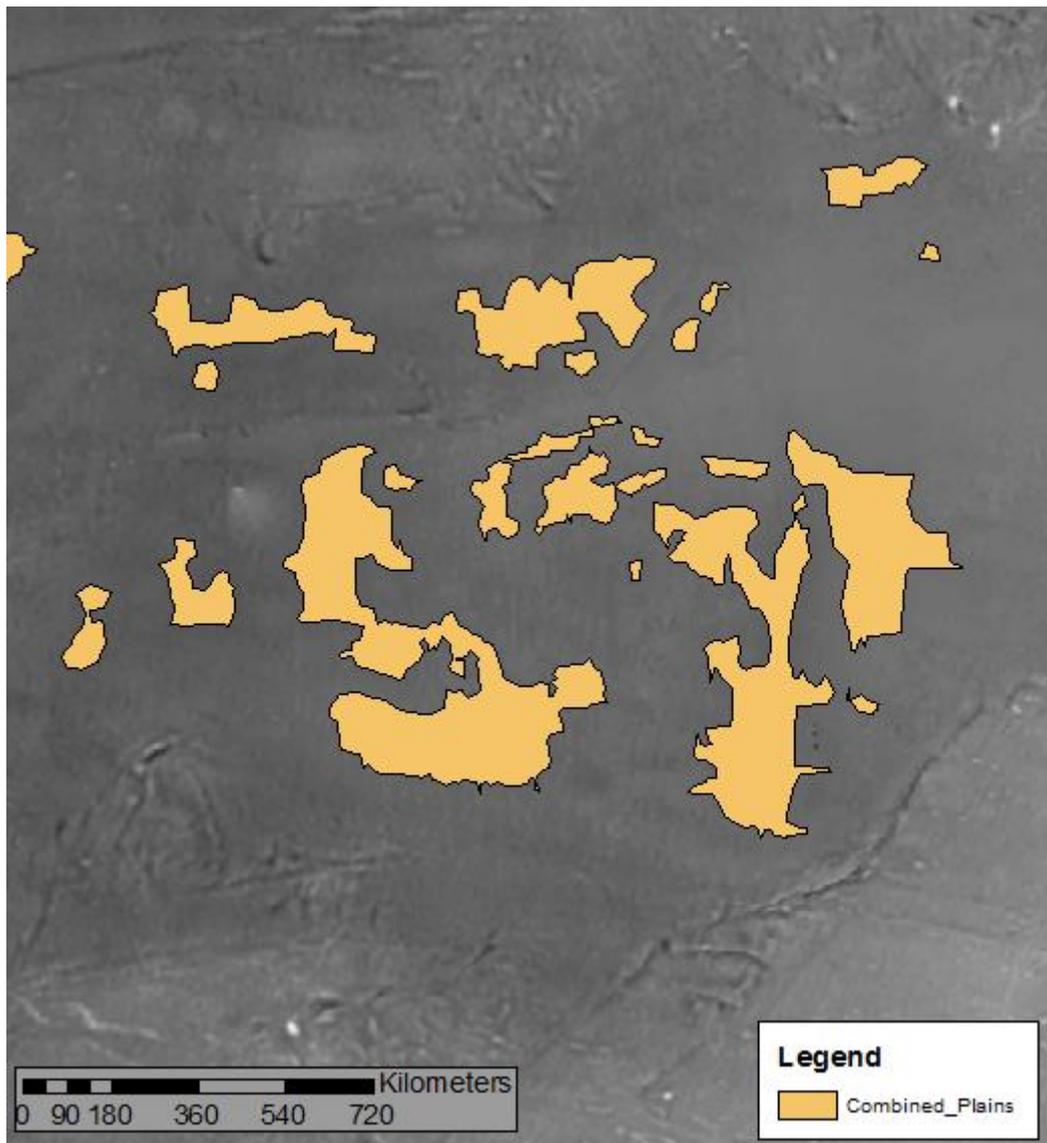
## **Possible Opportunity to Name New Abyssal Plains:**

If the current parameters are agreed on from the revised definition, 831 potential abyssal plains could exist. This is a large number and seems unlikely that this many individual plains could exist. Many of these plains are almost adjacent and may not be considered a separate entity. A reasonable solution to this would be to associate and consolidate all plains that are only 100 km apart from each other. When discussing distance in the scale of abyssal plains, 100 km is a trivial distance for another plain to be considered a completely unique entity. Therefore, it is proposed that all newly generated

abyssal plains polygons under 100 km apart should be grouped and identified as a singular plain with multiple parts, or perform a visual check to connect the parts as seen fit.

This test was performed in ArcMap on the data from Figure 1 and yielded a more realistic number of 249 abyssal plains. Many areas had considerable large groups of scattered small plains that were grouped together into one entity as seen in Figure 4. Additionally, there were many larger plains that had small abyssal plains nearby that the grouping also fixed as seen in Figure 5.

Already established separate abyssal plains may become snapped together to become a single plain. A visual check to remove these occurrences manually would be necessary.



**Figure 4.** Previously unidentified abyssal plains area that was extremely fragmented with the majority of the fragments being within 100 km of each other. This was performed with a minimum abyssal plains size of 850 km<sup>2</sup> with the coordinates (-118,-2) in the centre of the image for reference.

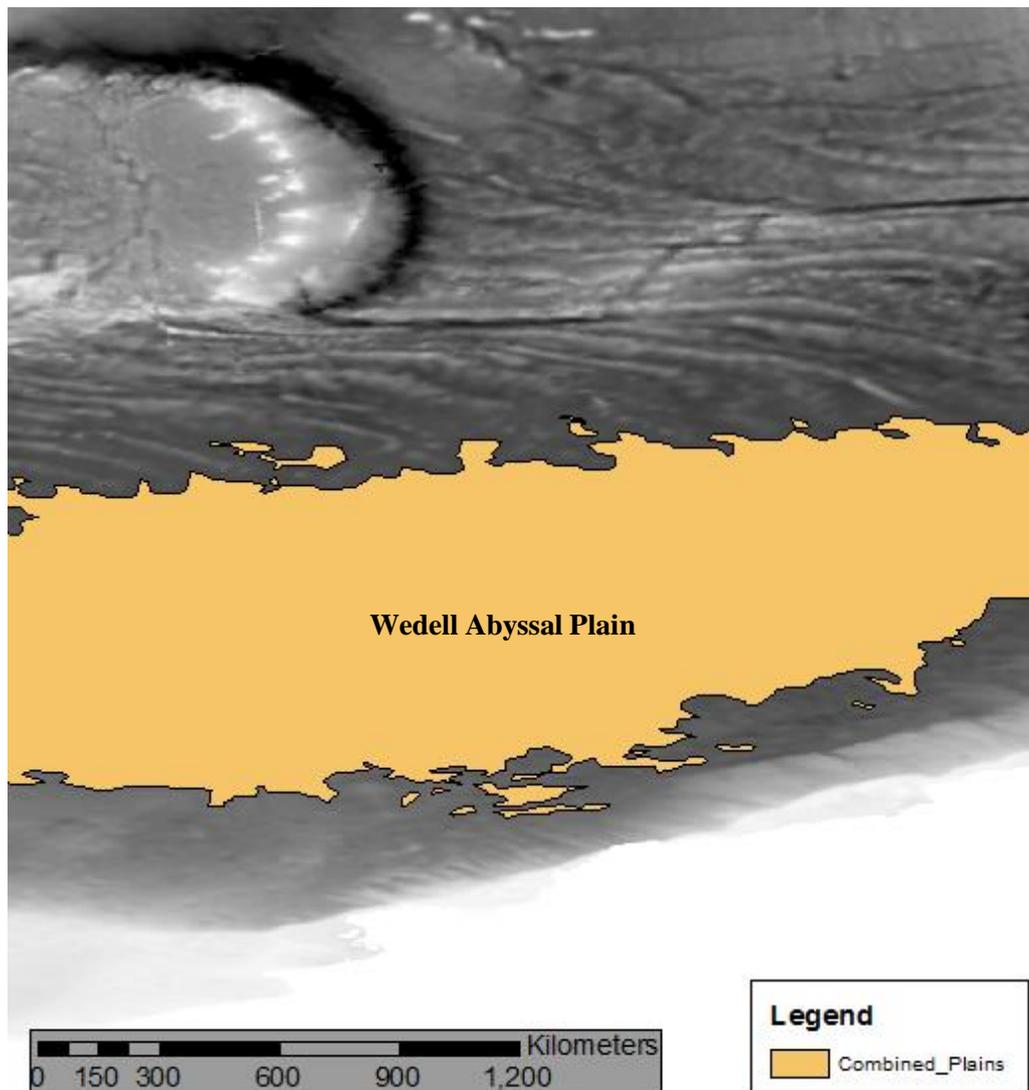


Figure 5. Wedell abyssal plain can be seen with some fragmentation on the boundary. These fragments can be snapped together to allow for a combined abyssal plain. All the small fragments in this image are under 100 km away from Wedell abyssal plain and would be associated with Wedell once combined. This was performed with a minimum abyssal plains size of 850 km<sup>2</sup>.

# Bibliography and Research Notes:

Angel, Martin V. "1 What is The Deep Sea?." *Fish Physiology*. Vol. 16. Academic Press, 1997. 1-41.

- Defines abyssal depths between 4000 and 6000 meters
- Hadal zone cover around 2% of the ocean floor

Dekavalla, Maria, and Demetre Argialas. "Object-based classification of global undersea topography and geomorphological features from the SRTM30\_PLUS data." *Geomorphology* 288 (2017): 66-82.

- States undersea feature classification can be biased and subjective
- Paper had the intention of classifying features partly based on the IHO B6 definition
- Defines slope gradient and local relief as the two most important parameters
- Classified areas as abyssal plains that had less than 300 meters of relief
  - o 300 meters up to 1000 m were classified as abyssal hills

Hannides, Angelos K., and Craig R. Smith. "The northeastern Pacific abyssal plain." *Biogeochemistry of Marine Systems*(2003): 208-237.

- States a depth deeper than 4000 meters
- State major differences between ocean floors with a depth of 2000 m and a depth of 4000 m due to difference in energetic hydrodynamic conditions

Harris, P. T., et al. "Geomorphology of the oceans." *Marine Geology* 352 (2014): 4-24.

- Classified under 300 meters of local relief as an abyssal plain
- Classified 300 – 1000 m of local relief to be abyssal hills area
- Classified abyssal mountains to be 1000 m of relief or more
- States Hadal zone starts at 6000 meters of depth

Seibold, Eugen, and Wolfgang Berger. *The sea floor: an introduction to marine geology*. Springer, 2017.

- General abyssal plains background information

Weaver, Philip Peter Edmond, and James Thomson, eds. "Geology and geochemistry of abyssal plains." (1987): 71-86.

- Mature abyssal areas have less abyssal hills
- A database of abyssal plains from the 80's can be found in this paper
- Used table 1 to determine an average size for abyssal plains. The average size of the abyssal plains in the table was 269,041.8 kilometers squared.

## Appendix III

# Detection Methodology of Undersea Basin

Shenghao Shi

## Summary

This report is about using GIS to detect undersea features. The platform used to conduct analysis is ArcMap 10.6 with spatial analyst extension. The undersea feature chosen for this project is the basin, whose definition is acquired through B-6. This is the second feature whose detection has been automated by CHS. The first one is seamount and the automation process is developed by Oliver Farwell.

## Background

B-6 is the standardization of undersea feature names, one of the IHO publications. B-6 contains the guideline for the standardization of undersea feature names, undersea feature name proposal, list of undersea feature generic terms and definitions etc.

Within the list of undersea feature generic terms and definitions, there are 43 generic terms and 17 generic terms used for harmonization with other gazetteers and definitions. The focus of this project is on the former.

Among all the generic terms, most majority of them are rather descriptive and general. Previously, my colleague Oliver has made a successful attempt to analyze a feature that has a clear numeric definition—seamount. This time, I tried to quantify a qualitative description i.e. basin.

### **SEAMOUNT**

A distinct generally equidimensional elevation greater than 1000 m above the surrounding relief as measured from the deepest isobath that surrounds most of the feature.

*Figure 3. B-6 definition of a seamount*

### **BASIN**

A depression more or less equidimensional in plan and of variable extent.

*Figure 4. B-6 definition of a basin*

For this project, the bathymetry data used is the ETOPO1 (bedrock) dataset from the National Oceanic and Atmospheric Administration (NOAA) with 1-minute resolution (about 1.8km). The data

is acquired through this site: <https://maps.ngdc.noaa.gov/viewers/wcs-client/>. Reason for choosing this data source is simply its accessibility. The analysis can be redone easily on a database with finer resolution.

## Definition Analysis

According to the B-6 definition, a basin is defined as “a depression more or less equidimensional in plan and variable extent”. From this definition, we can conclude the following key features of a basin:

1. It should be a depression, which means the center area should be lower than the edge area.
2. Also, the central area should be flatter than the surrounding of the basin.
3. It should be equidimensional, which means that the shape of the basin should, more or less, resemble an ideal round shape.

## Analysis Process

### 1. Basic Setting

To begin with, the ETOPO1 dataset includes the bathymetry of the entire earth's surface. The first step is to extract the Canadian water using the NOAA website, see figure 3. In this step, I deliberately chose a large area because the analysis does not base on the entire area. Having a large enough base dataset allows me to find an area of interest easily.

To extract the desired area, use either the select with a rectangle or the select with coordinate tool located at the top left corner of the website. For the record, the area chosen in this step is: 65.496 North, -122.094 East, 40.197 South, and -167.756 West. Then go to the bottom of the site, choose ETOPO1(ice) as the layer, GeoTIFF as the output format, then click on “click here to download” to download the data.

Start ArcMap, create a new blank map, load the tiff file download from the last step. Then as we can see the tiff file include both land and ocean bathymetry. To extract the ocean area only, we need to enable spatial analyst extension. Go to Customize> Extensions> Spatial Analyst to turn it on. Next, use Extract by Attributes tool, set the tiff file as input raster, and use "Value" < 0 as the formula. The output will be a raster where elevation less than 0 meters. See figure 4.

However, the result still contains too much data. To be able to reduce unnecessary computing time, I chose a smaller area of interest. To do so, open editor toolbar> editor> start editing> construction tools> rectangle to draw a rectangle in the desired area, which will be called the area of interest (AOI) in the rest of the passage. The relative location is shown in figure 5. Next, use Clip tool under System Toolboxes> Data Management Tools> Raster> Raster Processing> Clip. Use the bathymetry tiff file as Input Raster, use the AOI created in the last step as Output Extent. The output should be the bathymetry of the AOI.

By this step, the preparation is completed. The rest of the analysis will be based on the AOI only.

Specify an Area of Interest

North: 65.496  
West: -167.756 East: -122.094  
South: 40.197  
(signed decimal degrees)

OK Cancel Reset

1. Choose a Layer  
ETOPO1 (ice)  
Grid of Earth's surface depicting the top of the Antarctic and Greenland ice sheets (1-minute resolution)

2. Select an Area from the map  
-167.76, 40.197, -122.09, 65.496

3. Choose Output Format  
GeoTIFF

4. Download the Data  
[click here to download](#)

[Questions?](#) Warning: these data not to be used for navigation [Privacy Policy](#)

Figure 5. Extracting data from ETOPO1 database, NOAA

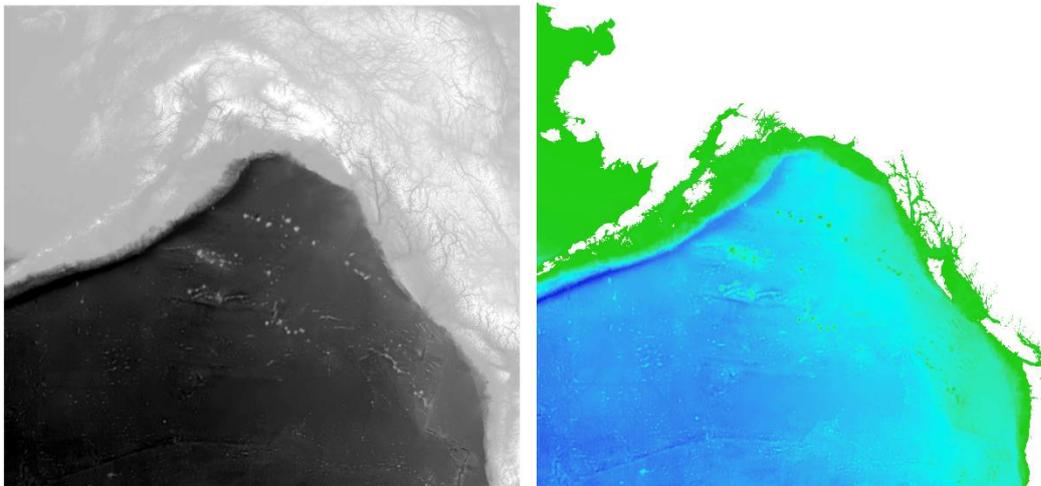


Figure 6. Before and after extract by attribute



Figure 7. Relative Location of the area of interest

## 2. Basin Division

In this step, we will use the hydrology tool to divide the AOI into basins.

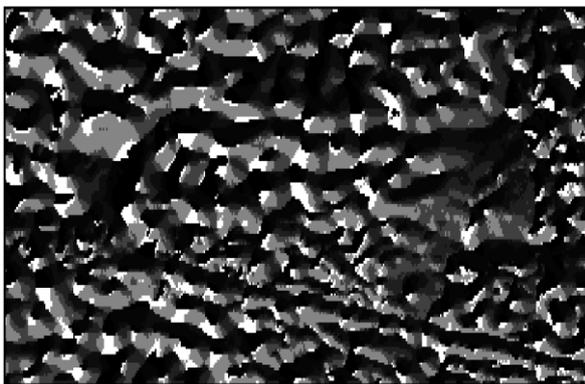


Figure 9. Flow Direction output for AOI



Figure 8. Basin tool output for AOI

First, go to System Toolboxes> Spatial Analyst Tools> Hydrology> Flow Direction. Use the clipped AOI bathymetry as input surface raster, leave all settings as default and run the tool. You will generate an output that looks like figure 6. Next, run the basin tool (also located under Hydrology). Use the flow

direction output as Input flow direction raster, the result will be a raster delineating all drainage basins.

As we can see, the basin size varies a lot. But generally speaking, the size of basins usually stays within the range of 25km -125km in terms of diameter. If we need to enlarge the size of each basin, there is a method suggested by Oliver Farwell—use the fill tool. This tool allows us to fill sinks in a surface raster to remove small imperfections in the data. Figure 8 is a simple illustration of how this tool works. For more detailed information, see the tool help in ArcMap.

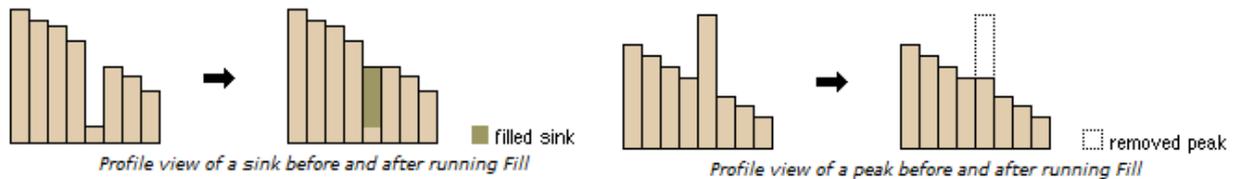


Figure 10. How fill tool works

To apply this method, follow the following steps: open fill tool under: Spatial Analyst Tools> Hydrology> Fill. Use the bathymetry raster as the input surface raster, enter Z limit, which is the maximum elevation difference between a sink and its pouring point to be filled. The greater the Z limit, the bigger the size of the basin is, meanwhile, the less accurate the bathymetric data are. After the fill, use the output of the fill as your new bathymetry raster. Repeat the step of flow direction, then basin tool. Figure 9 presents the basin tool output of the same AOI when the bathymetry is



Figure 11. Basin tool output using filled bathymetry, fill Z limit = 100m

filled by a Z limit of 100 meters.

The rest of the analysis is based on the unfilled bathymetry. But if desired, the same step can be followed using filled bathymetry.

After getting the basin layer, use Conversion Tools> From Raster> Raster to Polygon tool to convert basin raster to a polygon layer (Use basin raster as input raster). Thereby getting the vector shapefile of the basins, which will be used to conduct the next step of the analysis.

### 3. Identify Central and Edge Area

The objective of this step is to determine what should be categorized as the central and edge area for each basin in order to compare the center and the edge of each identified basin.

To begin with, we need to enable a hidden tool called the buffer wizard to identify the edge area. Open the Customize menu and choose to Customize mode. Select the Commands tab, then enter the text 'buffer wizard' in the 'Show commands containing' box. Drag the tool to a toolbar (the Tools toolbar is suggested).

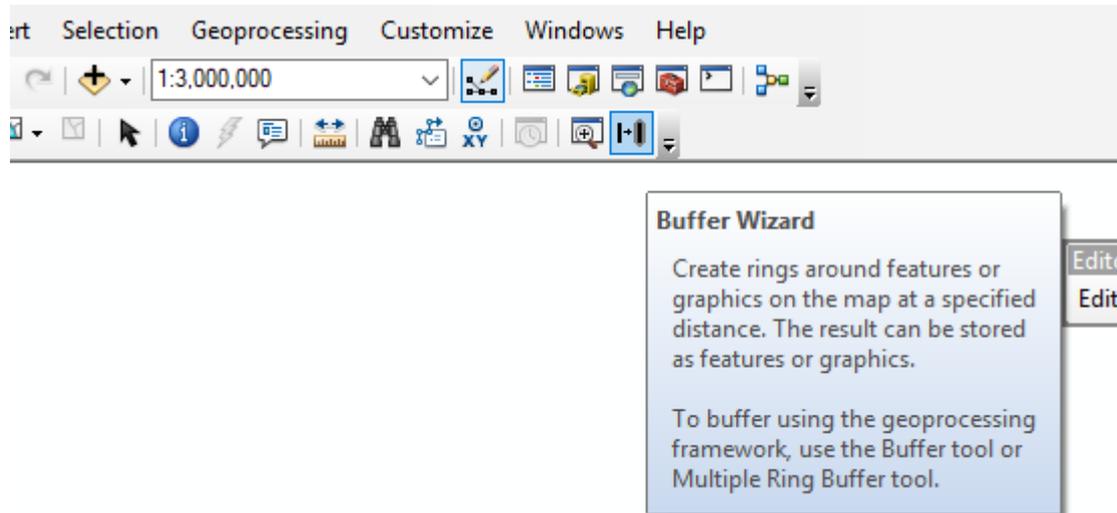


Figure 12. Buffer Wizard tool loaded into the toolbar

Next, we need to open the attribute table of the basin shapefile layer. Go to table option> add a field, and add five new fields called area, perimeter, Buffer\_5, Buffer\_3, and Buffer\_2 respectively, the type for all five should be set as a float. Once the new fields are ready, right click on the title of area and perimeter, select calculate geometry, choose yes on the warning window and calculate the area and the perimeter respectively. Please make sure the unit used is consistent. For the rest of the three fields, what we want to achieve is to calculate the length that is proportional to the surface area and the perimeter of each basin. So for these three fields, we use field calculator instead of calculating geometry. The formula used should be  $[\text{Area}] / [\text{Perimeter}] / 2$  or  $3$  or  $5$  (or another number) to generate 3 buffer distances for each basin (reason for choosing the number will be explained by the end of this section).

Now, open the buffer wizard, choose the basin shapefile layer as the features of a layer, and click next. Choose Based on a distance from an attribute choose one of the three buffer distances we calculated in the last step, make sure the distance units are consistent with the unit used when calculating the three buffer distances, click next. Select no for dissolve barriers between, select only inside the polygon(s) for the second option, and then click finish. Repeat the above steps using all three buffer distances. The result should resemble figure 11.

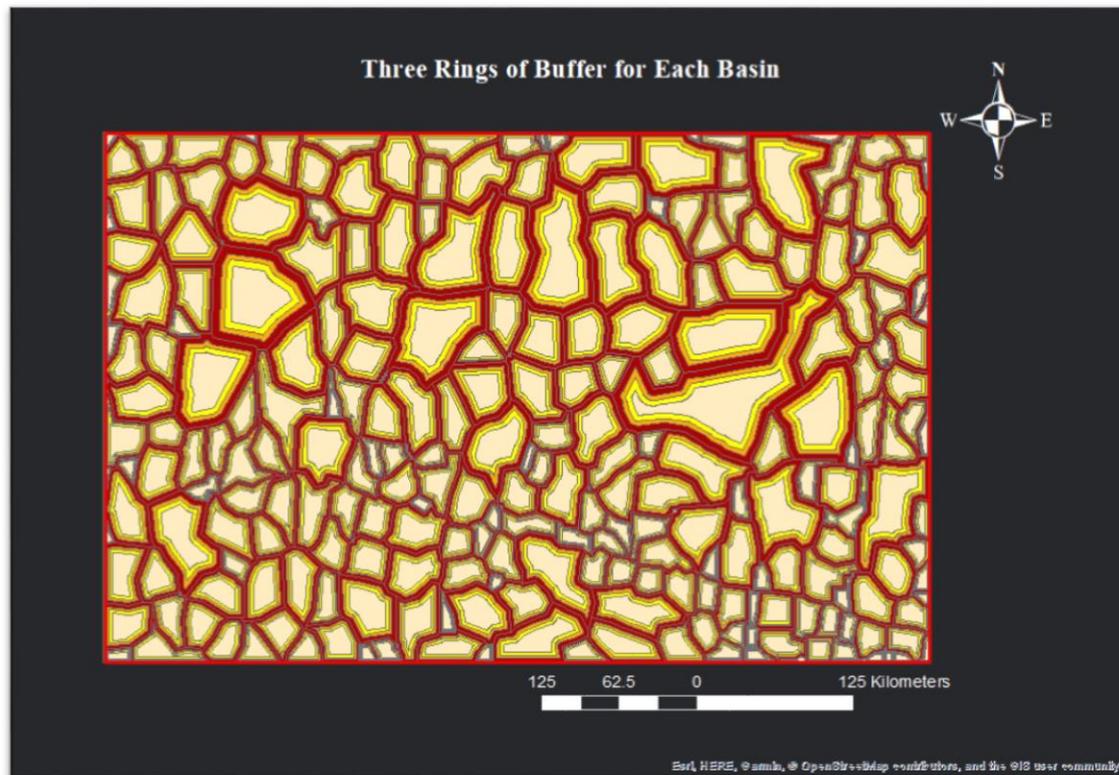


Figure 13. Result of inner buffer using three buffer distances

After identifying the edge area for each basin, the next step is to identify the centers. To do so, following the steps below: turn on the attribute table of the basin shapefile layer, go to table option> add a field, and add two new fields called X and Y, use Float type for both fields. Right, click on the cell X and cell Y, choose to calculate geometry > X coordinate of the centroid and Y coordinate of centroid respectively. Make sure the unit used are consistent. Go to table option again, choose export, click OK, select yes for the next pop out window to add the table to the map. Find the table, right-click it in the table of contents panel then select Display XY data. Use X as the X Field and Y as Y Field, which should be the default, then click OK. As the result, a new point layer will be added to the map, which is the mathematical center of the basins. Next, go to Geoprocessing> Buffer, set the new point file as input features. Since the point file is derived from the table that contains the data we use to create the rings of edge, this layer contains the same data. So in this step, when choosing the buffer distance, select Field, and choose the appropriate buffer distance. The output combined with the result of the last step should resemble figure 12.

*There is no absolute correct option in terms of choosing the buffer distance when calculating the edge area and the center area, which is why there are three buffer distances. Further research can be done on known undersea basins to figure out that on average, how many percent area on the edge of a basin descends most significantly. For example, if we find out that on average, the first one-fifth of the radius near the basins edge witnesses the sharpest greatest in elevation and has the sharpest slope. Then we can determine that the constant we used when calculating the buffer distance should close to 5.*

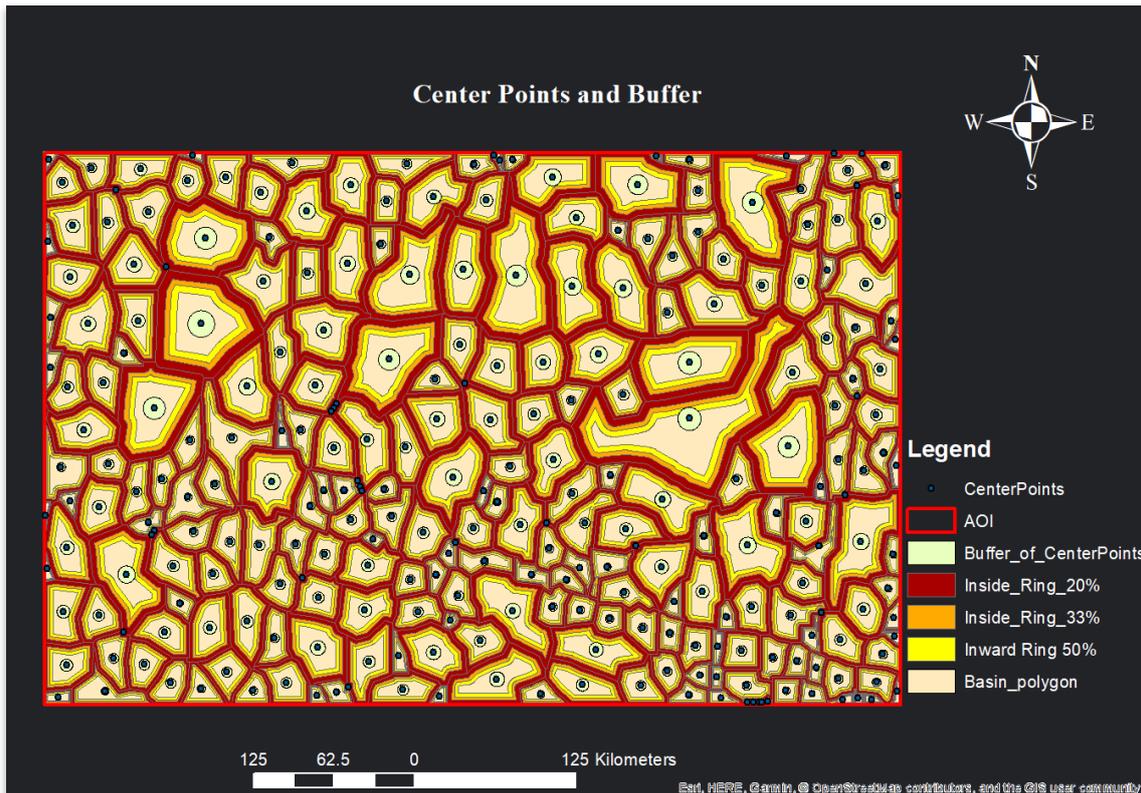


Figure 14. Result of combining edge buffer layer and center point buffer layer

*Or, alternatively, we can experiment with different constants within an area with known undersea basins. And see what constants output the most precise result for detection undersea basins.*

*For the rest of this project as well as figure 12, both center point buffer area and edge buffer area use buffer distance of Buffer\_3. i.e. the value of  $[\text{Area}] / [\text{Perimeter}] / 3$ .*

#### 4. Slope and Depth Value

To compare the center and the edge, we need to introduce slope and depth value from the bathymetry.

First, go to Spatial Analyst Tools > Surface > Slope, use the clipped bathymetry AOI layer as the input raster, leave all another setting as default, click OK. This tool will output a layer presents the slope differentials within the AOI, see figure 13.

Next, to import slope value and a depth value, we need to first convert them into point files. Go to Conversion tools > From Raster > Raster to Point, use bathymetry and slope layer as input raster, make sure the field selected is the one contains the real slope and a depth value, and convert them into point layers respectively. Then go to Analysis Tools > Overlay > Spatial Join.

For this tool, we need to use the edge area and buffered center area as Target Features and use the slope and bathymetry point files we created as Join Features. And therefore create a total of four new layers, which are edge area with slope value, edge area with depth value, center area with slope value, and a center area with depth value respectively. Also, in Field Map of Join Features, we need to configure the properties by doing the following: in the Field Map of Join Features, find the one

that contains the slope value/ bathymetry value, right-click on its name, and select properties. Find merge rule, select mean, and then click OK. By doing so, the depth/ slope value in each edge or center area will be the mean value of the entire area. Leave another setting as default and execute the Spatial Join tool four times.

To compare the differences between the center area and the edge area, we need to join the

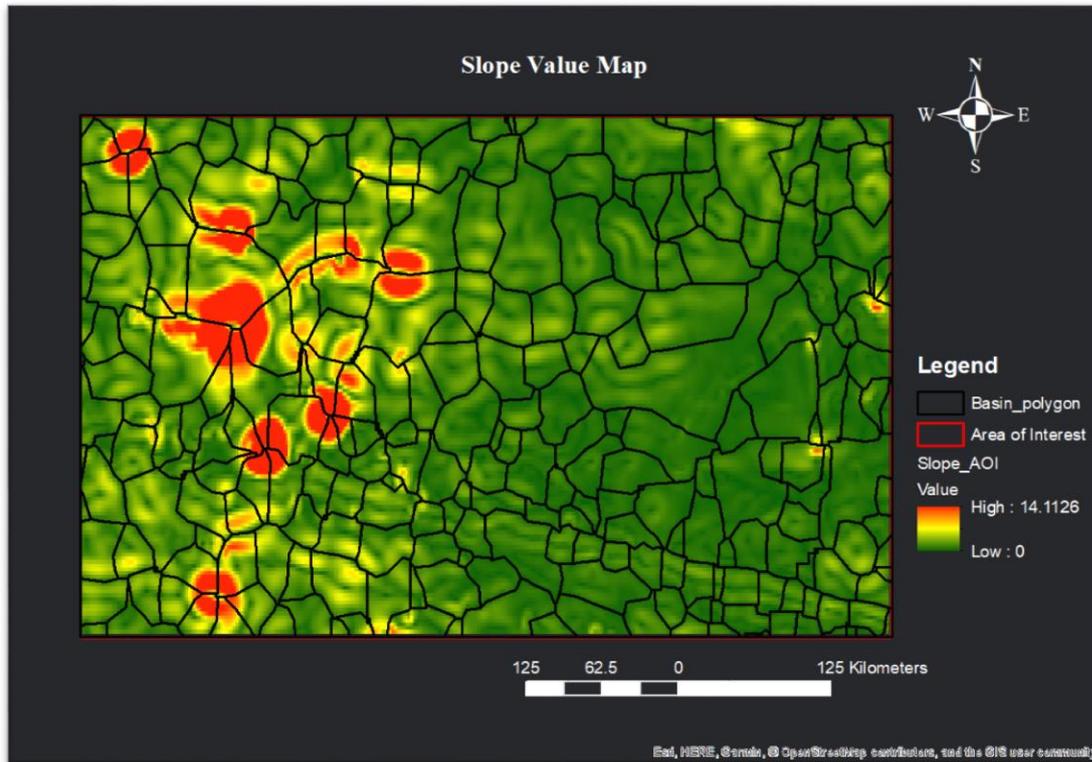


Figure 15. Slope value map for area of interest

attribute tables. Right click on the center area with slope value, select Join and Relates> Join. Choose the edge area with slope value in the second dropdown menu (This can be done another way around, aka use join function on edge area layer and select center area layer in the above step). In the first and third dropdown menu, select a field that is identical in both edge area and center area. In this case, I used the TARGET\_FID for both. And click OK. Now when you open the attribute table of the center area with slope value, you can see that the slope value for the center area is joined in based on TARGET\_FID.

Next, add a new field called Slope\_Diff using the add field tool. Right click on it (you will notice the name is longer than what you entered, which is expected because of the join), choose field calculator and deduct the slope value of the edge with the slope value of the center area. The result is that the new field is filled with the difference of slope value between the edge area and center area of each basin.

Repeat the above step to calculate the depth difference.

## 5. Overall Shape

In this section, I will explain how I tested the “equidimensional” criteria in the oceanic basin’s definition using two different methods.

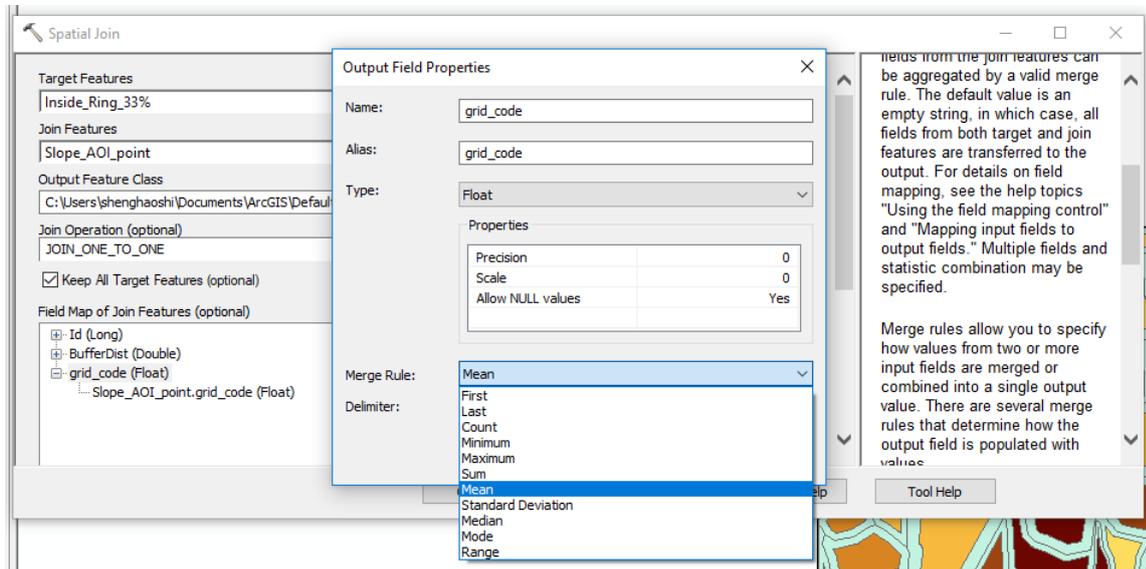


Figure 16. Spatial Join Configuration

## Illustration

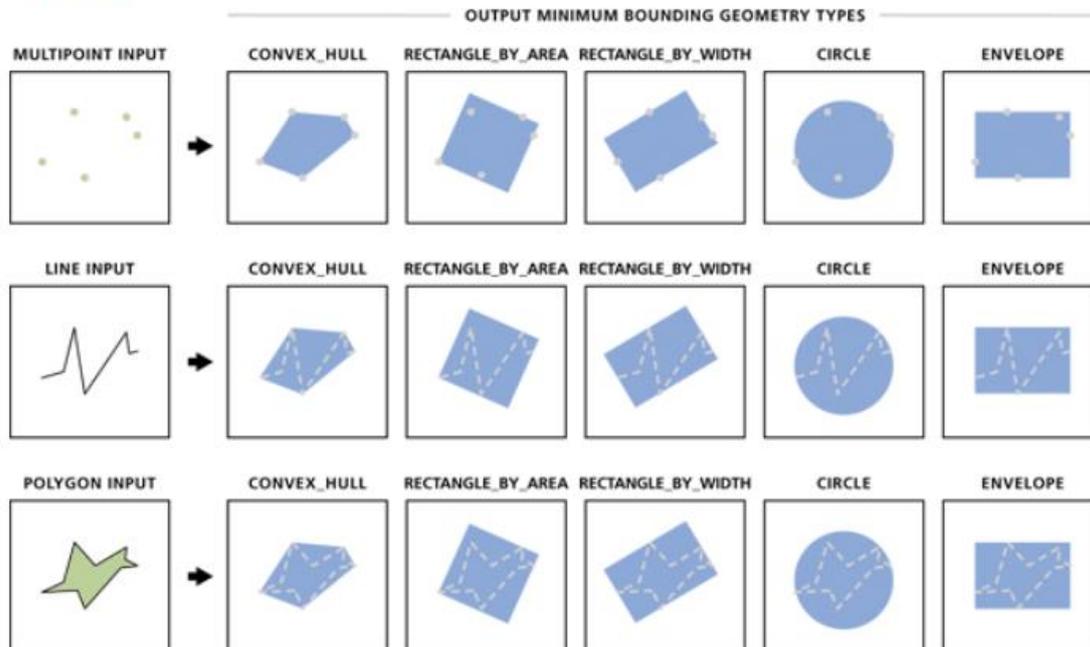


Figure 17. Graphical illustration of different type of minimum bounding geometry

First, equidimensional is an adjective applied to objects that have nearly the same size or spread in multiple directions. For a basin, it means that its length must be similar to its width. With this knowledge, the first method we will use is the minimum bounding rectangle.

The Minimum Bounding Geometry tool is located at: Data Management Tools> Features> Minimum Bounding Geometry. In this tool, we will use the basin polygon layer as the input feature, geometry type is rectangle by width. In addition, make sure that the box of “Add geometry characteristics as attributes to output (optional)” is checked. Otherwise, it will not produce the detailed measurements in the output layer. There are many types of geometry we can choose from. Figure 15 is a graphical depiction of them. We need to use the rectangle\_by\_width option, which draws rectangles with the longest line inside the shape as the width. The result will look like figure 17.

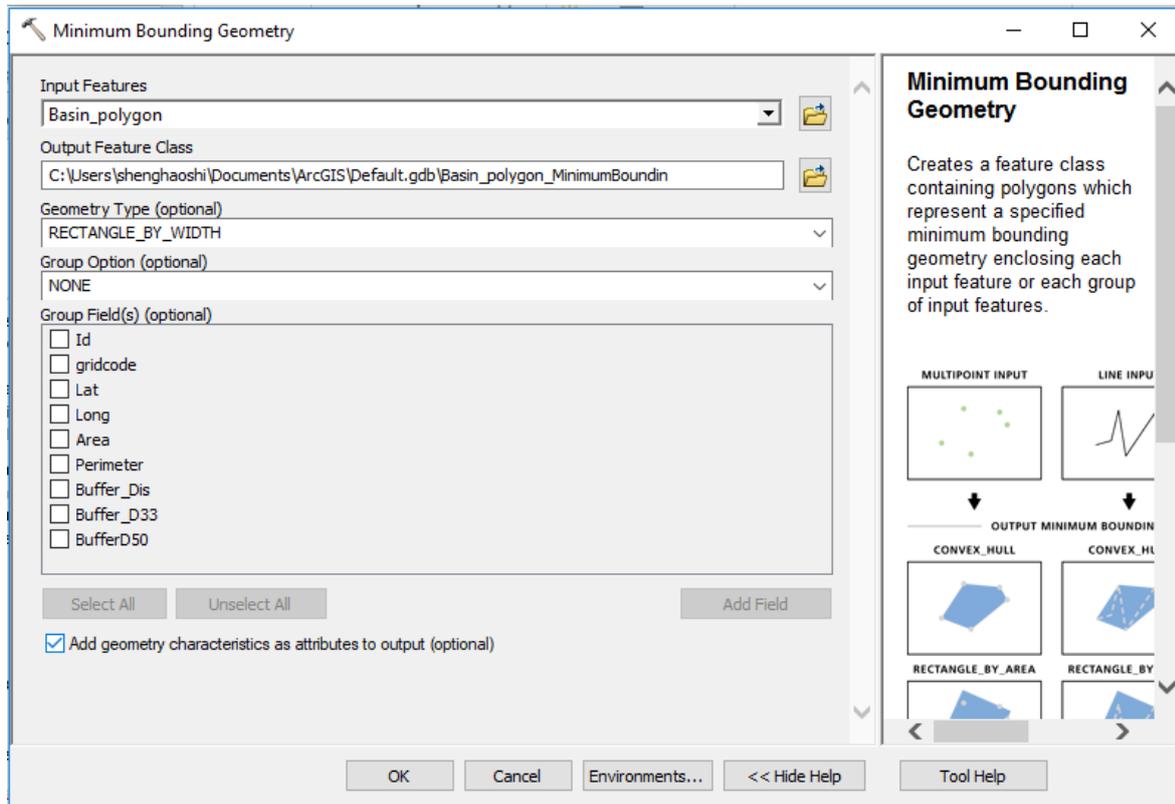


Figure 18. Minimum Bounding Geometry tool setting

In the result there will be a few new fields, among them, what we need is the MBG\_Width and MBG\_Length, which are the width and length of each rectangle. Next, in the attribute table, we add a new field called WLRatio, then use the field calculator to calculate the width to length ratio. The formula used should be  $[MBG\_Width] / [MBG\_Length]$ . The closer this output to 1, the more equidimensional the basin is.

Although the width-length ratio method is directly based on the definition of “equidimensional”, it is not a perfect way of measuring. For example, the shape of the capital letter U or T can have a width-length ratio very close to 1, but still not being equidimensional. To solve this issue, we need to ensure that basins with an irregular shape and a close to 1 width-length ratio can be detected. So I introduced a second method—the ideal circle area method.

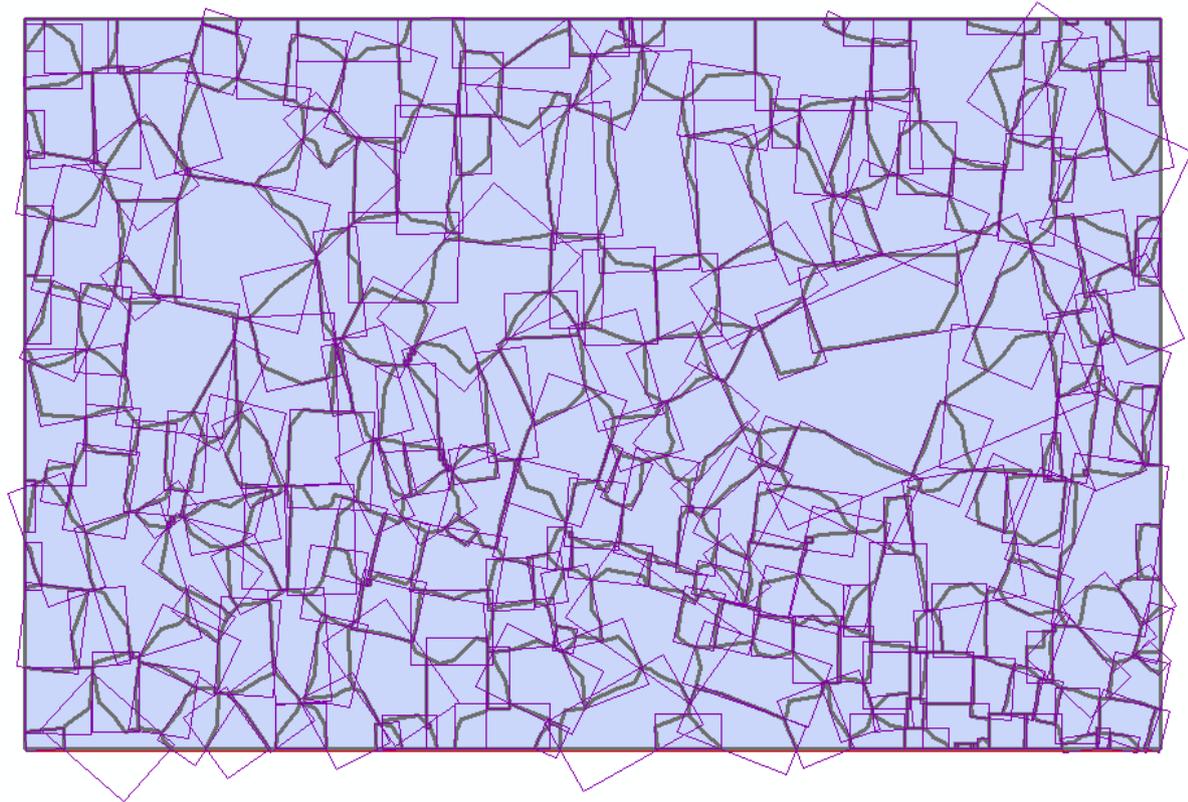


Figure 19. Output of the minimum bounding geometry tool

Mathematically speaking, a perfect equidimensional shape on a 2D surface is a circle since it has the universal diameter in any given direction. So what we need is to check the basin's surface area compared to an ideal circle. To do so, I started by assuming the basin is a circle, and divide its perimeter by 3.14, to calculate the diameter of that hypothetical circle. Next, divide the MBG\_Length value from the first method by the hypothetical diameter to produce an ideal circle ratio. Just like the minimum bounding geometry method, the closer the ratio to 1, the more likely that the basin is equidimensional.

## 6. Fuzzy Logic

After the above steps, we now have the following results: the edge to center slope differences for each basin, the edge to center depth differences, Length to width ratio, and the perfect circle ratio. In this step, we will use fuzzy logic to combine all four of them and produce a map of likelihood using fuzzy logic.

To do so, we first need to convert the value in four maps into a standard format using reclassify function.

First, we need to make four copy of the base basin layer. Right, click the basin polygon layer in the table of contents, select copy. Scroll up to find the layers, right click and select Paste Layer(s) for four times. Rename the four new copies as Basin with WL Ratio, Basin with Ideal Circle Ratio, Basin with Depth Diff, and Basin with Slope Diff respectively. Use the join function to import value for step 4 and 5. Use the same method described in step 4 to introduce the value into the four new layers.

Next, we need to reclassify the value into several classes. However, the reclassify tool in ArcMap is for raster data only. To reclassify vector data, we need to do the calculation manually using the field calculator.

We need to first use the built-in statistic tool to break the values into a few classes. To do so, right click on any of the four layers. Let's use the width to length ratio as an example. Right click on the layer and select properties. Go to the Symbology tab. In the left panel, select Quantities, Graduated colors. For Values, we shall use the width to length ratio value. On the right side, click the Classify button. In the pop-out window, select Natural Breaks (Jenks) classification method, which is the method designed to determine the best arrangement of values into different classes. We want to form 6 classes. Click OK, and the data will be divided into six classes with the value labeled, see figure 18. Write them down or take a screenshot, these values are what we need for the manual reclassification.

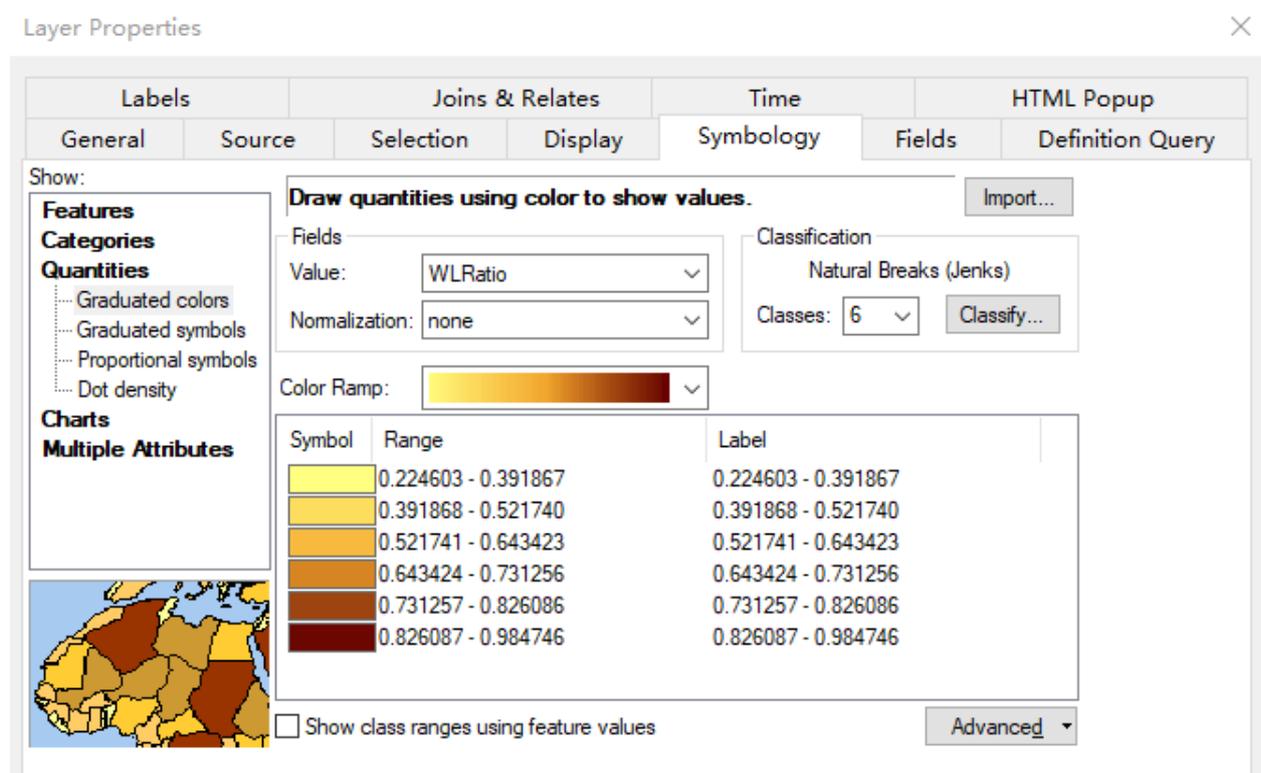


Figure 20. Natural Break data classification

Next, right click on the Basin with WL Ratio layer, open attribute table, and add a new field called Reclass\_WLRatio. Right click on the new field, and select field calculator. In the field calculator, choose VB Script parser, check the Show Codeblock box, and on the bottom, an extra box will show up, type x in that new box. In the Pre-Logic Script Code, use:

```

if [WLRatio] <= 0.391867 then
    x = 0
elseif [WLRatio] <= 0.521740 then
    x = 1
elseif [WLRatio] <= 0.643423 then

```

```

x = 2
elseif [WLRatio] <= 0.731256 then
x = 3
elseif [WLRatio] <= 0.826086 then
x = 4
else
x = 5
end if

```

This will reclassify the width to length ratio into six classes from 0 to 5. Replace [WLRatio] with the field you need to reclassify and repeat above step for the rest three layers. However, for slope differences and depth differences, the classification will be a little different. We need to replace class 0 to -10. And for that class, we need to put all the negative value in there. Because we want a way to get rid of the basins whose the center is higher or steeper than the edge so we give it a negative value instead of a low value.

The last step is to add the value of the four layers together to make the final fuzzy logic map. To do so, use the join function to join the four-layer together base on the same field, such as the Id or the Objective field. And add the four reclassified field together as a new field called FuzzyLogic.

Use the proper symbology setting to display the fuzzy logic value, we will get the final result.

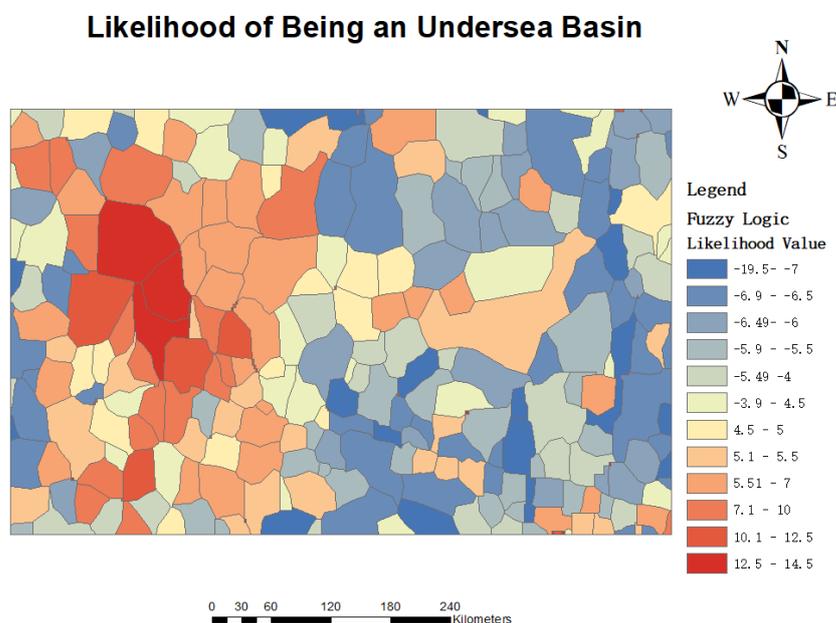


Figure 21. Fuzzy logic output, likelihood of being an undersea basin

## 7. Result Interpretation and Future Application

The final result is relatively easy to understand. Each polygon will be rated base on the four characteristics: edge to center depth differences, edge to center slope differences, width to length

ratio and ideal circle ratio. The closer the final value to 20 ( $4*5$ ), the polygon is more likely to be a basin based on B-6 definition.

However, this is still a possibility distribution instead of a full automation. In my opinion, manual check is still needed. What we can do is to isolate the polygons with high fuzzy logic value (such as 12.5 or higher) and prioritize on checking them. Figure 20 is an example of how the manual check can be done.

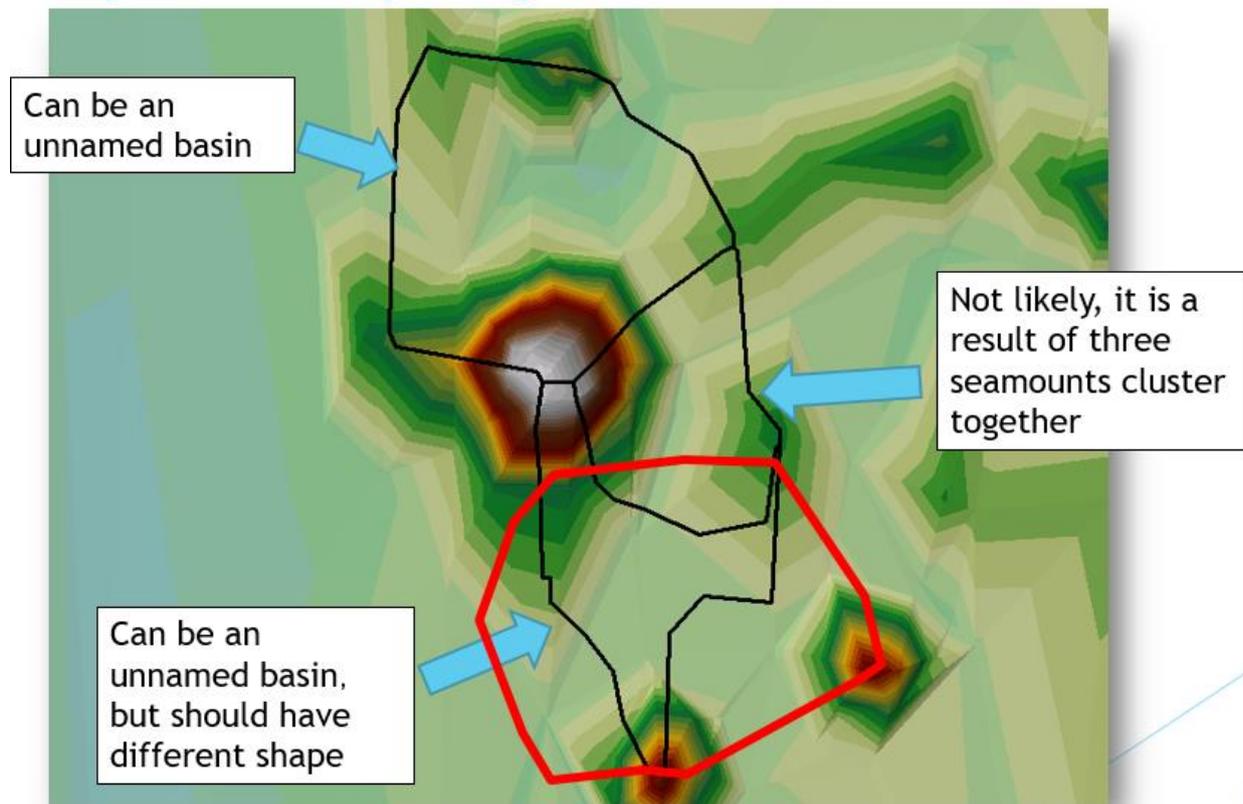


Figure 22. An example of manual check for the 3 polygon with highest value within AOI

According to the GEBCO undersea feature names gazetteer, currently there are 243 named basins around the world. In Canadian water, there are only 5-10 basins named (the number is an estimate based on visual check since GEBCO database does not allow user to do query base on national boundary). And all of them are fairly large ones.

In other words, smaller Basins can be identified and named using this application. The result can be submit to IHO for review. And if the IHO accepted our proposal then we will improve our understanding of the Canadian seafloor; or, if the IHO rejected, then we can ask for more detailed reasons and help to refine the B-6 definition of basin and potentially other features.

## Appendix IV

### Undersea Ridges Identification

*Shenghao Shi*

This is a quick summary of my method of identifying undersea ridges using ArcMap 10.6. It is partially inspired by the article Geomorphology of the oceans by P.T.Harris et al. The main method is to identify elongated areas with high TPI (topographic position index) value and relatively large area.

1. Open ArcMap, load the bathymetry file of the targeted area for analysis.  
*The bathymetry file is the ETOPO1 dataset from NOAA, with 1 arc minute resolution*
2. Calculate the TPI value base on the bathymetry data. In ArcMap, there is no built-in tool that can be used to calculate TPI. Therefore I acquired the *Land Facet Corridor Designer*, v. 1.2.884 developed by Jenness Enterprises through their website. ([http://www.jennessent.com/arcgis/arcgis\\_extensions.htm](http://www.jennessent.com/arcgis/arcgis_extensions.htm)) this tool allows the user to generate a TPI layer based on DEM.

After loading this tool into ArcMap, it will show up as a small window called Land Facet Analysis. Go to Land Facet Analysis> Topographic Position Index Tools> Calculate TPI raster. Use the bathymetry layer as the DEM raster layer, TPI type as the default. In the neighborhood options, select the desired neighborhood size and shape. In general, the larger the neighborhood, the Courser the final output will be. So the size should be controlled in a reasonable range. For my case, since my bathymetry has a coarse resolution (1 arc minute pixel size), chose a 3 cells radius.

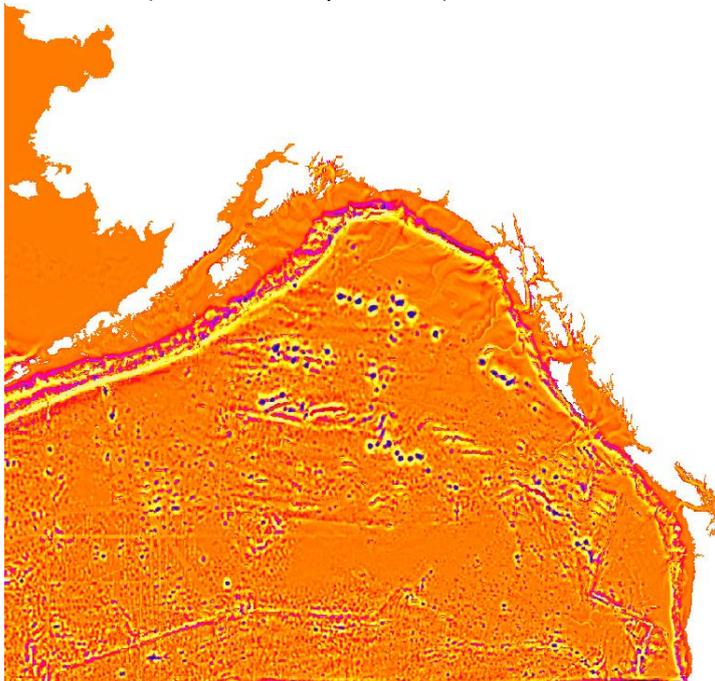


Figure 23. TPI raster layer with 50 cells radius

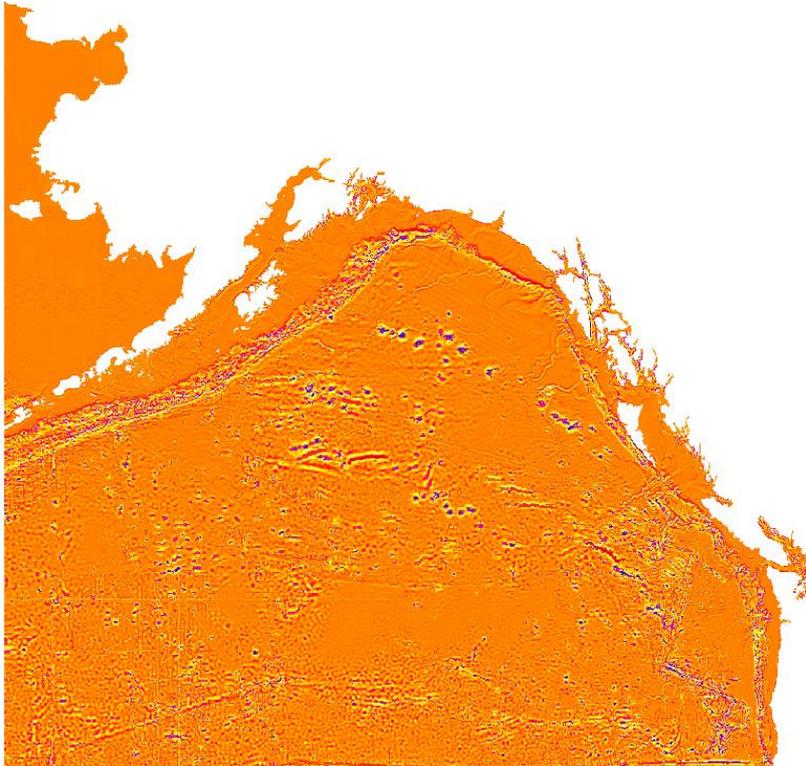


Figure 24. TPI raster layer with 3 cells radius

3. The Topographic Position Index (TPI) compares the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings, as defined by the neighborhood (ridges).

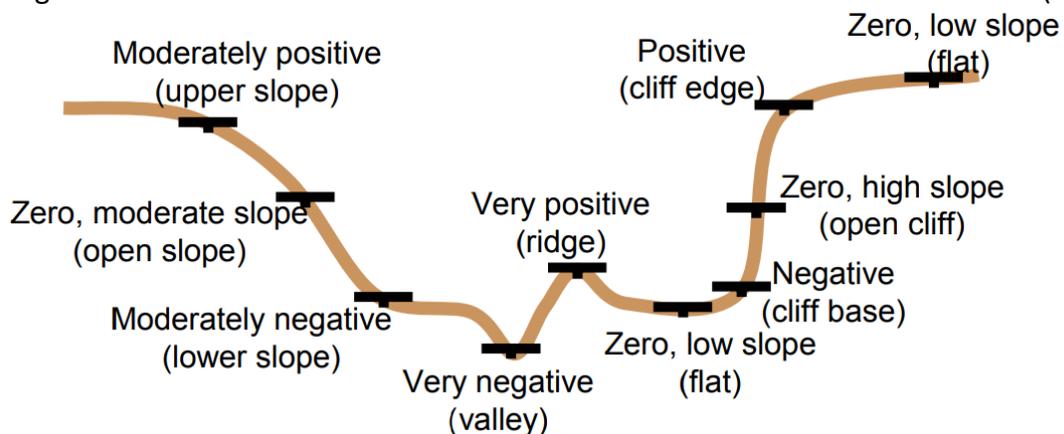


Figure 25. TPI value and corresponding terrain types, Weiss (2001)

4. Next, we need to reclassify the TPI to be able to identify the area with high TPI value. According to Weiss (2001), standard deviation is a repeatable method of creating classes. To be specific, ridge is usually considered to have TPI value higher than 1 standard deviation of the dataset (figure 4).

| Class | Description  | Breakpoints  |
|-------|--------------|--|
| 1     | ridge        | $> + 1 \text{ STDEV}$  |
| 2     | upper slope  | $> 0.5 \text{ STDV} \leq 1 \text{ STDV}$   |
| 3     | middle slope | $> -0.5 \text{ STDV}, < 0.5 \text{ STDV}, \text{slope} > 5 \text{ deg}$          |
| 4     | flats slope  | $\geq -0.5 \text{ STDV}, \leq 0.5 \text{ STDV}, \text{slope} \leq 5 \text{ deg}$ |
| 5     | lower slopes | $\geq -1.0 \text{ STDEV}, < 0.5 \text{ STDV}$                                    |
| 6     | valleys      | $< -1.0 \text{ STDV}$  |

Figure 26. Common classification breakpoints using standard deviation, Weiss (2001)

The standard deviation of the 3-cell TPI layer is 31.58391919874432. I used this value as the threshold to reclassify the raster layer into two categories: ridges and non ridges. After 3D visual check using ArcScene against many known ridges in the GEBCO database and elevations that is very likely to be unnamed ridges, I believe this value can be justified. Figure 5 shows one example of checking this method against an real life example. The image on top is a screenshot from the GEBCO beta database, the red dot represents the feature Eickelberg Ridge. The image in the middle is the TPI layer for the approximately same area. The image at the bottom is the reclassified TPI layer with threshold of 31.5839192. This example showcased the 1 standard deviation indeed helps us identify elevation areas.

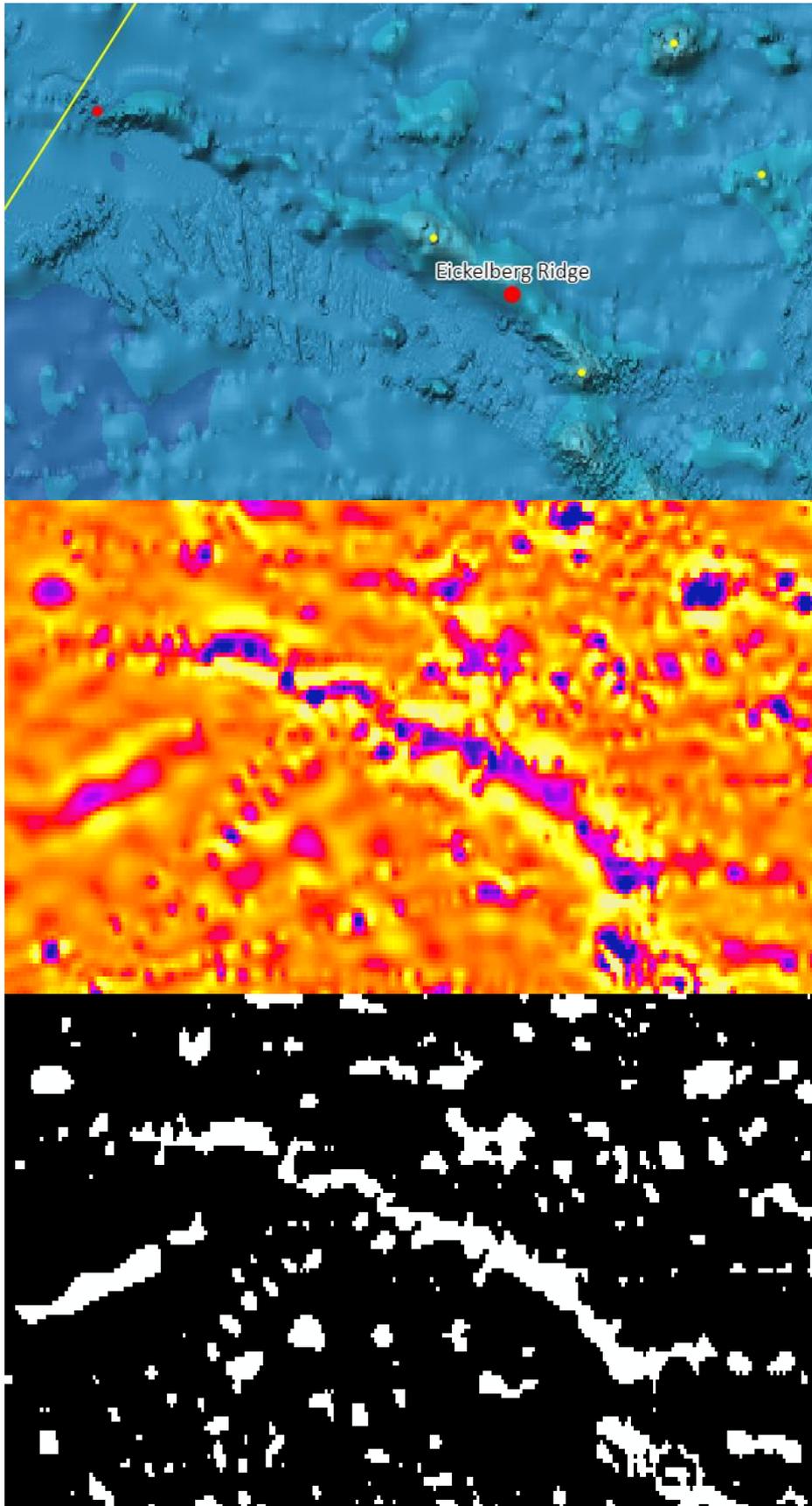


Figure 27. An example of TPI based identification method

5. After determining the breakpoint, we need to execute the reclassification to remove all areas with TPI value lower than the threshold. Open the reclassify tool, set value below

31.583919 to a new value (such as 1), set the rest to NoData, then execute. The result will be a raster layer with TPI value higher than 31.583919.

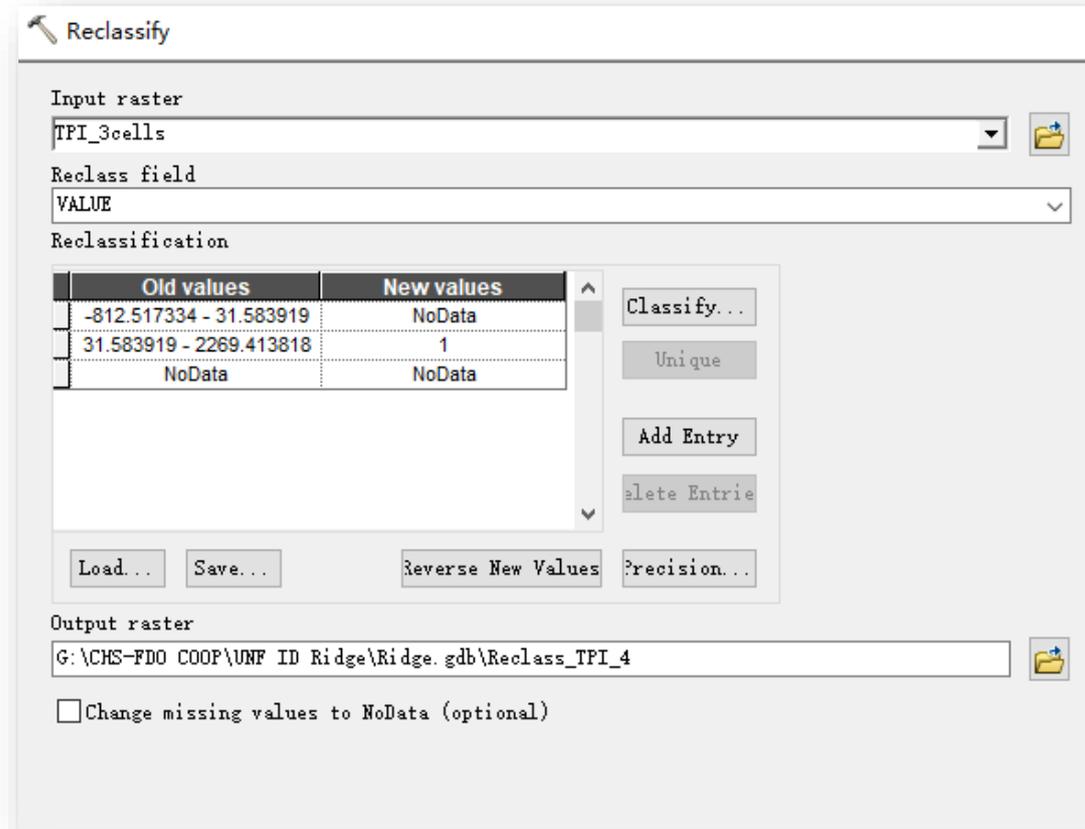


Figure 28. Classification setting

6. Next, we need to check the shape and only keep those linear shape features. First, use raster to polygon tool to convert the result from the last step into a vector file, then run the minimum bounding geometry tool, use the converted vector layer as input, use the RECTANGLE\_BY\_WIDTH as the Geometry Type. This tool will find the longest straight line within each polygon. Use that line as the width, draw a box around each individual feature. Be sure to check the Add geometry characteristics as attributes to output box when using this tool. This option will add two fields called MBG\_width and MBG\_Length to the attribute table which we need for the next step.
7. To determine the shape of the polygons, we need to calculate the width to length ratio. Open the attribute table, add a new field called WLRatio and set the type to float or double. Use the field calculator on the newly created field to calculate  $[MBG\_Width] / [MBG\_Length]$ . The larger the ratio it is, the more elongated the feature is. See figure 7.

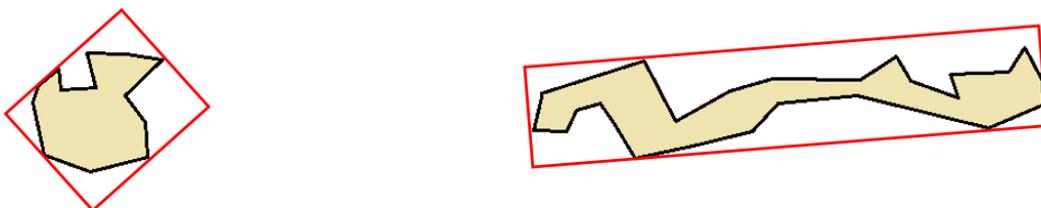


Figure 29. Length to width ratio illustration. Shapes with higher ratio value tend to be more linear.



Reference:

Harris, P.T. (2014). Geomorphology of the oceans. *Marine Geology, Volume 352* (1), Pages 4-24. <https://doi.org/10.1016/j.margeo.2014.01.011>

Weiss, A. (2001). *Topographic position and landform analysis. Poster presentation*, ESRI User Conference, San Diego, California, USA. [http://www.jennessent.com/downloads/TPI-poster-TNC\\_18x22.pdf](http://www.jennessent.com/downloads/TPI-poster-TNC_18x22.pdf)

## Appendix V

### Undersea Feature Identification Methodology - Sea Channel

Shenghao Shi

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#### Introduction

This document summarizes the discovery methodology for sea channels based on the B6 definitions. According to the IHO B-6 definition, a sea channel is:

An elongated, meandering depression, usually occurring on a gently sloping plain or FAN

By reading the sea channel definition in B-6, we can tell that this feature has four key criteria: 1) elongated, 2) meandering, 3) depression, 4) and occurring on a gently sloping plain or FAN. Part I & II are based on the key feature: depression, aka negative TPI value. Part III will focus on the other three: Elongated, Meandering, and Gently sloping/Flat.

#### I. Hydrology Analysis

The physical characteristics of sea channels resemble streams and rivers on land. They are all linear depression features that formed due to the erosion of water flow. Land channels are primarily the result of overland flow where saturation overland flow deepens to increase shear stress and begin channel incision (Bierman & Montgomery, 2014). While sea channels are “trough-shaped erosional features which occur on the deep ocean floor” (Shepard & Emery, 1941).

Draw upon the physical and developmental similarity of sea channels and land channels, we could utilize the hydrology toolbox in ArcMap to conduct our initial analysis. Detailed steps are:

1. Add the bathymetry DEM into your ArcMap project.
2. Run the fill tool on the DEM, name output “fill”  
*To smoothen the DEM, therefore, produce better flow direction for hydrology analysis*
3. Run the flow direction tool, use the fill as input surface raster.  
*This step basically assumes the raster surface is impermeable and outputs the direction of the flow for each cell base on its elevation differences compare to its neighbor cells.*
4. Run the flow accumulation tool, use the flow direction output from step 3 as input.
5. Use reclassify or raster calculator to separate flow accumulation into two categories. I used the raster calculator, the expression "FlowAccumulation" >= 500.  
*This will separate area with a high amount of flow accumulation with the rest, in other words, extract potential streams.*

*In here I made an assumption of using 500 as the breakpoint for flow accumulation. Typically, a flow accumulation value should be no less than 100. Generally speaking, the smaller the threshold, the more noises will be included. Figure 1 below shows the differences between the threshold of 100, 300 and 500 in green, yellow and blue respectively. The reason for choosing 500 is that I checked the output against the existing*

sea channels in the GEBCO database, 500 is the breakpoint that introduced a minimum amount of noise while ensured the integrity of the channels.

There is an article on analytic method for determining an appropriate threshold value for stream network delineation by Tarboton, Bras, & Rodriguez-Iturbe (1991). More related research will be done on this issue in the near future to further decide a validated threshold. For purely methodology development, 500 will be used for now to reduce the amount of work.

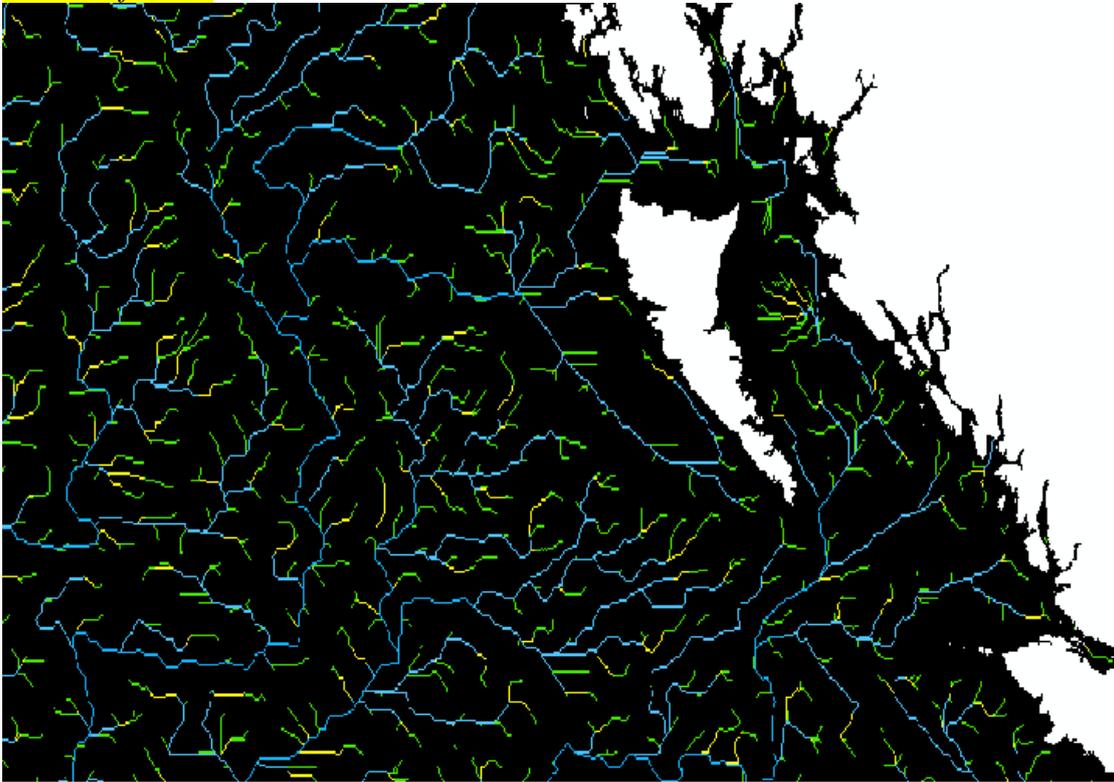


Figure 30. Flow accumulation threshold of 100, 300 and 500 in green, yellow and blue respectively.

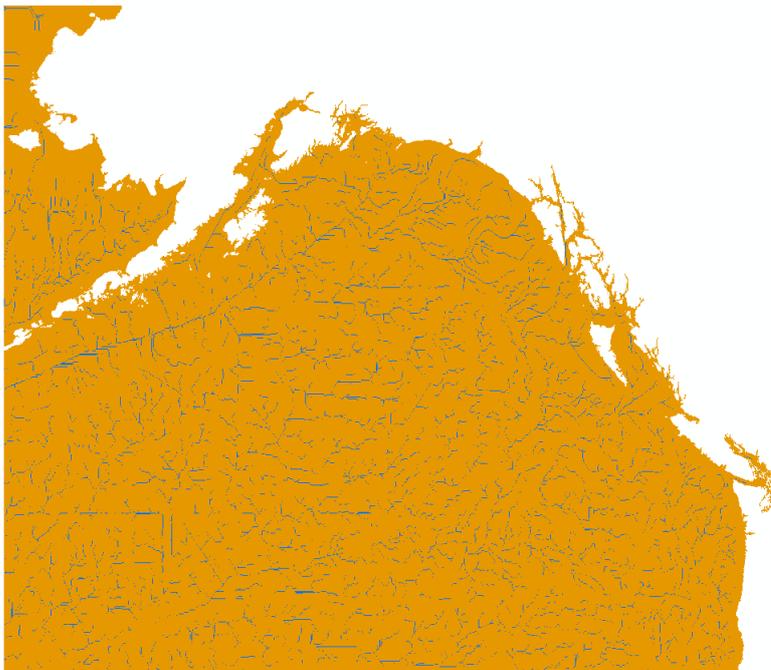


Figure 31. Flow accumulation reclassify result. Threshold = 500

6. Next, use the stream to feature tool on the reclassified layer produced by step 5. *This too converts a raster representing a linear network to features representing the linear network.*
  7. Use the stream order tool, input stream raster is the output from step 5, again.
  8. Run the stream to feature tool again, this time use output from step 7 as input stream raster. *The output is a polyline layer, which is our stream network for the AOI.*
  9. The result from step 8 contains many segments. In order to make it easier to process, run the dissolve tool on it to produce a dissolved stream network layer.
- By this step, we have had the hydrology analysis completed.



Figure 32. Identified streams

*By this step, we have identified potential stream network of the AOI. Some of the lines can very likely to be the centerline of sea channels. However, unlike a real drainage watershed, many of the streams are fictional. In order to remove ones that are not actual candidates of sea channels by comparing it with depression areas using TPI.*

## II. TPI based primary identification of the potential sea channels

In this part, we will identify depression areas using topographic position index. This method is partially inspired by the article Geomorphology of the oceans by P.T.Harris et al. (2014)

- To calculate the TPI value, we need to download a plug-in. I used the Land Facet Corridor Designer, developed by Jenness Enterprises through their website. ([http://www.jennessent.com/arccgis/arccgis\\_extensions.htm](http://www.jennessent.com/arccgis/arccgis_extensions.htm)) this tool allows the user to generate a TPI layer based on DEM.

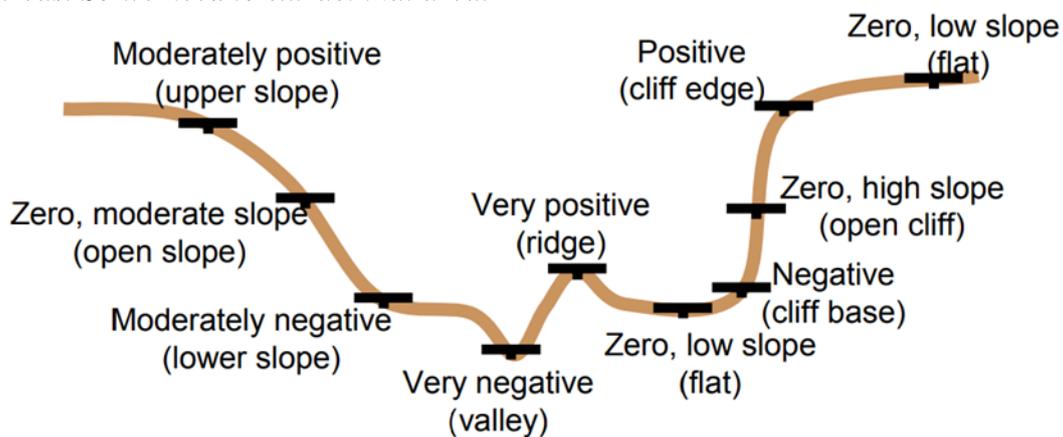
After loading this tool into ArcMap, it will show up as a small window called Land Facet Analysis. Go to Land Facet Analysis> Topographic Position Index Tools> Calculate TPI raster. Use the bathymetry layer as the DEM raster layer, TPI type as the default.

*In the neighborhood options, select the desired neighborhood size and shape. In general, the larger the neighborhood, the more generalized the final output will be. So the size should be controlled in a reasonable range.*

For this case, since this bathymetry has a coarse resolution (1 arc minute pixel size, roughly 1.8 km \* 1.8 km), chose a 3 cells radius, which translates to a TPI radius of 10.8km.

Name the output TPI\_3cells.

- The Topographic Position Index (TPI) compares the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell. Negative TPI values represent locations where its surrounding is higher than itself, in other words, depression areas. So we need to extract that area.



- Run the copy raster tool, set pixel type to 16\_BIT\_SIGNED. *The purpose of this step is to convert the TPI layer into a signed integer type, which is required by the next step.*
- Run the majority filter tool for the first time. This time choose four neighbors and replacement threshold as Majority.
- Run the majority filter tool for the first time. This time choose eight neighbors and replacement threshold as half.

*The purpose of step 13 and 14 is to remove the small imperfections in the TPI layer.*

- Next, right click on the second time majority filter output, and change its symbology to Classified. Choose the quantile classification method and give it a large number of classes. Change the coloration of different classes and compare them to known sea channels. Find a threshold that will include the most part of existing sea channels while introducing the least amount of noise.

*This method begins by choosing a black and white color ramp, and change the color of low-value ranks to red one by one. In this case, the threshold is -8. According to Weiss (2001), the typical depressions are areas with a value less than 1 standard deviation. However, this does not apply very well in the discovery of sea channels.*

*First, we shall look at a few known sea channels from the GEBCO database. By looking at figure 4, we can visually confirm that the three known sea channels have distinct TPI value compared to their surroundings.*

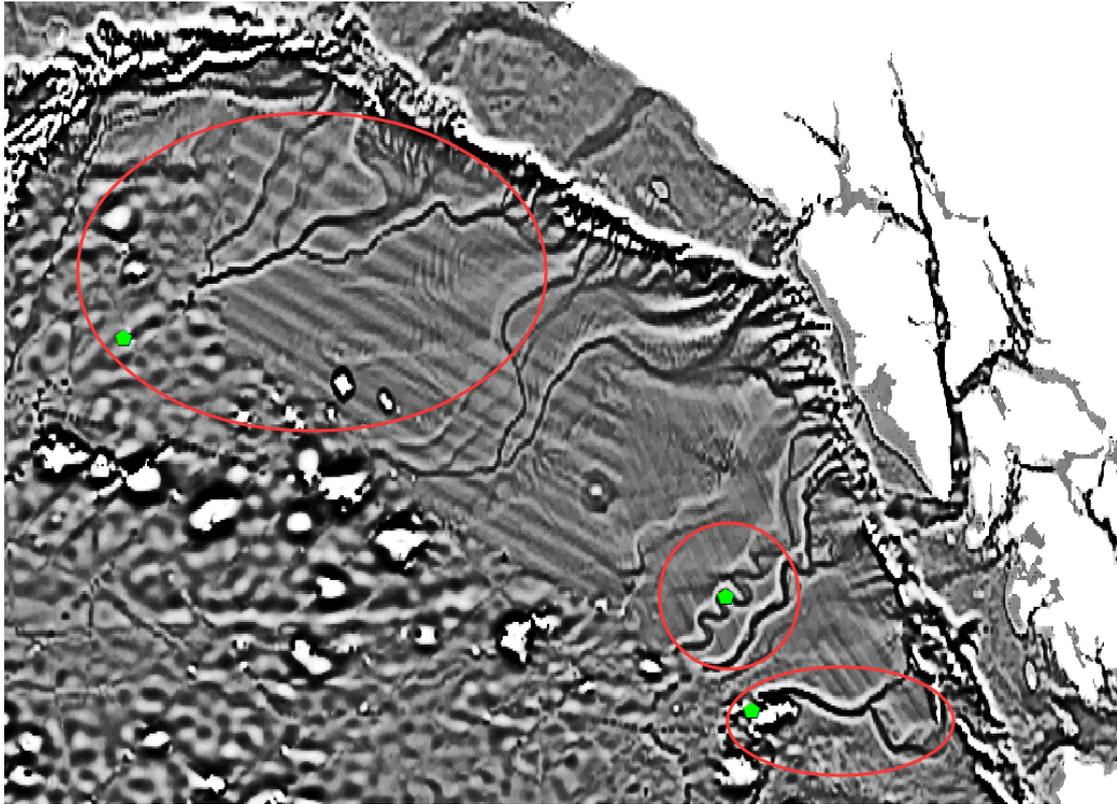


Figure 33. Known sea channels (represented by green pentagon) on TPI layer

*However, if we adopt the -1 standard deviation (in this case, -31.5), the result will be figure 5. We can tell that most of the sea channels are not properly represented.*

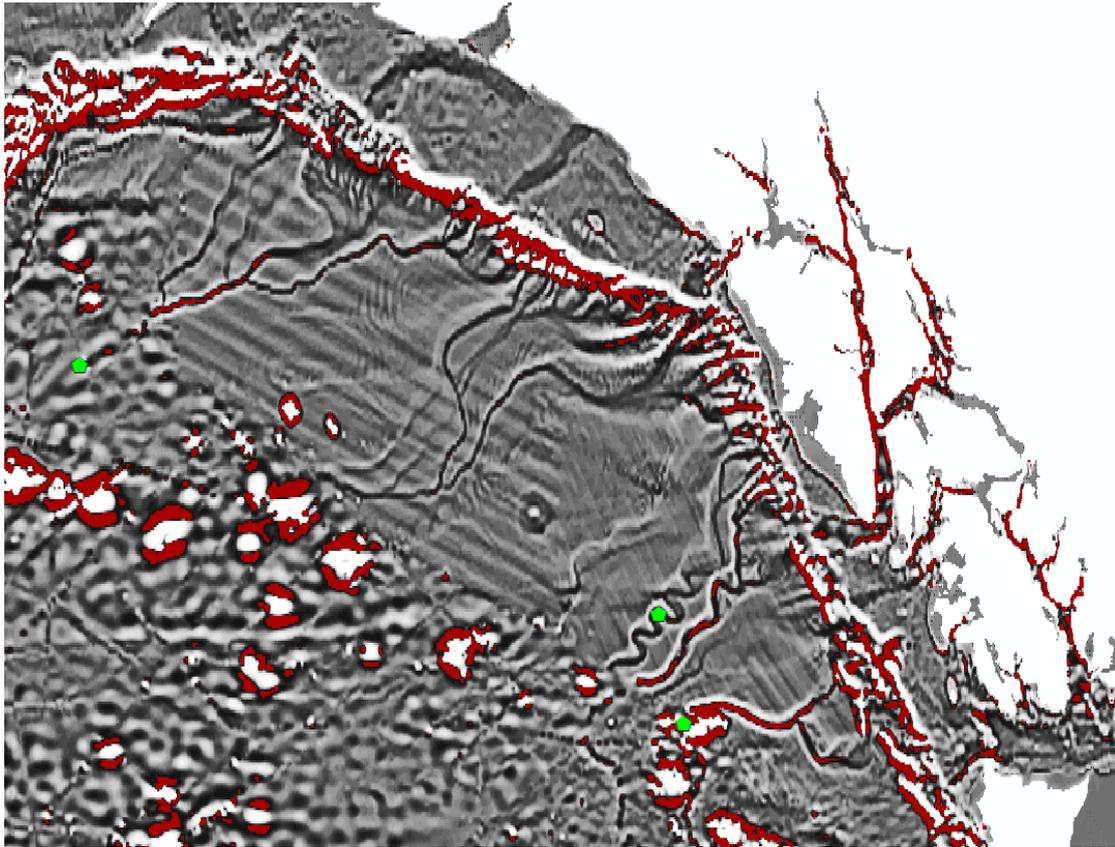


Figure 34. TPI value of the AOI, dark red stands for value less than -31.5

*By gradually raising the TPI threshold value, we find out that a the value of -8 (represented by orange), the known sea channels are presented most properly. If we keep increasing the TPI threshold to -6 (represented by yellow), a significant amount of noise will be introduced. Thus -8 was selected as the breakpoint for this analysis.*

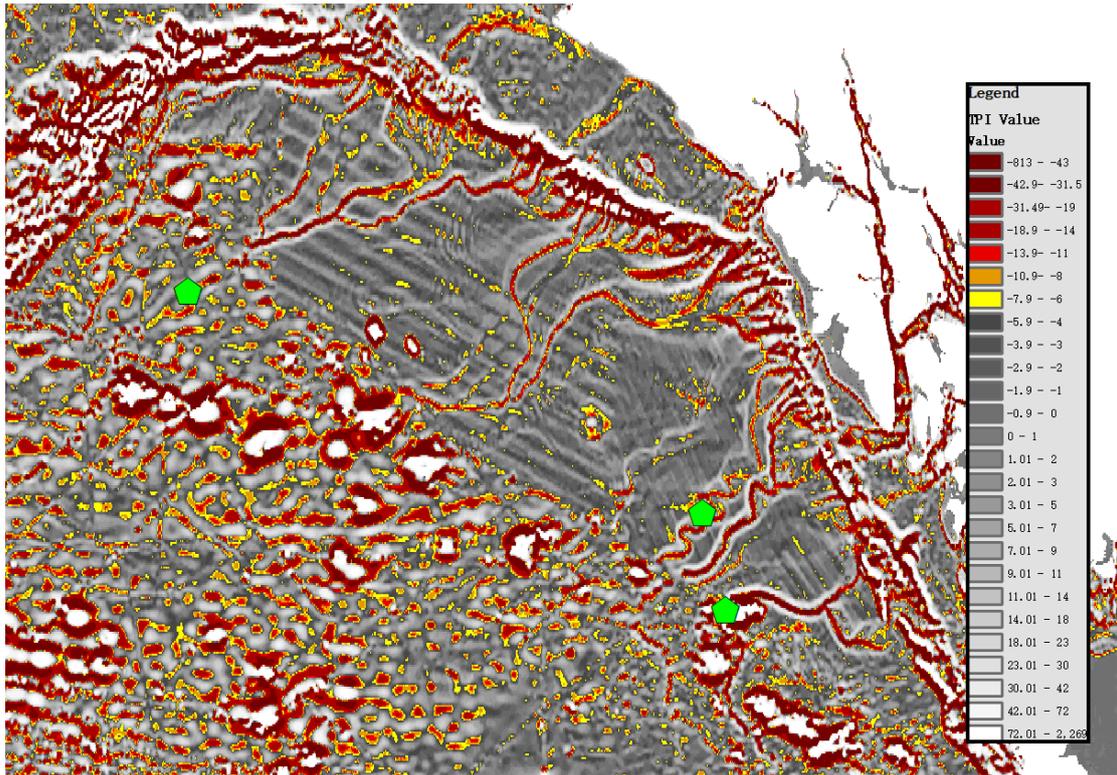


Figure 35. Reclassified TPI value of AOI with legend

16. Base on the result of step 15, run the reclassify tool to reclassify the layer into two classes: one above -8 one below -8

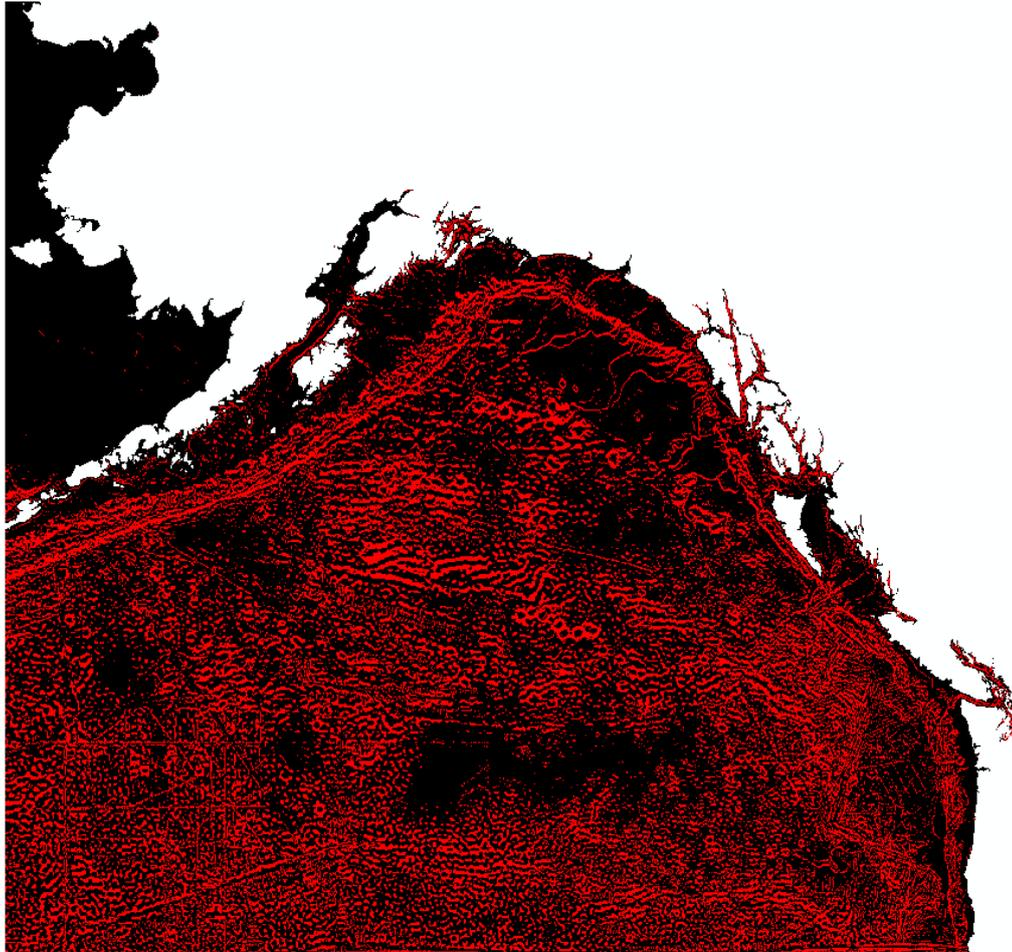


Figure 36. The result of step 16. Red areas= depressions

17. Run the extract by attributes tool to extract part where TPI value is less than -8.
18. Run the raster to polygon tool, use the result from step 17 as input, make sure to check the simplify polygon checkbox.
19. Use the output from step 17 as input, run the buffer tool, buffer the layer so it can overlap with the streams we produced previously without break the streams into too many pieces. The buffer distance I used is 1500 meters. This is the optimum result I get by experimenting with different parameter settings, it does not include too much error while also effectively prevents breaking continuous lines into too many pieces. Consider the pixel size of this bathymetry data is 1800 meter by 1800 meter, as well as the general width of known sea channels (Carter, 1988), is about 2-4 km for the floor, 4-8 km for shoulder, I believe this value is within a reasonable range.  
*The purpose of this step is to prepare for the next step.*
20. Run the dissolve tool on the 1500 meter buffer to merge the layer into one single polygon.  
*The purpose of this step is to reduce necessary breaks when clipping.*
21. Run the clip tool, use the dissolved stream as input feature (output of step. 9) and the dissolved 1500 meter buffer as clip features.  
*In this way, all identified stream that is within 1500 radius of the depression area will be identified. Note: the result will produce one single feature that includes all line segments*
22. Run the multipart to singlepart tool to break the output from the previous step into individual line segments.
23. Open the attribute table of the output of step 22. Add a new field called length\_km, run the calculate geometry function to calculate the length in km. Then select the lines that are

longer than 15 km, right click on the layer in the table of contents, go selection> create a layer from select features to remove the small segments.

Now we have many individual segments with tiny ones (<15km) removed.

*This removal threshold of 15 km is justified by the data in Carter (1988)'s article. The minimum length of the known sea channel is 200 km and many of them exceed thousands of kilometers.*

Table 1. Summary of physical characteristics of deep-sea channels described in the literature. (Carter, 1981.)

|                     | Channel length (km) | Width      |               | Depth (m)  | Levees*  |               | Axial slope         | Pelagic drape   | Heads                            | Ends   | Age (Myr)     |
|---------------------|---------------------|------------|---------------|------------|----------|---------------|---------------------|-----------------|----------------------------------|--|---------------|
|                     |                     | floor (km) | shoulder (km) |            | high (m) | wide (km)     |                     |                 |                                  |  |               |
| NAMOC               | 3800                | 1.5-7.5    | 6-16          | 100-200    | RB       | ≤ 30<br>18-87 | 1:1500 to<br>1:2100 | Yes             | †Continental slope off Greenland | Sohm Abyssal Plain (5000)                    | ?50           |
| Cascadia            | 2200                | 0.65-4.5   | 4-7           | 40-320     | RB       | ≤ 7.5<br>30+  | 1:625 to<br>1:4000  | No†             | Western U.S. margin              | Tufts Abyssal Plain (3500)                   | 5             |
| Bounty              | 1000+               | 1-2        | 5-7           | 150-650    | LB       | 10-<br>32-84  | 1:400 to<br>1:3300  | Yes             | Otago continental margin         | S.W. Pacific Abyssal Plain (4500+)           | 50+           |
| Vidal               | 800+                | 0.5-1.5    | 2-4           | 100-220    | No       | —             | 1:1100              | Yes             | Demerara Abyssal Plain           | Barracuda Abyssal Plain (5400)               | ?             |
| Maury               | 3500                | 3-10       | 5-15          | c. 100-300 | No       | —             | 1:500 to<br>1:1000+ | ?No             | Upper Rockall Basin              | Iberian Abyssal Plain (5300)                 | ≥ 13<br>(?60) |
| Surveyor            | 700                 | 0.5-3      | 5-8           | 100-450    | RB       | 13<br>40      | 1:500 to<br>1:1000  | ?No             | †Alaskan Slope                   | Aleutian Trench (5200)                       | ≤ 5           |
| Equatorial Atlantic | 1275                | 2-4        | 4-8           | 50-200     | LB       | 1-7<br>≤ 25   | 1:1040              | Yes<br>(≤ 60 m) | Brazil continental rise (4300 m) | Noronha fracture zone (5450)                 | 15-8          |
| Valencia            | 200                 | 0.5-4      | 5-10          | 200-350    | RB       | 1-2<br>≤ 40   | 1:150 to<br>1:600   | ?No             | Ebro fan                         | Valencia Fan (Balearic Abyssal Plain (2700)) | 5<br>(?20)    |

24. To break above line segments into individual pieces, the method is suggested by Richard Fairhurst. The steps are:

1. Buffer the lines a very, very small amount and create a single feature (multi-part polygon).
2. Explode the polygon buffer into its separate parts to form polygons that cover only the lines that touch within the very, very small buffer distance.
3. Calculate a long field in the polygons to be equal to the ObjectID of each exploded polygon.
4. Use the Spatial Join tool with the lines as the target and the polygons as the join features.

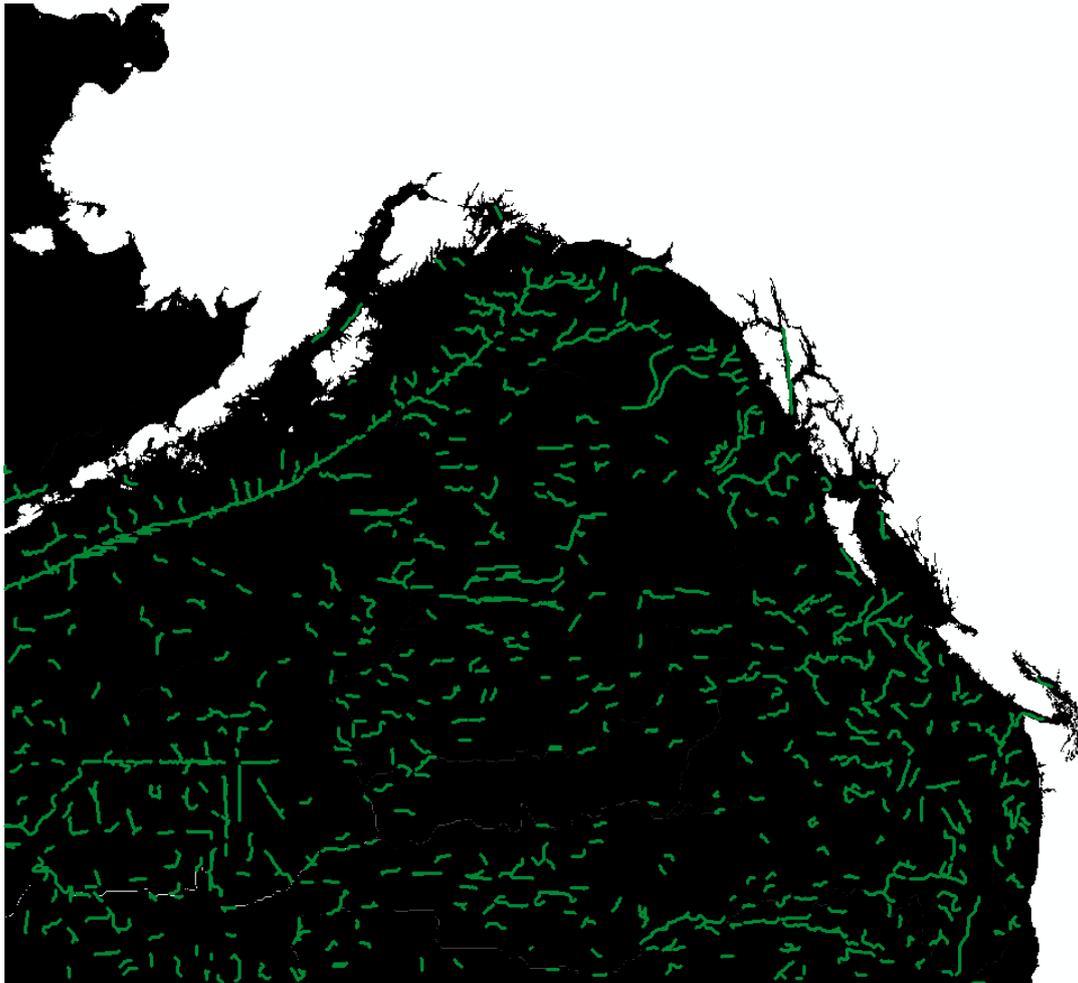
5. Dissolve the lines created by the spatial join output using the long field from the polygon that has the ObjectID of the polygon as the Dissolve field (Case field). Make sure the Create Multipart feature option is checked and the line ends option is unchecked.

You will end up with every line that touches another line at any crossing or intersection of any kind will have merged into a single polyline feature. These polyline features will nonetheless be a multi-part line feature anytime a line crossing or 3-way or greater intersection exists.

25. Next, repeat step 23, re-calculate the length, then remove small segments, this time use a larger **threshold of 50 km. This is backed up for the same reason of step 23**

*In this way (step 22-24) we will end up with line segments that do not have small pieces, has more than one endpoints, and with a minimum length of 50km.*

*By this step, we have finished the stream analysis and the output of this step will be the potential sea channels.*



*To summarize, Part I & II achieved the following: base on watershed analysis, find out areas with a high amount of fluid accumulation and consider them to be potential (sea) channels. Use TPI to identify significant depressions base on exanimate internationally recognized features. Merge two results to produce a layer of all potential channels that fit the word “**depression**”.*

*Base on all of that, I suggest that “depression” should include a minimum sea channel bottom depth difference value compare with its flat (or a better word, smooth) (can be defined by 1. STD of DEM 2. STD of the slope. 3. Counter density 4. Local relief) the surrounding sea floor.*

### III. Criteria Analysis

The sea channel definition in B-6 has four key criteria: elongated, meandering, depression, and occurring on a gently sloping plain or FAN. Part I & II is based on the criteria: depression. Part III will focus on the other three: **Elongated**, **Meandering**, and **Gently sloping/Flat**.

26. First, we need to create a layer that represents the criteria Elongated.

According to Carter (1988), the length of the sea channels varies from 200 to 3800 km. According to the manually digitized GEBCO sea channels, the length of the sea channels varies from 156 km to 739 km.

The potential sea channels identified by so far have the maximum length of 1202.51 km, and a minimum of 15.05 km.

Base on the above value, we can estimate that the minimum length of a sea channel should be no less than 150 km.

27. Reclassify the result manually using the field calculator again. The method of this step will be needed for a few more times for reclassifying other criteria.

1) **This step is not necessary for reclassify length, but can help us to generate statistics quickly.** Right click on the layer, go to properties, symbology, and choose Quantities> Graduated colors. Click on Classify, you will be able to classify your data with default functions. One that is commonly used is the Quantile method, it helps you to divide your data into several classes with an equal amount of data in each class.

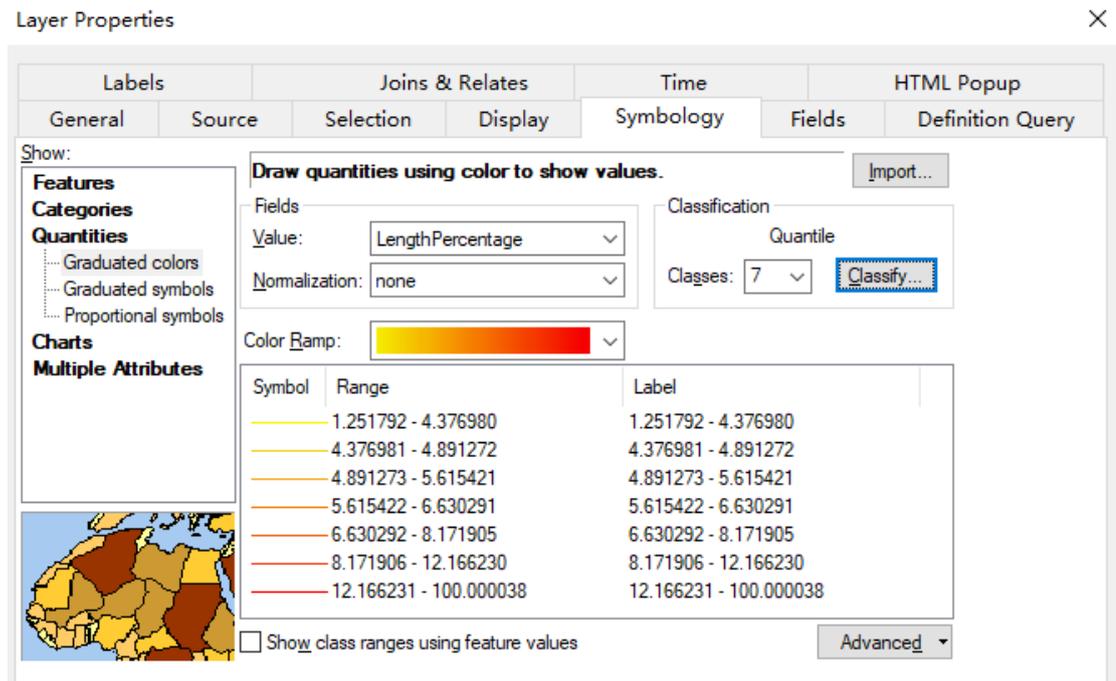


Figure 37. An example dividing data using classify function

2) Open the attribute table of the layer, add a new field and give it a name of your choice.  
 3) Run the field calculator, check the Show Codeblock checkbox, type x in the box below, in the box above, use expression:

```

if [field1] < value1 then
  x = 0
elseif [field1] < value2 then
  x = 1
elseif [field1] <= value3 then
  x = 2
else
  x = 3
end if

```

4) In this way, you can reclassify your data in vector layers. For this reclassification, we need to divide the data into 2 categories: length greater than 150 km as “1” and length less than 150 km as “0”.

Now, we have a field in the attribute table using 1 and 0 to differentiate whether the line segments reach the minimum length of 150 km or not.

28. Next, we need to create a layer that represents the criteria **Meandering**. Run the minimum bounding geometry tool, use a copy of the result of hydrology analysis (a copy of the output of step 25) as input features, choose RECTANGLE\_BY\_WIDTH as the geometry type, be sure to check the Add geometry characteristics as attributes to output (optional) checkbox. Note the input layer's coordinate system needs proper projection to ensure the right units are used.

*What it will produce is a minimum bounding rectangle for each line segments, which will contain the value of the width and length of that bounding rectangle. We will divide the actual length of the line with the length of the MBG rectangle. In this way, a straight line will have its length almost equal to the length of the rectangle, therefore a low number; while a more meandering line will produce a bigger result.*

### Illustration

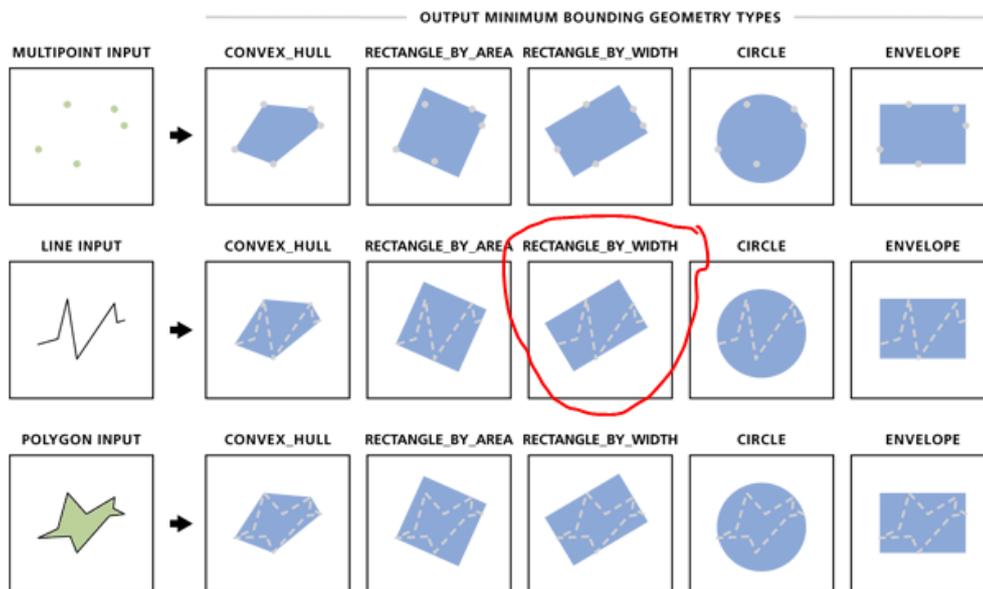


Figure 38. Different types of minimum bounding geometry

29. Right click on a copy of the output of step 25, go to Joins and Relates > Join. In the new Join Data window, choose ObjectID for the first box, choose the MBG output (step 28 output) in the second box, choose ObjectID again in the third box.  
*In this way, you will join the data from the MBG output and the output of the hydrology analysis together.*
30. Open the attribute table, add a new field called Lengthkm\_MBGLength, run the field calculator tool and calculate the field by dividing the length of the line in km with MBG\_Length.  
*The unit of MBG\_Length will be the same as the linear unit for the input of MBG tool, scale up or down the value to make sure that MBGLength and Lengthkm are using the same unit. In this way, the result will be the River Sinuosity Index. According to Horacio (2014), the RSI measures the degree of meandering of a riverbed, which is further used to differentiate river types.*
31. Reclassify the result manually using the field calculator. For input details, see step 27. The classification breakpoints used are: <1.05 (straight); 1.05-1.3 (sinuous); 1.3-1.5 (moderate meandering) and >1.5(meandering form), which is suggested by Dr. Horacio (2014). **Base**

on the suggest classifiers value and the observation result, I personally would suggest a Sinuosity Index greater than 1.3 should be used to quantify “meandering” in B6 definition.

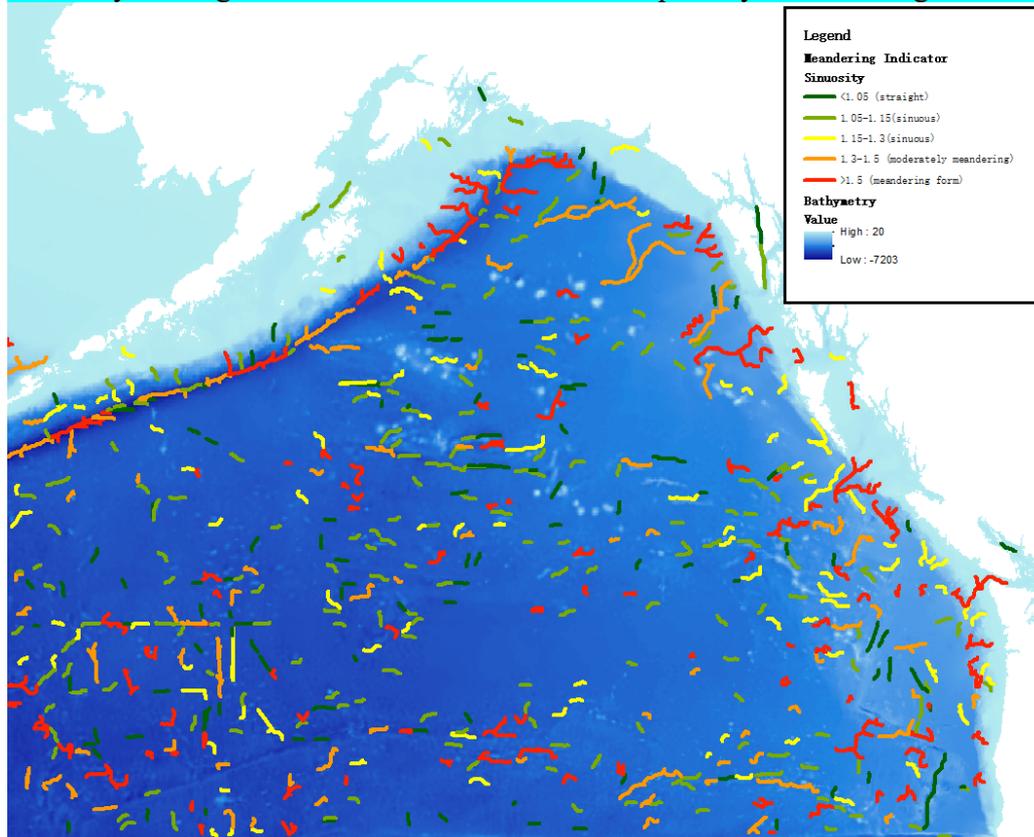


Figure 10. Potential sea channels, classified by sinuosity value

Lastly, we need to calculate the criteria **Gently sloping plain**. Which means there should be a consistent slope value in areas around the line segments, either close to zero, which means very flat; or a consistent value, means it is sloping, but don't have too much variation.

Note: to define *flatness*, there are for ways I can think of, they are: 1) standard deviation of the DEM 2) standard deviation of slope value of DEM 3) Contour line density 4) local relief. The issue with method 1 and 3 is if the area surface is sufficiently smooth, but is tilting, then the larger the area, the less accurate they become. This analysis will focus on STD of the slope. More work on using local relief as the defining factor of flatness will be done in the future.

32. First, run the slope tool on the bathymetry layer. Leave all setting as default.
33. Run the focal statistics tool, use the result of the last step as input raster, neighborhood type as a circle, radius 3 cells, statistics type STD.

*This will generate a layer showing the standard deviation value of the slope base on a 3 cells radius circle neighborhood. In other words, this is a flatness indicator.*

*The standard deviation value basically stands for 1/6 of the variability in the selected area. For example, if a line segment's surrounding area has an STD of 0.5, it means around 68% of the slope variance will stay within 2 STD, aka 1°; about 96% of the slope variance will stay within 4 STD, aka 2°; about 99.8% of the slope variance will stay within 6 STD, aka 3°.*

*Currently, we are still searching for literature and/or data for related descriptions of flatness to decide what STD value we should use as the threshold.*

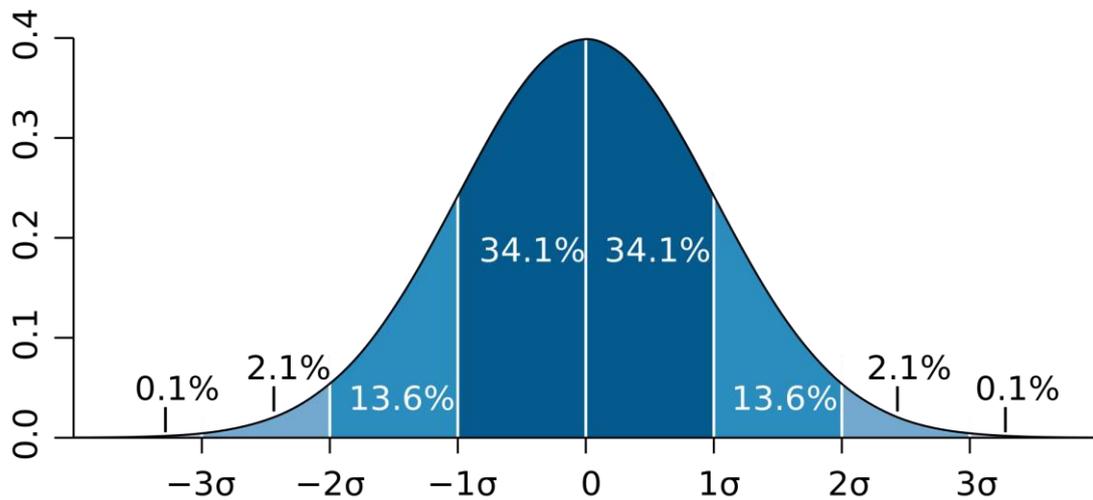


Figure 11. Normal distribution. Each colored band has a width of one standard deviation. M. W. Toews - Own work, based (in concept) on the figure by Jeremy Kemp, on 2005-02-09

34. Run the raster to point tool, convert the output of step 33 into a point layer.

35. Run the buffer tool on a copy of the output of step 25, set the buffer distance to 20 km.

The purpose of this step is to create areas that include area represents the surrounding of each line segments. The buffer distance of 20 km is chosen since it is large enough to include areas which are relatively extensive enough to negate the effect of small depressions or elevations to a certain extent. Also, it is small enough to not include areas that should not affect the local flatness. Although worth noticing, this value still has a certain level of arbitrariness.

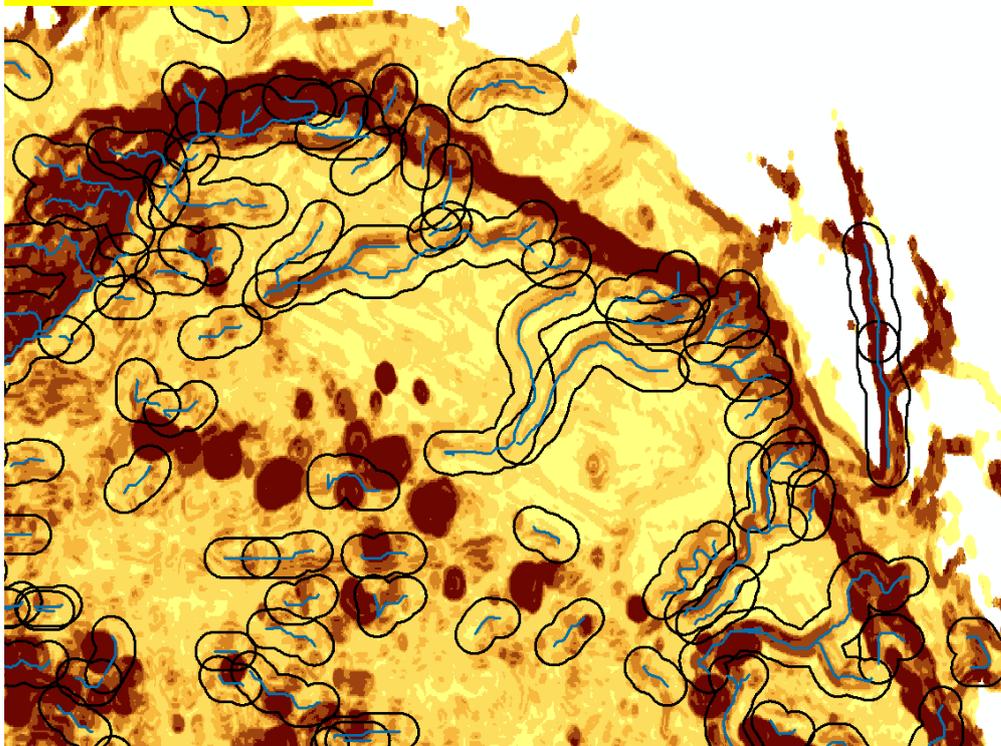


Figure 12. A close look at the coverage of 20 km buffer in the AOI

36. Run buffer tool on a copy of the output of step 25. Set the buffer distance to 8 km.

This step is aimed to create a buffer area that includes the floor and the shoulder of each sea channel. According to (Carter, 1988) and the manual measurement of digitized GEBCO sea channels, the common width of the sea channels varies from 5 to 15 km, with the minimum of 2 km and the maximum of 16 km. The 8km buffer will be created toward both directions, covering a maximum width of 16 km. Base on visual observation, the 8 km buffer effectively depict the extent of the existing sea channels.

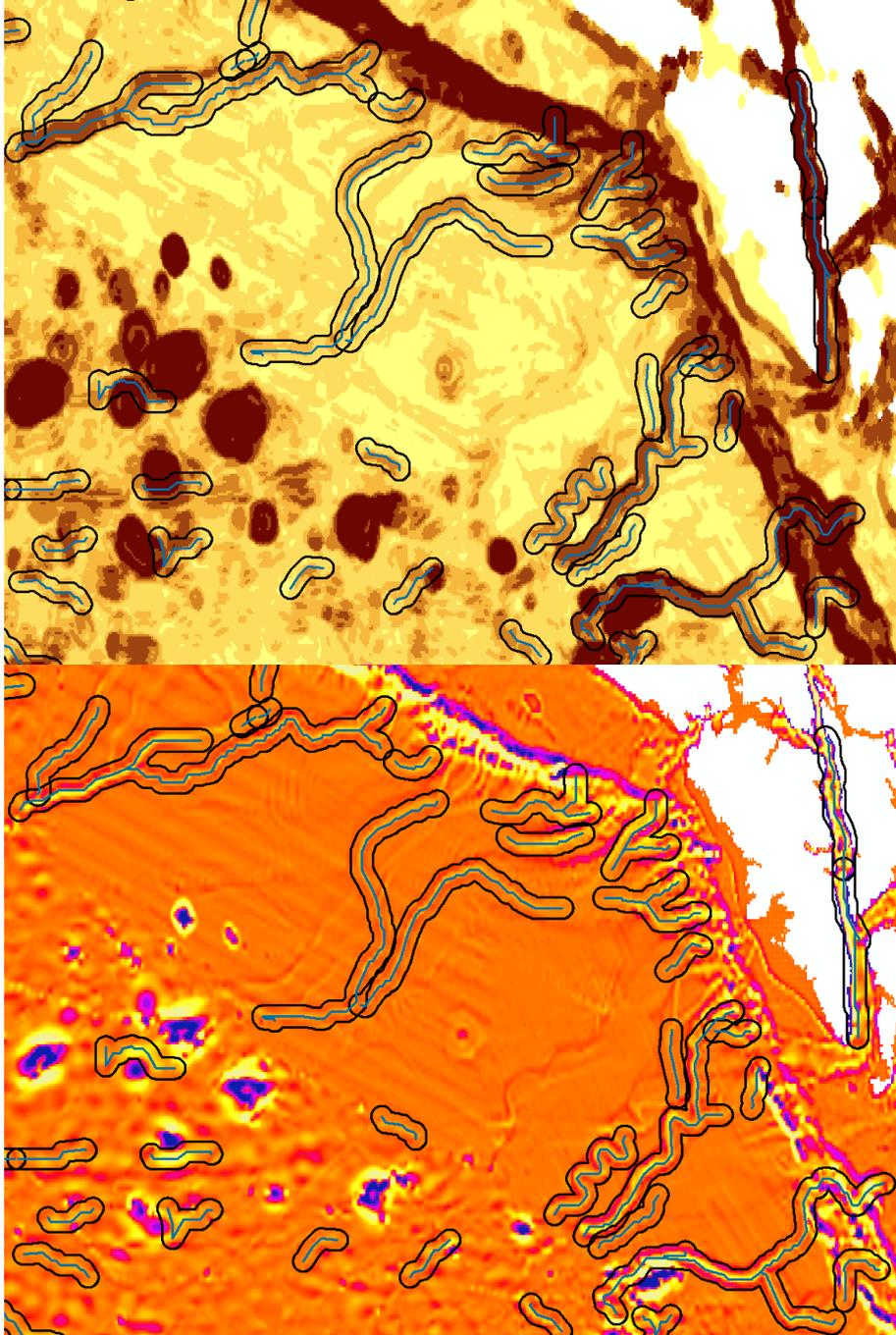


Figure 13. A close look at the coverage of 8 km buffer. Upper: STD of the slope. Lower: TPI

37. Run the erase tool, use the output of step 35 as input features, and use the output of step 36 as erase features.  
This step removes the potential sea channels from the surrounding area.
38. Run the spatial join tool, use the result of step 37 as target features, the result of step 33 as join features. In the field map of join features, find the field that contains the standard

deviation value from the STD point layer, light click, go to prosperities, change merge rule to **mean**. Remove all other unnecessary fields by right click and delete them.

*This step will calculate the average standard deviation of slope value in each line features' surrounding area.*

39. Open the attribute table of a copy of the output of step 25, go to Join and relates> Join. In the new Join Data window, choose ObjectID for the first box, choose the step 29 output in the second box, choose ObjectID again in the third box.

*In this way, you will join the slope's average STD from the surrounding areas to each corresponding lines from the hydrology analysis.*

40. Reclassify the result manually using the field calculator. Method sees step 27.

**For the dividing threshold, based on observing of the bathymetry, the TPI layer, the slope standard deviation layer, and slope STD's statistics. I divided them into 3 categories: less than 0.5, 0.5 to 0.65, greater than 0.65. These values have a certain level of arbitrariness.**

41. *By so far, you should have 3 layers that represent the **Elongated, Meandering, and Gently sloping/Flat** criteria respectively.*

Use the join function, to join the three layers together. To remove repeated columns in the attribute table, right click on the layer and select Data> Export Data. The attribute table of the exported layer will be editable.

42. Run selection> Select by attribute tool, use the joined layer as input, begin your selection using the method "Create a new selection", then switch to "Select from current selection".

Use a proper formula to select features that:

- 1) Longer than 150 km
- 2) Have a sinuosity index of 1.3 or greater
- 3) Have a slope standard deviation less than or equal to 0.5

Right click on the joined layer, go to Selection> Create layer from selected feature to create a new layer represents the lines fits the above criteria.

**In this way, we have finished the identifying of features that fit all of our criteria.**

43. The output (count: 20):

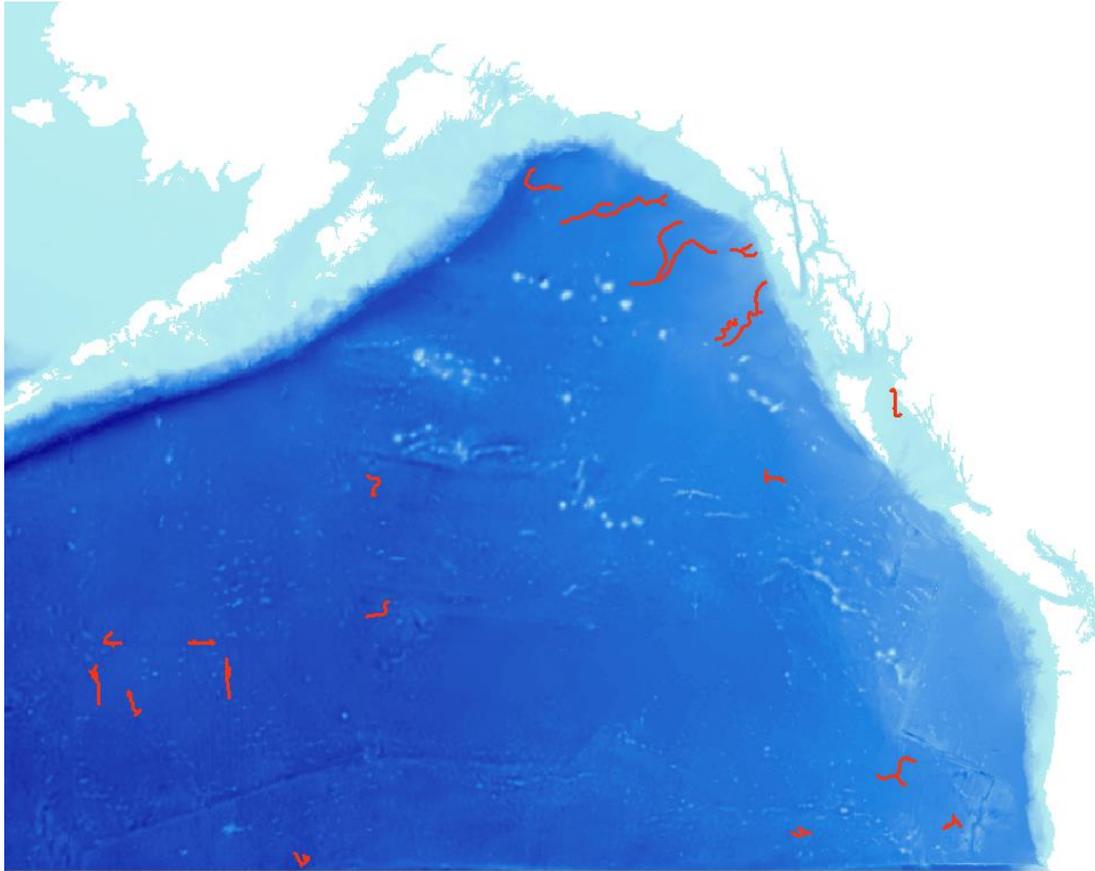


Figure 14. Output of potential sea channel where length  $\geq 150$  km, slope standard deviation  $\leq 0.5$  sinuosity  $\geq 1.3$

44. There are certain possibilities that some potential sea channels are excluded when it fails to fit criteria by a small amount. In order to not overlook potential channels, we want to go back to the first criteria: depression.  
Run raster to point tool, convert the TPI layer into point format.
45. Run spatial join tool, use a copy of joined layer from step 41 as target feature, TPI point layer as join feature. Choose WITHIN\_A\_DISTANCE\_GEODESIC as the match option, with a search radius of 950 meters. Make sure the merge rule is **mean**.  
*Since the target feature is line feature, and our point layer has a pixel size of 1 arc minute (1.8km by 1.8km), searching points within the distance of half of the pixels' side length allows the algorithm to collect values along the line.*
46. Change the symbology of the layer to Quantities > Graduated colors. In the classification setting, manually insert the value of -1 STD. In my case, the value is -31.5, round up to -32, which happen to be the minimum break value for my area of study. The result is shown in figure 15. According to Weiss (2001), -1 STD can effectively represent depressions. Thus, we want to make sure these profound depressions are not ignored.

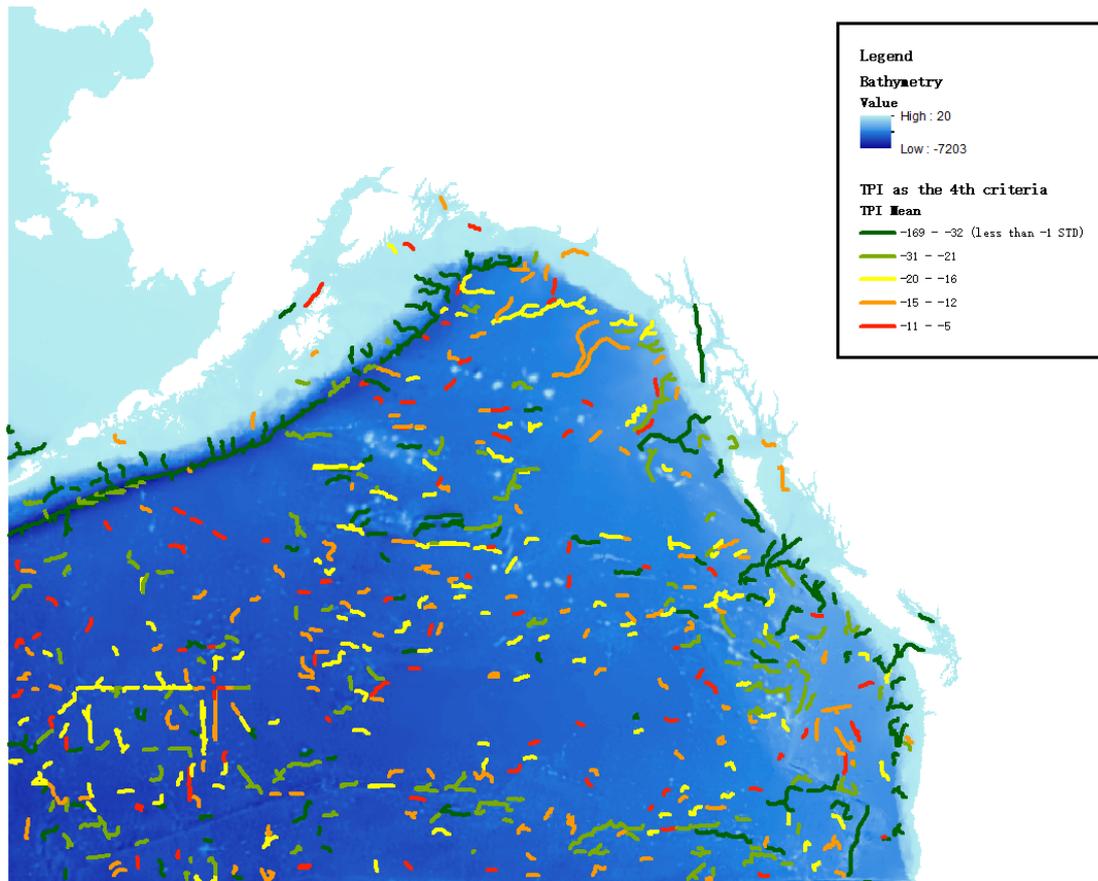


Figure 15. All potential sea channels reclassified by average TPI value

47. Use the join function, to join the TPI layers with the previous joined layer.
48. Run selection> Select by attribute tool, use the joined layer as input, begin your selection using the method “Create a new selection”, then switch to “Select from current selection”. Use a proper formula to select features that:
  - 1) Has to mean TPI value less than -32
  - 2) Longer than 150 km
  - 3) Have sinuosity index of 1.15 or greater
  - 4) Have a slope standard deviation less than or equal to 0.65
49. Right click on the joined layer, go to Selection> Create layer from selected feature to create a new layer represents the lines fits the above criteria.
50. The output (count 8, 1 overlaps with the output of step 43):

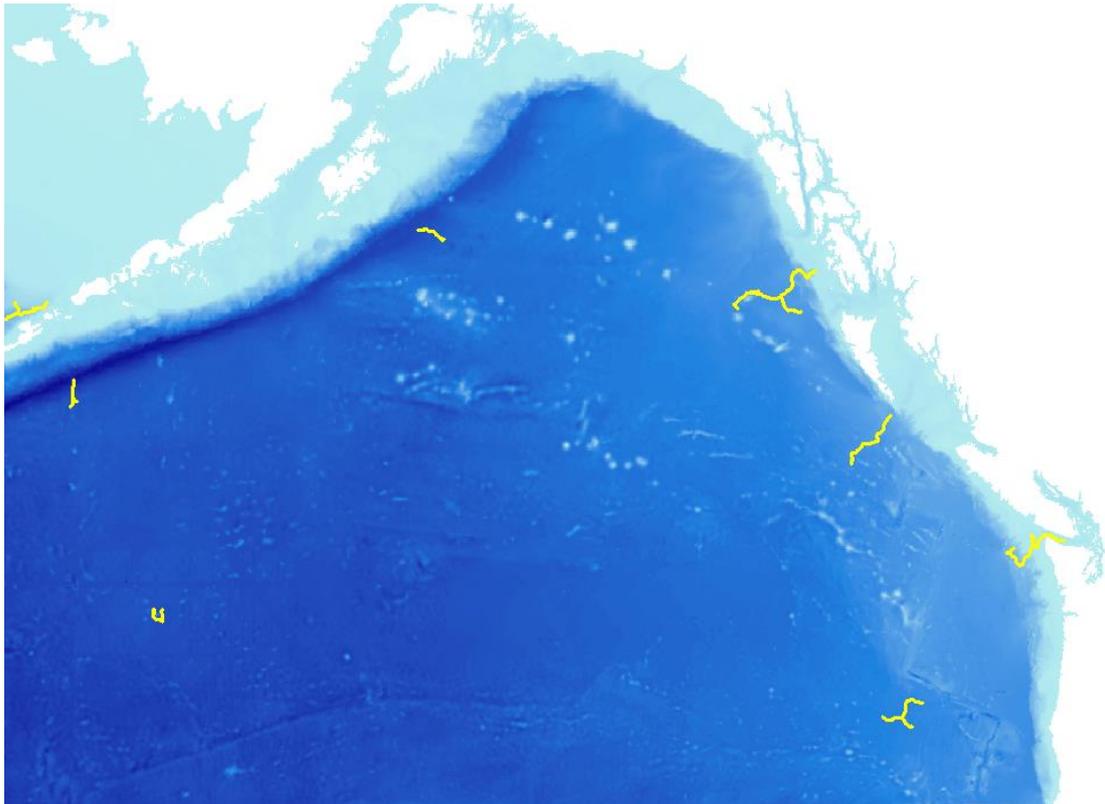


Figure 16. Output of potential sea channel where average TPI < -32, length >= 150 km, slope standard deviation <= 0.65 sinuosity >= 1.15

51. Overlay the result of step 43 and 50:

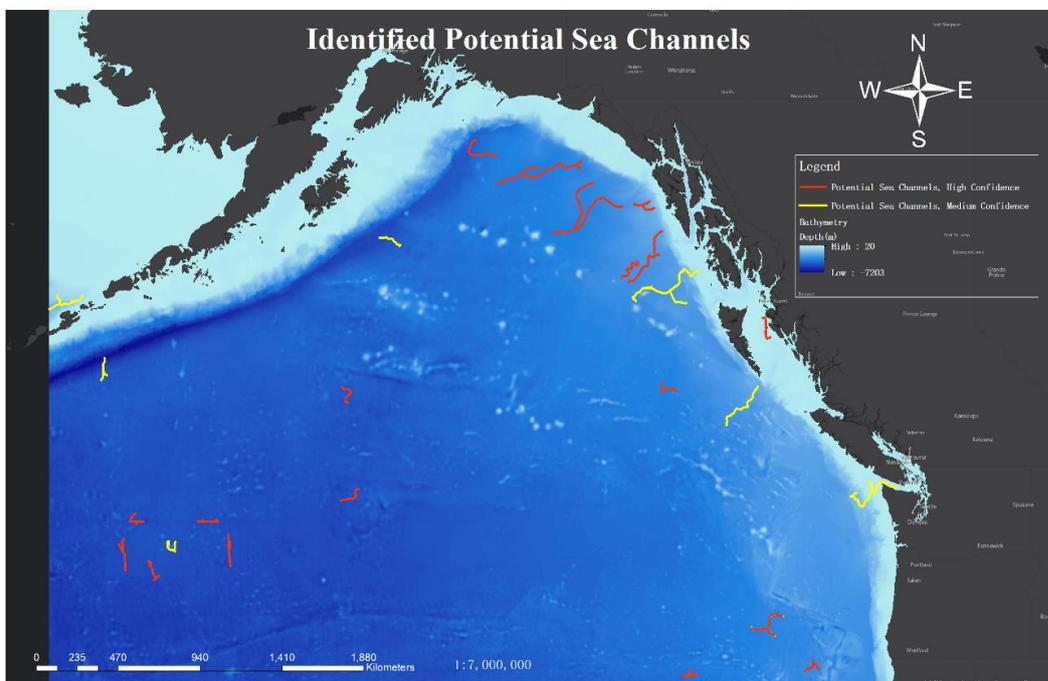


Figure 39. Methodology final output, identified potential sea channels

#### IV. Testing against GEBCO Database

In the SCUFN beta gazetteer, sea channels are categorized as “sea channel”, “seachannel” or “channel”. All of them can be found by word search on “channel”. Both *sea channel* and *channel* are generic terms recognized by B-6, however, *seachannel* with no space in between is irregular usage of the term.

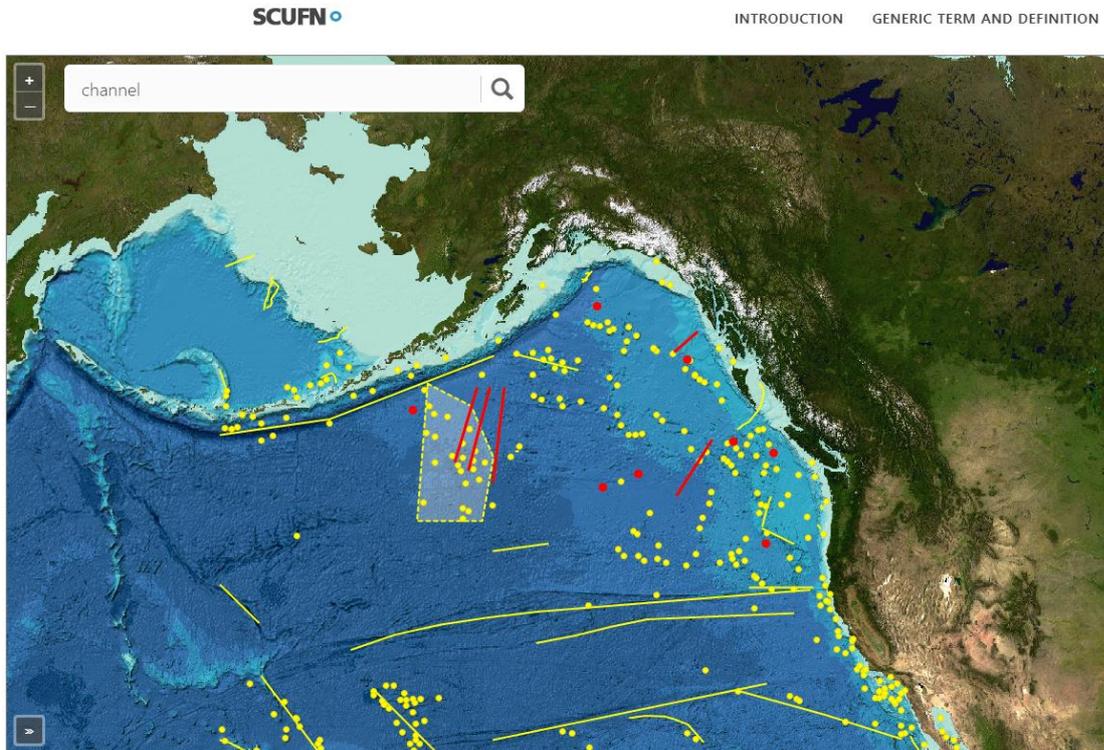


Figure 18. Known sea channels in the area of interest. Source: SCUFN beta gazetteer

The search within the area of study returns with 13 results, highlighted by red color. The existing features are presented with a single set of coordinate or a straight line, defined by a set of the coordinate of the start point and end point. Neither is a highly accurate way to depict of a sea channel. There is uncertainty I want to address: when a sea channel is shown as a single point, we do not know whether that is the start point, midpoint or end point.

The validation result is: 5 features are successfully identified; 1 feature might be identified; 7 features are not identified. As shown in figure 19.

First, the feature we could not confirm, the one marked as a question mark in the Gulf of Alaska is called Surveyor Sea Channel. Figure 20 shows a closer look at the area. If the coordinate in the SCUFN gazetteer marks the endpoint of the sea channel, then the feature our method detected on its east have a high possibility to be the Surveyor Sea Channel. If the coordinate is the center point of the feature, then our method did not pick it up.

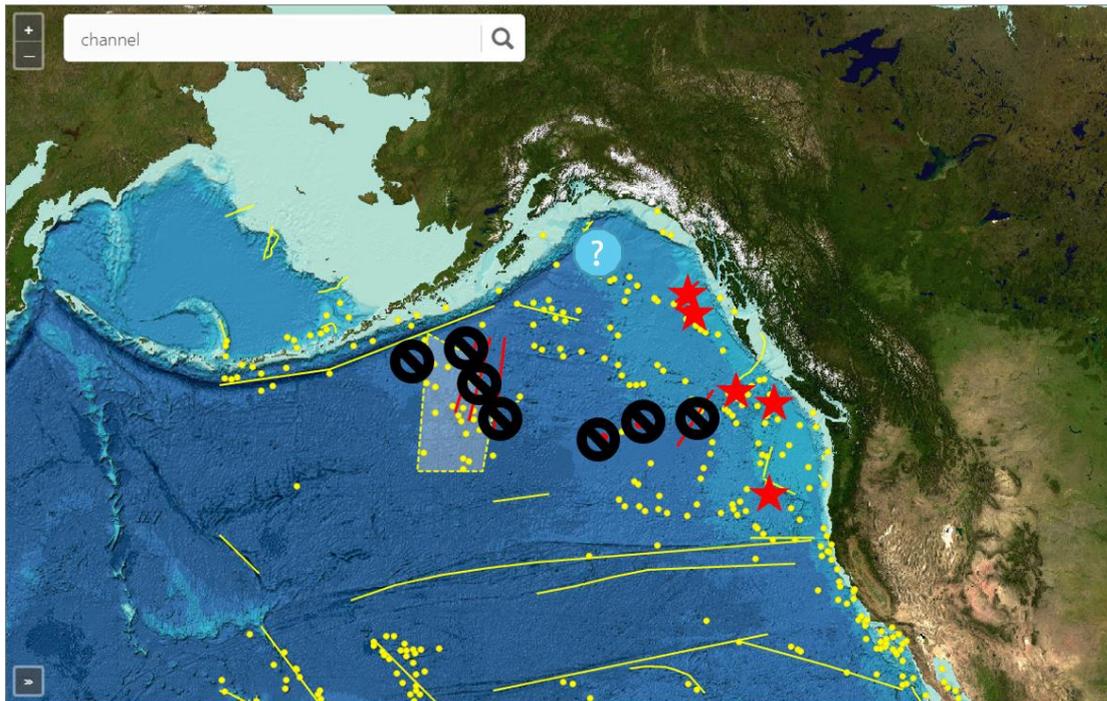


Figure 19. Validation result, methodology output vs SCUFN beta gazetteer. Red star = identified, Blue question mark = cannot confirm, Black = not identified

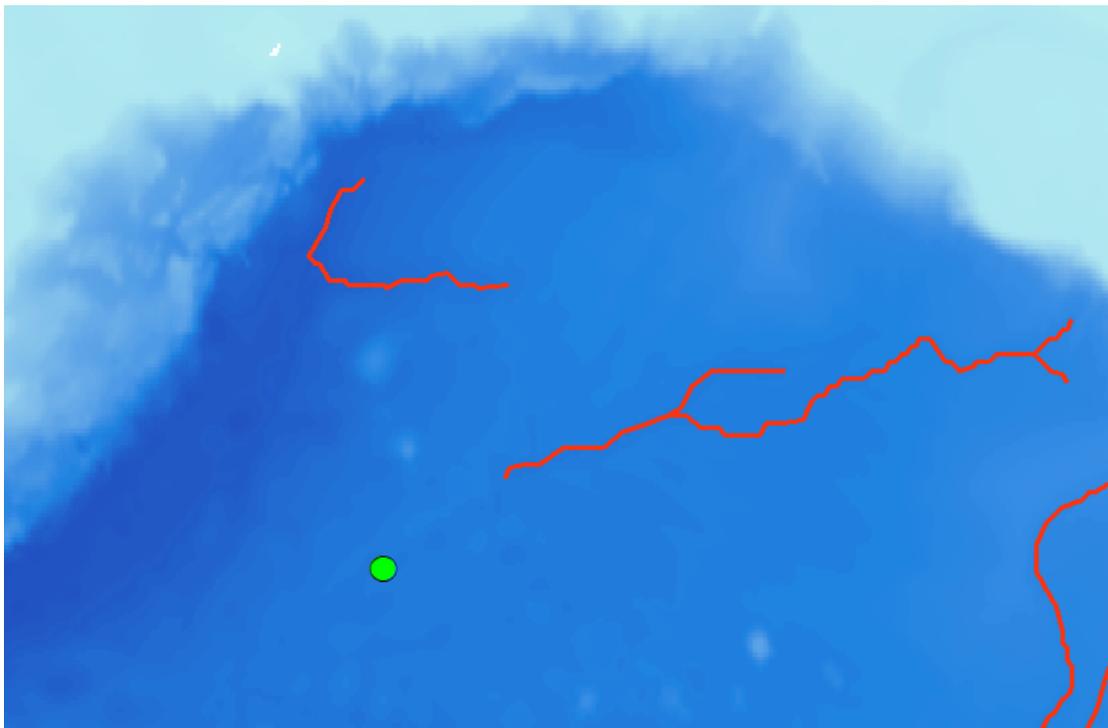


Figure 20. A closer look at the Surveyor Sea Channel, coordinate represented by a green dot, red lines is identified sea channels nearby.

Next, we checked the 7 features we failed to detect, the result reveals a different issue.

In all 7 locations, the seafloor bathymetry does not show anything resemble a sea channel. See figure 21 and 22.

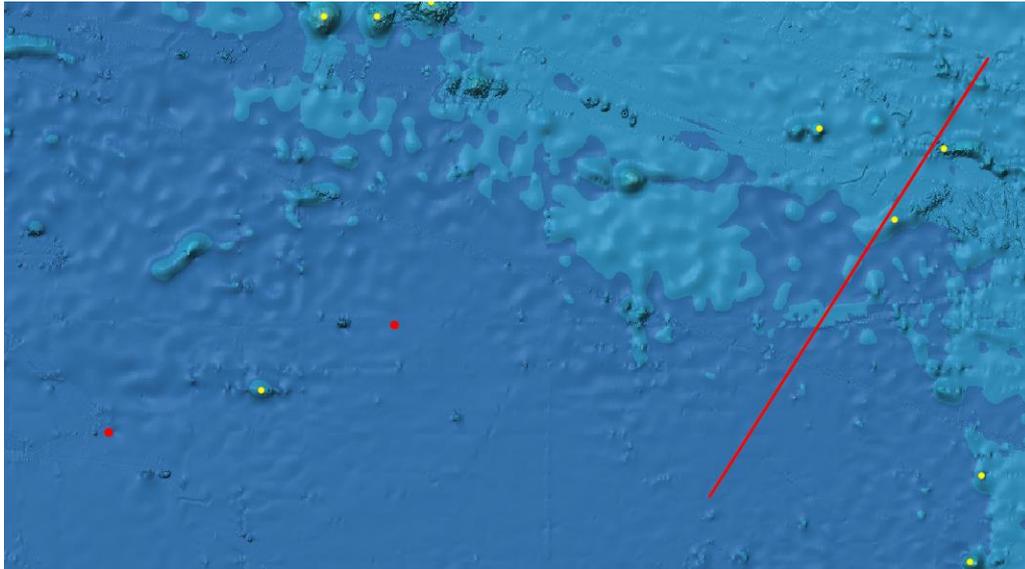


Figure 21. Existing sea channels' relative location on bathymetry. Feature name from left to right: Horizon Channel, Mukluk Channel, Moresby Seachannel

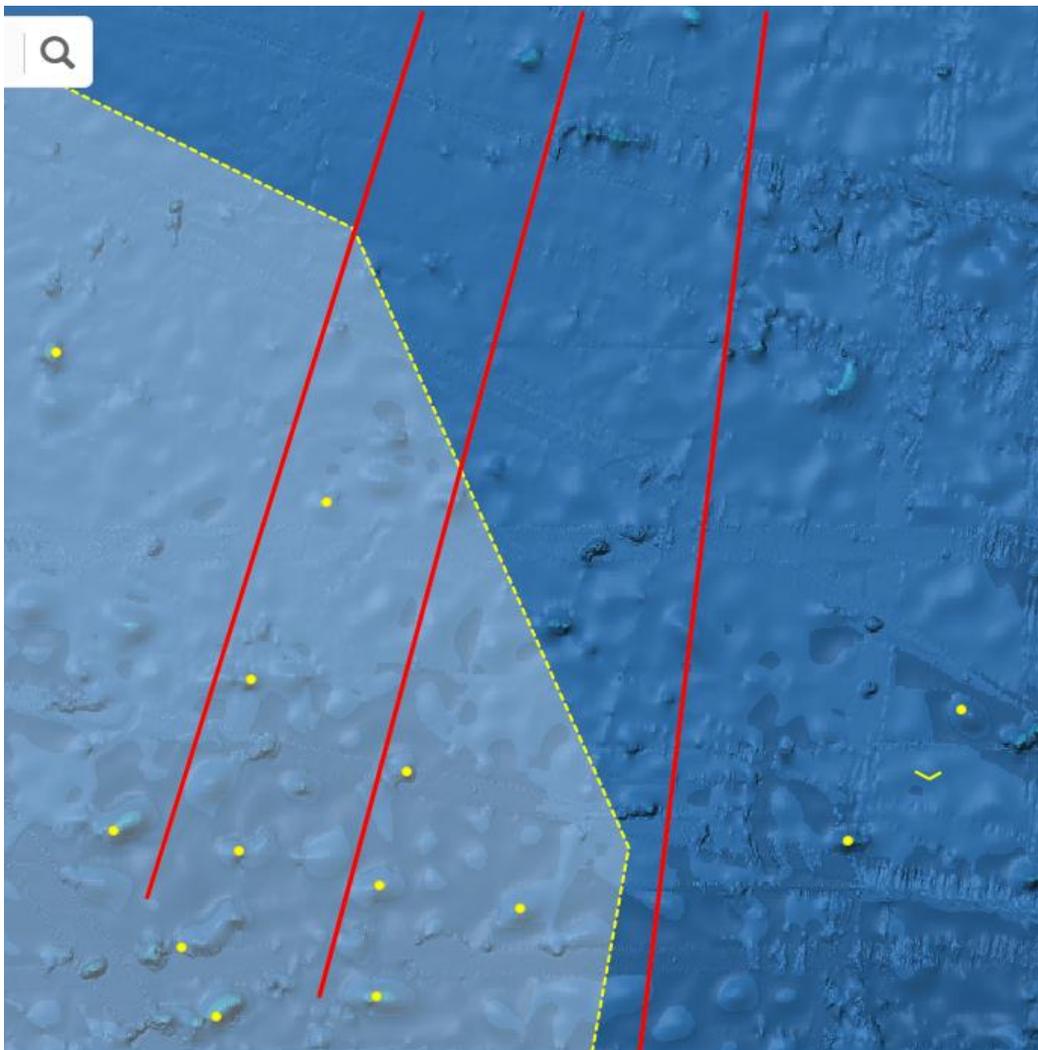


Figure 22. Existing sea channels' relative location on bathymetry. Feature name from left to right: Sagittarius Seachannel, Aquarius Seachannel, Taurus Seachannel.

Our understanding toward this matter is that since sea channels are formed due to erosion effect caused by ocean floor current, unlike streams and rivers on land, the flow direction ocean current can vary relatively easily. Therefore, certain undersea features including sea channel that does not consist of solid material, could be potentially covered by sediment therefore disappear on bathymetry. The sea channels can still be visible on another type of data such as seafloor material composition.

Note1: Sagittarius Seachannel, Aquarius Seachannel, and Taurus Seachannel were all proposed to SCUFN more than 40 years ago on the 6<sup>th</sup> SCUFN meeting in 1985.

[https://www.iho.int/mtg\\_docs/com\\_wg/SCUFN/SCGN1\\_to\\_SCUFN14/SCGN06\\_report\\_1985.pdf](https://www.iho.int/mtg_docs/com_wg/SCUFN/SCGN1_to_SCUFN14/SCGN06_report_1985.pdf)

Note2: According to SCUFN report, SCUFN21-09.2B, Horizon Channel and Mukluk Channel's validity has been questioned in the SCUFN 21, May 2008. This documents supports our validation methodology.

[https://www.iho.int/mtg\\_docs/com\\_wg/SCUFN/SCUFN21/SCUFN21-09.2B\\_Proposed\\_changes\\_in\\_GEBCO\\_Gazetteer\\_Part2.pdf](https://www.iho.int/mtg_docs/com_wg/SCUFN/SCUFN21/SCUFN21-09.2B_Proposed_changes_in_GEBCO_Gazetteer_Part2.pdf)

Note3: Moresby Seachannel was used as the example for sea channel in the SCUFN21-04.1A.

[https://www.iho.int/mtg\\_docs/com\\_wg/SCUFN/SCUFN21/SCUFN21-04.1A\\_B6\\_EF\\_2008.pdf](https://www.iho.int/mtg_docs/com_wg/SCUFN/SCUFN21/SCUFN21-04.1A_B6_EF_2008.pdf)

Lastly, visual check for successfully identified sea channels confirmed that all the identified features have the general shape and size that fits the B-6 definition.

In conclusion, we are confident to say that:

- 1) Our method tool is capable of discovering new sea channels base on the B-6 definition.
- 2) Some existing Sea Channels/ Channels could not be identified using bathymetry only.
- 3) The B-6 definition needs an update to properly function as official definition, and based on our analysis, we suggest a new definition for sea channel as follow:

A meandering linear depression with sinuosity typically greater than 1.3, at least no less than 1.15. Feature need to be no shorter than 150 km, usually occurring on a gently sloping plain or FAN where local slope standard deviation is typically less than 0.5 degree, at least no more than 0.65 degree.

## References:

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Shepard, P. & EMERYK, O. (1941) Submarine topography of the California coast: canyons and tectonic interpretation. *Spec. Pap. Geol. Soc. Am.* 31, 1-171.

Tarboton, D. G., Bras, R. L., & Rodriguez-Iturbe, I. (1991). On the extraction of channel networks from digital elevation data. *Hydrological Processes*, 5(1), 81-100. doi:10.1002/hyp.3360050107

Weiss, A. (2001). Topographic position and landform analysis. Poster presentation, ESRI User Conference, San Diego, California, USA. [http://www.jennessent.com/downloads/TPI-poster-TNC\\_18x22.pdf](http://www.jennessent.com/downloads/TPI-poster-TNC_18x22.pdf)

## Appendix VI

# Shelf and Slope Break Detection in ArcMap

Erin Turnbull | June 25, 2019

## Introduction

The IHO B-6 document “Standardization of Undersea Feature Names” provides definitions for generic terms used to classify undersea features. For shelves, this definition is as follows:

The flat or gently sloping region adjacent to a continent or around an island that extends from the low water line to a depth, generally about 200m, where there is a marked increase in downward slope (IHO 2017).

From this definition, it is clear that the key to identifying a shelf is to first locate the shelf-break, which is the line at which there is a “marked increase in downwards slope” (IHO 2017). The shallow area between the shelf-break and the shoreline is then the “shelf”.

## Methodology

One method for locating the shelf-break is to look at contour density (Harris et al. 2014). Harris et al. manually determined the location of the seaward boundary of the shelf based on a manual inspection of the spacing of contour lines, referred to here as the “contour density”. They determined that in most cases, the 100 m contour lines were sufficient; however, some areas required more detailed contour lines.

This approach adapts Harris et al.’s approach by developing a metric for contour density based on the shelves of Atlantic Canada, as classified by GEBCO. This approach works off of raster data. Raster “contour lines” are constructed by rounding each cell down to the next lower contour interval. For example, if contouring at -100 m, depths of -1 to -100 would be classified as “-100”, depths of -101 to -199 would be classified as “-200”. The minimum value of the 3x3 grid surrounded each cell is then calculated. Cells that have a different value from the minimum are part of the raster contour line.

Contour density is calculated as the difference between the maximum and minimum rounded values within a certain radius, divided by the contouring interval. Contour density is only calculated on cells that are part of a contour line; this forms a raster where each cell on a contour line has a value equal to the number of contour lines within the radius. **This assumes that contour lines are a fairly good representation of the boundaries of the slope.** Based on an analysis of Atlantic Canada, these cells are then reclassified by contour density into “Yes”, “Maybe”, and “No”. Cells not part of the contour lines are assigned a “No” value. Exact values for these parameters follow in the next section.

The slope is also typically steeper on the continental slope. Since contour lines are only an approximation of the beginning of the slope, this information is supplemented with the slope of each cell using the Slope tool. The slope values are also reclassified as “Yes”, “Maybe” and “No”.

The slope and contour density reclassifications are then combined, with the slope logical value taking the place of the contour density value where ever the contour density is “No”.

This data is cleaned up slightly using a Majority Filter, which replaces the cell if half or more of its eight neighbours disagree with its value. This eliminates small errors in the data and should be ok, as the continental slope is a broad feature. The “Maybe” cells are then assigned to be either “Yes” or “No” based on which is closer, using the Shrink tool.

The resulting data is run through the Boundary Clean tool, which makes slightly nicer edges on the shape and cleans up tiny spots. The end result is a fairly good representation of extensive sloping areas on the map, but it includes many areas that do not represent the continental slope.

By definition, the continental slope is the transition between the shelf (typically < 200 m) and the deeper ocean (> 3000 m). To identify these transitional areas, the results are grouped by region using Region Group and the minimum and maximum depths are calculated. In order to qualify as a continental slope, the region must transition from shallow enough water to deep enough water.

The last step for the slope is to convert qualifying regions into polygons. Small gaps are filled in these polygons using the Union and Dissolve tools, as the slope should be a contiguous area.

To identify the shelf, cells that are not part of the slope are also region grouped. The shelf must touch the shoreline, so regions with a shallow enough minimum depth are counted as part of the shoreline. In addition, the region cannot extend to too great a depth, otherwise it is not a shelf any more. These regions are also eliminated. The remaining cells are turned into polygons using the same process as for slopes.

## Parameterization

The methodology requires several key parameters. These values have been chosen based on what provides appropriate results for Atlantic Canada; however, these values may not be suitable for the entire world. Further adjustments need to be made based on a broader review of the results.

| Parameter                              | Value    | Rationale   |
|--|----------|---|
| Contour Interval                       | 50 m     | Harris et al. (2014) discuss the need to use 50 m contours, and even 10 m contours, in certain locations. 50 m contours are fairly quick to produce, so this is the value chosen for now. Some areas may require finer detail.  |
| Contour Radius                         | 15,000 m | These values were chosen based on an examination of the Atlantic region. 8 50m contours over 30,000 m corresponds to an average slope of about 1.33% or 0.76°. The shelf is typically under 0.5°. The “Maybe” cutoff is just below to ensure the nearby contours are included.  |
| Contour Density – Maybe Cutoff         | 7        |   |
| Contour Density – Yes Cutoff           | 8        |   |
| Slope – Maybe Cutoff                   | 0.5°     | As mentioned above, shelves are typically under 0.5°. Values above 1° are therefore likely steep enough to be part of the slope, if positioned correctly. Intermediate values will depend on their proximity to steeper or denser areas. This is based on a visual examination of the slope values near the dense contours. |
| Slope – Yes Cutoff                     | 1°       |   |
| Continental Slope Required Shallowness | -250 m   | The continental slope is connected to the shelf, which typically has depths of up to 200 m (IHO 2017). This value is chosen to be slightly deeper to be sure that the slope itself is included.   |

|                                  |         |  |
|----------------------------------|---------|--|
| Continental Slope Required Depth | -1000 m | This depth was chosen to ensure that the slope exits the mesopelagic zone. While slopes and rises tend to go much deeper, those depths may not be on the map.  |
| Shelf Nearshore Depth            | -2 m    | A shelf is defined as needing a cell at least this depth or shallower. -2 was chosen as rounding errors near the shore sometimes caused the shelf to not be picked-up correctly (i.e. there was no -1 cell). |
| Shelf Maximum Depth              | -1000 m | This depth was chosen to ensure that, if the slope could not be found, a shelf was not accidentally selected. Shelves are typically shallower than 200 m, so they definitely should not extend this deep.    |

## Discussion

In terms of meeting the B-6 definition, this approach mostly meets the existing criteria. By defining “marked increase in downwards slope” to mean “a change in contour depth of at least 400 m per 30 km or a slope within a cell of over 1°”, this provides a quantitative evaluation of the changing regional-scale slope over distance. One part that is not met is that it must be a “downwards” change in slope. Typically, there are no “upwards” changes that meet the parameters chosen, but “downwards” could be detected by looking only in the 180° wedge away from the direction of the closest 0 contour to each cell. However, this would take significant extra processing power to determine the direction of the nearest shoreline. The “flat or gently sloping” part is also not handled at the moment, as the contour density generally takes care of that. However, it should also be reviewed if more steeply sloping areas need to be excluded.

This approach assumes that all slopes that span the mesopelagic zone are continental slopes. This may not be a good assumption, but it is fairly likely true. Since shelves are also required to be shallow enough, an extraneous slope does not impact the identification of shelves.

The advantage of using contouring as the main method for feature detection is that it follows what is typically done today to identify features. Rarely do humans examine a raster of depths to identify features; as Harris et al. (2014) discusses, contours are commonly used in the manual identification of features. A contour-based process therefore has the advantage of being relatable and easy to confirm on an actual map.

However, this definition does not meet the UN’s definition of the continental slope (United Nations, 1982), which is based on the thickness of crustal sedimentary rock. Therefore, this technique should not be used for legal interpretations of the location of the slope. Alignment of the B-6 definition with the UN definition is one potential strategy, though the thickness of sedimentary rock cannot be determined by bathymetry alone.

All of the parameters assumed here have been chosen through examination of one area of the shelf in Atlantic Canada. Both the technique and the parameters should be verified and refined by comparing the results to the literature and to existing continental shelf polygons throughout the world.

## Proposed Refined B-6 Definition

Based on this work, a refined B-6 definition could be proposed as follows. Here, the values from the Parameterization section have been inserted; these need further review as per the Discussion section.

**Shelf Break:**

A line defined by the shoreward boundary of an area which deepens at a rate of at least 400 m per 30,000 m away from shore or has a localized slope of at least 1°. It may include adjacent areas which deepen at a rate of 350 m per 30,000 m or have a localized slope of at least 0.5°. It must span depths from 250 m to 1,000 m.

**Shelf:**

The flat or gently sloping region adjacent to a continent or around an island that extends from the low water line to the shelf-break.

## Conclusions

Here, I have presented a method for finding shelves based on an analysis of contour density on raster bathymetry files. The technique meets most of the current B-6 definition and suggests a refined definition that specifies what a “marked increase in downward slope” defines.

## References

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