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Using ArcGIS to Delineate the Outer Limits of the Continental Shelf in Accordance with Article 76 of the Law of the Sea

Laura Jan Cathers
University of Redlands

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Using ArcGIS to Delineate the Outer Limits of the Continental Shelf in Accordance with Article 76 of the Law of the Sea

A Major Individual Project submitted in partial satisfaction of the requirements
for the degree of Master of Science in Geographic Information Systems

by
Laura Jan Cathers

James Ciarrocca, M.S., Chair
Mark Kumler, Ph.D.

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Accordance with Article 76 of the Law of the Sea

The report of Laura Jan Cathers is approved.

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Mark Kumler, Ph.D.

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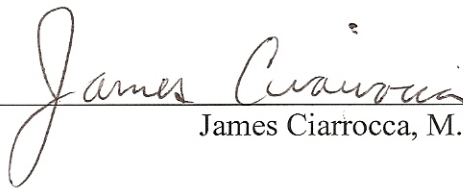James Ciarrocca, M.S., Chair

August 2008

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ABSTRACT

Using ArcGIS to Delineate the Outer Limits of the Continental Shelf in
Accordance with Article 76 of the Law of the Sea

by
Laura Jan Cathers

The United Nations Convention on the Law of the Sea established the opportunity for coastal nations to potentially extend their maritime territory beyond the 200 nautical mile Exclusive Economic Zone. The eligibility of a nation to submit such a claim to the United Nations (UN) is based on the delineation of the outer limits of the continental shelf. This requires the analyses of coastal baselines, bathymetry, and geophysical data, as well as calculating arcs using geodesic distances. The UN has established numerous guidelines that must be adhered to during analyses and strict standards for submitting a claim. This paper outlines a process that was developed for producing and analyzing Law of the Sea claims using ArcGIS, based on the regulations and guidelines prescribed by the UN in Article 76. A proof of concept was established using ArcGIS tools and applications, which was tested via a case study and mock submission. The final report includes recommendations for improving the workflow through future development of ArcGIS capabilities to meet all the necessary guidelines and standards.

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List of Terms and Acronyms

Baseline	The low water line along a nation's coastline, usually measured at low tide.
CEAS	Comprehensive Environmental Assessment System
CLCS	Commission on the Limits of the Continental Shelf
Continental shelf	"The continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance" (DOALOS, Paragraph 1, 2001).
Continental margin	"the submerged prolongation of the land mass of the coastal state, and consists of the seabed and subsoil of the shelf, the slope and the rise" (DOALOS, Paragraph 3, 2001).
ECS	Extended Continental Shelf
EEZ	Exclusive Economic Zone
ESRI	Environmental Systems Research Institute, Inc.
FGDC	Federal Geographic Data Committee
FOCS	Foot of the Continental Slope
GCS	Geographic Coordinate System
GDAIS	General Dynamics Advanced Information Systems
GIS	Geographic Information System
NAD	North American Datum
NGDC	National Geophysical Data Center
OLCS	Outer limits of the continental shelf
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
USGS	United States Geological Survey
WGS	World Geodetic System

1. Introduction

On 16 November 1994, the United Nations Convention on the Law of the Sea (UNCLOS) came into effect. This treaty established an opportunity for coastal nations to potentially extend their maritime territory beyond the currently recognized 200 nautical mile Exclusive Economic Zone (EEZ). Determination of one's eligibility for an extension of maritime territory is a politically and economically important issue that requires complex analyses of hydrographical, geophysical, and geological properties and their spatial relationships. Article 76 of the Convention provides the legal provisions for analyzing such data in the delineation of the outer limits of the continental shelf (OLCS) (see figure 1.1). The outcome of such analyses will determine a nation's eligibility to submit a claim to the United Nations (UN) for extended continental shelf (ECS); it is the responsibility of each nation to determine its own eligibility. This report outlines a project that was undertaken to determine the feasibility of using geographic information system (GIS) technology to conduct the analyses required under Article 76.
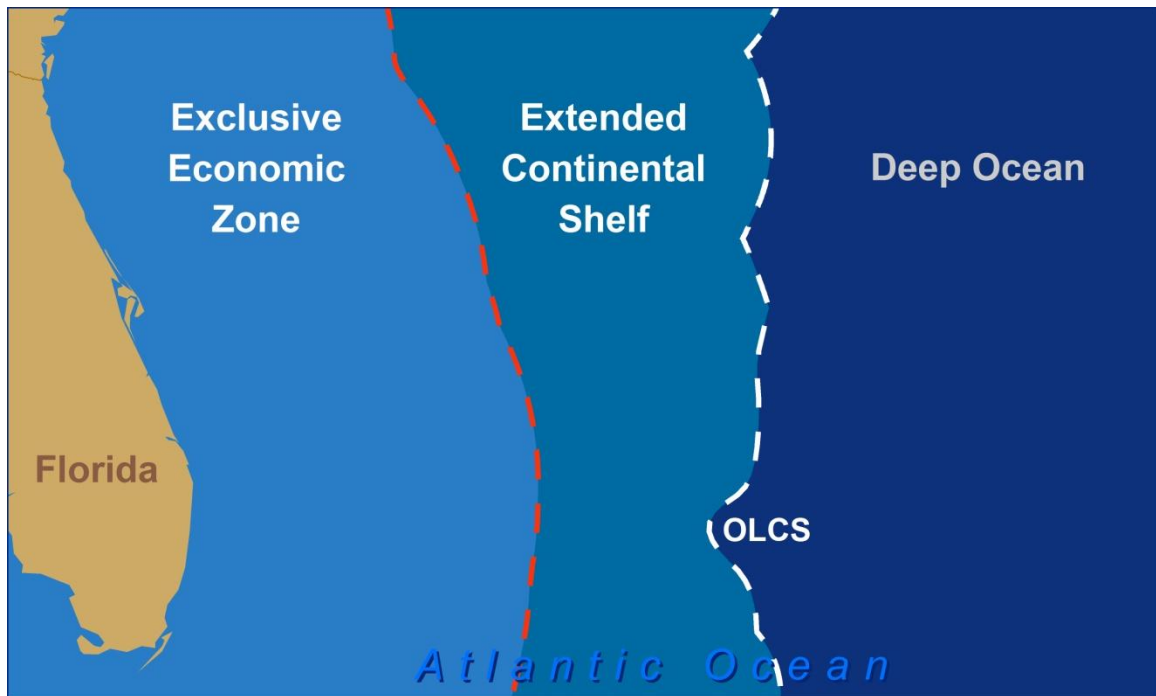
Figure 1.1: Extended Continental Shelf region delineated by the Outer Limit of the Continental Shelf as the seaward extent and the Exclusive Economic Zone as the landward boundary.

1.1. Background

In 1945, United States President Harry Truman proclaimed U.S. ownership over its continental shelf (U.S. Commission on Ocean Policy, n.d.), including the seafloor and its overlying waters (Cimino, Pruett & Palmer, 2000). Following what became known as the "Truman Proclamations", similar claims were made by additional nations, thus gaining the attention of the United Nations. In 1958, the UN convened in Geneva to address the

growing issue of regulating the seas. According to Cimino et al. (2000), "the Geneva conference then led to the formation of the United Nations Convention on the Law of the Sea."

The third United Nations Conference on the Law of the Sea convened several times from 1973 to 1982. This conference finalized and established the United Nations Convention on the Law of the Sea, which came into effect in 1994. UNCLOS outlines an extensive set of rules for regulating and determining the geographic area that constitutes a nation's legal maritime boundaries. Taking into consideration many political, economic and physical variables, it has been described as an "unprecedented attempt by the international community to regulate all aspects of the resources of the sea and uses of the ocean" (Division for Ocean Affairs and the Law of the Sea (herein DOALOS), n.d.).

Prior to this convention, all coastal nations that do not share the specified area with opposing or adjacent nations were entitled, yet also limited, to the 200 nautical mile Exclusive Economic Zone. This limit is measured from a baseline, which is typically the low water line along a coast. The EEZ is the maritime territory in which a coastal state holds sole exploitation rights for all natural resources (FGDC Marine Boundary Working Group (herein FGDC), n.d.). However, in accordance with the UN Convention on the Law of the Sea, many nations are now eligible to submit claims for the expansion of specific marine rights beyond the currently recognized EEZ. Eligibility for an extension of maritime territory is determined by establishing a universally accepted baseline and analyzing several variables, including topographic, hydrographic, and other geological and geophysical data in accordance with Article 76. Nations must submit their claims, based on such analyses, to the CLCS by the 13 May 2009 deadline to be eligible for review (Commission on the Limits of the Continental Shelf (herein CLCS), 1999).

1.1.1. The Convention

The Convention is divided into 17 parts, then subdivided further into sections, incorporating a total of 320 articles. This project, however, focused strictly on the technical implementation of Article 76, *Definition of the continental shelf,* in Part VI of the Convention, titled *Continental Shelf.* Article 76 has been studied and described in several references and guidelines published by the United Nations Division on Ocean Affairs and the Law of the Sea, Office of Legal Affairs. Such publications include the *Training Manual for delineation of the outer limits of the continental shelf beyond 200 nautical miles and for preparation of submissions to the Commission on the Limits of the Continental Shelf* (DOALOS, 2006), as well as the *Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf* (CLCS, 1999) (herein referred to as the Guidelines), which have been referenced extensively in preparation, guidance, and support of this project.

Despite the focus on Article 76, many of the Convention's other Articles are pertinent for understanding the data, for proper interpretation of Article 76 and related material, and for understanding the importance of delineation and recognition of these boundaries. UNCLOS provides guidance regarding the delineation and definition of several other

boundaries that are important to the delineation of the continental shelf, specifically: baselines, territorial seas, contiguous zones, and EEZs. Additionally, UNCLOS is the source for international regulations over foreign and domestic activities within these maritime zones pertaining to surface and subsurface vehicles and activities, aircraft operations in related air space, and dealings with the seabed and subsoil. Regulated activities include, but are not limited to, traversing and transporting, surveying and experimentation, exploitation and conservation of resources, and pollution control. Considerations also include legalities such as criminal jurisdiction onboard foreign vessels, "rights of land-locked … [and] geographically disadvantaged states" (DOALOS, Article 69 & 70, 2001), and "rights of protection of the coastal state" (DOALOS, Article 25, 2001).

The specific privileges, responsibilities, regulations, and limitations of those coastal nations that are awarded rights over the extended continental shelf are outlined in the remainder of Part VI of the Convention, specifically noting Articles 77 through 85. Rights of the coastal nations within the EEZ, defined as the "area beyond and adjacent to the territorial sea … [yet] shall not extend beyond 200 nautical miles from the baseline," are outlined in Part V (DOALOS, 2001). Primarily, within the EEZ the coastal nation has:

> sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters superjacent to the seabed and of the seabed and its subsoil, and with regard to other activities for the economic exploitation and exploration of the zone, such as the production of energy from the water, currents and winds (DOALOS, Article 56, 2001).

The EEZ provides coastal nations jurisdiction for establishing artificial islands, installations and other structures within this zone, as well as laying submarine cables and pipelines. Such jurisdiction also allows for decisions by the coastal nation regarding immigration laws and conducting marine scientific research. Coastal nations maintain the right of utilization of the living resources within their EEZ and act as the regulatory body regarding access to these resources by foreign parties (DOALOS, Article 62, 2001). They also maintain the responsibility of conserving such resources (DOALOS, Article 61, 2001).

Extending beyond the EEZ, into the region referred to as the extended continental shelf, the scope of a coastal nation's rights and responsibilities are modified. The continental shelf, as defined in Article 76, "comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin" (DOALOS, Article 76, 2001). The continental margin is defined as that which:

> comprises the submerged prolongation of the land mass of the coastal [nation], and consists of the seabed and subsoil of the shelf, the slope and the rise … [but] does not include the deep ocean floor with its oceanic ridges or the subsoil thereof (CLCS, 2007).

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If the continental margin does not extend beyond the recognized 200 nautical mile EEZ, then the EEZ regulations referred to in Part V of the Convention remain of primary relevance. However, where the juridical continental shelf extends beyond 200 nautical miles from the baseline, some differences in the rules and regulations come into effect. The coastal nation maintains the right to explore and exploit the natural resources of the continental shelf, as well as the exclusive right to authorize or deny other parties of partaking in such activities without their consent (DOALOS, Article 77, 2001). However, utilization and regulation of said resources, including both living and non-living, are limited to those that are confined to the seabed and subsoil. These may include mineral resources as well as sedentary species or living organisms that maintain continuous contact with the seabed or subsoil (DOALOS, Article 77, 2001). The coastal nation does not sustain any rights pertaining to the "superjacent waters or of the air space above those waters" (DOALOS, Article 78, 2001) beyond the EEZ. The superjacent waters are those immediately above the seafloor. The right to lay cables and pipelines are not restricted to the coastal nation and they may not hinder other nations from doing so (DOALOS, Article 79, 2001). However, Article 79 also states that the coastal nation may exercise the right to formulate and enforce conditions upon which such activities may take place within one's jurisdiction (DOALOS, Article 79, 2001). Regarding artificial islands and other structures, the same rules outlined for EEZs in Article 60 of Part V also applies to the extended continental shelf (DOALOS, Article 80, 2001).

Coastal nations are afforded several advantages by claiming, and obtaining recognition of, their extended continental shelves. Nations stand to profit primarily from economic gains, though they may also increase opportunities for scientific advancements and strategic advantages.

2. Literature Review

This project was initiated to address a need for delineating complex maritime boundaries; the goal was to identify a suitable GIS solution. However, in order to emphasize why this is such an important undertaking one may ask, why are maritime boundaries so important? Is there sufficient evidence to prove that GIS could provide an appropriate and capable solution for delineating these boundaries in accordance with Article 76? Further, has anyone done this before?

2.1. Importance of Maritime Boundaries

As emphasized by Palmer and Pruett (2007), "maritime boundaries affect all those engaged in offshore activities, from extractive industries such as fisheries and petroleum to the conduct of marine scientific research". The potential ramifications of not having instituted the appropriate methods of delineating maritime boundaries attest to the critical nature of proper establishment and recognition of such claims. Without receiving recognition and publication of one's maritime claims "ownership of living and non-living resources may be questioned," (Cimino et al., 2000) causing potential conflict and economic loss. Additionally, the risk of poor delineation resulting in disputed jurisdiction or shortchanging a nation of its potential claim could have significant economic and political impacts. Specifically, Cimino et al. (2000) estimate that "in dealing with exploration and recovery of resources such as minerals, oil, petroleum, and fish, etc. a distance of a few hundred meters can have significant economic consequences." For the U.S. alone, conservative calculations estimate the approximate worth of potential U.S. territory gains, of at least 386,000 square miles, will equal approximately $1.3 trillion in resources (Gagnon, 2008). However, the current U.S. claim of approximately three-million square miles overlaps "boundaries with other nations in 25 situations," according to the Federal Geographic Data Committee (FGDC) Marine Boundary Working Group (2008). International maritime boundaries need to be recognized and agreed upon in order to resolve these and the ubiquitous other similar disputes.

2.2. GIS as a Solution

The delineation of maritime boundaries presents a complex problem, especially under the scrutiny of the CLSC, that requires analyses of such variables as geophysical and bathymetric data (Cimino et al., 2000). These complex data sets are required to locate and analyze the foot of the continental slope, which Gagnon (2008) agrees is difficult to accomplish. "For centuries," Gagnon explains, "nations marked what they owned at sea by measuring out from their shoreline." However, once UNCLOS came into effect in 1994, not only was more at stake, but the complexity involved in marking a nation's territory significantly increased. Given the significance and complexity of this inherently spatial problem, the Law of the Sea deserves a spatial solution and GIS seems to offer a suitable answer.

The process is complex in that one cannot simply use a buffer function within GIS to generate a boundary, as pointed out by Ball (1997), and further explained by the FGDC (2007):

offshore boundary lines are measured along an arc over the earth's ellipsoidal surface (chord length); therefore, arc distance varies with latitude and azimuth corresponding to variations in the radius of the earth's surface. As a result, the arc length must be computed (in three-dimensional space) separately for each stretch of coastline.

This essentially explains the foundation of the "envelope of arcs" process mandated by the Convention for establishing distance measurements utilized in the delineation of the OLCS.

As of 2000, there were "few published case studies involving GIS to delineate a maritime boundary," as recalled by Cimino et al. (2000). Since then, however, several studies have utilized GIS for the storage, management, analysis, and delineation of maritime boundaries. Support is growing with proof that GIS can provide a solid solution for the complex delineation of maritime boundaries, such as those necessary for the Law of the Sea analysis. For example, General Dynamics Advanced Information Systems (GDAIS) has constructed the Global Maritime Boundaries Database, which relies on GIS as a principal tool (Cimino et al., 2000). Additionally, the Australian ECS claim to the CLCS, based primarily on GIS analysis, proved that it is capable of producing the necessary results in meeting the CLCS requirements (Cimino et al., 2000). GDAIS continues to support the role of GIS in delimitation of maritime boundaries and establishing claims under the UNCLOS regulations. As asserted by Cimino et al. (2000):

A GIS will continue to provide the basic interactive tools to register, document, and publish the spatial coordinates that constitute elements of the boundaries and limits claimed under the guidelines of UNCLOS. GIS has become an important present-day tool for the positioning of points that form a maritime boundary.

CARIS LOTS is one program that has been developed specifically for delineating the necessary boundaries under the Law of the Sea using GIS. This program has been tested and reviewed by the United Kingdom Hydrographic Office (UKHO). Others have also tested CARIS LOTS, though some are still looking for a better GIS solution. However, in the UKHO (n.d.) review of CARIS LOTS, an analyst stated "it has taken time and ingenuity to develop confidence in the methodology of the application and the accuracy of results. In addition, it has taken time to build trust in a system that will produce answers to complex questions at the touch of a single button." However, the UKHO (n.d) also exhibits an understanding of the effectiveness and importance of an application developed to be user friendly for non-GIS-experts that will run "GIS processes in the background." The review lauded CARIS LOTS for providing "a series of single function buttons which will trigger a fairly complex set of GIS commands on the underlying data" (UKHO, n.d.). This review helps provide an understanding of the pros and cons of previous attempts at a GIS solution for the Law of the Sea, as well as what the users are looking for in a system.

The Comprehensive Environmental Assessment System (CEAS) provides another example of relevant GIS studies. CEAS is an integrated ArcInfo GIS application for the U.S. Naval Oceanographic Office (NAVOCEANO) that was developed to provide a specific set of tools for data assessment and product generation using oceanographic, geophysical, and bathymetric data. All of these data types are similar to those used to delineate the OLCS. Specifically, CEAS uses bathymetry data to derive slope and aspect on-the-fly, and produce three-dimensional bathymetry grids (Naval Oceanographic Office, S. S., 1996). This system was designed specifically to execute naval support requirements. However, as an integrated program, not all functions are performed within the ESRI software environment. Likely, this is primarily due to the elementary nature of the 3-dimensional analytic capabilities within ArcGIS. However, three-dimensional analysis is a necessary analytical component in order to determine and display the slope of the continental shelf and determine the maximum change in gradient utilizing 3-D profiles, while still taking into consideration the other parameters mandated under Article 76. Examination of such examples were used to help further establish the best methodologies in automating and simplifying a user-friendly process and set of specified tools within ArcGIS for defining and displaying maritime boundaries.

3. Problem Statement

Recent estimates state that "two-thirds of the world's maritime boundaries remain unresolved" (Fugro Pelagos, 2006). Vague boundaries impose unnecessary limitations on military operations, scientific exploration, and industries such as fishing, oil and gas. Major consequences can arise where boundaries are unclear, including economic losses and international disputes. It is, therefore, important to define unambiguous geographic boundaries, including the continental shelf, and to apply a legal regime that is recognized by the international community. The UN has defined the parameters in legal and scientific terms, but requires that individual nations remap their oceans and delineate their boundaries in accordance with these parameters.

The deadline for submitting a claim is 13 May 2009. There is an urgent need to develop an efficient application that can store, manage, and analyze large amounts of spatial data, perform complex and technical analyses, and produce standardized delineations of the juridical outer limits of the continental shelf that coastal nations can use in support of their claims.

3.1. Client

The project sponsor was the Nautical Team at Environmental Systems Research Institute, Inc. (ESRI), with Mr. Rafael Ponce as the direct advisor and Ms. Kim Kearns as the technical liaison. Mr. Ponce provided assistance in locating and obtaining necessary data for the case study, and provided continued assistance and feedback throughout the course of the project. Mr. Ponce's role as client was critical in providing internal contacts within ESRI and the user community, as well as providing a base of domain knowledge and a foundation from past experience with the Law of the Sea. Ms. Kearns provided software assistance, training recommendations, and technical support as needed. Environmental Systems Research Institute GIS software, ArcGIS, is used by more than 300,000 organizations worldwide (ESRI, 2007). Among those organizations are many national governments that are potentially eligible to submit claims for extended continental shelves and use ArcGIS at different levels and phases of studies at their national agencies. Representatives of several nations have requested guidance, training, or services from ESRI regarding the delineation of their continental shelf boundaries. For this reason, the Nautical Team at ESRI was interested in developing an ArcGIS-based application that provides coastal nations with a workflow model for conducting the analyses required to establish their claims based on Article 76 of the Convention.

3.2. Proposed Solution

Satisfying the requirements of Article 76 involves a considerable amount of spatial analyses, for which GIS could potentially provide an effective means for conducting. Working with ESRI, a goal was to conduct a feasibility study regarding the extent to which ArcGIS is capable of meeting the needs and standards of Article 76. The desired outcome was to provide ESRI with a workflow model and an efficient configuration of a specialized set of tools for use within the ESRI software framework. An additional goal was to provide guidance on the processes required in delineation of the OLCS. The proposed final product was an ArcGIS-based application, in which the user could insert the required data into a model and use the tools provided to analyze the complex data

necessary for a submission to the UN Commission on the Limits of the Continental Shelf (CLCS). Overall, this system was expected to provide a GIS solution that will help coastal nations and United Nations' analysts to determine the location of the OLCS for each coastal nation, thus allowing nations to legitimately make a claim for extended continental shelf. Step-by-step instructions were expected to be provided, along with the necessary tools for analysts to utilize in delineating their boundary.

In meeting these goals, a list of necessary requirements would be established for conducting a case study and developing a workflow model. Incorporating both the client and UN requirements, this checklist encompasses the necessary processes and inclusions, as well as the rules that must be adhered to during data collection and processing, analysis, and development (see section 4.1 and 4.2 for requirements). Then a coastal region was chosen and used in a case study to test various processes and analytical techniques for the establishment of a workflow model, as well as conduct a mock-submission to test the final application.

4. Requirements Analysis

Through discussions with the client on interpreting the Law of the Sea and establishing the client's priorities, two lists of requirements were developed for this project; functional and nonfunctional. These requirements were developed to satisfy the typical customer use case (see Appendix B) for a coastal nation to submit an admissible claim. The use-case is based on the analytical requirements of Article 76 and those further explained in the Guidelines (CLCS, 1999).

4.1. Functional Requirements

- The system will delineate the outer limits of the continental shelf (OLCS) in order to determine the extended continental shelf (ECS) in accordance with Article 76 of UNCLOS for the area of interest.
- The system will comply with the Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf of the United Nations Division for Ocean Affairs and the Law of the Sea.
- The system will function with both pointer and keyboard commands.
- The system will include a workflow model.
- The system will include a specialized toolset.
- The system will include a database schema that users can utilize to generate their own database.
- The system will provide an output for results of analyses and calculations.
- The system will conduct envelope of arcs calculations to locate a constraint line that is 350 nautical miles (M) from the baseline (input data).
    - The system will output the result as a feature class in the output database (350M limit).
- The system will conduct envelope of arcs calculations to delineate a constraint line that is 100 nautical miles seaward from the 2,500 meter (m) isobath within the area of interest.
    - The system will output the result to the database (2500m plus 100M limit).
- The system will conduct analysis to combine the results from the constraint lines.
- The system will output to the database the line defined by the most seaward segments along the two input lines to form one continuous constraint line for the extent of the area of interest.
- The system will conduct analysis to determine whether the Constraint Line exceeds the Exclusive Economic Zone (EEZ, input data); is it further seaward from the baseline than the EEZ?
    - The system will output to the database the line defined by the most seaward segments among the EEZ and Constraint Line to form one continuous line for the extent of the area of interest (final constraint line).

- The system will conduct calculations to identify the points of maximum change in gradient at the base of the slope within the area of interest.
  - The system will output the results to the database (foot of the continental slope).
- The system will conduct envelope of arcs calculations to delineate a line that lies 60 nautical miles seaward from the foot of the continental slope (FOCS).
  - The system will output the results to the database (FOCS plus 60M).
- The system will conduct calculations to identify the locations where the sedimentary thickness is greater than or equal to one percent of the distance from that location to the FOCS.
  - The system will output the results to the database (percent sediment).
- The system will conduct calculations to compile the results from the FOCS plus 60M and percent sediment.
  - The system will output to the database the line defined by the most seaward segments along the two formula lines to form one continuous line for the extent of the area of interest (Formula line).
- The system will conduct calculations to determine if the final constraint line feature exceeds the formula line, and identify where.
  - If the final constraint line and formula lines do not cross and the final constraint line is further seaward than the formula line from the baseline, than the complete formula line is output as the outer limits of the continental shelf (OLCS).
  - If the final constraint line and formula lines do not cross and the final constraint line is closer to the baseline than the formula line, then the final constraint line is output as the OLCS.
  - If the final constraint line and formula lines do cross, then a new line must be created using line segments from both features; maintaining only the sections of the formula line that are closer to the baseline than the final constraint line and use the final constraint line to connect those line segments in the areas where the formula line extends further seaward from the baseline than the final constraint line.
  * The resulting line is the extended continental shelf boundary.
- The system will conduct distance measurements using an envelope of arcs process to establish geodesic measurements.
- The system will output the results of the calculations to the database.
- The system will accept input data from the database (all data must cover the same extent, specified by the user):
  - Bathymetry contours (vector feature class)
  - Bathymetry grid (raster)
  - Seabed geology (raster)
  - Coastal baselines (vector feature class)
  - Exclusive economic zone (EEZ) (vector feature class)

- International and maritime boundaries (vector)

4.2. Nonfunctional Requirements

- The system procedures shall preserve data integrity. Data outputs shall maintain the same level of data quality as the input data from which it was derived through system procedures.
- The system shall be constructed completely within the Environmental Systems Research Institute's (ESRI) Geographic Information System (GIS) software environment, utilizing currently available tools, extensions, and capabilities (e.g. display, store, manipulate, and retrieve geographic data).
- Input data must be compatible with ESRI's GIS software.
- The System must produce data in ESRI standardized formats.
- The system's analyses and outputs shall comply with the Scientific and Technical Guidelines of the Commission on the Limits of the Continental Shelf of the United Nations Division for Ocean Affairs and the Law of the Sea.
- The analytical processes must function in accordance with Article 76 of UNCLOS.

5. Methodology

The conceptual steps involved require locating the final constraint line, locating the final formula line, and then delineating the OLCS (see figure 5.1, also Appendix C). There are three primary lines from which the constraint lines and formula lines are established: the baseline, 2,500 meter isobath, and the FOCS (see Figure 5.2).

There are two constraint lines: measured at 350 nautical miles (M) seaward from the baseline, and 100 nautical miles seaward from the 2,500 meter isobath. Then the formula lines from which the actual extent of the OLCS is determined must be delineated. First, however, the location of the foot of the continental slope must be established. Then the formula lines are delineated based on the FOCS, including measuring 60 nautical miles seaward from the FOCS and determining the extent to which the sediment thickness is at least one percent of the distance to the FOCS. Then one must determine where the formula lines are restricted by the constraint lines. Though, in definition these concepts may seem simple, the processes of delineation are actually quite complex. The remainder of Section 5 discusses the methodology that was used to develop a process for delineating the OLCS within an ArcGIS environment.
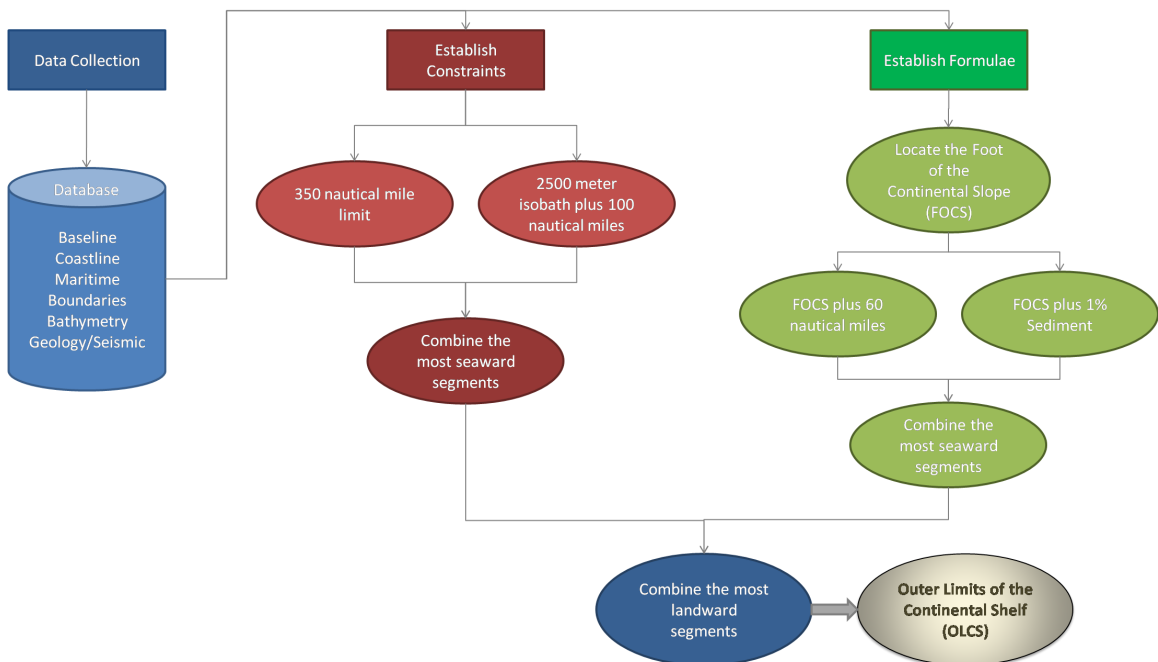
Figure 5.1: Article 76 Workflow.
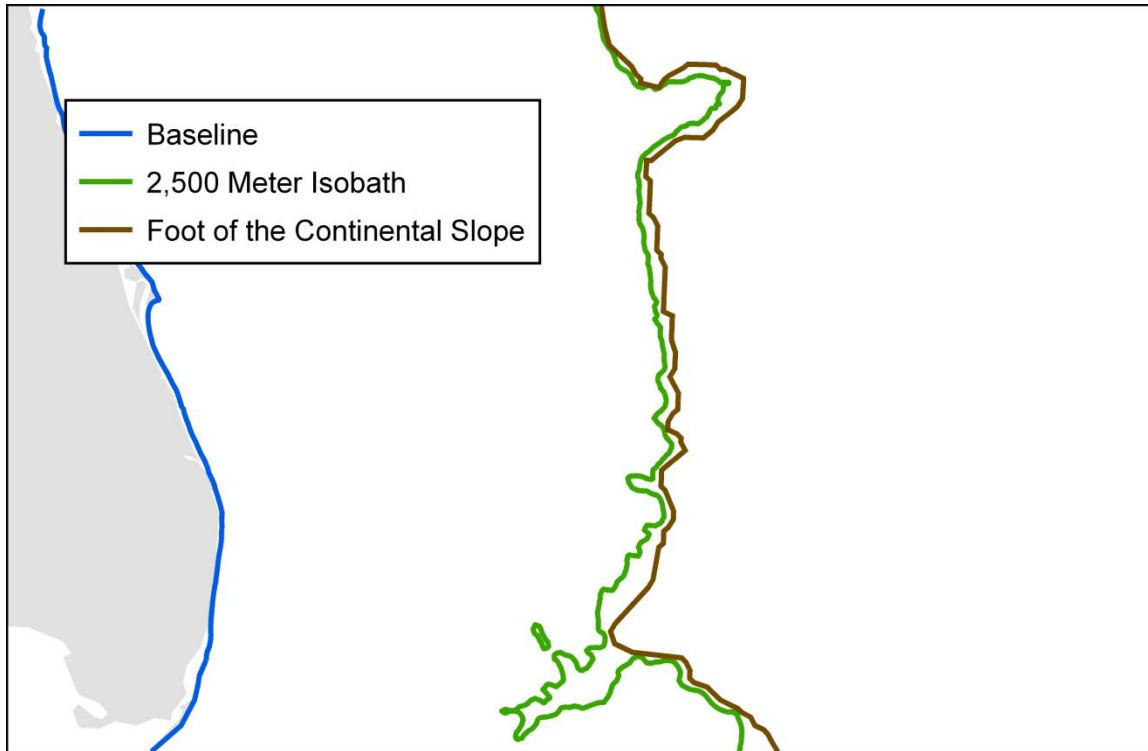
Figure 5.2: Primary lines used to determine the OLCS.

5.1. Setting up the Case Study

A coastal region off Florida's eastern shoreline was selected for conducting the case study (see Figure 5.3). This region was chosen due to its manageable size and the availability of sufficient data. This data and region, however, do not represent official work towards a real submission, nor will the conclusions of this study be considered official. Trial processes were developed and tested using the study area to create a proof of concept for an ArcGIS Article 76 workflow model. Through conducting research on the numerous GIS tools available, tools that could offer potential solutions or contribute to the analysis process were identified and used to develop potential processes. Particularly for the more complex problems, several prospective processes and algorithms were tested using various familiar and newly researched tools and commands. By researching several potential ways of conducting the same analysis, the processes and results could be compared in order to determine the most accurate and efficient methods for implementing the regulations set forth by Article 76. Additionally, this process helped determine areas of the analyses in which ArcGIS software was weak with regard to its ability to compute, display, and provide essential outputs.
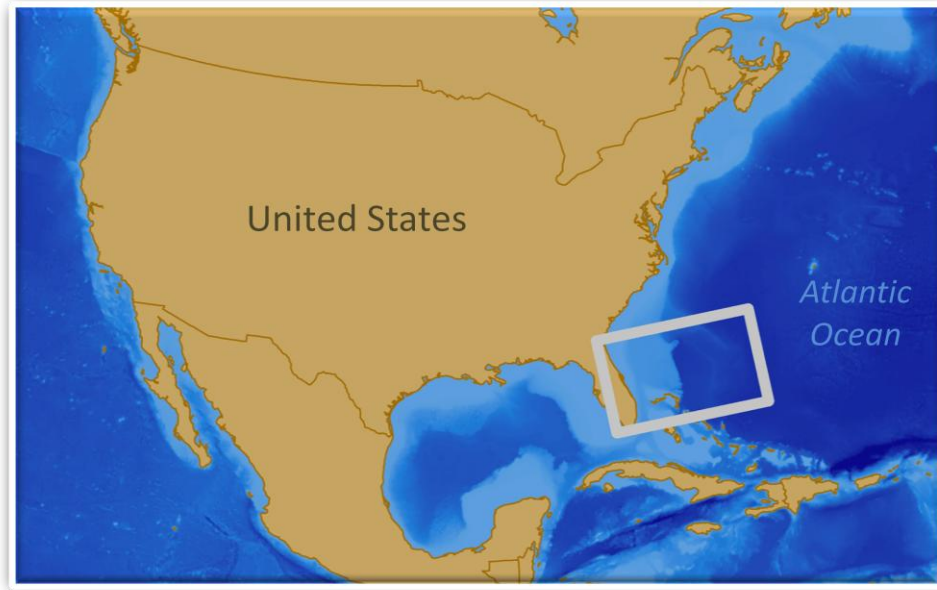
Figure 5.3: Study area off Florida's eastern coast is outlined in gray.

5.2. Data Collection

The foundation data necessary to begin the analyses included baseline data, coastline data, bathymetric contours, bathymetry grid, and a sediment thickness raster. These necessary data files were downloaded from various internet sources listed in Table 5.1. The bathymetry contours originally acquired did not cover the entire study area extent. Instead, they were derived from the bathymetry grid using ArcGIS analysis tools. The baseline points were also generated in ArcGIS using the baseline file.

Table 5.1: Data Sources

Data File	Data Source
Florida baseline	United States Geological Survey, Coastal and Marine Geology Program
ETOPO2 grid	National Geophysical Data Center (NGDC), NOAA
Sediment thickness grid	National Geophysical Data Center (NGDC), NOAA
Medium resolution shoreline (polygon)	Coastal Geospatial Data Project, NOAA
Medium resolution digital vector shoreline (line)	United States Geological Survey, Coastal and Marine Geology Program

5.3. Analysis

5.3.1. Data Preparation

The spatial reference had to be identified and properly defined for the downloaded files before they could be used in ArcGIS. The data necessary for analyzing the constraint lines were unprojected in a geographic coordinate system. These data files, including the baseline and coastline, were defined as Geographic Coordinate System, World Geodetic System (WGS) 1984, which is the format in which the CLCS prefers to receive data for ECS claims. The raster data, however, required a projection that utilized the same units of measurement along both the horizontal and vertical axis. The vertical values for both the bathymetry and the sediment thickness were in meters. A local reference system, State Plane Coordinate (SPC) Florida East North American Datum (NAD) 1983, which utilizes meters as the linear unit, was assigned to these data sets. Additionally, an extent was determined within which the analyses were to be contained. This extent spanned the entire length of Florida's eastern coastline from north to south and encompassed an expanse of the Atlantic Ocean approximately 500 nautical miles seaward. A new shapefile was created as a single polygon representing the study area extent, which was then used as the boundary to which all data were clipped (see Figure 5.4).
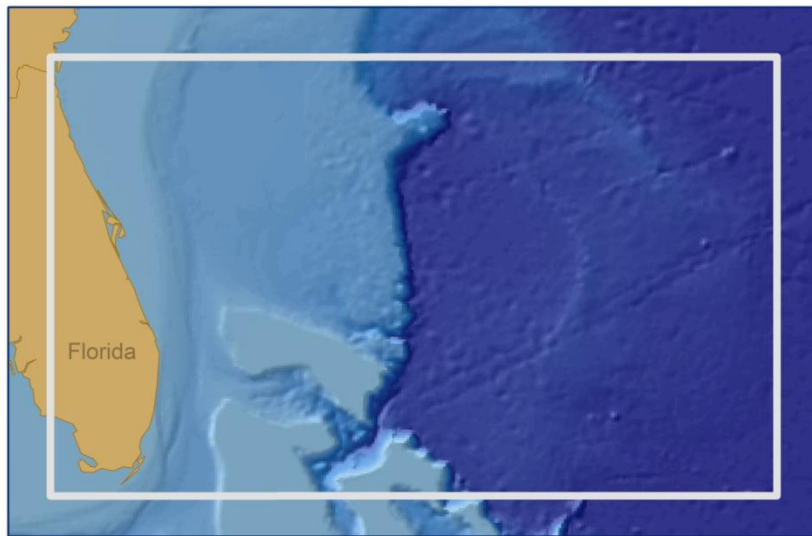
Figure 5.4: Study area extent outlined in gray.

The analyses for determining the constraint lines is heavily based on geodesic distance calculations from the baseline. However, these calculations are to be conducted from a series of points along the baseline, which are designated by the analyst or nation. The primary parameters under which such points are decided is that they must be no farther apart than 60 nautical miles. The baseline data acquired for the Florida coast contained only the line; the baseline points needed to be identified for the study area (see Figure 5.5). In ArcMap, the baseline line feature class was added to an empty map document. Then, because the line was actually made up of a series of line segments, the selected extent was dissolved into a single line segment, to then be effectively divided into 60 nautical mile segments. The segments were generated using the Divide tool under the

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Editor Toolbar, then used to place nodes at each vertex, as well as the end points, in order to obtain the necessary baseline points at distances no greater than 60 nautical miles. Note, this is simply the method chosen to determine points strictly for generating usable data for the purpose of this case study. During a real submission process a much more methodical and meticulous procedure of identifying the most advantageous points would be conducted.
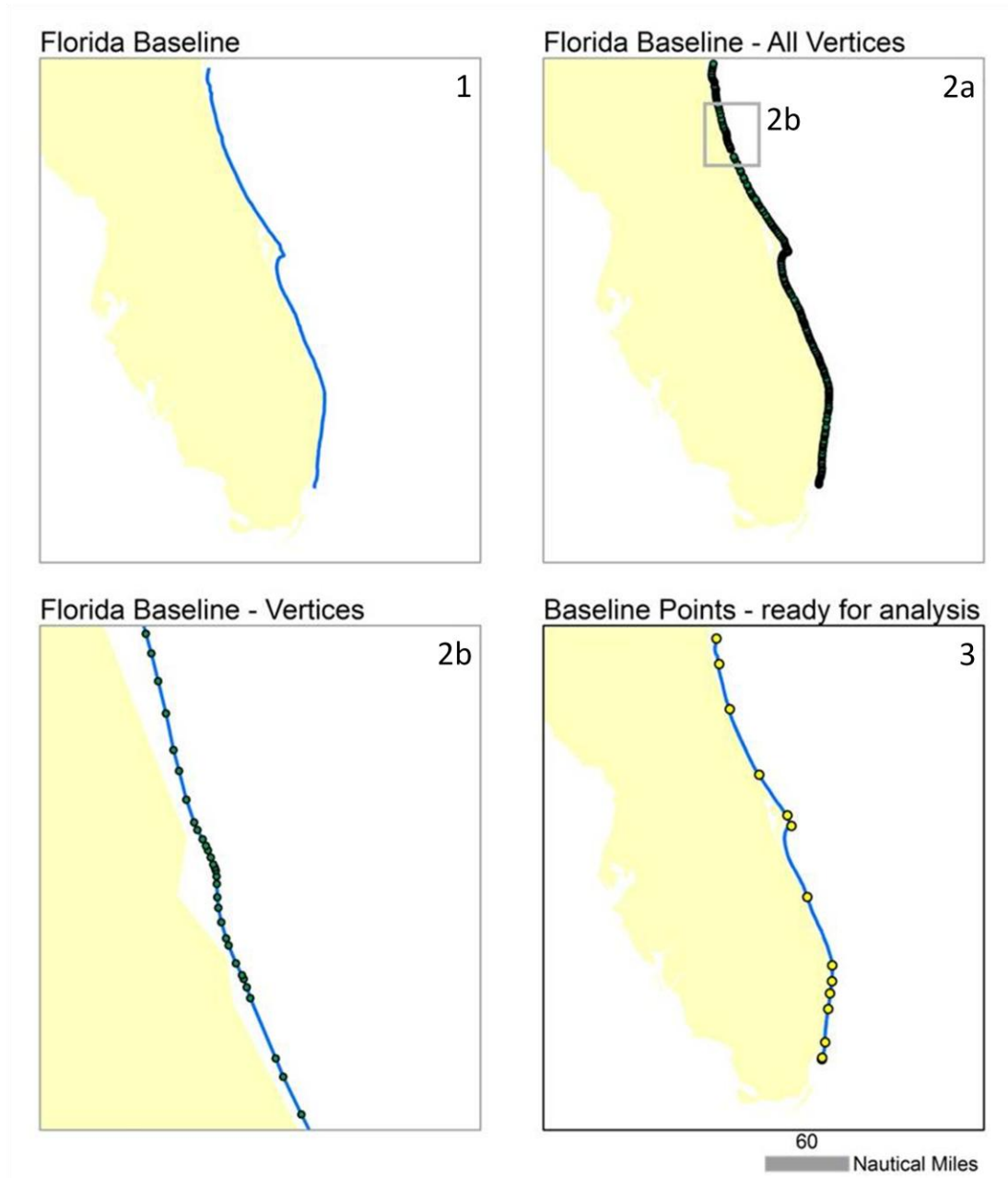
Figure 5.5: Establishing the baseline points.

This study assumes all necessary base data listed in the requirements (section 4.1) have been surveyed, collected, and meet the necessary standards for quality and accuracy. Such processes are not part of Article 76 and must be addressed prior to utilizing the processes specified in this study.

5.3.2. Delineating the Constraint Lines

The baseline points are necessary for delineating both the EEZ (which is not directly part of this study) and the 350 nautical mile constraint line as mandated by the Convention. The baseline is the origin from which seaward measurements are made, using an envelope of arcs process, to identify the location of these two lines (see Figure 5.6).

Baseline Points	350M Arcs	2500m Isobath Points
Baseline	350M Constraint	Bathymetry Contours
200M Arcs	2500m + 100M Arcs	500m Intervals
Exclusive Economic Zone	2500m + 100M Constraint	2500m Isobath
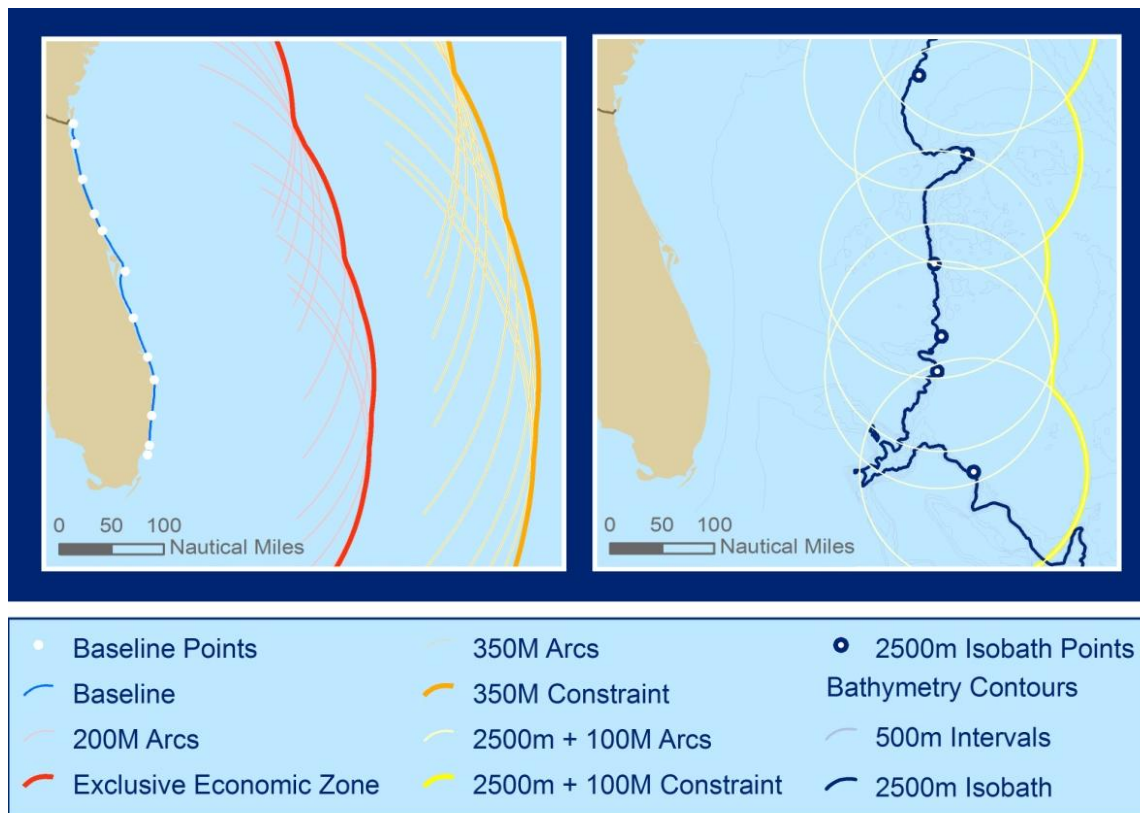
Figure 5.6: Illustration of how the Envelope of Arcs process is used to generate the constraint lines, measured from the baseline as well as an isobath.

The envelope of arcs process produces a series of arcs of circles as a product of geodesic measurements, similar to a buffer, around each point at a specified distance (i.e., 200M and 350M). However, at the time of the case study, ArcGIS did not have the functionality to conduct such geodesic measurements, so a simple buffer was used to generate the lines based on arcs of measured straight-line, flat-earth distances. As utilizing the buffer tool was a workaround and temporary stand-in for a more efficient alternative currently under development, some additional steps were taken to reach the necessary output of a continuous line feature for the measured constraint lines. The buffer tool, from the ArcToolbox Proximity Analysis tools, was run with the Dissolve

Type option set to All producing a polygon completely surrounding all baseline points at the specified distance. The polygon was then converted to a line feature and clipped to exclude all land features. This process was used to conduct to all distance measurements, including, for purposes of this study the exclusive economic zone, as well as the 350 nautical mile limit (see Figure 5.7).
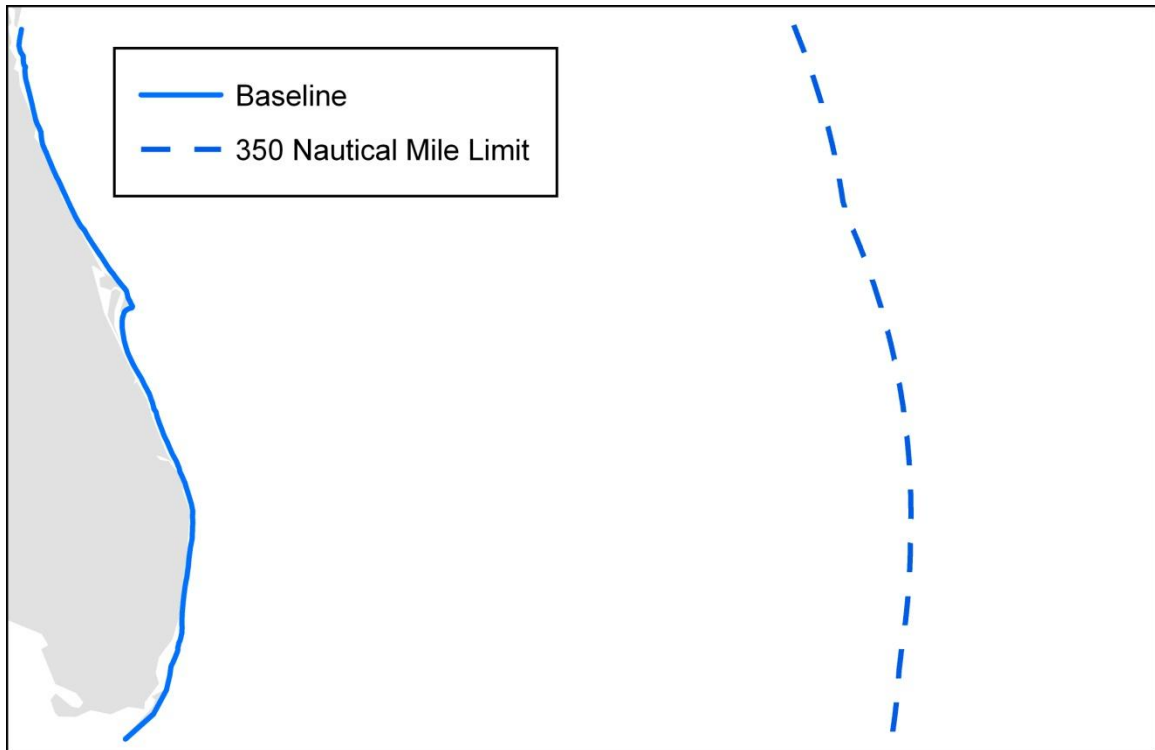
Figure 5.7: Baseline and 350 nautical mile limit.

The second constraint line is generated at a distance of 100 nautical miles from the 2,500 meter (m) isobath, in the seaward direction from the baseline. An isobath is a line of constant depth, essentially a contour line representing the depth of the sea floor. Isobath data, also referred to as bathymetric contours, is a required dataset from which the 2,500 meter isobath should be easily derived. However, in the absence of isobath data, the contours can be easily and automatically generated in ArcMap using a bathymetry grid, which is also required data. To demonstrate this, bathymetric contours were generated at 500 meter intervals from ETOPO2 (see Figure 5.8) using the Create Contours tool on the 3D Analyst toolbar. The 2,500 meter isobath was then selected and exported as a separate file.
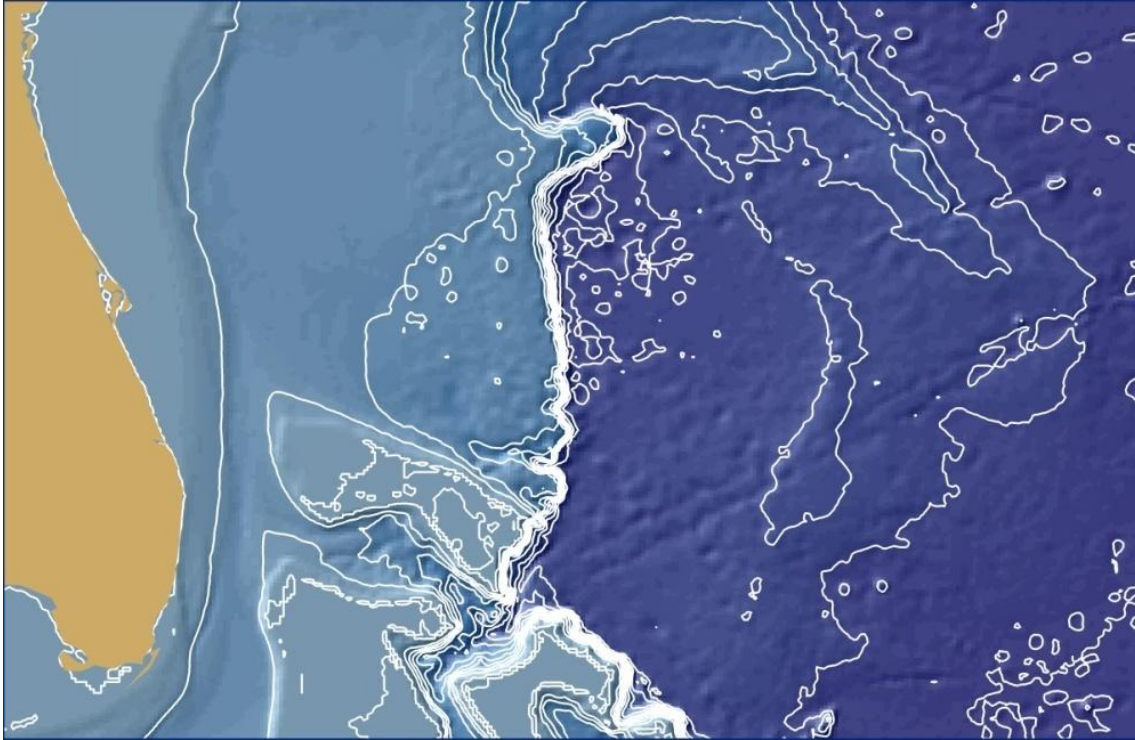
Figure 5.8: Bathymetric contours at 500 meter intervals overlaid on the ETOPO2 grid.

The final constraint line is also a product of the envelope of arcs process, though this time the measurements were derived from points along the selected isobath, not the baseline. Points were established along this meandering line, though this time manually, taking into consideration the shape of the isobath and most advantageous locations. The isobath points also had to be placed no greater than 60 nautical miles apart. This was adhered to during selection and checked prior to running the analysis. Once again, a buffer and the additional processes used to determine the earlier constraint lines were repeated for the generation of the 2,500 meter isobath plus 100 nautical mile limit (see Figure 5.9).
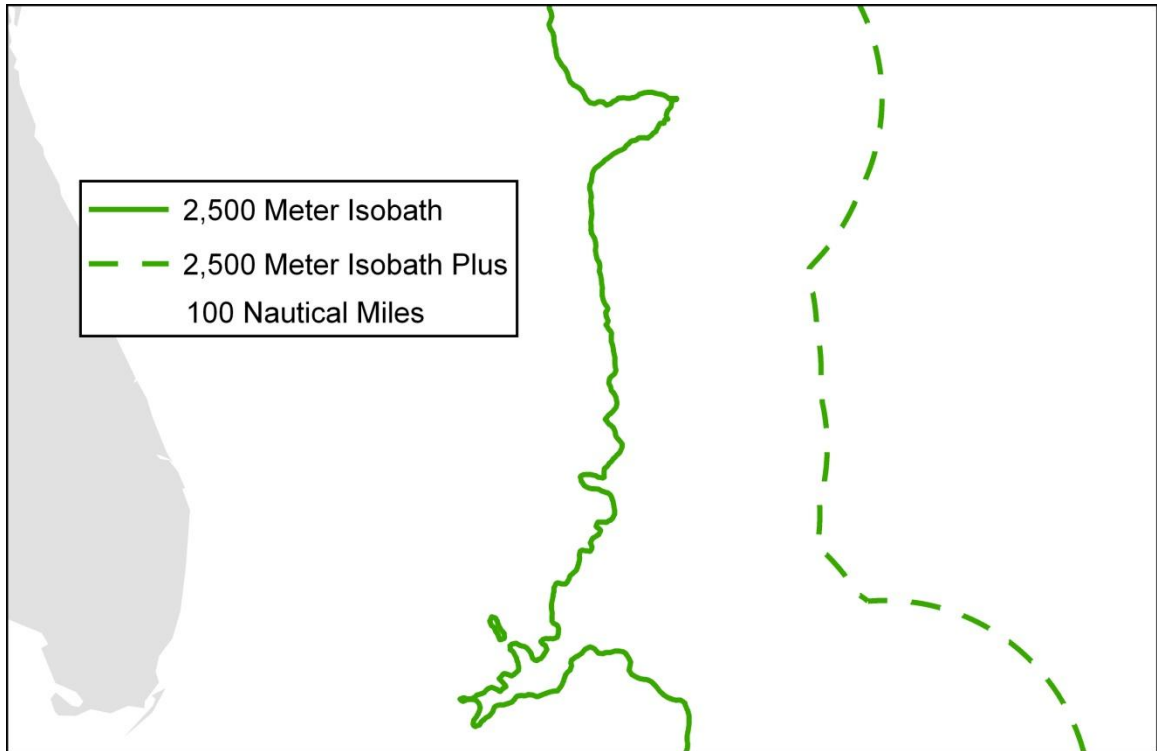
Figure 5.9: 2,500 meter isobaths and the line measured 100 nautical miles seaward from the 2,500 meter isobaths.

The preliminary constraint lines (350M limits and 2,500m isobath plus 100M) were then combined to form a single continuous constraint line. The final constraint line was composed of the most seaward sections of the constraint lines (see Figure 5.10). This was achieved by creating a union between the polygons that encompass the area between the coastline and the preliminary constraint lines. The area was then dissolved to remove superfluous interior lines and the polygon was converted to a line feature. Editing was necessary to remove the unnecessary bounding lines, maintaining only the segments that represented the most seaward extent of the constraint lines, which ran relatively parallel to the general trend of the baseline and bathymetric contours.
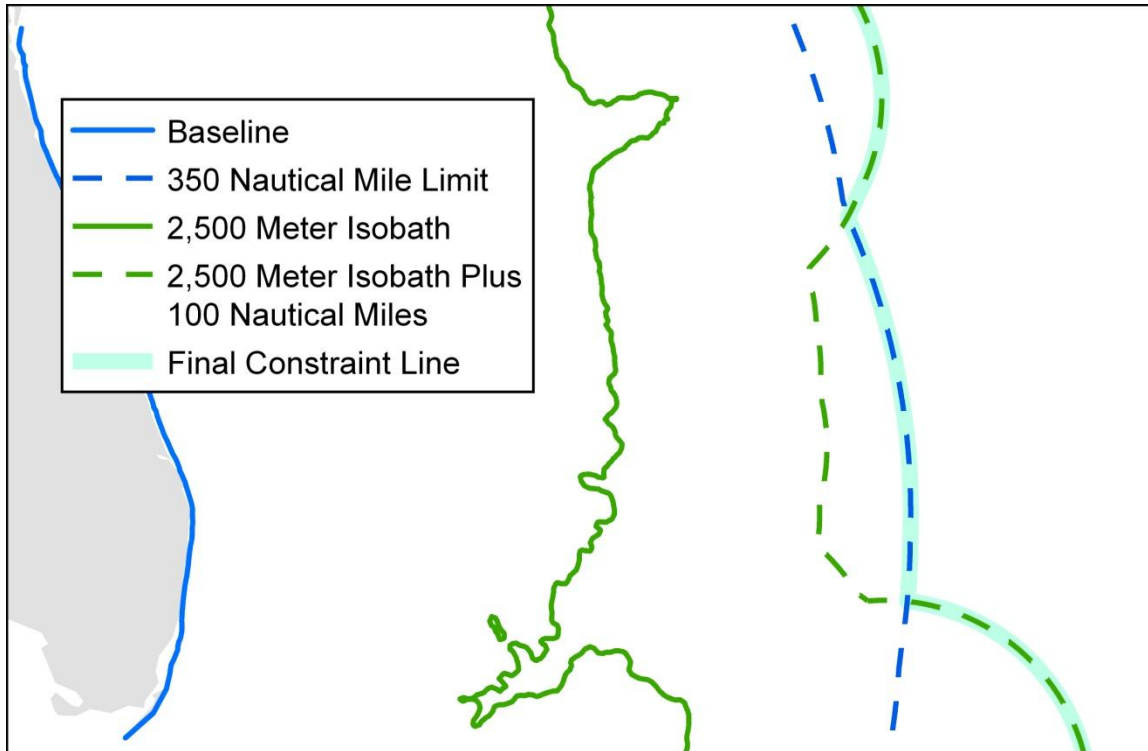
Figure 5.10: Preliminary and final constraint lines.

5.3.3. Delineating the Formula Lines

By definition, the final constraint line establishes the boundary within which the potential extended continental shelf claim may be made. The OLCS may only reach as far as, or follow, the constraint line if the formula lines reach or extend beyond the constraint line. Two formula lines are established, based on the foot of the continental slope (FOCS). These lines are used to establish a final formula line in the same way that the final constraint line was established from the combination of the calculated limits.

Paragraph 4 (a) of Article 76 states that:

> For the purposes of this Convention, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by either:
>
> (i) a line delineated … by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope; or
>
> (ii) a line delineated … by reference to fixed points not more than 60 nautical miles from the foot of the continental slope (DOALOS, Article 76, 2001).

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These two formula lines are herein referred to as the FOCS plus one percent sediment formula line, and the FOCS plus 60 nautical mile formula line. However, in order to establish these formula lines, the FOCS must first be delineated, which alone is a complicated line to determine spatially.   Paragraph 4 (b) of Article 76 legally establishes that "the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base" (DOALOS, Article 76, 2001). This delineation is a multi-step process, requiring the initial determination of the "region defined as the base of the continental slope" (CLCS, 1999, p. 38). This section of analyses requires the use of the bathymetry grid. As stated by the CLCS (1999, p. 38) in section five of the Guidelines:

> The Bathymetric database used in the delineation of the foot of the continental slope in a submission may include … the following data:
>
> - Single-beam echo sounding measurements;
> - Multi-beam echo sounding measurements;
> - Hybrid side-scan sonar measurements;
> - Interferometric side-scan sonar measurements; and
> - Seismic reflection-derived bathymetric measurements.

For the purpose of this study the most available data was used, as the primary purpose was to test the processes and software capabilities. ETOPO2 was used for all raster bathymetry analyses.

Analyses of the nature of the surface of the continental margin and the ocean floor were necessary to locate the FOCS. To produce a surface appropriate for such analyses, the Curvature tool, located in the 3D Analyst toolbox in ArcGIS, was utilized to generate a curvature surface using the bathymetry raster as the input surface. The curvature tool determines the change in slope throughout a surface, assigning positive and negative values for each cell, which represent the nature of the change in the surface based on its immediate surrounding cells.   As ESRI stated in the ArcGIS 9.2 Desktop Help *Curvature* document, the curvature output "is the second derivative of surface [or in other words] the slope of the slope" (Environmental Systems Research Institute (herein ESRI), 2008, Curvature). There are three total outputs produced when utilizing this tool; the automatic output is curvature, and the two optional outputs are a profile curvature and plan curvature, each of which utilizes a different set of surrounding cells determined by the direction of the calculated change. The original curvature surface is calculated based on all eight surrounding cells (see Figure 5.11).
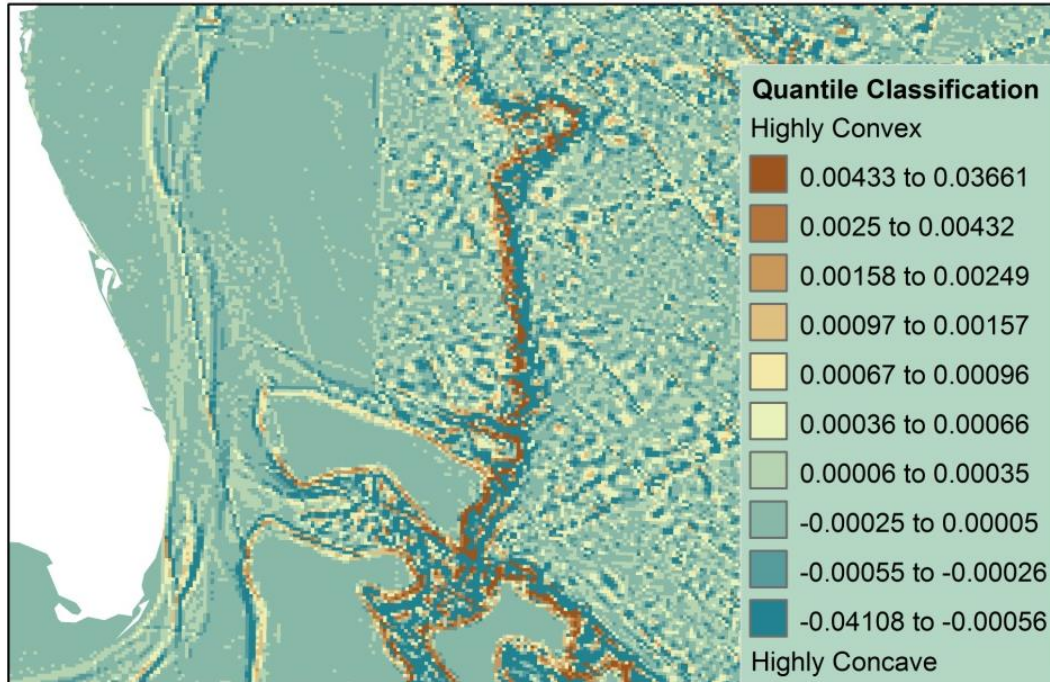
Figure 5.11: Curvature Surface, classified using the Quantile method and 10 class breaks.

The profile curvature calculates the "rate of change of slope" (ESRI, 2008, Curvature) by utilizing only those cells influencing the curvature "in the direction of the maximum slope" (ESRI, 2008, Curvature) (see Figure 5.12).
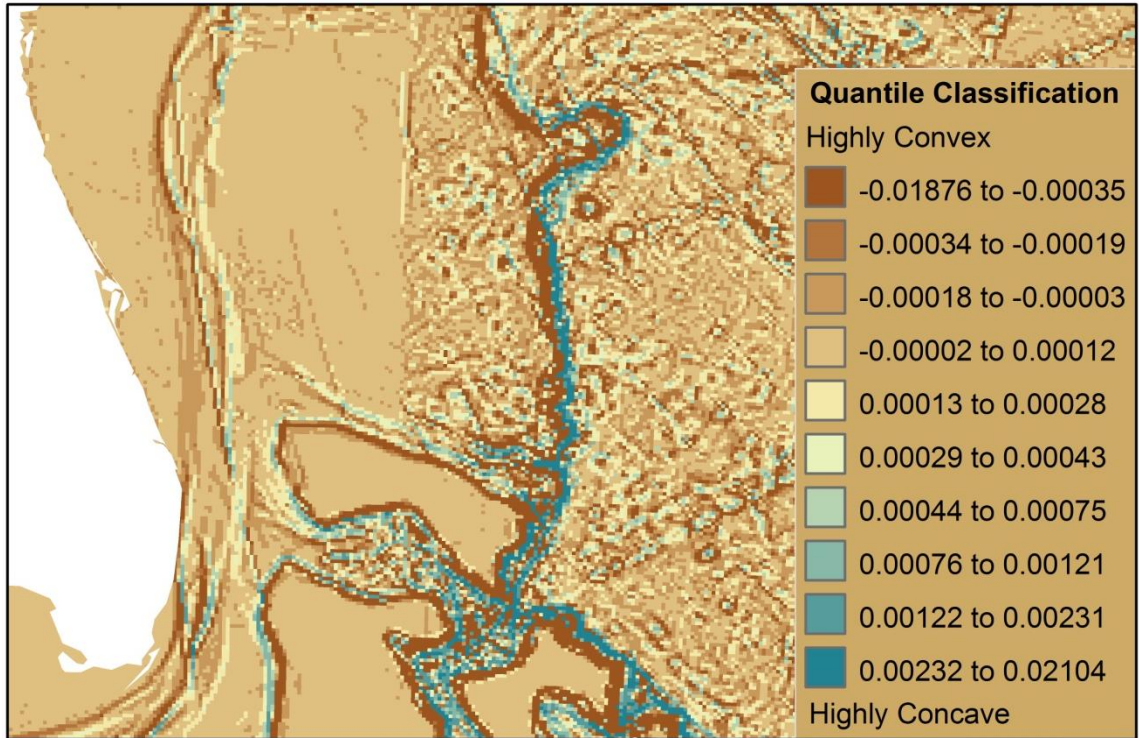
Figure 5.12: Profile Curvature Surface, classified using the Quantile method and
10 class breaks.

The plan curvature is calculated "perpendicular to the direction of the maximum slope"
(ESRI, 2008, Curvature) (see Figure 5.13).
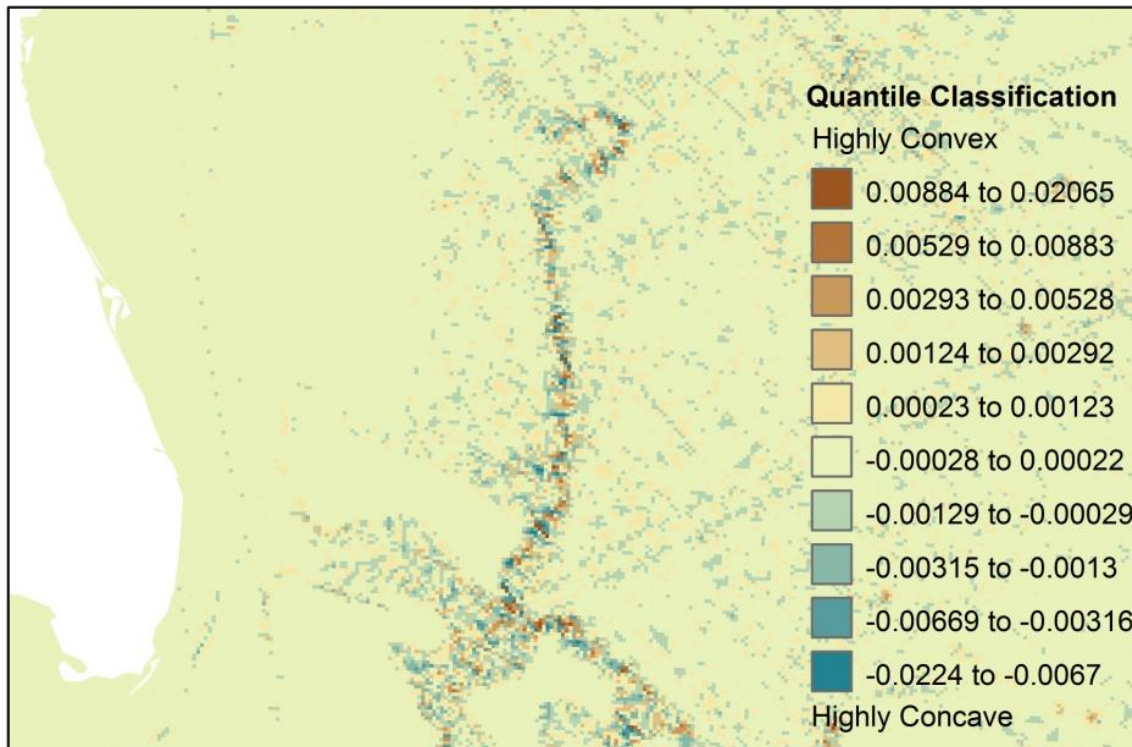
Figure 5.13: Plan Curvature Surface, classified using the Quantile method
and 10 class breaks.

The values associated with each curvature represent the degree to which the curvature is
concave or convex. The values range between negative and positive decimals, for which
the interpretation of the values vary between each output. A value of zero always
represents a flat surface and as the values, positive or negative, get larger they indicate an
increase toward the extreme nature of the curvature. Thus, the maximum change in
gradient will have the most extreme concave nature at the foot of the continental slope. If
there is a steep drop off at the base of the continental slope, as is common, the extreme
concave shape will be located just seaward from a highly convex region representing the
top of the drop-off.

All three curvature surfaces were produced and analyzed. They were compared to the
bathymetry and to each other to determine which output provided the most accurate
representation of the change in gradient perpendicular to the bathymetric contours. A
hillshade was created from the bathymetry raster to overlay with each curvature surface
for better visual interpretation and analyses. Each surface was classified using several
techniques to compare how well the outputs and resulting classes represented the change
in gradient. The classifications and visual analyses were then compared to a series of
profile graphs that were generated for each surface. In the absence of a 3-dimensional
profile renderer, the profile graphs provided a 2-dimensional profile view of the data at
designated transects. The profiles of the raw bathymetry showed a profile of the change
in surface depth from the coastline well beyond the base of the continental slope (see
Figure 5.14). Graphs were also established for the curvature surfaces, representing the
change in curvature throughout the surface of the continental margin and beyond. These

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graphs were used to identify the point of maximum change in gradient along the profile. The points along the bathymetric profile graphs where the foot of the continental slope was apparent were selected and indentified. The identify option within the profile graph window was used to highlight this location on the map and provide the coordinates of the selected point, which were used to compare the classifications and values of the curvature surfaces used. This helped to establish the location of the base of the continental slope and determine which curvature surface best represented that.
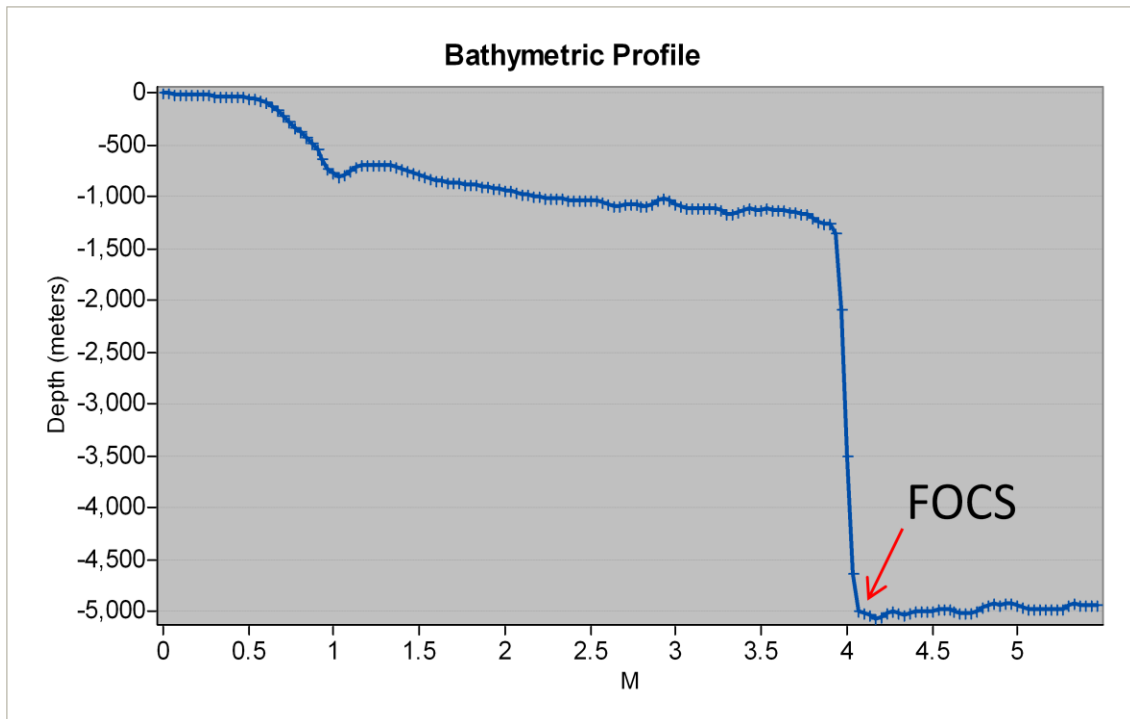
Figure 5.14: Bathymetric profile graph indicating the location of the Foot of the Continental Slope (FOCS).

Additionally, a selection of points was indentified along the curvature profile graphs at the locations indicating the maximum change in gradient, both on the map and in the tables, and then compared with the classifications and values of the curvature surfaces used. This helped determine which of the curvature surfaces most accurately indicated the change in gradient and, therefore, the foot of the continental slope. Following this analyses, the profile curvature was determined to provide the most accurate representation for this study area.

The profile curvature was then classified using several methods to determine which provides the best classification scheme for the data. These included Quantile and Jenks Natural Breaks. Both of these were analyzed for this study using varying numbers of classes, though based on the analyses ten classes were selected as the most appropriate for this data. The Quantile classification method divides the data into classes, each with the same number of features. When the curvature output raster was classified into ten classes using the Quantile method based on the values, the result established a set of classes each comprising ten percent of the values. Thus, a selection of the values in the

highest class would encompass the top ten percent of the values. This was determined by examination to be the best way to represent and analyze the data. Based on the interpretation guidelines provided by the ArcGIS 9.2 Desktop Help *Curvature* document (ESRI, 2008), it was determined that the values representing the greatest change in gradient at the base of the slope, where the curvature is upwardly concave, are those which are significantly positive. Therefore, the cell selection should include those with the highest positive values. After significant analyses of the data, it was determined best to use ten quantile classes with a selection of the top ten-percent of values (the top class), since the values of interest are the extreme positive values (see Figure 5.15). This selection seemed to capture most of the FOCS without including too broad of a selection.

Profile Curvature

▨	coastline
🟩	0.002307 - 0.021036
⬛	0.001215 - 0.002306
⬛	0.000747 - 0.001214
▨	0.000434 - 0.000746
▨	0.000278 - 0.000433
▨	0.000122 - 0.000277
▨	-0.000034 - 0.000121
▨	-0.00019 - -0.000035
▨	-0.000346 - -0.000191
🟨	-0.018765 - -0.000347
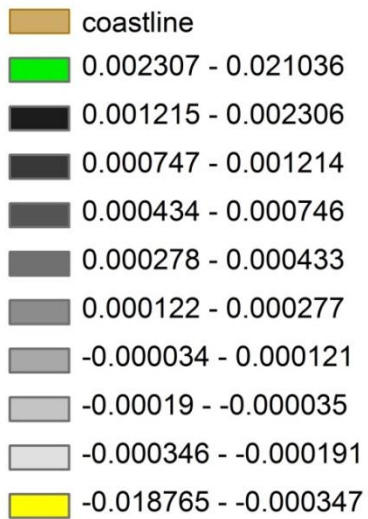
High positive values indicate the surface is highly concave, meaning the slope is significantly changing to an upward trend.

Where the value extremes are close indicates the base of the continental slope, where the very high values are representative of the maximum change in gradient; therefore, identifying the foot of the continental slope.

Low negative values indicate the surface is highly convex; meaning the top of a drop off or significant change in slope from relatively flat or uphill to a downward trend.
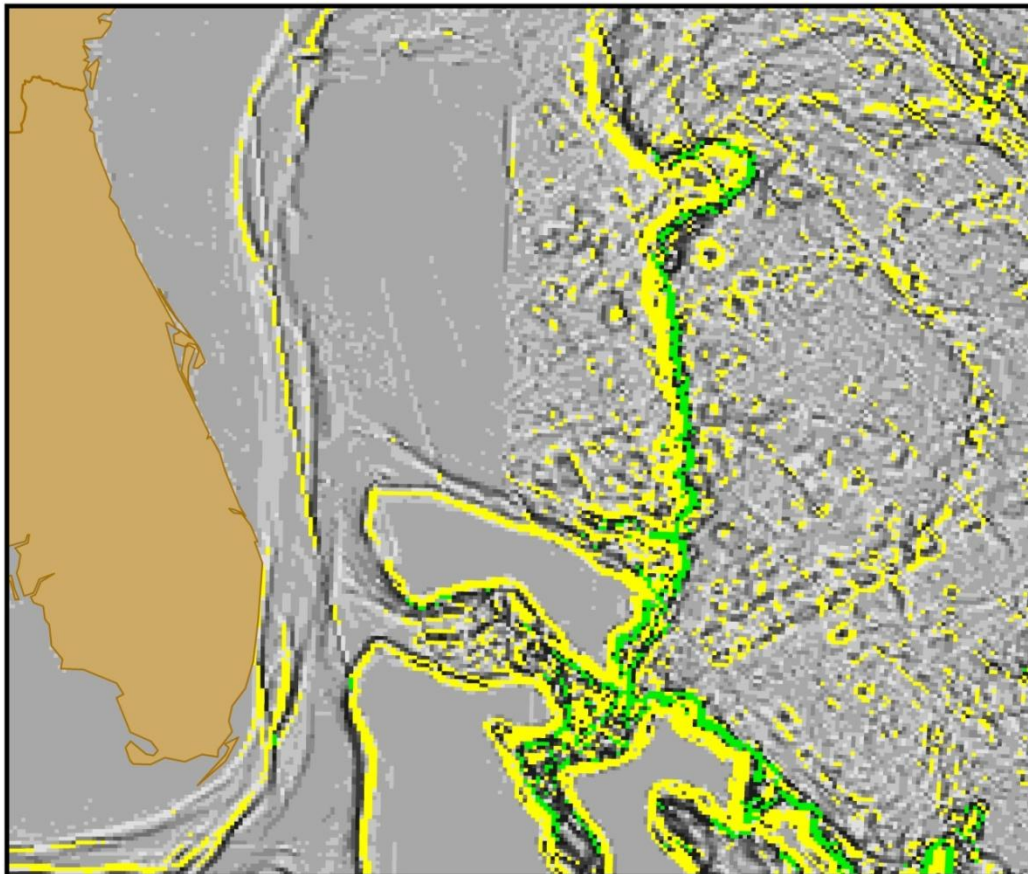

Figure 5.15: Classified profile curvature highlighting the foot of the continental slope in green.
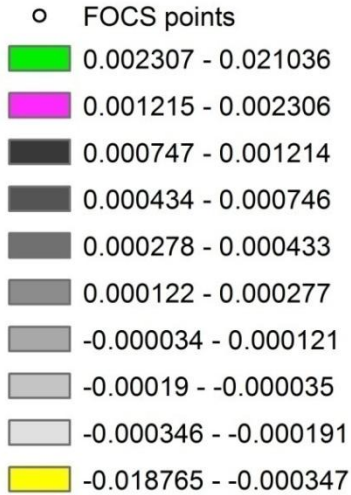
The selected cells needed to be extracted in order to establish points at these locations. Using command line in ArcGIS to implement the Extract by Attributes command with the necessary parameters, the cells with the desired values – those within the range of the top ten percent – were exported as a separate raster.

The command line syntax used for the Extract by Attributes command was retrieved from ArcGIS 9.2 Desktop Help for *Extract by Attributes* (ESRI, 2008). The input, output, and value parameters were set specific to this project. The following command was used:

> ExtractByAttributes_sa
> C:\UNCLOS\results_temp\profile_curv
> "value >= 0.0210364"
> C:\UNCLOS\results_temp\curv_extract

The extracted cells were then converted to points. These points also included some locations that contained values within the specified range, but outside the region containing the base of the continental slope. Therefore, it was best to manually analyze the points overlaid on the original bathymetry grid and, separately, on the curvature surface which are both visualized best when draped over a hillshade. This was used to help visually locate the base of the continental slope and those points that would likely need to be removed. However, the use of profile graphs was key to identifying the actual location of the FOCS and determining which points to utilize for generating the line. The points feature class was then edited, deleting all unnecessary points and maintaining only those that (1) fell at the base of the continental slope, (2) were most advantageous, and (3) were no greater than 60 nautical miles apart. The final points representing the FOCS were then used to generate a continuous line. The Convert Locations to Paths (points to lines) for ArcGIS 9.2 script, downloaded from the ArcScripts webpage (Palmer, n.d.), was used to automate the line generation. Once the line was generated, it was manually reviewed and analyzed in comparison to the curvature surface and original points selected along the projected FOCS. Keeping in mind that the maximum change in gradient values as selected for the entire area generally pertain to the FOCS line, those values are potentially not quite as extreme and as a result not relevant throughout the entire length of the line. As was found in the case study, the general trend of the line missed some curves and was lacking vertices at important locations. The extreme values initially selected did not extend all the way to the edge of the study area. Thus, further analyses of these areas was necessary to identify the maximum change in gradient values and their locations for these less extreme portions of the FOCS (see Figure 5.16). These locations were then added as vertices and the line was recalculated to incorporate a more accurate representation for the final delineation of the FOCS (see figure 5.17).

Profile Curvature

- ○ FOCS points
- 🟩 0.002307 - 0.021036
- 🟪 0.001215 - 0.002306
- ⬛ 0.000747 - 0.001214
- ⬛ 0.000434 - 0.000746
- ⬛ 0.000278 - 0.000433
- ⬛ 0.000122 - 0.000277
- ⬜ -0.000034 - 0.000121
- ⬜ -0.00019 - -0.000035
- ⬜ -0.000346 - -0.000191
- 🟨 -0.018765 - -0.000347

The second highest positive values were used to fill in gaps where the surface's concave nature was not as extreme, yet was determined through analysis to indicate the point of maximum change in gradient for less extreme areas along the base of the continental slope, and therefore, represent the foot of the continental slope.
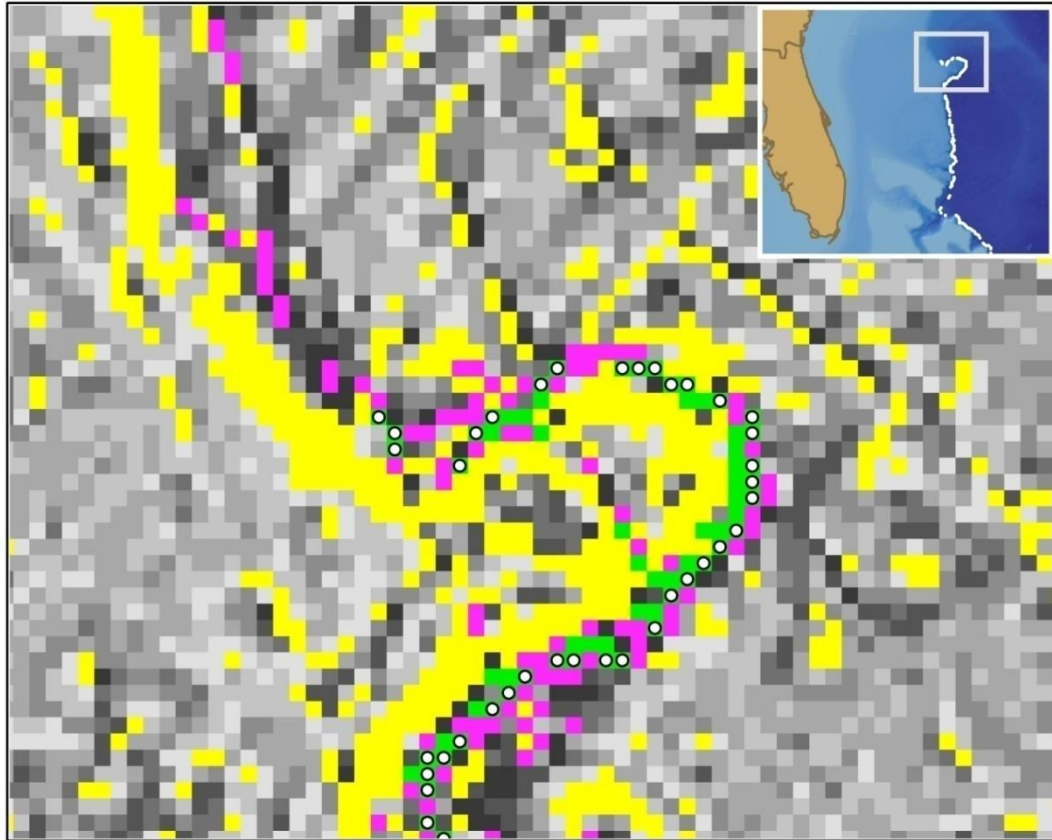
Figure 5.16: Placement of points delineating the foot of the continental slope. The magenta cells indicate less extreme values than the green cells, yet represent the maximum change in gradient for some regions along the FOCS.

Figure 5.17: Foot of the Continental Slope.

The FOCS points feature class also remained necessary as the basis for the envelope of arcs measurement in determining the FOCS plus 60 nautical mile formula line. Since, the data required some additional editing prior to generating the envelope of arcs, a copy of FOCS points was saved to preserve the original data. Unnecessary points were deleted and the envelope of arcs was generated in the same way as the constraint lines, using a distance of 60 nautical miles (see Figure 5.18).
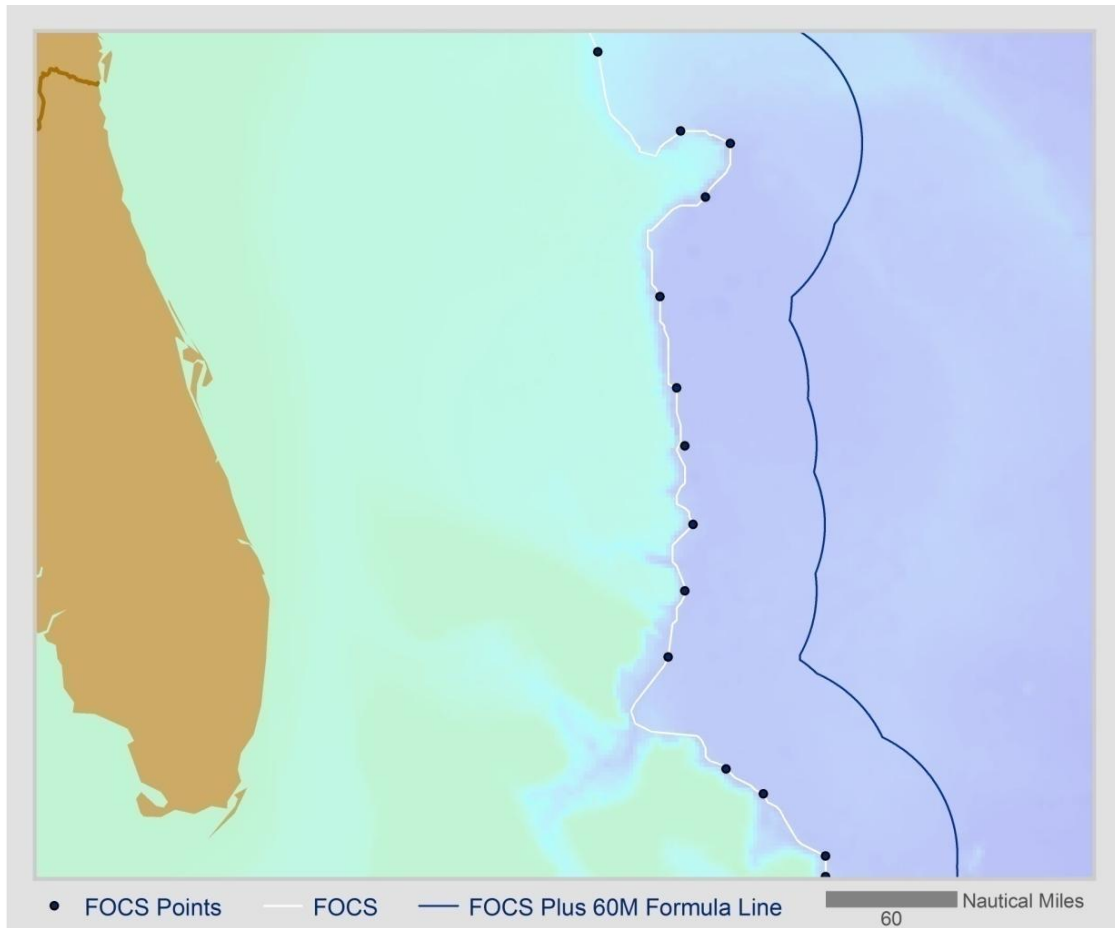
Figure 5.18: Foot of the continental slope plus 60 nautical miles

Determining the locations where the sediment thickness is at least one percent of the distance from the specified location to the FOCS (see figure 5.19) required a multistep process. The FOCS was used to calculate a raster with the same extent and output cell size as the sediment raster (see Figure 5.20).
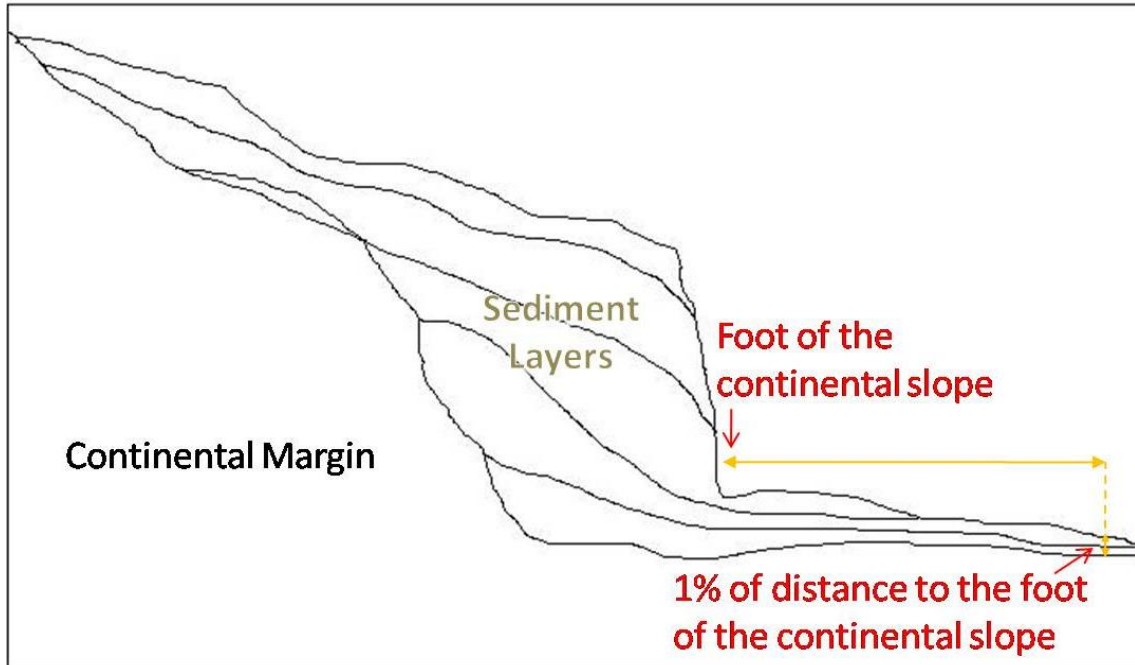
Figure 5.19: Locating the extent of 1% sediment thickness
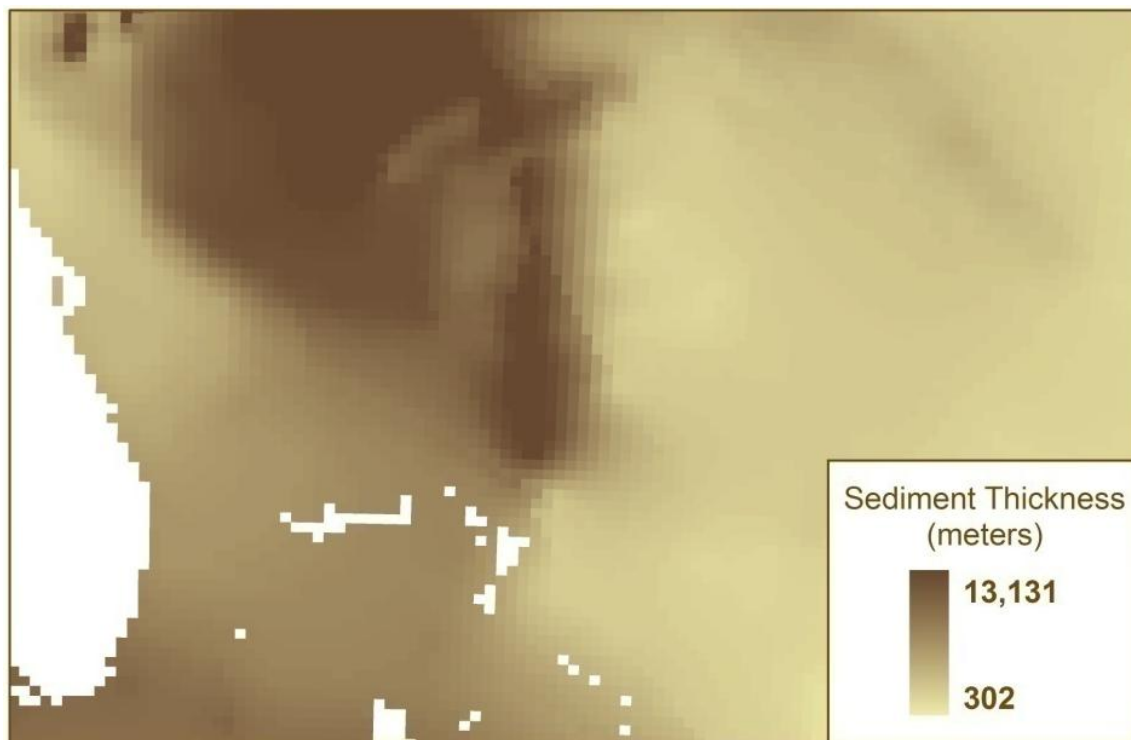
Figure 5.20: Sediment thickness raster

The Euclidean Distance tool was used to calculate values for the raster, Dist_FOCS, assigning each cell a value representing the distance from that cell to the closest point along the FOCS (see Figure 5.21).
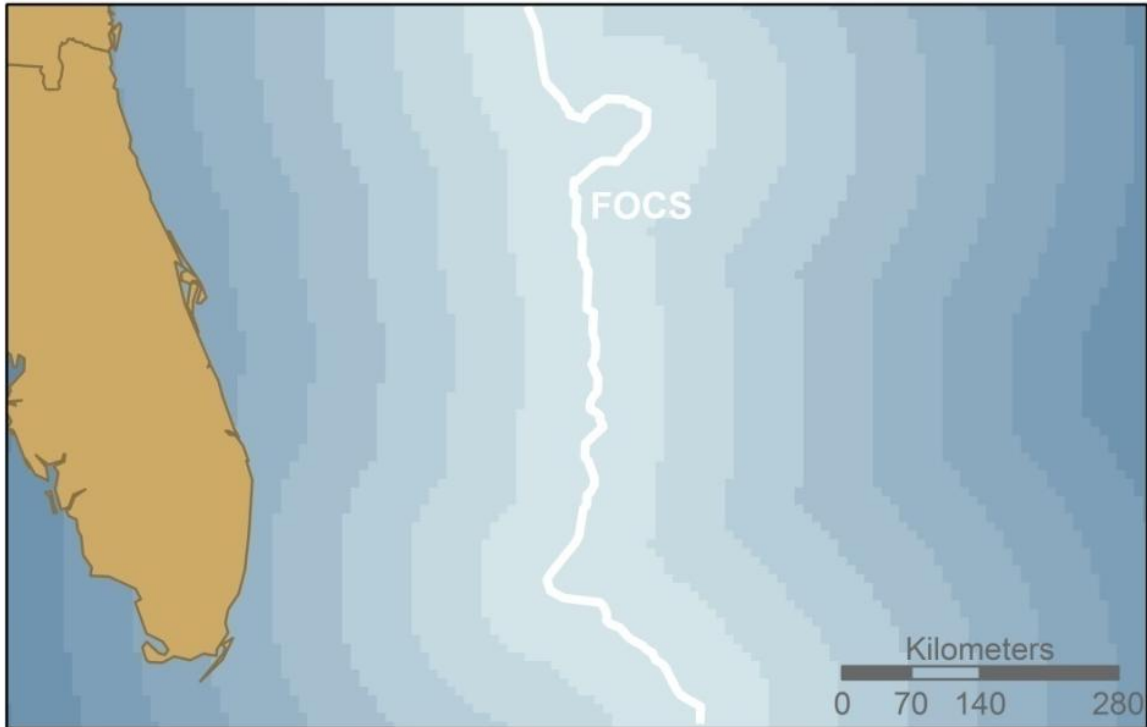
Figure 5.21: Distance to FOCS raster.

Since the final result needed to be point features and several calculations were necessary between the distance and sediment rasters, both grids were converted to points using the Raster to Point tool. This process generated a point at the center of each cell, which maintained the value for the associated cell. This process was conducted separately for each file. This conversion automatically assigns the field name of "Grid_Code" to the value field for all output files, so the distance and thickness values had the same field heading. A calculation was necessary to determine the percentage of sediment thickness to distance. As a result, these two values needed to be compiled into one table where each point had both values associated with it. Consequently, both fields cannot have the same heading. A field was added to the attribute table of the distance points file named Dist_FOCS, then calculated based on the Grid_Code field to assume its values. The Grid_Code field was then deleted so as not to be confusing once joined with the sediment points file. Additionally, all features whose distance to the FOCS were zero needed to be removed because they are both irrelevant and will not allow the calculation to run properly as there cannot be zeros in the denominator of an equation. The features in which the distance to the FOCS were greater than zero were selected and exported as a new file and prior to joining the sediment and distance points, a field, named perc_sed, was added to the sediment points attribute table. This field was generated for the purpose of storing the percentage values calculated between the sediment thickness and distance points data following the join. This step had to be done prior to the join, because ArcMap would not allow a field to be added after the tables were joined. Then the spatial join was conducted to create a single points file that joined the data from each input file based on location. The sediment points file adopted the Dist_FOCS value from the point that was closest in proximity to each of the sediment points. The empty perc_sed field

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was maintained and set to be calculated. This field was populated using the field calculator, which divided the sediment thickness value stored in the Grid_Code field by the distance value in the Dist_FOCS field to determine the percentage of sediment thickness to the distance to the FOCS as a decimal (see Figure 5.22).
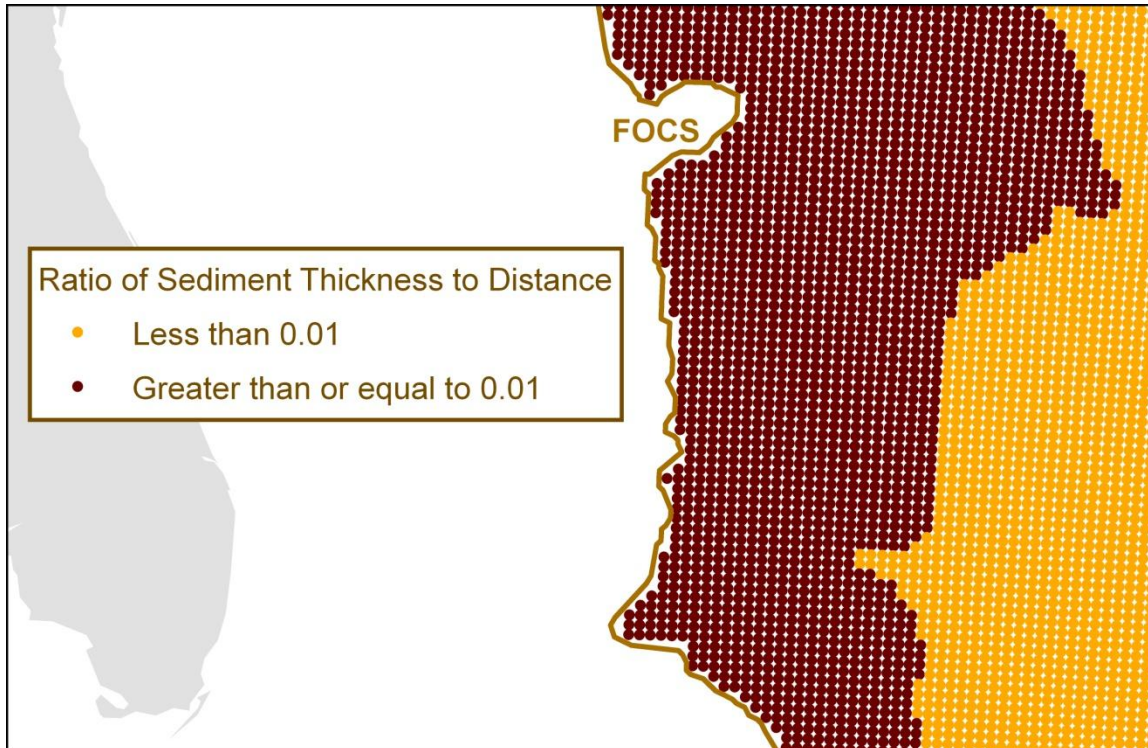
Figure 5.22: The ratio of sediment thickness to distance to the FOCS.

The desired result was to locate the points where the sediment thickness is at least one percent of the distance to the FOCS. A selection from the calculated field was used to export only those features where perc_sed was greater than or equal to 0.01, and saved as a new file. This one-percent sediment file was then utilized to determine the most seaward extent for which this formula criterion was met (see Figure 5.23).
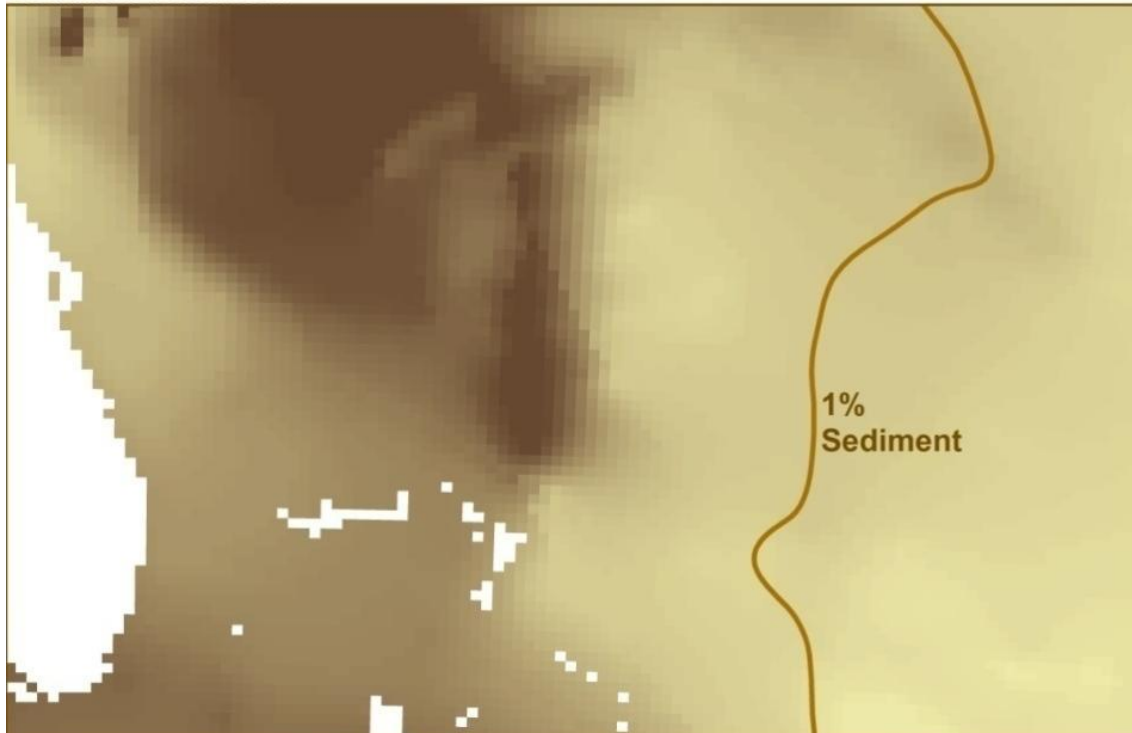
Figure 5.23: Formula line determined by the seaward extent at which the sediment thickness is at least one percent of the distance to the FOCS.

In order to delineate the actual line, the points had to be converted to raster, then to a polygon, which was dissolved to remove all the lines that had divided the original raster cells. The polygon to line process produced an outline of the area's extent. Because the polygon and ultimately the line were produced from a raster footprint the edges were initially rigid and stepped. A smoothing process was used to smooth the line. The Smooth Line tool was tested to determine the best settings to maintain the most accurate line while providing enough smoothing to provide a better output. The Polynomial Approximation with Exponential Kernel (PAEK) smoothing algorithm was used with a 60 nautical mile smoothing tolerance. The PAEK algorithm uses a "parametric continuous averaging technique" to calculate smoothed lines based on a tolerance (ESRI, 2008, How Line Smooth Works). The smoothed line was then converted back to a polygon with smoother edges.

Once the FOCS had been located and both formula lines were generated they needed to be combined into a final formula line. The most seaward segments of both formula lines were combined using the area polygons generated for each formula (see Figure 5.24) and a union was used to join the polygons. The output was then dissolved to remove the inner lines. The polygons and boundary lines were both useful, but needed to be projected to the same reference system as the constraint data for the final analysis of the OLCS. Consequently, the dissolved formula area polygon was projected to the Geographic Coordinate System WGS 1984, then converted from polygon to line.
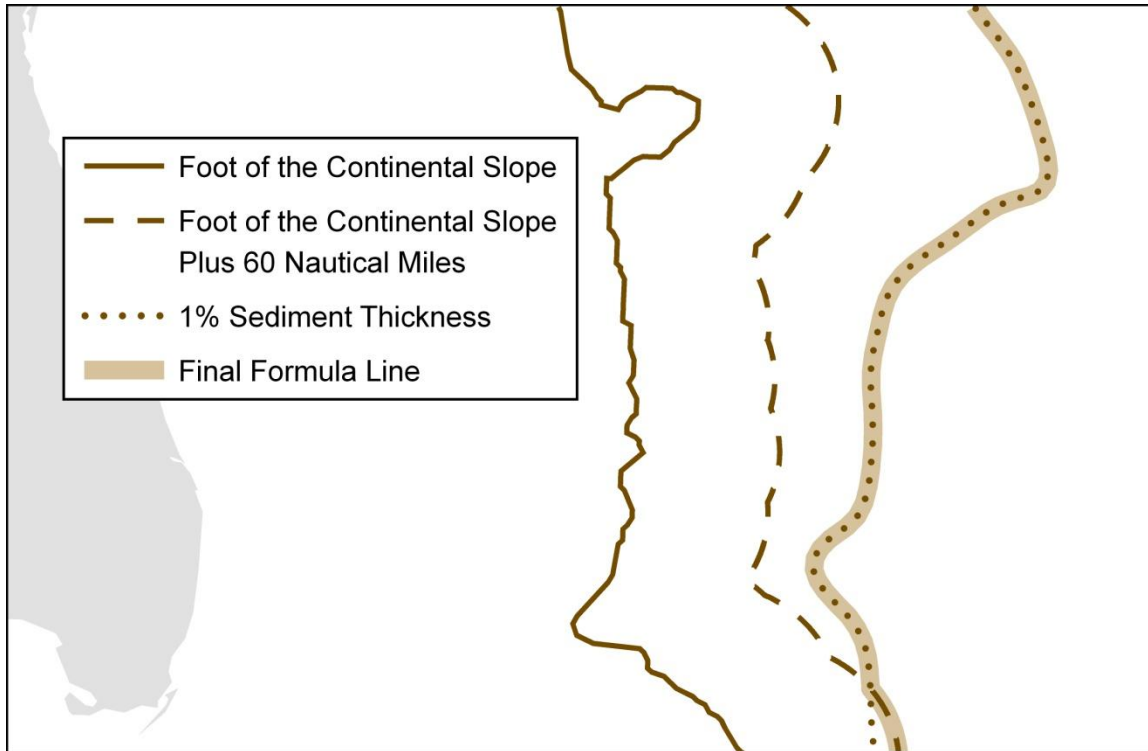
Figure 5.24: Intermediate and final formula lines.

5.3.4. Delineating the OLCS

Paragraph 7 of Article 76 states:

> the coastal [nation] shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by coordinates of latitude and longitude (DOALOS, Article 76, 2001).

The outer limits of the continental shelf can only extend as far seaward as the formula line and may only extend to that distance if it is within the constraint lines. The constraint and the formula lines needed to be combined maintaining only the most landward segments of the two lines (see Figure 5.25). For this process, the Intersect tool was utilized to overlay the polygons for the constraint and formula areas and output only the area where both overlap. The polygon to line process was then run to export the line boundary and a copy of this line was created to preserve the original data. The copy was then edited to maintain only the necessary segments that represent the actual boundary of the OLCS; those segments which ran approximately parallel to the general trend of the baseline.
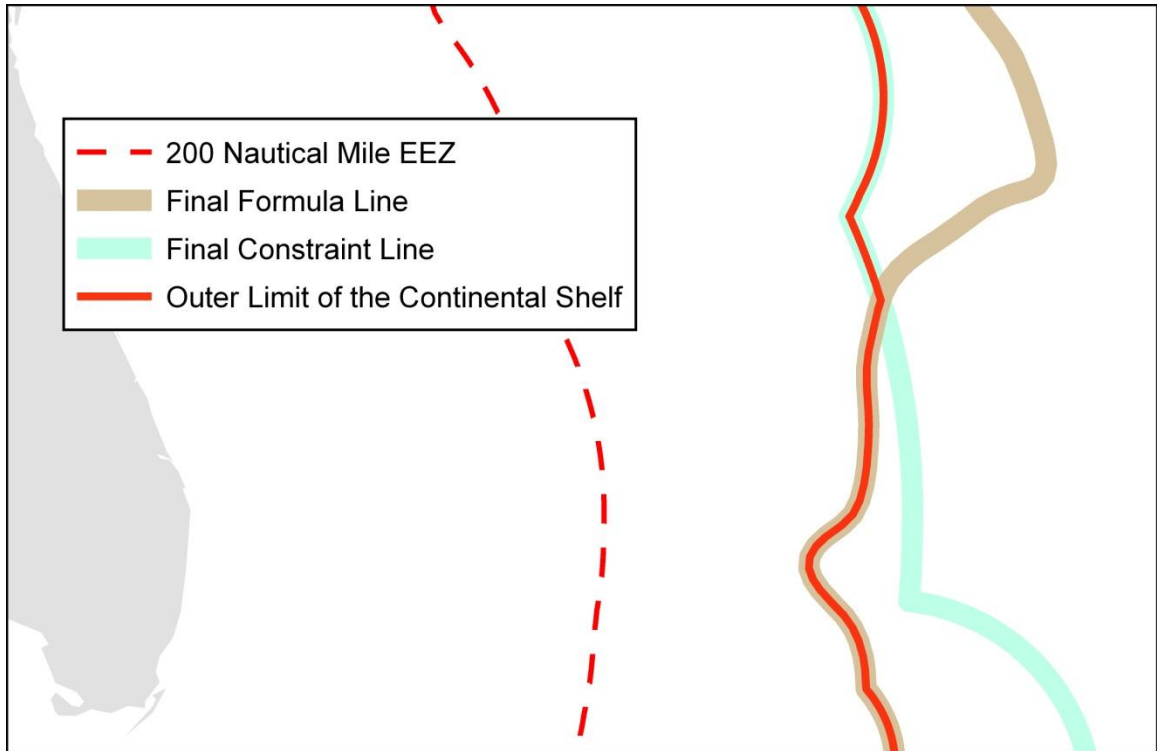
Figure 5.25: Final constraint and formula lines, shown relative to the EEZ.

The Convention requires that the boundary be defined by a series of fixed points. In order to derive the points that define the OLCS the Feature Vertices to Points tool was used to generate a new file containing the vertices from the line as points. The distances between points were measured to ensure that the distance between each point was no greater than 60 nautical miles. Two new fields, Point_X and Point_Y, were then generated in the attribute table using the Add XY Coordinates tool, which created the fields and populated them with the latitude and longitude associated with each point (see Figure 5.26).

FID	Shape *	POINT_X	POINT_Y
0	Point	-74.308801	31.58681
1	Point	-74.308976	31.586304
2	Point	-74.310115	31.583036
3	Point	-74.311262	31.579769
4	Point	-74.312415	31.576505
5	Point	-74.313575	31.573243
6	Point	-74.314742	31.569984
7	Point	-74.315915	31.566727
8	Point	-74.317095	31.563472
9	Point	-74.318282	31.56022
10	Point	-74.319476	31.556971
11	Point	-74.320677	31.553724
12	Point	-74.321884	31.550479

Figure 5.26: Attribute table of coordinates defining the OLCS.

The resulting points file provides the necessary "points, defined by coordinates of latitude and longitude," (DOALOS, 2001) as required for a submission.

This methodology was developed and finalized through a series of trial and error and testing processes. Several tools and various methods were attempted for each process and their outputs analyzed to determine the best possible way of producing the desired and necessary results.

6. Design

6.1. System Description

Components necessary for the system to run include a standalone computer workstation that meets the minimum configuration standards set by ESRI in order to support ArcGIS 9.2. An ArcInfo-level software license from ESRI for ArcGIS 9.2 is also necessary, as well as several extensions for ArcGIS. Necessary data components include a vector file of baseline points; vector line feature classes including the baseline, coastal and maritime boundaries; and bathymetric contours. Offshore geology data, including sediment thickness values, in either vector or raster format are necessary, as well as a bathymetry grid for the area of interest. The system also includes a database component utilizing ArcCatalog for storage, management, manipulation, and retrieval of the associated data inputs and outputs. ArcGIS extensions necessary for the system are Spatial Analyst and 3D Analyst (see Figure 6.1). Additionally, a script provided on the ArcScripts webpage, Convert Locations to Paths (Points to Lines) (Palmer, n.d.), proved to be essential. Model Builder was also heavily utilized for generating and editing workflow models.
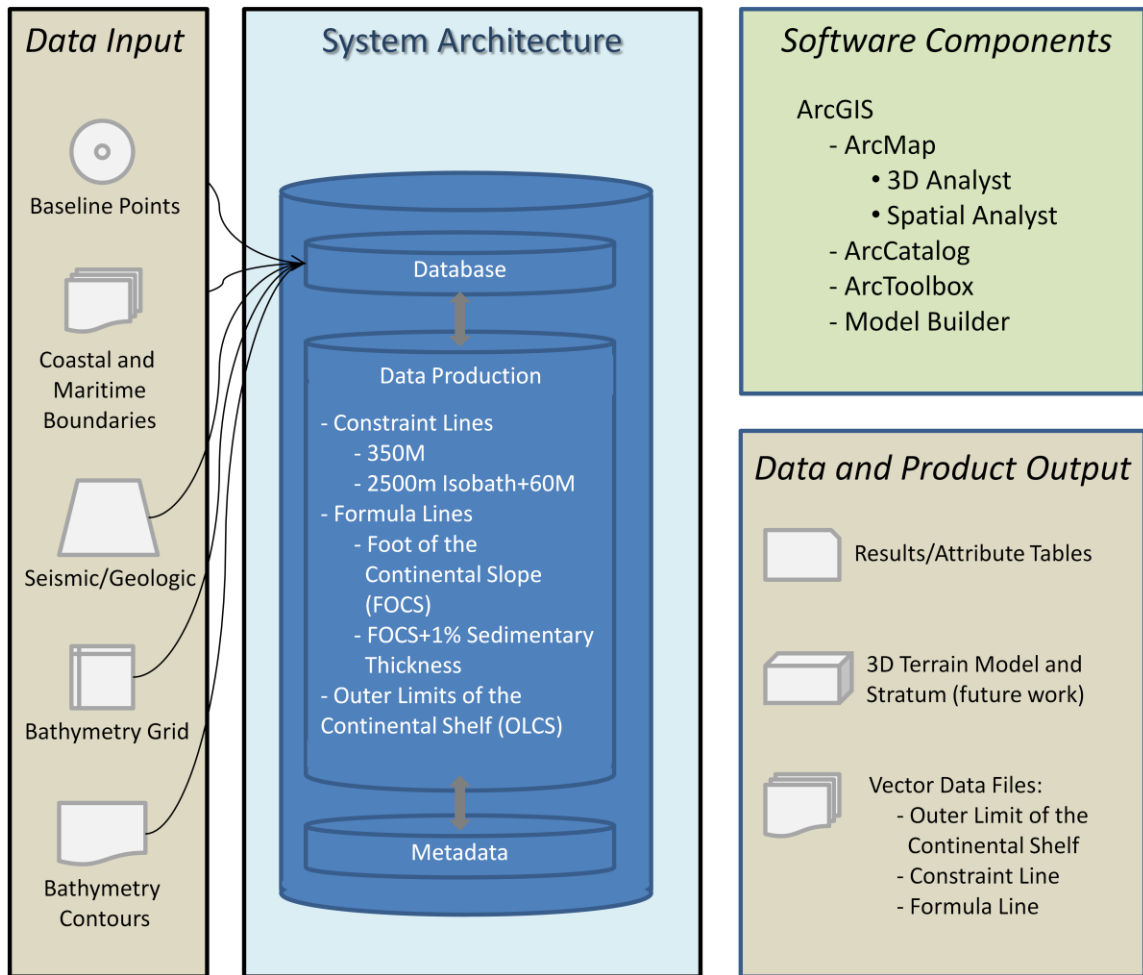
Figure 6.1: System Architecture.

6.2. Software Description

The workflow models were created within ESRI's ArcGIS environment. The analyses were conducted primarily within ArcMap and the database component was managed in ArcCatalog. The workflow model was created primarily using out-of-the-box software components, though there are several tools and extensions that still need to be customized specifically for the Law of the Sea application. A workflow model has been created using Model Builder, utilizing standard ArcGIS tools and functionality from ArcToolbox, as well as elements from ArcGIS extensions. Components of the workflow model include the tools listed in Table 6.1.

Table 6.1: LOS - Article 76 Tools

Add Field	Euclidean Distance
Add XY Coordinates	Extract by Attributes
Buffer	Feature Vertices to Points
Calculate Field	Hillshade
Clip	Point to Raster
Con	Polygon to Line
Contour	Raster to Polygon
Convert Locations to Paths (Points to Line)	Select
Delete Field	Spatial Join
Dissolve	Union

Additional functionality will need to be added through the creation of customized tools and the potential development of additional extensions or software applications developed by ESRI. These new developments must perform the following processes (see Recommendations, section 7.3, for details):

- Generate accurate envelope of arcs, using spherical distance calculations to create arcs at a specified distance, in a specified direction from points.
- Generate traces parallels.

- Combine the series of arcs and traces parallels to form a solid line while clipping all other line segments that:
  - fall within the envelope
  - are internal to all intersections
  - fall landward of the final boundary line.
- Automate the selection and combination of either the seaward or landward (as determined by the specified process) line segments to form a single solid line.
- Create and display 3-dimensional profiles.

6.3. Database Design

ArcCatalog was utilized to organize a database to store and retrieve both the foundation data and the many files created throughout the analyses processes. A new folder, UNCLOS, was created to store the foundation data; the data necessary to begin the analyses as listed in the requirements (section 4.1). Within the UNCLOS folder was an additional folder where the results from the analyses were stored. While conducting analysis or working with the data in ArcMap, the environment settings must be set for both the working directory, mapped to UNCLOS, and the scratch directory, mapped to the results folder within UNCLOS.

6.4. User Interface Design

The user may interact with the data, tools, and models, either through ArcCatalog or ArcMap. Data will be stored, managed, and retrieved by means of a database. Data inputs consist of digital vector feature classes, raster grid files, and tables (e.g. DBF). Data will be loaded into the database by the user in a manner specified by the user, including:

- Keyboard (e.g. typed in values)
- Pointer/mouse (e.g. copy/paste, drag and drop within ArcCatalog)
- Scanning analog data sources (e.g. maps, nautical charts)
- Digitize scanned analog or digital data sources (e.g. Electronic Nautical Charts (ENC))

It is the user's responsibility to make sure that the data imported to or created in the database have a common spatial reference system. The user shall also set the environment settings in ArcGIS to recognize the appropriate reference system and workspace locations. Data will then be input into the system through utilization of the workflow model data parameters. When a model is run, it will automate the necessary data creation, naming mechanisms, output, and storage of raster or vector feature classes into the specified output location within the database. Most output data created during this process is used later in the model as inputs for additional analyses. To ensure that the model runs accurately and without problems, it is critical that the output locations and naming conventions specified in the models are not altered.

Following the creation of the database, the user will interact with the system primarily in ArcMap through implementation of the Article 76 workflow models and utilization of the tools in the LOS - Article 76 toolbox, as instructed in the User Guide (see Appendix D). Each model is an automated process conducting a series of functions that may output several interim data files, and requires only minimal input of the necessary parameters by the user. For example, the user should indicate the correct database location using either a pointer/mouse to navigate and select, or by typing in the destination and using a keyboard for navigation and the prompting of processes. Additional user input can be significant at times, requiring editing skills and the use of individual tools and visual analyses as instructed in the User Guide.

The final output of the system – the concluding result from implementing the Article 76 workflow models – includes both a digital vector line and a points feature class representing the Outer Limits of the Continental Shelf (OLCS), along with the associated tables, which are stored in the database. The OLCS feature classes, both the geography of the features and the tabular data (attribute tables), can be visualized in ArcCatalog (see Figure 6.2) or ArcMap (see Figure 6.3).
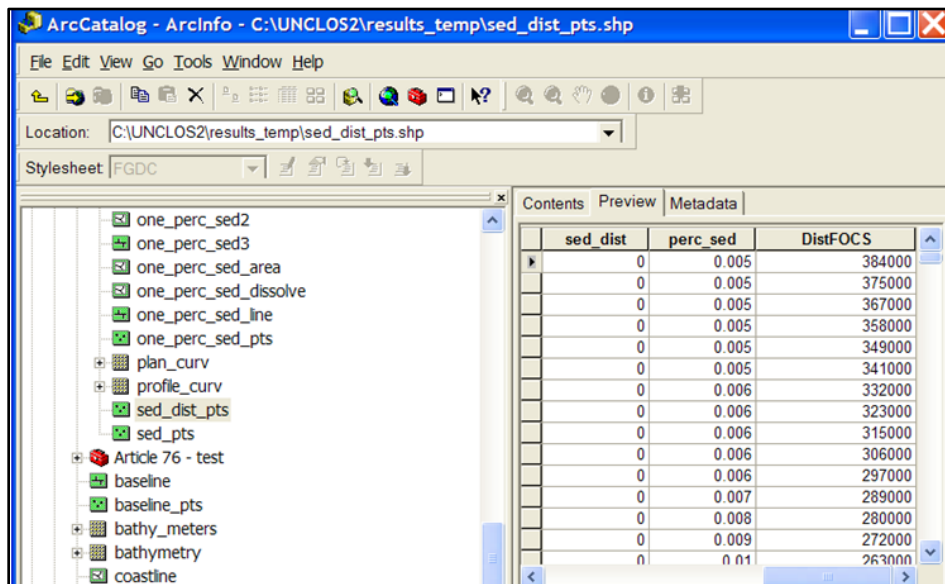
Figure 6.2: ArcCatalog Interface.
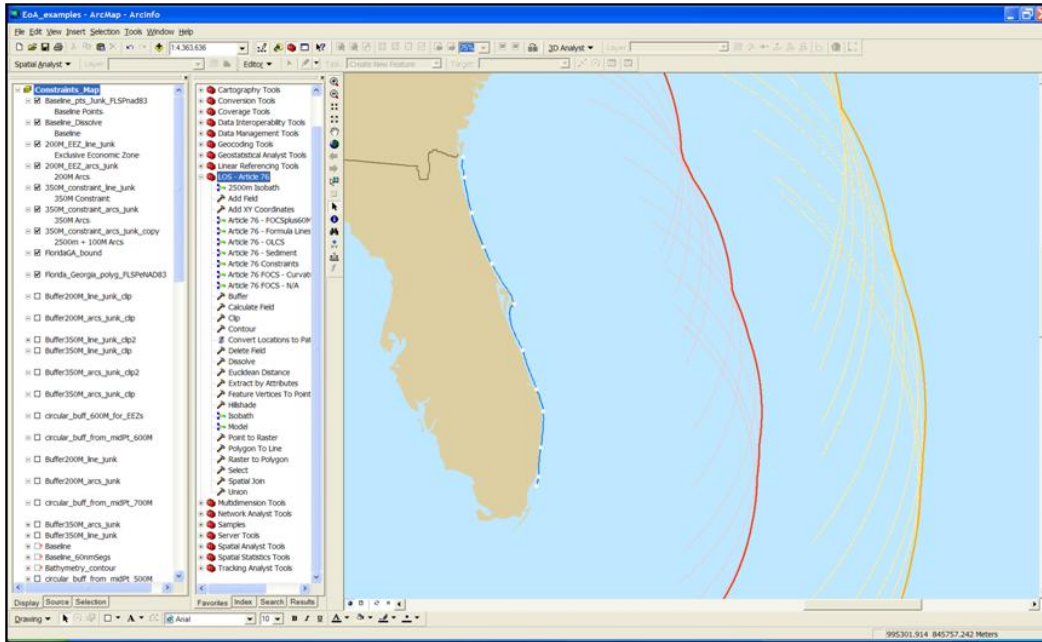
Figure 6.3: ArcMap Interface.

The results of the analyses can also be exported to other table or database formats (e.g. Excel or Access), and static images of the geometry can be exported to various image formats (e.g. jpg). Additional evaluation and testing of the outputs, which is outside of the parameters of this system, must be completed by the user prior to submitting a claim to the United Nations.

7. Discussion

7.1. Results

The case study provided the necessary feasibility analysis to adequately assess the strengths and weaknesses of ArcGIS software in conducting the Article 76 analyses from an analyst and general user's perspective. The analysis was possible, though with some inefficient yet necessary work arounds at some points in the process. The final result of the analyses produced a delineation of the OLCS as a series of fixed points with recorded geographic coordinates as necessary. Thus, this project demonstrates that coastal nations can successfully use GIS to determine whether they are eligible to submit claims for extended continental shelf. The ultimate question determining this conclusion is: does the OLCS extend seaward from the EEZ? At the conclusion of this case study the answer was yes (see Figure 7.1).
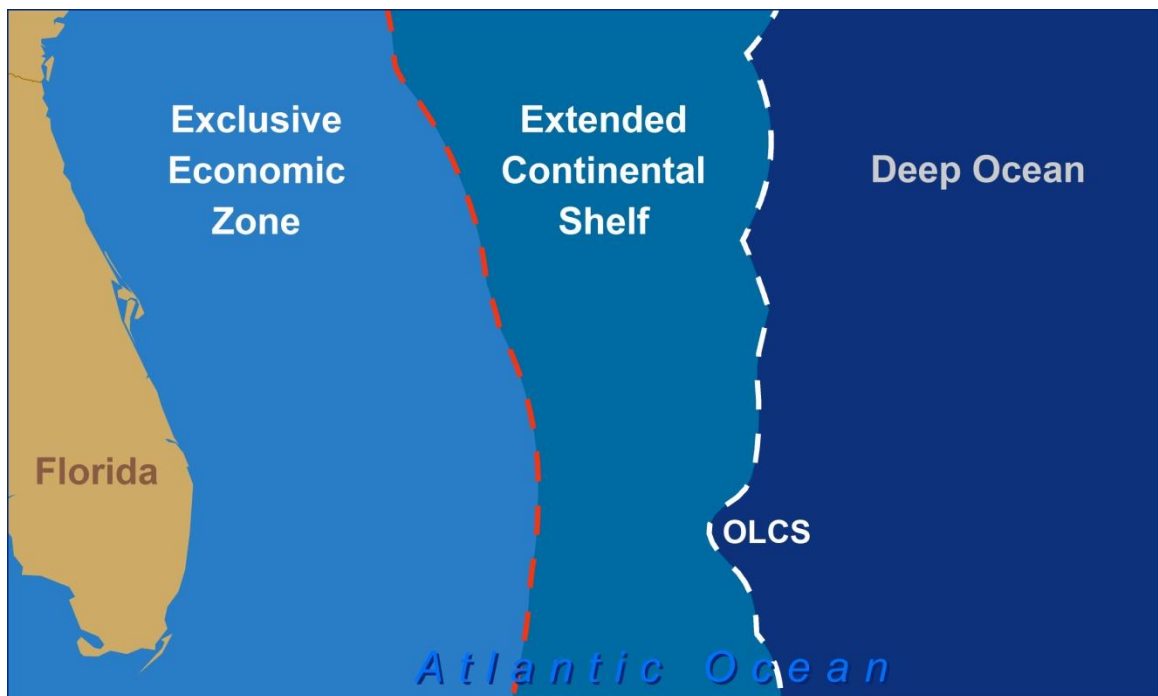
Figure 7.1: Location of OLCS in relation to the EEZ.

Following the case study the analyses methods were finalized and models were generated for the sequences of processes that could be automated, though user input is necessary at several critical points; sometimes significant edits, analysis, and decisions are required to be made manually by a knowledgeable analyst. The tools utilized throughout this process, and a series of six models, have been compiled and saved in an ArcGIS toolbox named LOS - Article 76. A mock submission was then conducted to test the models, tools, and analytic methods determined throughout the case study. A user guide was also developed to offer instructions for how one would follow this process, utilizing the tools and models provided, as well as guidance on the additional steps requiring significant analyst input (see Appendix D).

7.2. Conclusion

The initial goal of this project was to develop an automated application that would generate the outer limits of the continental shelf based on minimum data input requirements. Throughout the requirements analyses and research processes two important things were discovered. First, it would not be possible to develop a completely automated application. Computers do not have the analytic ability to make certain decisions and data editing tasks throughout the process that require, in some cases significant, analyst input. Second, even if the process could be completely automated, most scientists and analysts, those whom the potential application and this proof of concept were developed, would not like it to be overly automated as they would have difficulty establishing trust in the system (UKHO, n.d.). The results of this process are very important to any nation determining them, as well as internationally. It is imperative that the analyst be very meticulous and detailed in their analysis, data collection, and understanding of both the processes and results. It is easier for an analyst to trust the quality, accuracy, and integrity of the data and results if they have firsthand knowledge of the processes through which the data are being generated and manipulated. The analyst needs to not only understand, but trust the algorithms being processed and calculations being made. It is also necessary for the analyst to manage the settings and projections, as well as understand the data conversions and transformations taking place so they can all be explained and accounted for in the necessary documentation in support of their final claim.

A goal in the development of this proof of concept has been to maintain the proper balance, which is not necessarily easy to pin-point, between ease of use and a more complex yet trusted interface. The scientific community may prefer a more detailed layout of the processes to aid in their development of trust in both the calculations and solutions derived from the system. However, less experienced GIS users may be more comfortable with a simpler interface, requiring minimal interaction with the GIS directly and more-automated processes producing easily-understood graphic results. These preferences and needs were taken into consideration during the engineering of the series of models and the specialized LOS - Article 76 toolbox created for ArcGIS. Though the Article 76 proof of concept process for ArcGIS does require user input in several locations, this provides the user with opportunities to become familiar with and gain confidence in the processes as they work with the system, providing critical input and analytic decisions as necessary. Furthermore, the models are constructed in a way that can hide the complex functions that will run in the background from a potentially overwhelmed analyst, requiring only the input parameters be specified. On the other hand, the model processes, calculations, algorithms, and additional parameters can easily be studied and edited by a more confident GIS user with the simple click of a button. Either way, the user input requires more specialized knowledge of the regulations of the Convention and the Guidelines than GIS-specific experience. The user guide provides ample explanation of the user-directed GIS tasks necessary for a novice user to be able to master them.

During the preliminary requirements analysis it also became evident that ESRI's software may not be fully capable of conducting all the required processes and functions in order

to establish admissible claims. Therefore, it became necessary to either program and develop customized tools or extensions, or accept that it would not be possible to develop a complete workflow model strictly utilizing ArcGIS's current functionality. Given the time limitations imposed on this project, the goal shifted slightly, taking these challenges into account and was geared more towards the development of a proof of concept than the originally anticipated application. This revision required additional documentation reporting on the extent to which ArcGIS is currently capable of performing the necessary analyses without further customization.

The final result of this study was a semi-automated proof of concept, consisting of several workflow models and an Article 76 toolbox. The toolbox contains the tools an analyst would need in order to follow the same process that proved successful in the case study and mock submission. The case study was successful in that the processes were completed to the best of the abilities of the ArcGIS software at the time of this study. Additionally, the case study revealed several necessary upgrades that will need to be addressed prior to obtaining the ability to completely analyze and support the delineation of the OLCS for an admissible claim for extended continental shelf. This proof of concept was developed with the expectations that once fully implemented, it will help fulfill user requests regarding continental shelf claims and analyses, possibly increase the customer market for ESRI, and generate potential opportunities for ESRI to offer additional services.

7.3.   Recommendations

Recommendations on areas needing improvement or requiring development of the ArcGIS software focus on three functional areas: (1) the ability to appropriately develop the envelope of arcs and traces parallels, (2) potentially automate the line generation based on these outputs, and (3) improve the capabilities of working with 3-dimensional data. ESRI currently has in development an Arcs of Circles tool designed to produce the envelope of arcs using the correct geodesic measurements. The Arcs of Circles tool also provides the option for producing the traces parallels. Because the tool currently can only be utilized with polygons as input; it cannot process the calculations properly for a series of points as mandated by the Convention. This oversight was discovered during testing of the tool in the early stages of the case study analyses. ESRI is working to finalize the development of this tool in order to work with points and be utilized for the envelope of arcs processes necessary for accurately delineating the OLCS. Once this tool is developed and successfully tested with accurate results, it should be incorporated into the LOS - Article 76 models. The buffer tool was used as a less accurate substitute for the Arcs of Circles tool throughout the case study. Therefore, wherever the buffer tool was used in the models should be replaced by the Arcs of Circles. Once the substitution is made, additional testing will be required to ensure that it does not interrupt the flow of the models and to determine if additional accommodations will need to be made as a result of the update.

The second suggested improvement would be the development of an automated line generation process for combining two or more overlapping lines (sometimes crossing multiple times) based on a specified rule. Ideally the analyst would specify whether it

was necessary to use the closest or furthest segments relative to the baseline, which would then be selected and fused at the points of intersection to create a single line that met the specified rule. Such a function would be very useful in combining the preliminary constraints into one constraint line, combining the formula lines into one formula line, as well as combining the constraint and formula lines in a more efficient and streamlined process.

The one area where ArcGIS is least equipped to provide a complete Law of the Sea solution is in the realm of 3-dimensional data display and analysis. Competing applications, including CARIS LOTS, provide the ability to do advanced analyses and displaying of 3-dimensional data, which are extremely beneficial for both bathymetric and geological (sediment thickness) analyses. The best form of analysis available for the proof of concept uses raster images of 3-dimensional data, yet relies on external calculations utilizing the cell values and converting the grid to vector point features. Cell size and accuracy of the original grid partially determines how accurate the final results are, though it is unclear how much accuracy and precision may be lost in the data conversion processes. Additionally, 2-dimensional profile graphs were relied upon as supporting evidence for the location of the foot of the continental slope, instead of the more highly regarded 3-dimensional profiles. More advanced developments for 3-dimensional data in ArcGIS would significantly improve the abilities of the Article 76 analyses processes and results, as well as the level of confidence in the application among the user community.

These significant developments will be necessary in order to finalize the processes into a complete and more efficient workflow that produces accurate results and supporting data.

7.4. Future Work

Though this project focused solely on the requirements of Article 76, the Law of the Sea covers several related issues, establishing additional regulations requiring complex analyses. Significant future work could be done to help support Article 76 and provide a complete Law of the Sea solution. For an analyst utilizing the Article 76 Workflow for ArcGIS, the creation of a semi-automated process for delineating baselines and baseline points would provide valuable assistance. The baseline is the foundation for much of Article 76, and the Law of the Sea in general, analyses and calculations. Therefore, despite how "rigorous the GIS application and however much you trust its processes, the quality of a solution will only ever be as good the data put in" (UKHO, n.d.). Apparently there are applications available that claim to provide "a quick solution to the task of building the baseline model" (UKHO, n.d.). However, UKHO warns that "they are totally inadequate a basis for calculating accurate limits" (UKHO, n.d.). Therefore, a trusted system to help nations develop accurate and supportable baseline models is much needed and would significantly help in providing the foundation data necessary for Article 76 analyses and solutions.

Additional research that would provide added benefit to the Article 76 analysis results would be a process for locating the boundary limitations between nations with adjacent

coasts to establish the reach of the OLCS. The limit as established in Article 76 determines the distance of the OLCS from the baseline, and ultimately the coastline, at any given point along the coast. However, the point at which that segment of the boundary ends and turns toward the coast requires additional data and analyses. An additional challenge is added when there are potential conflicts between nations whose coastlines face each other on opposite sides of a water body. This analysis would potentially require further review of treaties and international regulations, though a process that would determine the bounding lines that run perpendicular to the baseline and join at the ends of the OLCS would provide added value for the Article 76 application. It could also potentially streamline the process of delineating the OLCS if merged into a single workflow; allowing for a better estimate of the study area, creation of more accurate polygons, and clipping of lines to their actual extent.

UNCLOS provides guidance and regulations, including very specific formulae, for several maritime delineations other than those required in Article 76. Such delineations include normal, straight, and archipelagic baselines, territorial sea, contiguous zones, and "the legal status of waters forming straits used for international navigation" (DOALOS, 2001), to list just a few. Thus, a complete Law of the Sea application could benefit from the future analyses of these additional requirements. Many of the tools necessary to conduct such analyses are likely included in the Article 76 toolbox, or at least available in the compilation of ArcGIS toolboxes. However, the construction of specialized processes and application specific tool sets for the numerous additional articles of the Convention could help produce a comprehensive Law of the Sea solution.

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Appendix A – United Nations Convention on the Law of the Sea, Part VI, Article 76, Definition of the continental shelf

PART VI

CONTINENTAL SHELF

Article76

Definition of the continental shelf

1. The continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance.

2. The continental shelf of a coastal State shall not extend beyond the limits provided for in paragraphs 4 to 6.

3. The continental margin comprises the submerged prolongation of the land mass of the coastal State, and consists of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof.

4. (a) For the purposes of this Convention, the coastal State shall establish the outer edge of the continental margin wherever the margin extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by either:

> (i) a line delineated in accordance with paragraph 7 by reference to the outermost fixed points at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope; or

> (ii) a line delineated in accordance with paragraph 7 by reference to fixed points not more than 60 nautical miles from the foot of the continental slope.

(b) In the absence of evidence to the contrary, the foot of the continental slope shall be determined as the point of maximum change in the gradient at its base.
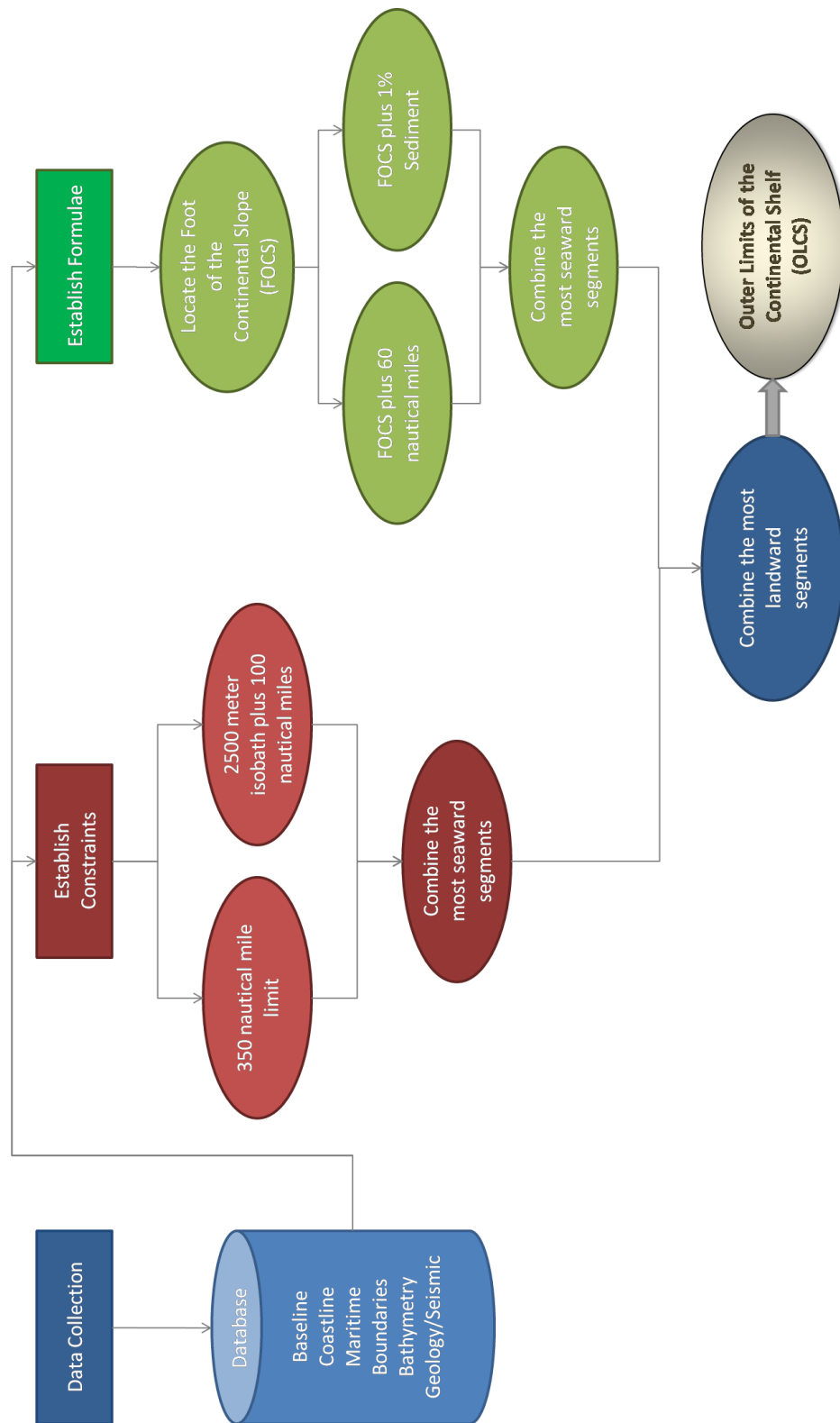
5. The fixed points comprising the line of the outer limits of the continental shelf on the seabed, drawn in accordance with paragraph 4 (a)(i) and (ii), either shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured or shall not exceed 100 nautical miles from the 2,500 metre isobath, which is a line connecting the depth of 2,500 metres.

6. Notwithstanding the provisions of paragraph 5, on submarine ridges, the outer limit of the continental shelf shall not exceed 350 nautical miles from the baselines from which the breadth of the territorial sea is measured. This paragraph does not apply to submarine elevations that are natural components of the continental margin, such as its plateaux, rises, caps, banks and spurs.

7. The coastal State shall delineate the outer limits of its continental shelf, where that shelf extends beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured, by straight lines not exceeding 60 nautical miles in length, connecting fixed points, defined by coordinates of latitude and longitude.

8. Information on the limits of the continental shelf beyond 200 nautical miles from the baselines from which the breadth of the territorial sea is measured shall be submitted by the coastal State to the Commission on the Limits of the Continental Shelf set up under Annex II on the basis of equitable geographical representation. The Commission shall make recommendations to coastal States on matters related to the establishment of the outer limits of their continental shelf. The limits of the shelf established by a coastal State on the basis of these recommendations shall be final and binding.

9. The coastal State shall deposit with the Secretary-General of the United Nations charts and relevant information, including geodetic data, permanently describing the outer limits of its continental shelf. The Secretary-General shall give due publicity thereto.

10. The provisions of this article are without prejudice to the question of delimitation of the continental shelf between States with opposite or adjacent coasts.

Appendix B – Use Case

Use Case Name	Article 76 Workflow
Description	Outline the process necessary for coastal nations to delineate the extended continental shelf boundary for their nation
Actors	Analysts (from national governments and the United Nations Committee on the Limits of the Continental Shelf)
Triggers	Article 76 of the United Nations Convention on the Law of the Sea
Major Inputs	1) Bathymetry contours (vector) 2) Bathymetry grid (raster) 3) Baselines (vector) 4) Seabed geology (sedimentary thickness, raster or vector) 5) Exclusive Economic Zone (EEZ, vector) 6) Recognized international and maritime boundaries (vector)

Major Outputs	1) Vector and raster files
	    a. Final constraint line
	    b. formula line results
	    c. Final boundary for the extended continental shelf; outer limits of the continental shelf (OLCS)
	2) Results tables (Excel spreadsheet or database format)

Process Steps	1) Set environment settings for the geographic extent and workspace (location of database stored on the computer/network/server).
	2) Insert specified data into Article 76 workflow model (from database/specified workspace).
	3) Run workflow models
	    a. Use Envelope of Arcs process to calculate a line feature 350 nautical miles from the baseline (350M limit).
	    b. Locate the 2500 meter isobath from the bathymetry data.
	    c. Use Envelope of Arcs process and the bathymetry contour data to calculate a line feature 100 nautical miles from the 2500 meter isobath (2500 meter isobaths plus 100 nautical mile constraint).
	    d. Combine the two constraint lines, maintaining only the most seaward segments from the baseline forming a single continuous constraint line.

	e. Determine the Foot of the Continental Slope (output), as the maximum change in gradient using the bathymetry grid as the analysis (input) layer. f. Use the Envelope of Arcs process and the Foot of the Continental Slope (input) to calculate a line feature 60 nautical miles seaward (away from the baseline) from the Foot of the Continental Slope (output FOCS plus 60 nautical miles formula line). g. Using Euclidean distance meaurments calculate the distance to the FOCS for each cell in the bathymetry grid for the extent of the area of interest (output Dist_ FOCS raster). h. Calculate the distance-to-thickness ratio to determine the percentage of the thickness of the sediment compared to the distance to the Foot of the Continental Slope for each cell (percent sediment). i. Select the cells with values equal to one percent or greater. j. Use the selected cells to determine the extent of the area where sediment thickness equals at least one percent of the distance to the FOCS. k. Compare the FOCS plus 60 nautical miles and one percent sediment boundaries. If they intersect, then output a line feature that consists of the most seaward continuous line segments, if they do not cross, then the outermost line will be the only output (formula line). 4) Generate boundary file for the extended continental shelf a. Combine the most landward segments of the final constraint and formula lines to delineate the OLCS.
Preconditions	1) Necessary data is available and has been collected. 2) The reference system for each shapefile and/or feature class has been correctly defined and projected if necessary. 3) The data is of sufficient quality and meets the accuracy standards of Article 76.
Post-Conditions	Extended continental shelf boundary feature class has been created in the database and the user has the information required to determine the eligibility of the study nation to submit a claim to the CLCS for extended continental shelf.
Assumptions	1) Baselines have already been generated and undergone QAQC. 2) The data utilized meets the quality and accuracy standards of UNCLOS and the CLCS.

Appendix C – Article 76 Workflow

Appendix D – ArcGIS Article 76 Workflow User Guide

Instructions for delineating the OLCS in ArcGIS

Data:
Create a geodatabase to store the foundation data, including;

- baseline
- coastline
- bathymetry contours/isobaths (if already created) (named: bathy_contours)
- bathymetry grid (named bathymetry)
- sediment thickness raster (or a points matrix) (named sediment)

* If bathymetry contours are not available, use the Isobath model or run the contours tool using the bathymetry grid as the input, to generate contours at 500 meter intervals. Keep in mind the potential difference in projections between the grid, and therefore of the output, and the projection that the contours need to be in (same as the vector data).

* For the purpose of utilizing the models most efficiently, it is suggested to create a reasonably sized rectangular feature class called extent encompassing the potential study area. Include the entire shoreline yet limit the area to the extent that could potentially be included in the ECS.

Data preparation:
Data should be clipped to a reasonable extent encompassing the study area.
Data should have a spatial reference correctly defined and projected if necessary. Equidistant projections are suggested for the vector foundation data, with the direction of accurate distance preservation perpendicular to the general trend of the baseline, for accurate distance calculations. However, the bathymetry and sediment thickness grids are an exception. In order to run the curvature analysis in locating the foot of the continental slope, both the horizontal and vertical units must be the same. Bathymetry is typically measured in meters; therefore, the bathymetry grid needs to be in a projection that utilizes meters as the linear unit. Additionally, since the sediment thickness data analysis is based on the bathymetry and results of the bathymetric analysis, the sediment data should have the same spatial reference as the bathymetry grid. All final outputs can be reprojected to a standard reference system.

* Suggestion: when projecting the raster data, use a name that conveys the projection or linear units (e.g. bathy_meters and sed_meters)

Delineating the Constraint boundaries:
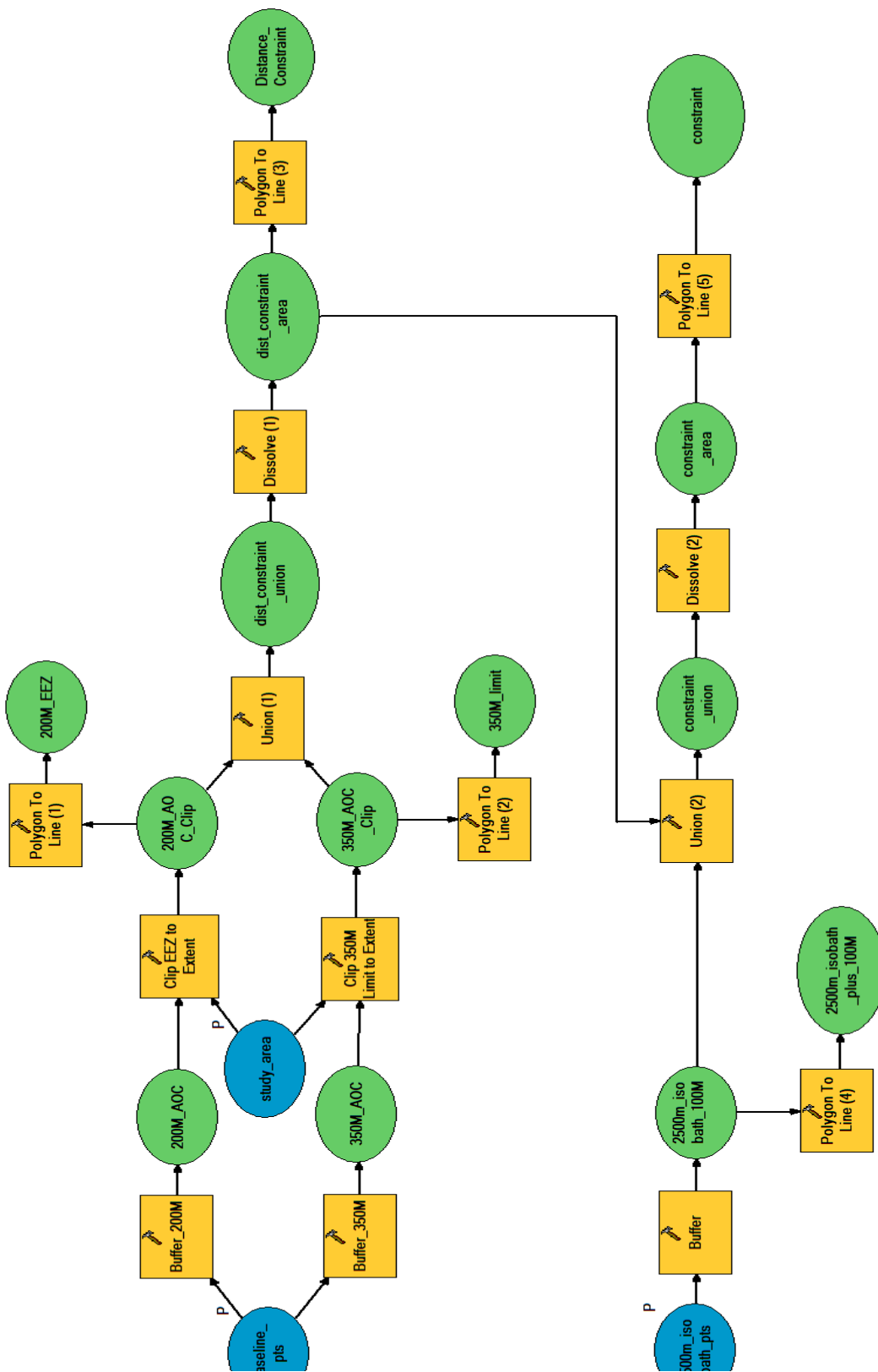
➢ Open a new ArcMap document.

- Open ArcToolbox and add the Article 76 toolbox. This toolbox contains the models to follow for the general analysis processes as well as the tools necessary to run the models and additional essential tasks.

- Set the Environment Settings. Under General Settings specify the current workspace (location where the foundation data is stored) and the scratch workspace as the location designated for output files during analysis.

- Add data: baseline, coastline, and any additional background or reference data that may be useful.

- Open the Feature Vertices to Points tool.

  - Fill in the tool's dialog box using the baseline as the input feature and call the output baseline_vertices (it should save to your designated scratch workspace).
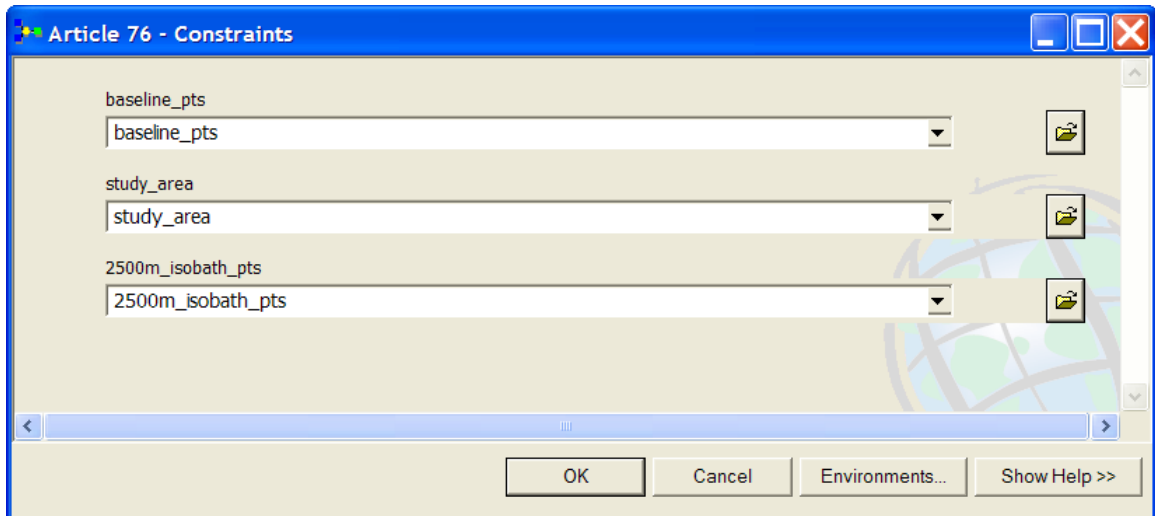 - Make sure to specify Point Type as ALL.
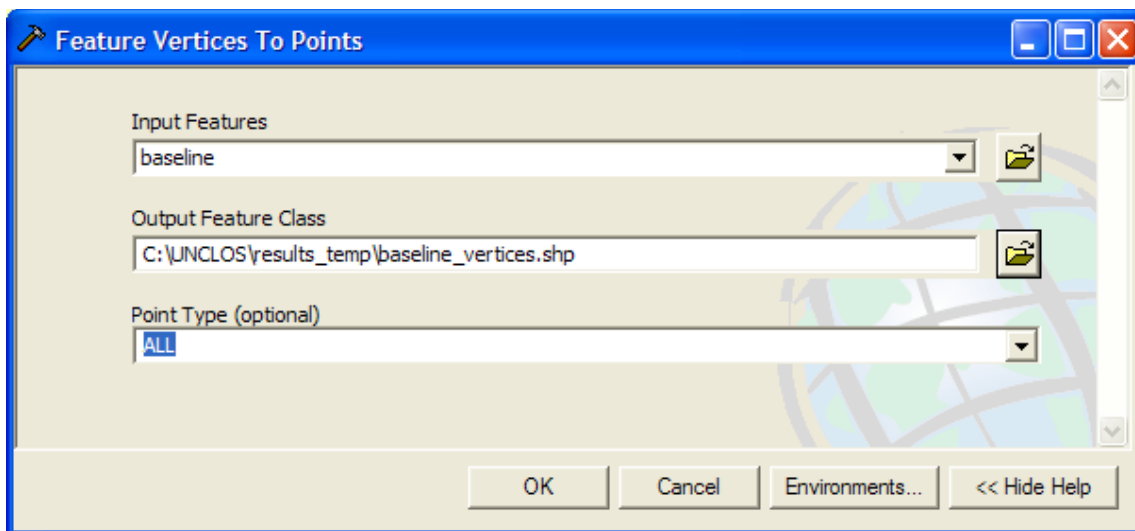
- Save a copy of the output, baseline_vertices, as baseline_pts to your scratch workspace.

- Add baseline_pts to the map display.

- Start an editing session. From the Editor toolbar dropdown select Start Editing and specify baseline_pts as the target layer.

        *** This section requires significant analyst input!

- Determine which points are most advantageous, those points furthest from the baseline, to use for generating the envelope of arcs. Delete all unnecessary points, maintaining only those that were selected as the most advantageous, while ensuring there are no gaps between points 60 nautical miles or greater.

  o Save edits and stop editing.

➢ Add data: bathy_contours

➢ Select and export the 2500m isobath as a new file called 2500m_isobath.

  o Either use Select by Attributes and then export the 2500m Isobath as a new shapefile/feature class, or run the 2500m Isobath model with bathy_contours as the input data.

➢ Open the Feature Vertices to Points tool.

  o Fill in the tool's dialog box using 2500m_isobath as the input feature and call the output 2500m_isobath_vertices (it should save to your designated scratch workspace).
  o Make sure to specify Point Type as ALL.

➢ Save a copy of the output, 2500m_isobath_vertices, as 2500m_isobath_pts to your scratch workspace.

➢ Add 2500m_isobath_pts to the map display.

➢ Start an editing session. From the Editor toolbar dropdown select Start Editing and specify 2500m_isobath_pts as the target layer.

  *** This section requires significant analyst input!

  o Determine which points are most advantageous, those points furthest from the baseline, to use for generating the envelope of arcs. Delete all unnecessary points, maintaining only those that were selected as the most advantageous, while ensuring there are no gaps between points 60 nautical miles or greater.

  o Save edits and stop editing.

➢ Open the Article 76 Constraints model

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The window title bar reads: **Article 76 - Constraints**

- baseline_pts
  - baseline_pts
- study_area
  - study_area
- 2500m_isobath_pts
  - 2500m_isobath_pts

OK Cancel Environments... Show Help >>

- o The tool parameters should be set correctly. However, the model can be edited if necessary, so make sure the data paths are correct.
- o Run the model.
- o The final Constraint line should be added to the map display.

Delineating the Foot of the Continental Slope (FOCS):

➢ Insert a new data frame or open a new map document. This is necessary if the projection of the bathymetry and sediment data differ from the projection assigned to the vector data in the previous analysis.

* If bathymetry isn't already in an adequate projection, one that utilizes meters (or the same units as the depth values) as the linear (or horizontal) units, use the project raster tool to select an appropriate projection and save as a new raster.

* The baseline, and potentially coastline, data are helpful for providing perspective during analysis of the FOCS. Therefore, it would be useful to project the baseline, and additional features that may be helpful, to the same projection as the raster data and save as new files to utilize during the following analysis. However, ArcGIS will project them on the fly if not correctly projected.

➢ Add data: bathy_meters, baseline, and coastline

➢ Open the Article 76 FOCS – Curvature model
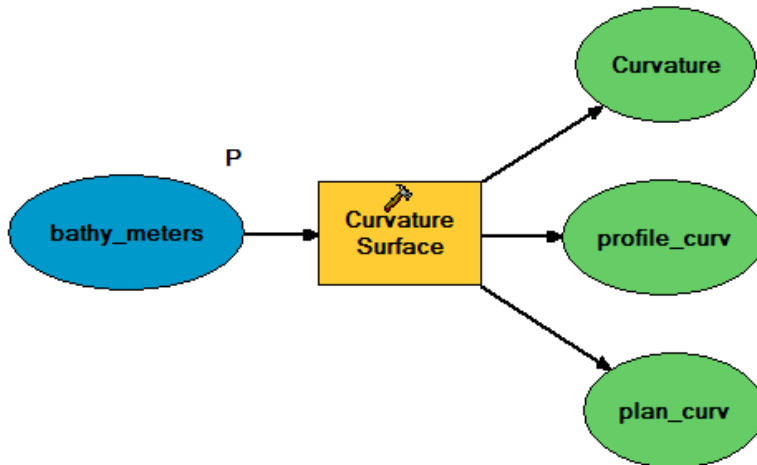
o   The only parameter is the bathymetry grid, which should be clipped to the study area and correctly projected (named bathy_meters).
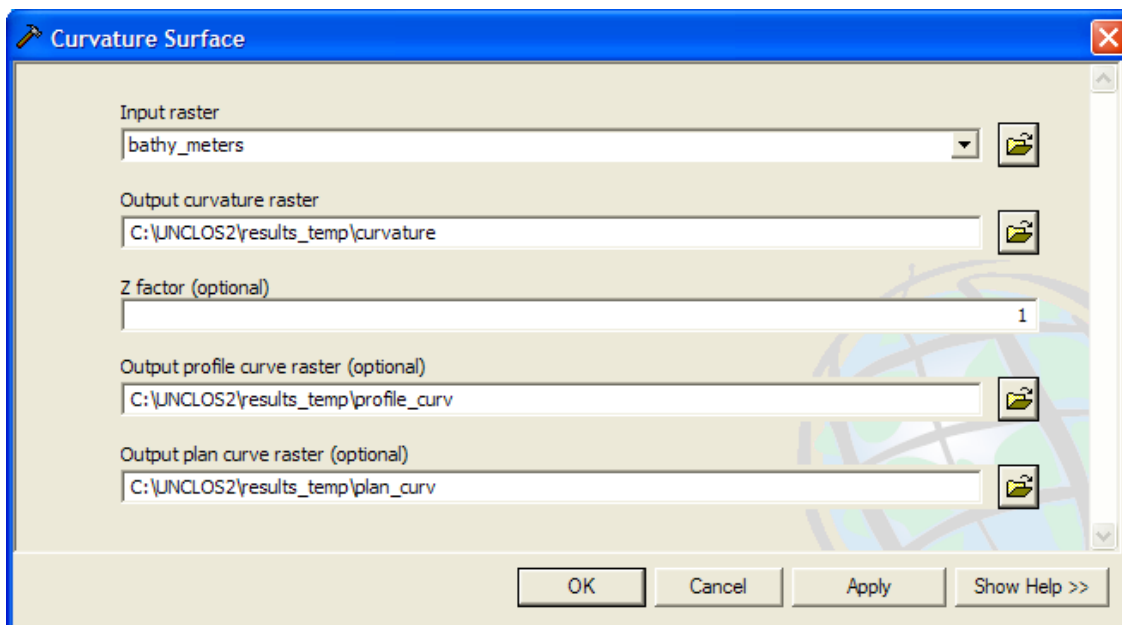

o   Run the model
o   All three curvature outputs should be displayed: curvature, profile_curv, and plan_curv.

➢   Analyze each curvature surface output individually by selecting one layer at a time.

*** This section requires significant analyst input!

- o It is useful to create a hillshade of the bathymetry grid to overlay the curvature surfaces on for further visual analysis.

  - ▪ The hillshade tool is located in the Article 76 toolbox.

➢ From the 3D Analyst toolbar select the bathymetry grid as the target Layer, then select the Interpolate Line tool

Create Profile Graph tool
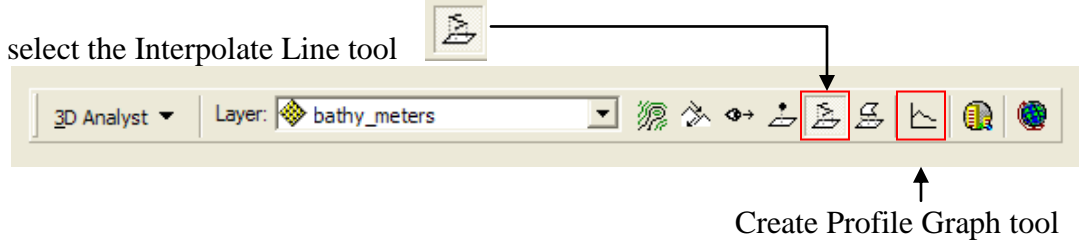
- o Draw a line perpendicular to the general trend of the contours (intersecting the baseline and the 2500m Isobath at approximately 90 degrees) seaward from the baseline to the edge of the study area.
- o With the line highlighted, select the Create Profile Graph tool to display a graph of the bathymetric profile along the line selected.

  - ▪ The profile graphs can be studied and utilized to help determine the base of the continental slope, and, more specifically, the point of maximum change in gradient (i.e. the foot of the continental slope).
  - ▪ Points along the graph can be selected and their x,y locations can be identified, as well as their location on the map.

- o It is recommended to create and analyze a profile graph for at least every baseline point (created earlier).
- o Create and analyze profile graphs for each curvature surface, in addition to visually analyzing and overlaying the curvature surfaces on the hillshade and bathymetry, to help detect which output best represents the change in gradient across the surface of the continental shelf.
- o Classifying the output data using varying methods highlights the differences in the curvature surfaces and help determine the base of the continental slope. Jenks Natural Breaks and Quantile are the most highly recommended classification methods.

  - ▪ The extreme values represent areas where the surface is highly convex at one end and highly concave at the other end of value spectrum (which values represents which characteristic varies between the outputs). Areas where the very high and very low values follow a similar trend and are close in proximity likely represent the region of the base of the continental slope, if the highly concave values are most seaward.

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- Areas where the surface exhibits a highly convex nature is representative of a drop-off or change in aspect from a relatively flat or upward trend to a sharp downward slope. Conversely, areas where the surface exhibits a highly concave nature is representative of change in slope from a downward trend to a relatively flat or upward slope.

  * Instructions for interpreting the data can be found in the ArcGIS 9.2 Desktop Help documentation on the topic of Curvature (ESRI, Curvature, 2008). The values produced for each of the three curvature outputs are interpreted differently, thus this document should be referenced to determine the proper interpretation of the curvature output one decides to use for further analysis. Table C.1 can also be referenced:

Table C.1: Curvature Values

	Concave Values	Convex Values
Curvature	Negative	Positive
Profile Curvature	Positive	Negative
Plan Curvature	Negative	Positive

- It will be necessary to test various classification methods and number of classes to determine which values best represent the points of maximum change in gradient at the base of the continental slope; thereby indicating the location of the foot of the continental slope.

  Example: if the curvature values are classified into ten classes using the quantile method (each class has the equal number of features), than each class will represent ten-percent of the values. The classes at either extreme will represent the top and bottom ten percent. In some cases this may be a useful way to classify the curvature values.

➢ Determine which curvature surface most accurately represents the foot of the continental slope.

   o Determine the range of values that best indicates the points of maximum change in gradient along the FOCS, without selecting a range that is too large.

      - Take note of the value range for use in the Extract by Attributes command.

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- ➢ Use the Extract by Attributes command to export cells from the curvature raster based on a selection of values determined above. Either:

    - o Use the Extract by Attributes tool located in the Article 76 toolbox, which requires an SQL expression.

        - ▪ SQL where clause syntax: (ESRI, Extract by Attributes, 2008)

            "value" >= 0.0210364
    Or

    - o Use the command line window in ArcMap, select command line from the Window dropdown on the main menu.

        - ▪ Command Line Syntax: (ESRI, Extract by Attributes, 2008)

            ```
            ExtractByAttributes_sa
            In-raster
            Where_clause
            Out_raster
            ```

            Example:

            ```
            ExtractByAttributes_sa
            C:\UNCLOS\results_temp\profile_curv
            "value >= 0.0210364"
            C:\UNCLOS\results_temp\curv_extract
            ```

- ➢ Use the Raster to Point tool in the Article 76 toolbox to convert the extracted raster cells to points. One point will be created at the center of each cell and will maintain the value of that cell.

        *** This section requires analyst input!

- ➢ The point file will likely include locations that contained values within the specified range, although are outside the region containing the base of the continental slope. Therefore, it is best to manually analyze the points overlaid on the original bathymetry grid and, separately, on the curvature surface, to help identify the points at the base of the continental slope and which points would likely need to be removed.

    - o The profile graphs may once again be helpful as well in identifying the actual location of the FOCS and determining which points to use for generating the line.

- ➢ Make a copy of the curvature points file named FOCS_pts.

- Add data: FOCS_pts

- Start an editing session and specify FOCS_pts as the target layer.

  - Delete all unnecessary points, maintaining only those that are located at the base of the continental slope, are most advantageous, and no greater than 60 nautical miles apart.

- Save edits and stop editing.

- Use the Convert locations to Paths (points to lines) tool to generate a line connecting the points from the FOCS_pts layer.

  - Once the line is generated, manually review and analyze the line in comparison to the curvature surface and original points selected along the projected FOCS.

  - Some editing may be necessary where the line did not follow the correct sequence between points.

  - Note that additional values may need to be incorporated from the raster (repeat the Extract by Attributes and Raster to Point processes) to fill in potential gaps. The maximum change in gradient values as selected for the entire area may generally pertain to the FOCS line; however, the values throughout some sections of the line might not be so extreme and therefore the selected values may not be relevant throughout the entire FOCS.

  - If the initial line generated missed some essential curves, was lacking vertices at important locations, or stopped short of the extent, further analysis of these areas may be necessary to identify the maximum change in gradient values and their locations for these less extreme portions of the FOCS. In this case, return to the classifications, select an appropriate class that captures the missed points, and repeat the Extract by Attributes and Raster to Point processes.

  - Add the new points as vertices and recalculate the line to incorporate a more accurate representation for the final delineation of the FOCS.

- Make a copy of the FOCS_pts, saved as FOCS_AOC_pts. If there are more than one points feature class make sure to combine them into one file for the following analysis.

Delineating the FOCS plus 60 nautical mile formula

➢ Insert a new Data Frame in ArcMap.

➢ Add data: FOCS_AOC_pts.

➢ Start an editing session and specify FOCS_AOC_pts as the target layer.

    o Delete all unnecessary points, maintaining only those that are
       located at the base of the continental slope, are most advantageous,
       and no greater than 60 nautical miles apart.

➢ Save edits and stop editing.

➢ Open the Article 76 FOCS plus 60M model.
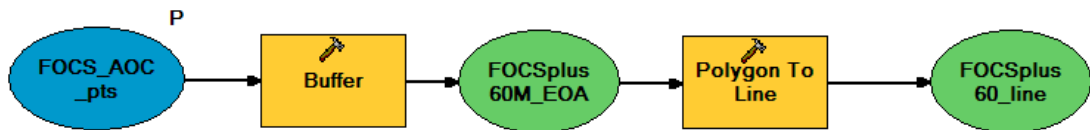
    o Make sure the FOCS_AOC_pts are set as the input parameter.
    o Run the model.
    o The bounding line representing the FOCS plus 60 nautical mile
       formula line should be displayed.

➢ Start an editing session and specify FOCSplus_60_line as the target layer.

➢ Delete all line segments other than the most seaward boundary line
   segment running parallel the general trend of the FOCS.

➢ Save edits and stop editing.

Delineating the FOCS plus 1% sediment thickness formula

➢ Add data: sediment

* If the sediment raster is not already in a projection that uses meters as the linear
units, then use the Project Raster tool to select an appropriate projection (should be
the same as the projection used to project the bathymetry raster) and save as a new
raster named sed_meters. The new projection should be the same as the projection
used to project the bathymetry raster.

➢ Add new Data Frame.

➢ Add data: sed_meters, FOCS

➢ Open the Article 76 Sediment model:

➢ Fill in the parameters, which not only include selecting the correct input features, but also require the user to specify the extent and cell size for the Euclidean Distance calculation of the FOCS feature.

     o   The first input should be the sed_meters raster
     o   The second input should be the FOCS line feature
     o   Extent should be selected as Same as Layer sed_meters
     o   Cell size should be selected as Same as Layer sed_meters

➢ Run the model.

Set the extent and cell size to the same as sed_meters!
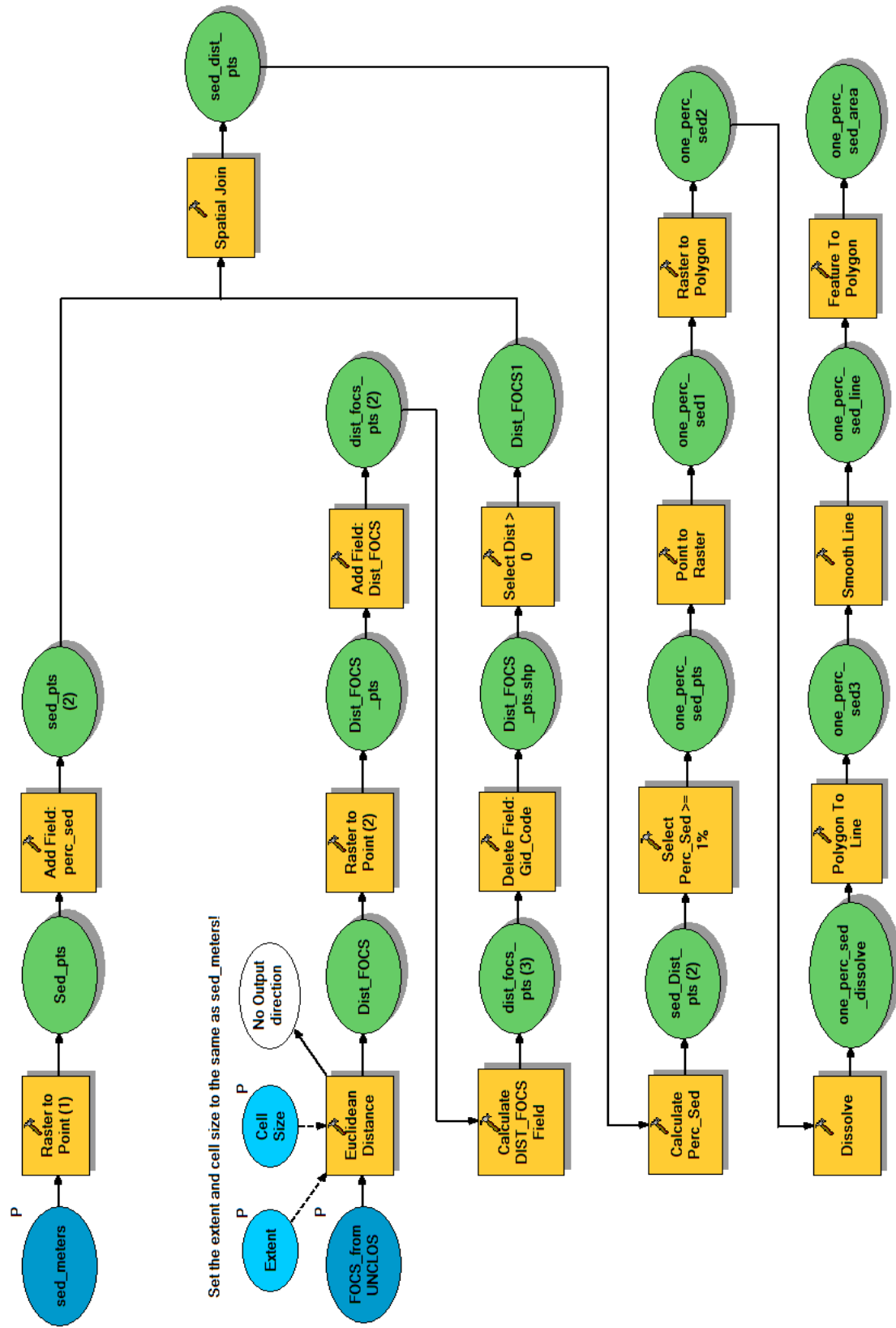
➢ The bounding line and a polygon representing the area where the sediment thickness at each point is greater than one-percent of the distance from that point to the FOCS should be displayed.

Delineating the combined formula line

➢ Open the Article 76 Formula Lines model.
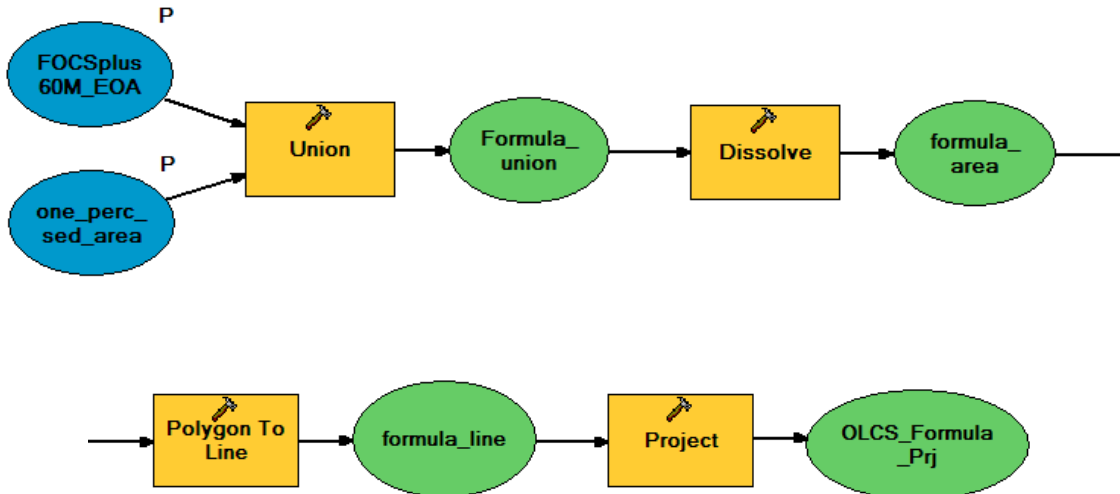
➢ Check the input parameters. Also, specify the projection that the final data needs to be in (same as original vector files).

➢ Run the model.

➢ The model generates a combined boundary for the most seaward segments of the formula lines. It also reprojects the data to the same reference system as the constraint data for the final analysis of the OLCS.

Delineating the OLCS

➢ Insert a new Data Frame.

➢ Add data: constraint_area, OLCS_Formula_prj
➢ Open the Article 76 - OLCS model
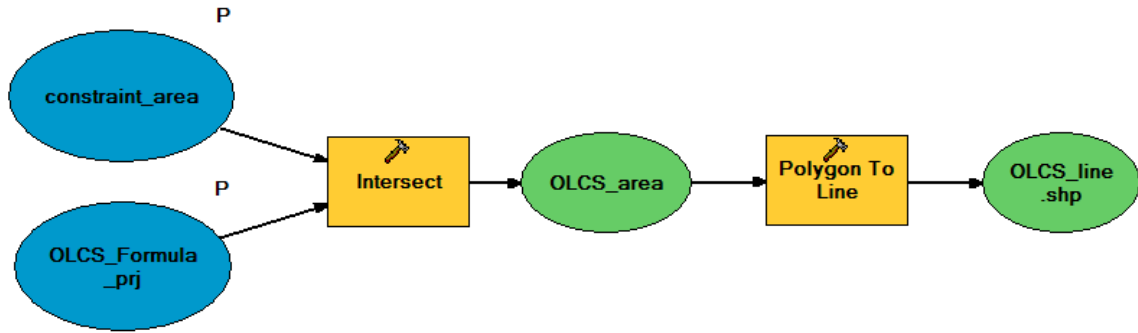
➢ Input the two data sets as the input parameters.

➢ Run the model.

➢ The bounding line of the OLCS should be displayed, of which the most seaward segment approximately parallel to the general trend of the baseline represents the outer limits of the continental shelf.

➢ Save a copy of the final output, OLCS_line, called OLCS.

➢ Add data: OLCS

➢ Start an editing session

   o Delete all line segments other than the most seaward boundary line segment running parallel to the general trend of the baseline.

➢ Save edits and stop editing.

➢ Use the Feature Vertices to Points tool to generate a series of points that define the OLCS.

➢ The Convention only requires points at a minimum of 60 nautical miles apart. Therefore, points can be selected to be removed or added along the line if necessary (where gaps may exceed 60 nautical miles). These changes can be made in an editing session.

➢ To add the coordinate data to the attribute table for each point, open the Add XY Coordinates tool and select OLCS points layer.

➢ Run the tool.

➢ Open the attribute table for the OLCS points to view the coordinate data. Two new fields be added; Point_X and Point_Y, which hold the longitude and latitude values for each point.

Attributes of OLCS_pts

FID	Shape *	LEFT_FID	RIGHT_FID	POINT_X	POINT_Y
0	Point	-1	0	-74.308801	31.58681
1	Point	-1	0	-74.308976	31.586304
2	Point	-1	0	-74.310115	31.583036
3	Point	-1	0	-74.311262	31.579769
4	Point	-1	0	-74.312415	31.576505
5	Point	-1	0	-74.313575	31.573243
6	Point	-1	0	-74.314742	31.569984
7	Point	-1	0	-74.315915	31.566727
8	Point	-1	0	-74.317095	31.563472
9	Point	-1	0	-74.318282	31.56022
10	Point	-1	0	-74.319476	31.556971
11	Point	-1	0	-74.320677	31.553724
12	Point	-1	0	-74.321884	31.550479

Record: |◄ ◄ [1] ► ►| Show: All Selected   Records (0 out of 1289 ▼

➢ The resulting points file provides the necessary "points, defined by coordinates of latitude and longitude," as required for a submission.

The United Nations Convention on the Law of the Sea provides additional guidance on how to determine the boundaries between adjacent nations. However, this is not part of Article 76. Additional analysis will be necessary to determine the boundaries from the coastline of the nation to the ends of the OLCS boundary defined above. Such analysis will also determine the exact length and area for which the OLCS extends for each nation.