July 2019

Visualization of Uncertain Boundaries of Undersea Features

Hyowon Ban
California State University, Long Beach, hyowon.ban@csulb.edu

Hyo Hyun Sung
Ewha Womans University, hhsung@ewha.ac.kr

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Abstract

There have been several studies that detect, measure, analyze, and visualize the undersea features by using technologies in multiple disciplines including geography and oceanography. However, definitions of the undersea features often vary among the existing leading literature. Due to this reason the geographical boundary for a certain undersea feature is sometimes not identical among the definitions. In this study, we explore semantic uncertainty in the definitions of some undersea features and apply approaches from fuzzy-set theory and geographic information science on empirical bathymetric data to visualize the uncertain boundaries of the undersea features. Results from this study demonstrate that the representation based on the fuzzy-set approach can be useful for dealing with the semantic uncertainty of the undersea features.

1   INTRODUCTION

Undersea features consist of many different types, such as banks, plateaus, and seamounts (IHO 1994). Studies in some disciplines, including geography and oceanography, have aimed to detect, measure, analyze, and visualize undersea features using advanced technologies such as geographic information science (GIScience), remote sensing, and bathymetry (Wessel et al. 2010; Williams et al. 2009; Wright 1999). However, the definitions of certain undersea features provided in the existing leading literature are not identical (ACUF 2005; IHO; Neuendorf 2005). This ambiguity can be problematic when these features are visualized on maps since the boundaries of a feature differ according to certain definitions. For example, sometimes a seamount is defined as "a distinct, generally-equidimensional elevation greater than 1,000 m above the surrounding relief as measured from the deepest isobath that surrounds most of the feature" (IHB 2013). The definition consists of attributes of elevation and shape. On the other hand, a seamount is also defined as "an elevation rising generally more than 1,000 m and of limited extent across the summit" (ACUF). In a similar as well as different way from the definition in IHB (2013), this definition in ACUF consists of attributes of elevation and areal extent. If a map of a seamount is drawn based on each of the two definitions, the two maps would not show the identical extent or geographical boundary for the same seamount and this would be problematic.

The existence of multiple definitions of a single concept can create semantic uncertainty (Fisher 1999), and the geographical boundaries of the same undersea feature may not be identical across definitions. Uncertainty in definitions can be problematic for communication and decision-making among stakeholders in terms of the undersea environment. A significant body of the literature discusses vagueness in terrain modeling related to the ontological definitions (Mark and Smith 2004; Smith and Mark 2003) and analysis of landforms (Arrell et al. 2007; Fisher et al. 2004).

Researchers and stakeholders have made efforts to name undersea features in the study areas of this research and locate them on maps (GEBCO 2018; KHOA et al. 2011 and 2014). However, few studies have addressed the issue of the semantic uncertainty in definitions of the undersea features and the dilemma of visualizing their geographical boundaries on maps. Another issue is that many of the existing studies represent each undersea feature as a dot rather than as geographical boundaries. In addition, some studies represent undersea features—e.g., the seamounts–on maps based on their water depths or elevation values. However, as the definitions of the seamounts also have other attributes in addition to the water depth or elevation, the geographical boundaries of seamounts should be visualized based on the multiple attributes in the definitions. Lastly, it would be more appropriate to visualize the extent of the undersea features using fuzzy or graded boundaries than crisp boundaries to deal with the semantic uncertainty in the definitions. For example, it is very difficult to say that an elevation of 999.9 m above the surrounding relief does not fulfill one of requirements of the elevation attribute of the definition of seamounts—"an elevation rising generally more than 1,000 m (ACUF)" mentioned above—for it belongs to the sorites-paradox problems.

A recent study introduced an ontology of undersea features for landform classification and developed a tool for visualizing the classified landforms with crisp boundaries (Yan et al. 2014). The study claimed that the vagueness of undersea feature boundaries should be considered when these features are visualized. In this study, the term for each undersea feature type (bank, seamount, or plateau) had vague ontology since each term has multiple definitions (Section 3.2).

With these issues in mind, this research attempts to answer the following question: when an undersea feature has semantic uncertainty, how should its geographic boundary be represented on maps? We first identified the semantic uncertainty, or vagueness, in existing definitions of selected undersea features. We then applied fuzzy-set theory and existing GIScience approaches to empirical bathymetric data to measure and visualize the uncertain spatial boundaries of these features.

According to the literature, detecting and representing the undersea features on maps can be challenging due to limitations of existing technologies related to profiles, resolution, and multiple sources of bathymetric data (Kitchingman and Lai 2004; Kitchingman et al. 2007; Morgan et al. 2005). Some efforts have been made to address these problems. For example, Zhu et al. (2016) revealed that certain places in multiple gazetteers are categorized in different types, and the work proposed a bi-directional representation of the ontology of place names using data-driven techniques and spatial statistics. Lord-Castillo et al. (2009) suggested a spatial data model and a tool for the standardization of ocean and coastal data types.

Despite these efforts, few existing works address semantic uncertainty in the definitions of undersea features and their spatial boundaries. Falick (1966) has argued that some approaches used in geography might be helpful in addressing this uncertainty. Indeed, GIScience has contributed to many areas of oceanography including problem-solving, management, analysis of spatial data, assessment of uncertainties in data, and mapping the ocean environment (Wessel et al.; Williams et al.; Wright). In this study, we utilized existing GIScience methodologies to represent the semantic uncertainty of undersea features.

2   BACKGROUND

2.1   Spatial Boundaries of Undersea Features

To answer the research question, we used a bathymetric sector of the study area called East Sea that is displayed in Figure 1. The study area consisted of ten types of undersea features including banks (Hupo Bank), basins (Onnuri Basin, Saenal Basin, and Ulleung Basin), escarpments (Usan Escarpment), gaps (West Gap of Ulleung, East Gap of Ulleung, and Korea Gap), plateaus (Gangwon Plateau, Ulleung Plateau, and Korea Plateau), reefs (Wangdol Reef), ridges (Igyuwon Ridge, Jugam Ridge, and Usan Ridge), seamounts (Kiminu Seamount, Anyongbok Seamount, and Haeoreum Seamount), tablemounts or guyots (Simheungtack Tablemount and Isabu Tablemount), and troughs (Usan Trough). Figure 1 presents the undersea features based on the water depths of bathymetric data with a resolution of 140 m. The figure also provides a reference map of the features (KHOA 2014).
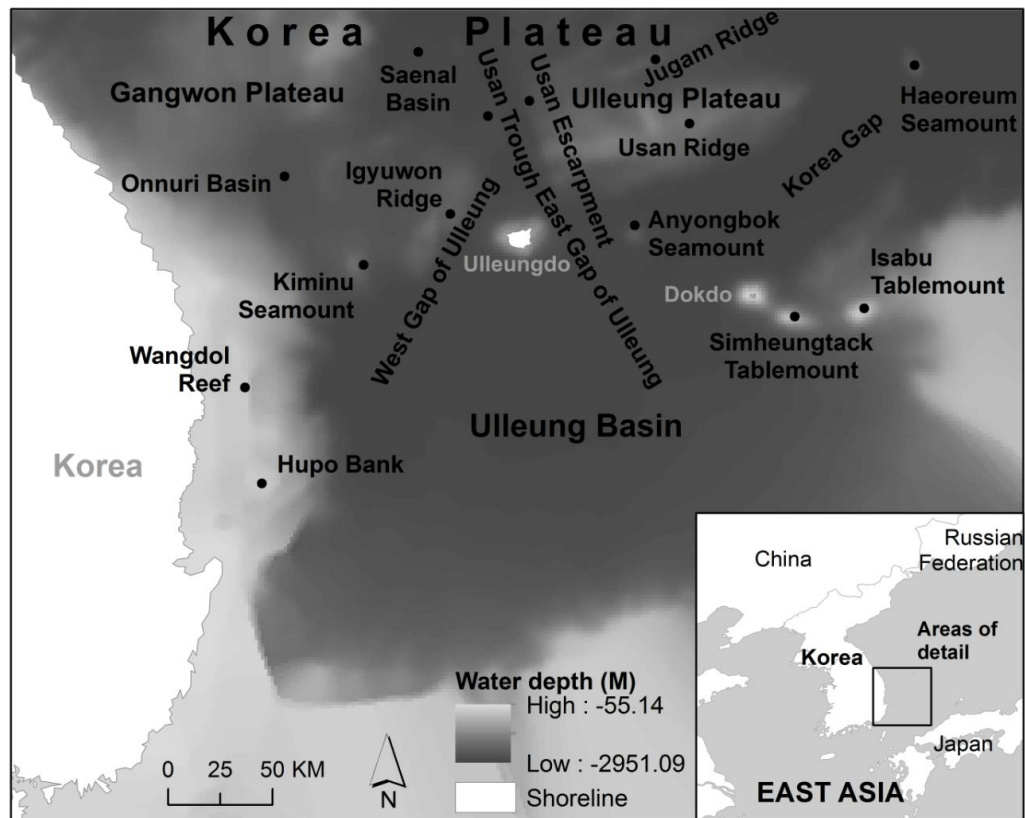
Figure 1. Undersea features in the East Sea study area (redrawn based on KHOA (2014))

According to the literature, the ten types of undersea feature in the study area—bank, basin, escarpment, gap, plateau, reef, ridge, seamount, tablemount, and trough—may have multiple definitions (Appendix 1). Though Appendix 1 includes five example references, most types of undersea features show that some of its definitions from the references are identical (see descriptions in Gazetteer and B-6 for banks; S-32 and B-6, and Gazetteer and ACUF for basins; S-32 and B-6 for escarpments; S-32, B-6, and ACUF for gaps; S-32 and B-6 for plateaus; S-32 and B-6, and Gazetteer and ACUF for tablemounts; S-32, B-6, and ACUF for troughs for details), very similar (see S-32 and B-6 for reefs; B-6 and Glossary of Geology for ridges; S-32 and ACUF for seamounts for details), or unique by using specific values (see Glossary of Geology for plateaus for details). Besides, each definition consists of one or more quantitative and qualitative attributes that express specific characteristics. For example, banks are described as having three attributes that are both qualitative and quantitative. They are areas with "an elevation at depths generally less than 200 m," and these depths provide "sufficient [space] for safe surface navigation." Additionally, banks are "commonly found on the continental self or near an island (see the descriptions in Gazetteer and B-6 for banks in Appendix 1 for details). The other undersea features listed in Appendix 1 also feature several quantitative or qualitative attributes.

2.2   Semantic Uncertainty of Spatial Concepts

Spatial uncertainty exists in various aspects of spatial concepts, such as data quality, accuracy, scale, and semantics (Li et al. 2017). Some works have discussed vagueness and perceptions of landforms. For instance, Guilbert and Moulin (2017) published a brief review on object-based image analysis and cognitive approaches, and Gerçek et al. (2011) suggested a fuzzy—indistinct or non-crisp—classification system for representing ambiguities in the attributes and geographical space of landforms. This study focuses on the uncertainty of the semantics of definitions of undersea features. Many existing studies address the positional uncertainty of undersea features (Baba and Seama 2002; Bell Jr 1975; Goff and Jordan 1988; Pitcher et al. 2008; Wynn et al. 2000). Wynn et al. introduced methods to determine the location of seamounts using slope and sediment distribution. Similarly, some approaches for modeling undersea topography have been introduced (Baba and Seama), but few existing studies have addressed the semantic uncertainty that becomes problematic when mapping undersea features. Section 3 describes how we measured the semantic uncertainty of the selected undersea features and visualized their uncertain boundaries.

3   METHODOLOGY

3.1   Study Area and Data

This study focuses on existing definitions of undersea features found in the literature. Three different types of undersea features were selected for the purposes of this study (Figure 1): banks, plateaus, and seamounts.

We used the bathymetric data for the study area provided by the KHOA. The KHOA collected the data from oceanographic cruise Haeyang 2000 between 1996 and 1997. All data were acquired through multibeam swath bathymetry conducted using multibeam-sonar system SeaBeam 2100 (Sea Beam Instruments, Inc.). The swath of the data was limited to less than 2 km to ensure 100% coverage of the study area. A Trimble DGPS 4000DS was used as the differential GPS (DGPS), and the estimated positional accuracy was ± 0.0027 nautical miles (or NM). A single ping of the SeaBeam 2100 produces up to 151 beams that measure the depths in roughly 1-degree widths. The accuracy of the depth measurement was approximately 0.5% error of the depth, lower than the 1% error that is the IHO standard for depths greater than 100 m (L-3 Communications SeaBeam Instruments 2000; Smith and Satake 2006; IHB 2008; Banul 2014). The data were processed to remove noise (KHOA 2000), and the original data was converted to three-dimensional point data using Global Mapper software (Blue Marble Geographics 2012). The data consisted of 8.03 million three-dimensional point features including *x* and *y* coordinates and water-depth values of each location within the study area. The original point data in the xyz format had a resolution of 1.5 km. The three-dimensional point data were converted to digital elevation model (DEM) data using ArcGIS 10.6 (Esri 2018) with a resolution of 140 m. We chose the resolution of DEM data to interpolate more detailed bathymetric information in the study areas and to keep regionally specific and local characteristics in the data. In general, smaller grid cell sizes such as 5 m provide more sensitivity than larger grid cell sizes (Erskine et al. 2007; Kienzle 2004). Additionally, grid cell size can be selected based on the topographical characteristics of the study area and the nature of the analysis (Wechsler 2007). We note

that a finer resolution for the DEM data was not available due to the low resolution of the original bathymetric data and technical limitation of this study. Section 3.2 introduces existing definitions of the undersea features examined in this study.

3.2 Uncertainty in Definitions of Undersea Features

This study focused on the definitions of banks, plateaus, and seamounts since these features have quantitative expressions that make it comparatively easier to measure uncertainties in their definitions. According to the literature, each definition of a bank, plateau, or seamount includes one or more of the attributes described below (ACUF; GEBCO; IHO; IHB 2013; Neuendorf).

3.2.1 Banks

From the existing definitions of banks included in Appendix 1, the current definition examines the following two attributes:

Attribute 1: An elevation with a water depth of less than 200 m
Attribute 2: A relatively flat-topped elevation of the seafloor at a shallow depth

Attribute 1 utilizes the quantitative expression of a water depth of 200 m to describe banks. However, the empirical water depth of Hupo Bank ranges between 100 m and 200 m (GEBCO), and the expression of "less than 200 m" itself may include a water depth that is too shallow to sail safely, such as a value lower than 30 m. Due to the reason, we considered that the water depth values described in GEBCO are more realistic than the values expressed in Attribute 1. Therefore, we adopted the GEBCO value for Hupo Bank and called it Attribute 1a in this study and defined it as follows:

Attribute 1a: An elevation with a water depth ranging between 100 m and 200 m

Attribute 2 consists of a qualitative expression of elevation or relief form, and we applied it to the empirical data in Section 3.3.2. In addition, Appendix 1 suggests that the water depth of banks should be "sufficient for safe surface navigation." The water depth safe for surface navigation can usually be defined using under keel clearance (UKC); this is the distance between the lowest point at a ship's keel and the highest point of the undersea area beneath the ship (Parker and Huff 1998). Under keel clearance can change depending on the depth and draught of the ship, water level changes over time, and flow beneath the ship (Gourlay 2006; Gucma and Schoeneich 2009; Parker and Huff). However, it would be too complex to consider the detailed concept of "safe surface navigation" in this study. For this reason, the concept of water depth is not considered in the definition of a bank in this study.

3.2.2 Plateaus

From the existing definitions of plateaus (Appendix 1), this study considers the following three attributes:

Attribute 1: Over 200 m in elevation above the seafloor
Attribute 2: A broad, flat-topped and ill-defined elevation of the seafloor

Attribute 3: One or more relatively steep sides

This study examines all of the three attributes of plateaus. Attribute 1 may have a limited influence on boundary measures since the water depth of the three plateaus is much deeper than 200 m. For instance, the water depth of the Gangwon Plateau ranges between 900 m and 1,500 m, the depth of the Ulleung Plateau ranges between 800 m and 2,300 m (GEBCO), and the water depth of the Korea Plateau ranges between 600 m and 1,500 m (Lee et al. 2002).

3.2.3   Seamounts

From the existing definitions of seamounts (Appendix 1), this study focuses on the following three attributes:

Attribute 1: An elevation rising more than 1,000 m above the sea floor
Attribute 2: A distinct and generally equidimensional elevation in a conical form
Attribute 3: A discrete large isolated elevation or a group of elevations

This study examines all three attributes of seamounts. The three seamounts in the study area are located above the sea floor (Figure 1). The water depth of Kiminu Seamount ranges between 868 m and 1,968 m (GEBCO), and its elevation above the sea floor is about 1,100 m according to the bathymetric data. Additionally, the water depth of Anyongbok Seamount ranges between 457 m and 2,100 m (GEBCO), and its elevation above the sea floor is about 1,643 m. The water depth of Haeoreum Seamount ranges between 849 m and 2,549 m (Choi and Kwon 2006), and its elevation above the sea floor is 1,700 m.

3.3   Measuring the Uncertain Boundaries of Undersea Features

Several approaches that use point objects can be applied to define the geometric boundaries of certain phenomena, including minimum convex polygon (MCP), *k*-nearest neighbor convex hull (k-NNCH), and concave hull (De Berg et al. 1997; Getz and Wilmers 2004; Meulman and Klomp 1999; Moreira and Santos 2007; Park and Oh 2012). The boundaries identified using such approaches are usually crisp. For this reason, it is difficult to capture spatial phenomena that originally have fuzzy or graded boundaries such as mountains, forests, and soils by representing them as crisp points. This section explains how the uncertain spatial boundaries of undersea features can be measured using the fuzzy-set approach and empirical bathymetric data.

3.3.1   The fuzzy-set approach

The fuzzy-set approach is one useful method for addressing the uncertainty of concepts (Zadeh 1965). It measures the extent to which a definition accurately describes a concept using the fuzzy-set membership function (MF) and its values. Fuzzy-set MF values may range between 0 and 1, with a value of 1 indicating full membership, a value of 0 indicating no membership, and a value of 0.5 indicating the half membership of a concept (Fisher). Several mathematical methods exist for defining fuzzy-set MFs. A fuzzy-set MF can have either an open or closed form, and the shape drawn as a graph can be linear, s-shaped, sinusoidal, negative exponential, or sigmoidal (Burrough et al.

2015; Robinson 2003). For this study, we developed fuzzy-set MFs for the undersea features that consisted of multiple linear graphs based on the concepts we address in this study (Ban 2012).

3.3.2   *Combinatory approaches for fuzzy-set membership functions*

When a concept consists of multiple fuzzy-set MFs, the MFs can be combined using mathematical procedures that include algebraic product, absolute difference, convex combination, union, and intersection (Robinson; Zadeh). The definitions of the undersea features in Section 3.2 consist of multiple attributes that are formalized as fuzzy-set MFs. In this study, we combined the multiple fuzzy-set MFs of each definition by taking the average of the MFs. First, we used the DEM data to convert the fuzzy-set MFs of the attributes of each undersea feature to a series of raster datasets. Afterward, we used map algebra to calculate the average of the raster datasets (Ban and Ahlqvist 2009). The sections below describe the procedure followed for each undersea feature.

- *Bank*

Based on the description of the fuzzy-set approach in Section 3.3.1 above and Attribute 1a of the definition of a bank in Section 3.2.1, we assigned a fuzzy-set MF value of 0.5 as the breakpoint for locations with half membership as banks, such as those that have a water depth of 100 m or 200 m. For instance, areas with a water depth 90 m or 210 m would have MF values lower than 0.5 and fit the definition of a bank less closely. At the same time, areas with water depths of 110 m or 190 m would have MF values higher than 0.5 and fit the definition of a bank more closely. In Figure 2, areas with a water depth of 150 m have an MF value of 1 and fully fit the definition of a bank. Based on the values, the two-simple linear MFs can be developed for areas with depth values X that are greater than or equal to 200 m and less than 100 m (Figure 2).
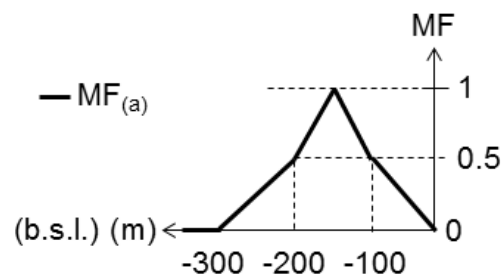
$$MF_{(a)} = 0 \qquad\qquad \textit{where } X\ (X < -300) \qquad\qquad (1)$$
$$MF_{(a)} = 0.005 \cdot X + 1.5 \quad \textit{where } (-300 \leq X < -200)$$
$$MF_{(a)} = 0.01 \cdot X + 2.5 \quad \textit{where } (-200 \leq X < -150)$$
$$MF_{(a)} = -0.01 \cdot X - 0.5 \quad \textit{where } (-150 \leq X < -100)$$
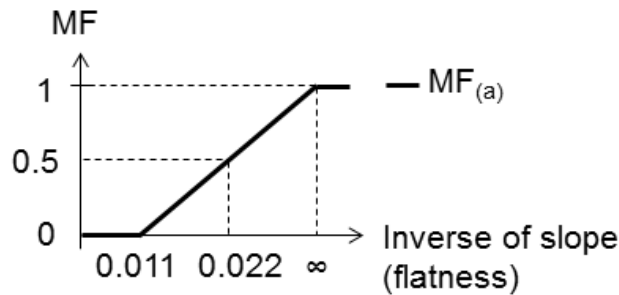$$MF_{(a)} = -0.005 \cdot X \qquad \textit{where } (-100 \leq X < 0)$$

X: Elevation
MF: Membership function values (max. 1, min. 0)

Figure 2. Example of fuzzy-set membership functions for Attribute 1a of the definition of a bank

Since a feature with a water depth of less than -100 m or more than -200 m would fit the definition of a bank less closely, two other simple linear MFs can be developed for areas with depth values X that are 1) greater than or equal to -300 m and less than -200 m and 2) greater than -100 m and less than 0 m. Locations with a water depth of more than -300 m are assigned an MF value of 0 since a water depth of -300 m is too deep for a location to be considered a bank (Figure 2). The fuzzy-set MFs for Attribute 1a consist of five simple linear equations, and the parameters of each equation are based on the water depth values of the study area (Equation 1). Subsequently, we applied the MFs to the empirical DEM data and created a raster dataset consisting of the fuzzy-set MF values.

According to Attribute 2 of the definition of banks in Section 3.2.1, banks are areas that have relatively flat-topped elevation. The expression does not specify any numerical values, but the degree of flatness can be gauged using numerical measures of elevation. The flatness of landforms such as valleys and creeks can be quantified by calculating the inverse of their slopes (Gallant and Dowling 2003), and the "upness" of hills can be determined to create a landscape position index (Dowling et al. 2003). The flatness of a landform can be also measured using the ray-tracing algorithm that projects multiple radians from each center of land surface to gauge azimuth and angle (Dobson and Campbell 2014). Other studies quantify the ratio of summit width to basal width using schematic sections (Mukhopadhyay and Khadge 1990; Wiles et al. 2014), but in this study, it was difficult to measure the summit widths and basal widths of Hupo Bank due to its dynamic figure. The length of its shape is approximately 85 km, and its width ranges between 1 km and 16 km. In addition, the three peaks at the top of Hupo Bank have different elevations (Choi et al. 2008; Kim and Park 2014). The study followed Gallant and Dowling's approach and calculated the inverse of Hupo Bank's slopes to determine flatness.

$$MF_{(a)} = 45.45 \cdot X - 0.5 \ where \ X \ (0.011 \le X < \infty) \tag{2}$$
$$MF_{(a)} = 0 \qquad where \ (0 = X < 0.011)$$

X: Diameter of top to diameter of bottom of bank (%)
MF: Membership function values (max. 1, min. 0)

Figure 3. Example of fuzzy-set membership functions for Attribute 2 of the definition of a bank

To measure the flatness of Hupo Bank, we first calculated the slope of the bank as raster data and obtained the inverse of the slope values of each data pixel. We assigned the fuzzy-set MF value of 0.5 to areas with an inverse slope value of 0.022, which is the inverse of 45 degrees. Additionally, we assigned an MF value of 0, which indicates

extreme steepness, to areas with an inverse slope value of less than 0.011, which is the inverse of 90 degrees. A membership function value of 1 was assigned to areas with an infinite inverse slope value, which is the inverse of 0 degree (Figure 3). Two linear equations were developed for Attribute 2 based on the assigned MF values (Equation 2), and these equations were applied to a dataset consisting of the inverse of the empirical slope values of the study area. As the result, we created a raster dataset consisting of the fuzzy-set MF values for Attribute 2.

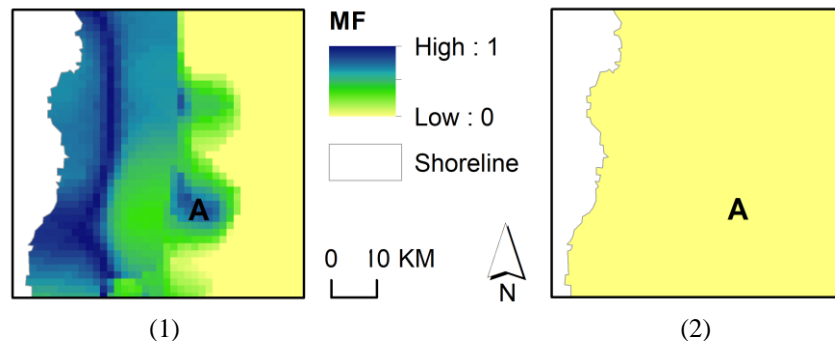<div align="center">(1)   (2)</div>

Figure 4. (1) Visualization of Figure 2 (Attribute 1a of Hupo Bank in Area A) and (2) Figure 3 (Attribute 2 of Hupo Bank in Area A)

Figures 4(1) and 4(2) visualize the semantic differences between the two definitions (attributes 1 and 2) of a bank. It was difficult to determine whether one definition was superior to the other due to ambiguity. As a result, we adopted both definitions in this study by combining the fuzzy-set MFs of Hupo Bank taking the average of the two raster datasets. Through this process, we attempted to answer the research question: when an undersea feature has multiple definitions, how should its boundary be represented? Section 4.1 visualizes the results of applying the fuzzy-set MFs to the banks in the study area.

- *Plateaus*

Attribute 1 of the definition of a plateau in Section 3.2.2 references elevation from the ocean floor. To generate fuzzy-set MF values for Attribute 1, we assigned an MF value of 0.5 to locations with an elevation of 200 m and an MF value of 1 to locations with an elevation higher than 400 m. In addition, we assigned an MF value of 0 to locations with an elevation of 0 m (Figure 5). Using the assigned MF values, we developed two linear equations for Attribute 1. The parameters of each equation were based on the elevation values of the study area (Equation 3). We then applied Equation 3 to the DEM data for Gangwon Plateau, Ulleung Plateau, and Korea Plateau. As the result, we created a raster dataset consisting of the fuzzy-set MF values of Attribute 1 of the three plateaus.
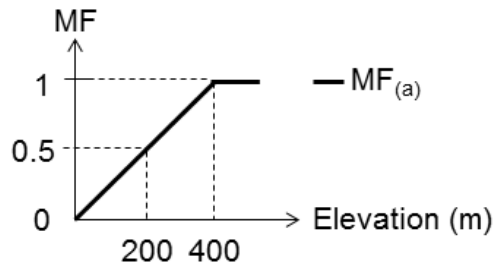
$$MF_{(a)} = 0.0025 \cdot X \quad where \ X \ (X \leq 400) \tag{3}$$
$$MF_{(a)} = 1 \qquad \quad where \ (X > 400)$$

X: Elevation

MF: Membership function values (max. 1, min. 0)

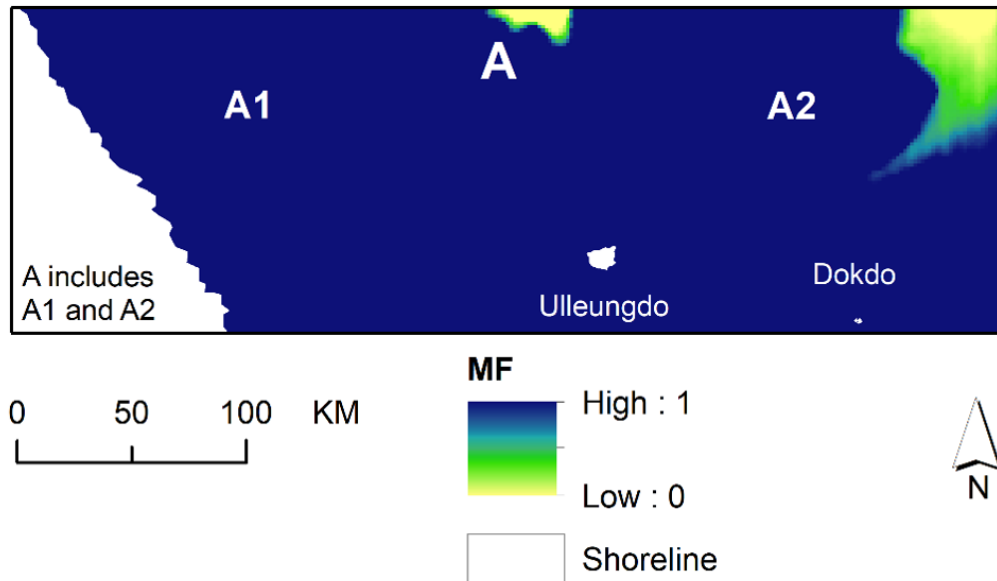Figure 5. Example of fuzzy-set membership functions for Attribute 1 of the definition of a plateau

Figure 6. Visualization of Figure 5: (A) Korea Plateau, (A1) Gangwon Plateau, and (A2) Ulleung Plateau

Figure 6 visualizes the fuzzy-set membership values for Attribute 1 of the definition of a plateau. Most of the areas of the three plateaus (A, A1, and A2) have very high MF values indicated by the dark blue color. For this reason, Attribute 1 does not represent the detailed boundaries of the plateaus in the study area.

Attribute 2 of the definition of a plateau in Section 3.2.2 describes plateaus as flat-topped areas. We adopted Attribute 2 of the definition of a bank and the MFs in Equations 1 and 2 to gauge the flatness of the plateaus in the study area. Afterward, we created a raster dataset that consisted of the flatness values of the three plateaus calculated by applying the MFs to the data for the inverse of the slopes.

According to Attribute 3 of the definition of a plateau in Section 3.2.2, plateaus have one or more relatively steep sides. Based on Attribute 3, we measured degrees of

slope by applying the MFs to the DEM data and rescaling the value ranges to be between 0 and 1. We created a raster dataset consisting of the slope values of the three plateaus.

Figures 4(2) and 6 visualize the semantic differences between the two definitions (Attributes 1 and 2) of a plateau. It was difficult to determine whether one definition was superior to the other due to ambiguity. As a result, we adopted all definitions by combining the MFs of the plateaus. We calculated the average of the three raster datasets and created a new raster dataset consisting of the average membership values. Section 4.2 visualizes the results of applying the MFs to plateaus in the study area.

- *Seamounts*

Attributes 1 and 3 of the definition of seamounts described in Section 3.2.3 quantify the elevation of the features, and Attribute 2 addresses the compactness of the feature shapes. In this study, we developed the fuzzy-set MFs of the three attributes 1, 2, and 3 by extending Ban.

For Attribute 1 of seamounts, we assigned a fuzzy-set MF value of 0.5 to areas with an elevation 1,000 m above the sea floor (Figure 7). Attribute 1 defines a seamount as an area with a peak higher than 1,000 m. Areas that meet the condition may have larger MF values than those of seamounts. With this in mind, we assigned an MF value of 0 to areas with an elevation of 0 m and an MF value of 1 to areas with an elevation 2,000 m or higher (Figure 7). We developed two linear equations for the fuzzy-set MFs of Attribute 1 and applied the MFs to the DEM data (Equation 4). As the result, a raster dataset was created consisting of the fuzzy-set MF values of Attribute 1 of seamounts.
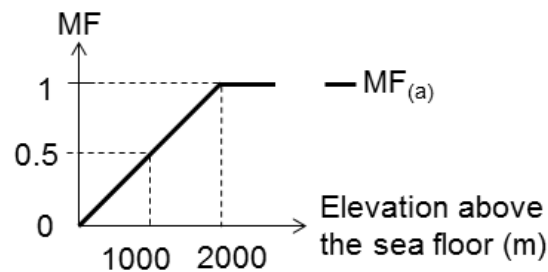
$$MF_{(a)} = 0.0005 \cdot X \ where \ X \ (X \leq 2000) \qquad (4)$$
$$MF_{(a)} = 1 \qquad where \ (X > 2000)$$
X: elevation
MF: Membership function values (max. 1, min. 0)

Figure 7. Example of fuzzy-set membership functions for Attribute 1 of the definition of a seamount
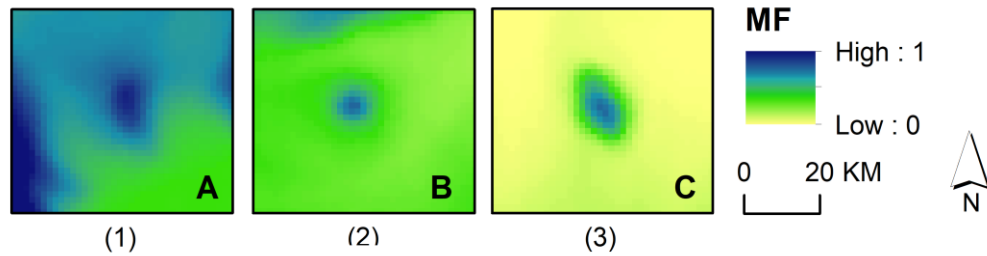
Figure 8. Visualization of Figure 7: (1) Kiminu Seamount, (2) Anyongbok Seamount, and (3) Haeoreum Seamount

Figure 8 visualizes the fuzzy-set membership values of Attribute 1 of the definition of a seamount. Some rough heterogeneity in the membership values of the three seamounts (A, B, and C) is illustrated by colors ranging from dark blue (high membership) to light yellow colors (low membership).

According to Attribute 2, seamounts should have a conical form. As with Attribute 2 of the definition of a bank, the verbal expression of Attribute 2 does not utilize any numeric values. However, the degree of conical formation can be quantified using numerical values (Burago et al. 2001). A cone can have multiple shapes depending on its location, the height of its peak, and the size of its bottom. To examine Attribute 2, we measured the roundness of the bottom of the three seamounts in the study area. Examining the various types of conical shapes was beyond the scope of this study due to the complexity of measurement for each type.

Several methods are available for measuring the roundness of a shape, such as isoperimetric inequality (Musin 1997; Osserman 1978), compaction index (CI) (Hammond 1970; Hammond and McCullagh 1978), and compactness ratio (Angel et al. 2010; Griffith et al. 1986; MacEachren 1985). More recent studies have demonstrated that approaches using moment of inertia (MI) generally provides better results than other approaches in terms of computational efficiency and positional accuracy (Li et al. 2014; Li et al. 2013). Of these approaches, CI is one of the most useful for measuring compactness, but it is limited in its ability to differentiate the compactness of some objects, such as a rectangle and an oval of the same size (Slocum et al. 2008). We measured and compared both the CI and MI values of the three seamounts in the study area to determine the features' compactness.

According to Hammond (1970) the CI of a feature can be measured using Equation (5):

$$I_i = \frac{Area\ of\ the\ region_i}{Area\ of\ the\ Smallest\ Inscribing\ Circle_i} \tag{5}$$

In this equation, *i* is the region and the value of *I* ranges between 0 and 1 (Mahmood Mayo 2012). The CI values of the three seamounts were measured using Equation (5) (Table 1a).

According to Li et al. (2013) the MI of a shape can be measured using Equation (6) and raster data:

$$I_g = \sum_{s,t\ where\ M(s,t) \neq null} z_g^2 r^2 \tag{6}$$

In this equation, I is the MI value, g is the centroid of a shape, (s, t) indicates the row and column of a cell, M is a rectangular matrix, z_g is the Euclidean distance between any pixel centroid and the centroid of the shape, and r is the cell size of M.

Based on Equation (6), the MI values of the three seamounts were normalized by the MI values of a circle of the same area size with the shape of each seamount (Table 1b). Normalization was necessary because the MI values are higher for larger shapes.

Table 1. Compaction indices and normalized moments of inertia for the three seamounts

Name	Kiminu Seamount	Anyongbok Seamount	Haeoreum Seamount
(a) CI values	0.74	0.54	0.73
(b) nMI values	0.96	0.93	0.91

Table 1 illustrates the differences in compactness of the three seamounts. All three seamounts had CI values that were smaller than the normalized moments of inertia (nMI). Based on the CI values, Kiminu Seamount (A in figure 9) is the most compact, followed by Haeoreum Seamount (C in figure 9) and Anyongbok Seamount (B in figure 9). When nMI is considered, the order of most to least compact changes to Kiminu Seamount, Anyongbok Seamount, and Haeoreum Seamount. In this study, we adopted the nMI values because they provide a stronger explanation of the compactness of the seamounts' empirical shapes. As the result, we created a raster dataset consisting of the nMI values for Attribute 2 of seamounts.
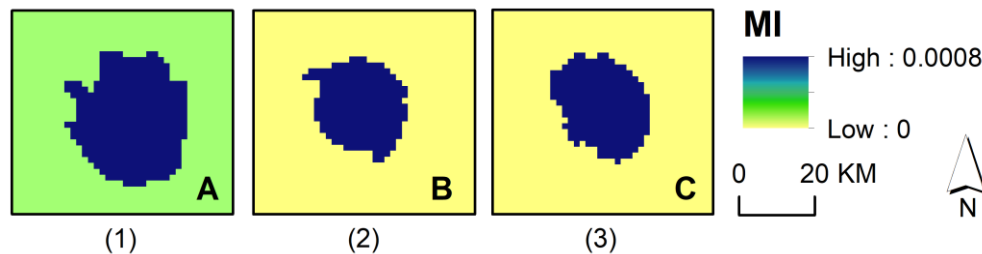

Figure 9. Visualization of the raster dataset of the normalized moments of inertia values in Table 1: (1) Kiminu Seamount, (2) Anyongbok Seamount, and (3) Haeoreum Seamount

Figure 9 visualizes the fuzzy-set membership values of Attribute 2 of the definition of seamounts. The moments of inertia values clearly differentiate the seamounts from surrounding areas with crisp boundaries.

According to Attribute 3 of the definition presented in Section 3.2.3, the slope values of seamounts increase abruptly (KHOA 2004). Since the distribution of slope values may vary, the corresponding fuzzy-set MFs for Attribute 3 may also vary for individual seamounts. The fuzzy-set MFs can be developed by including the slope of the seafloor around each seamount (Equation 10a), the mean of the seamount slope that changes abruptly above the seafloor (Equation 10b), and the maximum seamount slope (Equation 10c). It should be noted that values a, b, and c in Equation (6) can vary for individual seamounts. We assigned an MF value of 0.5 to Area b in Equation (6) as the cross-over point, a full MF value of 1 to Area c, and an MF value of 0 to Area a (Figure 10a).

As illustrated in Figure 10a, we developed fuzzy-set MFs for Attribute 3 of the three seamounts and applied the MFs to the DEM data (Figures 10b, 10c, and 10d;

Equations 7, 8, and 9). The results of each equation were generated as a separate raster dataset.

(a)
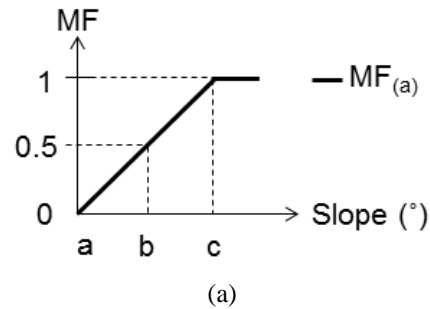
$$MF_{(a)}: \quad \text{Depends on empirical spatial data of each seamount} \qquad (6)$$

a: Slope of seafloor around a seamount
b: Mean of seamount slope that changes abruptly above seafloor
c: Maximum seamount slope
X: Slope
MF: Membership function values (max. 1, min. 0)
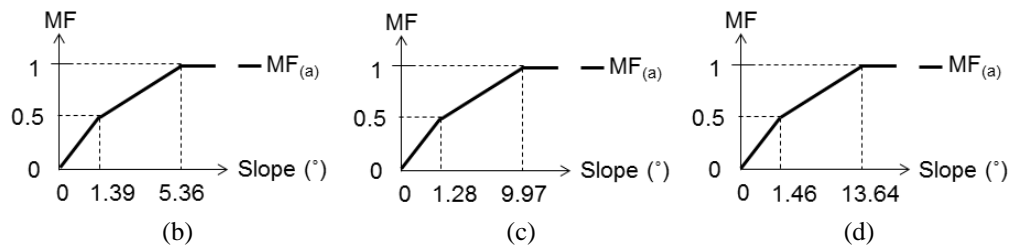
(b)　　　　　　　　　(c)　　　　　　　　　(d)

(b)　　$MF_{(a)} = 0.36 \cdot X \ where \ X \ (X \leq 1.39)$ 　　　　　　　　(7)
　　　　$MF_{(a)} = 0.126 \cdot X \ where \ X \ (X > 1.39 \ and \ X \leq 5.36)$
　　　　$MF_{(a)} = 1 \ where \ X \ (X > 5.36)$

(c)　　$MF_{(a)} = 0.391 \cdot X \ where \ X \ (X \leq 1.28)$ 　　　　　　　　(8)
　　　　$MF_{(a)} = 0.058 \cdot X \ where \ X \ (X > 1.28 \ and \ X \leq 9.97)$
　　　　$MF_{(a)} = 1 \ where \ X \ (X > 9.97)$

(d)　　$MF_{(a)} = 0.342 \cdot X \ where \ X \ (X \leq 1.46)$ 　　　　　　　　(9)
　　　　$MF_{(a)} = 0.041 \cdot X \ where \ X \ (X > 1.46 \ and \ X \leq 13.64)$
　　　　$MF_{(a)} = 1 \ where \ X \ (X > 13.64)$

Figure 10. Fuzzy-set membership functions of (a) Attribute 3 of the definition of seamounts, (b) Kiminu Seamount, (c) Anyongbok Seamount, and (d) Haeoreum Seamount

Figure 11. Visualization of Figures 10(b), 10(c), and 10(d): (1) Kiminu Seamount (Figure 10b), (2) Anyongbok Seamount (Figure 10c), and (3) Haeoreum Seamount (Figure 10d)
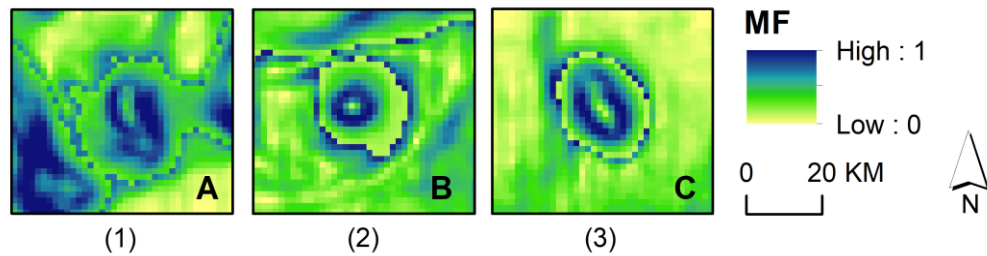
Figure 11 visualizes the fuzzy-set membership values of the definition of seamounts for the three seamounts in the study areas. Figures 8(1), 8(2), 8(3), 9(1), 9(2), 9(3), 11(1), 11(2), and 11(3) demonstrate semantic differences in the three definitions (attributes 1, 2, and 3) of seamounts. It was difficult to determine whether one definition was superior to the others due to ambiguity of the definitions. As a result, we adopted all three definitions by combining the fuzzy-set MFs of each of the three seamounts. We combined these values by calculating the average of the three raster datasets and creating a new raster dataset that consisted of the average values. Section 4.3 visualizes the results generated by applying the fuzzy-set MFs for seamounts.

4 RESULTS

This section presents the results found using the methods described in Section 3.3 to examine the selected undersea features in the study area.

4.1 Banks

Figure 12 presents the results of Section 3.3.2 concerning the definition of a bank. Figure 12(1) visualizes the fuzzy-set membership values of Hupo Bank (A) based on the attributes of elevation (Figure 4[1]) and slope (Figure 4[2]). Bluer colors indicate a closer fit with the definition of a bank while greener and yellower colors indicate a weaker fit. Figure 12(1) illustrates heterogeneity in the membership values of Hupo Bank's central areas and periphery. However, the existing literature typically represents this heterogeneity with a dot or label (Choi et al.; GEBCO). For most areas of Hupo Bank, the values of the inverse slopes for Attribute 2 of the definition of a bank were very similar. Despite the similarities in relation to Attribute 2, the membership values for Attribute 1a of the definition of a bank revealed clearer differences in fitting with the definition among each pixel within the Hupo Bank area. This variation in membership values exposed the uncertain boundary of the bank.
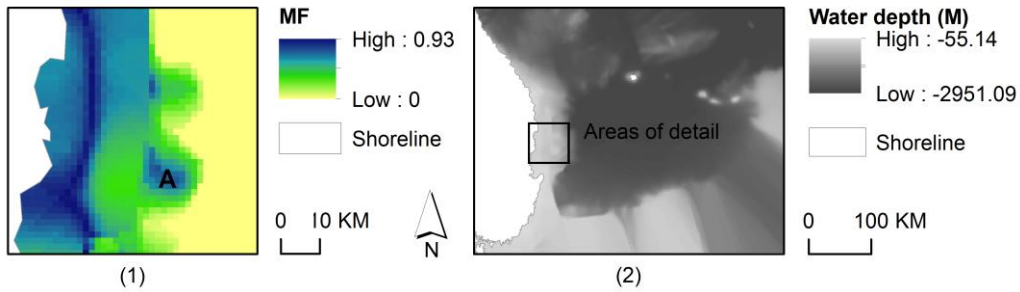
Figure 12. Uncertain boundary of (A) Hupo Bank based on (1) membership values and (2) the bank's location in the study area

4.2   Plateaus
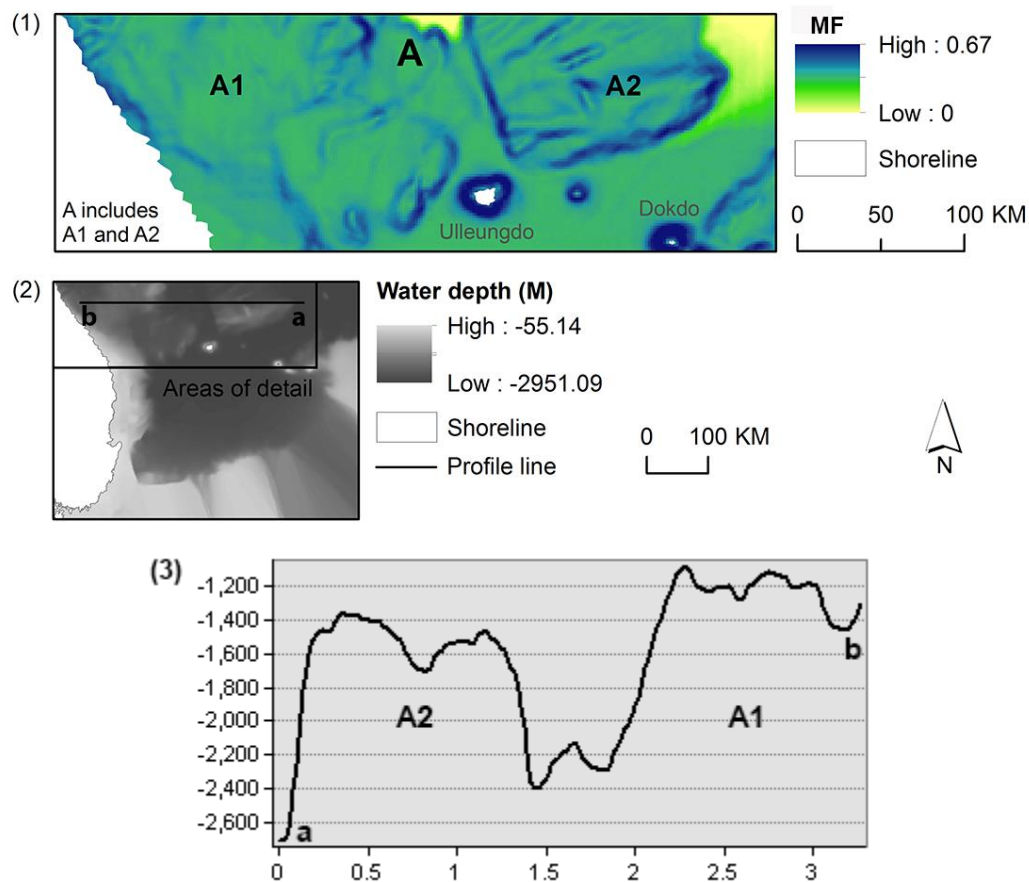
Figure 13. Uncertain boundaries of (A) Korea Plateau, (A1) Gangwon Plateau, and (A2) Ulleung Plateau based on (1) membership values, (2) their locations in the study area, and (3) a profile of the Korea Plateau

Figure 13(1) visualizes the membership values of the three plateaus measured in Section 3.3.2. Areas of Korea Plateau (A) include both Gangwon Plateau (A1) and Ulleung Plateau (A2) (Kim et al. 2012). Figure 13(1) presents the detailed membership values of the three plateaus based on their elevation, the flatness of their top areas, and their slopes.

Bluer colors indicate a closer fit to the definition of a plateau while greener and yellower colors indicate a weaker fit. Figure 13(1) also illustrates the heterogeneity in plateau membership values that the existing literature often represents as dots, labels, or shaded bathymetry (GEBCO; Kim et al.). Additionally, the blue boundaries of Gangwon Plateau (A1) and Ulleung Plateau (A2) in Figure 13(1) indicate higher membership values than other areas with less blue coloring since the membership values were determined based on degrees of elevation, flatness of top areas, and steepness.

Part of the Korea Plateau is in North Korea, and this study examined areas of the plateau that are in South Korea due to the limited availability of bathymetric data. Figure 13(3) presents the profile of the water depth in some areas of Korea Plateau based on line $\overline{ab}$ in Figure 13(2). In Figure 13(3), Ulleung Plateau (A2) is generally deeper than Gangwon Plateau (A1).

4.3   Seamounts
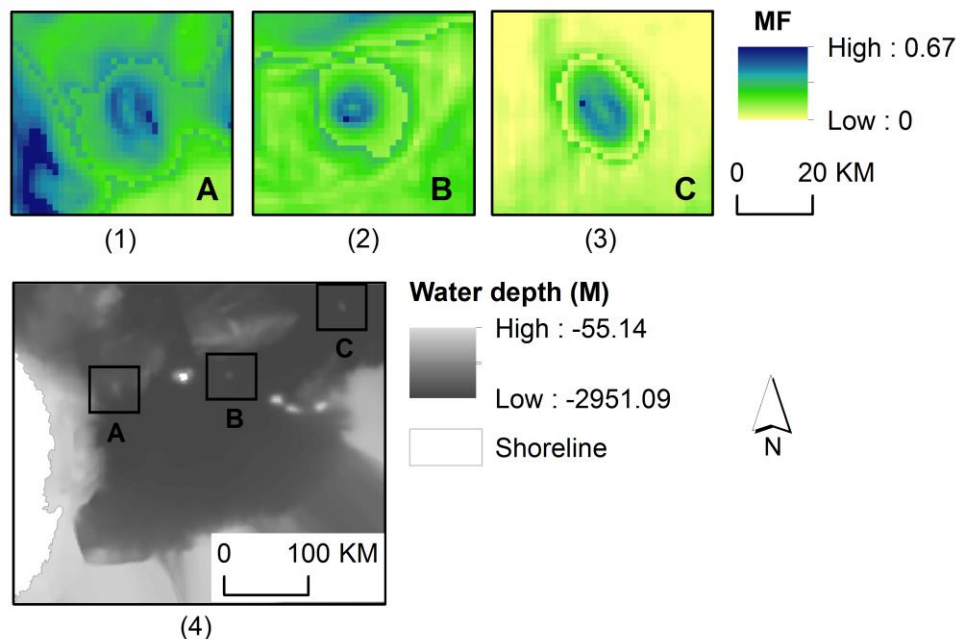
Figure 14. Uncertain boundaries of (A) Kiminu Seamount, (B) Anyongbok Seamount, and (C) Haeoreum Seamount based on (1, 2, 3) their membership values and (4) their locations in the study area

Figure 14 visualizes the membership values of the three seamounts measured in Section 3.3.2 based on elevation, nMI index, and slope. Bluer colors indicate a closer fit to the definition of a seamount while greener and yellower colors indicate a weaker fit. Figures 14(1), 14(2), and 14(3) illustrate heterogeneity in seamounts' degrees of membership that the existing literature represents as dots, labels, or shaded bathymetry (Choi and Kwon; GEBCO). Additionally, the membership values of the periphery areas of the seamounts appear to be much higher than those of the surrounding areas in Figures 14(1), 14(2), and 14(3) because the slopes in the seamount areas change abruptly.

In summary, Figures 12(1), 13(1), 14(1), 14(2), and 14(3) demonstrate a way to represent boundaries of undersea features that have multiple definitions to answer the research question of the study. In specific, they visualize example undersea features

including banks, plateaus, and seamounts on maps by using fuzzy boundaries to address their semantic uncertainty.

5   DISCUSSION

One of two limitations of this study is that its approach to semantic uncertainty addressed only three types of undersea features and focused on parts of their existing definitions. For this reason, the semantics of the definitions developed in this study are limited. Additionally, the fuzzy-set functions of the undersea features in the study area may not be applicable to other undersea features in different regions that are of the same type. The semantic model approach may be a weak method for determining the membership functions of certain parameters (Burrough 1989). For example, values of crossover points and upper and lower bounding in the fuzzy-set memberships of Hupo Bank might not directly apply to other banks in different regions due to their unique undersea environments. In addition, GEBCO provided more realistic values for water depth in the Hupo Bank areas than the definition of a bank presented in other literature discussed in Appendix 1. It is difficult to determine what parameters can be included in universal definitions of undersea feature types, especially when the particular environment of each feature is considered. Though geological processes are universal, they also yield structures and features in different contexts, such as depth or age. The other limitation of this study is that the resolutions of the original bathymetric data and the DEM data driven from the original data are not high enough to capture more detailed characteristics of the undersea features in the study areas. It would be helpful to have higher resolution of bathymetric data available to produce better results of the study.

In this study, we chose linear or trapezoidal functions for the fuzzy-set MFs out of other types of functions since the values of the concepts of water depth, flatness or steepness, elevation, and for slope can be measured straightforward (Robinson; Stefanakis et al. 1999). However, the fuzzy-set MFs might be developed by using non-linear types such as Gaussian and sigmoidal functions to focus on other characteristics of the undersea features—e.g., parametrizing the rate of the function—as well (Robinson). Additionally, this study used the simple average operation to combine multiple fuzzy-set MFs. Other combinatory approaches with different weighted values for each MF could be considered in studies with specific questions.

Besides, some other types of undersea features have uncertain qualitative definitions for which it is difficult to quantify membership values using empirical data (see descriptions for canyons and sea channels in Appendix 2 for details). Future studies should give further consideration to these undersea features.

Stakeholders in the areas of management, planning, research, and environmental policymaking may find GIScience useful for processing multiple types of information (Haddad et al. 2005). Oftentimes academics find it challenging to explain the concept of uncertainty to non-academic stakeholders and policymakers. Geovisualizing uncertainty can be a helpful step for stakeholders working with bathymetric data and hydrographic maps and charts. A future extension of this study could also include development and user evaluations of a web-based interactive system for mapping the uncertain boundaries of undersea features. This system could be beneficial for both stakeholders and the public to communicate with each other about the semantic uncertainty of undersea features. Finally, three-dimensional visualization of the uncertain boundaries of features could support intuitive comparisons of the semantic uncertainties of feature definitions.

6   CONCLUSION

The goal of the study to identify and illustrate semantic uncertainty of the undersea features concept was addressed by the development of fuzzy-set based conceptual descriptions. The fuzzy-set membership functions of the uncertain definitions of the undersea features were analytically measured, combined, and visualized. Three types of undersea features were investigated, and in particular cases the definitions of the undersea features were formally represented in fuzzy-set based conceptual spaces (Figures 2, 3, 5, 7, and 10). When these definitions were applied to empirical bathymetric data, they visualized uncertain fuzzy spatial boundaries of the undersea features.

To answer the research question, we addressed semantic uncertainty in some definitions of undersea features, gauged the semantic uncertainty by using the fuzzy-set approach, and visualized the fuzzy boundaries of the undersea features by using GIScience. The results of this study indicate that the semantic uncertainty of the definitions of the undersea features should be addressed, specifically when representing them on maps. The results showed that the fuzzy-set approach is useful for capturing semantic uncertainty in some definitions of undersea features. We argue that geographical extent of the undersea features that have the semantic uncertainty should be visualized by using fuzzy boundaries rather than point features or crisp boundaries. As illustrated in Section 4, the fuzzy-set approach can clearly reveal heterogeneity in membership of definitions that may be missed by non-fuzzy or crisp approaches. Based on these findings, this study provides a new application for research on semantic uncertainty in GIScience.

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APPENDIX

Appendix 1. Existing definitions of the undersea-feature types in the study areas (S-32 [IHO 1994]; B-6 [IHB 2013]; Gazetteer [GEBCO 2018]; ACUF 2005; Glossary of Geology [Neuendorf 2005])

Type	Reference	Definition
Bank	S-32	an isolated (or group of) elevation(s) of the sea floor, over which the depth of water is relatively shallow, but sufficient for safe surface navigation
	Gazetteer and B-6	an elevation at depths generally less than 200 m, but sufficient for safe surface navigation. Commonly found on the continental shelf or near an island
	ACUF	elevations, typically located on a shelf, over which the depth of water is relatively shallow but sufficient for safe surface navigation
	Glossary of Geology	a relatively flat-topped elevation of the seafloor at shallow depth (generally less than 200 m), typically on the continental shelf or near an island
Basin	S-32 and B-6	a depression, in the sea floor, more or less equidimensional in plan and of variable extent
	Gazetteer and ACUF	a depression more or less equidimensional in plan and of variable extent
	Glossary of Geology	a more or less equidimensional depression of the seafloor
Escarp-ment	S-32 and B-6	an elongated, characteristically linear, steep slope separating horizontal or gently sloping sectors of the sea floor in non-shelf areas

	Gazetteer	an elongated, characteristically linear and steep slope that separates horizontal or gently sloping regions
	ACUF	an elongated and comparatively steep slope separating flat or gently sloping areas
	Glossary of Geology	a long, more of less continuous cliff or relatively steep slope facing in one general direction, breaking the continuity of the land by separating two level or gently sloping surfaces, and produced by erosion or faulting
Gap	S-32, B-6, and ACUF	a narrow break in a ridge or a rise
	Gazetteer	a narrow break in a ridge, rise or other elevation
	Glossary of Geology	a passage that connects two abyssal plains of different levels, through which clastic sediments are transported
Plateau	S-32 and B-6	a flat or nearly flat elevation of considerable areal extent, dropping off abruptly on one or more sides
	Gazetteer	a large, relatively flat elevation that is higher than the surrounding relief and has one or more relatively steep sides
	ACUF	a comparatively flat-topped feature of considerable extent, dropping off abruptly on one or more sides
	Glossary of Geology	a broad, more or less flat-topped and ill-defined elevation of the seafloor, generally over 200 m in elevation
Reef	S-32	a mass of rock or coral which either reaches close to the sea surface or is exposed at low tide, posing a hazard to navigation
	B-6	a mass (or group) of rock(s) or other indurated material lying at or near the sea surface that may constitute a hazard to surface navigation
	Gazetteer	a shallow elevation composed of consolidated material that may constitute a hazard to surface navigation
	ACUF	a surface-navigation hazard composed of consolidated material
	Glossary of Geology	a ridgelike or moundlike structure, layered or massive, built by sedentary calcareous organisms, especially corals, and consisting mostly of their remains; it is wave-resistant and stands above the surrounding contemporaneously deposited sediment
Ridge	S-32	a long elevation of the ocean floor with either irregular or smooth topography and steep sides, often separating ocean basins
	B-6	an isolated (or group of) elongated narrow elevation(s) of varying complexity having steep sides
	Gazetteer	an elongated, elevated feature of varying complexity and size
	ACUF	a long narrow elevation with steep sides
	Glossary of Geology	an elongate, steep-sided elevation of the ocean floor, having rough topography
Seamount	S-32	an isolated or comparatively isolated elevation rising 1,000m or more from the sea floor and of limited extent across the summit
	B-6	a discrete (or group of) large isolated elevation(s), greater than 1,000m in relief above the sea floor, characteristically of conical form
	Gazetteer	a distinct generally equidimensional elevation greater than 1,000m above the surrounding relief as measured from the deepest isobath that surrounds most of the feature
	ACUF	an elevation rising generally more than 1,000m and of limited extent across the summit

Type	Reference	Definition
Table-mount	S-32 and B-6	an isolated (or group of) seamount(s) having a comparatively smooth flat top
	Gazetteer and ACUF	a seamount having a comparatively smooth flat top
	Glossary of Geology	a type of seamount that has a flat top
Trough	S-32, B-6, and ACUF	a long depression of the sea floor characteristically flat bottomed and steep sided and normally shallower than a trench
	Gazetteer	a long depression generally wide and flat bottomed with symmetrical and parallel sides
	Glossary of Geology	an elongate depression of the sea floor that is wider and shallower than a trench, with less steeply dipping sides

(top partial row) Glossary of Geology — an elevation of the sea floor, 1,000m or higher, either flat-topped (called a guyot) or peaked (called a seapeak). Seamounts may be either discrete, arranged in a linear, random grouping, or connected at their bases and aligned along a ridge or rise

Appendix 2. Existing qualitative definitions of some types of undersea features (S-32 [IHO 1994]; Gazetteer [GEBCO 2018]; ACUF; Glossary of Geology [Neuendorf 2005])

Type	Reference	Definition
Canyon	S-32 and B-6	an isolated (or group of) relatively narrow, deep depression(s) with steep sides, the bottom of which generally deepens continuously, developed characteristically on some continental slopes
	Gazetteer	an elongated, narrow, steep-sided depression that generally deepens down slope
	ACUF	a relatively narrow, deep depression with steep sides, the bottom of which generally has a continuous slope
	Glossary of Geology	a long, deep, relatively narrow, steep-sided valley confined between lofty and precipitous walls in a plateau or mountains area
Sea channel	S-32 and B-6	a continuously sloping elongated discrete (or group of) depression(s) found in fans or abyssal plains and customarily bordered by levees on one of both sides
	Gazetteer	an elongated, meandering depression, usually occurring on a gently sloping plain or fan
	ACUF	a continuously sloping, elongated depression commonly found in fans or plains and customarily bordered by levees on one or two sides
	Glossary of Geology	N/A