Application of Coastal and Marine Ecological Classification Standard (CMECS) to remotely operated vehicle (ROV) video data for enhanced geospatial analysis of deep sea environments

By

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The Coastal and Marine Ecological Classification Standard (CMECS) provides a comprehensive framework of common terminology for organizing physical, chemical, biological, and geological information about marine ecosystems. Federally endorsed as a dynamic content standard, all federally funded data must be compliant by 2018; however, applying CMECS to deep sea datasets and underwater video have not been extensively examined. The presented research demonstrates the extent to which CMECS can be applied to deep sea benthic habitats, assesses the feasibility of applying CMECS to remotely operated vehicle (ROV) video data in near-real-time, and establishes best practices for mapping environmental aspects and observed deep sea habitats as viewed by the ROV's forward-facing camera. All data were collected during 2014 in the Northern Gulf of Mexico by the National Oceanic and Atmospheric Administration's (NOAA) ROV *Deep Discoverer* and ship *Okeanos Explorer*.

DEDICATION

I dedicate this work to all my friends and family who offered solace during late night calls and celebrated all the minuscule achievements along the way. A special feeling of gratitude goes towards Daniel T. John for providing emotional support and not hesitating to scribble over the numerous drafts with a very bold, red pen (insert obnoxiously long list of unnecessary items here, here, here, and here). Above all, I especially would like to thank Gregory H. Ruby – a physical oceanographer for over 37 years and the world's best dad since 1992 – for instilling my love for the sea and inspiring me to boldly travel the world. No matter what vessel I embark on or ocean I sail, I will always be your first mate, dive buddy, and little girl.

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CHAPTER I

INTRODUCTION

Deep sea exploration is conducted by numerous governments, private companies, non-governmental organizations, and academic institutions using a range of platforms and sensors. One such platform commonly used for deep sea exploration are tethered robotic submersibles known as remotely operated vehicles (ROVs), which are often employed to collect underwater video imagery. The resulting underwater video data are an integral part of deep sea research and reveal aspects of that environment that are not generally available from other data sources or platforms. Deep sea ROV video imagery provides significant scientific as well as societal benefits and is becoming more widely available to researchers. However, despite some initial organizational workshops, the oceanographic community has yet to coalesce around a single strategy for managing, streaming, annotating, storing, archiving, and spatially depicting this relatively new data format.

One strategy for effective management of ROV video data is the creation of a standard method for classifying environmental features observed in the video imagery. To that end, the Federal Geographic Data Committee (FGDC) approved the Coastal and Marine Ecological Classification Standard (CMECS) as a dynamic content standard in 2012 in order to ensure uniformity of marine environmental classification across different spatiotemporal scales and geographic locations [*U.S. Geological Survey*, 2012]. CMECS is a lexicon of common marine nomenclature that provides a comprehensive and flexible framework for classifying biological species, water column properties, and seafloor morphology as well as composition. CMECS was developed to accommodate a range of data sources focusing on estuarine, lacustrine, coastal, and offshore environments, including the deep sea [*Federal Geographic Data Committee*, 2012]. Although CMECS is designed for application to underwater video imagery, investigators within the oceanographic research community have not widely adopted this federally mandated standard to classify deep sea video data. The hierarchal structure and ability of CMECS to consolidate complex ecological information from different data sources is valuable to regulators and policy makers – especially where data coverage is relatively low, access is limited, and vulnerable habitats are being negatively impacted at a rapid rate (i.e., deep sea habitats) [*Ramirez-Llodra et al.*, 2010; *Stolt et al.*, 2011; *Federal Geographic Data Committee*, 2012; *Carollo et al.*, 2013; *Weaver et al.*, 2013; *Neves et al.*, 2014; *Yoskowitz et al.*, 2016].

NOAA's Office of Exploration and Research (OER) holds a federal legislative mandate to explore our largely unknown ocean for the purpose of discovery and the advancement of knowledge [*United States Senate*, 2009]. NOAA's Ship *Okeanos Explorer* is operated by OER and is currently the only federally funded ship designated for ocean exploration. Outfitted with a suite of oceanographic instruments, *Okeanos Explorer* operates two ROVs capable of diving to 6,000 meters along with complex sonar systems capable of mapping elements within the water column, seafloor bathymetry, and subsurface stratigraphy at water depths upwards of 9,000 meters. The ship is also equipped with a state-of-the-art telepresence system that broadcasts near-real-time communications (audio and video) and scientific information (e.g., bathymetry, ROV video, etc.) to shore-side scientists and the public via satellite and internet [*Manley*, 2008; *National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2014].

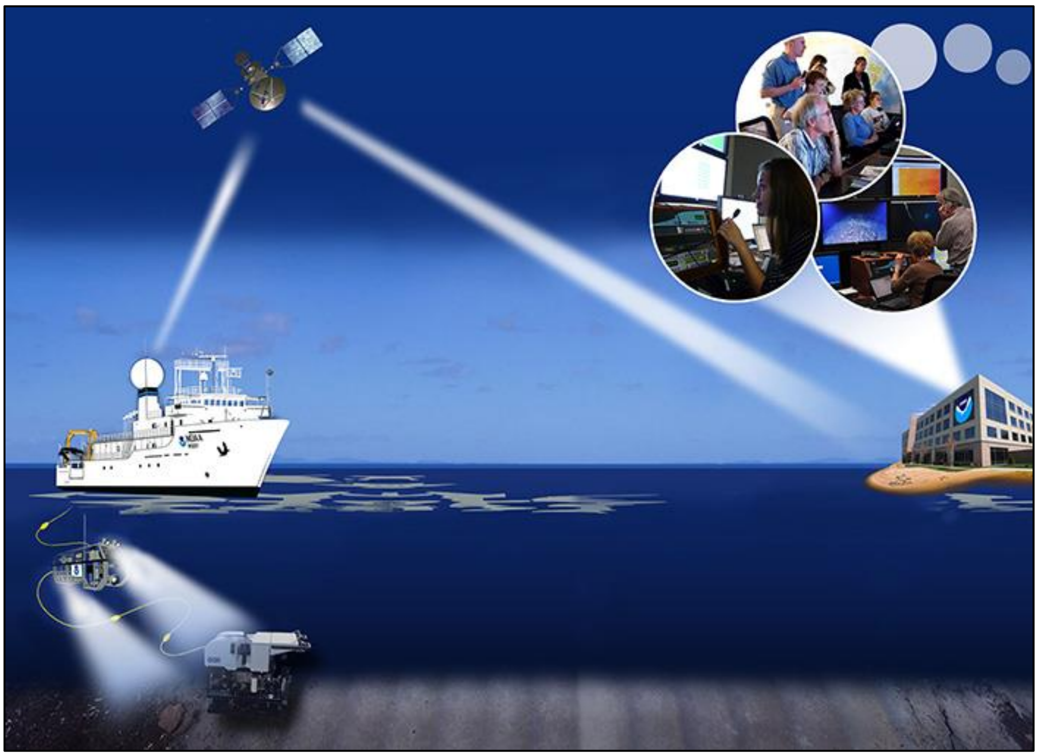

Figure 1.1 *Okeanos Explorer* Telepresence System

The telepresence system onboard the *Okeanos Explorer* allows shore-side researchers to interact with shipboard scientists and technicians during the initial collection of data with minimal delay of live ROV video data. The tandem arrangement of ROVs via a fiber optics tether, with *Seirios* situated between the ship and *Deep Discoverer*, is also portrayed [*National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2015].

Bathymetric mapping data, video clips, highlight images, scientific notes, event logs, dive descriptions, environmental observations, and other summary products generated by the *Okeanos Explorer* and its ROVs are uploaded to OER's *Ocean Exploration Digital Atlas*[1] for public distribution 15-90 days after the conclusion of each exploratory cruise. Presently, these video data are most often utilized by scientists directly involved with *Okeanos Explorer* expeditions as a result of knowledge gained through their participation in the initial collection process. Unfortunately, many scientists not directly involved in the collection of these data do not use this potentially valuable data source due to the amount of time that is necessary to review tens to hundreds of hours of video in order to determine its relevance to their research goals.

The OER Video Portal[2] was recently established to provide external scientists with a platform for querying, discovering, and accessing video data from *Okeanos Explorer*. Although this website supports queries based on keywords, observation dates, depth parameters, dive site name, cruise name, and geographic coverage, a visualization tool for geospatially representing video content is not provided. Nonetheless, having the ability to view and search for the spatial distribution of a particular characteristic (e.g., substrate) or a single attribute (e.g., glass sponges) throughout the entire video archive would lessen the amount of time spent analyzing unwarranted video and would promote scientific inquiry. Innovative visualization tools presented herein will allow external scientists, otherwise unfamiliar with OER video data, to rapidly determine the abundance and spatial distribution of features of interest, and thus assess the applicability of video data obtained by *Okeanos Explorer* and its ROVs to their research goals.

[1]OER's *Ocean Exploration Digital Atlas* web address: www.ncddc.noaa.gov/website/google_maps/OE/mapsOE.htm

[2] OER's Video Portal web address: www.nodc.noaa.gov/oer/video

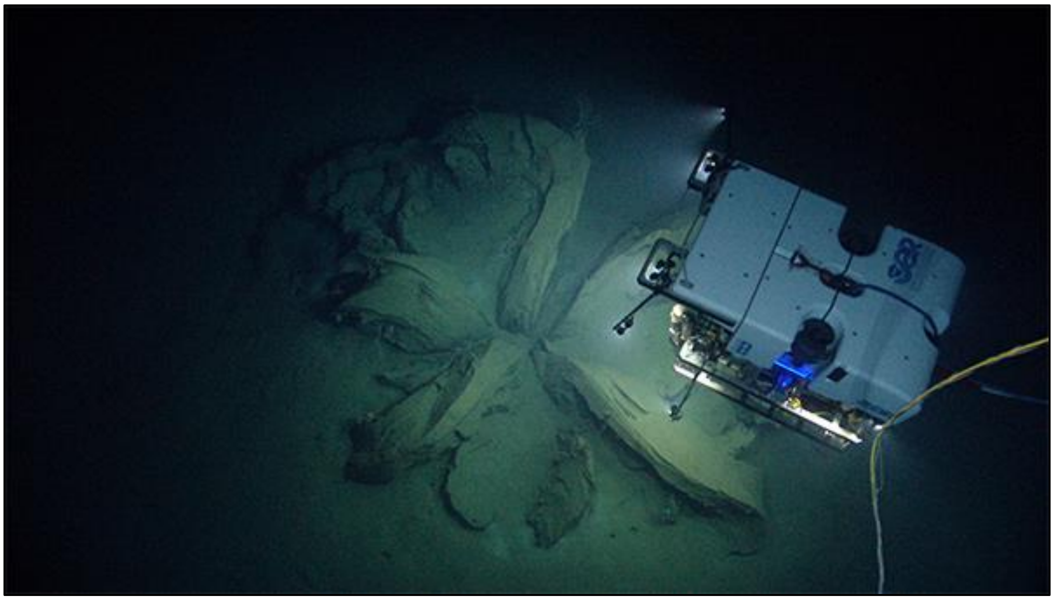

Figure 1.2 ROV *Deep Discoverer*

Seirios retains an “aerial” view of *Okeanos Explorer*’s main ROV *Deep Discoverer* for improved navigation around seafloor features. In this image, the ROVs are investigating a newly discovered extruded tar lily originally thought to be a shipwreck in the Northern Gulf of Mexico (EX1402L3 *Seirios* Highlight Image).

Guidance for applying CMECS to deep sea environments and underwater video is vital to those affected by the NOAA mandate requiring full adoption and implementation of CMECS by 2018, including those who oversee data collected by *Okeanos Explorer*’s main ROV *Deep Discoverer* [*National Science and Technology Council*, 2016]. CMECS implementation on ROV video data when combined with the existing event log – a text document containing all scientific entries between shipboard and shore-side scientists during the initial collection of video data – will result in a consistent ecological index of each ROV dive considerably more valuable than current methods alone. Integrating CMECS components and subunits within the accompanying metadata files will increase data visibility by providing a more standardized approach for querying the data.

Representing ecosystem classifications and other measured environmental characteristics geospatially is necessary to adequately visualize and evaluate spatial relationships within the observed benthic habitats. Previously, CMECS has most often been applied to shallow water ecosystems with large spatial extents and data obtained through more traditional, non-video methods (e.g., aerial and satellite imagery, systematic surveying, and sonar data). Unlike *Deep Discoverer*, conventional seafloor mapping endeavors that use ROVs as the primary data source collect those data in a systematic grid pattern. Accordingly, mapping spatially constrained deep sea video observations made by *Deep Discoverer* within the aphotic zone deviates from standard practice and requires an unconventional approach. Therefore, a CMECS-compliant visualization system, customized for the deep sea, that allows members of the scientific community to rapidly determine if video data content is relevant to their research based on geospatial coverage of the observed characteristics would strengthen OER's Video Portal, satisfy the upcoming CMECS mandate, and directly benefit internal and external scientists.

To address the literary gap pertaining to CMECS applications within deep sea environments and provide guidance to those performing research with ROV video data as well as present NOAA with visualization tools for displaying water column properties and video content, the presented research utilizes data acquired by *Okeanos Explorer* and its ROV *Deep Discoverer* during the 2014 Exploration of the Gulf of Mexico to demonstrate the following:

- The extent in which CMECS may be applied to deep sea benthic habitats

- The practicability of implementing CMECS to ROV video and ancillary data in near-real time applications
- Processing techniques necessary to generate cartographic representations of the observed CMECS-compliant data for enhanced spatial analyses within a GIS

This work evaluates the extent to which CMECS can be applied to deep sea benthic habitats in the Northern Gulf of Mexico through analysis of one hundred extracted ROV images (frame grabs) and assesses the feasibility of applying the classification scheme in near-real-time to underwater video data collected from ten ROV dives in the same geographic region. The presented geospatial techniques depict environmental aspects of the surrounding water column by producing interpolated surfaces of salinity, dissolved oxygen concentration, temperature, and local bathymetry, as well as CMECS-compliant classification maps of the observed benthic habitats. Two data mapping approaches – buffered and viewshed – were employed on subsequent video classifications to ascertain a preferred method for data visualization. The buffered approach annularly maps specified CMECS units; while the viewshed approach only maps within the seafloor domain presumably viewed by the ROV's forward-facing camera. Methods found herein provide CMECS guidance for deep sea and ROV video applications as well as best practices for annotating and spatially depicting ROV video observations for enhanced geospatial analysis of deep sea benthic habitats.

CHAPTER II

LITERATURE REVIEW

2.1 OER & *Okeanos Explorer*

Established in 2007, NOAA's Office of Ocean Exploration and Research (OER) is the first government agency dedicated to discovery, innovation, and systematic exploration of the world's oceans. OER is tasked with increasing scientific knowledge, generating new avenues of scientific inquiry, developing and utilizing an array of advanced technologies, and publically distributing all observed data, research, and discoveries [*Anon*, 2009; *National Oceanic and Atmospheric Administration*, 2010a, 2010b, 2011]. Between 2004 to 2008, the United States Navy Ship *Capable* (T-AGOS 16) was decommissioned, converted into a NOAA research vessel, and renamed *Okeanos Explorer* (R 337) in order to serve the exploration mission of OER. Originally configured as a submarine surveillance vessel, the ship underwent significant modifications during the conversion process to accommodate multiple sonar systems, ROVs, a dynamic positioning system, and telepresence capabilities [*Manley*, 2008; *National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2016].

Okeanos Explorer functions in two exploration modes: mapping cruises (small scale surveys using sonar systems) and ROV cruises (large scale surveys of more detailed observations). In general, mapping cruises are performed prior to and in conjunction with ROV cruises to establish areas of interest for more detailed ROV investigations. Ship operations range from reconnaissance, site characterization, and water column exploration to opportunistic surveying [*National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2016]. Knowledge generated by OER and *Okeanos Explorer* – as related to complex climate, coastal, and ocean systems – further enables the broader agency of NOAA to protect, restore, and manage observed ecosystems [*Anon*, 2009; *National Oceanic and Atmospheric Administration*, 2010a].

2.2 ROV *Deep Discoverer*

Okeanos Explorer has been equipped with the unmanned ROV *Deep Discoverer* since 2013. *Deep Discoverer* has six high-definition video cameras; two robotic arms; four lighting swing bars providing 144,000 lumens of light; four sample collection boxes; and a conductivity, temperature, and depth instrument (CTD) with an attached dissolved oxygen sensor [*Manley*, 2008; *National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2016; *Rogers*, 2016]. The main, forward-facing camera onboard *Deep Discoverer* is an Insite Pacific Zeus Plus HDTV color zoom camera with a 10:1 super wide angle zoom lens [*Rogers*, 2016]. Additionally, two forward positioned lasers at a fixed 10 centimeter separation provide a scale for size estimations of observed objects. Video data exist in three resolutions: full-length resolution broadcast quality (145 Mbps, 1080i, ProRes 422 SQ), “high” resolution video highlights (10 Mbps), and “low” resolution segments for web streaming (1.5 Mbps). All archived video are encoded with a time-stamp and geo-reference coordinates. ROV navigation (coordinates, depth, and altitude) and attitude (heading, pitch, and roll) information are also recorded in a log file. *Deep Discoverer* is accompanied by a secondary ROV, *Seirios*, which carries an additional high-definition camera, 108,000 lumens of light, as well as a CTD and dissolved oxygen sensor. The tandem ROVs can dive to a maximum depth of 6,000 meters (Figure 1.1) [*National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2016; *Rogers*, 2016].

2.3 Gulf of Mexico Exploration

The Gulf of Mexico is a semi-enclosed 1,500,000 square kilometer basin located south of the United States of America and east of Mexico. The Gulf of Mexico encompasses an array of complex geologic features, diverse ecosystems, and natural resource reserves, which provide the surrounding populous with numerous cultural (e.g., shipwrecks), economic (e.g., resource extraction), and recreational (e.g., deep sea fishing) resources [*Aharon and Fu*, 2000; *Powell and Haedrich*, 2003; *Cordes et al.*, 2008; *Ramirez-Llodra et al.*, 2010; *Carollo et al.*, 2013; *Allee et al.*, 2014; *Yoskowitz et al.*, 2016]. Bathymetric features transition basinward from coastal plains, continental shelves, slopes, and rises to an abyssal plain. Deep sea benthic habitats in the Gulf of Mexico range from reef-forming cold water coral and sponge communities to complex chemosynthetic ecosystems [*Aharon et al.*, 1992; *Aharon and Fu*, 2000; *Powell et al.*, 2003; *Cordes et al.*, 2008].

Okeanos Explorer conducted cruises in the Gulf of Mexico during the 2011, 2012, and 2014 field seasons. Ship missions in 2011 were limited to testing the newly added multibeam and singlebeam sonar systems which imaged hydrocarbon seeps. Two mapping cruises and one ROV cruise took place in 2012 using the now retired ROV *Little Hercules*. *Okeanos Explorer* spent 2013 surveying the Northeast Atlantic and then returned to the Gulf of Mexico for the 2014 field season. Two mapping cruises and one ROV cruise were performed as part of the 2014 Exploration of the Gulf of Mexico mission. Cruises focused on surveying bathymetric (i.e., submarine canyons and salt domes) and water column (i.e., hydrocarbon seeps and mud volcanos) features as well as cultural heritage sites (i.e., shipwrecks) in the northern and eastern portions of the Gulf of Mexico [*National Oceanic and Atmospheric Administration - Office of Ocean Exploration and Research*, 2014]. This thesis focuses on data collected within the Northern Gulf of Mexico during cruise number EX1402L3 of the 2014 field season as this was the only time that *Deep Discoverer* was used in the region.

Figure 2.1 2014 Investigations within the Northern Gulf of Mexico

Bathymetric features explored by *Okeanos Explorer*'s sonar and ROV systems during EX1402L3 are depicted. The eastern portions along the West Florida Escarpment are not shown as they were not used within this study.

2.4 ROV Video Annotations

The rapid technological advancement of video cameras used on ROVs has created a data access and management problem within the oceanographic research community. Streaming, annotating, storing, and archiving video data has become problematic with the file size of today's high-definition cameras far exceeding those of traditional lower definition data formats. Many organizations are independently developing various video processing techniques resulting in disparate progress. Members of the oceanographic community have been working towards common solutions for these issues through scientific workshops and meetings (e.g., Underwater Video Workshop (June 2016), NOAA's Environmental Data Management Workshop (January 2017), and CMECS GeoTools Special Interest Meeting (February 2017)). However, the community has yet to develop and agree upon a common strategy for working with this relatively new and challenging data format.

Video annotations are a textual way of identifying visual content. Transcribing video data and indexing it by time and location allow users to search through the observable content for data of interests without having to watch the full video recording. Thorough video annotations are imperative for discoverable, useable, and understandable underwater video archives and metadata files [*Monterey Bay Aquarium Research Institute*, n.d.; *Juniper et al.*, 2000; *Leslie et al.*, 2010; *Jenkyns et al.*, 2013; *Anon*, 2016; *Bassett et al.*, 2017]. Similar to other aspects regarding underwater video, there is no single standardized approach, software, or terminology index for annotating video data.

Monterey Bay Aquarium Research Institute's (MBARI) Video Annotation and Reference System (VARS), Canadian Scientific Submersible Facility's (CSSF) Interactive Real-Time Logging System (IRL), Ocean Networks Canada's (ONC) SeaScribe, and Instant Messaging Service (IMS) chatrooms are some of the leading annotation approaches currently employed by members of the oceanographic research community. VARS is a software interface and database system that provides various tools for annotating, cataloging, retrieving, and viewing near-real-time and archived video; VARS is not limited to a single ROV platform or video format and is considered applicable to any video dataset that requires searchable annotations [*Monterey Bay*

Aquarium Research Institute, n.d.]. IRL is a Hypertext Markup Language (HTML) designed for annotating video collected by the ROPOS (Remotely Operated Platform for Ocean Sciences) ROV. This data acquisition and archiving system provides a geographical user interface (GUI) to a network of computers which allows each scientist to annotate independently. IRL compiles various inputs and annotations into a searchable file format at the end of each ROV dive [*Juniper et al.*, 2000; *Leslie et al.*, 2010]. The SeaScribe software interface allows multiple analysts to concurrently annotate underwater video in real-time. SeaScribe is neither ship nor ROV specific and generated outputs transition well into SeaTube – an ONC portal for archived video and ancillary data [*Jenkyns et al.*, 2013].

Current annotation efforts for *Deep Discoverer* are limited to text entries made by shore-side and shipboard scientists through an IMS group chatroom; these annotation entries make up the accompanying event log. OER provides a list of abbreviations for common observations – referred to as dive codes – to help standardize video annotations. The following bullets represent some of the dive codes applied to video collected by *Deep Discoverer*[3].

- BIV – Bivalve
- COR – Coral
- CNI – Cnidarian
- FSH – Fish
- USO – Unidentified sessile object

[3] The most up-to-date dive codes are accessible online at: http://oceanexplorer.noaa.gov/okeanos/collaboration-tools/im-eventlog/dive-codes.html.

- SAD – Sand
- CAR – Carbonate Feature
- SCP – Scarp
- ANT – Anthropogenic Object (trash, trap lines, etc.)

Unfortunately, event log entries are manually transcribed and are prone to misspellings, unrelated conversations, and timestamp disparities. Many of these dive codes are embedded within the attached ROV metadata files.

A separate python-based ROV Data Analyzer software developed by Mashkoor Malik, of OER, was employed as a means to address issues related to CMECS implementation on deep sea habitats and ROV video. This software produces a "hot keyboard" GUI of up to 60 unique identifiers or "keys". The hot keyboard interface is similar to keyboard shortcuts in that a selected key represents a specific annotation which is then integrated into a generated output text file containing concomitant ROV coordinates, video timestamp, and annotator's name. This software is specific to underwater video and ancillary data similarly formatted to that collected by ROV *Deep Discoverer*. Additionally, the software has since been adjusted and is theoretically applicable to real-time annotations of live ROV video collected by *Deep Discoverer* (M. Malik, personal communication, 2016). The presented work employs the ROV Data Analyzer software because of its intended use for *Deep Discoverer* datasets, ability to annotate post-dive video, the generated output format, and possible applicability to live *Deep Discoverer* video data in real-time operations.

2.5 Coastal and Marine Ecological Classification Standard (CMECS)

The Marine and Coastal Spatial Data Subcommittee of the Federal Geographic Data Committee (FGDC) endorsed and published the Coastal and Marine Ecological Classification Standard (CMECS) in June of 2012 [*Federal Geographic Data Committee*, 2012; *U.S. Geological Survey*, 2012]. This document is the first to assimilate estuarine, lacustrine, coastal, and offshore environments into a single classification scheme compatible with all observational technologies and methodologies. This broad applicability facilitates the integration of existing datasets from a range of platforms and sensors. These attributes along with the hierarchal structure make CMECS valuable to regulators and policy makers who often need to compile complex datasets to make informed decisions [*Stolt et al.*, 2011; *Carollo et al.*, 2013; *Weaver et al.*, 2013].

Published literature, existing classification schemes, expert opinions, extensive field testing, and multiple peer reviews were used to develop, assess, and revise the CMECS document. A 120-day public comment period in August 2010 also allowed the marine science community to evaluate the document [*U.S. Geological Survey*, 2012]. Additionally, the standard will periodically undergo subsequent revisions to maintain relevance [*Federal Geographic Data Committee*, 2012]. Once widely applied, CMECS will facilitate interdisciplinary research and decision-making across terrestrial and coastal ecosystem boundaries as well as support conservation management objectives, habitat suitability models, resource exploitation oversight, and change detection programs across varying political jurisdictions and spatiotemporal scales [*Madden and Goodin*, 2007; *Shumchenia and King*, 2010; *Gandomi et al.*, 2011; *Stolt et al.*, 2011; *Federal Geographic Data Committee*, 2012; *U.S. Geological Survey*, 2012; *Carollo et al.*, 2013;

Allee et al., 2014; *Neves et al.*, 2014; *Yoskowitz et al.*, 2016; *Bassett et al.*, 2017]. NOAA mandates full utilization of CMECS by federally funded organizations and projects by 2018 [*National Science and Technology Council*, 2016].

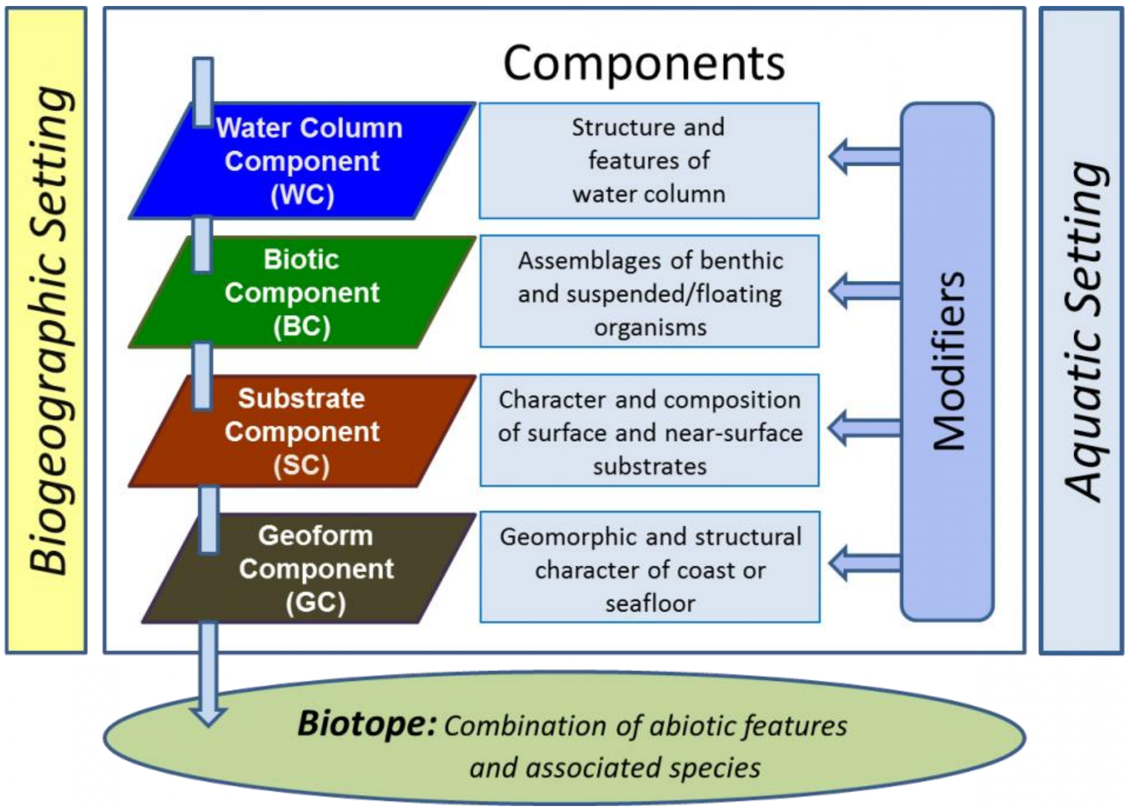

Figure 2.2 CMECS Structure

The general structure along with apt descriptions of CMECS settings, components, modifiers, and biotope along are conveniently displayed above [*Federal Geographic Data Committee*, 2012].

CMECS is divided into two settings (biogeographic and aquatic) and four components (water column, geoform, substrate, and biotic). Settings provide general descriptors to the location under investigation while components contribute hierarchal identifiers for existing biology, features within the water column, and the morphology as well as composition of the seafloor. The water column component describes the bathymetric layer in which the data are being collected along with the surrounding salinity, temperature, hydroforms, and biogeochemical features. The geoform component characterizes regional and local bathymetric features – the tectonic, physiographic, and level 1 geoforms are intended for regional use (> $1km^2$) while smaller features (< $1km^2$) are represented as level 2 geoforms. The substrate component specifies seafloor composition and origin (geologic, biogenic, or anthropogenic). The biotic component identifies benthic biology that are fixed (e.g., attached, burrowing, or inferred) or closely associated with the seafloor (i.e., slow moving organisms that cannot move beyond the defined unit boundary within one day) and suspended or floating planktonic organisms (e.g., algae, jellyfish, or microbes). Free-swimming organisms (e.g., fishes, marine mammals, or cephalopods) are not included within this classification scheme. Additionally, CMECS offers descriptive modifiers where components may be lacking.

All classifications are defined by the dominant feature (> 50% coverage, composition, biomass, or numbers of individuals). Less dominant contributors (< 50%) within the substrate and biotic components may be classified under the subsequent co-occurring elements modifier (substrate and biotic modifiers) and associated taxa (biotic modifier only). Classified components and their associated subunits can be compiled into a biotope; however, this study will not address biotopes due to their complexity, which focuses on specific repeating interactions between biotic communities and particular environmental units. The hierarchal structure of CMECS allows for simplistic classifications when more detailed information is unknown, unobservable, or unwarranted. A website operated by NatureServe – a non-governmental organization that aided in the initial creation of CMECS – provides an easily navigable online database of CMECS components and subunits[4]. For a more complete overview of CMECS and unit definitions, refer to the CMECS Version 4.0 Manual [*Federal Geographic Data Committee*, 2012].

When this project began, no investigators had applied CMECS to deep sea benthic habitats or underwater video datasets. Existing publications focus on assessing CMECS implementations prior to the document's 2012 release; evaluating CMECS as a national schema; applying CMECS to coastal, estuarine, and offshore ecosystems; or translating existing standards [*Madden and Goodin*, 2007; *Todd and Greene*, 2007; *Lund and Wilbur*, 2007; *Cochrane*, 2008; *Keefer et al.*, 2008; *Moses et al.*, 2010; *Shumchenia and King*, 2010; *Trusel et al.*, 2010; *Greene et al.*, 2010; *Harper and Ward*, 2010, 2012; *Stolt et al.*, 2011; *Gandomi et al.*, 2011; *Weaver et al.*, 2013; *De Chambure et al.*, 2013; *Allee et al.*, 2014; *Ansari et al.*, 2014]. Many of the recently published journal articles, reports, tutorials, and tools provide translations between datasets classified with existing schemes to output datasets compliant with the CMECS schema – these translations are commonly referred to as crosswalks [*North Atlantic Landscape Conservation Cooperative*, n.d.; *Madden and Goodin*, 2007; *Harper and Ward*, 2010; *National Oceanic and Atmospheric Administration - Office for Coastal Management*, 2016]. It has been discussed that providing a crosswalk to current practices satisfies the NOAA mandate for CMECS integration.

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[4] NatureServe's CMECS Catalog is accessible online at: cmecscatalog.org.

Recently, Bassett et al. (2017) published a report evaluating the applicability of CMECS to deep sea ROV surveys in the Northeastern Pacific through multiple expeditions performed by the vessels: *Okeanos Explorer* and *E/V Nautilus*. Video classifications were made in real-time via telepresence capabilities through the established IMS by prefacing the annotation with ">CMECS" to comply with the upcoming CMECS mandate. Real-time geoform and substrate annotations are limited to the subsequent event logs and were not geospatially represented. Image classifications and the water column components were defined post-dive. A MS Access database was used to house image classifications, while water column information were classified within a tabular format based on minimum and maximum values. The study did not delve into the biotic component as they determined its complexity warrants separate consideration [*Bassett et al.*, 2017].

2.6 Representing the Data Geospatially

2.6.1 Cartographic Depictions of CMECS-Compliant Datasets

Given that CMECS is focused on the classification of ecosystem properties at varying hierarchal levels, spatiotemporal scales, and data formats, the CMECS document intentionally lacks direct mapping and modeling protocols allowing users to spatially depict classified environments as they deem appropriate. Some guidance for cartographically representing compliant datasets is discussed, but no stipulations are enforced. Mapping in CMECS units is a geospatial representation of the distribution, extent, patterns, and variation of the observable ecological features [*Federal Geographic Data Committee*, 2012]. Literature review yielded many publications that included map products of the classified habitats which emphasized the relevance for depicting compliant datasets in a geospatial manner. Mapped environmental aspects represented all four components (geoform, substrate, water column, and biotic) with varying spatiotemporal resolution, spatial extent, and ecosystem concentrations [*Todd and Greene*, 2007; *Lund and Wilbur*, 2007; *Madden and Goodin*, 2007; *Cochrane*, 2008; *Trusel et al.*, 2010; *Greene et al.*, 2010; *Harper and Ward*, 2010, 2012; *Moses et al.*, 2010; *Shumchenia and King*, 2010; *Gandomi et al.*, 2011; *Stolt et al.*, 2011; *Weaver et al.*, 2013]. Although many of these applications are limited to shallow water ecosystems with a more uniform spatial distribution of data coverage obtained through non-video methods; some offshore applications classified bathymetric features (e.g., slope, rugosity, etc.) obtained from sonar data in conjunction with CMECS classified point data obtained from other sources (e.g., sample grabs, water column instruments, etc.) [*Cochrane*, 2008; *Greene et al.*, 2010; *Trusel et al.*, 2010; *De Chambure et al.*, 2013]. Additionally, Cochrane et al. (2008) utilized underwater video to assess sonar interpretations, but video was not the primary data source. CMECS-compliant maps produced within this study using ROV video and grab samples were depicted as point data [*Cochrane*, 2008].

2.6.2 Cartographic Depictions of ROV Data

Mapping spatially constrained, high resolution deep sea video observations (unsystematically collected) without the accompanying sonar data deviates from standard practices and requires an unconventional mapping approach. Deep sea benthic habitats are more typically mapped using ROV video data in addition to sonar data resulting in a more uniform spatial distribution of data. More specifically, bathymetric map layers are generated using sonar data while images extracted from ROV video (often in lieu of the actual video stream) act as a visual confirmation for inferences made from sonar data [*Cochrane*, 2008; *Guinan et al.*, 2009; *Locker et al.*, 2010]. If autonomous underwater vehicles (AUVs) and ROVs are the primary surveying technology, surveys are conventionally performed in a grid pattern prior to any local investigations on specific features [*Yoerger et al.*, 2007; *Cochrane*, 2008; *Locker et al.*, 2010]. ROV operations – as performed by *Deep Discoverer* – are planned around specific targets of interest, also referred to as way points, and do not generally operate in a grid pattern which results in unsystematic dive tracks. Locker et al. (2010) considers video obtained from ROV dives operating in this manner are best suited for habitat characterization and not for habitat mapping due to the sparse data coverage. Nonetheless, geospatially representing observed video content without the accompanying sonar data is considered useful for data discovery, visualization, and the promotion of scientific inquiry.

CHAPTER III

METHODS

3.1 Data Preparation

All data used in this thesis were collected by *Okeanos Explorer* and its ROV *Deep Discoverer* between April 10th and May 1st of 2014 during cruise EX1402L3 in the Northern Gulf of Mexico. Ten of the sixteen ROV dives from cruise EX1402L3 were selected for CMECS classification (Dives 01, 02, 03, 04, 06, 08, 09, 10, 11, and 12). These dives were conducted on the Texas – Louisiana continental slope north of the Sigsbee Escarpment (Figure 3.1). Data analyzed from these dives were limited to benthic observations in order to excluded data collected during the ROV descent and ascent through the water column.

Video data utilized in this thesis were downloaded from the National Centers for Environmental Information (NCEI) office located at the John C. Stennis Space Center, Mississippi; however, the OER Video Portal has since been created, which allows users to stream and download reduced resolution video or place an order for full resolution video. Dive summary products (reports, highlight images, and event logs), ROV navigation information (coordinates, depth, and altitude), and environmental parameters collected by the onboard CTD sensor (salinity, temperature, and dissolved oxygen) were acquired from NOAA's *Okeanos Explorer Digital Atlas* data portal. ROV attitude data (heading, pitch, and roll) were downloaded from the NOAA Central Library[5].

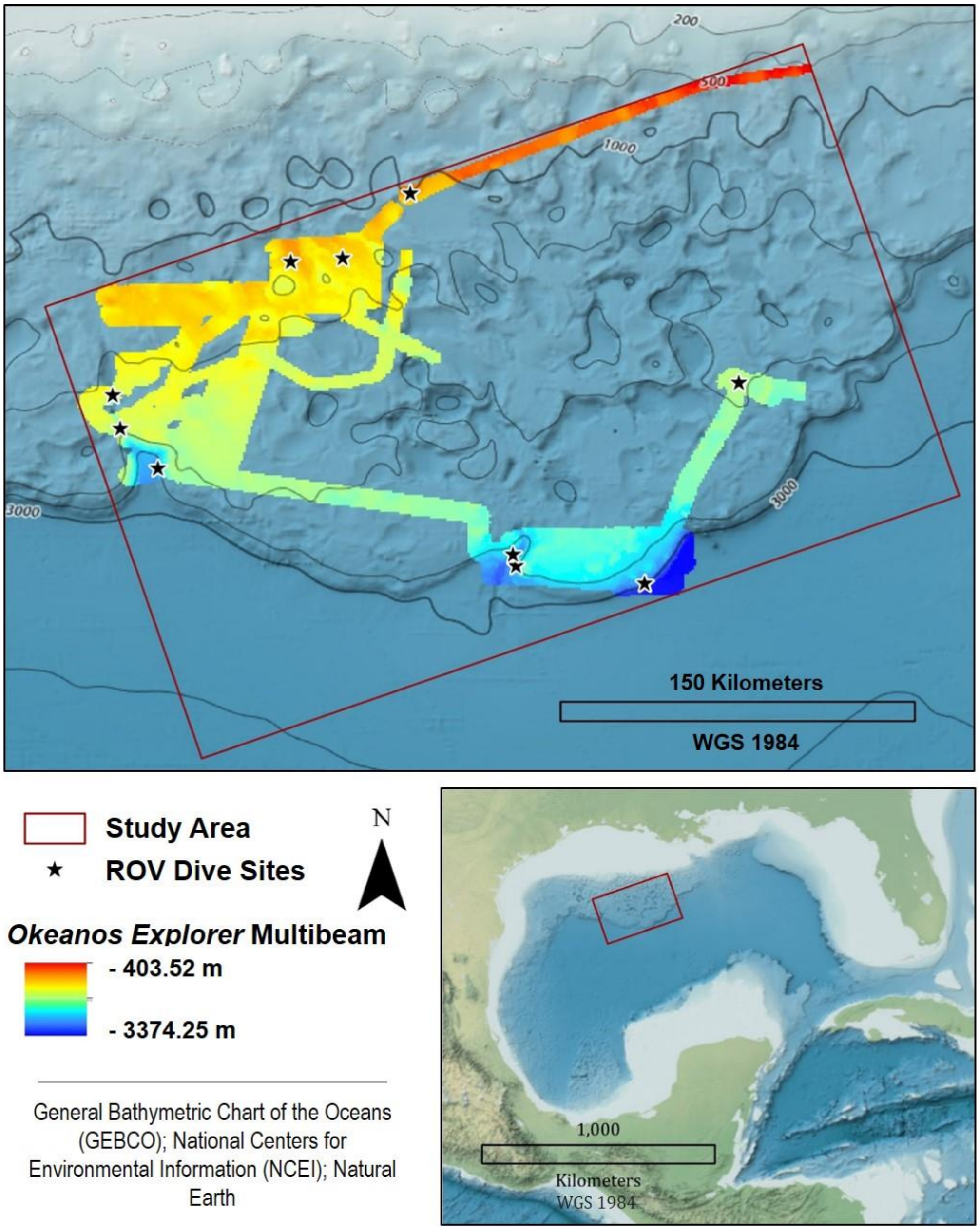

Figure 3.1 EX1402L3 – Northern Gulf of Mexico ROV Dive Sites

[5] NOAA Central Library's data services can be accessed at: www.nodc.noaa.gov

Initial processing of raw data was preformed prior to CMECS implementation. Raw CTD data were processed through Sea Bird Electronics (SBE) Data Processing software v.7.26.1 to extract ROV depth and altitude (m), temperature (°C), salinity (PSU), and dissolved oxygen (mg/L) parameters. The subsequent CTD files underwent quality control (i.e., negative values and spurious values outside the CMECS classification ranges were removed) and had the following total depth field appended within MS Excel.

$$\text{Total Depth} = -(\text{ROV Depth} + \text{ROV Altitude}) \tag{3.1}$$

CTD data obtained by *Seirios* was used in lieu of *Deep Discoverer* for Dive 01 as *Deep Discoverer*'s CTD .hex data file was empty and unrecoverable by NOAA. Many of the dives containing multiple CTD files consisted of gaps (< 1 hour) when concatenated. Those data were also unrecoverable and *Seirios* CTD data were not used to fill the missing data segments.

Although the following data preparation steps are unnecessary for image and video classification, they are needed for subsequent geospatial visualization. Raw ROV attitude data were analyzed within MS Excel where negative values were removed. Scripts were developed with MATLAB to interpolate CTD and attitude data at a 1Hz sampling frequency to match the ROV navigation data. Additionally, timestamps indicating the time of data collection within the CTD and attitude data were altered to unix time in order to match the timestamp information of the ROV navigation files. In preparation for viewshed development, three columns (lower heading, upper heading, and viewing distance) were appended to the 1Hz attitude files using the following formulas within MS Excel.

$$\text{Lower Heading} = \text{If}\ ((\text{Heading} \geq 22°), (\text{Heading} - 22°), (\text{Heading} + 338°)) \qquad (3.2)$$

$$\text{Upper Heading} = \text{If}\ ((\text{Heading} \geq 338°), (\text{Heading} - 338°), (\text{Heading} + 22°)) \qquad (3.3)$$

$$\text{Viewing Distance} = 5 \qquad (3.4)$$

These columns will be ingested within a GIS model for subsequent viewshed creation – the model will generate a five meter line (based on viewing distance value) extending in the direction of both the lower and upper headings.

3.2 CMECS Application to ROV Data

3.2.1 Image Classifications

One hundred highlight images (ten from each dive) were selected to evaluate CMECS's applicability to deep sea benthic habitats in the region. A MS Excel spreadsheet containing image metadata (i.e., image file name, cruise identification number, dive number, date and time, unix time, latitude and longitude, ROV depth and altitude, calculated total depth, and accompanying CTD data) along with all applicable CMECS setting subunits, component subunits, and select modifiers was developed to house the associated image classifications. The following modifiers were explored and defined when applicable:

- physicochemical oxygen modifier (water column component)
- physiochemical photic quality modifier (water column component)
- additional descriptor modifier (geoform and substrate components)
- co-occurring elements modifier (substrate and biotic components)
- associated taxa modifier (biotic component)

Furthermore, the bathymetric feature modifier was devised to accommodate whether the data were collected on a named bathymetric feature (e.g., Bryant Canyon); this modifier accompanies the geoform component.

Subsequent classifications were based on visual analysis of highlight image content and regional bathymetry as well as direct translation of numerical data simultaneously collected with onboard sensors. Water column subcomponents and modifiers were classified through direct comparison of CTD data and CMECS unit definitions to achieve the translation indicated below (Table 3.1). The ship-produced multibeam sonar bathymetry data and regional bathymetric charts were used to determine small scale geoform subcomponents not visually identifiable within the ROV video (i.e., tectonic and physiographic settings as well as level 1 geoform subunits); named bathymetric features were indicated within the ROV dive summaries. All nested subunits within the level 2 geoform subcomponent, substrate and biotic components, and remaining modifiers were classified through visual analysis of highlight image content.

Table 3.1 Numerical Categories of Classified Water Column Units

Layer Subcomponent	**Marine Oceanic Layer**	**Total Depth (meters)**
	Epipelagic Layer	< 200
	Mesopelagic Layer	200 to < 1000
	Bathypelagic Layer	1000 to < 4000
	Abyssalpelagic Layer	4000 to < 6000
	Hadalpelagic Layer	≥ 6000
Salinity Subcomponent	**Salinity Regime**	**Salinity (PSU)**
	Oligohaline Water	< 5
	Mesohaline Water	5 to < 18
	Lower Polyhaline Water	18 to < 25
	Upper Polyhaline Water	25 to < 30
	Euhaline Water	30 to < 40
	Hyperhaline Water	≥ 40
Temperature Subcomponent	**Temperature Category**	**Degrees (°C)**
	Frozen/Superchilled Water	≤ 0
	Very Cold Water	0 < 5 (liquid)
	Cold Water	5 to < 10
	Cool Water	10 to < 15
	Moderate Water	15 to < 20
	Warm Water	20 to < 25
	Very Warm Water	25 to < 30
	Hot Water	30 to < 35
	Very Hot Water	≥ 35
Oxygen Physicochemical Modifier	**Oxygen Regime Values**	**Oxygen Concentration (mg/L)**
	Anoxic	0 to < 0.1
	Severely Hypoxic	0.1 to < 2
	Hypoxic	2 to < 4
	Oxic	4 to < 8
	Highly Oxic	8 to < 12
	Very Oxic	≥ 12

The above numerical divisions represent class breaks within the three water column subcomponents and applicable modifier.

3.2.2 Video Classifications

3.2.2.1 ROV Data Analyzer Software

Next, CMECS was applied to classify video data in near-real-time using the hot keyboard GUI provided by the annotation tool within the ROV Data Analyzer software.

The term near-real-time refers to annotating archived video data with limited to no pausing of the video stream. Because almost all participating researchers and scientists remotely access *Deep Discoverer* video data via the internet broadcast live stream (145 Mbps, 1080i, ProRes 422 SQ), the described methods were conducted with video data at that resolution. During initial startup of the Data Analyzer software, the user is prompted for the following input parameters:

- video file (with standard *Okeanos Explorer* naming convention)
- ROV event log file
- time format of event log (unix time or hh:mm:ss format)
- ROV navigation file
- folder location of VLC media player software

Upon successful input of required startup information, the software interface provides a platform in which users can search by event log entry or timestamp and either geospatially display the data as points along the ROV dive track or view the referenced video segment (Figure 3.2).

The video annotation tool requires additional input of a text file containing up to 60 unique identifiers for the hot keyboard interface construction. As the video plays, all selected annotations (hot keys) are written into a secondary event log (new text file) with the following format: date (MM/DD/YYYY), UTM timestamp (hh:mm:ss), annotator's name, annotation, unix timestamp, ROV latitude, and ROV longitude. The hot keyboard also provides an additional button (SnapShot) for saving screen grabs of the video. The ROV Data Analyzer software is still under development and is not publically released without request (M. Malik, personal communication, 2016).

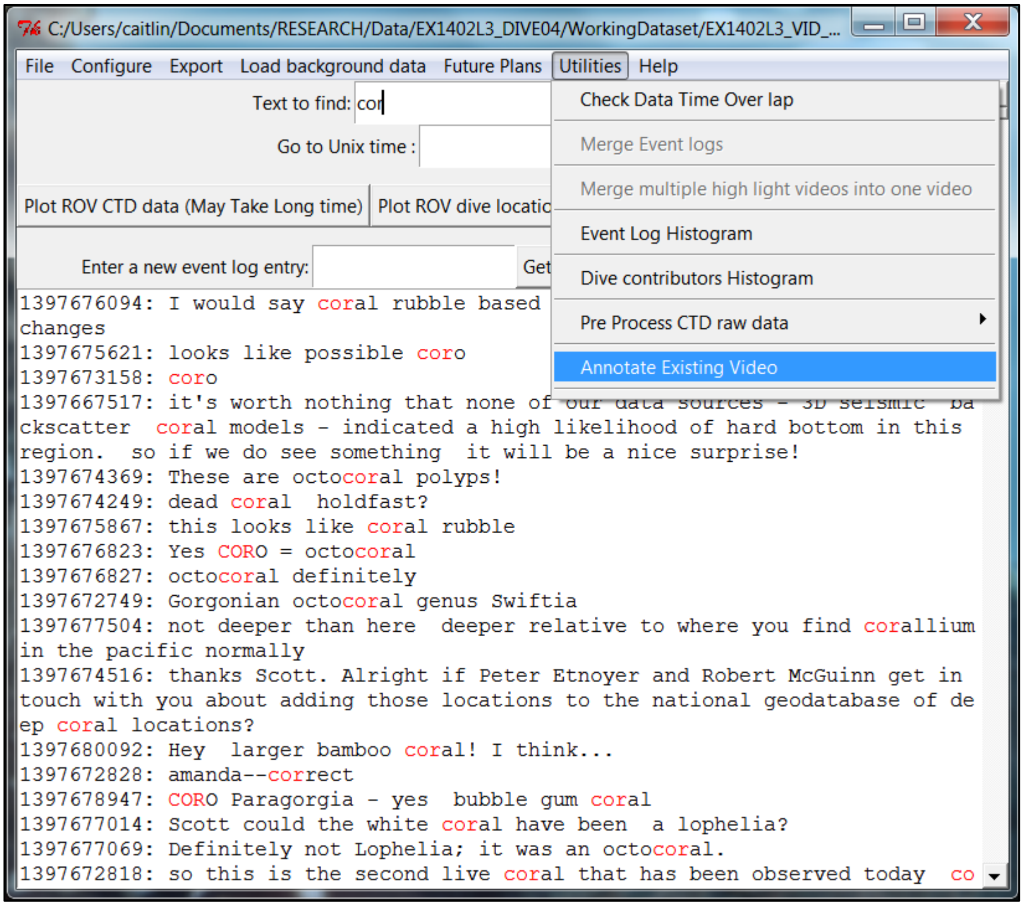

Figure 3.2 Main ROV Data Analyzer Software Interface

This software ingests various data (i.e., video, event log, navigation, sonar, and CTD data) associated with the ROV operations onboard Okeanos Explorer and provides a GUI for annotating video data.

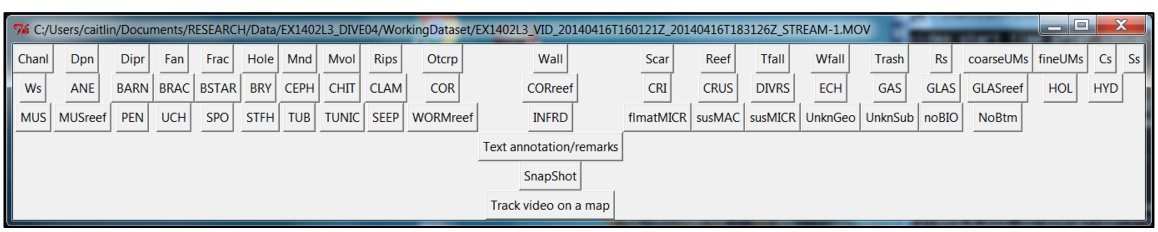

Figure 3.3 ROV Data Analyzer Hot Keyboard Interface

The Annotation Tool within the software converts a list of hot keys (up to 60 unique identifiers) to produce a hot keyboard; the above keyboard was utilized for every video annotated.

3.2.2.2 Annotation List

It was necessary to combine or remove some CMECS units from the annotation list to avoid exceeding the hard-coded limit of 60 unique hot keys. Initial reduction was limited to CMECS units not directly applicable to deep sea environments. For example, neither beaches, shoals, nor tidepools are level 2 geoforms feasibly located within the deep sea. Because benthic habitats were the primary focus, planktonic biota – with the exception of suspended macroalgae and suspended microbes – were not classified. CMECS units indicating features too small (e.g., structure forming microbes) or too large (e.g., ridge) for video observations were also excluded. So too were units indicating features generally avoided by *Deep Discoverer* (e.g., buoys, wind energy structures, and drilling rigs), atypical for the study region (e.g., hydrothermal vents), or that would result in a dive data access being restricted (e.g., wreck).

CMECS geoform and biotic units containing similar definitions were combined. For example, the level 2 geoforms hole/pit and pockmark have similar definitions and may prove difficult to differentiate without pause. Additionally, biotic groups of organisms divided by benthic interactions (e.g., attached anemones and burrowing anemones) were combined. All brittle star and basket star groups were combined due to taxonomic similarity; this subphylum combination reflects the equivalent dive code used onboard the *Okeanos Explorer* – ASR (Asteroid). In contrast, a glass sponge hot key (GLAS) was incorporated to specify observations of non-reef forming Hexactinellida rather than grouping them within the attached sponges group. Similar to Bassett et al. (2017), four hot keys were added to classify areas in which the related component was unknown or unobservable (i.e., UnknGEO, UnknSub, NoBIO, and NoBtm).

Table 3.2 Annotation List Preparations – Level 2 Geoforms

Condensed Classification	Full Name of CMECS Unit(s) within Condensed Classification	Reason to Combine	Reason for Removal
Cave	Cave		Atypical to Region
Channel	Channel		
Cone	Cone		Atypical to Region
Depression	Depression		
Diapir	Diapir		
Dike	Dike		Atypical to Region
Fan	Fan		
Fracture	Fracture		
Hole(s)	Hole/Pit; Pockmark	Similar Definitions	
Hydrothermal Vent(s)	Hydrothermal Vent Field; Hydrothermal Vent	Similar Definitions	Atypical to Region
Karren	Karren		Atypical to Region
Knob	Knob		Atypical to Region
Ledge	Ledge		Atypical to Region
Mound(s)	Mound/Hummock; Cone	Similar Definitions	
Mud Volcano	Mud Volcano		
Platform	Platform		Atypical to Region
Ridge	Ridge		Undiscernable in Video
Ripples	Ripples; Sediment Wave Field	Similar Definitions	
Rock Outcrop	Rock Outcrop		
Scarp/Wall	Scarp/Wall; Overhang (Cliff) Feature	Similar Definitions	
Scar	Scar		
Pavement Area	Pavement Area		Undiscernable in Video
Slope	Slope		Undiscernable in Video

Table 3.2 (Continued)

Condensed Classification	Full Name of CMECS Unit(s) within Condensed Classification	Reason to Combine	Reason for Removal
Reef Complex	Reef Complex		
TreeFall	TreeFall		
WhaleFall	WhaleFall		
Buoy	Buoy		Avoided
Cable	Cable		Avoided
Dredge Disturbance	Dredge Deposit; Dredge Disturbance	Similar Definitions	Avoided
Drilling Rig	Drilling Rig		Avoided
Trash	Lost/Discarded Fishing Gear; Trash Aggregation (Substrate)	Similar Definitions	
Wind Energy Structure	Wind Energy Structure		Avoided
Wreck	Wreck		Restricts Dive

This table specifies the basis on which level 2 geoform units applicable to deep sea environments were either combined, added, or omitted from the annotation list used within the ROV Data Analyzer software.

Table 3.3 Annotation List Preparations – Biotic Component

Condensed Classification	Full Name of CMECS Unit(s) within Condensed Classification	Reason to Combine	Reason for Removal
Anemones	Attached Anemones; Burrowing Anemones		
Barnacles	Barnacles		
Brachiopods	Attached Brachiopods; Braciopod Bed	Similar Definitions	
Brittle/Basket Stars	Brittle Stars on Hard or Mixed Substrates; Soft Sediment Brittle Stars; Attached Basket Stars; Soft Sediment Basket Stars	Taxinomically Similar	
Bryozoans	Attached Bryozoans; Soft Sediment Bryozoans	Similar Definitions	
Cephalochordates	Cephalochordates		
Chitons	Chitons		
Clam Bed	Clam Bed		
Corals	Attached Corals		
Coral Reef Biota	Deepwater/Coldwater Coral Reef Biota		
Crinoids	Attached Crinoids; Soft Sediment Crinoids	Similar Definitions	
Crustaceans	Mobile Crustaceans on Hard or Mixed Substrates: Mobile Crustaceans on Soft Sediments	Similar Definitions	
Diverse Colonizers	Diverse Colonizers; Diverse Soft Sediment Epifauna	Similar Definitions	
Echiurid Bed	Echiurid Bed		
Gastropods	Gastropod Reef; Sessile Gastropods	Similar Definitions	
Glass Sponges Reef	Glass Sponges Reef		
Holothurians	Attached Holothurians; Holothurian Bed	Similar Definitions	
Mussels	Attached Mussels; Mussel Bed	Similar Definitions	
Mussel Reef	Mussel Reef		
Oysters	Oyster Reef; Attached Oysters; Oyster Bed	Similar Definitions	Atypical to Region
Pennatulid Bed	Pennatulid Bed		

Table 3.3 (Continued)

Condensed Classification	Full Name of CMECS Unit(s) within Condensed Classification	Reason to Combine	Reason for Removal
Sea Urchins	Attached Sea Urchins; Sea Urchin Bed; Burrowing Sea Urchins	Similar Definitions	
Sponges	Attached Sponges; Sponge Bed	Similar Definitions	
Starfish	Attached Starfish; Starfish Bed	Similar Definitions	
Tube Builders	Attached Tube-Building Fauna; Larger Tube-Building Fauna; Small Tube-Building Fauna	Similar Definitions	
Tunicates	Attached Tunicates; Tunicates Bed	Similar Definitions	
Seep Community	Vent/Seep Community		
Worm Reef	Worm Reef Biota		
Inferred Fauna	Inferred Fauna; Burrows/Bioturbation (Geoform)	Similar Definitions	
Structure Forming	Structure Forming Microbes		Unobservable in Video
Suspended Microbes	Suspended Microbes		
Boring Fauna	Mineral Boring Fauna; Wood Boring Fauna	Similar Definitions	Unobservable in Video
Burrowing Fauna	Larger Deep-Burrowing Fauna; Smaller Surface-Burrowing	Similar Definitions	More Descriptive
No Observable Biota	Roughly based on Oogalzoic		

This table specifies the basis on which biotic units applicable to deep sea environments were either combined, added, or omitted from the annotation list used within the ROV Data Analyzer software.

Table 3.4 Final Annotation List

Hot Key	Condensed Classification	CMECS Component			Altered
		Geoform	Substrate	Biotic	
Chanl	Channel	X			No
Dpn	Depression	X			No
Dipr	Diapir	X			No
Fan	Fan	X			No
Frac	Fracture	X			No
Hole	Hole(s)	X			Yes
Mnd	Mound(s)	X			Yes
Mvol	Mud Volcano	X			No
Rips	Ripples	X			Yes
Otcrp	Rock Outcrop	X			No
Wall	Scarp/Wall	X			Yes
Scar	Scar	X			No
Reef	Reef Complex	X			No
Tfall	Tree Fall	X			No
Wfall	Whale Fall	X			No
Trash	Trash	X			Yes
Rs	Rock Substrate		X		No
coarseUMs	Coarse Unconsolidated Mineral		X		No
fineUMs	Fine Unconsolidated Mineral		X		No
Cs	Coral Substrate		X		No
Ss	Shell Substrate		X		No
Ws	Worm Substrate		X		No
ANE	Anemones			X	No
BARN	Barnacles			X	No
BRAC	Brachiopods			X	Yes
BSTAR	Brittle/BasketStars			X	Yes
BRY	Bryozoans			X	Yes
CEPH	Cephalochordates			X	No
CHIT	Chitons			X	No
CLAM	Clam Bed			X	No
COR	Corals			X	No
CORreef	Coral Reef Biota			X	No
CRI	Crinoids			X	Yes
CRUS	Crustaceans			X	No
DIVRS	Diverse Colonizers			X	Yes
ECH	Echiurid Bed			X	No
GAS	Gastropods			X	Yes
GLAS	Glass Sponges			X	New
GLASreef	Glass Sponges Reef			X	No

Table 3.4 (Continued)

Hot Key	Condensed Classification	CMECS Component			Altered
		Geoform	Substrate	Biotic	
HOL	Holothurians			X	Yes
HYD	Hydroids			X	Yes
MUS	Mussels			X	Yes
MUSreef	Mussel Reef			X	No
PEN	Pennatulid Bed			X	No
UCH	Sea Urchins			X	Yes
SPO	Sponges			X	Yes
STFH	Starfish			X	Yes
TUB	Tube Builders			X	Yes
TUNIC	Tunicates			X	Yes
SEEP	Seep Community			X	No
WORMreef	Worm Reef Biota			X	No
INFRD	Inferred Fauna	X		X	Yes
flmatMICR	Mat/Film Forming Microbes			X	No
susMAC	Suspended Macroalgae			X	No
susMICR	Suspended Microbes			X	No
UnknGeo	Unknown Geoform	X			New
UnknSub	Unknown Substrate		X		New
noBIO	No Observable Biology			X	New
NoBtm	No Observable Bottom	X	X	X	New

The above list specifies the hot keys used for classifying EX1402L3 video along with a status of whether the key was altered or not.

3.2.2.3 Classifying the Video

Geoform, substrate, and biotic hot keys were initially selected as soon as the seafloor came into view at the beginning of each dive video. Other keys were subsequently selected as relevant features were observed in the video stream. The diverse colonizers (DIVRS) key under the biotic component and rapid combination of substrate keys are the only exceptions to the subsequent selection of keys at the initial feature observation. When a complex community came into view, the DIVRS key was selected followed by any other biotic unit observed within the community; the DIVRS key was again selected – immediately followed by the next observable biotic component

– to end the diverse community observation. For example, the following key sequence entails that anemones, mussels, and gastropods were observed in a complex seep community structure: DIVRS, ANE, MUS, SEP, GAS, DIVRS. Biotic subunits contained within the diverse colonizers were not geospatially represented; however, this may be an aspect to expand upon in future applications. To exploit the co-occurring elements spatial modifier associated with the substrate component, the dominating substrate key would be selected subsequently followed by the co-occurring substrate key (less than 10 seconds). Approximately fifty-four hours of ROV video were annotated using the ROV Data Analyzer Software.

3.2.2.4 Post-processing of Video Annotations

A post-processing script was written in MATLAB to parse the annotations from a single column into four columns representing the observed geoform, substrate, and biotic units. The fourth column encompasses observed biotic units within the diverse community (i.e., biotic unit is classified as DIVRS). This script combines substrate areas defined with a co-occurring element. For example, the rapid selection of Rs (rock substrate) followed by Ss (shell substrate) results in Rs_Ss (rock substrate with co-occurring shell substrate). Additionally, NoBtm replaces any classified unit with the associated unknown/unobservable key (i.e., UnknGeo, UnknSub, and noBIO). The post-processing script also completes the dataset by creating a new row for every second and applying the selected hot key for each column until a differing unit is defined.

3.3 Geospatial Processing Techniques

The presented geospatial techniques employ scripts, tools, and models to produce cartographic representations of the benthic habitats, from video classification results, within a geospatial information system (GIS). All pre-/post-processing scripts were written in MATLAB; while tools within ESRI's ArcMap v.10.3.1 and the Split by Attribute Tool – a plug-in created by the U.S. Geological Survey [*U.S. Geological Survey*, 2015] – were utilized to develop geospatial processing techniques. ESRI's Model Builder was the main interface used in model creation. Additionally, all data were converted from the native geographic coordinate system (WGS 1984) to a more appropriate projected coordinate system (UTM Zone 15 North).

3.3.1 Interpolating Environmental Parameters

The Environmental Parameters Model creates four interpolated surfaces representing local bathymetry, temperature, dissolved oxygen, and salinity at a 0.5 meter cell size resolution within a 10 meter buffer (radius) surrounding the ROV dive track. This model prompts user input for the following parameters:

- geodatabase table containing environmental observations along with the ROV coordinates and a unix timestamp
- output geodatabase
- scratch workspace
- 2-digit dive number (for inline variable naming)
- corresponding 10 meter buffer
- combined feature class containing all of the merged ROV dive track buffers

These data were projected prior to interpolation using an inverse distance weighted approach (IDW) within the spatial analyst toolbox. A CMECS classification template was also developed for the salinity and temperature subcomponents as well as the physicochemical oxygen modifier for rapid display of CMECS units. Raster data were semi-transparently displayed over their associated CMECS units; this was done manually by copying each raster layer and applying the appropriate CMECS classification template.

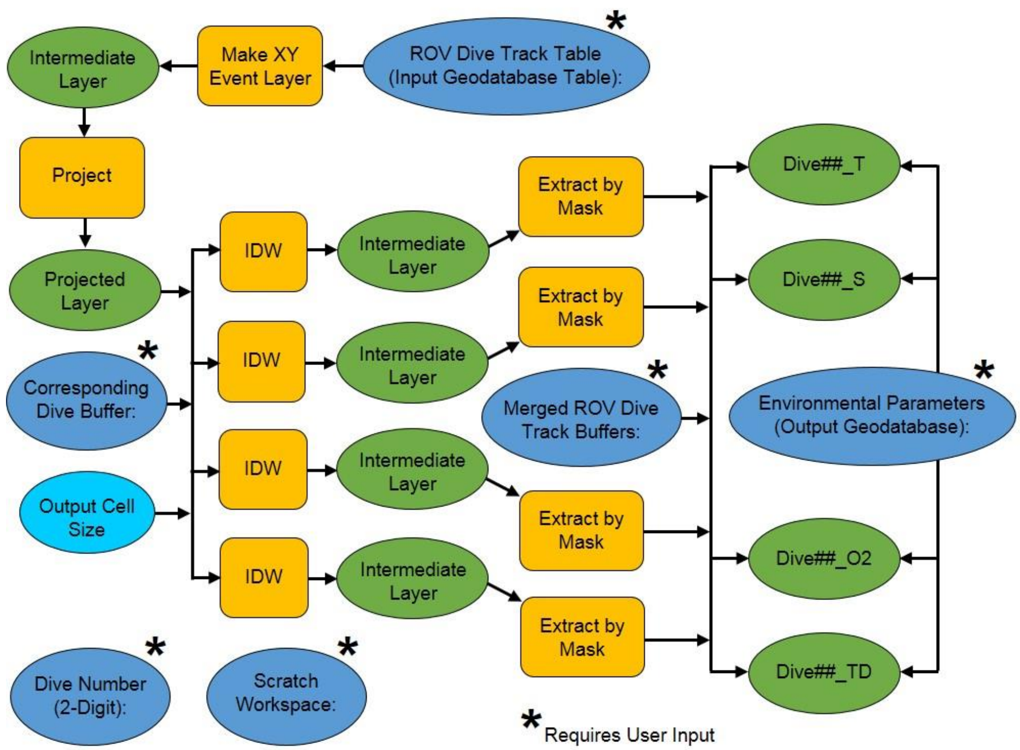

Figure 3.4 Environmental Parameters Model

The Environmental Parameters Model ingests the required input layers created from combined ROV navigation and pre-processed CTD data to generate subsequent interpolated surfaces of the surrounding temperature, salinity, dissolved oxygen concentration, and total depth of the seafloor. This is not an iterative model and each dive must be processed separately. Data are projected into UTM Zone 15N; however, this should be altered for datasets not within this UTM zone.

3.3.2 Cartographical Representing Classified ROV Video Data

Once the text files generated from the ROV Data Analyzer software were parsed, the data were spatially joined to the associated ROV navigation and attitude files. Two mapping approaches were used to generate habitat maps – a buffered approach and a viewshed approach. The buffered approach applies a 5 meter buffer dissolved by each CMECS component, while the viewshed approach limits the mapped area to a wedge-shaped polygon extending 5 meters in the direction of the ROV's heading representing the area most-likely viewed by the *Deep Discoverer*'s main, forward-facing camera. The viewing distance was set to a constant variable of 5 meters in the direction of the ROV's heading and does account for camera zoom or obstructions within the camera frame. Since the level of zoom is not recorded and the wedge-shaped polygon is redrawn for every second of recorded data providing adequate overlap, the angle of coverage for *Deep Discoverer* was assigned to 44°. Future applications may find it more beneficial to widen this to one more representative of the 10:1 super wide angle zoom lens onboard *Deep Discoverer*; however, 44° was chosen to lessen spurious classifications near the outer boundaries when camera zoom is applied. Since CMECS specifies that components must be categorized by the dominant feature, the viewshed approach was thought to lessen the amount of overlapping units and erroneous classifications in the subsequent habitat maps by limiting the mapped areas to those likely viewed within the ROV video. Considering that *Deep Discoverer* remains relatively level, ROV roll and pitch parameters were not included within the viewshed model.

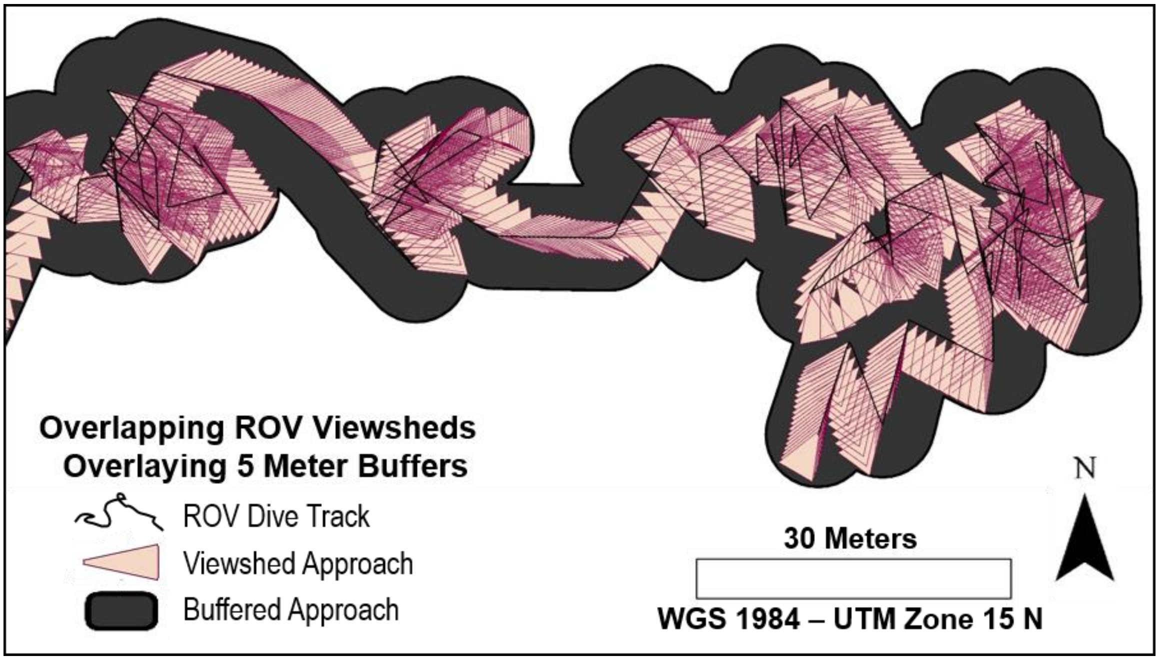

Figure 3.5 Comparison of Geospatial Modeling Approaches

The above map illustrates viewshed polygons created along the ROV dive track; viewshed polygons superimpose the buffered polygon generated from the same ROV dive track data.

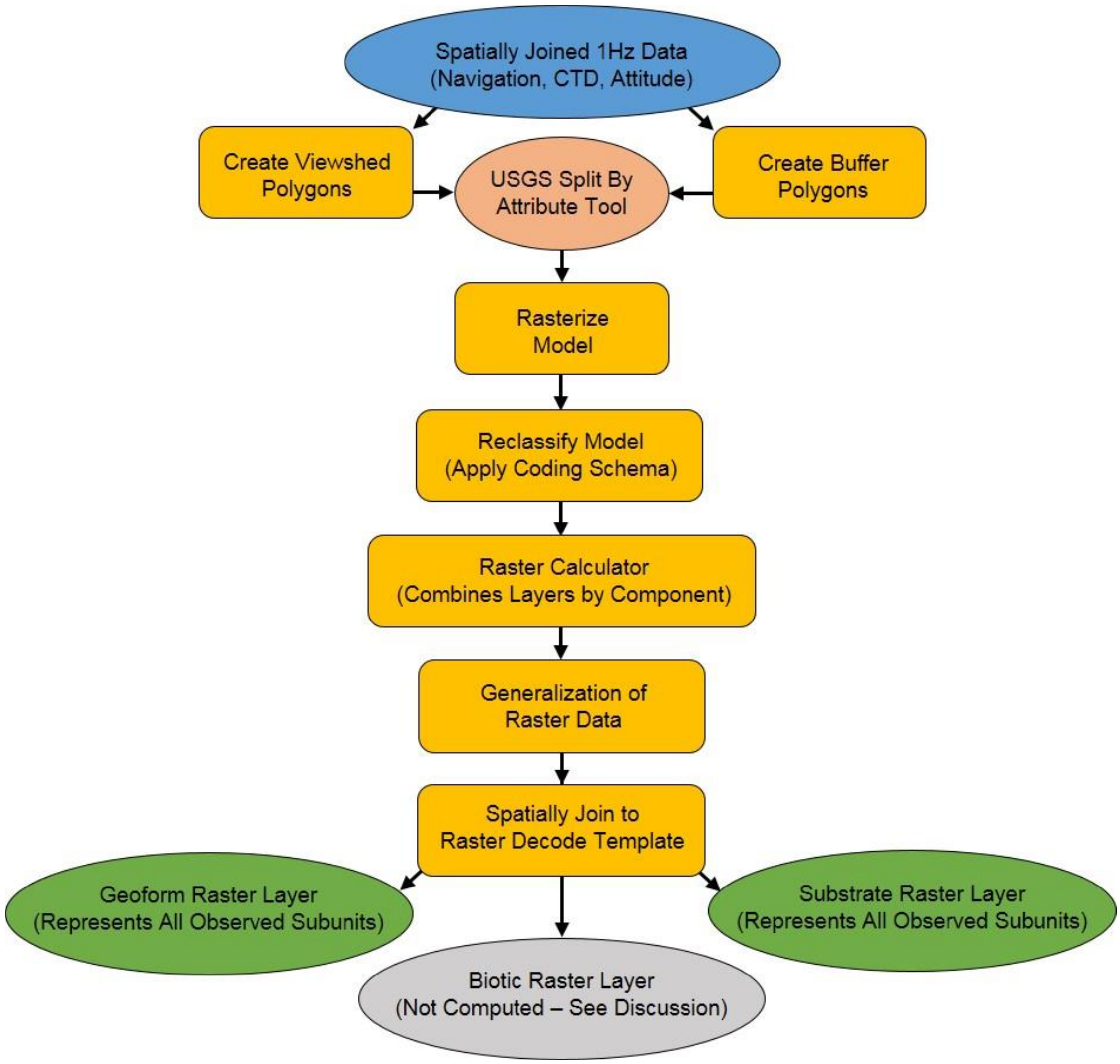

Figure 3.6 General Mapping Workflow

Both approaches follow the same general workflow with the exception of additional steps needed to create the wedge-shaped polygons.

Once the buffered and viewshed polygons were created, the USGS Split by Attribute Tool was used to split polygons by each unit within their associated component (e.g., reef layer, rock outcrop layer, mound layer, etc.). These separated polygons were then rasterized and reclassified using a numerical coding schema (Tables 3.5 and 3.6) prior to each component being recombined into a single raster layer using the following general expression within ESRI's raster calculator tool.

$$\text{Output Raster} = \text{Con}(((\sum(\text{rasters}))>\text{UnknownValue}), ((\sum(\text{rasters}))-\text{UnknownLayer}), (\sum(\text{rasters}))) \quad (3.5)$$

This conditional statement limits the maximum output raster value to their associated unknown or unobserved hot key value (UnknGeo, UnknSub, or noBIO) so that areas classified as both observed and unobserved default to the observed unit and do not conflict with one another. The coding scheme ensures that the resulting output raster layer can be decoded to determine any number of unit combinations. Three generalization processes were employed to eliminate spurious classes created on the edges of various unit combinations. The majority filter and boundary clean tools smooth zone edges to provide a cleaner raster product – both tools are located within ESRI's generalization toolset (spatial analyst toolbox). The third process removed unique overlapping classifications that covered an area less than a single viewshed (roughly 30 pixels). Every class containing a pixel count of ≤ 30 was manually deleted from the attribute table through an editing session. All geospatial models and submodels used to complete the above workflow (Figure 3.6) are graphically depicted within Appendix A; more mechanical details are included within the appendix.

Table 3.5 Substrate Raster Codes

Raster Code	Unit	Hot Key
1	Rock Substrate	Rs
3	Coarse Unconsolidated Mineral Substrate	coarseUMs
5	Fine Unconsolidated Mineral Substrate	fineUMs
10	Coral Substrate	Cs
30	Shell Substrate	Ss
50	Worm Substrate	Ws
100	Rock with Co-Occurring Coral Substrate	Rs_Cs
300	Rock with Co-Occurring Shell Substrate	Rs_Ss
500	Rock with Co-Occurring Worm Substrate	Rs_Ws
1000	Coarse Unconsolidated Mineral with Co-Occurring Coral Substrate	coarseUMs_Cs
3000	Coarse Unconsolidated Mineral with Co-Occurring Shell Substrate	coarseUMs_Ss
5000	Coarse Unconsolidated Mineral with Co-Occurring Worm Substrate	coarseUMs_Ws
10000	Fine Unconsolidated Mineral with Co-Occurring Coral Substrate	fineUMs_Cs
30000	Fine Unconsolidated Mineral with Co-Occurring Shell Substrate	fineUMs_Ss
50000	Fine Unconsolidated Mineral with Co-Occurring Worm Substrate	fineUMs_Ws
100000	Unknown Substrate	UnknSub

Table 3.6 Geoform Raster Codes

Raster Code	Unit	Hot Key
1	Bioturbation	INFRD
3	Channel	Chanl
5	Depression	Dpn
10	Diapir	Dipr
30	Fan	Fan
50	Fracture(s)	Frac
100	Hole(s)	Hole
300	Mound(s)	Mnd
500	Mud Volcano(s)	Mvol
1000	Ripples	Rips
3000	Rock Outcrop	Otcrp
5000	Scarp/Wall	Wall
10000	Scar	Scar
30000	Reef Complex	Reef
50000	Tree Fall	Tfall
100000	Whale Fall	Wfall
300000	Trash	Trash
500000	Unknown Geoform	UnknGeo

A master CMECS template containing every possible unit combination was developed for geoform and substrate components using MS Excel. Each file contains three columns representing hot key abbreviations, CMECS units, and their associated raster codes. Substrate combinations that represent duplicate information share the same hot key abbreviations and CMECS units so that final cartographic representations are not repetitious. For example, separate substrate classes with raster codes of 300 (rock with co-occurring shell) and 310 (rock with co-occurring shell / shell) essentially represent the same substrate class and are thus combined. Resulting geoform and substrate layers were spatially joined to the appropriate master CMECS template based on the numerical coding scheme and cartographically displayed using the unique values within the CMECS unit column. Issues associated with the biotic raster layers will be discussed in a later chapter.

CHAPTER IV

RESULTS

The methods presented within the previous chapter were applied to one hundred still images and approximately fifty-four hours of underwater video. All classified highlight images, with their affiliated CMECS components, are presented in Appendix B. CMECS units were combined within each associated component to consolidate repetitive information. For example, an image classified as Cold Euhaline Water in the Marine Oceanic Mesopelagic layer denotes the temperature, salinity, and layer subcomponents. This condensed classification retains the core CMECS identifiers (e.g., cold, Euhaline, and mesopelagic layer) while introducing broader identifiers for clarification (e.g., marine and oceanic). Furthermore, images that lack sufficient data to classify a particular CMECS unit – in some instances an entire component – are not listed. The following CMECS units remained consistent throughout the dataset:

- Warm Temperate Northwest Atlantic – Northern Gulf of Mexico (biogeographic setting)
- Marine Oceanic Subtidal (aquatic setting)
- Passive Continental Margin (geoform tectonic setting)
- Aphotic (water column physicochemical photic quality modifier)

Only sixteen of the one hundred highlight images classified had notable elements not specifically addressed by CMECS, including: brittle stars attached to biota, paleodictyon, brine ecosystems, and the presence of gas hydrate.

Table 4.1 Observations Requiring Particular CMECS Considerations

Dive Number	Number of Observations			
	Brittle Stars	Paleodictyon	Brine	Hydrate
Dive 02			6	
Dive 03	4			1
Dive 06		1		
Dive 12	1			3

The distribution of observed phenomenon throughout the dataset that were not directly classifiable using CMECS are depicted above

Interpolated surfaces of bathymetry, temperature, salinity, and dissolved oxygen, as produced with the Environmental Parameters Model, are depicted within Appendix C. Each temperature, salinity, and dissolved oxygen map contains two representations of the same data. The continuous raster values, displayed using a semi-transparent stretched gray color ramp, superimpose their associated CMECS unit(s) which are displayed as discrete classes. This visualization approach simultaneously represents the more detailed interpolations along with the appropriate CMECS unit(s).

The spatial distribution – as derived from both the buffered approach and viewshed approach – of level 2 geoforms and substrate classes/subclasses for each ROV dive are displayed in Appendix D. Combined habitat layers of the biotic component are difficult to interpret due to the excessive number of classifications produced by the conditional statement within the raster calculator. The ramification of this will be further examined within the next chapter. The total count (per dive) of overlapping classifications (e.g., Hole(s)/Scar/Ripples, Scar/Ripples, Channel/Bioturbation, etc.) were compared to evaluate the relative values of these differing methodologies for mapping benthic habitats utilizing ROV video annotations. Analyses of geoform and substrate maps were performed independently from one another due to the more complex combinations employed within the substrate depictions.

The viewshed mapping approach decreased the number of overlapping geoform classes in nine of the dives and increased the number in one dive relative to the buffered mapping approach. The number of overlapping substrate classes decreased in four dives and increased in one. These data reflect unknown substrate and geoforms as well. These results were not statistically analyzed due to the small sample size.

Table 4.2 Comparisons of Total Number of Overlapping Classifications

Dive Number	Geoform			Substrate		
	Buffered		Viewshed	Buffered		Viewshed
Dive 01	22	>	18	14	>	13
Dive 02	9	>	7	7	>	2
Dive 03	14	>	9	11	>	10
Dive 04	5	<	6	2	=	2
Dive 06	11	>	10	1	=	1
Dive 08	8	>	7	4	<	5
Dive 09	11	>	7	3	=	3
Dive 10	17	>	11	4	>	3
Dive 11	13	>	10	2	=	2
Dive 12	2	>	1	1	=	1
Mean	**11.20**		**8.60**	**4.90**		**4.20**
Standard Deviation	**5.77**		**4.35**	**4.43**		**4.08**
Standard Error of the Mean	**1.46**		**0.97**	**1.40**		**1.29**

The viewshed approach decreased the number of overlapping geoform classes in nine of the dives and increased in one. The number of overlapping substrate classes decreased in four dives and increased in one.

CHAPTER V

DISCUSSION

5.1 CMECS Implementation

Considering no CMECS applications on deep sea habitats existed prior to this study, sample applications on still images were employed to postulate the degree in which CMECS could be applied to these complex ecosystems. Through these limited sample applications, it was hypothesized that CMECS would be able to classify all images and ancillary data products to the following levels (when applicable):

- all levels within the biogeographic and aquatic settings
- layer, salinity, temperature, and biogeochemical feature subcomponents along with the oxygen physicochemical modifier within the water column component
- all subcomponents within the geoform component down to the Level 1 and 2 geoform types
- substrate subclass within the substrate component
- all hierarchal levels nested within the biotic component

Upon analysis of one hundred highlight images, CMECS was – for the most part – applicable to deep sea environments in the Northern Gulf of Mexico. Only sixteen images contained notable elements not specifically representable through CMECS units (Table 4.1). To address some of these non-typical elements, brittle stars attached to biological surfaces were classified as co-occurring attached brittle stars or listed under the associated taxa as attached brittle stars and the paleodictyon was classified using the level 2 burrows/bioturbation geoform.

The presence of gas hydrate was denoted using the additional descriptors modifier (geoform). Rock composition (e.g., carbonate) and the presence of brine were also included within the additional descriptors modifier (substrate).

Although CMECS is intended to provide descriptive terminology for standardized classification, some variability may incur with multiple analysts. Numerous classifying analysts would not only ensure that all of the observed phenomenon are documented, but subsequent coinciding entries would provide a method of quality control. For example, if two analysts document a particular observation in the same CMECS unit, then it can be assumed that the observation is indeed as classified.

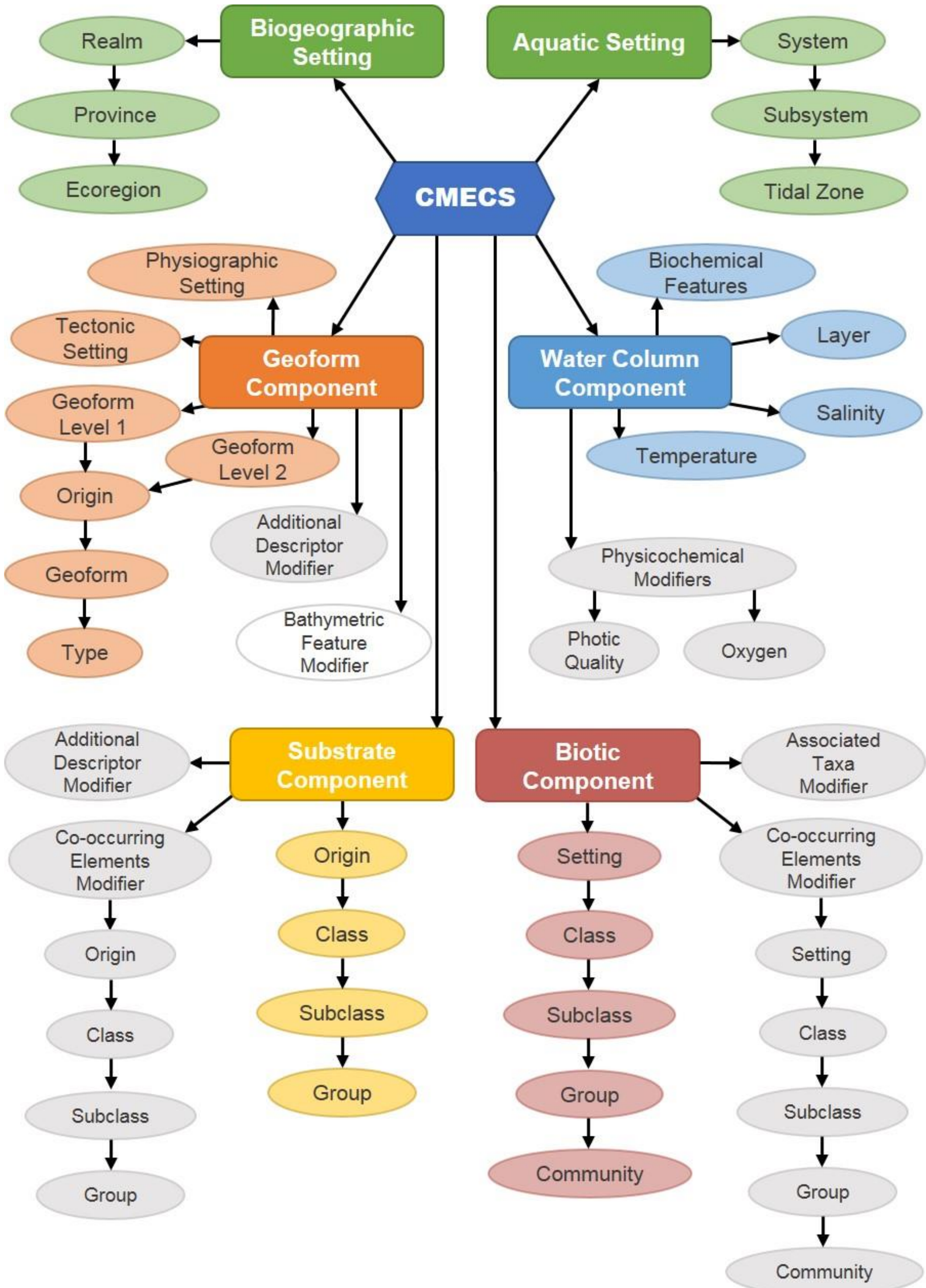

Figure 5.1 Hierarchal Levels Applied to ROV Imagery

The above figure depicts the hierarchal levels used to classify observed ecosystems within the highlight imagery; the proposed bathymetric feature modifier is also included.

Successful application of CMECS to video data in near-real-time by a single annotator was anticipated to be plausible if constrained to the more general, upper-level hierarchal tiers of the standard. Specifically, these tiers are:

- level 2 geoforms
- substrate class and occasional subclass (i.e., fine and coarse unconsolidated mineral substrate)
- co-occurring substrate class and subclass
- varying levels within the biotic component

It was suspected that more detailed CMECS classifications would either require multiple annotators or more time than is available during near-real-time video data collection operations. Resulting classifications from the dataset used within this thesis coincide with limiting video classifications to the above described CMECS tiers. Classifying the ROV video using the hot keyboard was effective for areas containing homogenous ecosystems; however, it was challenging to classify the geoform, substrate, and biotic components in more complex, heterogeneous ecosystems without pausing the video. This was especially true when the camera panned back and forth between two distinctly different ecosystems requiring the simultaneous selection of multiple components (e.g., barren seafloor to seep community). Often, the video would have to be rewound to classify the missed start of an observation or fix an incorrect hot key selection. Since the selected keys were post-processed to represent a defined variable over a range in time, it was difficult to remember which keys were selected (especially for more complex ecosystems) and so the generated text file had to be closely monitored during the initial annotations as the user became familiar with the annotation process. Therefore, some adjustments are necessary prior to future operational use for enhanced functionality.

To address these limitations, there should be an individual designated to annotate each component (i.e., geoform analyst, substrate analyst, and biotic analyst) and have the selected key appear differently (e.g., key appear indented, highlighted, bolded, etc.) as a reminder to which annotation is being applied. The visual indicator would be especially useful for classifying diverse colonizers and co-occurring substrates. Having different annotators assigned to each component would also allow for the development of component-specific annotation lists, which would allow for the separation of combined classes to better represent CMECS. For example, the geoform analyst would use the geoform annotation list of all possible level 2 geoform units applicable to deep sea environments. Furthermore, the post-processing script used to parse through and organize annotations into separate columns (geoform, substrate, biotic, and contains) could be directly incorporated into the ROV Data Analyzer software. This would generate an output of the temporal range(s) in which annotations were observed rather than only recording the initial time in which the observations were annotated. Providing the annotation data as a temporal range (timeframe) would allow the spatial depiction of these observations along the dive track. For example, recording the initial time of a reef observation would result in the reef being cartographically represented as a single point along the dive track; however, recording the timeframe in which that reef was observed would result in that reef being cartographically represented as a line segment within the overall dive track.

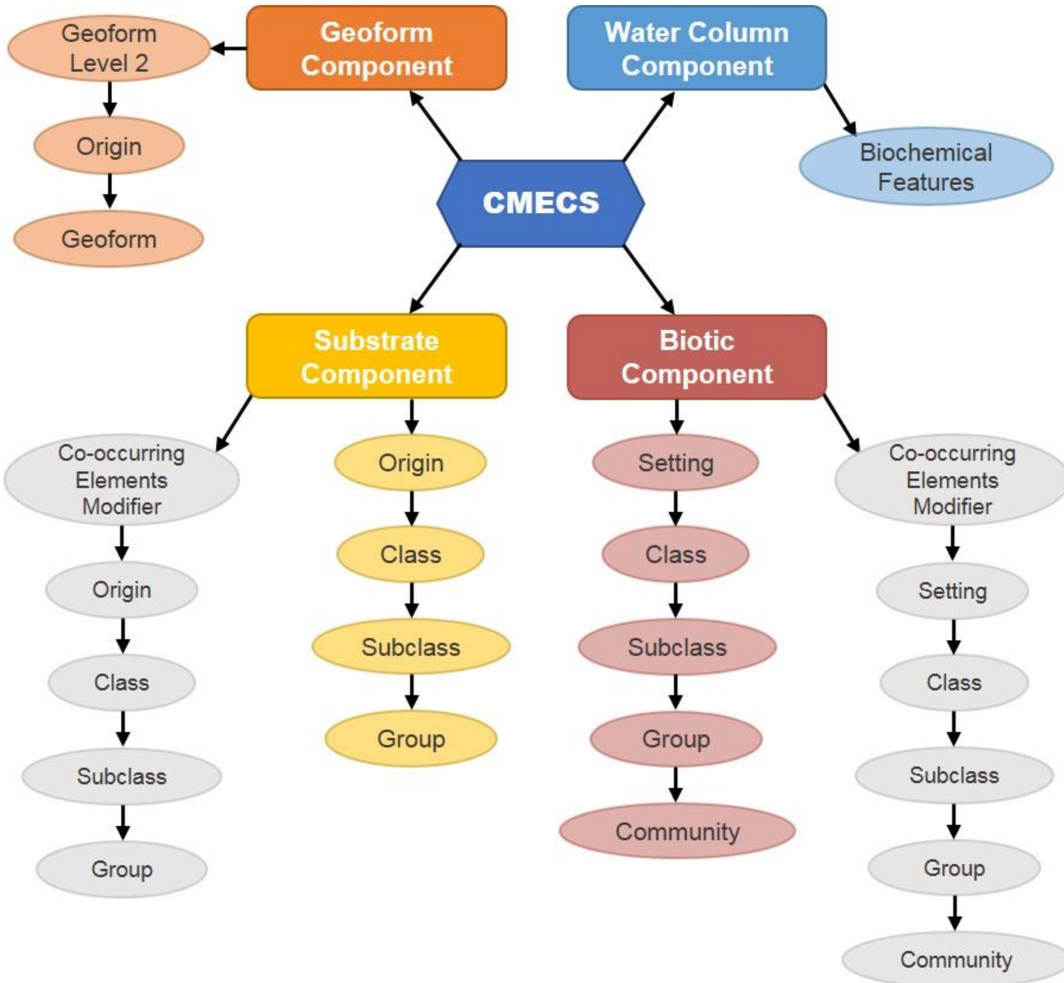

Figure 5.2 Hierarchal Levels Applied to ROV Video Data

This figure portrays the hierarchical levels applied to the underwater video using the hot keyboard; classifying video in more detailed hierarchal levels is not recommended.

5.2 Suggested CMECS Improvements

The following adjustments to the CMECS document are recommended based on the observations made throughout this project. The biotic group “brittle stars on hard or mixed substrates” under the attached fauna subclass be renamed “attached brittle stars” to reflect the numerous observations of brittle stars secured to the surrounding biology (e.g., brittle stars attached to corals) rather than the actual substrate. Another suggestion under the biotic component would be in reference to the discrepancies related to the glass sponges. There is a specific biotic subclass for the Hexactinellida (glass sponges) under the reef biota class (glass sponge reef biota); however, no subunit exists for non-reef forming glass sponges. A biotic group under the attached fauna subclass may be of some use to describe these unique sponges prior to reef establishment.

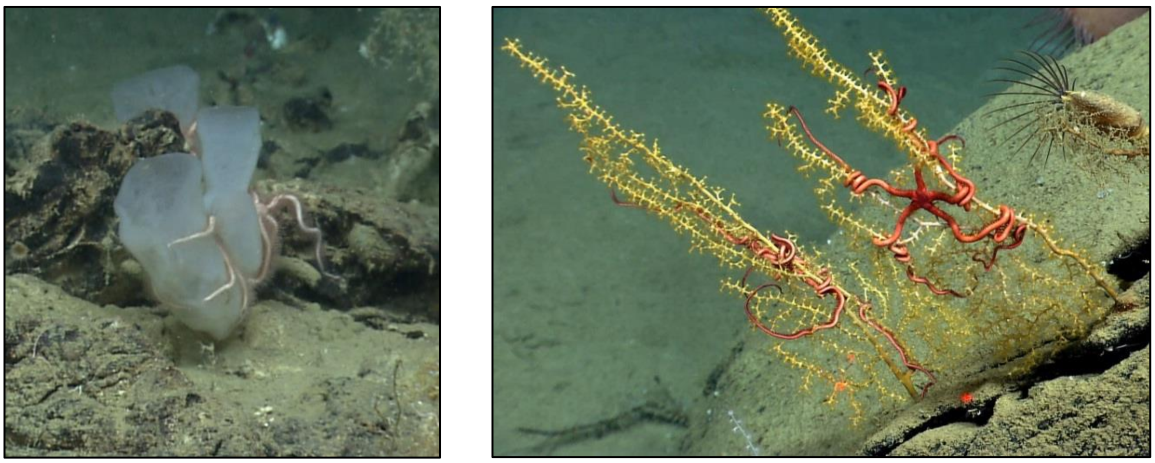

Figure 5.3 Brittle Stars Attached to Biology

The above cropped, highlight images represent two instances where brittle stars were attached to the surrounding biology rather than the hard or mixed substrate; the left image also represents the presence of non-reef forming glass sponges. Full images and applied CMECS classifications are located in Figures B.21 and B.94, respectively.

Furthermore, the "Bathymetric Feature Modifier" is proposed to accompany the geoform component. This modifier would describe whether the data were collected on a named bathymetric feature (e.g., Bryant Canyon) as defined by the General Bathymetric Chart of the Oceans (GEBCO) Subcommittee on Undersea Feature Names (SCUFN). The bathymetric feature name is denoted within both the accompanying dive summary and metadata file but not proposed by the CMECS document. Internationally accepted named bathymetric features are considered to be common identifiers linked to specific physical features on the seafloor and thus need CMECS support. Moreover, distinctions between seep types (e.g., oil or methane) may be a desirable subunit to the biogeochemical feature seep classifier.

5.3 Geospatial Techniques

Geospatially representing the observed deep sea features and environmental parameters recorded as video annotations is possible through the methods described in this thesis. Geospatial visualization of this information allows scientists to better understand information contained within video data files and more acutely determine its applicability to their research priorities. Given this and the particular applicability of CMECS to deep sea ecosystems, it would benefit OER – and other federally funded organizations who fall under the 2018 CMECS mandate – to incorporate and cartographically represent CMECS annotations applied to ROV video data. Including the geospatial distribution of these data into existing web-based portals would allow end-users a visualization tool that is superior to tabular data access formats.

5.3.1 Environmental Parameters

The environmental data collected by the CTD instrument on the ROV is geospatially represented as two overlapping layers: the interpolated surface semi-transparently displayed over the associated CMECS unit(s). The CMECS-compliant discreet classes mark large changes within those data while the overlain interpolated surface depicts continuous variability within those CMECS units. Although a majority of the mapped dives do not contain a wide range in observed environmental values (80% of the temperature, salinity, and dissolved oxygen layers have a range of less than 1 unit), displaying the data geospatially provides end-users a way to visually assess data quality, variability, and spatial distribution. Additionally, the spatial representation of conductivity (salinity), temperature, and dissolved oxygen values may allow end users to make initial inferences about physical phenomenon and proximal features that may be controlling their variability. This visualization tool may prove to be especially beneficial for dives in deep sea environments that are known to contain a wider range in salinity, temperature, and dissolved oxygen values such as hydrothermal vents, cold seeps, or brine ecosystems. However, it should be noted that no salinity anomalies were observed throughout Dive 02, which focused on brine pools. Absent (either unrecorded or removed in quality control) and possibly erroneous values (not removed by the level of quality control performed) within Dives 02, 03, 04, 08, 09, 10, and 11 created spurious artifacts within the resulting dissolved oxygen surfaces as the IDW tool interpolated past the bounds of the data.

The two-dimensional interpolated surfaces of seafloor bathymetry based on the total depth calculations were created for each dive. The resulting continuous raster surfaces are a more useful way to display the data than a polyline or a table. These surfaces appear to be especially useful for dives in which the ROV observations were focused around specific targets (waypoints). For example, Dive 12 primarily focused on two extruded asphalt features resulting in a very high spatial density of total depth measurements around the features. Dives of this nature provide a denser bathymetric data coverage than transit dives (i.e., dives that move in a direct track line between points with minimal loitering or doubling back). Because all dives fell into a single CMECS category (i.e., no depth values within a single dive crossed the defined unit boundaries), the localized bathymetric surfaces were not geospatially displayed in CMECS layers. Instead, the continuous interpolated surfaces are displayed using a similar color ramp to the coarser (30 meter) multibeam sonar bathymetric data, while the accompanying CMECS layer name is textually defined within the map legend to retain compliance with CMECS. The interpolated surfaces provide valuable information lost if the same data were solely displayed using discreet CMECS layers. Displaying the CMECS layer component may best be used for more regional bathymetric analyses.

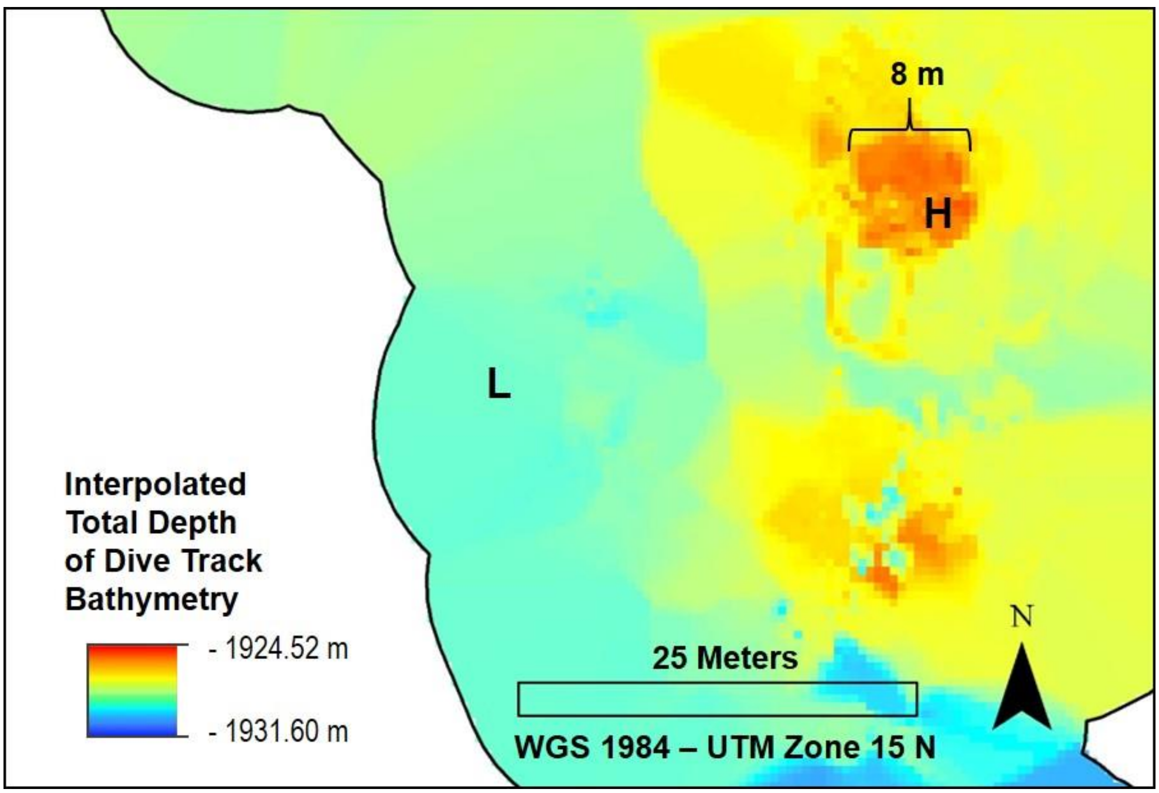

Figure 5.4 Local Bathymetry of Extruded Asphalt Feature from Dive 12

As indicated above, these increased data allow for more accurate height and width estimates of the geologic feature when geospatially represented. The topographic high (H) of the mapped tar lily is -1,926m while the surrounding topographic low (L) is approximately -1,929m.

Figure 5.5 ROV Image of Extruded Asphalt Feature from Dive 12

Originally speculated as a wreck, investigations executed by ROV Deep Discoverer revealed otherwise. Refer to Figure B.93 for fully CMECS classification of this image.

5.3.2 Habitat Mapping

Both CMECS classification mapping approaches (buffered and viewshed) represented the spatial distribution of observed benthic habitat properties with varying degrees of detail. Although the initial intention was to recombine the individual CMECS raster layers into a single habitat map for each component (i.e., map of combined substrate units, map of combined geoform units, and map of combined biotic units), combing the biotic units into a single raster dataset was not practical due to the number of unique and combined classes generated by the raster calculator output.

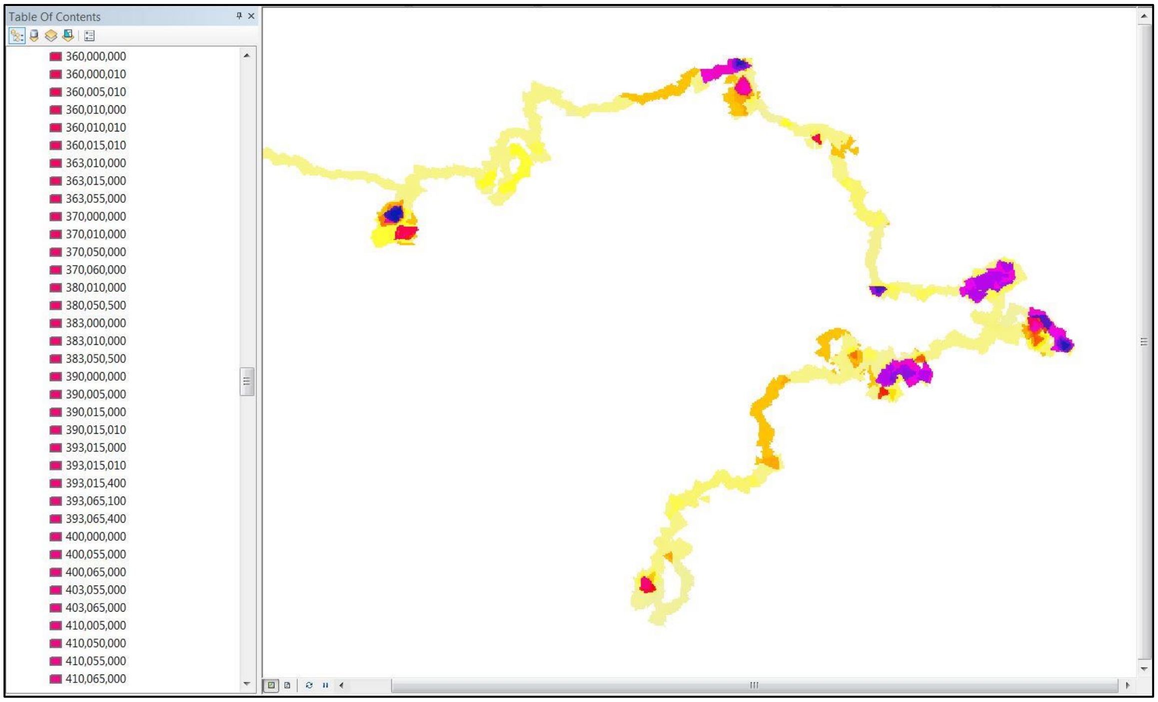

Figure 5.6 Combined Biotic Classifications

The above screenshot represents the impractical biotic map of over six hundred unique classes (not all shown within ArcMap's Table of Contents) generated when applying the conditional statement to the nineteen unique identifiers within raster calculator; this number does not reflect observed classes within the areas labeled as "diverse colonizers".

Since the suggested platform for the resulting data layers is an online map service, displaying individual and combined layers for the geoform and substrate components is suggested, while only the individual layers need be shown for the biotic component (Figure 5.7). Offering the option to query and view specific uncombined data layers gives end-users more flexibility in exploring these data and identifying video data of interest. Providing individual layers also allows for end-users to employ their own generalization criteria rather than the generalization steps employed on the combined raster layers within this thesis (i.e., majority filter, boundary clean, and removal of combined classes containing less than 30 pixels). Furthermore, making these data available through a map service will allow users to rapidly assess the data through multiple spatiotemporal scales and extents without having to download copious amounts of data. Having the ability to zoom into the combined datasets – especially those more complex – further clarifies the spatial distribution of observed benthic habitat characteristics.

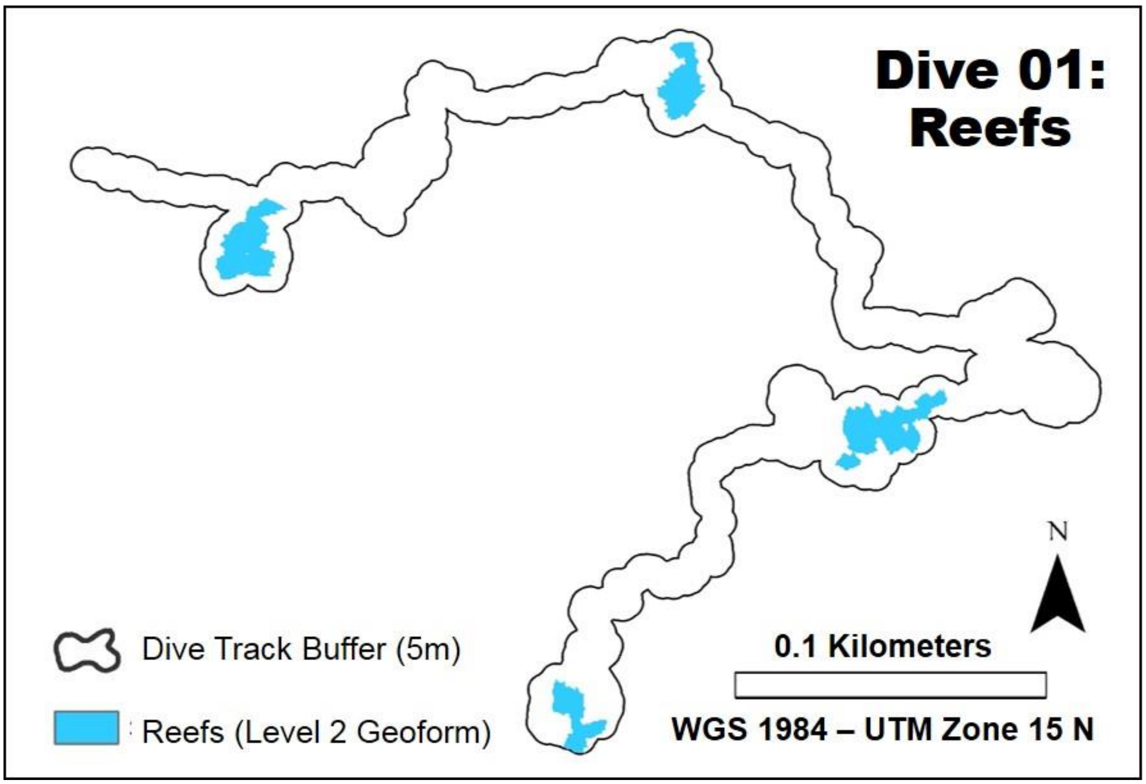

Figure 5.7 Individual View of Level 2 Geoform Unit

End-users interested in a specific component unit may prefer the option to query and view the desired unit individually rather than in a combined map layer as represented in Appendix D. The above distribution of reefs throughout Dive 01 was developed using the viewshed approach.

Mapping the observed CMECS units with the viewshed approach reduces the number of combined classes created during the coalescence of individual data layers among most of the dives – with the exception of the geoform component within Dive 04 and the substrate component within Dive 08 which both increase by a single class (Table 4.2). It is thought that is a result – in part – of the generalizations made and the joining of similar classifications (e.g., rock with co-occurring shell / rock classification being absorbed within the rock with co-occurring shell classification). The additional classes would had been eliminated if the third generalization process – removal of combined data layers with a pixel coverage of less than or equal to 30 pixels – reflected a higher count criteria (e.g., removals based on pixel count ≤ 40 pixels). The particular geoform class (mound(s)/hole(s)) within Dive 04's viewshed habitat map covered an area of 34 pixels, while the particular substrate class (rock with co-occurring substrate/coarse unconsolidated minerals/fine unconsolidated minerals) within Dive 08's viewshed habitat map covered an area of 39 pixels. These pixel counts are just beyond the bounds of the defined criteria (count ≤ 30). Since CMECS specifies that all units be defined based on dominant feature type, any decrease in the number of overlapping classes is favorable. Furthermore, the viewshed mapping approach removes classified areas not observed by the ROV that were classified within the buffered approach. For example, the buffered approach would classify unobserved areas located 5 meters behind the ROV the same as those observed within 5 meters in front of the ROV, while the viewshed approach would only classify the observed areas located within 5 meters in front of the ROV.

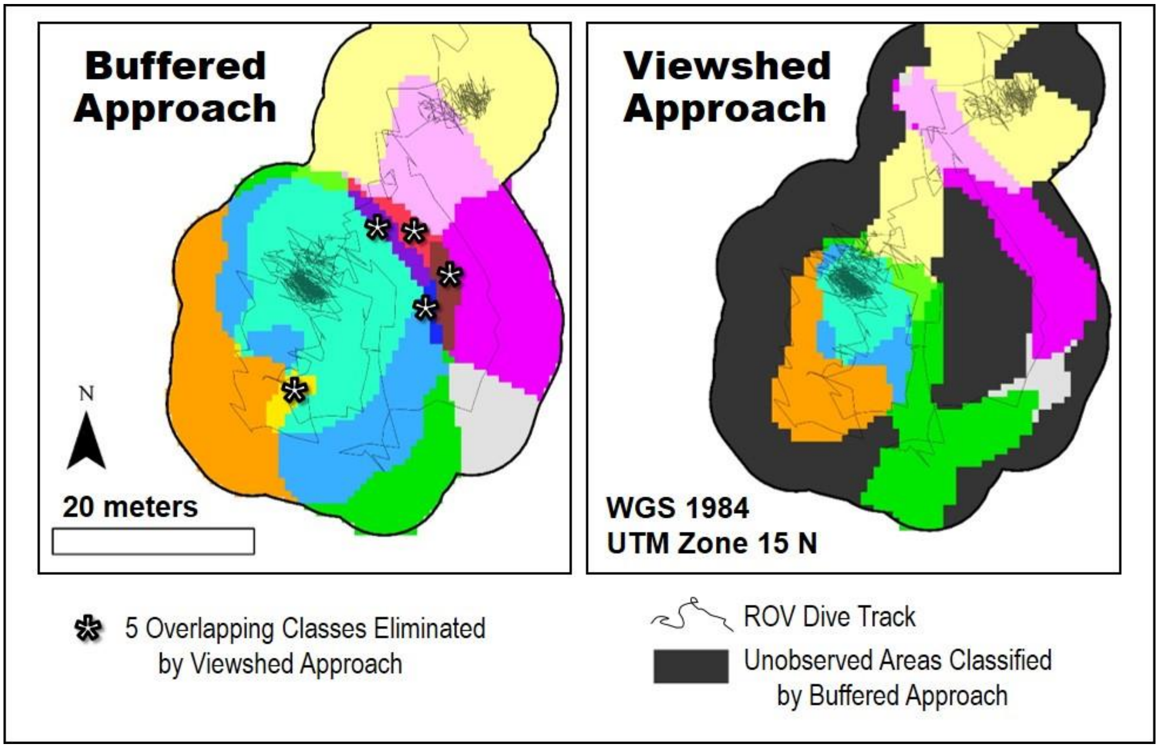

Figure 5.8 Local Comparison of Approaches within Dive 01

The above figure emphasizes the observed decrease in classifications on a more localized scale by comparing level 2 geoform outputs generated by the two approaches within the south-most portion of Dive 01. The viewshed approach completely eliminates five overlapping classes throughout this portion of the dive track by only representing areas observed by the *Deep Discoverer*'s forward-facing camera. Note that the large black area between the dive track within the viewshed map was classified within the buffered mapping approach even though this area was most likely not viewed by the ROV.

Although the viewshed maps provide more realistic representations of the observed seafloor by only displaying areas presumably viewed by the ROV's main camera, disparities still exist within these data layers. The most obvious being that this methodology only works as long as the annotations are being made through the lens of the ROV's forward-facing camera. Dive 12 did periodically switch to the nadir-viewing camera to better plot and mosaic image the newly discovered, extrusive asphalt features; subsequent viewsheds created during these video segments are inherently erroneous.

This was the only time in which the forward-facing camera was not used for the entire dataset used within this thesis. Additionally, the 5 meter viewing distance may incorrectly classify obscured features in bathymetric terrains within higher vertical relief. For example, a reef structure with a 2 meter diameter located 1 meter in front of the ROV, may result in the misclassification in the areas 3-5 meters away from the camera that are obscured by the reef structure. In contrast, the viewing distance may exclude areas outside of the 5 meters that were indeed observed in optimal viewing conditions (e.g., clear waters with flat bathymetric terrain). In creating the viewshed coverage, occasionally, a singular viewshed polygon would not be aligned with the surrounding viewsheds; these are thought to be a result from not performing a more thorough quality control on the ROV attitude data prior to viewshed creation. It is unknown to how many classes were created due to these faulty viewsheds.

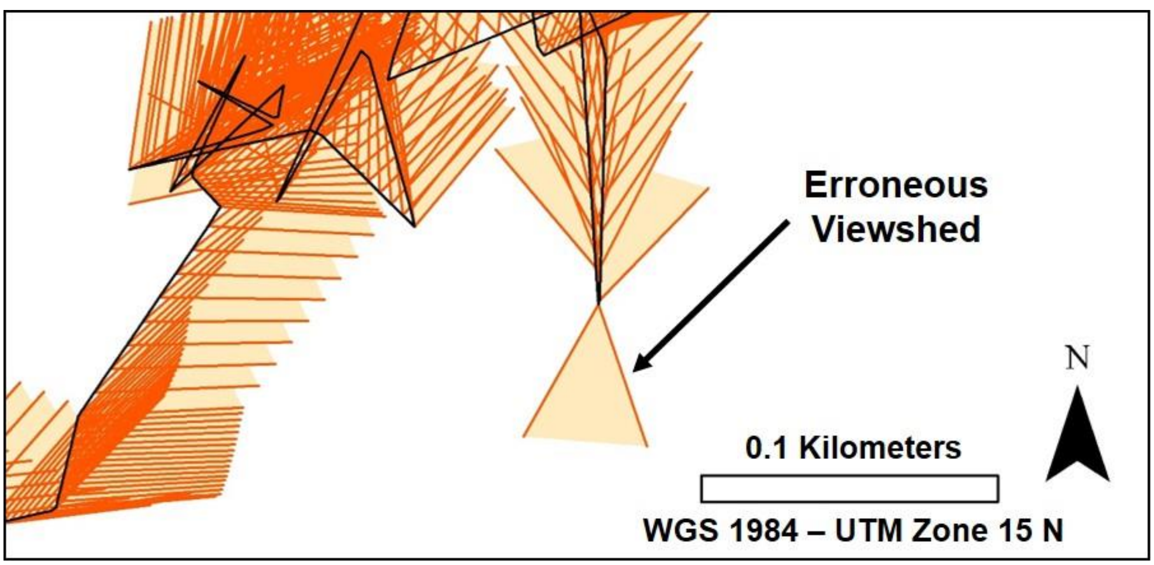

Figure 5.9 Example of Erroneous Viewshed

The erroneous viewshed is evident in the viewshed polygons formed along the ROV dive track from Dive 06.

5.3.3 Combining Geospatial Data for Enhanced Analysis

One interesting discovery within the dataset – that might not otherwise been detected – is the salinity distributions along Dive 06. Seven substantial decreases in salinity are more notably observed within the discrete representation of data in CMECS units than the semi-transparently superimposed interpolated salinity layer (Figure 5.10). Having the ability to individually sort through the unique biotic classifications indicated spatial correlation between some deep sea coral patches and areas of decreased salinity (Figure 5.11). The original video was not reviewed to distinguish associated coral taxa; however, this may be of interest to those focused on deep sea coral research. This discovery exemplifies the benefits of geospatially representing the environmental parameters and habitat information observed within the ROV video and directly illustrates a benefit of mapping CMECS classifications.

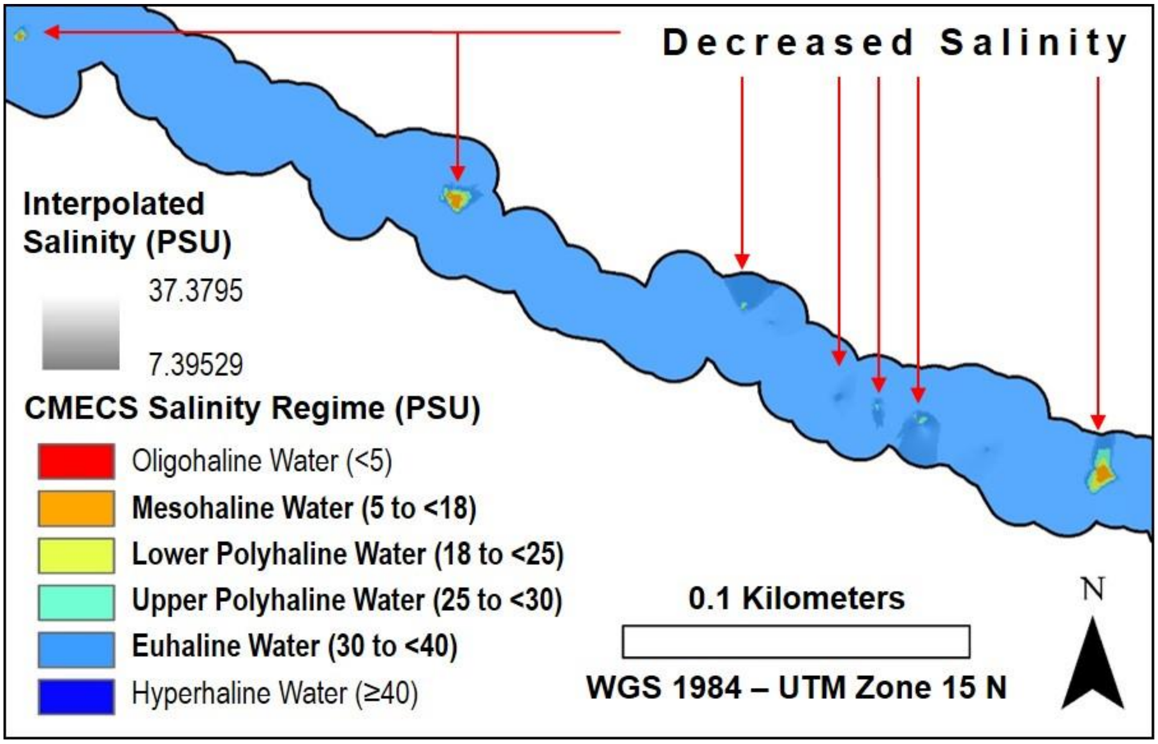

Figure 5.10 Decreased Salinity throughout Dive 06

The above overlain surfaces highlight steady decreases in salinity measurements along multiple areas along the dive track.

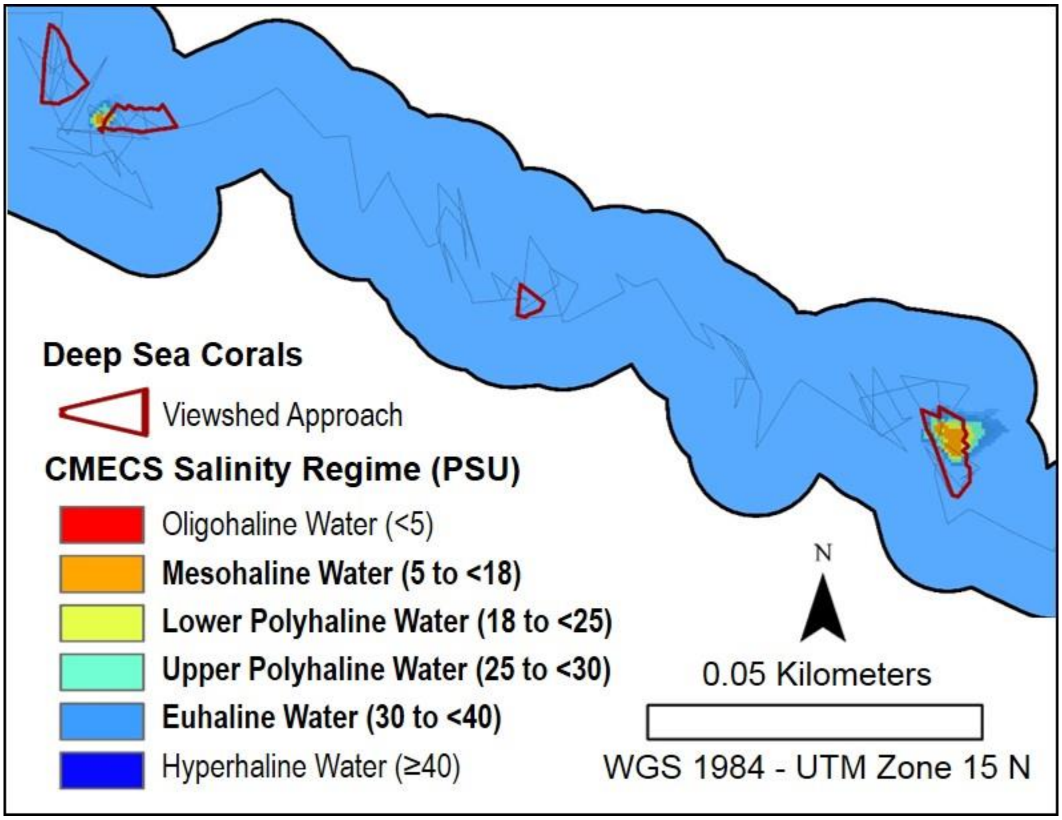

Figure 5.11 Deep Sea Coral Presence in Decreased Salinity Regions

Individually sorting through the unique habitat types revealed the alignment of some deep sea coral patches with areas of decreased salinity. The coral polygons were created through the viewshed mapping approach.

CHAPTER VI

CONCLUSION

As determined through the Northern Gulf of Mexico dataset consisting of one hundred still images and approximately fifty-four hours of video, implementing CMECS and geospatially representing underwater video of deep sea habitats is feasible and yields results superior to current visualization tools. Mechanisms employed are specific enough to support operational development of annotation procedures as related to NOAA's ROV *Deep Discoverer* and broad enough to benefit those within the oceanographic community concerned with the annotation, visualization, and delivery of underwater video. However, it is important to note that inferences and suggestions found herein are based on observations of a single ecoregion. Implementing CMECS to different deep sea habitats on multiple spatiotemporal scales is necessary to fully assess the appropriateness of applying CMECS to these predominantly unexplored ecosystems.

The presented research adequately responds to the literature gap of applying the federally mandated ecological standard – CMECS – to deep sea benthic habitats. The employed protocols give guidance on how these complex ecosystems and datasets may be classified, annotated, and mapped. Widespread CMECS implementation in these data deficit regions will promote improved habitat suitability modeling, conservation management objectives, resource exploitation oversight, and change detection initiatives across political jurisdictions and spatiotemporal scales [*Madden and Goodin*, 2007;

Shumchenia and King, 2010; *Gandomi et al.*, 2011; *Stolt et al.*, 2011; *Federal Geographic Data Committee*, 2012; *Carollo et al.*, 2013; *Allee et al.*, 2014; *Neves et al.*, 2014; *Yoskowitz et al.*, 2016; *Bassett et al.*, 2017]. Geospatially representing CMECS-compliant environmental and habitat information enhances ROV data and provides scientists with an improved visualization tool in which video content can be rapidly viewed – lessening the need to download and analyze tens to hundreds of hours of unwarranted video data. Offering these geospatially depicted, CMECS-compliant data through an online service will further facilitate interdisciplinary research and decision-making among a wide range of end-users.

6.1 CMECS Application to ROV Data

The findings presented in this thesis demonstrate the application of CMECS to deep sea benthic habitats in the Northern Gulf of Mexico as observed through still and video imagery collected by NOAA's ROV *Deep Discoverer*. They additionally indicate best practices for cartographically visualizing video data. Given that all one hundred highlight images were successfully classified using CMECS, it has been shown to be an effective classification tool for these data. However, some limited adaptations to the standard are recommended to better classify deep sea environments. For instance:

- Addition of "Bathymetric Feature Modifier" under the geoform component
- Renaming of "Brittle Stars on Hard or Mixed Substrate" to "Attached Brittle Stars" under the biotic group tier
- Addition of the "Attached Glass Sponges" under the biotic group tier to accommodate non-reef forming glass sponges

The presented research indicates that applying CMECS to ROV video in near-real-time with a single annotator is not feasible. However, videos were successfully annotated with the occasional pause and minimal rewinding of video to adjust for key selection errors within more complex benthic environments. The hot keyboard functionality may better support near-real-time application through multiple annotators – each dedicated to classifying a specific CMECS component.

6.2 Representing ROV Data Geospatially

The described geospatial processing techniques produce cartographic representations of CMECS classifications that promote data discovery, accelerated data analysis, and data visualization – especially when used within the context of a GIS. All map products retain CMECS-compliance to varying degrees of hierarchal detail. The viewshed mapping approach – which limits the classified area to that presumably viewed by the ROV's main, forward-facing camera – decreases the number of overlapping classes in a majority of the classified ROV dives. Although the viewshed approach is considered superior, the buffered approach may be the only option to those mapping underwater video data that lack the required vehicle and camera attitude information necessary for viewshed creation.

In conclusion, it would benefit NOAA – and other federally funded organizations with similar criterion – to incorporate comparable mechanisms and cartographically represent deep sea ecosystems through existing web-based, map portal(s). Offering the combined and individual CMECS-compliant map layers as an online service would provide scientists with the flexibility to view, query, and download the preferred files at multiple spatiotemporal scales. As a result, the ROV video and ancillary data would be more discoverable and conducive to accelerated habitat assessments. Since NOAA already delivers many of their products through online platforms (i.e., Okeanos Explorer Atlas, Ocean Exploration Digital Atlas, and OER Video Portal), integrating these additional geospatial layers into current practices would be relatively seamless.

6.3 Future Work

6.3.1 Improvements for ROV Viewshed Development

The viewshed mapping approach can be improved upon by incorporating additional parameters during the initial development of the viewshed polygons. Investigations within the following aspects – as related to viewshed creation and validation – would further enhance the accuracy in cartographically displaying ROV video content using the viewshed mapping approach:

- Determine correlation between camera viewing angle and camera zoom
- Incorporate camera pan, tilt, and zoom in viewshed creation
- Further assess appropriate viewing distance and viewing angle to validate the suggested values
- Determine level of mapping accuracy as related to actual observations (possibly through incorporating nadir imagery in future dives)

Although ROV *Deep Discoverer* remains relatively level, integrating values of camera pan and tilt would increase the accuracy of each individual viewshed coverage. Camera zoom is a highly variable parameter that directly effects the camera viewing angle. The correlation between camera viewing angle and camera zoom should be investigated and incorporated within viewshed development. It is recognized that the level of camera zoom is not a recorded parameter by *Deep Discoverer*; however, constraining each viewshed by the level of enacted camera zoom would provide a more realistic representation of the observed benthic habitats.

6.3.2 Future Work towards Operational Use

Additional work is needed to make methods presented in this thesis operationally viable. Separating annotation lists by component to include every subunit applicable to the deep sea (globally) would allow for the extraction of site specific annotation lists when necessary and further support standardization efforts. Incorporating current dive codes applicable to desired CMECS units and accommodating the suggested adjustments within the ROV Data Analyzer software should also be considered. Map products can be more efficiently generated by combing the described geospatial processing techniques within a python script. Moreover, subsequent steps for delivering the environmental and habitat maps alongside current ROV products through existing online portals would also have to be established and integrated with ongoing procedures.

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APPENDIX A

GEOSPATIAL MODELS

A.1 Models for Buffer and Viewshed Polygon Creation

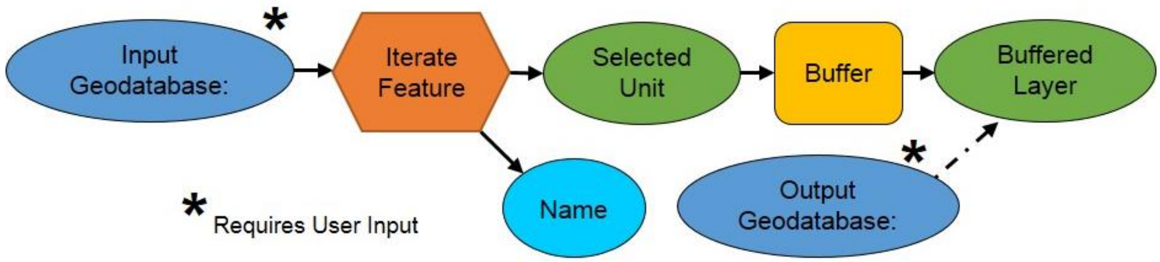

Figure A.1 Create Buffers Model

This model iterates through each 1Hz data feature layer to create a 5m buffered polygon.

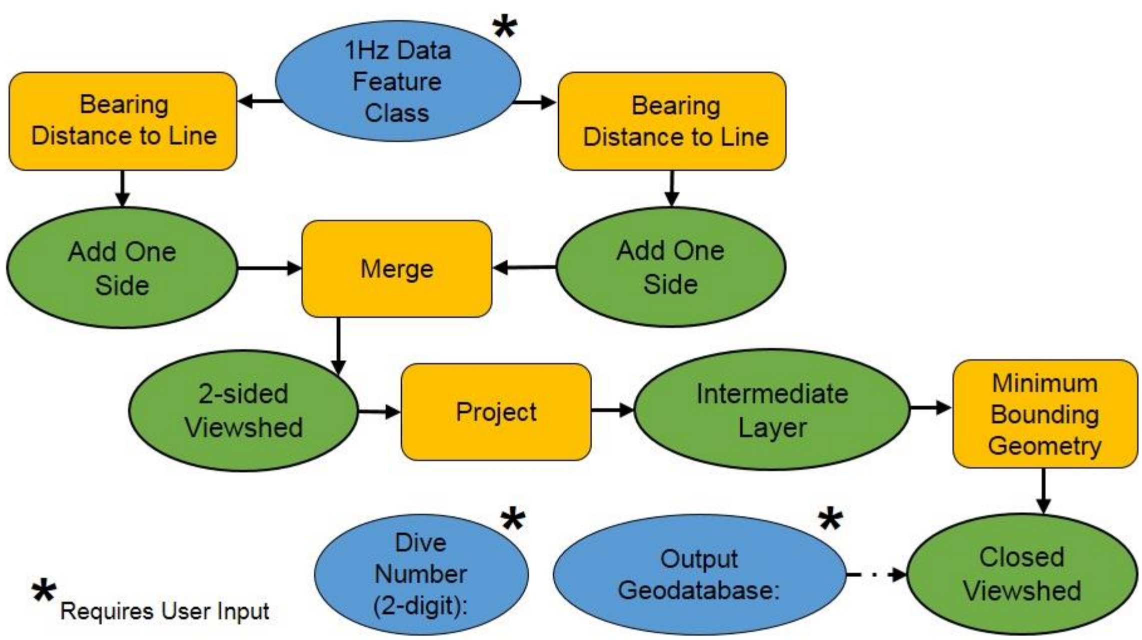

Figure A.2 Create Viewsheds Model

This model pieces together a 44° wedge-shaped polygon for every data point throughout the input 1Hz data feature class. This model was separately run for each dive track as the accompanying dive buffer output generated by the Create Buffers Model was used to set the processing extent.

A.2 Polygon to Raster Conversions

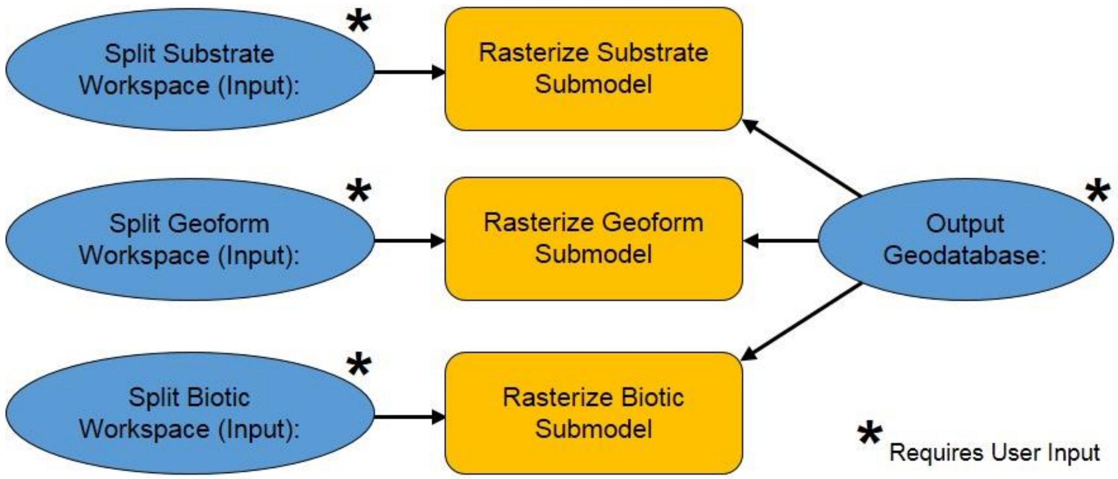

Figure A.3 Rasterize All Components Model

This model runs the below workflow for each component. Submodels had to be created since ESRI's Model Builder does not allow the use of multiple iterators within a single model.

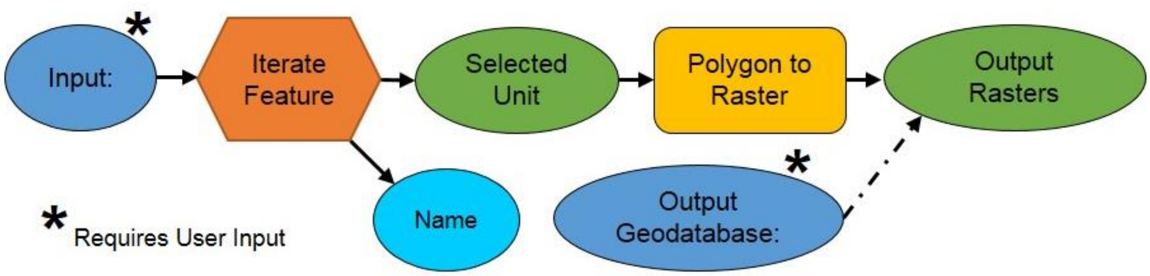

Figure A.4 Rasterize Submodel Example

This model iterates through the geodatabases created by the USGS Split By Attribute tool and generates a subsequent raster layer within the specified output geodatabase for each input feature class.

A.3 Applying Raster Coding Schema

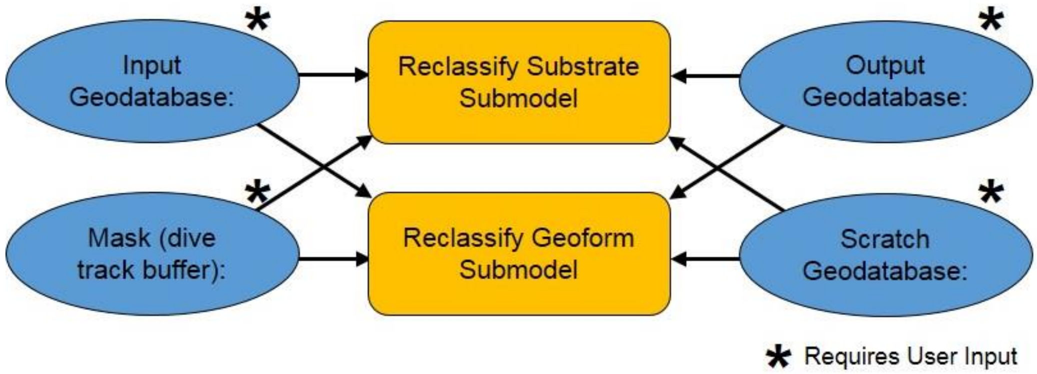

Figure A.5 Reclassify All Components Model

This model is the only one accessed by the user; the remaining models are submodels ingested by this model. Models had to be tiered into submodels and sub-submodels since ESRI's Model Builder does not allow the use of multiple iterators within a single model.

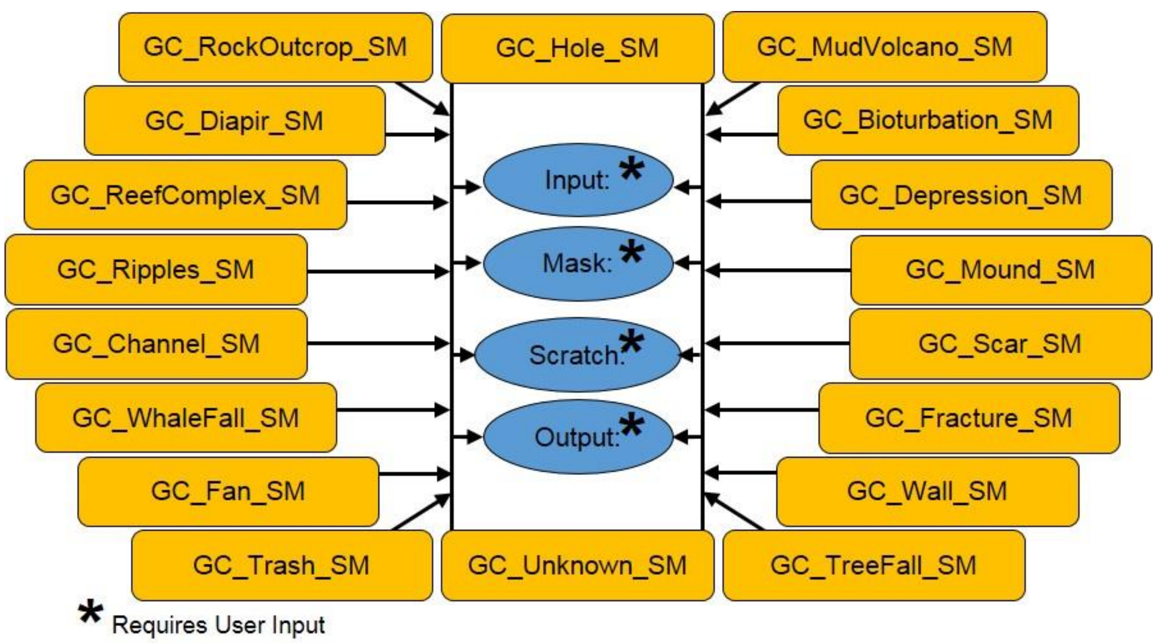

Figure A.6 Reclassify Submodel Example

The above model goes through every possible hot key abbreviation sub-submodel (next model) and applies the appropriate raster code based on appended name (e.g., *Otcrp, *Rs, etc.). A similar submodel with substrate hot keys was also developed and utilized.

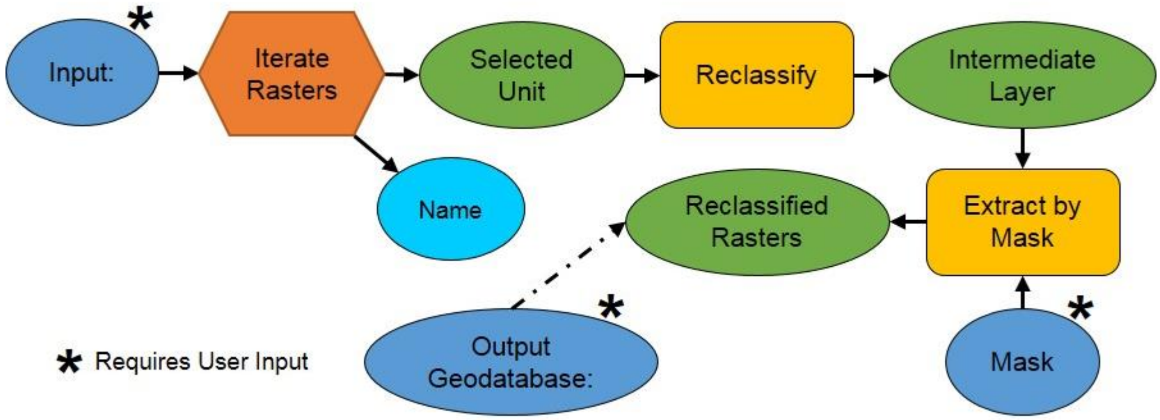

Figure A.7 Reclassify Sub-Submodel Example

The above model is the general workflow that iterates through the input dataset, selects a particular raster layer based on a specified abbreviated hot key name appended to the filename, and applies the appropriate raster code. A sub-submodel was created for each possible unique hot key. Outputs are not generated for unselected hot keys.

A.4 Raster Generalizations

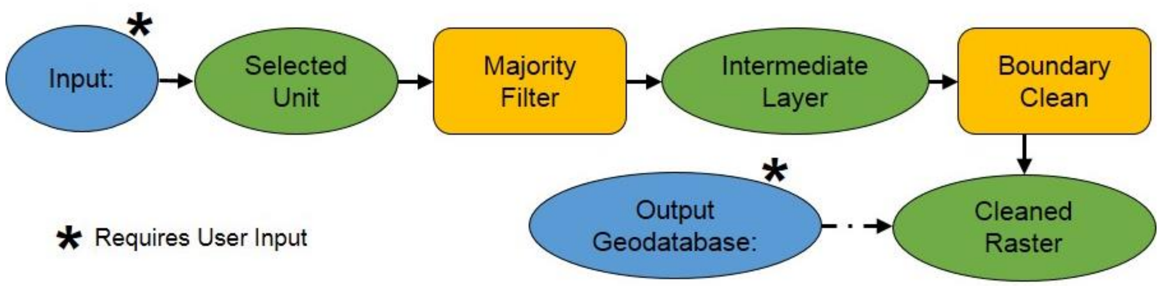

Figure A.8 Finalize Combined Raster Outputs Model

The above model removes "island" pixels by applying a majority filter (consumes the disassociated pixels based on the surrounding neighborhood of cells) and boundary clean (smooths zonal boundaries) to provide a cleaner raster product; this model was applied to all combined substrate and geoform raster layers (i.e., buffered and viewshed outputs).

APPENDIX B

CLASSIFIED HIGHLIGHT IMAGES

B.1 Dive 01

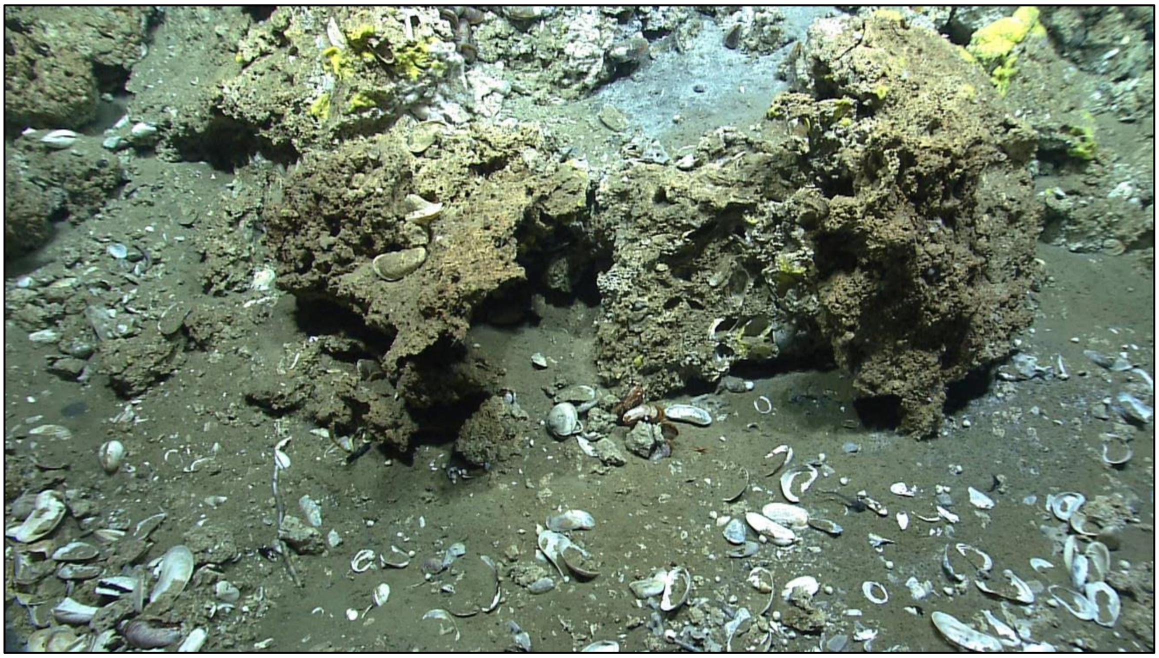

Figure B.1 Dive 01, Image 01:
EX1402L3_IMG_20140412T152854Z_ROVHD_MOUND_TIGHT

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Authigenic Carbonate Rock Outcrop located on a Platform (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Rubble

Biotic: Attached Sponges with Co-occurring Attached Mussels

Figure B.2 Dive 01, Image 02: EX1402L3_IMG_20140412T153157Z_ROVHD_AUDIO_MUD_VOL

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Located on a Platform (Level 1) on a Continental Slope

Substrate: Rock Substrate

Biotic: Attached Mussels

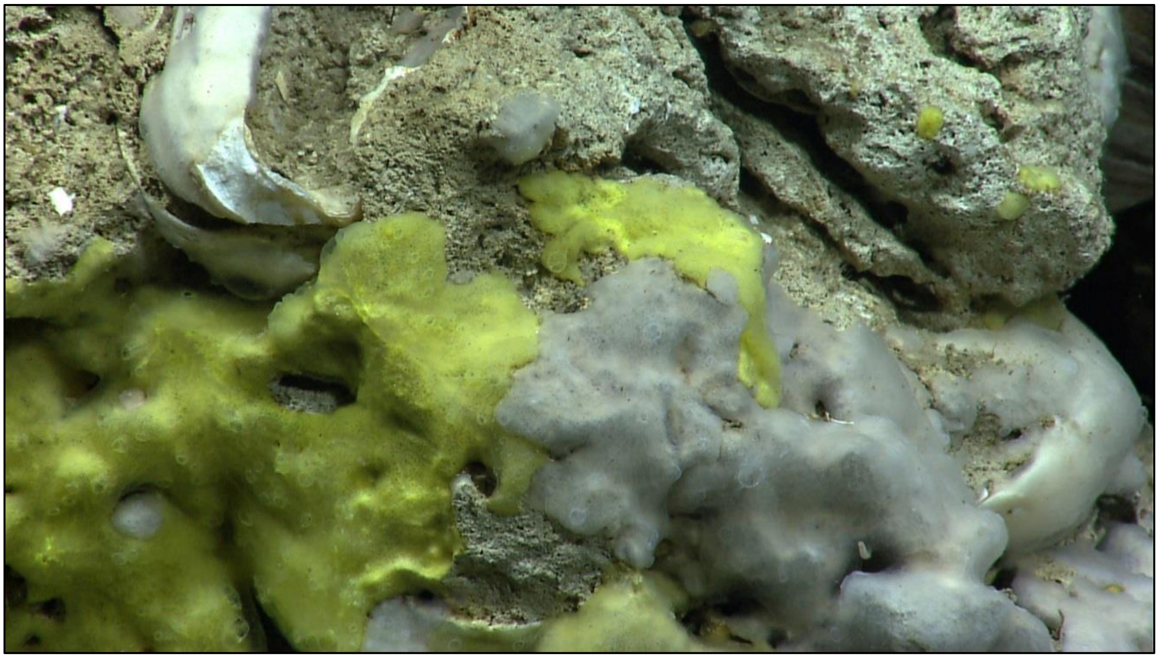

Figure B.3 Dive 01, Image 03: EX1402L3_IMG_20140412T154434Z_ROVHD_MAT_MUS

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Authigenic Carbonate Rock Outcrop located on a Platform (Level 1) on a Continental Slope

Substrate: Mussel Reef Substrate

Biotic: Attached Sponges

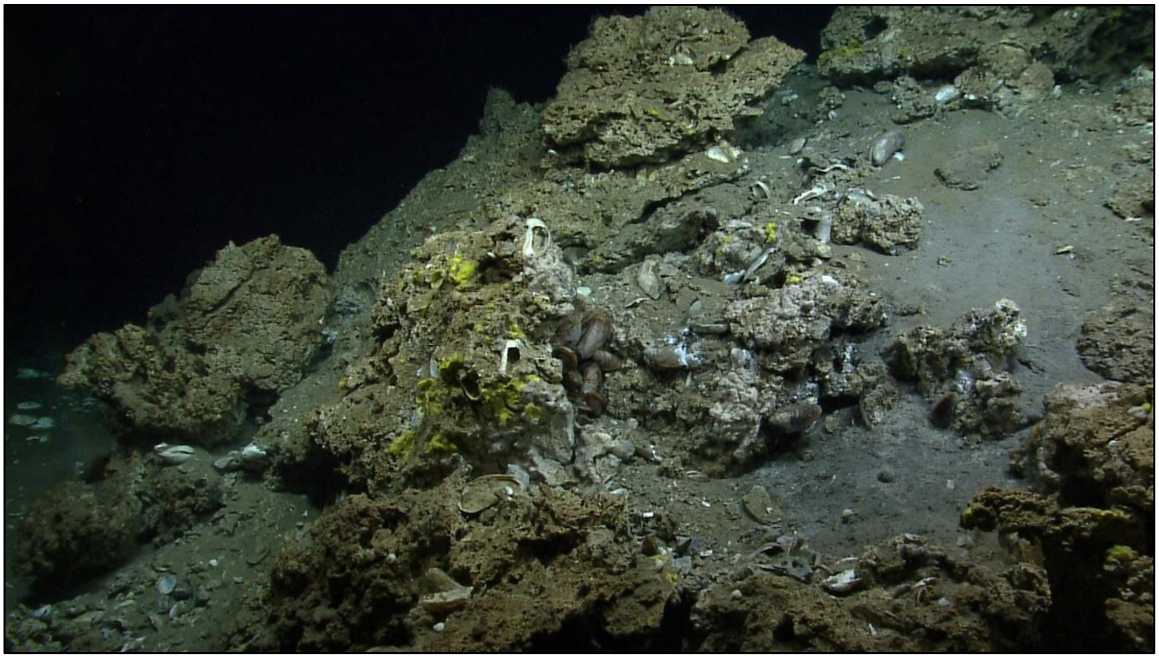

Figure B.4 Dive 01, Image 04: EX1402L3_IMG_20140412T154754Z_ROVHD_SPO

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Authigenic Carbonate Rock Outcrop located on a Platform (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Rubble

Biotic: Diverse Colonizers of Attached Mussels and Attached Sponges

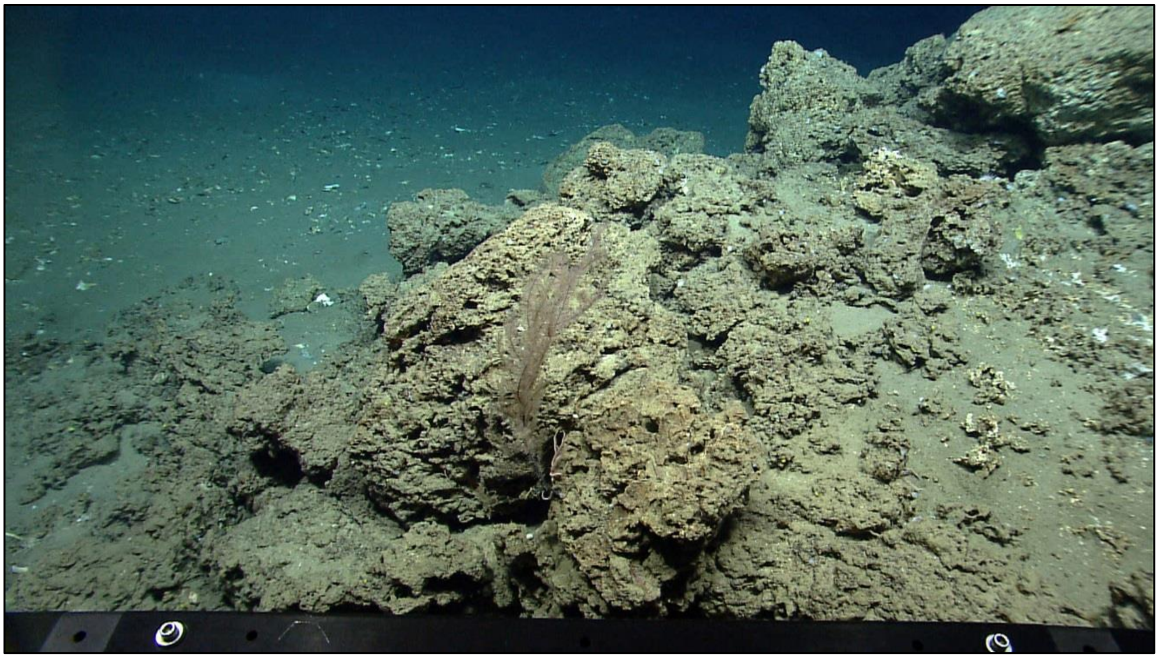

Figure B.5 Dive 01, Image 05:
EX1402L3_IMG_20140412T161823Z_ROVHD_MOUND

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Authigenic Carbonate Rock Outcrop located on a Platform (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Rubble

Biotic: Attached Corals

Figure B.6 Dive 01, Image 06:
EX1402L3_IMG_20140412T163908Z_ROVHD_MUS_URC

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Authigenic Carbonate Rock Outcrop located on a Platform (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Reef Substrate

Biotic: Mussel Reef with the following Associated Taxa: Sea Urchins

Figure B.7 Dive 01, Image 07: EX1402L3_IMG_20140412T164008Z_ROVHD_MUS_URC

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Located on a Platform (Level 1) on a Continental Slope

Substrate: Coarse Unconsolidated Mineral Substrate

Biotic: Attached Mussels with the following Associated Taxa: Sea Urchins and Gastropods

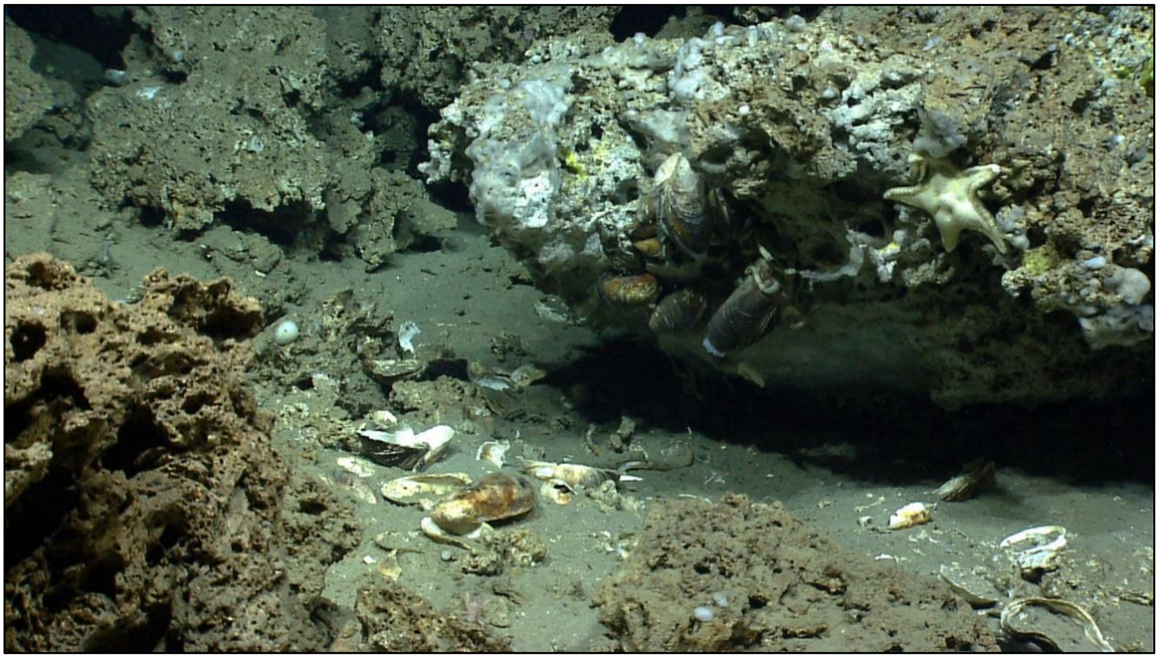

Figure B.8 Dive 01, Image 08: EX1402L3_IMG_20140412T174113Z_ROVHD_STARFISH_ZOOMED

Water Column: Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Authigenic Carbonate Rock Outcrop located on a Platform (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Rubble

Biotic: Diverse Colonizers of Attached Mussels and Attached Sponges with Co-occurring Attached Tube-Building Fauna and the following Associated Taxa: Starfish

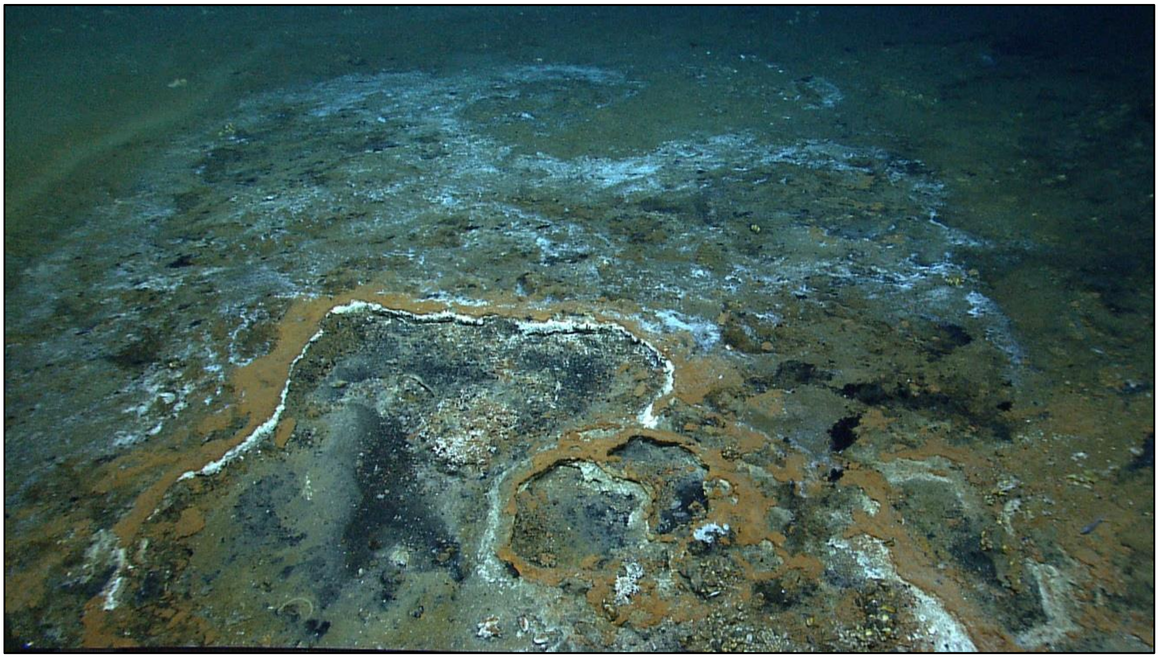

Figure B.9 Dive 01, Image 09:
EX1402L3_IMG_20140412T181809Z_ROVHD_OIL_FIELD_01

Water Column: Cold Euhaline Water with Seep on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Located on a Platform (Level 1) on a Continental Slope

Substrate: Unconsolidated Mineral Substrate

Biotic: Bacterial Mat/Film

Figure B.10 Dive 01, Image 10:
EX1402L3_IMG_20140412T185157Z_ROVHD_OIL_BUBBLES

Water Column: Cold Euhaline Water with Seep on the Benthic Boundary Layer in the Marine Oceanic Mesopelagic Layer (Oxic)

Geoform: Located on a Platform (Level 1) on a Continental Slope

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Mussels

B.2 Dive 02

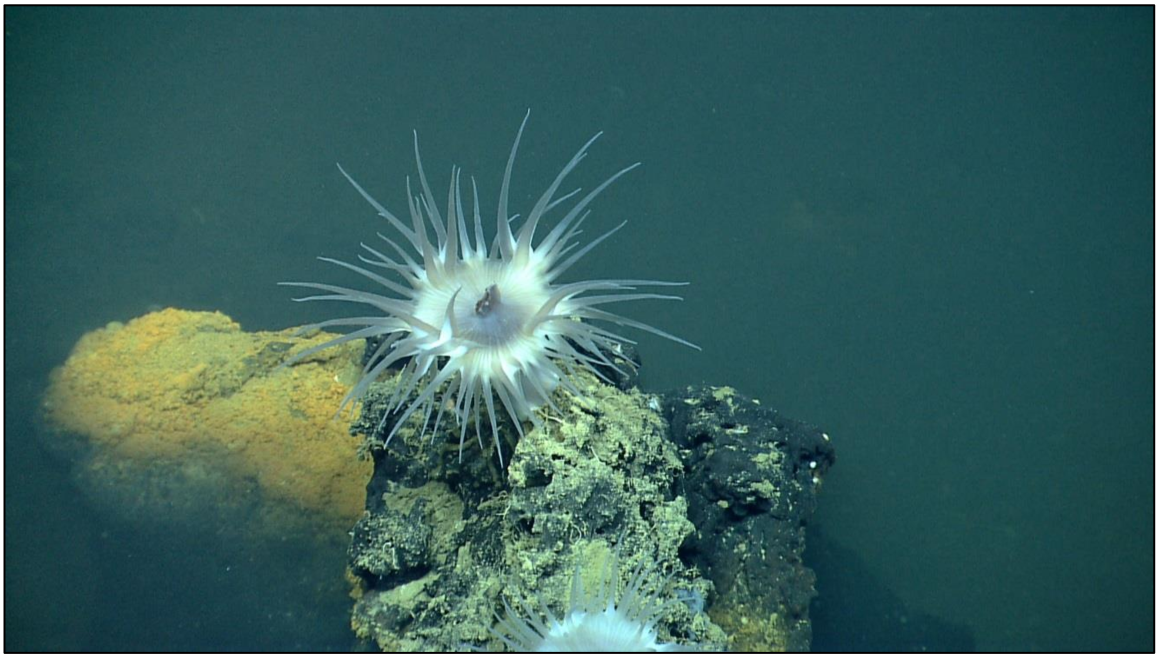

Figure B.11 Dive 02, Image 01:
EX1402L3_IMG_20140413T151720Z_ROVHD_ANM_BRIN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Depression (Level 2) on a Continental Slope

Substrate: Gravel sized Coarse Unconsolidated Mineral Substrate (Brine Pool)
Biotic: Attached Anemones

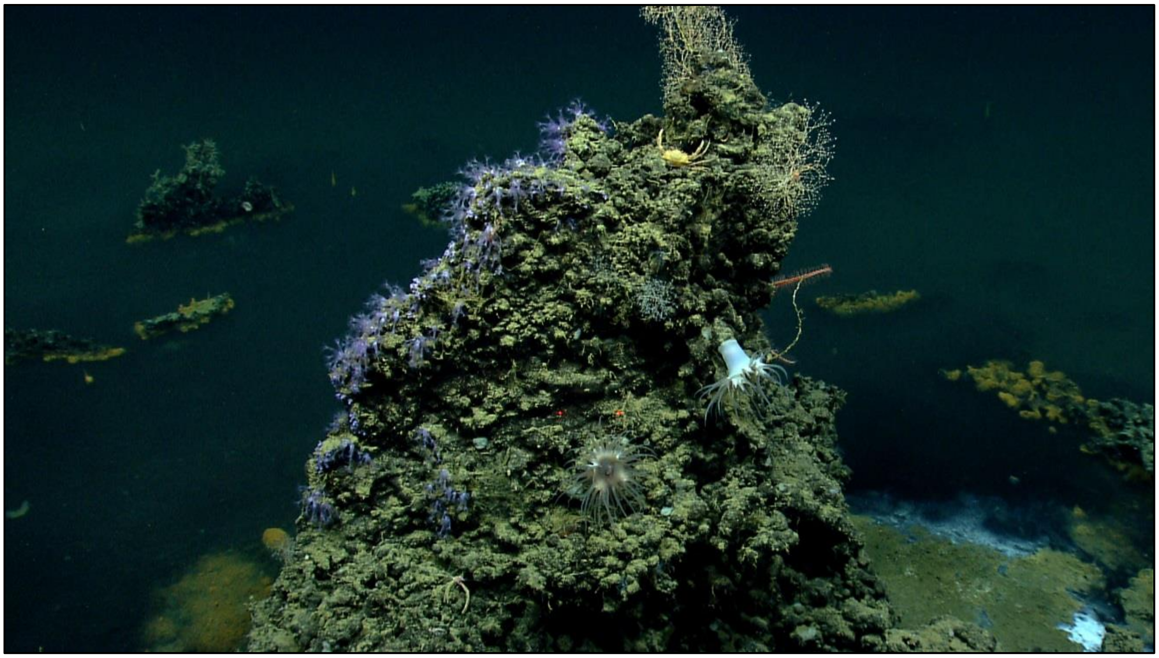

Figure B.12 Dive 02, Image 02: EX1402L3_IMG_20140413T152345Z_ROVHD_BRIN_ACN_SHI_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Depression (Level 2) on a Continental Slope

Substrate: Gravel sized Coarse Unconsolidated Mineral Substrate (Brine Pool)

Biotic: Attached Octocorallia with Co-occurring Attached Anemones and the following Associated Taxa: Shrimp and Crab

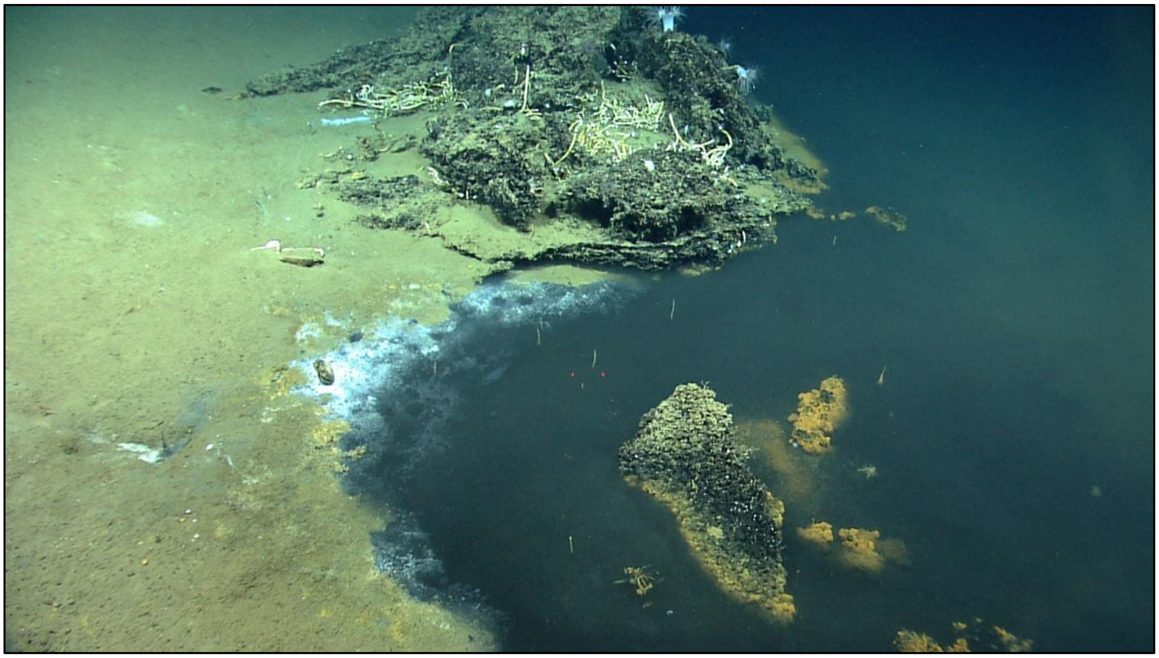

Figure B.13 Dive 02, Image 03:
EX1402L3_IMG_20140413T160105Z_ROVHD_TUB_MUS_BRIN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Depression (Level 2) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate (Brine Pool)

Biotic: Attached Tube-Building Fauna with Co-occurring Attached Anemones

Figure B.14 Dive 02, Image 04:
EX1402L3_IMG_20140413T160543Z_ROVHD_TUB_CRA_ACN_SQA

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Authigenic Carbonate Outcrop on a Continental Slope

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate (Brine Pool)

Biotic: Attached Tube-Building Fauna with Co-occurring Attached Anemones and the following Associated Taxa: Crab and Squat Lobsters

Figure B.15 Dive 02, Image 05:
EX1402L3_IMG_20140413T160929Z_ROVHD_TUB_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Authigenic Carbonate Outcrop on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Tube-Building Fauna

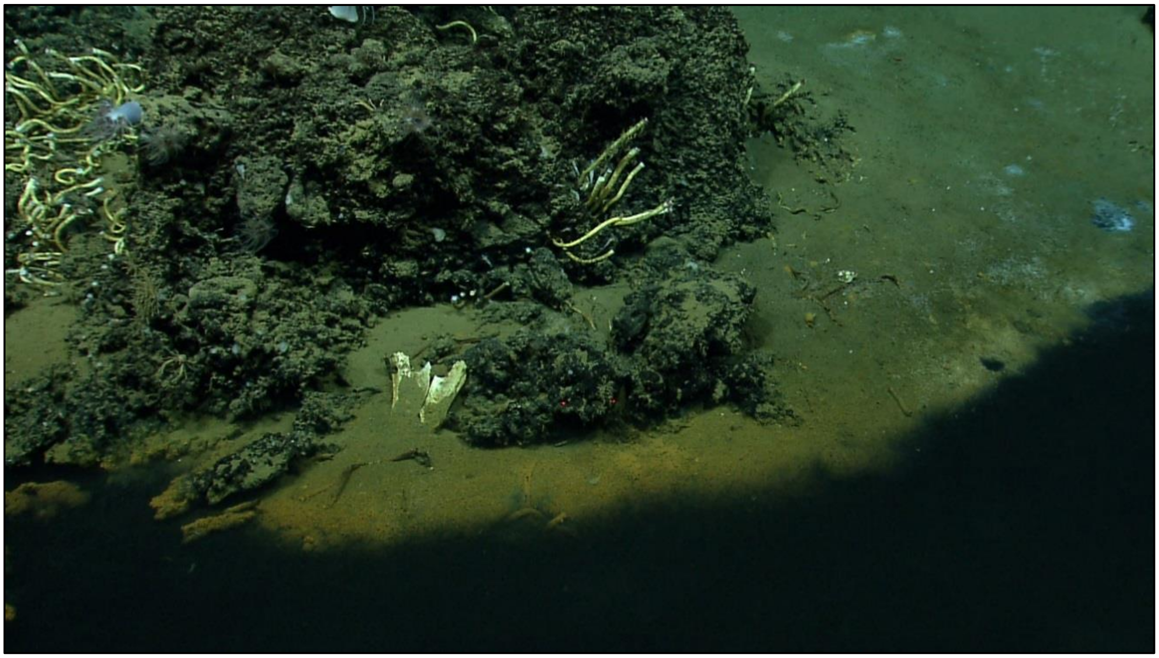

Figure B.16 Dive 02, Image 06:
EX1402L3_IMG_20140413T161307Z_ROVHD_FORM

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Hypoxic)

Geoform: Authigenic Carbonate Outcrop on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Rubble (Brine Pool)

Biotic: Attached Tube-Building Fauna with Co-occurring Attached Anemones and the following Associated Taxa: Squat Lobster

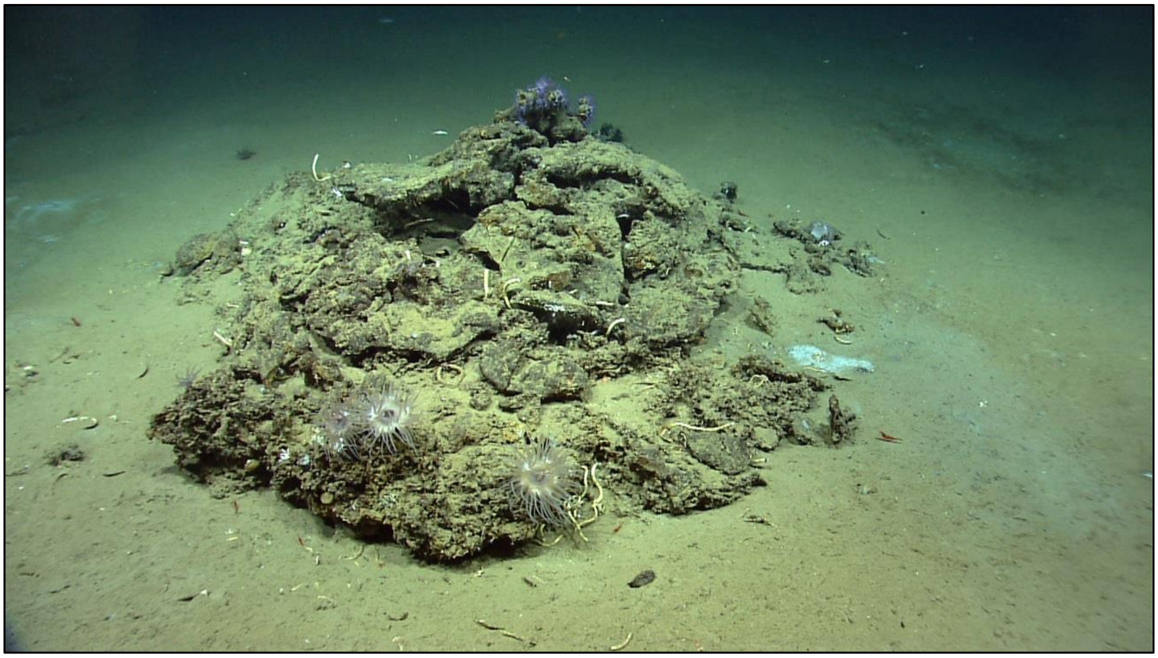

Figure B.17 Dive 02, Image 07:
EX1402L3_IMG_20140413T170233Z_ROVHD_TUB_SQA_CORO_01

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Authigenic Carbonate Outcrop on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Rubble

Biotic: Diverse Colonizers of Attached Anemones, Attached Octocorallia, and Attached Tube-Building Fauna with the following Associated Taxa: Shrimp and Squat Lobster

Figure B.18 Dive 02, Image 08:
EX1402L3_IMG_20140413T172332Z_ROVHD_BUBBLES_OIL_04

Water Column: Very Cold Euhaline Water with Seep on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Mollusk Reef on a Continental Slope

Substrate: Mussel Reef Substrate with Co-occurring Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Diverse Colonizers of Attached Anemones and Attached Tube-Building Fauna with the following Associated Taxa: Sea Urchins

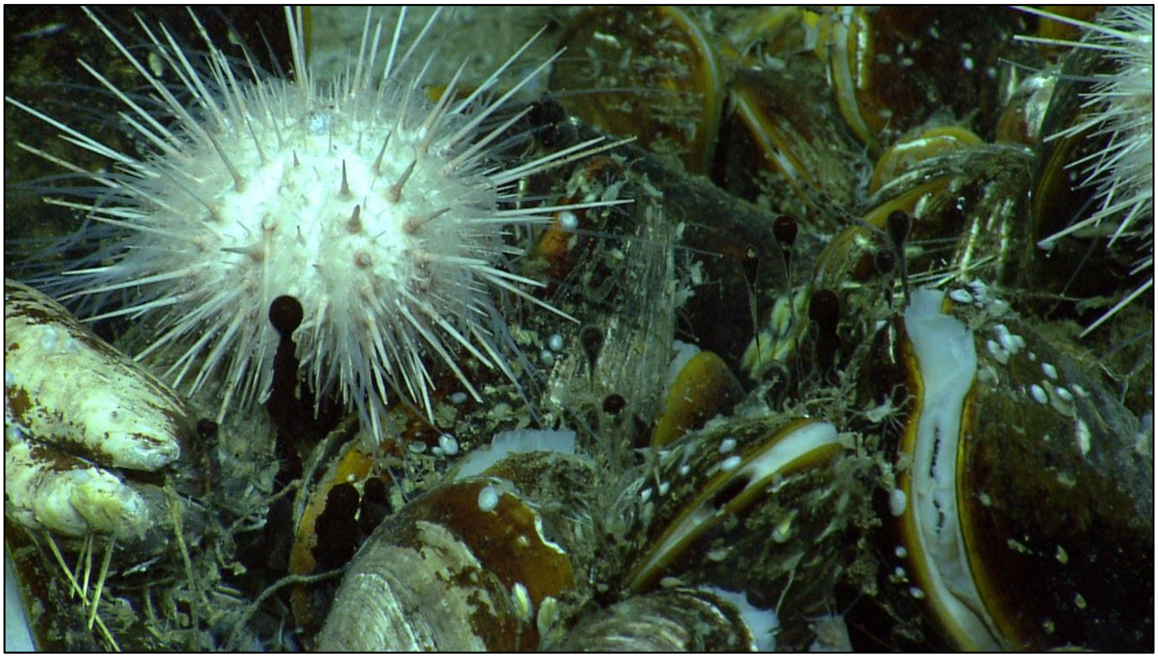

Figure B.19 Dive 02, Image 09:
EX1402L3_IMG_20140413T172809Z_ROVHD_BUBBLES_OIL_05

Water Column: Very Cold Euhaline Water with Seep on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Continental Slope

Biotic: Attached Mussels with Co-occurring Attached Limpets and the following Associated Taxa: Sea Urchins

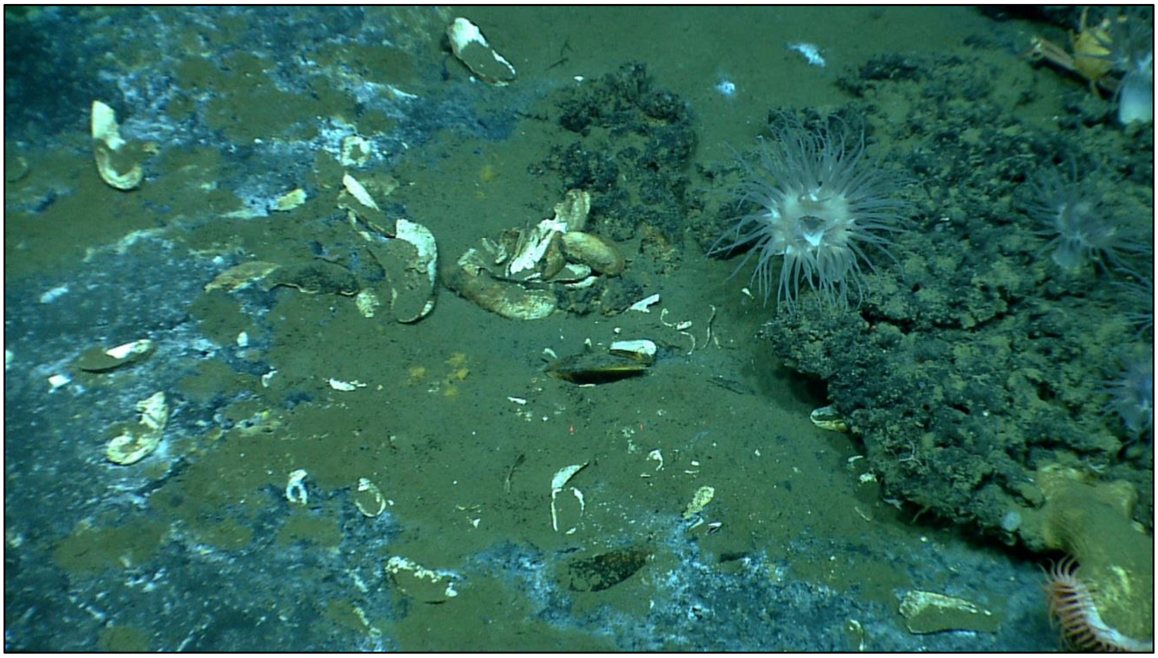

Figure B.20 Dive 02, Image 10:
EX1402L3_IMG_20140413T181812Z_ROVHD_OD_BRINE_POOL_01

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Rubble (Brine Pool)

Biotic: Attached Anemones with Co-occurring Bacterial Mat/Film

B.3 Dive 03

Figure B.21 Dive 03, Image 01:
EX1402L3_IMG_20140414T150822Z_ROVHD_SPO_OPH

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Diverse Colonizers of Attached Octocorallia and Attached Sponges with the following Associated Taxa: Hexactinellid and Brittle Stars

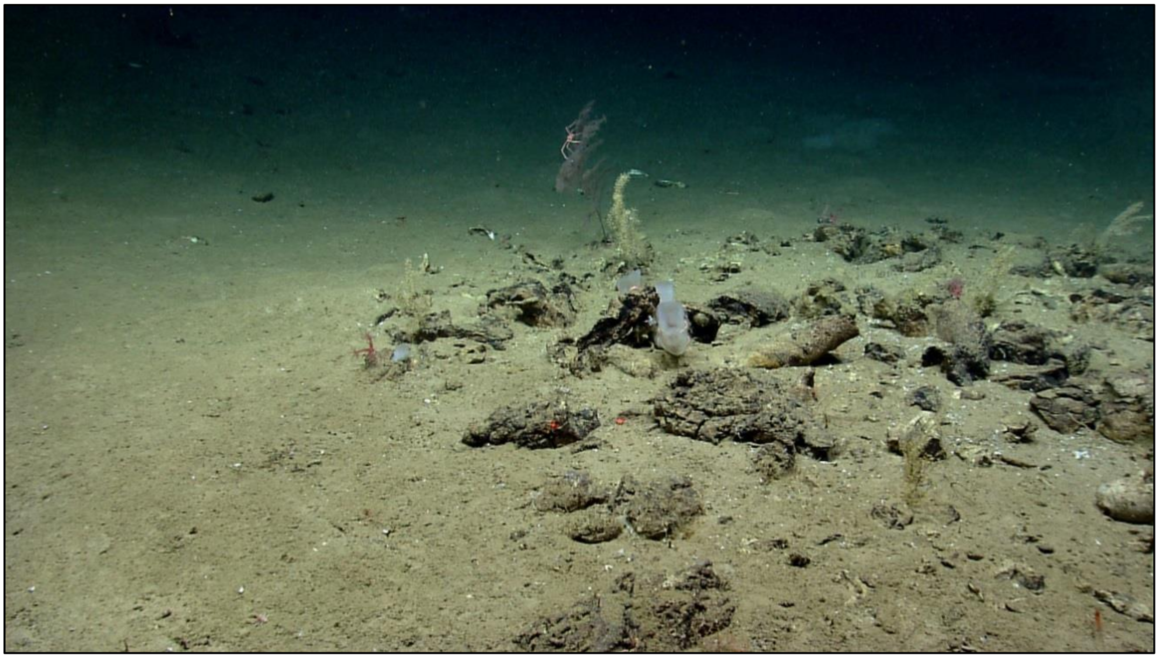

Figure B.22 Dive 03, Image 02: EX1402L3_IMG_20140414T151306Z_ROVHD_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Diverse Colonizers of Attached Corals and Attached Sponges with Co-occurring Attached Anemones and the following Associated Taxa: Hexactinellid, Octocorallia, Black Coral, Brittle Stars, and Squat Lobsters

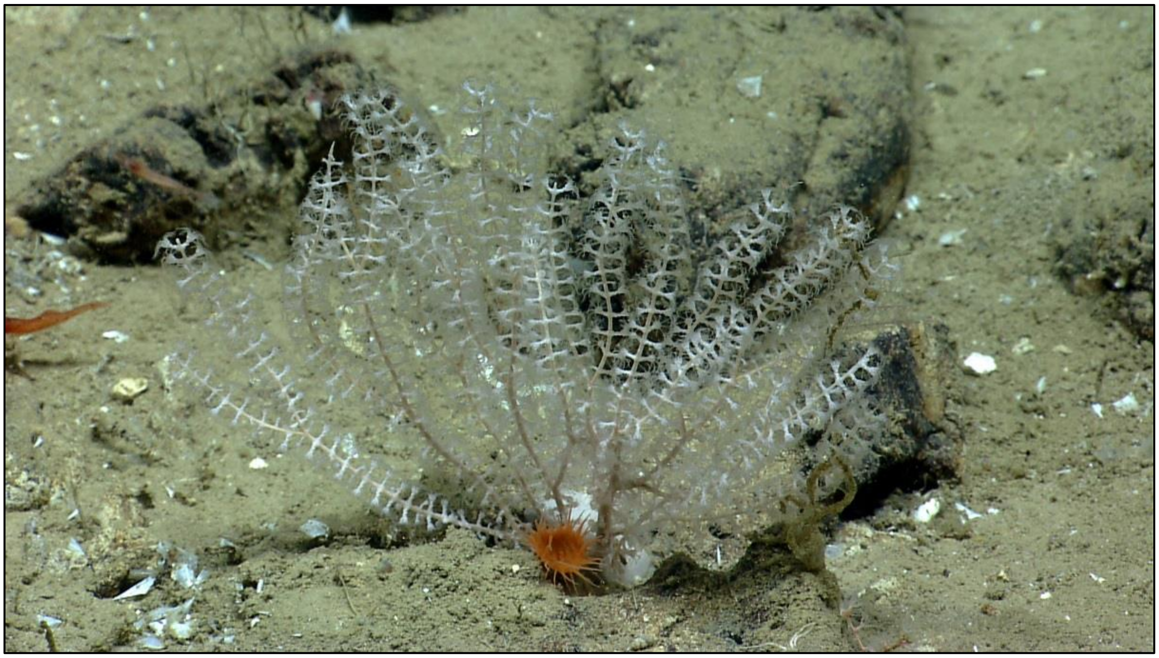

Figure B.23 Dive 03, Image 03:
EX1402L3_IMG_20140414T152221Z_ROVHD_COR_)ACN_SHI

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) on a Continental Slope

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Attached Corals with Co-occurring Attached Anemones and the following Associated Taxa: Shrimp

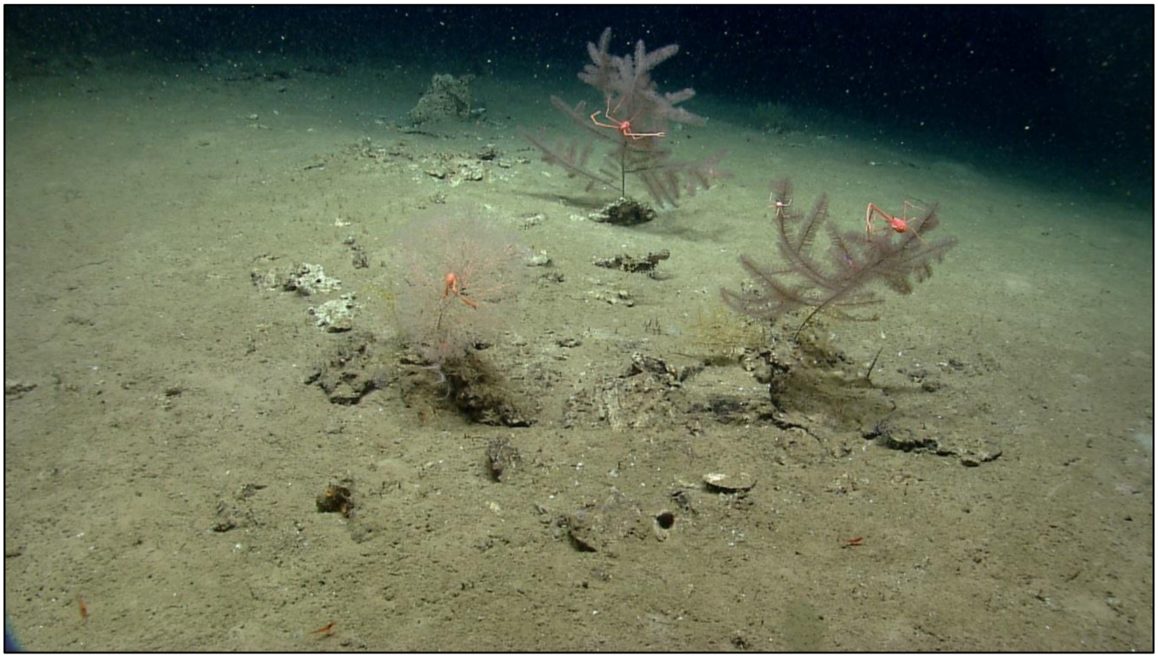

Figure B.24 Dive 03, Image 04:
EX1402L3_IMG_20140414T155022Z_ROVHD_COR_SQA

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Rubble

Biotic: Attached Corals with the following Associated Taxa: Squat Lobsters

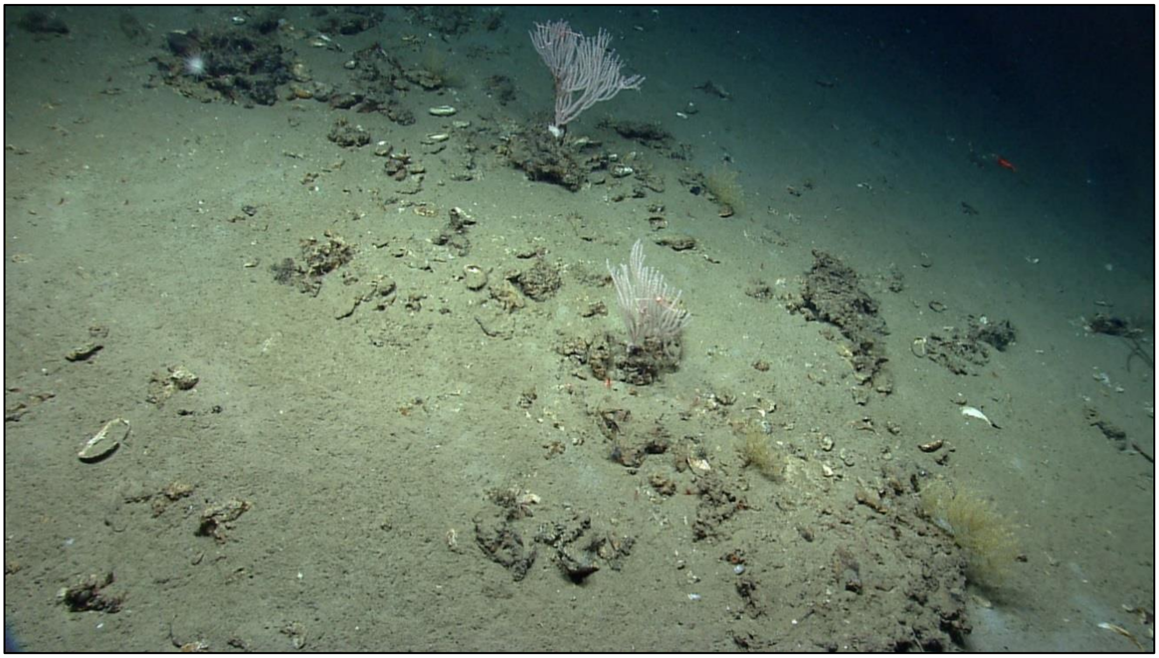

Figure B.25 Dive 03, Image 05: EX1402L3_IMG_20140414T161841Z_ROVHD_COR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Highly Oxic)

Geoform: Slope (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Rubble

Biotic: Attached Corals with the following Associated Taxa: Sea Urchins and Squat Lobsters

Figure B.26 Dive 03, Image 06:
EX1402L3_IMG_20140414T163944Z_ROVHD_MUS_SHELLS

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) on a Continental Slope

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Sponges with Co-occurring Bacterial Mat/Film and the following Associated Taxa: Shrimp

Figure B.27 Dive 03, Image 07:
EX1402L3_IMG_20140414T164454Z_ROVHD_MUS_SHELLS

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Mollusk Reef on a Slope (Level 1) on a Continental Slope

Substrate: Mussel Reef Substrate with Co-occurring Coarse Unconsolidated Mineral Substrate

Biotic: Mussel Reef

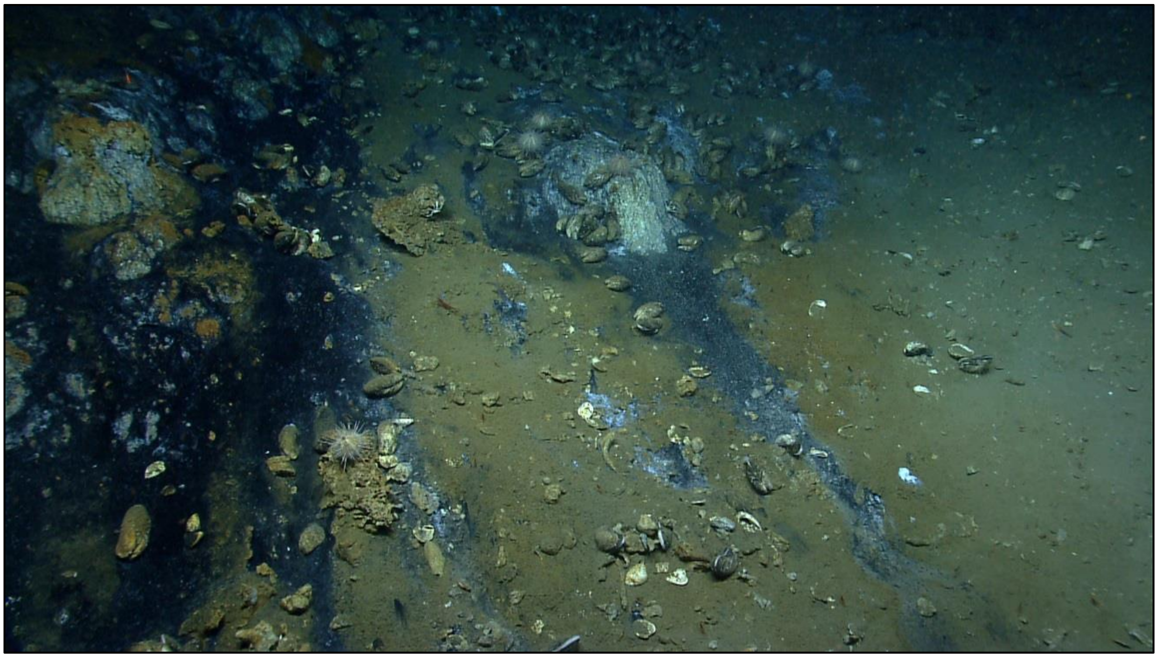

Figure B.28 Dive 03, Image 08: EX1402L3_IMG_20140414T165937Z_ROVHD_POTENTIAL_HYDRATE

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) on a Continental Slope (Gas Hydrate)

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Rubble

Biotic: Bacterial Mat/Film with Co-occurring Attached Mussels and the following Associated Taxa: Sea Urchins and Shrimp

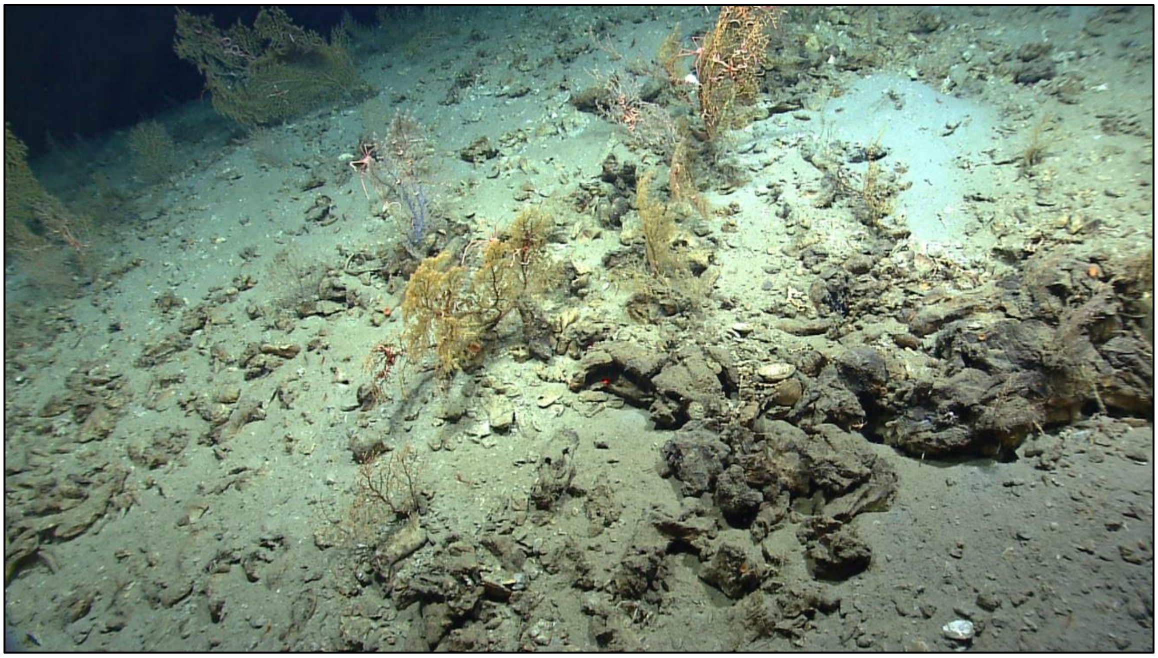

Figure B.29 Dive 03, Image 09:
EX1402L3_IMG_20140414T175041Z_ROVHD_COR_OPH_SQA

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Authigenic Carbonate Outcrop located on a Slope (Level 1) on a Continental Slope

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate with Co-occurring Mussel Rubble

Biotic: Diverse Colonizers of Attached Corals, Attached Mussels, and Attached Anemones with the following Associated Taxa: Brittle Stars and Squat Lobsters

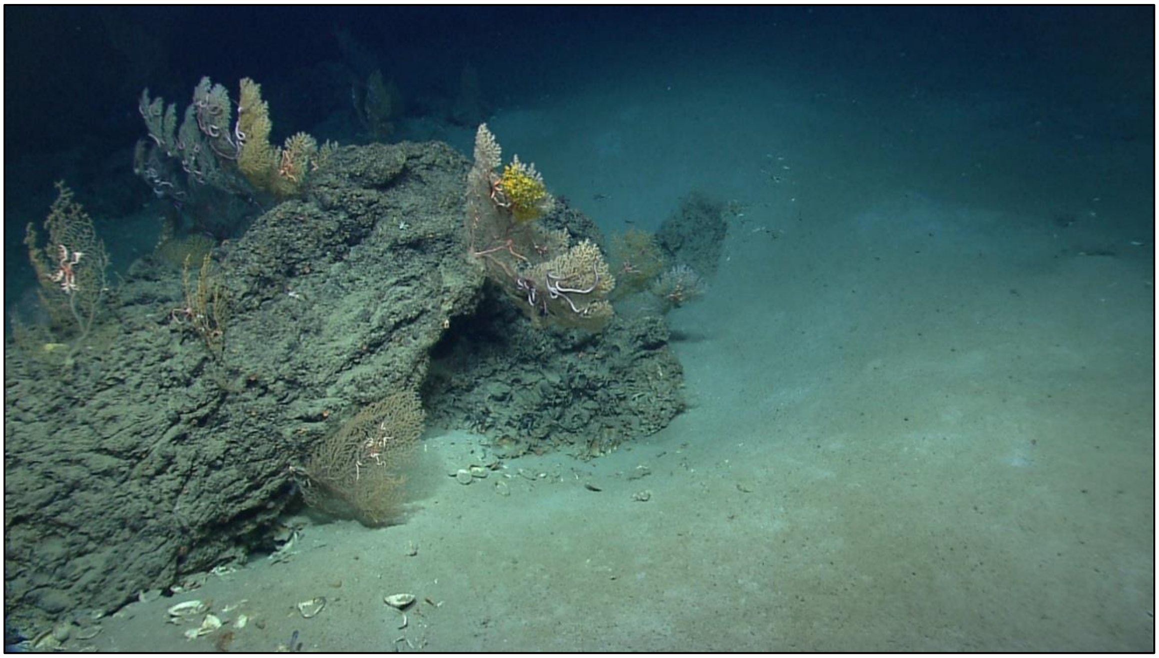

Figure B.30 Dive 03, Image 10: EX1402L3_IMG_20140414T175633Z_ROVHD_ROCK_COR_SQA_OPH

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Authigenic Carbonate Outcrop located on a Slope (Level 1) on a Continental Slope

Substrate: Rock Substrate with Co-occurring Fine Unconsolidated Mineral Substrate and Mussel Rubble

Biotic: Attached Corals with the following Associated Taxa: Brittle Stars and Squat Lobsters

B.4 Dive 04

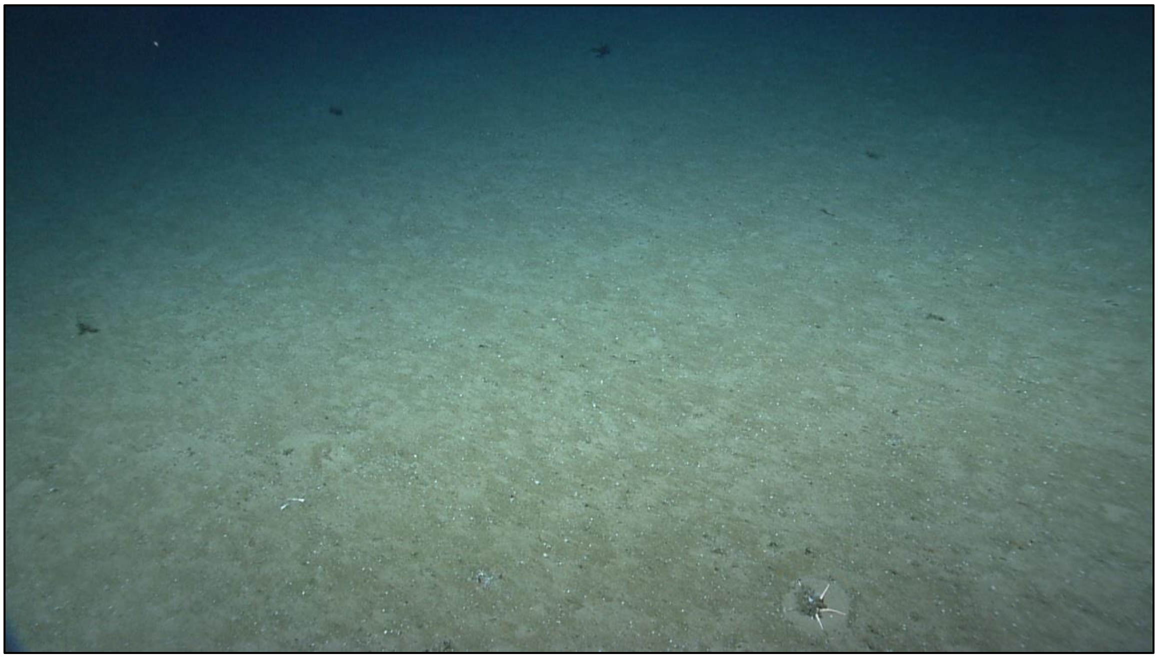

Figure B.31 Dive 04, Image 01: EX1402L3_IMG_20140416T153740Z_ROVHD_CURRENT_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Soft Sediment Brittle Stars

Figure B.32 Dive 04, Image 02:
EX1402L3_IMG_20140416T154924Z_ROVHD_SPO_SHI_SAR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Attached Sponges with the following Associated Taxa: Hexactinellid and Shrimp

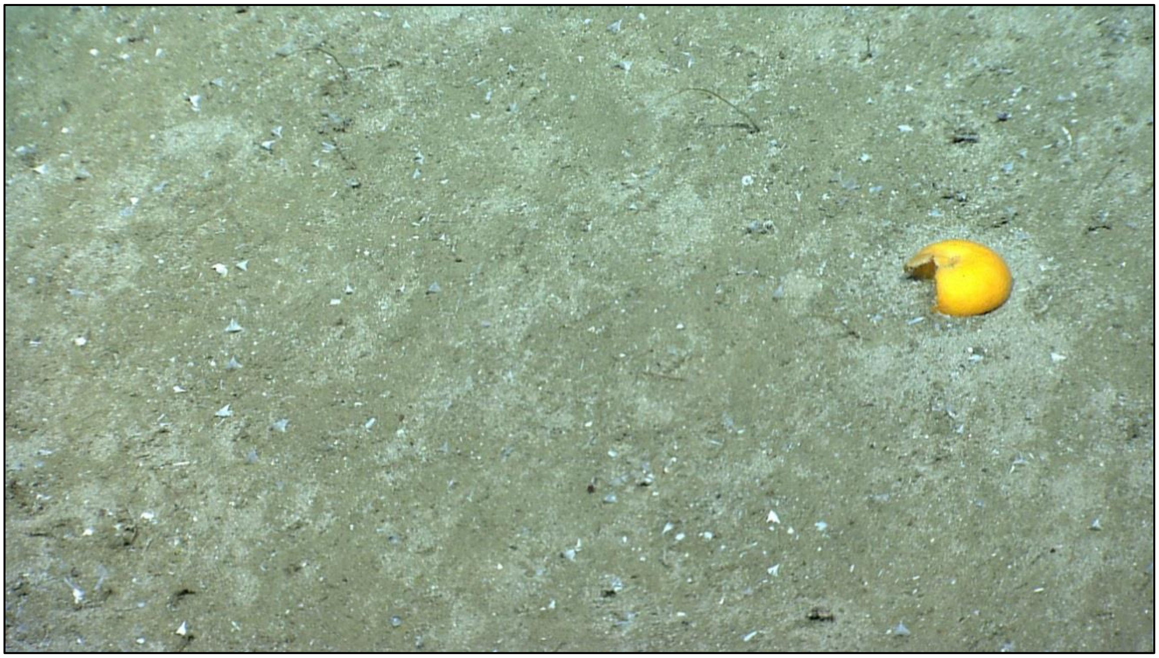

Figure B.33 Dive 04, Image 03:
EX1402L3_IMG_20140416T161025Z_ROVHD_TRASH_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash and Trash

Figure B.34 Dive 04, Image 04: EX1402L3_IMG_20140416T161611Z_ROVHD_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Attached Venus Flytrap Anemones

Figure B.35 Dive 04, Image 05:
EX1402L3_IMG_20140416T170858Z_ROVHD_COR_SHI

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Bamboo Coral with the following Associated Taxa: Shrimp

Figure B.36 Dive 04, Image 06: EX1402L3_IMG_20140416T172305Z_ROVHD_PARCHMENT_WORMS

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Larger Tube-Building Fauna with Co-occurring Sargassum Particles with the following Associated Taxa: Parchment Worms

Figure B.37 Dive 04, Image 07:
EX1402L3_IMG_20140416T180028Z_ROVHD_ACN_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Burrowing Anemones

Figure B.38 Dive 04, Image 08:
EX1402L3_IMG_20140416T181214Z_ROVHD_FSH_SARGASSUM

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Sargassum Rafts

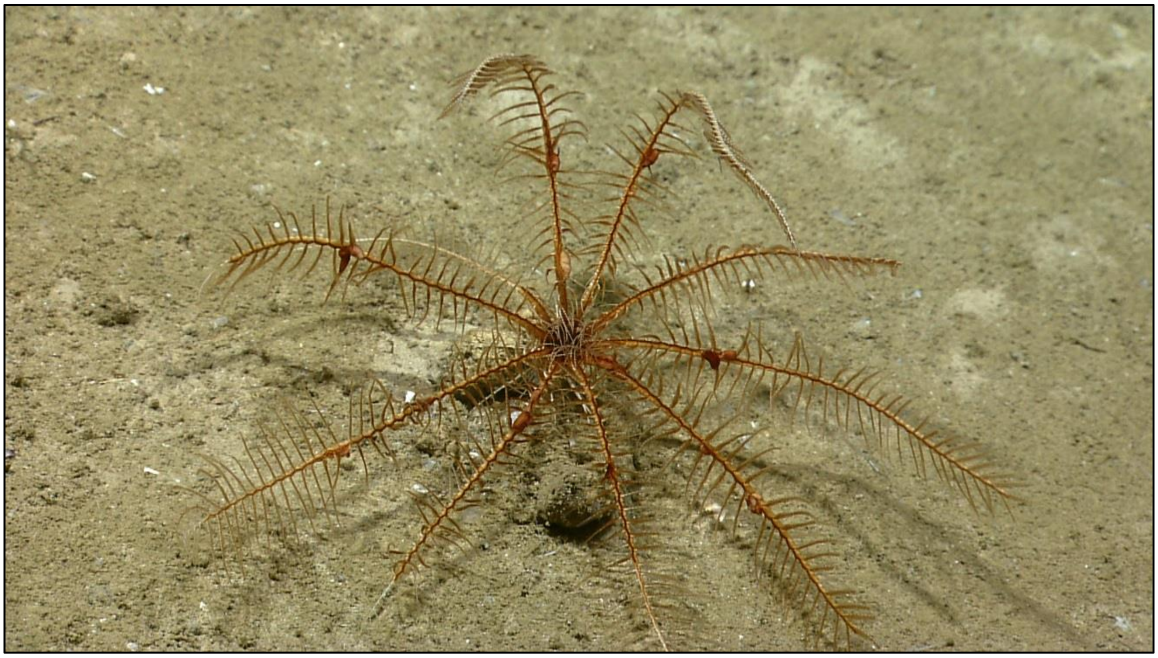

Figure B.39 Dive 04, Image 09: EX1402L3_IMG_20140416T185631Z_ROVHD_CRI

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Crinoids

Figure B.40 Dive 04, Image 10: EX1402L3_IMG_20140416T202344Z_ROVHD_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Hyalonema

B.5 Dive 06

Figure B.41 Dive 06, Image 01: EX1402L3_IMG_20140418T153759Z_ROVHD_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Burrowing Anemones

Figure B.42 Dive 06, Image 02:
EX1402L3_IMG_20140418T161202Z_ROVHD_SPO_ACN_CRA

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Authigenic Carbonate Outcrop in a Submarine Canyon (Keathley Canyon)

Substrate: Carbonate Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Figure B.43 Dive 06, Image 03:
EX1402L3_IMG_20140418T161737Z_ROVHD_SPOSAR_CAR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Rock Substrate

Biotic: Attached Sponges with Co-occurring Sargassum Particles

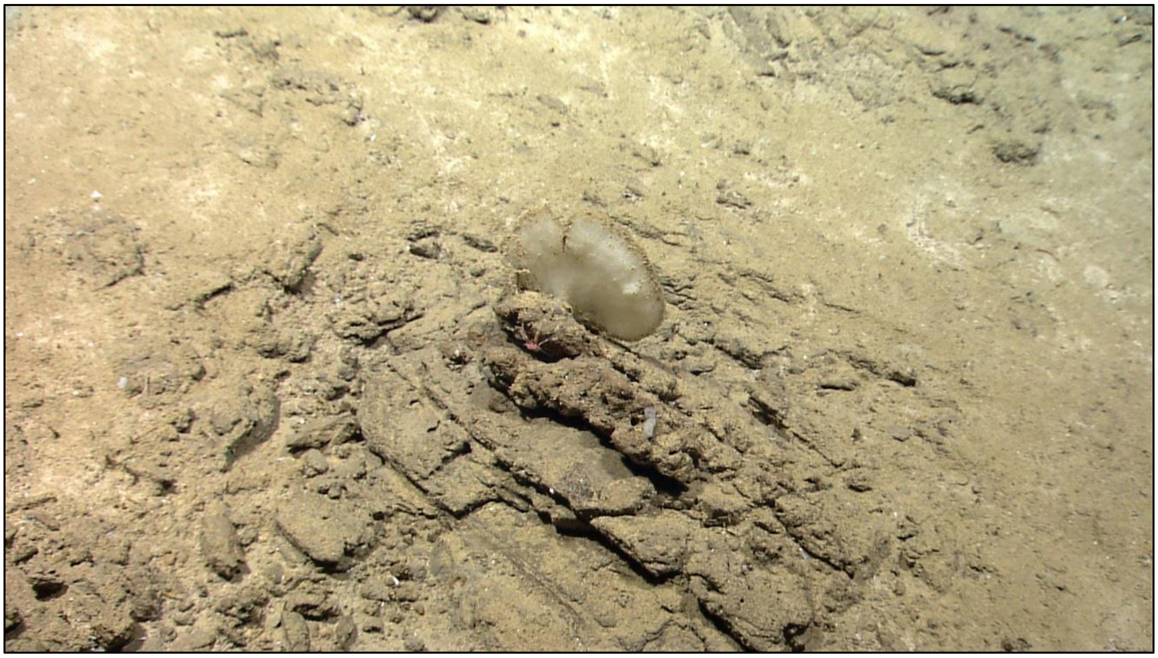

Figure B.44 Dive 06, Image 04:
EX1402L3_IMG_20140418T162834Z_ROVHD_WIDE

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Sponges

Figure B.45 Dive 06, Image 05:
EX1402L3_IMG_20140418T180214Z_ROVHD_IRON_ROPE_COIL

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Trash

Biotic: Sargassum Particles

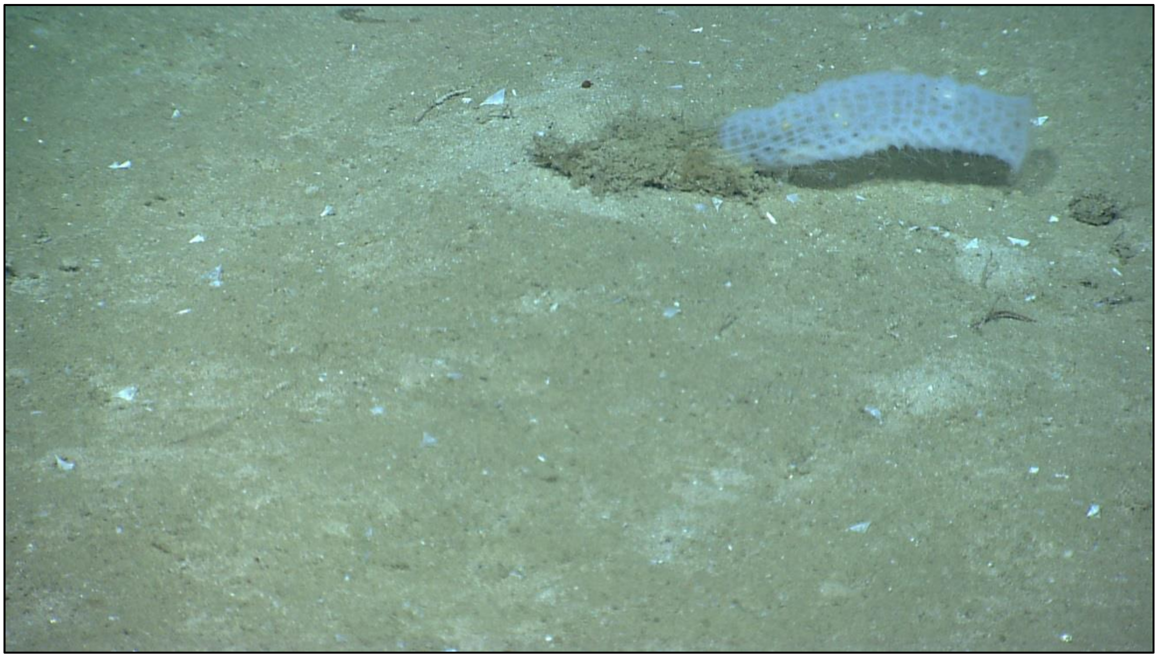

Figure B.46 Dive 06, Image 06: EX1402L3_IMG_20140418T184831Z_ROVHD_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Sponges with the following Associated Taxa: Hexactinellid

Figure B.47 Dive 06, Image 07:
EX1402L3_IMG_20140418T185233Z_ROVHD_SQA_COR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Bamboo Coral with the following Associated Taxa: Squat Lobster

Figure B.48 Dive 06, Image 08:
EX1402L3_IMG_20140418T190207Z_ROVHD_HUMMOCKS

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Mound/Hummock in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

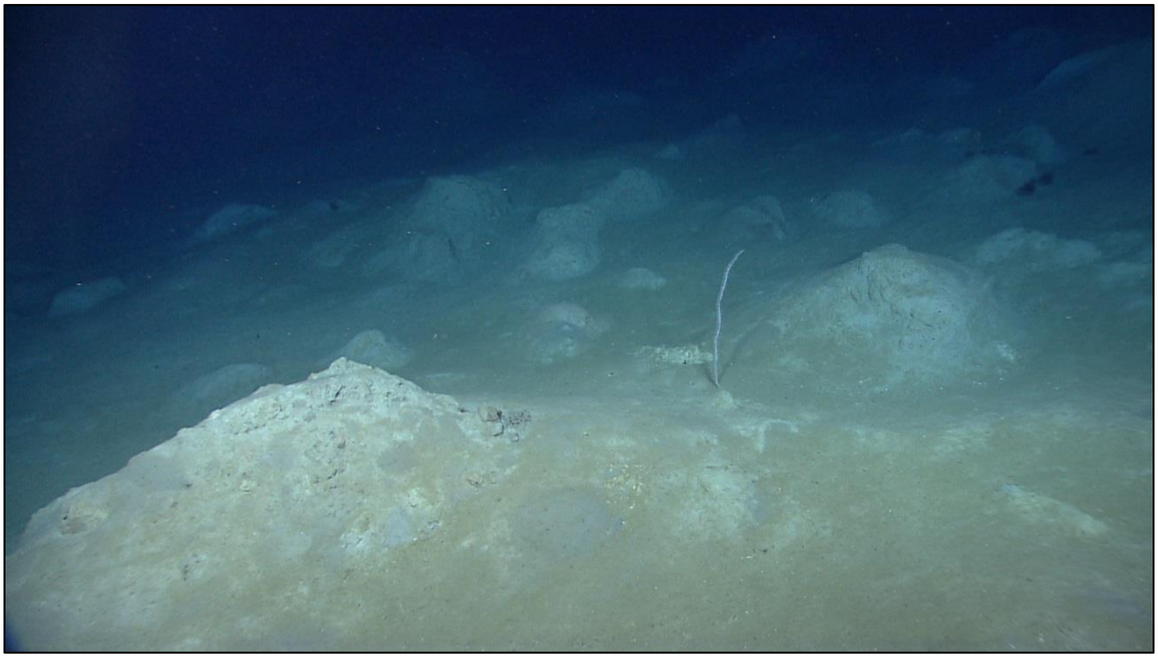

Figure B.49 Dive 06, Image 09: EX1402L3_IMG_20140418T195333Z_ROVHD_HUMMOCKS_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Mound/Hummock in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Bamboo Coral

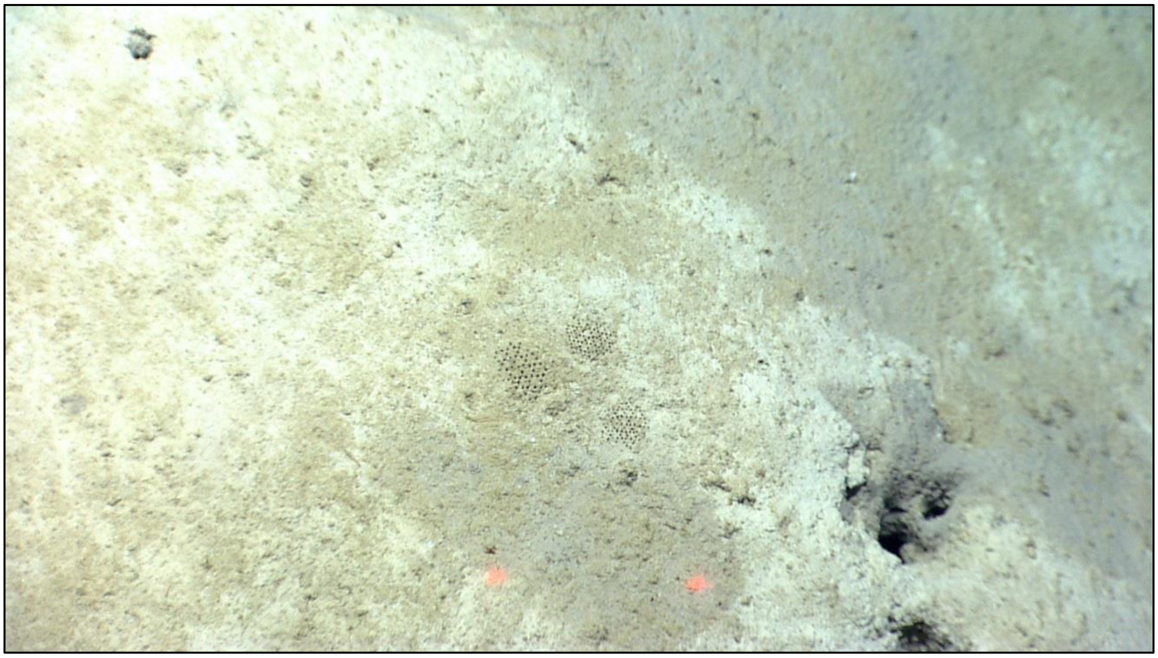

Figure B.50 Dive 06, Image 10: EX1402L3_IMG_20140418T200924Z_ROVHD_PALEODICTYON

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Burrows/Bioturbation in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

B.6 Dive 08

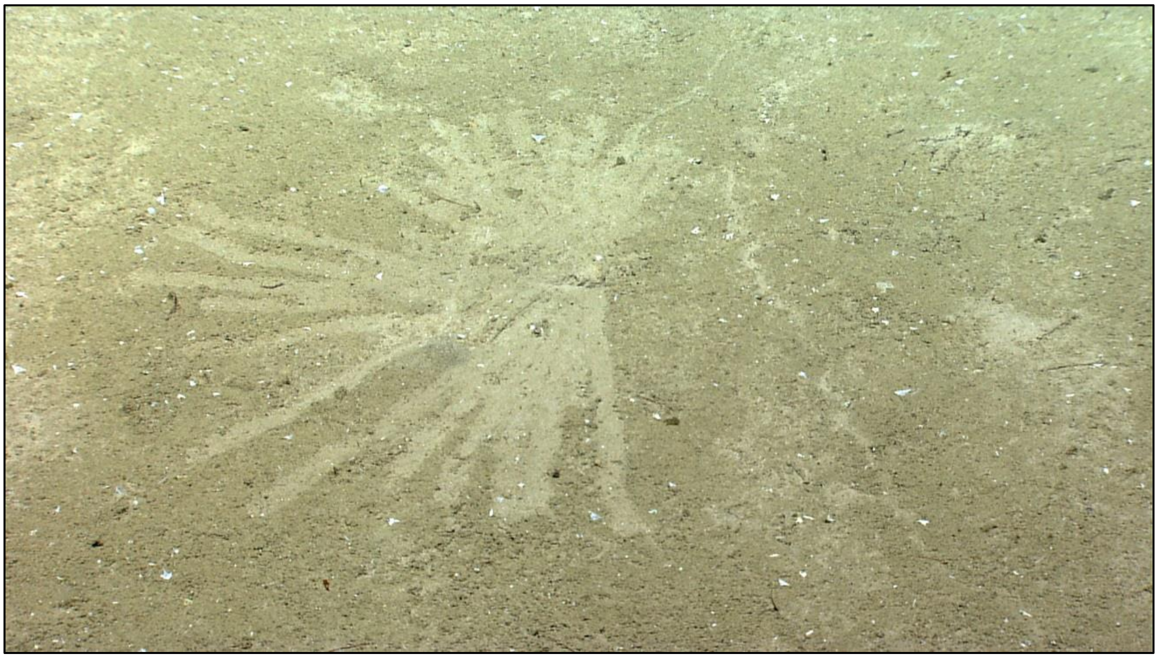

Figure B.51 Dive 08, Image 01:
EX1402L3_IMG_20140420T151045Z_ROVHD_ECHIURAN_TRAILS

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Bioturbation on a Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Echiuran Trails

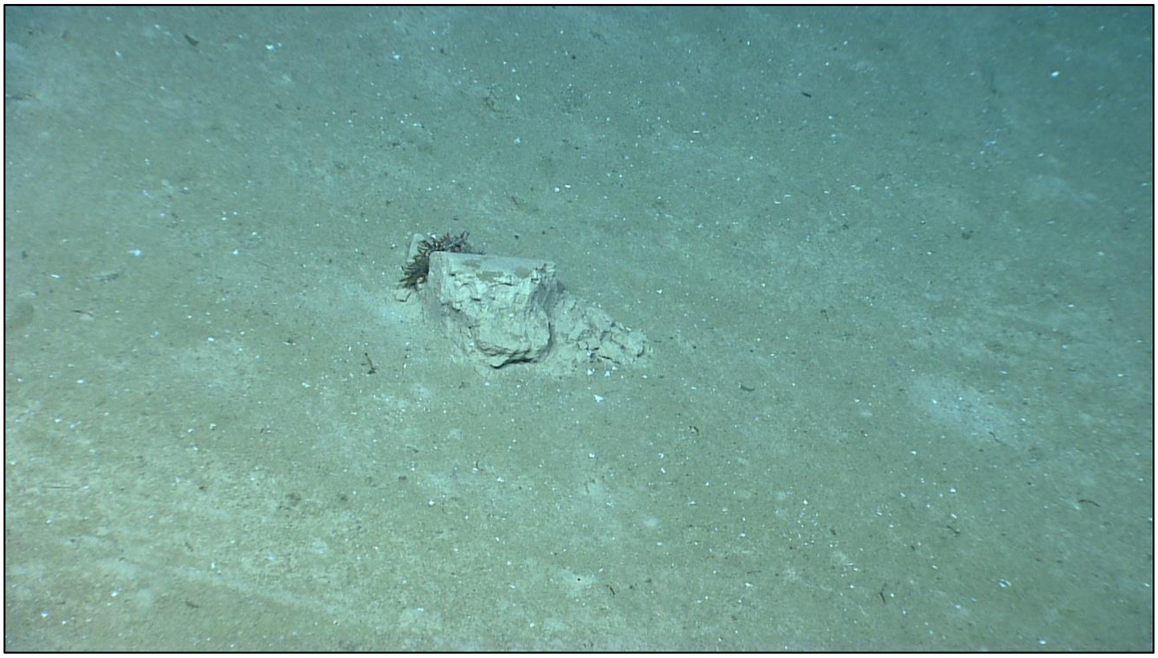

Figure B.52 Dive 08, Image 02: EX1402L3_IMG_20140420T152537Z_ROVHD_HARD_SUBSTRATE_SAR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Sargassum Particles

Figure B.53 Dive 08, Image 03:
EX1402L3_IMG_20140420T152828Z_ROVHD_SPONGE

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Hexactinellid with Co-occurring Inferred Fauna

Figure B.54 Dive 08, Image 04: EX1402L3_IMG_20140420T154853Z_ROVHD_PINK_WHITE_COLONIA

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Sargassum Particles

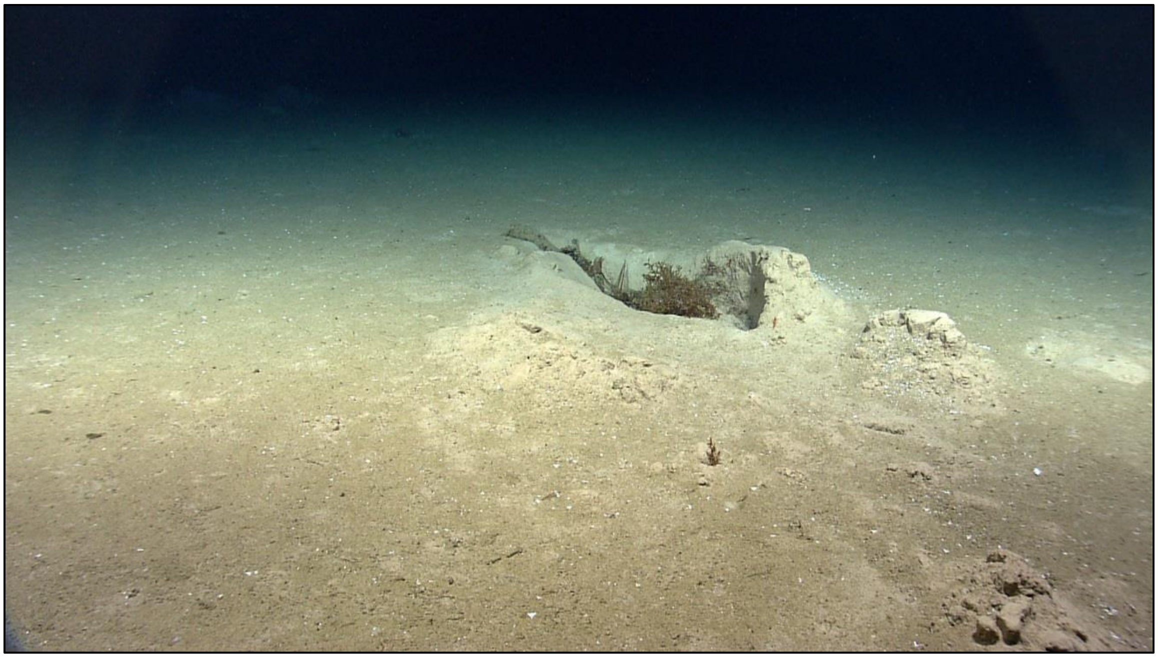

Figure B.55 Dive 08, Image 05:
EX1402L3_IMG_20140420T170839Z_ROVHD_SAR_SHI

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Hypoxic)

Geoform: Hole/Pit on a Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Sargassum Particles

Figure B.56 Dive 08, Image 06: EX1402L3_IMG_20140420T184502Z_ROVHD_ACN_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Venus Flytrap Anemones

Figure B.57 Dive 08, Image 07:
EX1402L3_IMG_20140420T192846Z_ROVHD_SPO_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Hyalonema with Co-occurring Attached Venus Flytrap Anemones and the following Associated Taxa: Hexactinellid

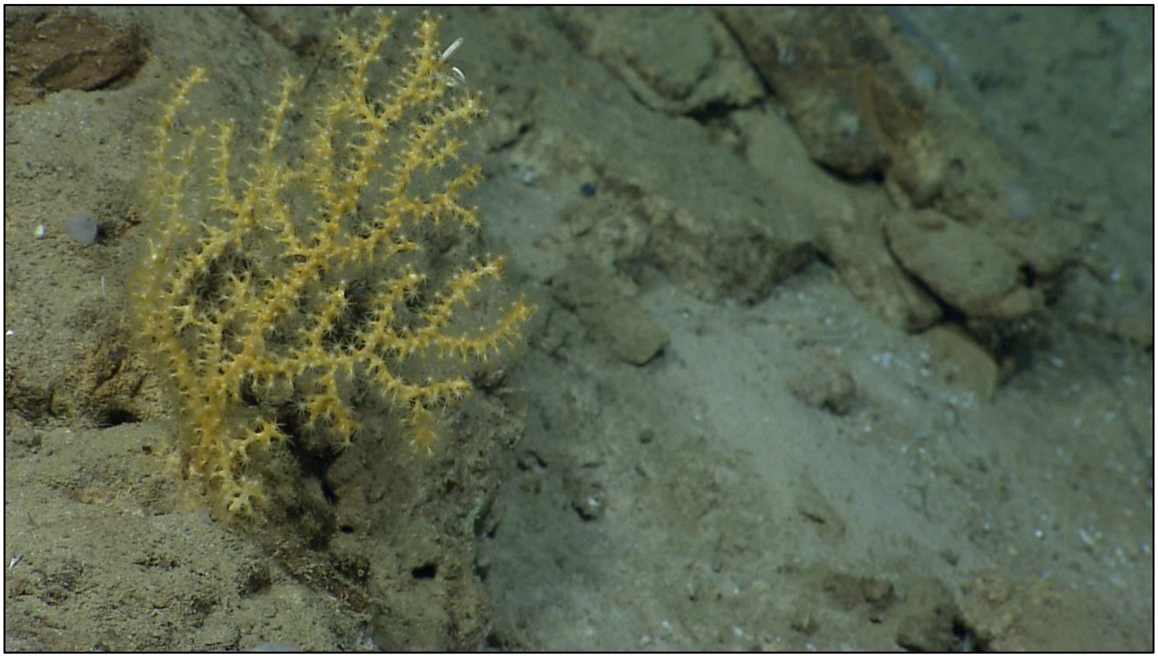

Figure B.58 Dive 08, Image 08:
EX1402L3_IMG_20140420T200331Z_ROVHD_CORO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Coarse Unconsolidated Mineral Substrate

Biotic: Attached Corals with Co-occurring Attached Barnacles

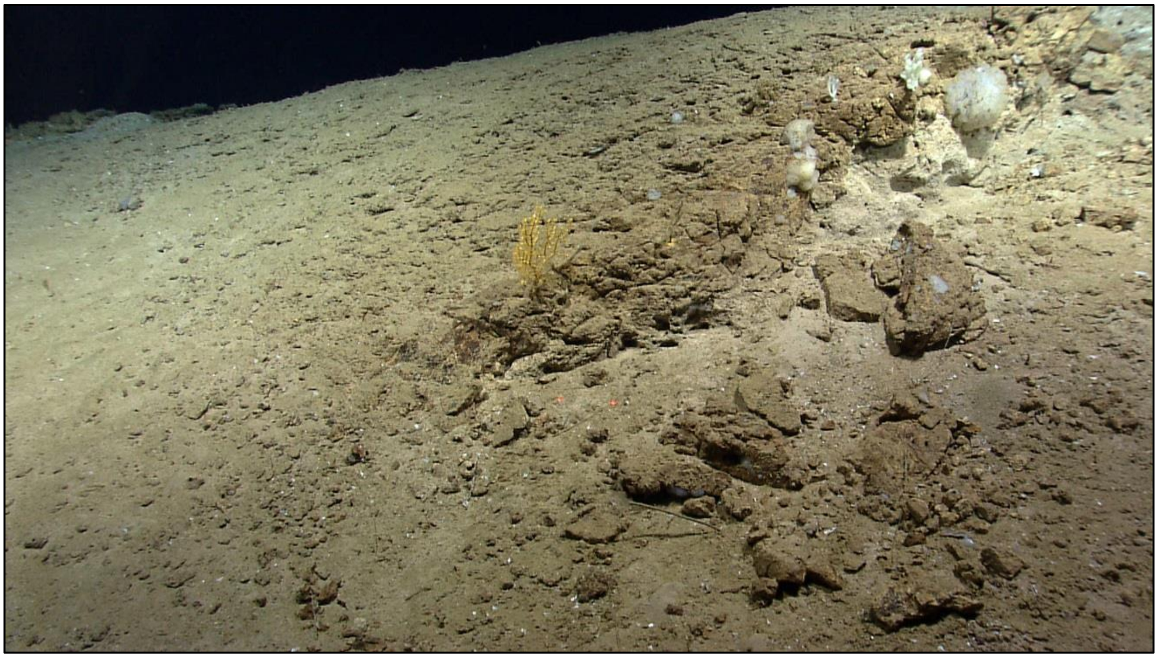

Figure B.59 Dive 08, Image 09:
EX1402L3_IMG_20140420T200555Z_ROVHD_SPO_CORO

Water Column: Very Cold Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Coarse Unconsolidated Mineral Substrate

Biotic: Attached Sponges with Co-occurring Attached Corals

Figure B.60 Dive 08, Image 10:
EX1402L3_IMG_20140420T200617Z_ROVHD_SPO_CORO

Water Column: Very Cold Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) in a Submarine Canyon (Keathley Canyon)

Substrate: Coarse Unconsolidated Mineral Substrate

Biotic: Attached Sponges with Co-occurring Attached Corals and the following Associated Taxa: Sessile Gastropods and Squat Lobster

B.7 Dive 09

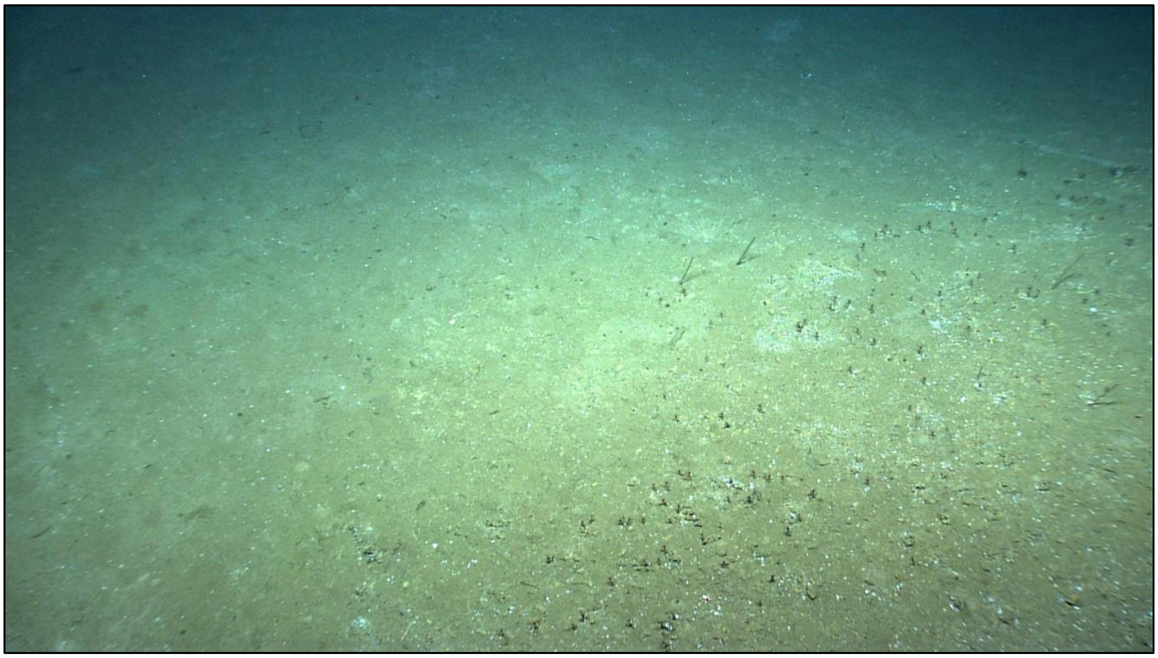

Figure B.61 Dive 09, Image 01: EX1402L3_IMG_20140421T150954Z_ROVHD_WORM_TUBES

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Small Tube-Building Fauna

Figure B.62 Dive 09, Image 02: EX1402L3_IMG_20140421T152220Z_ROVHD_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Burrowing Anemones

Figure B.63 Dive 09, Image 03:
EX1402L3_IMG_20140421T170541Z_ROVHD_SHI_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Highly Oxic)

Geoform: Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

Biotic: Burrowing Anemones

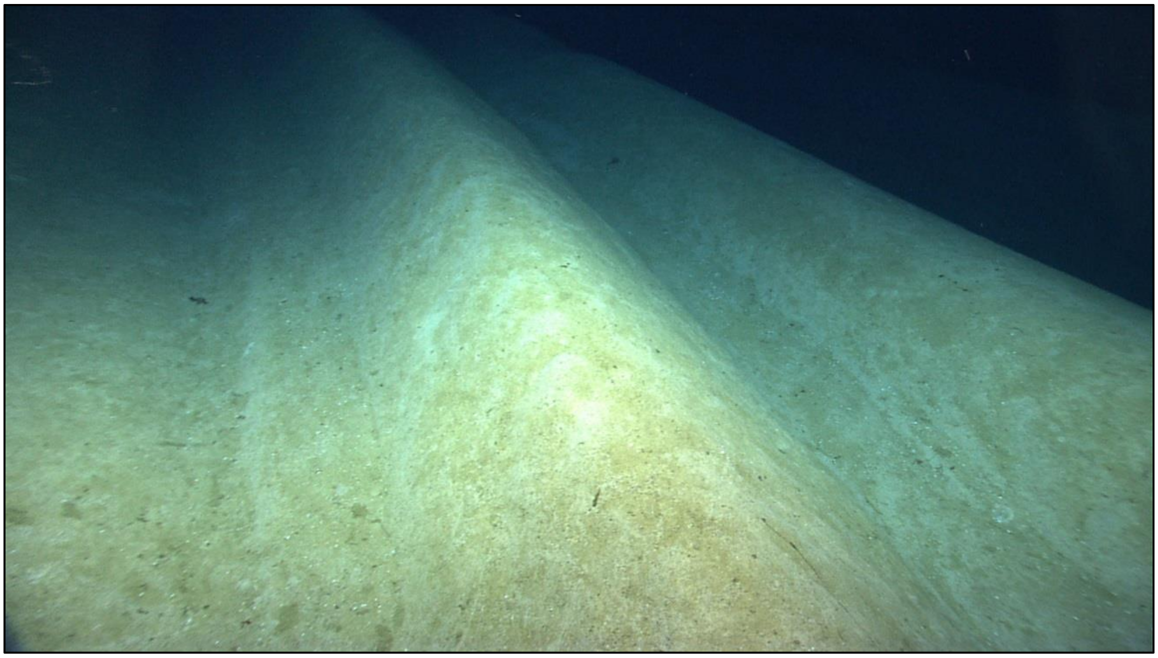

Figure B.64 Dive 09, Image 04:
EX1402L3_IMG_20140421T172722Z_ROVHD_CHANNEL

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Megaripples on a Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

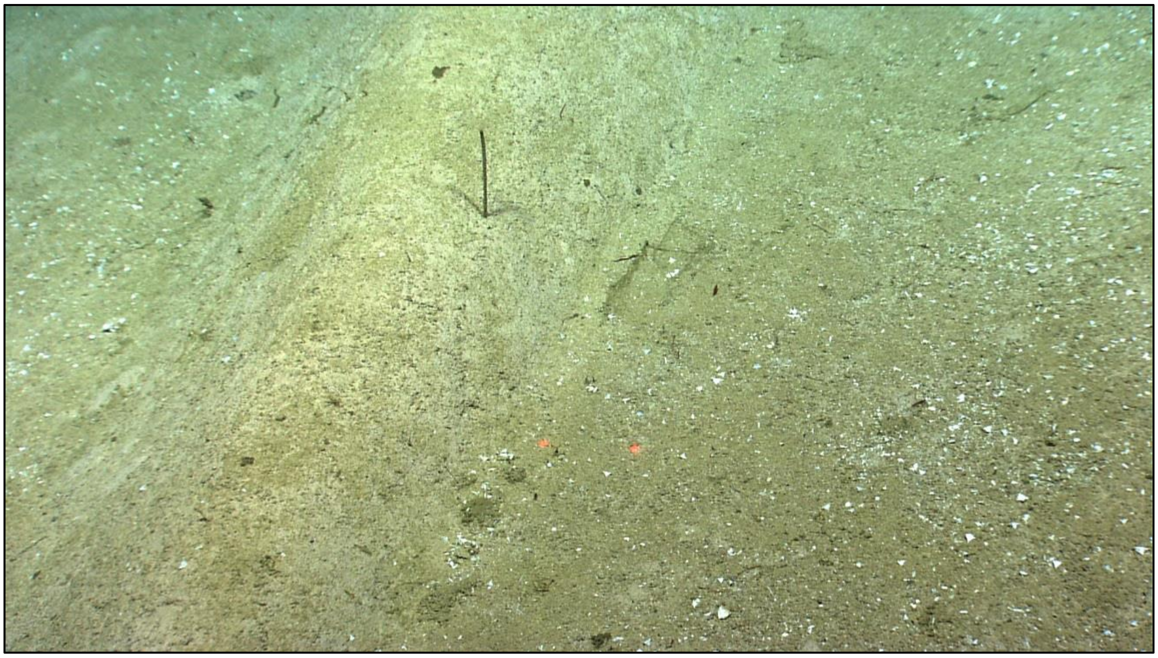

Figure B.65 Dive 09, Image 05:
EX1402L3_IMG_20140421T174231Z_ROVHD_TUBE_WORM_AUDIO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Megaripples on a Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Small Tube-Building Fauna

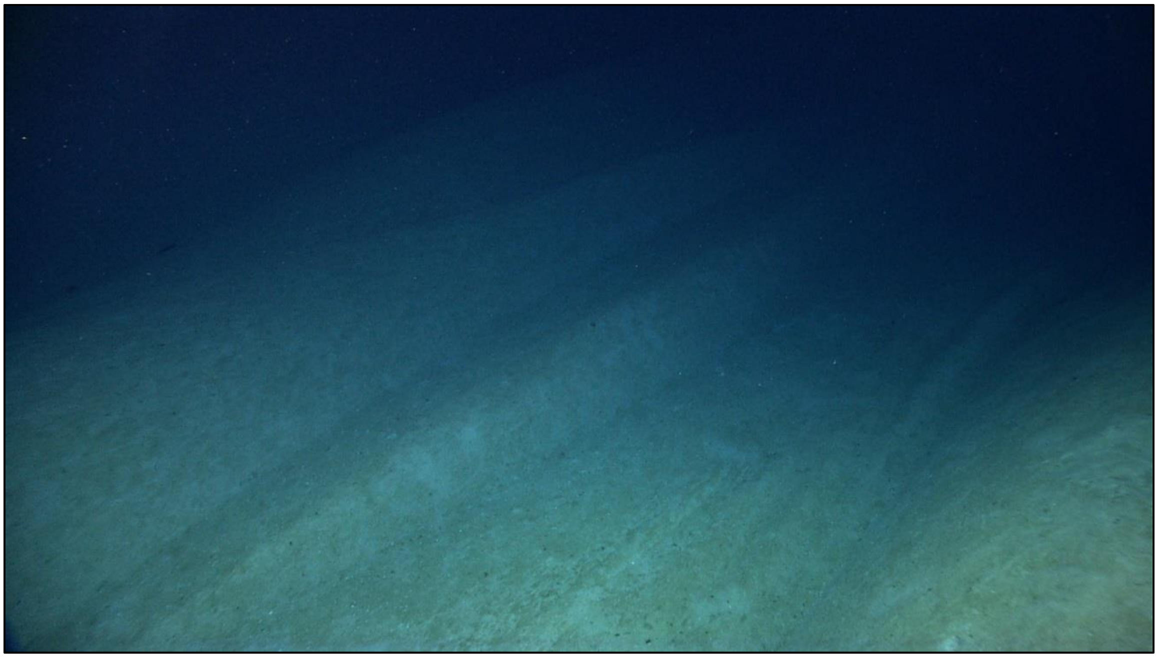

Figure B.66 Dive 09, Image 06:
EX1402L3_IMG_20140421T175510Z_ROVHD_CHANNEL

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Megaripples on a Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

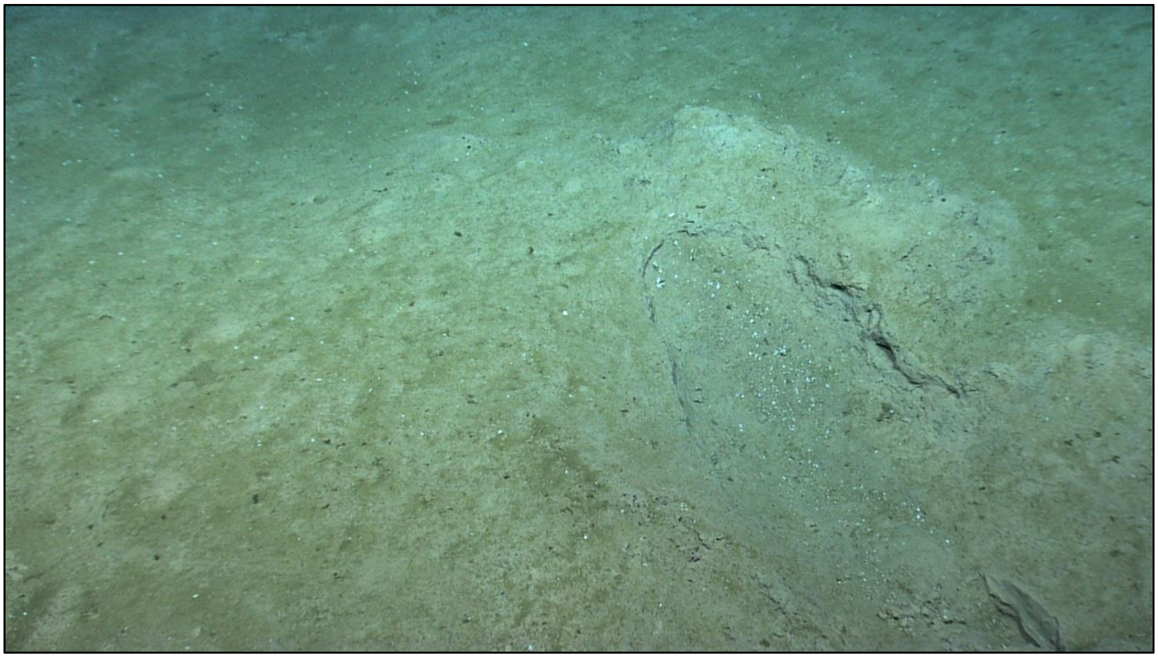

Figure B.67 Dive 09, Image 07:
EX1402L3_IMG_20140421T181555Z_ROVHD_SILT_BOTTOM

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Highly Oxic)

Geoform: Scar on a Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Figure B.68 Dive 09, Image 08:
EX1402L3_IMG_20140421T182616Z_ROVHD_HOLES

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Highly Oxic)

Geoform: Hole/ Pit on a Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

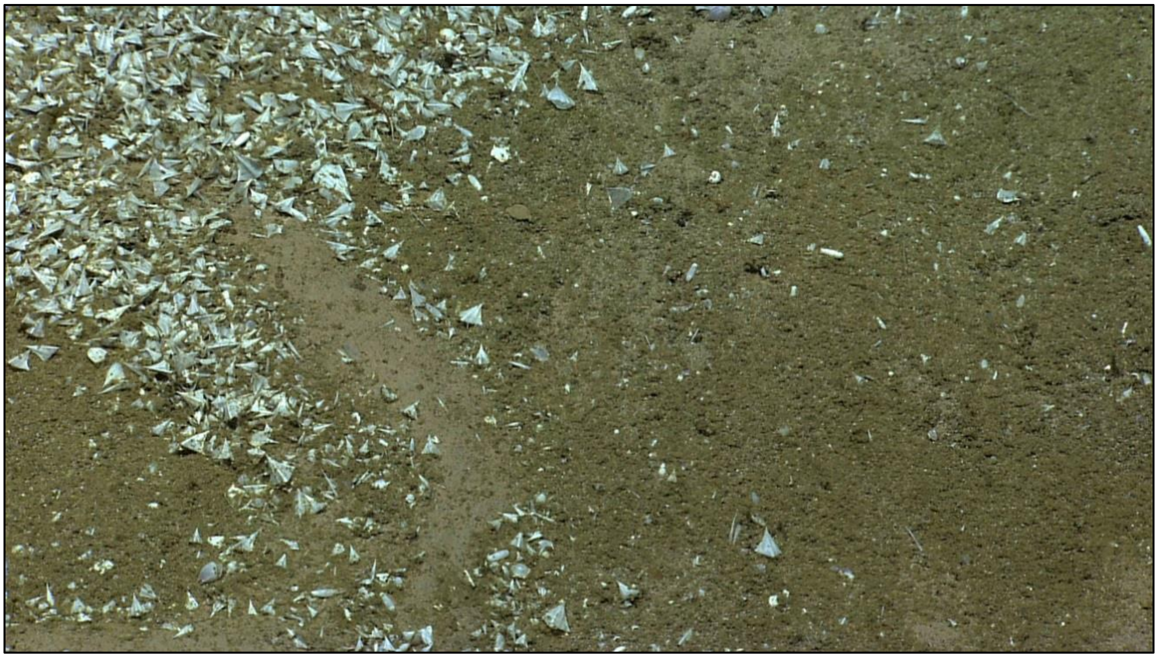

Figure B.69 Dive 09, Image 09:
EX1402L3_IMG_20140421T183708Z_ROVHD_TER_SHELLS

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Shell Hash

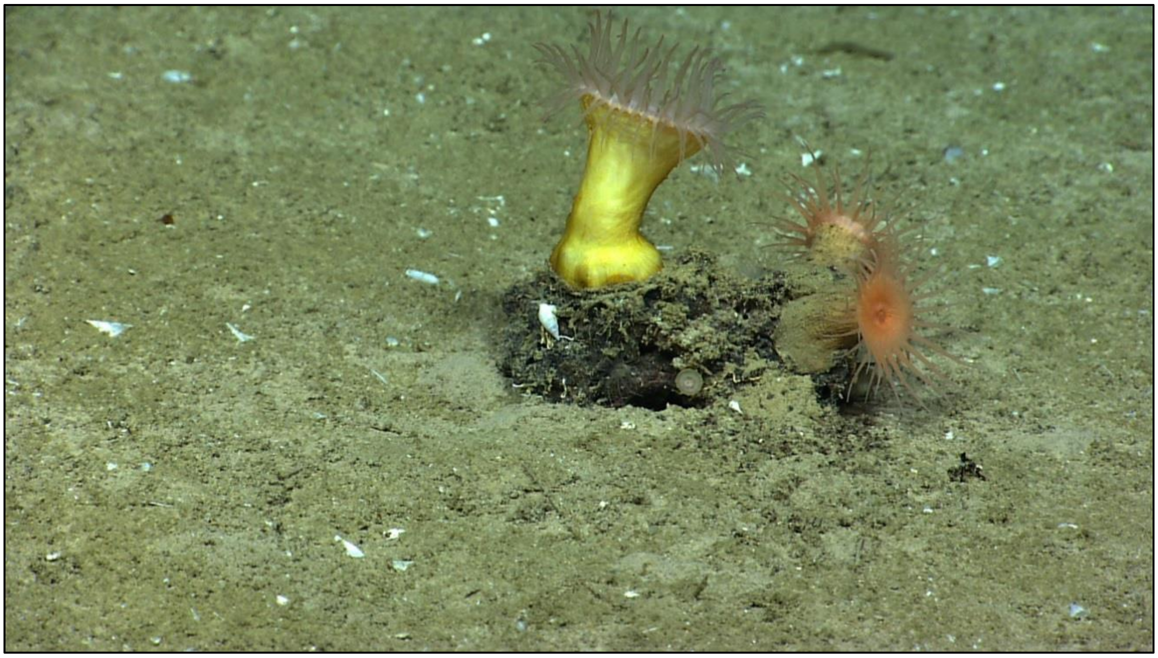

Figure B.70 Dive 09, Image 10: EX1402L3_IMG_20140421T192834Z_ROVHD_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Ridge (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Coarse Unconsolidated Mineral Substrate with Co-occurring Shell Substrate

Biotic: Burrowing Anemones with the following Associated Taxa: Sessile Gastropods

B.8 Dive 10

Figure B.71 Dive 10, Image 01:
EX1402L3_IMG_20140422T174506Z_ROVHD_SPO_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Venus Flytrap Anemones with Co-occurring Attached Hexactinellid

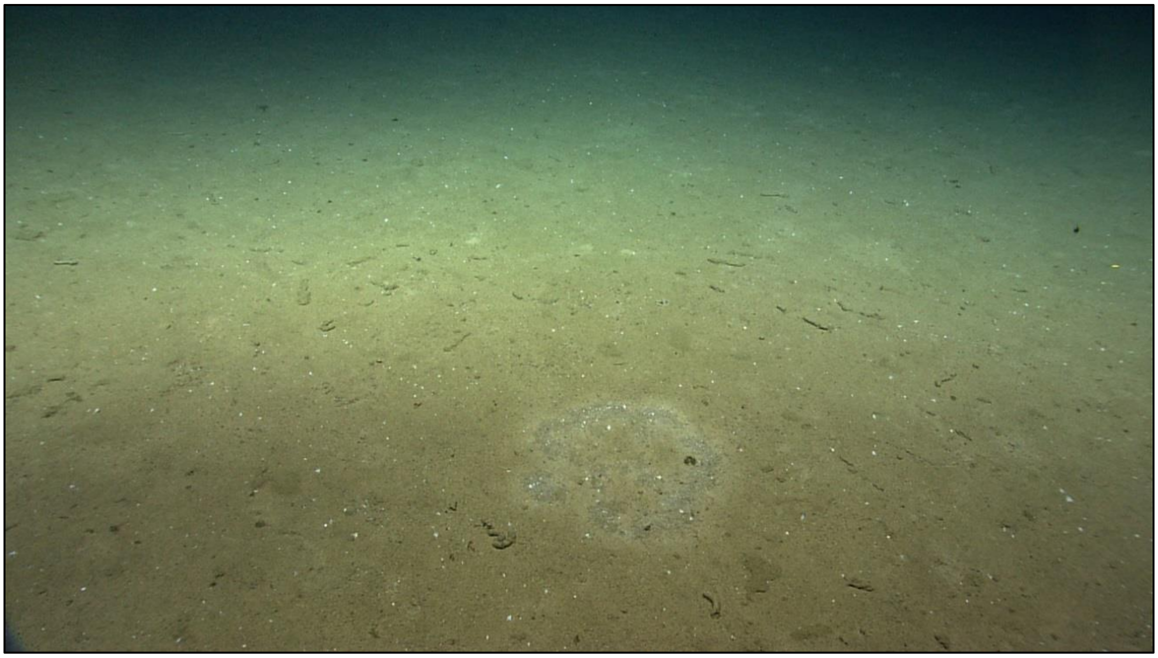

Figure B.72 Dive 10, Image 02:
EX1402L3_IMG_20140422T175427Z_ROVHD_WIDE_BOTTOM

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Figure B.73 Dive 10, Image 03:
EX1402L3_IMG_20140422T180339Z_ROVHD_TRASH_ACN

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Trash with Co-occurring Fine Unconsolidated Mineral Substrate

Biotic: Attached Anemones with Co-occurring Attached Venus Flytrap Anemones

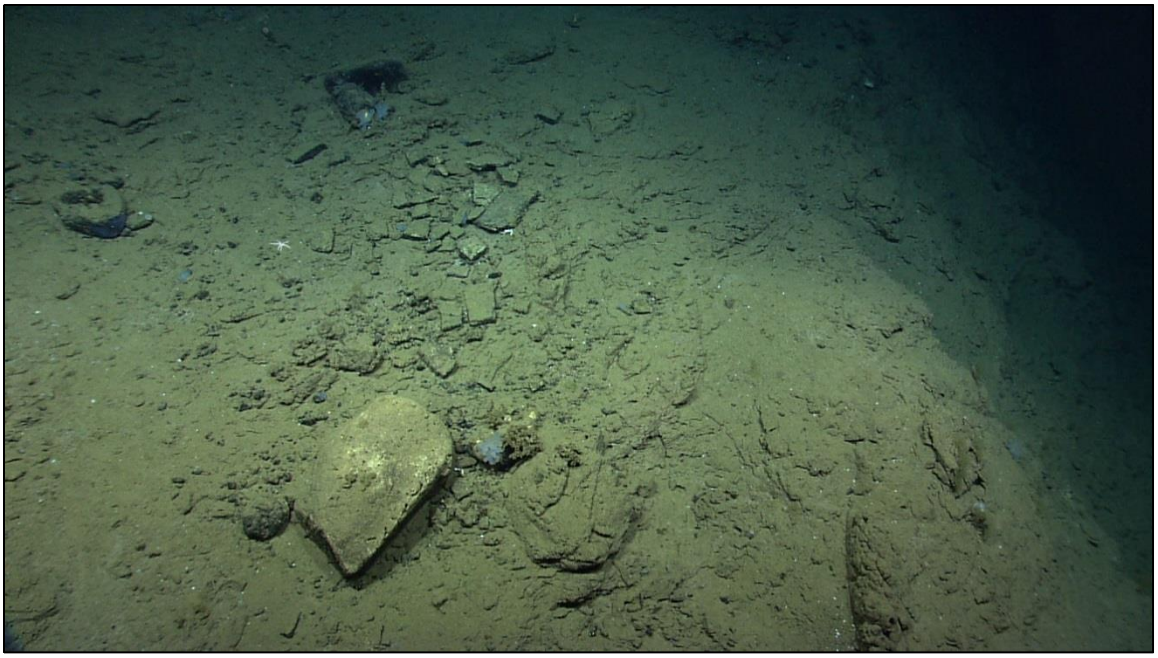

Figure B.74 Dive 10, Image 04:
EX1402L3_IMG_20140422T183226Z_ROVHD_ASN_SPO_CRA_ROCK

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Sponges with Co-occurring Starfish

Figure B.75 Dive 10, Image 05:
EX1402L3_IMG_20140422T184552Z_ROVHD_TRASH

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Coarse Unconsolidated Mineral Substrate with Co-occurring Trash

Biotic: Attached Anemones

Figure B.76 Dive 10, Image 06: EX1402L3_IMG_20140422T191146Z_ROVHD_WIDE_AUDIO_ACN_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Gravel Mixes of Coarse Unconsolidated Mineral Substrate

Biotic: Attached Hexactinellid with Co-occurring Sessile Gastropods

Figure B.77 Dive 10, Image 07: EX1402L3_IMG_20140422T191852Z_ROVHD_MAT

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Bacterial Mat/Film

Figure B.78 Dive 10, Image 08: EX1402L3_IMG_20140422T195733Z_ROVHD_SQA_SHI

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Crustaceans with the following Associated Taxa: Squat Lobster

Figure B.79 Dive 10, Image 09:
EX1402L3_IMG_20140422T200454Z_ROVHD_WIDE_OUTCROP

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Erosion Scarp on a Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Rock Substrate with Co-occurring Unconsolidated Mineral Substrate

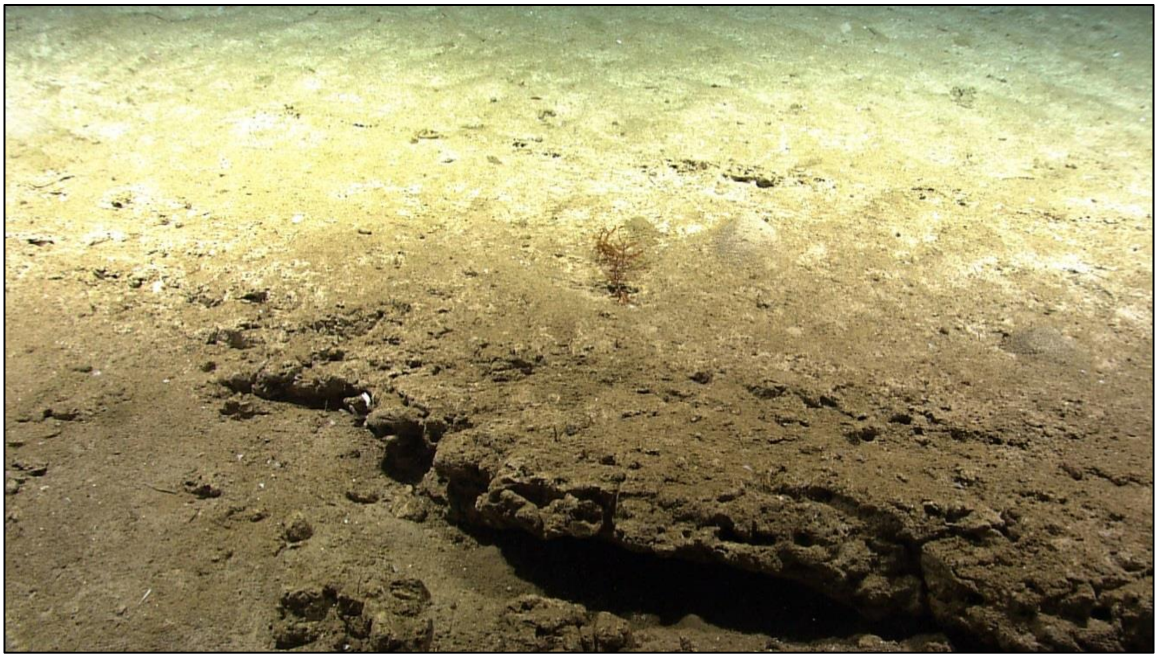

Figure B.80 Dive 10, Image 10:
EX1402L3_IMG_20140422T201118Z_ROVHD_SARG

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Slope (Level 1) in a Submarine Canyon (Bryant Canyon)

Substrate: Coarse Unconsolidated Mineral Substrate

Biotic: Sargassum Particles

B.9 Dive 11

Figure B.81 Dive 11, Image 01:
EX1402L3_IMG_20140423T152804Z_ROVHD_NEW_ACN

Water Column: Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Fine Unconsolidated Mineral Substrate

Biotic: Attached Anemone

Figure B.82 Dive 11, Image 02:
EX1402L3_IMG_20140423T155259Z_ROVHD_TRASH_SEDIMENT

Water Column: Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Trash

Figure B.83 Dive 11, Image 03:
EX1402L3_IMG_20140423T161438Z_ROVHD_ACN_WOR

Water Column: Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Coarse Unconsolidated Mineral Substrate

Biotic: Attached Anemones with Co-occurring Attached Sponges

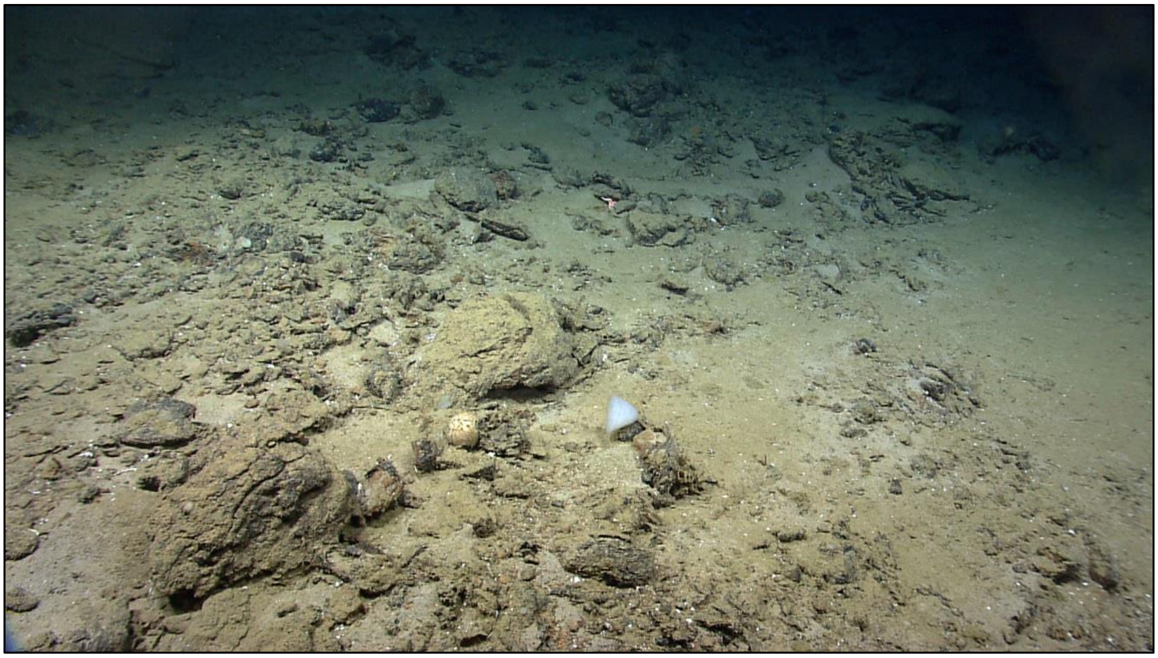

Figure B.84 Dive 11, Image 04:
EX1402L3_IMG_20140423T162940Z_ROVHD_SPO_BALL_ORANGE

Water Column: Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Authigenic Carbonate Outcrop located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Carbonate Gravel Mixes Coarse Unconsolidated Mineral Substrate with Co-occurring Trash

Biotic: Attached Sponges

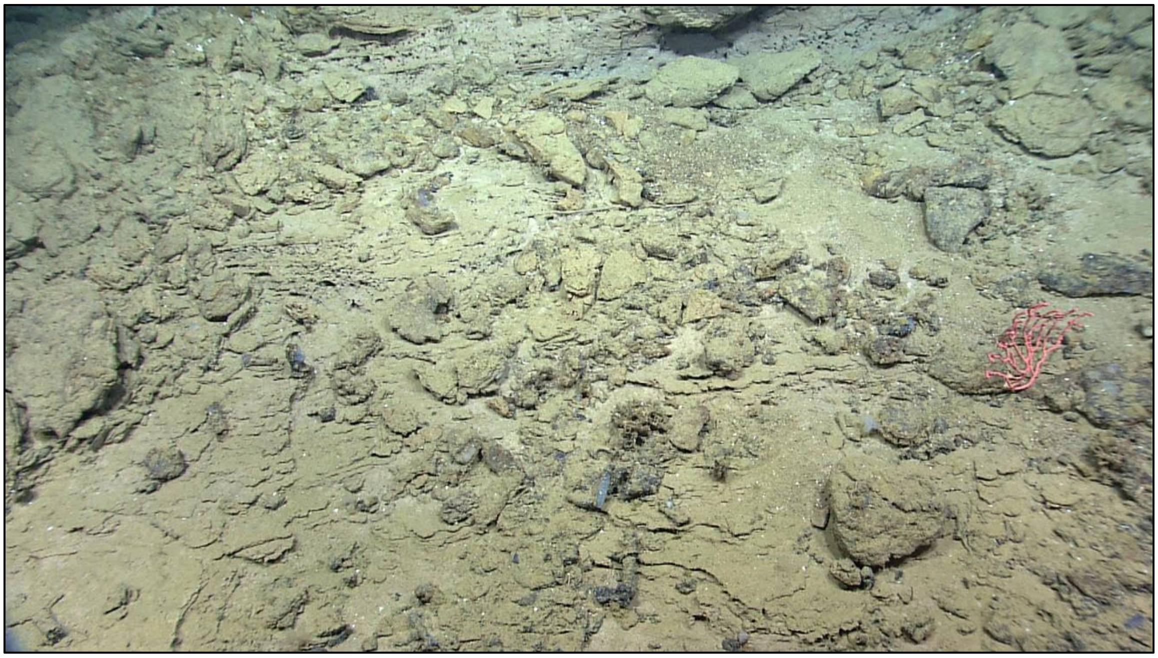

Figure B.85 Dive 11, Image 05: EX1402L3_IMG_20140423T170335Z_ROVHD_COR

Water Column: Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer

Geoform: Authigenic Carbonate Outcrop located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Carbonate Gravel Mixes Coarse Unconsolidated Mineral Substrate

Biotic: Attached Corals with Co-occurring Attached Sponges

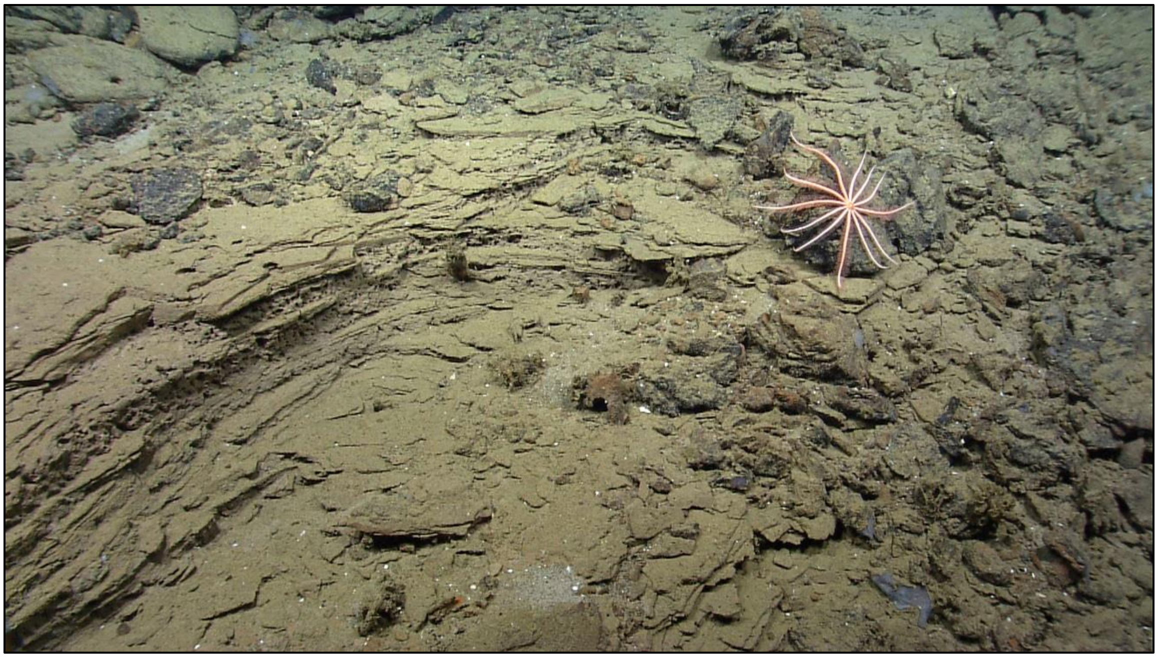

Figure B.86 Dive 11, Image 06: EX1402L3_IMG_20140423T172243Z_ROVHD_ASN_BRISINGID

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Authigenic Carbonate Outcrop located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Carbonate Gravel Mixes Coarse Unconsolidated Mineral Substrate

Biotic: Attached Brittle Stars on Hard or Mixed Substrates

Figure B.87 Dive 11, Image 07:
EX1402L3_IMG_20140423T172954Z_ROVHD_CONCRE_TUB_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Carbonate Gravel Mixes Coarse Unconsolidated Mineral Substrate

Biotic: Diverse Colonizers of Attached Sponges and Attached Anemones with Co-occurring Larger Tube-Building Fauna

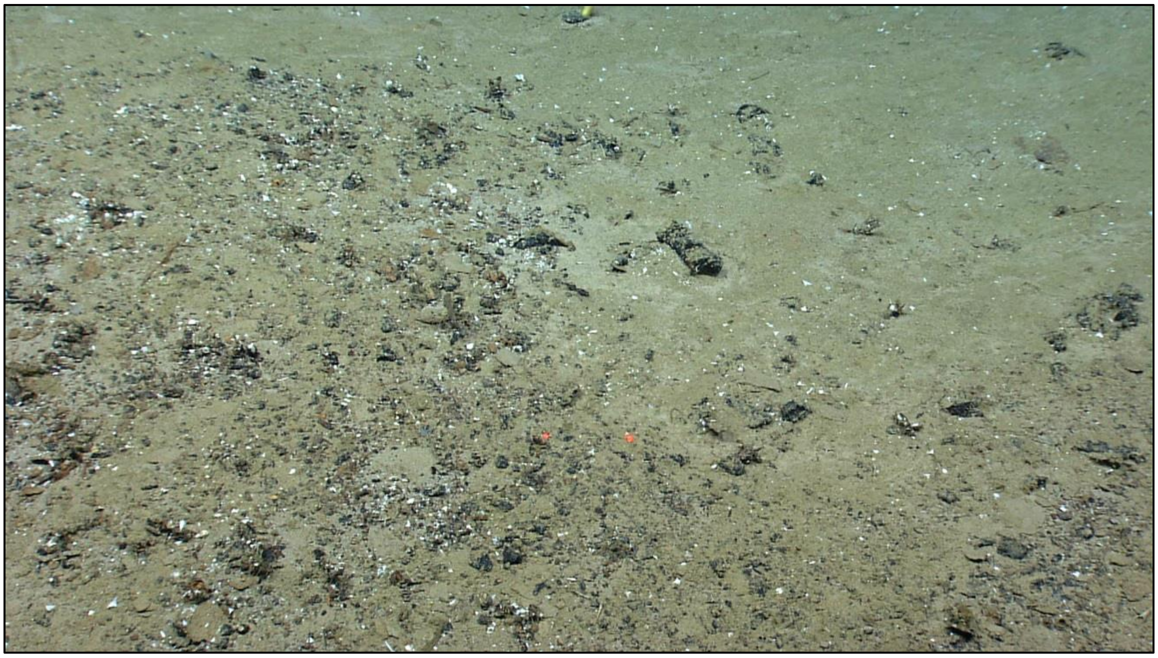

Figure B.88 Dive 11, Image 08:
EX1402L3_IMG_20140423T174841Z_ROVHD_RUBBLE

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Very Oxic)

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Fine Unconsolidated Mineral Substrate

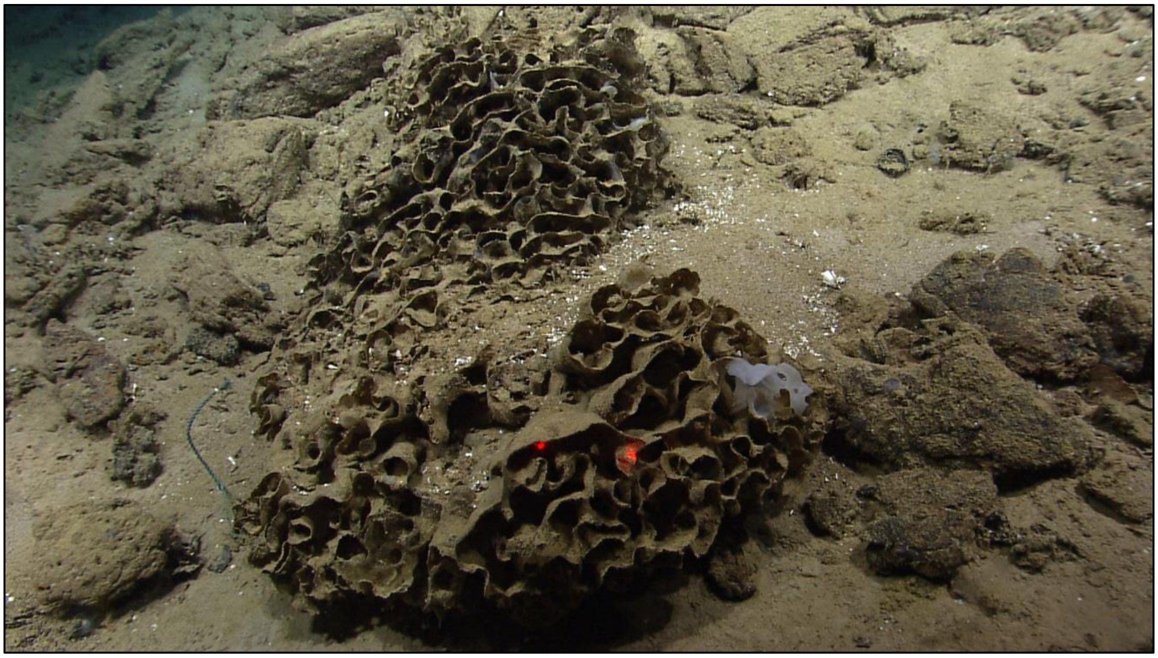

Figure B.89 Dive 11, Image 09:
EX1402L3_IMG_20140423T185645Z_ROVHD_OUTCROP_SPO

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Authigenic Carbonate Outcrop located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Carbonate Gravel Mixes Coarse Unconsolidated Mineral Substrate with Co-occurring Trash

Biotic: Attached Sponges

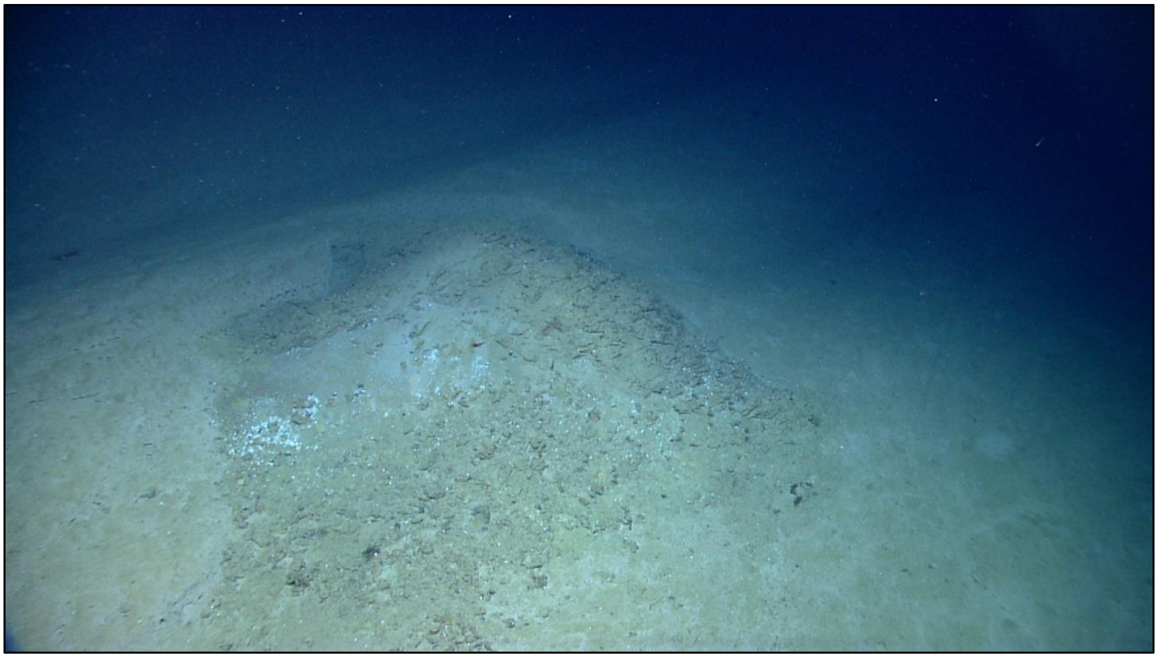

Figure B.90 Dive 11, Image 10:
EX1402L3_IMG_20140423T190314Z_ROVHD_MOUND

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Mound/Hummock on a Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Fine Unconsolidated Mineral Substrate

B.10 Dive 12

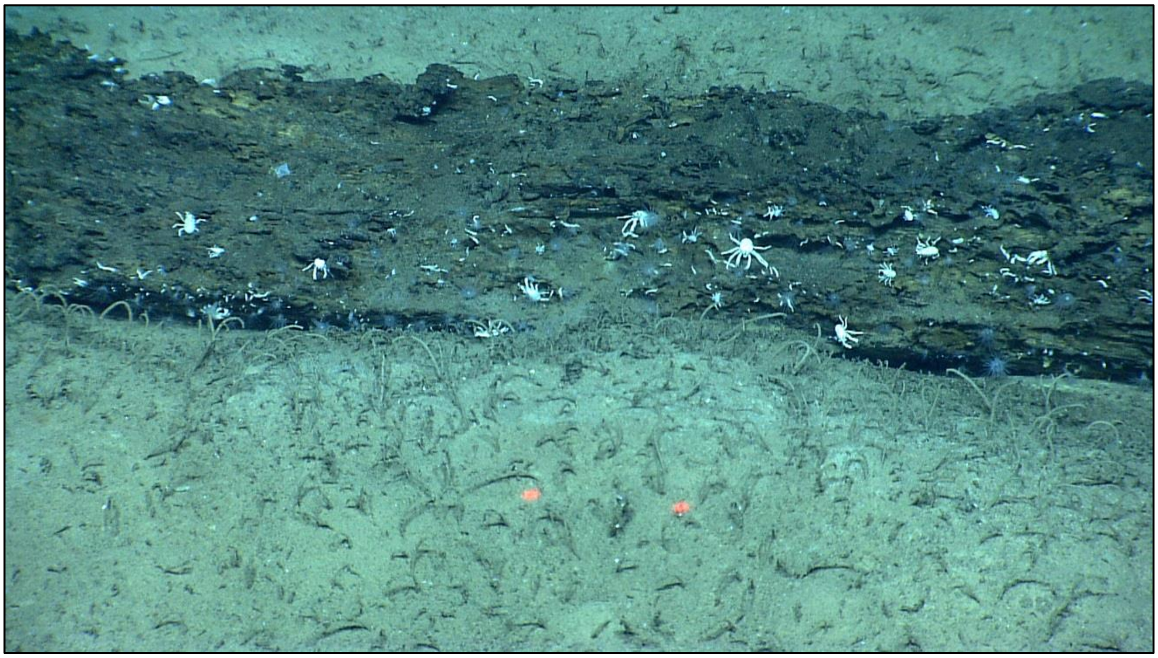

Figure B.91 Dive 12, Image 01:
EX1402L3_IMG_20140424T151033Z_ROVHD_WOOD

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Fine Unconsolidated Mineral Substrate with Co-occurring Woody Debris

Biotic: Small Tube-Building Fauna with Co-occurring Crustaceans

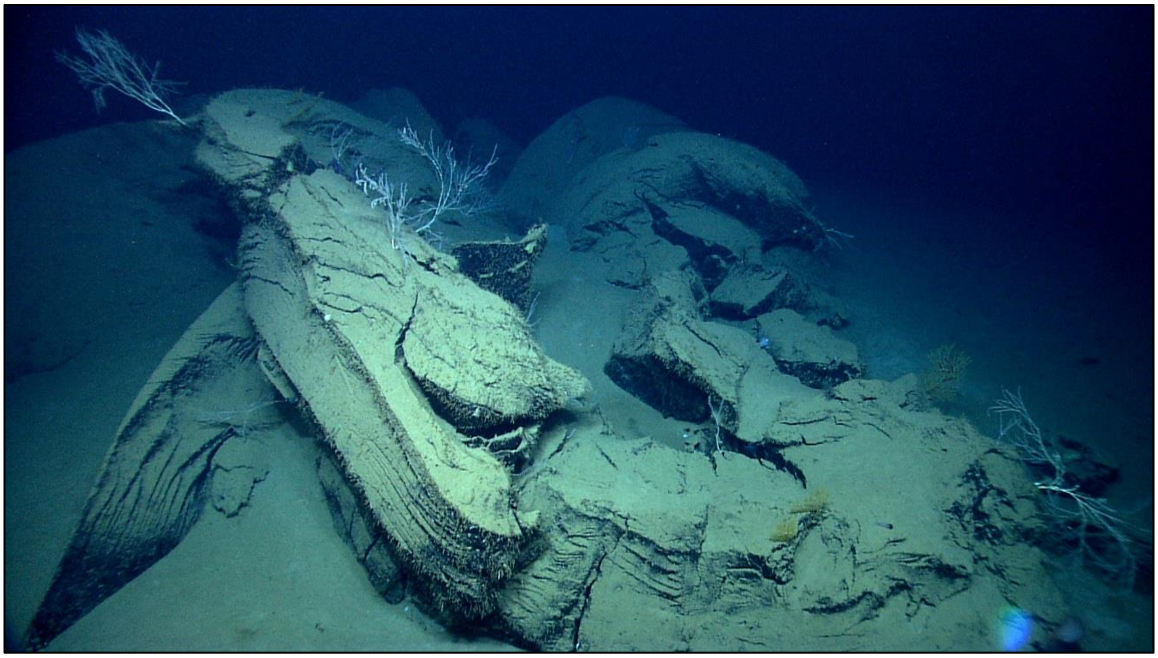

Figure B.92 Dive 12, Image 02:
EX1402L3_IMG_20140424T152122Z_ROVHD_OBJECT_02

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Geologic Substrate

Biotic: Attached Corals

Figure B.93 Dive 12, Image 03:
EX1402L3_IMG_20140424T152414Z_ROVHD_OBJECT_03

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Geologic Substrate

Biotic: Diverse Colonizers of Attached Anemones, Attached Corals, and Attached Sponges

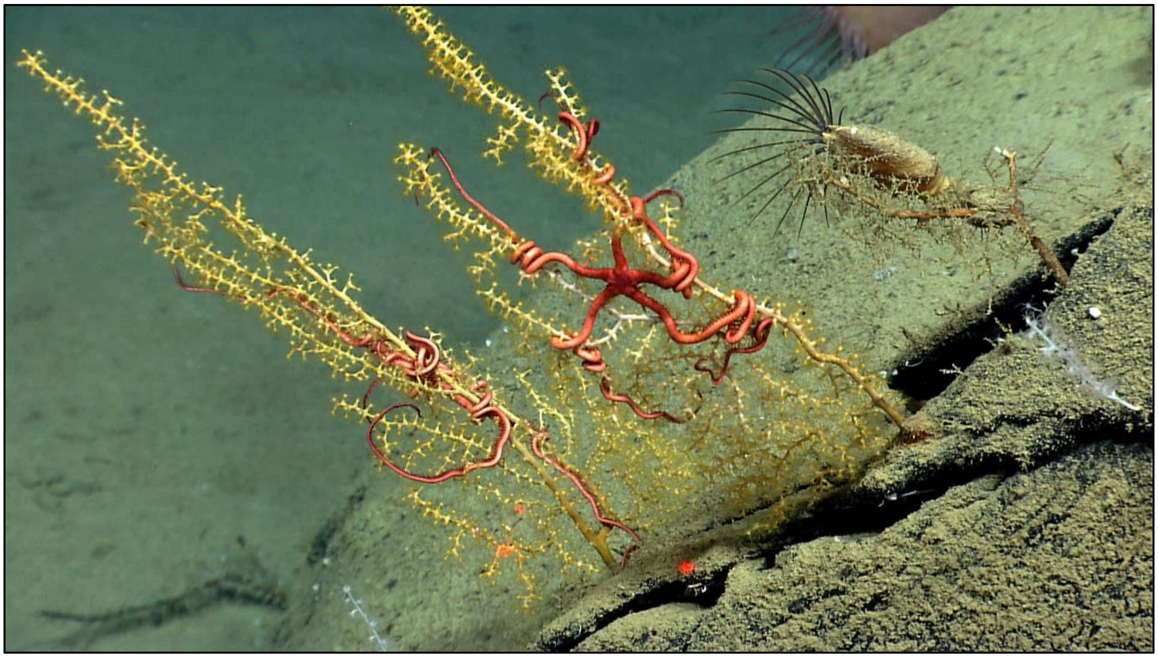

Figure B.94 Dive 12, Image 04:
EX1402L3_IMG_20140424T155006Z_ROVHD_OBJECT_09

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Geologic Substrate

Biotic: Diverse Colonizers of Attached Octocorallia, Barnacles, and Brittle Stars with Co-occurring Attached Hydroids

Figure B.95 Dive 12, Image 05:
EX1402L3_IMG_20140424T161632Z_ROVHD_OBJECT_16

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment) (Gas Hydrate)

Substrate: Geologic Substrate

Biotic: Large Tube-Building Fauna with Co-occurring Burrowing Anemone and Attached Hydroids

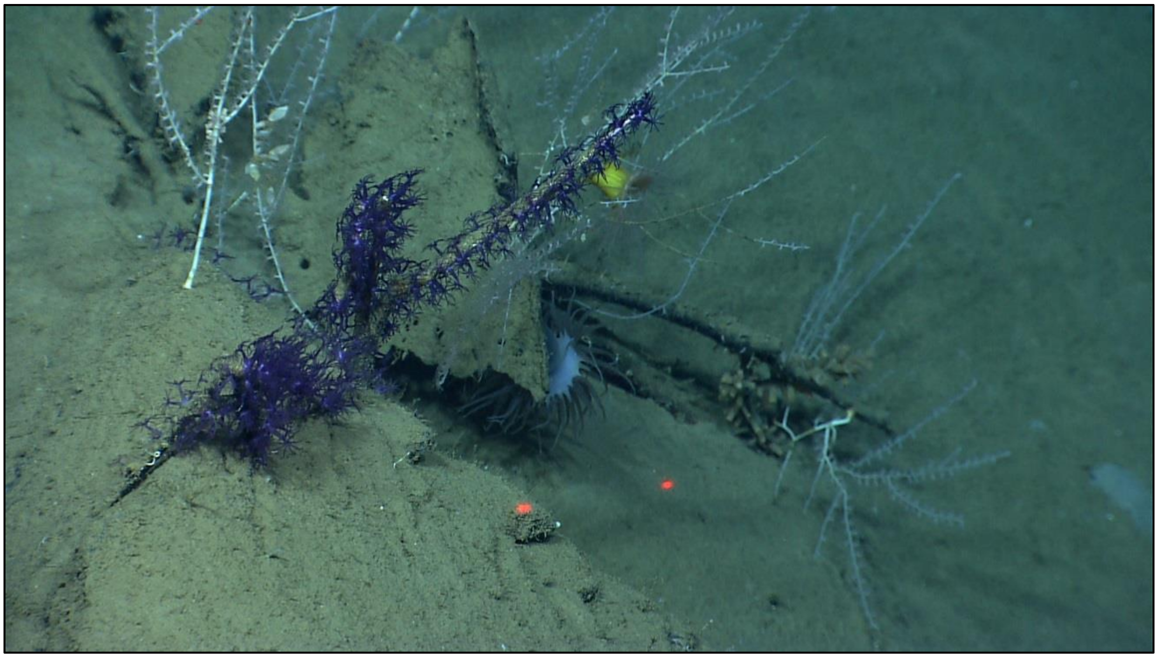

Figure B.96 Dive 12, Image 06:
EX1402L3_IMG_20140424T162458Z_ROVHD_OBJECT_18

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment)

Substrate: Geologic Substrate

Biotic: Attached Corals with Co-occurring Anemones and Barnacles

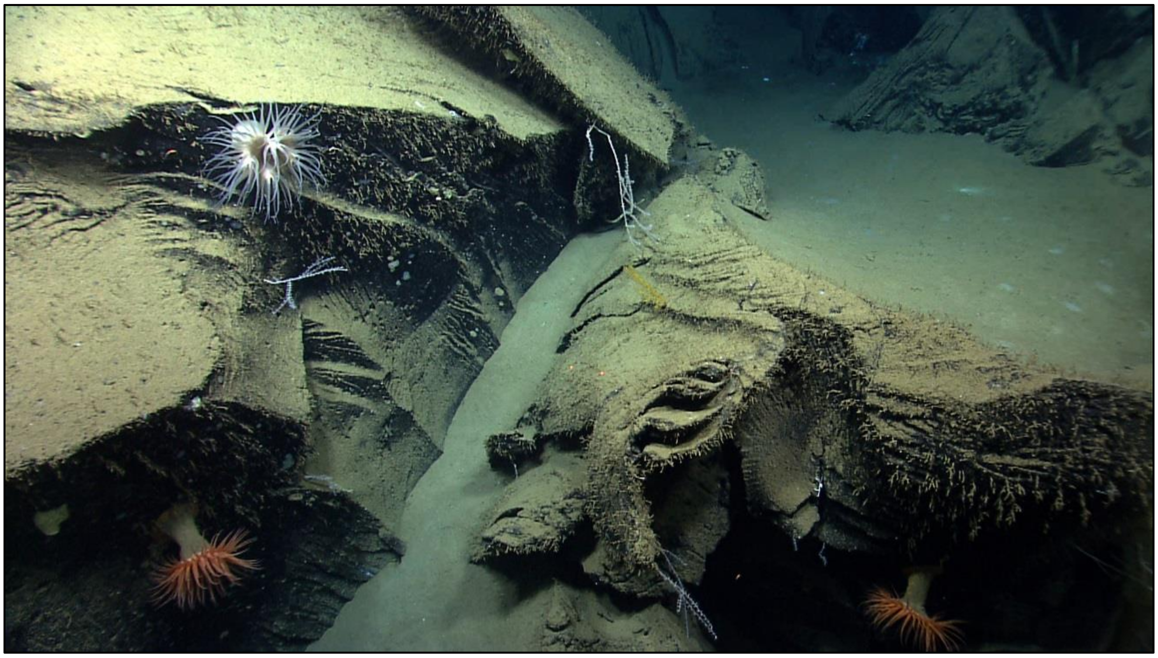

Figure B.97 Dive 12, Image 07:
EX1402L3_IMG_20140424T172239Z_ROVHD_OBJ2_TUBE_COR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Geologic Substrate

Biotic: Diverse Colonizers of Attached Anemones, Attached Tube-Building Fauna, and Attached Corals with Co-occurring Attached Hydroids

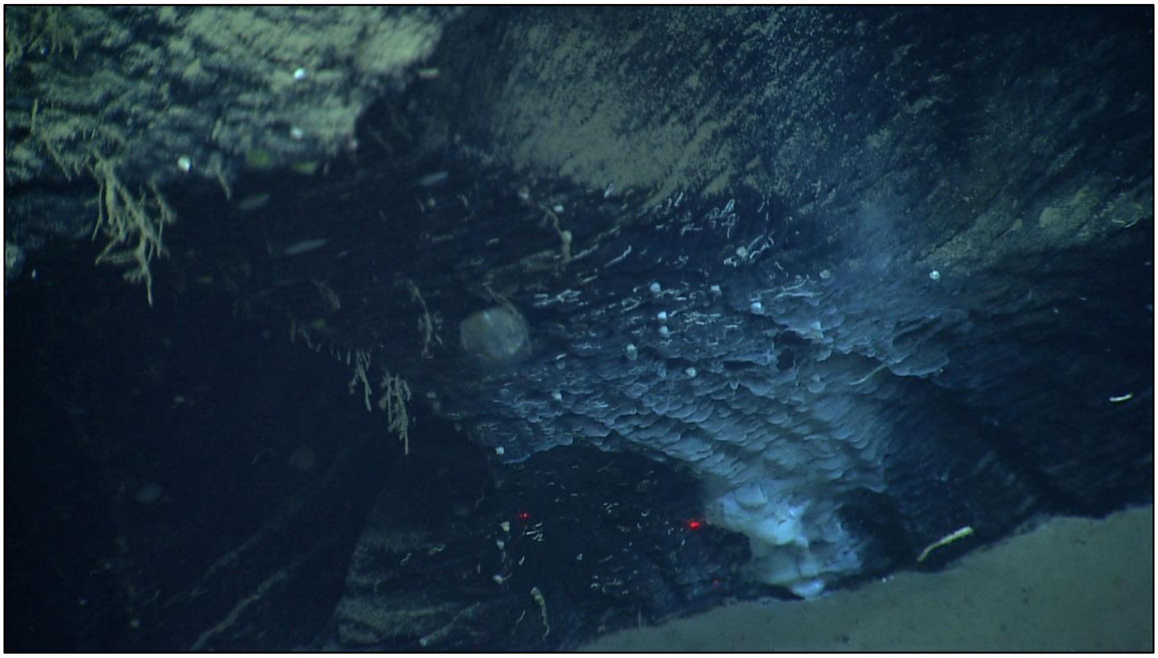

Figure B.98 Dive 12, Image 08:
EX1402L3_IMG_20140424T173251Z_ROVHD_OBJ2_HYDRATE

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment) (Gas Hydrate)

Substrate: Geologic Substrate

Biotic: Attached Hydroids

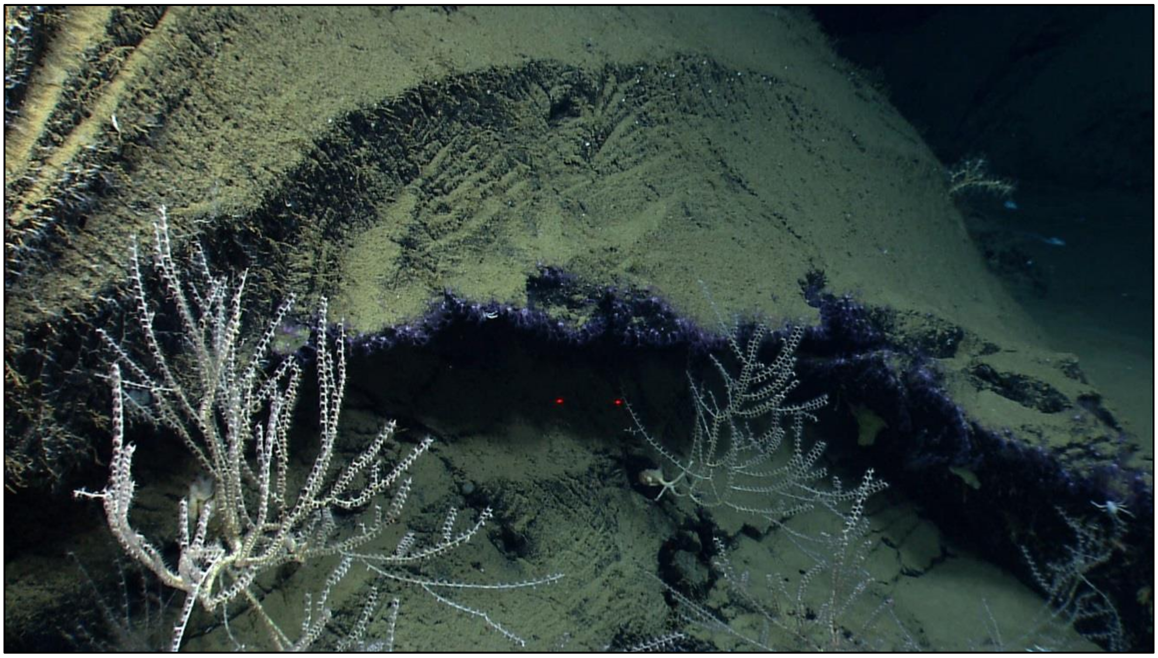

Figure B.99 Dive 12, Image 09:
EX1402L3_IMG_20140424T175454Z_ROVHD_OBJ2_COR

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Tar Mound located on a Slope (Level 1) on a Continental Slope (Sigsbee Escarpment)

Substrate: Geologic Substrate

Biotic: Attached Corals with Co-occurring Attached Tube-Building Fauna

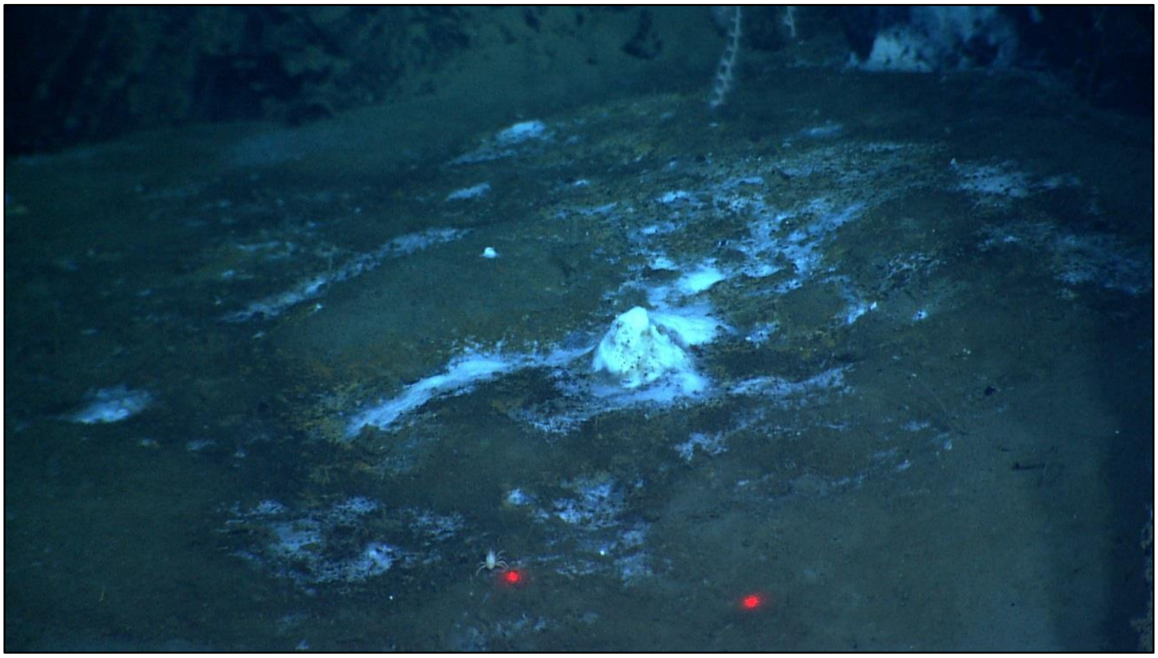

Figure B.100 Dive 12, Image 10:
EX1402L3_IMG_20140424T175832Z_ROVHD_OBJ2_HOL

Water Column: Very Cold Euhaline Water on the Benthic Boundary Layer in the Marine Oceanic Bathypelagic Layer (Oxic)

Geoform: Slope (Level 1) located on a Continental Slope (Sigsbee Escarpment) (Gas Hydrate)

Substrate: Geologic Substrate

Biotic: Attached Bamboo Corals

APPENDIX C

MAP PRODUCTS OF ENVIRONMENTAL PARAMETERS

C.1 Dive 01

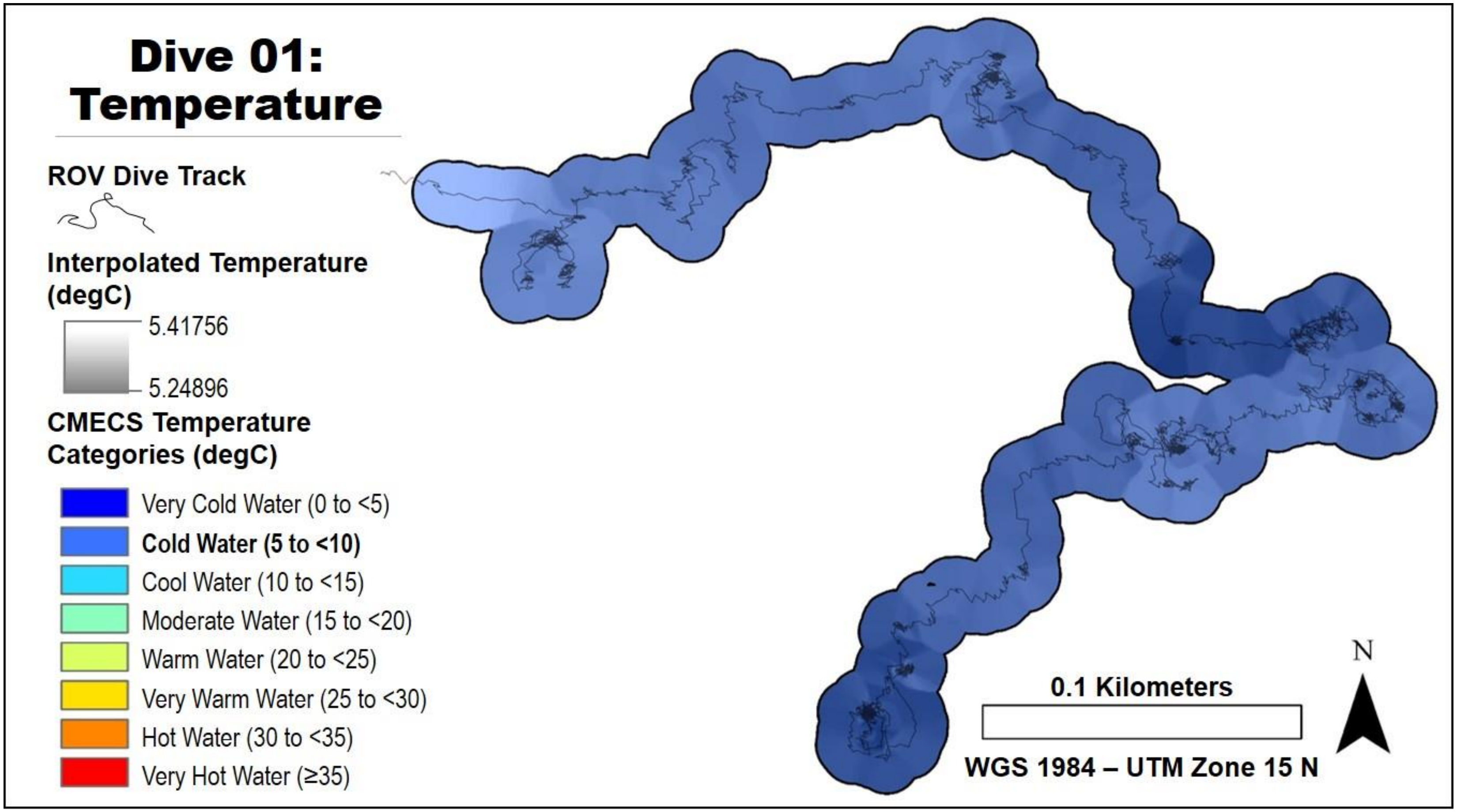

Figure C.1 Interpolated Temperature Gradient throughout Dive 01

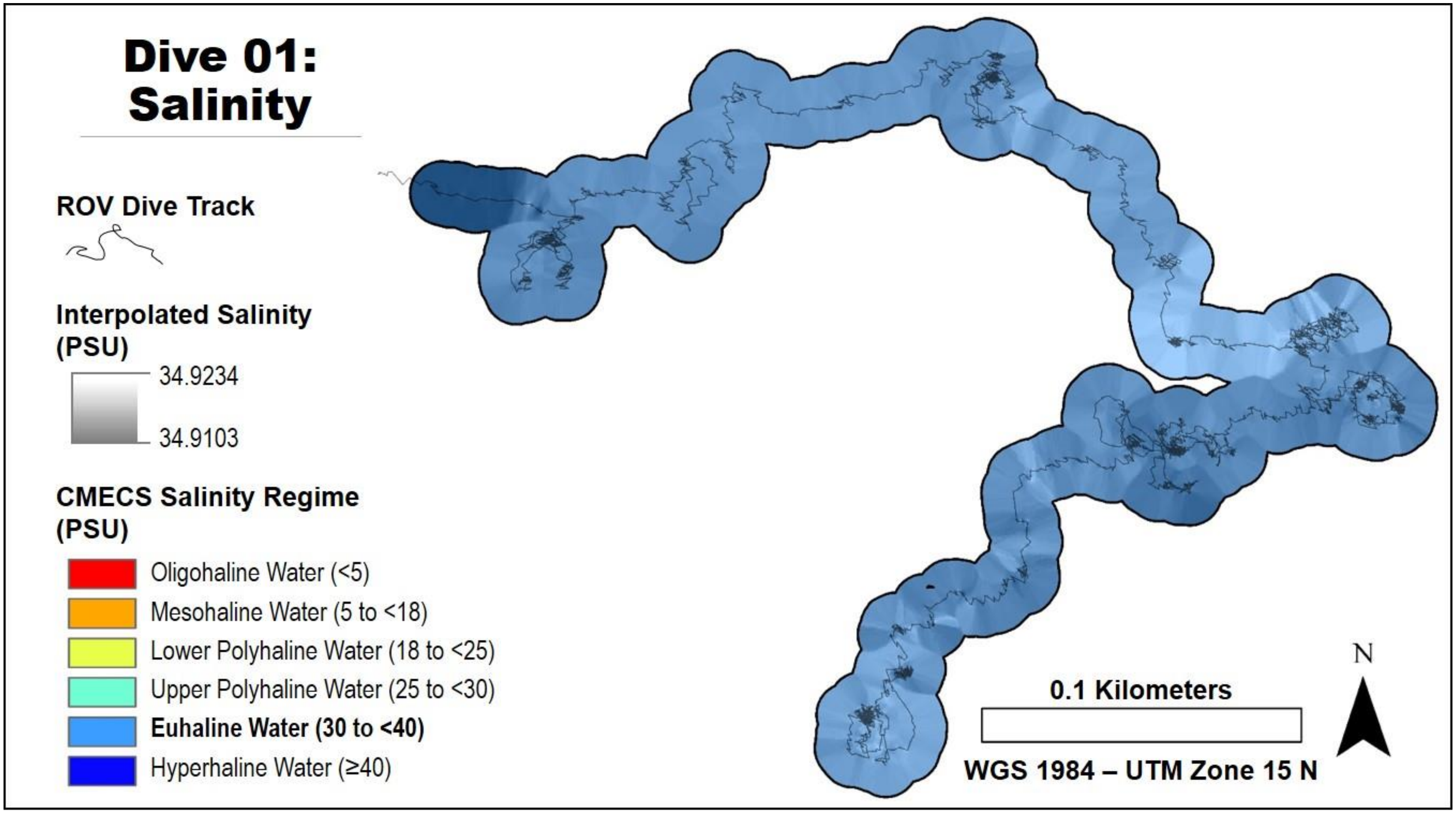

Figure C.2 Interpolated Salinity Concentration throughout Dive 01

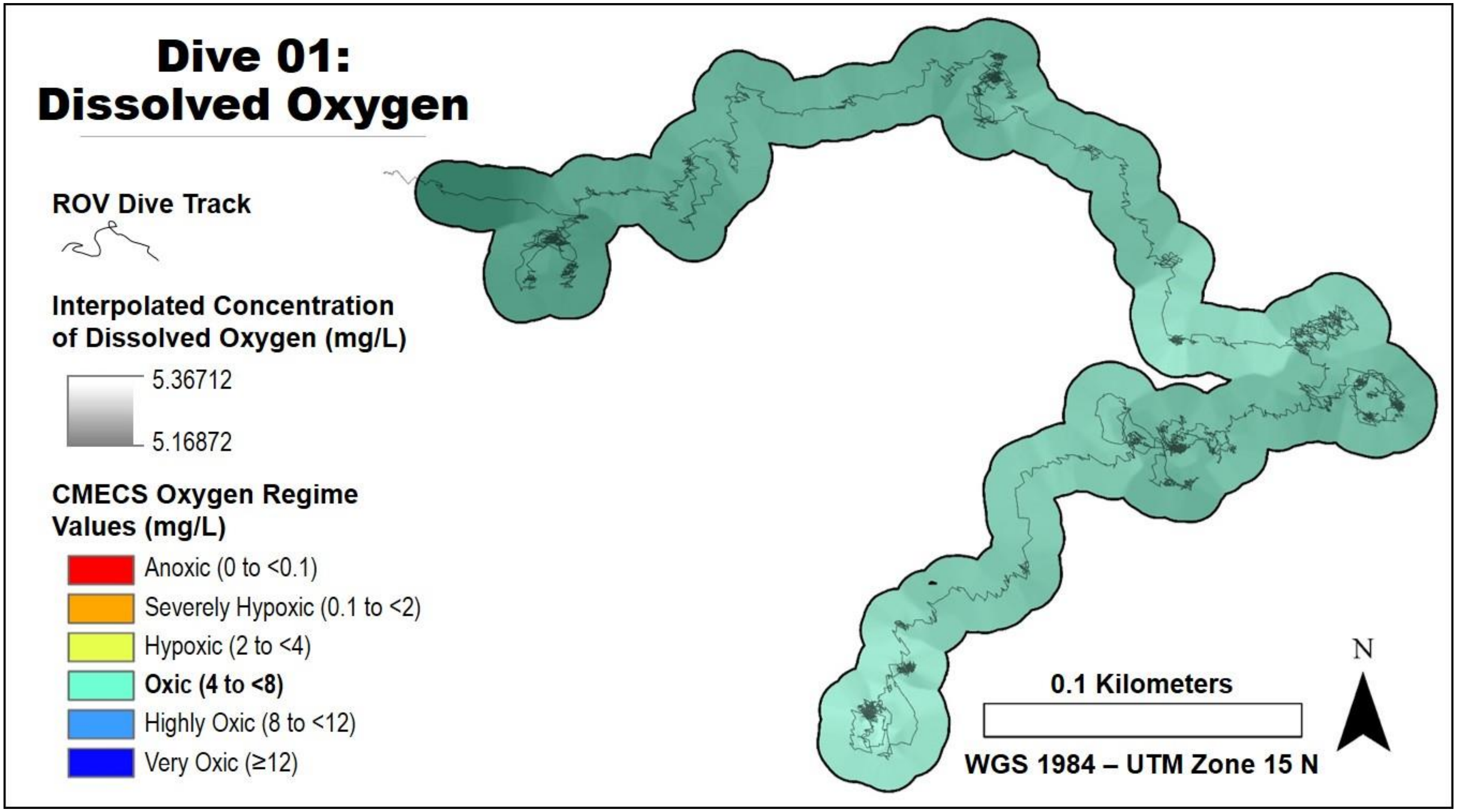

Figure C.3 Interpolated Dissolved Oxygen Concentration throughout Dive 01

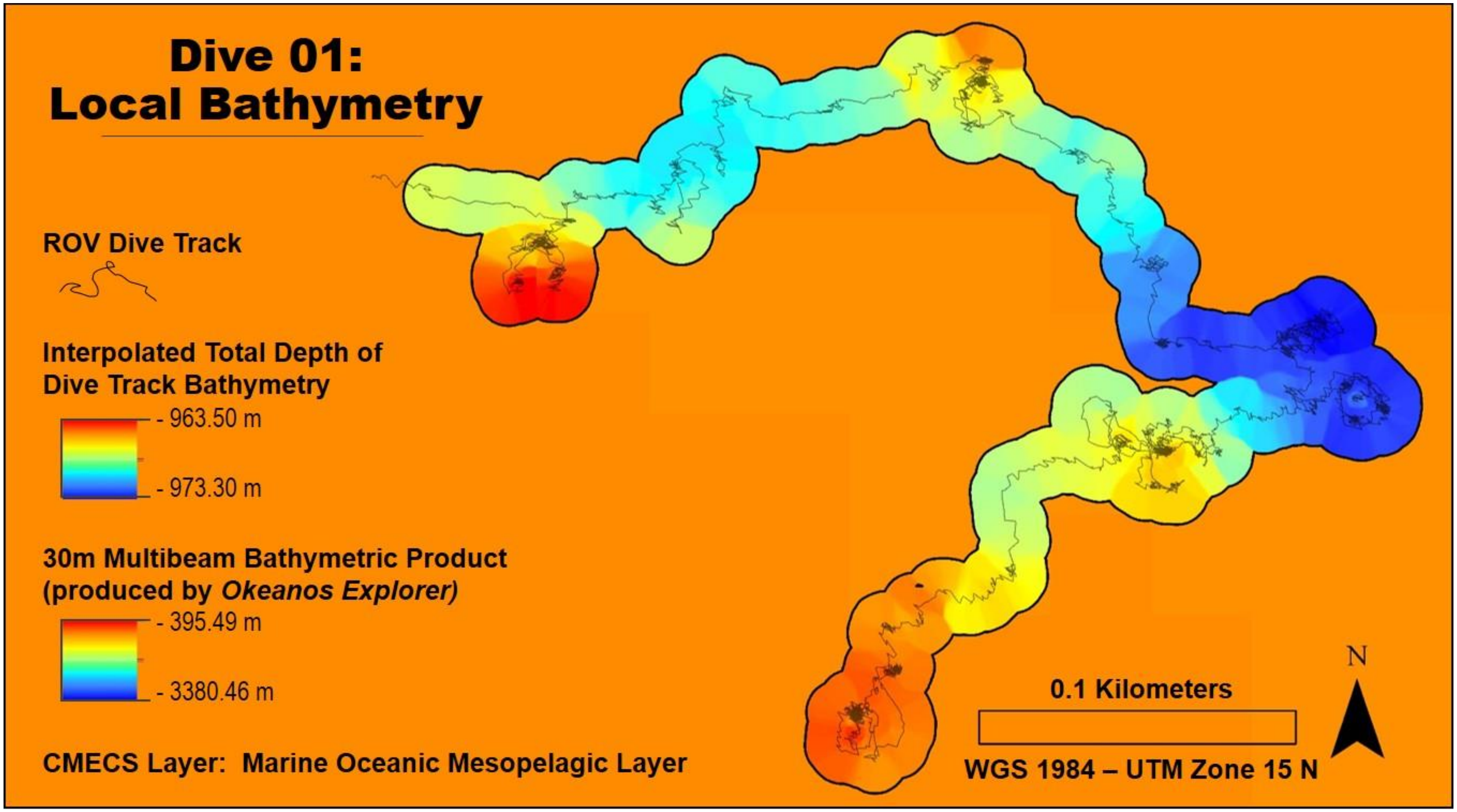

Figure C.4 Interpolated Total Depth of Seafloor throughout Dive 01

C.2 Dive 02

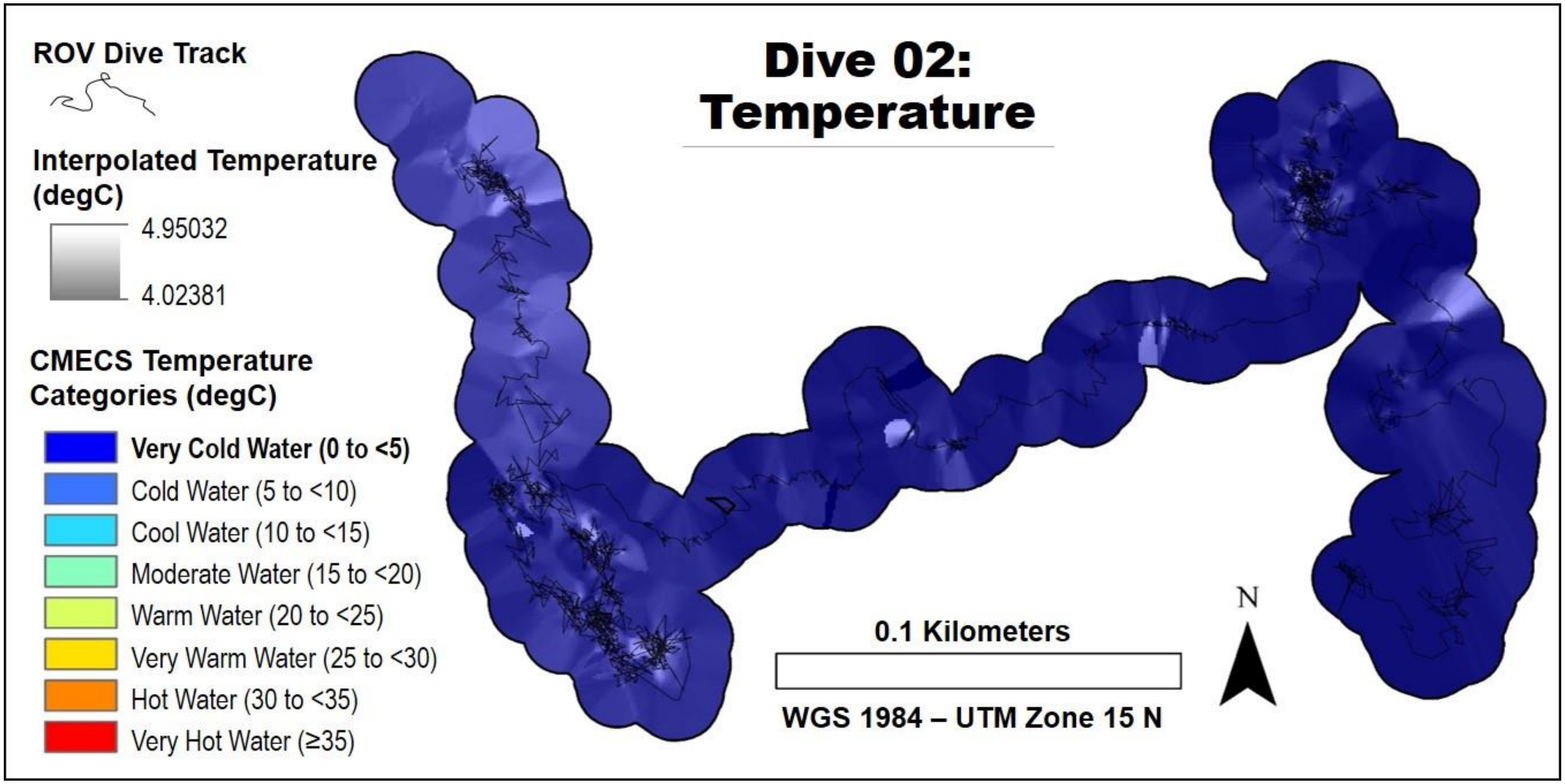

Figure C.5 Interpolated Temperature Gradient throughout Dive 02

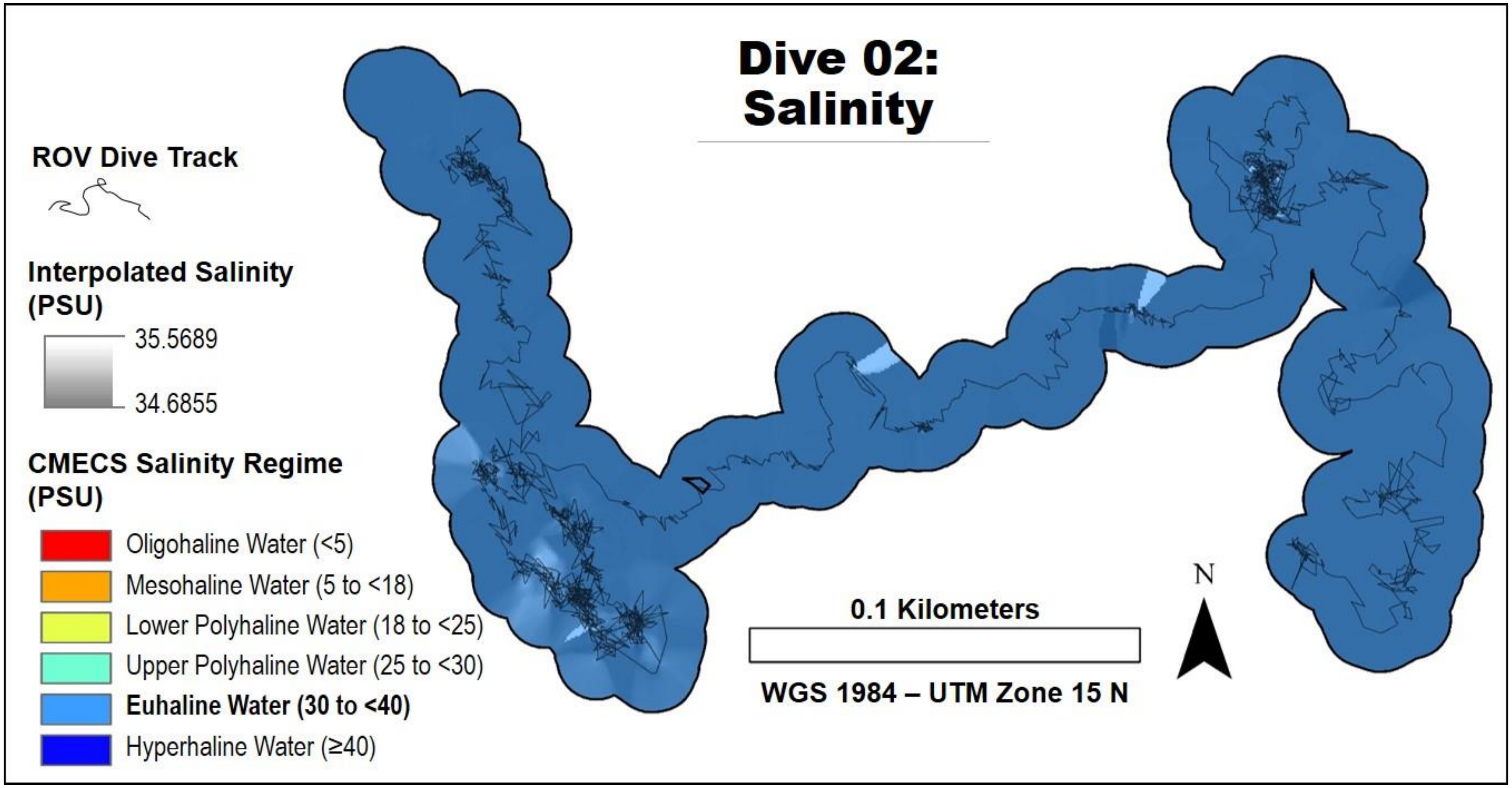

Figure C.6 Interpolated Salinity Concentration throughout Dive 02

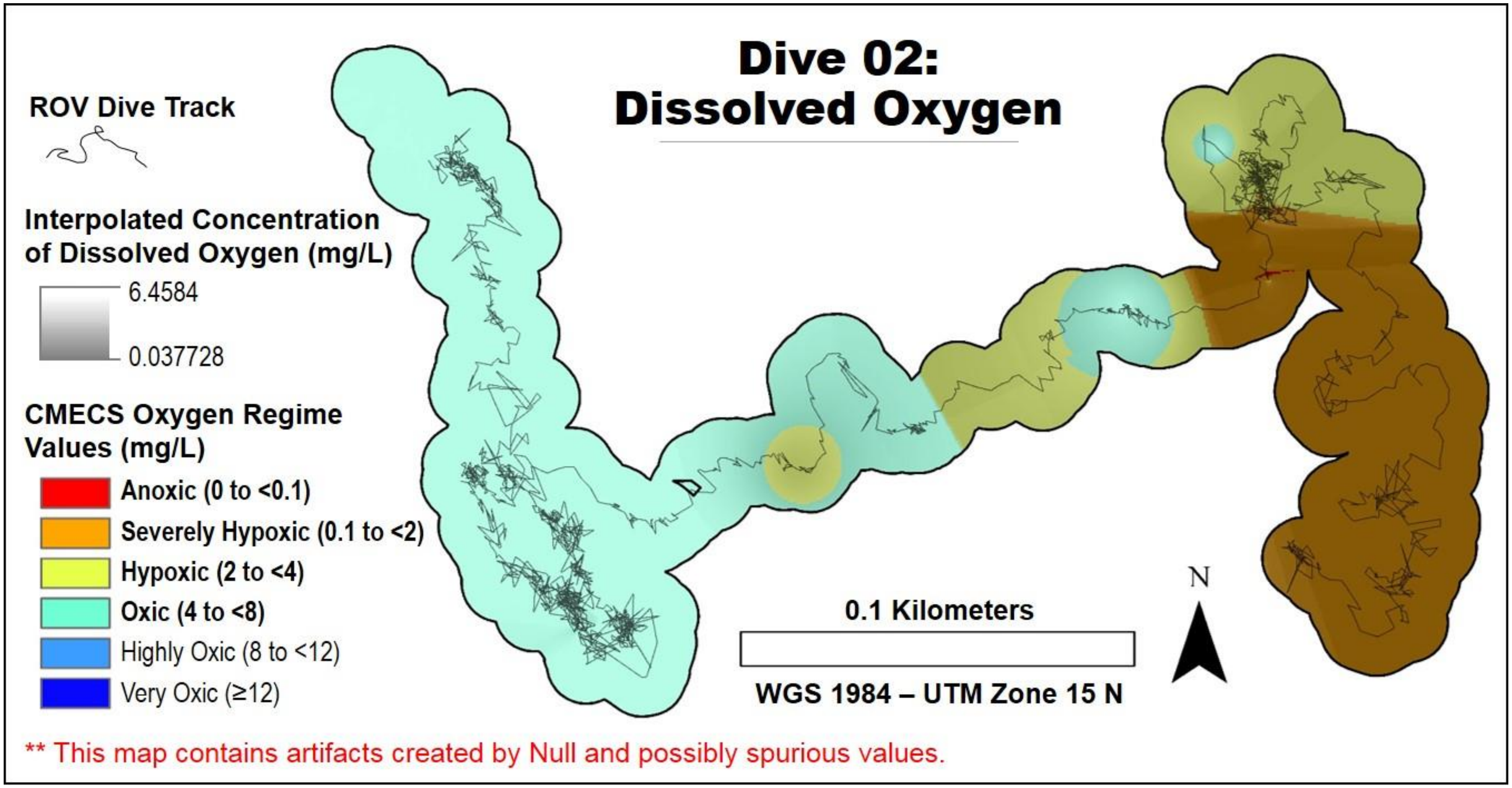

Figure C.7 Interpolated Dissolved Oxygen Concentration throughout Dive 01

This map contains artifacts created by Null and/or possibly spurious values.

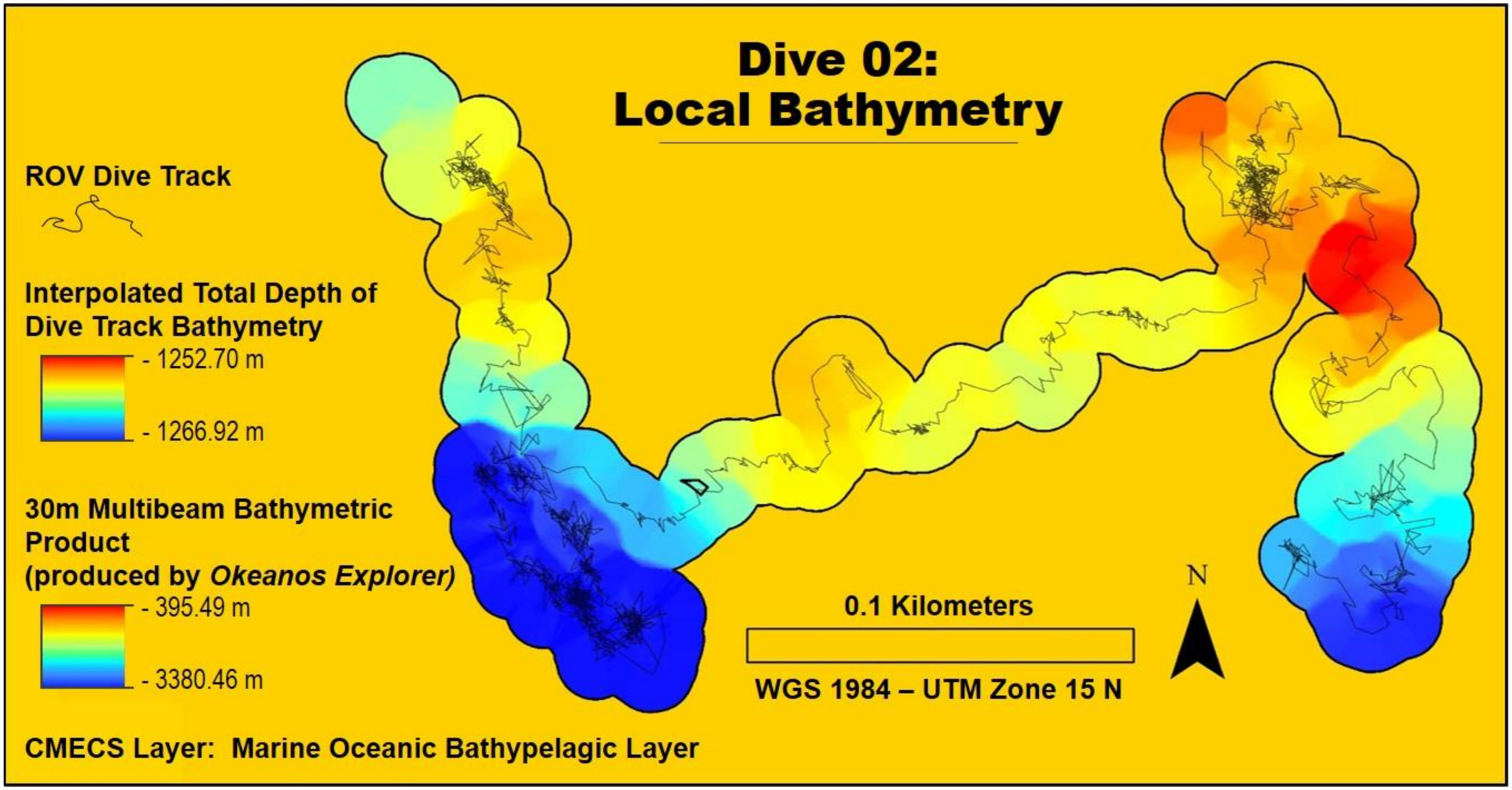

Figure C.8 Interpolated Total Depth of Seafloor throughout Dive 02

C.3 Dive 03

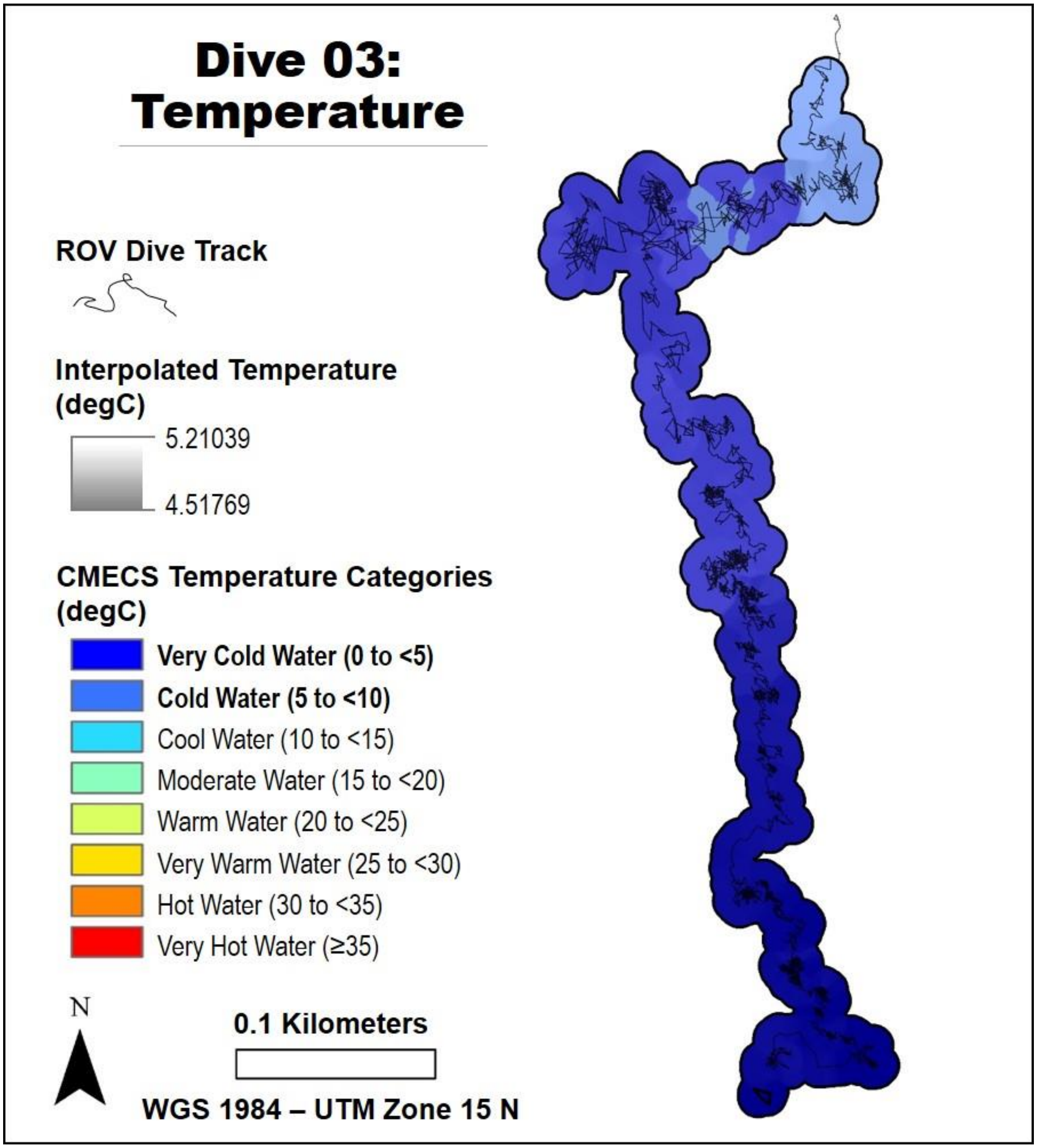

Figure C.9 Interpolated Temperature Gradient throughout Dive 03

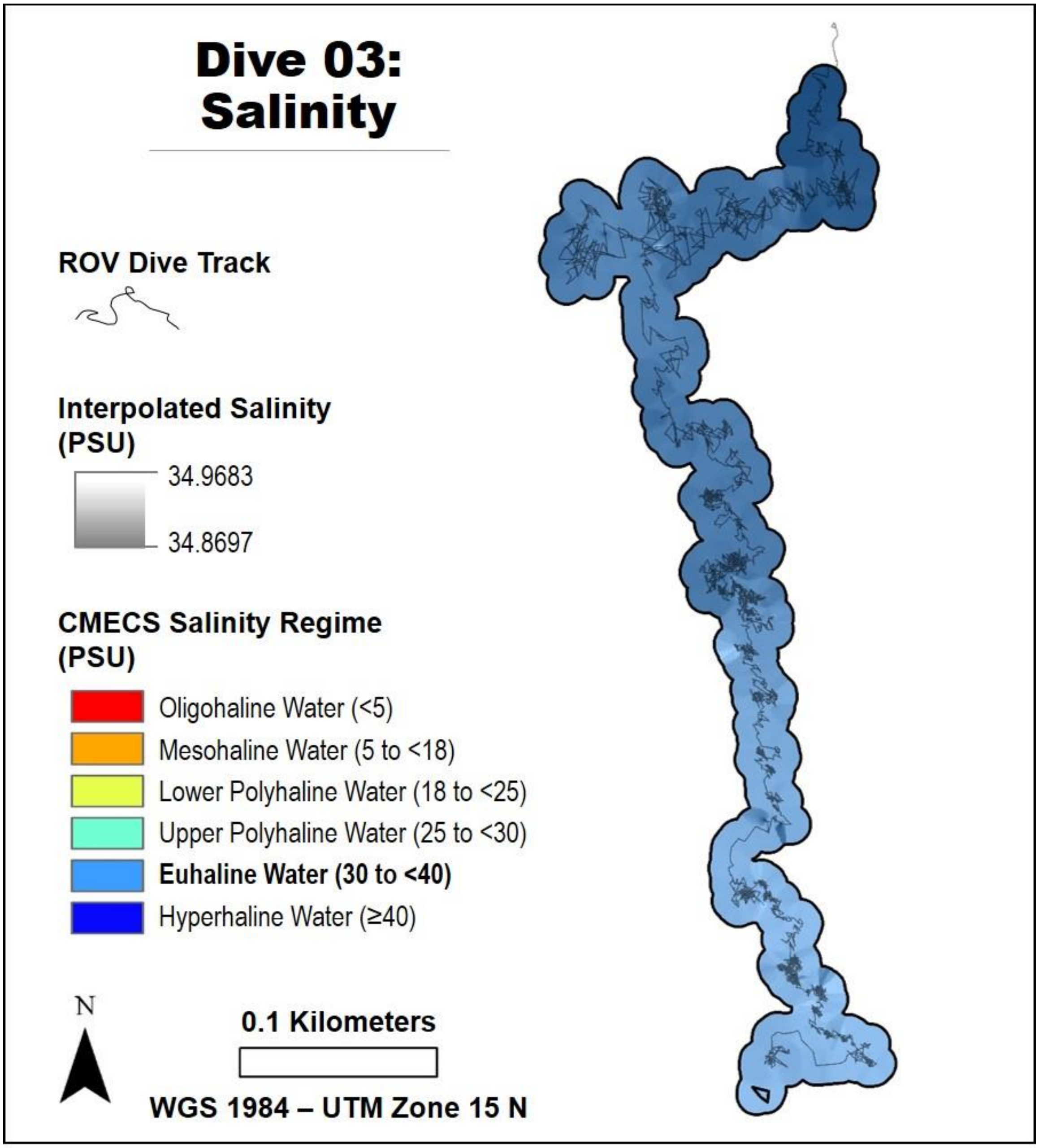

Figure C.10 Interpolated Salinity Concentration throughout Dive 03

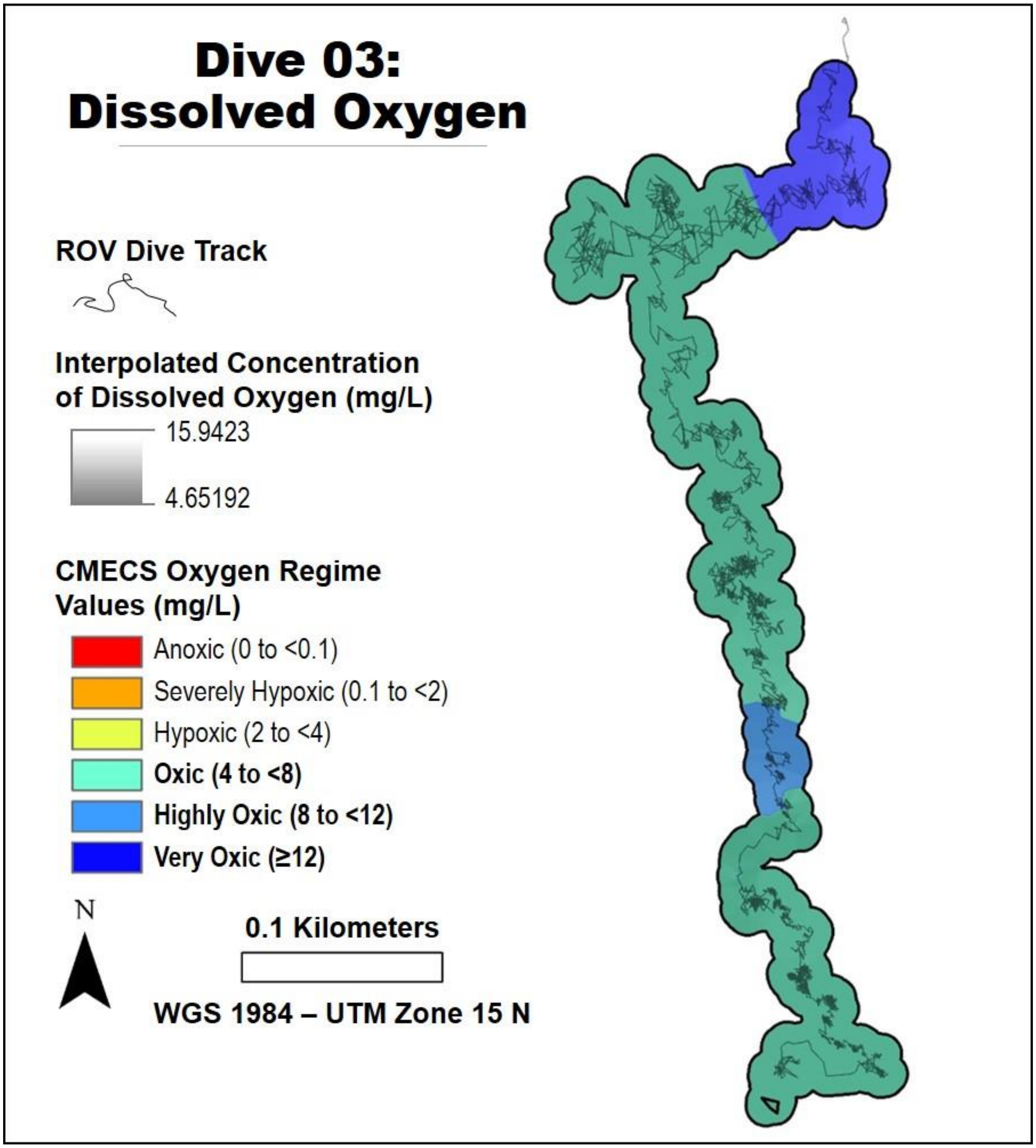

Figure C.11 Interpolated Dissolved Oxygen Concentration throughout Dive 03

This map contains artifacts created by Null and/or possibly spurious values.

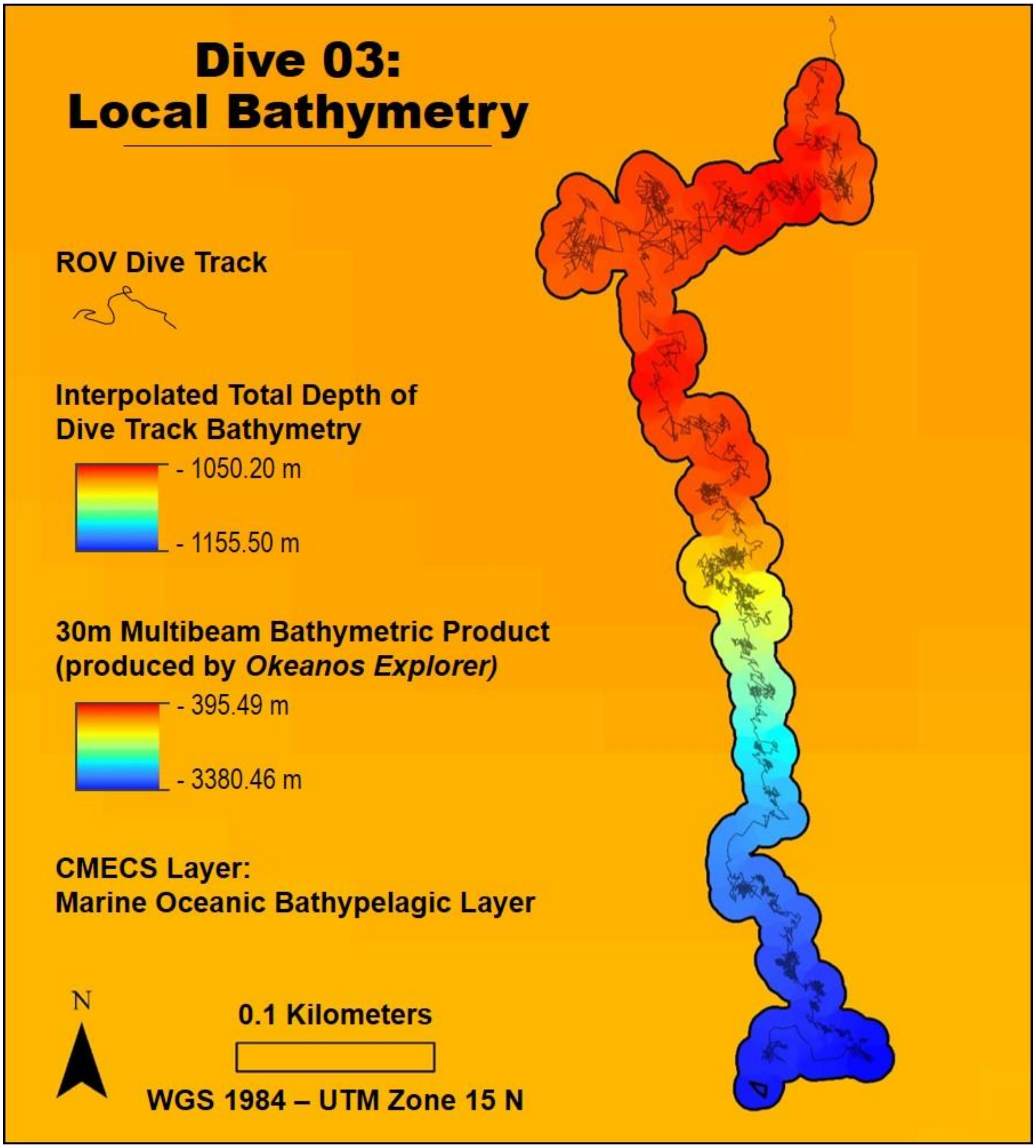

Figure C.12 Interpolated Total Depth of Seafloor throughout Dive 03

C.4 Dive 04

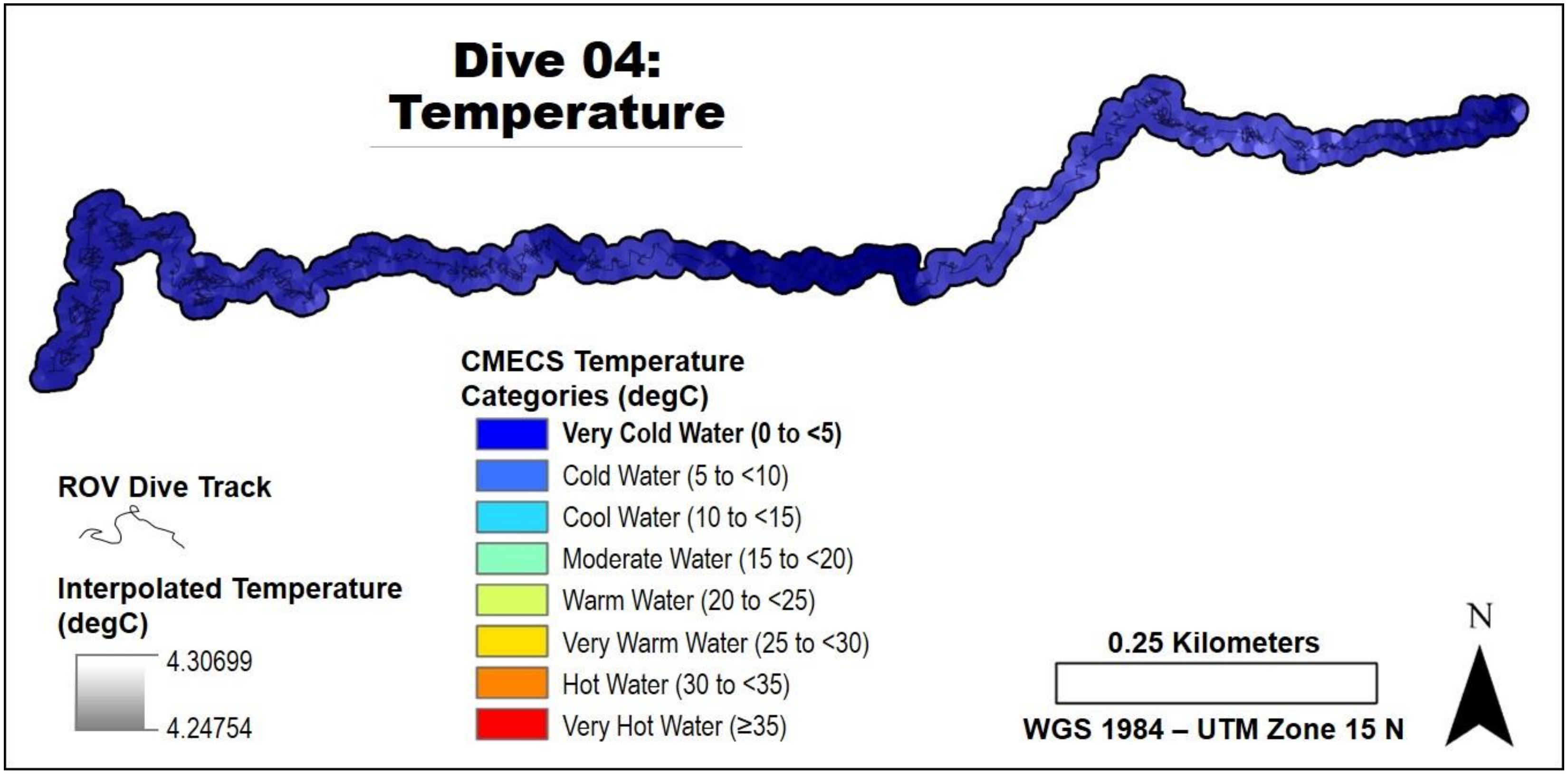

Figure C.13 Interpolated Temperature Gradient throughout Dive 04

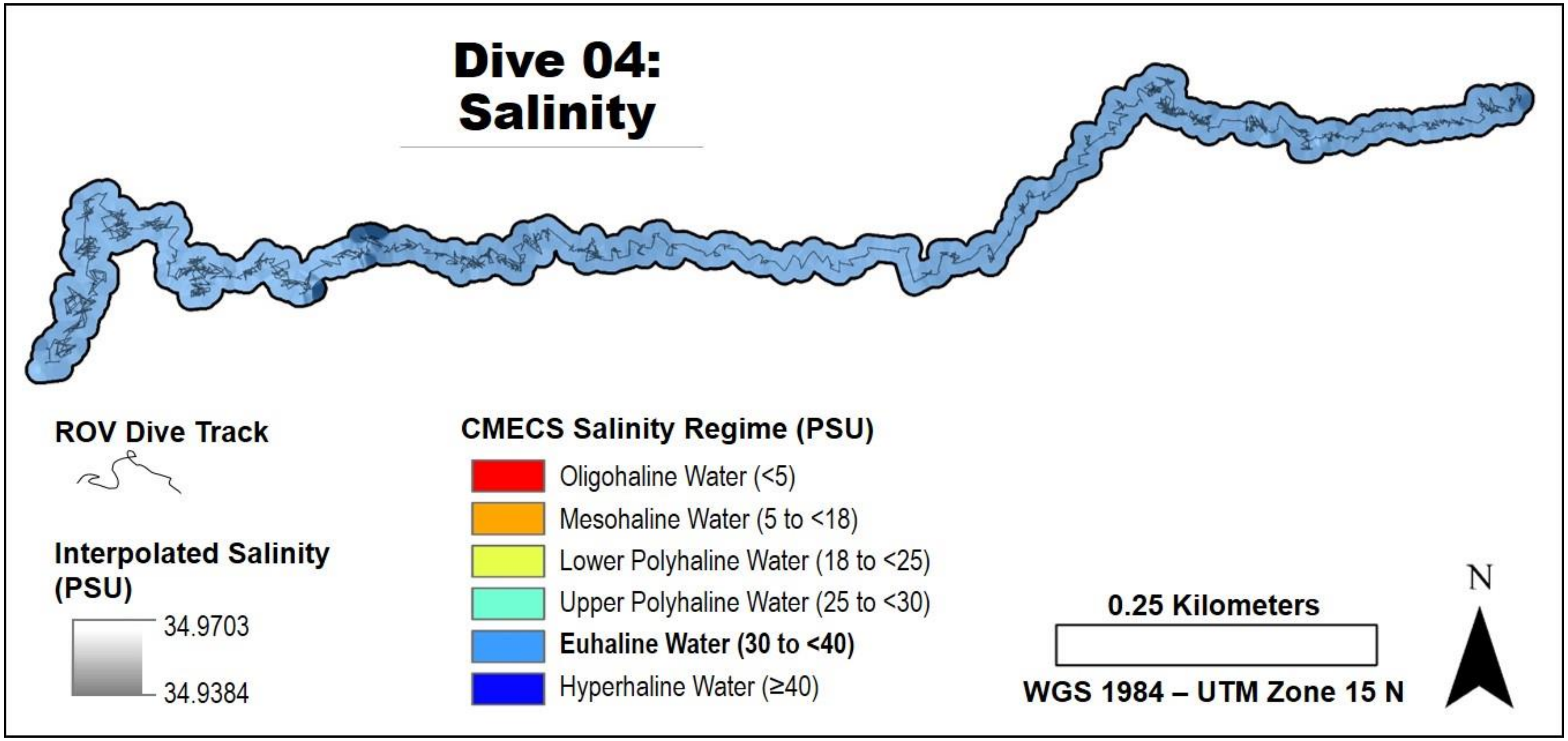

Figure C.14 Interpolated Salinity Concentration throughout Dive 04

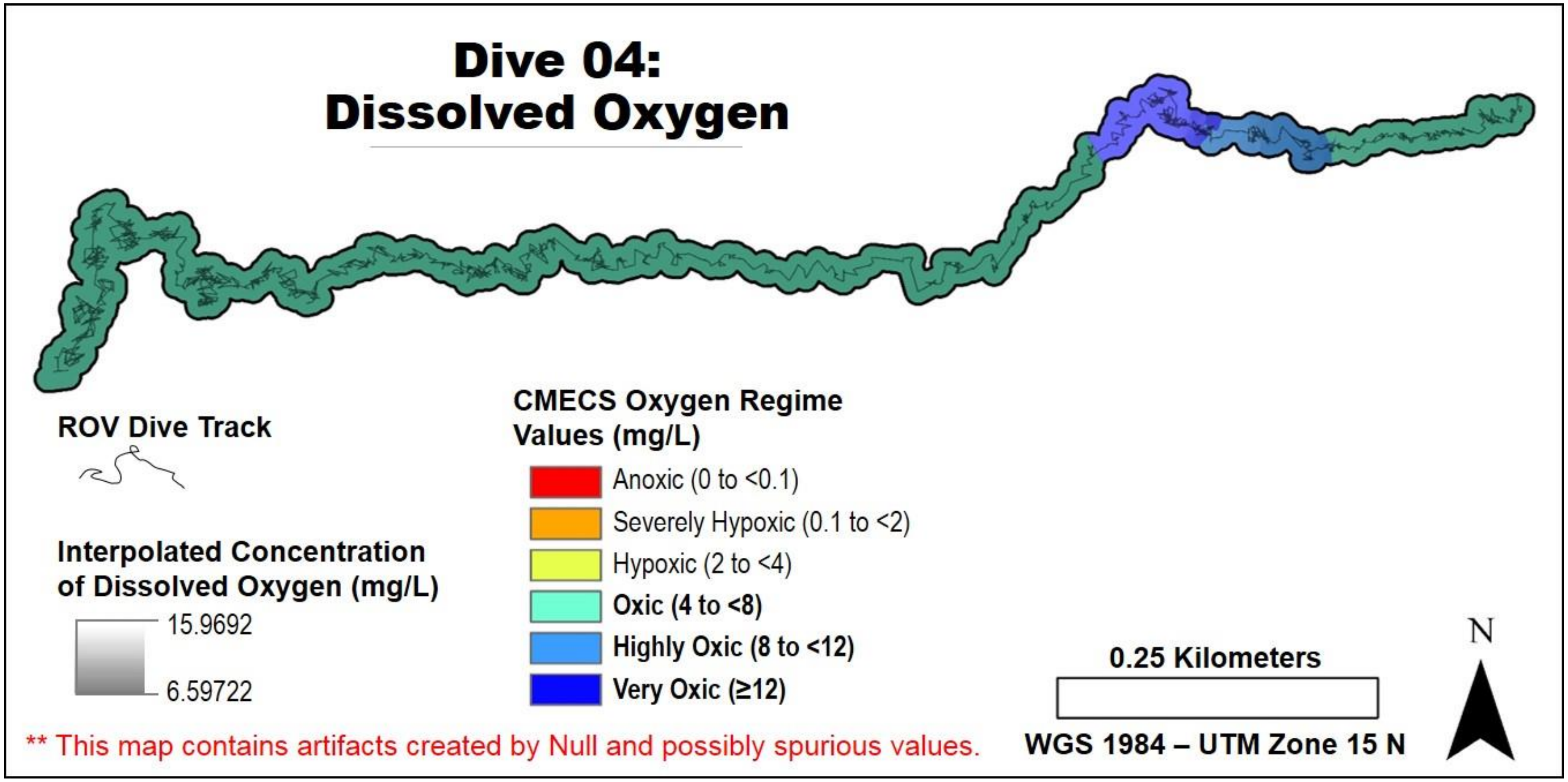

Figure C.15 Interpolated Dissolved Oxygen Concentration throughout Dive 04

This map contains artifacts created by Null and/or possibly spurious values.

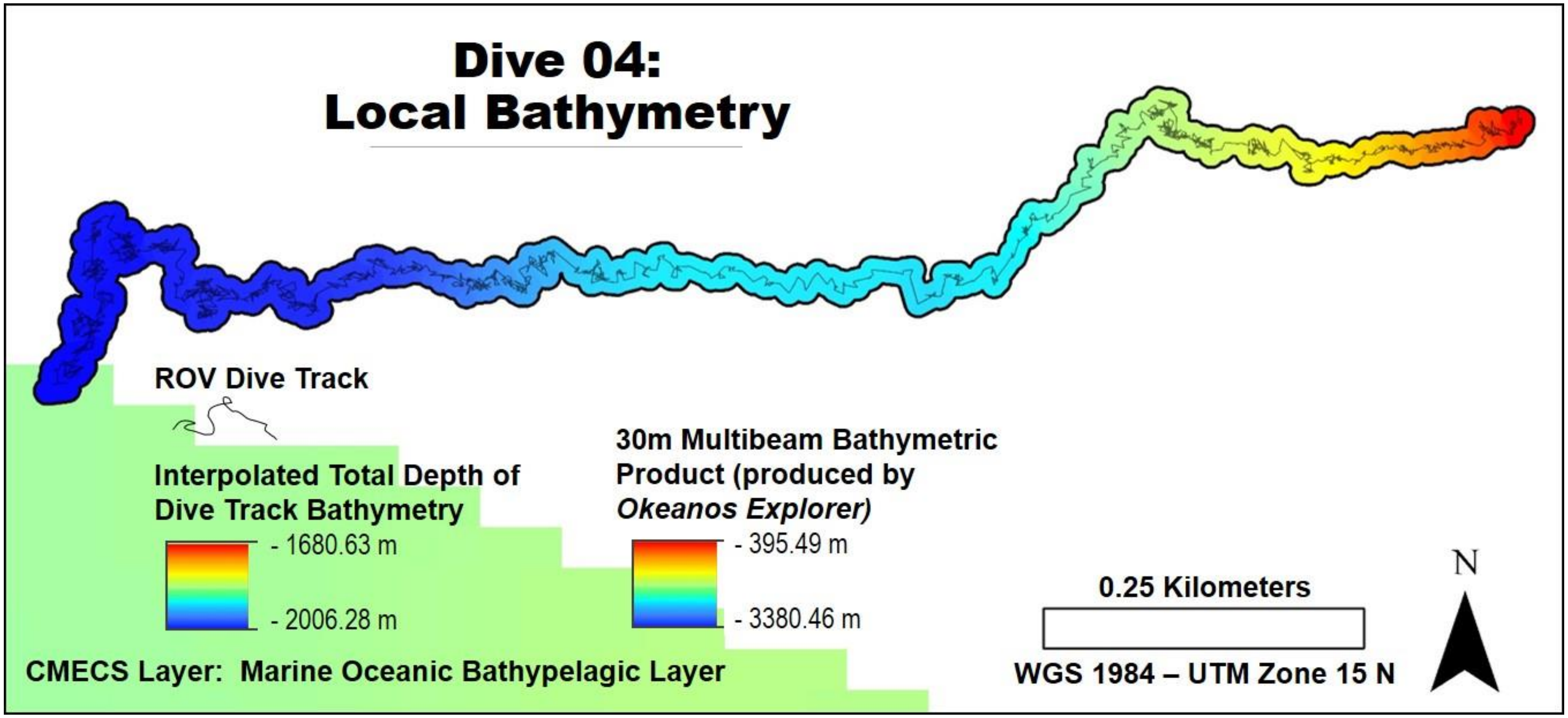

Figure C.16 Interpolated Total Depth of Seafloor throughout Dive 04

C.5 Dive 06

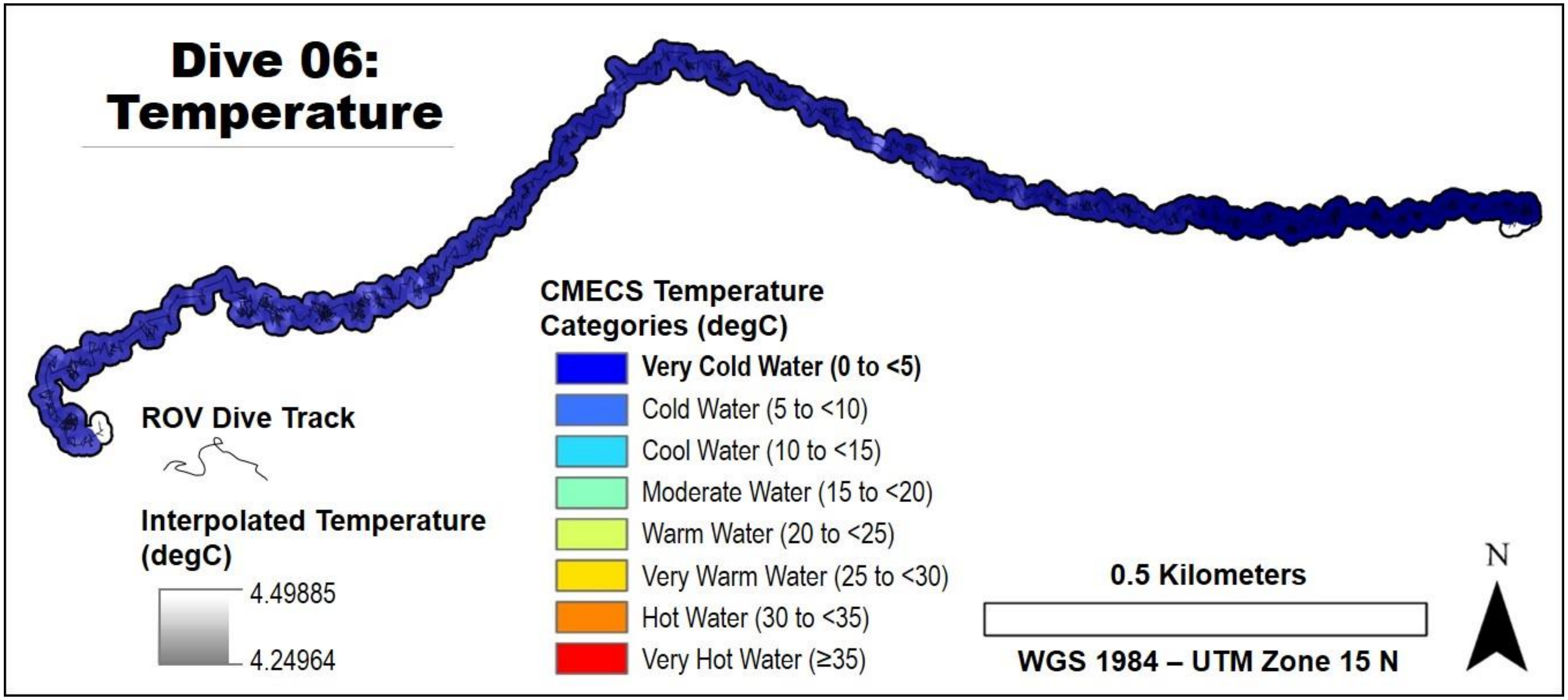

Figure C.17 Interpolated Temperature Gradient throughout Dive 06

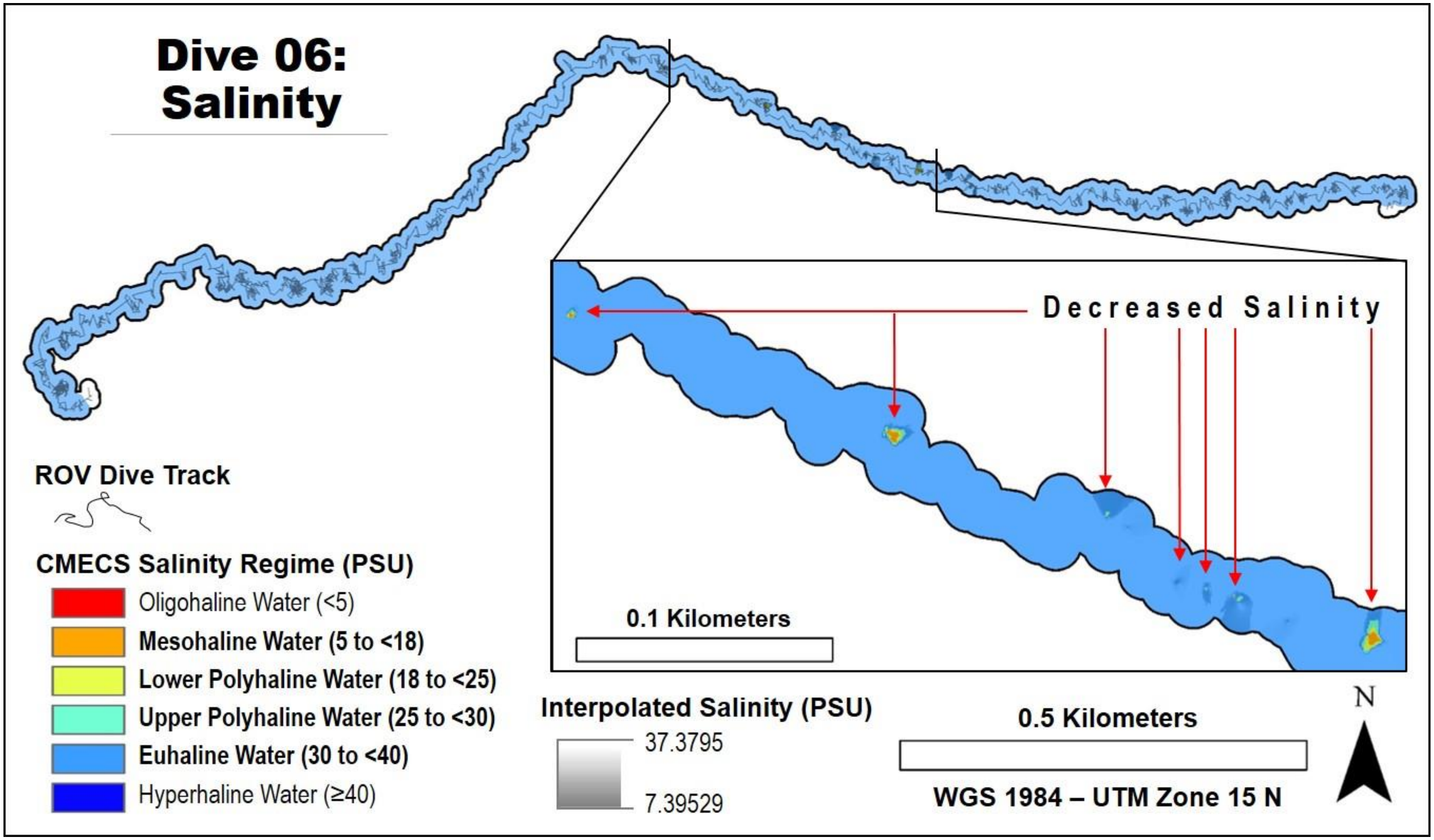

Figure C.18 Interpolated Salinity Concentration throughout Dive 06

The above overlain surfaces highlight steady decreases in salinity measurements along multiple portions of the dive track.

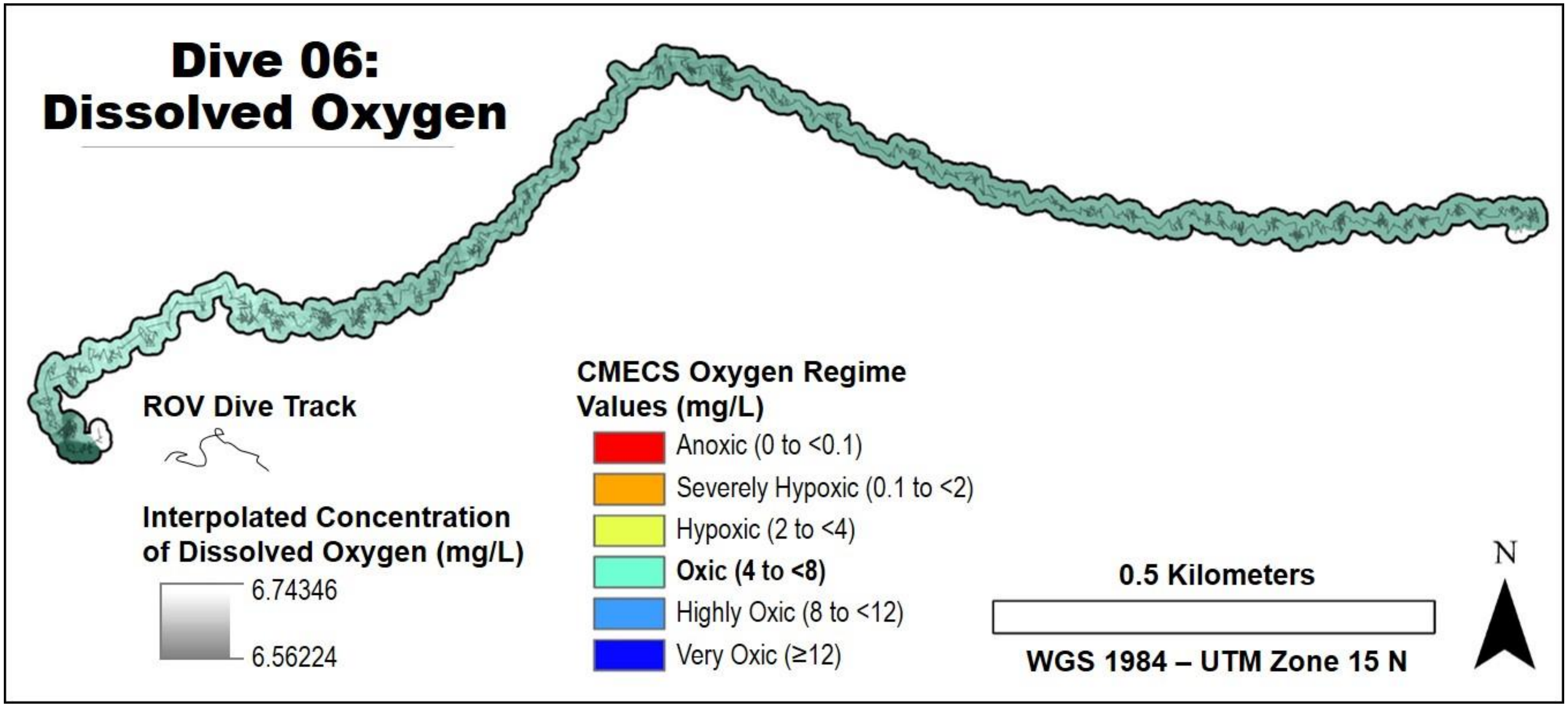

Figure C.19 Interpolated Dissolved Oxygen Concentration throughout Dive 06

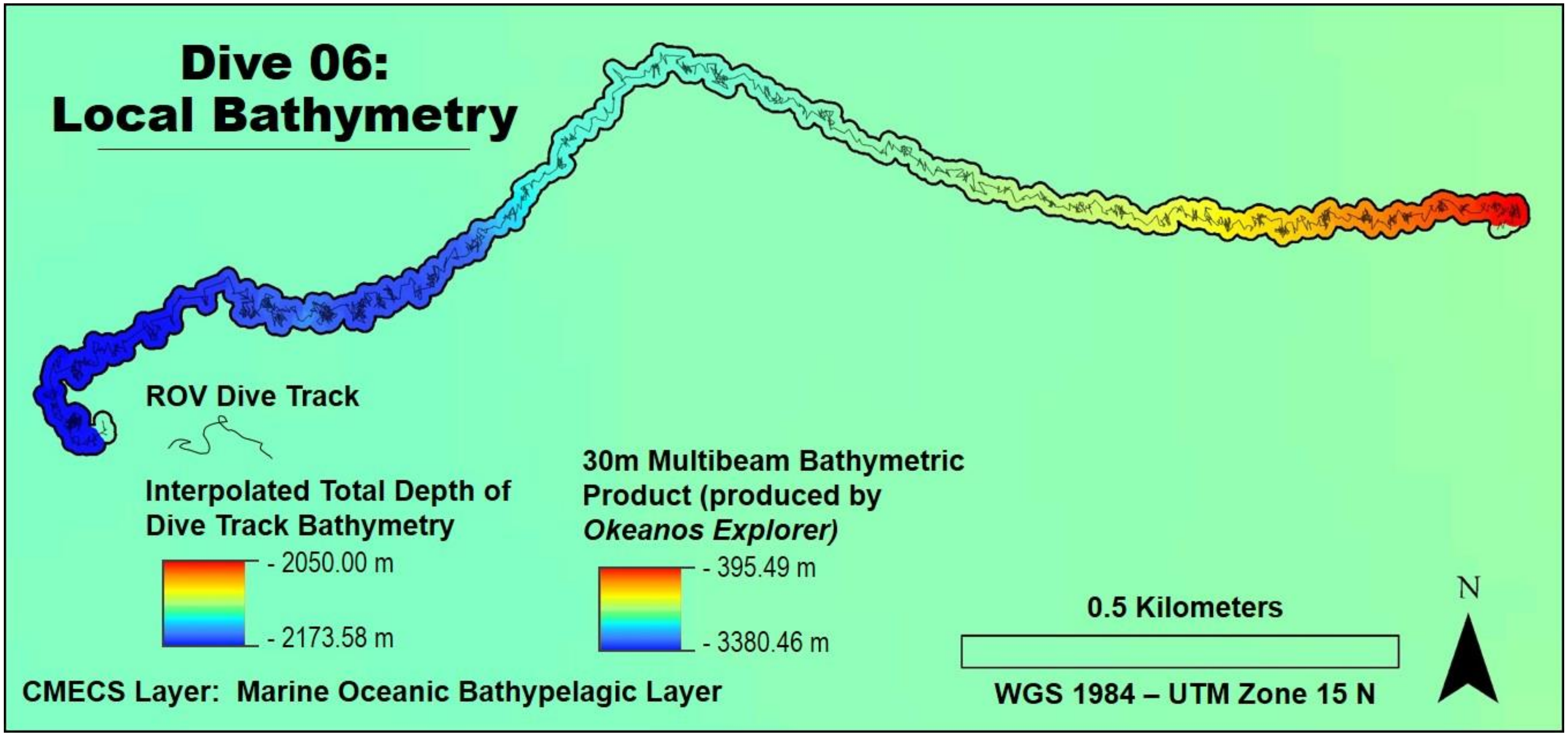

Figure C.20 Interpolated Total Depth of Seafloor throughout Dive 06

C.6 Dive 08

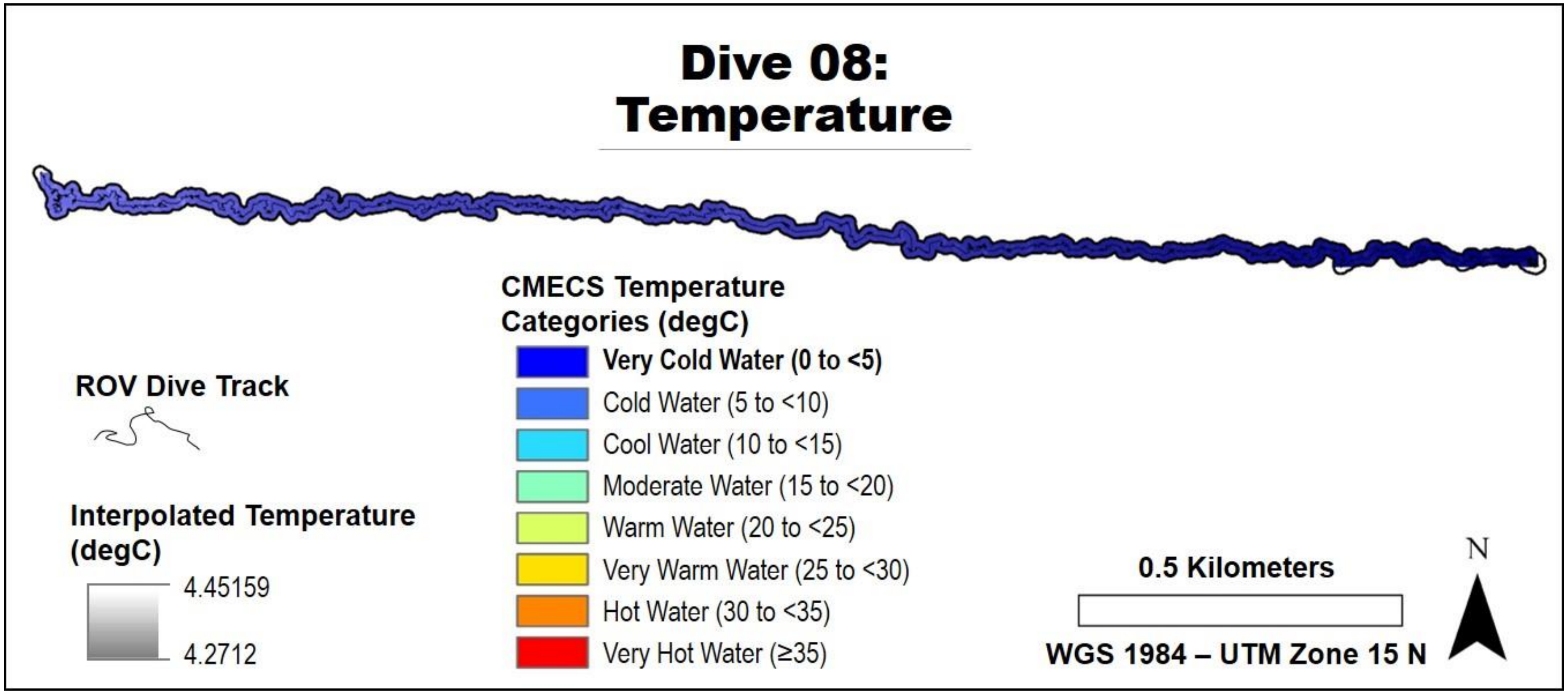

Figure C.21 Interpolated Temperature Gradient throughout Dive 08

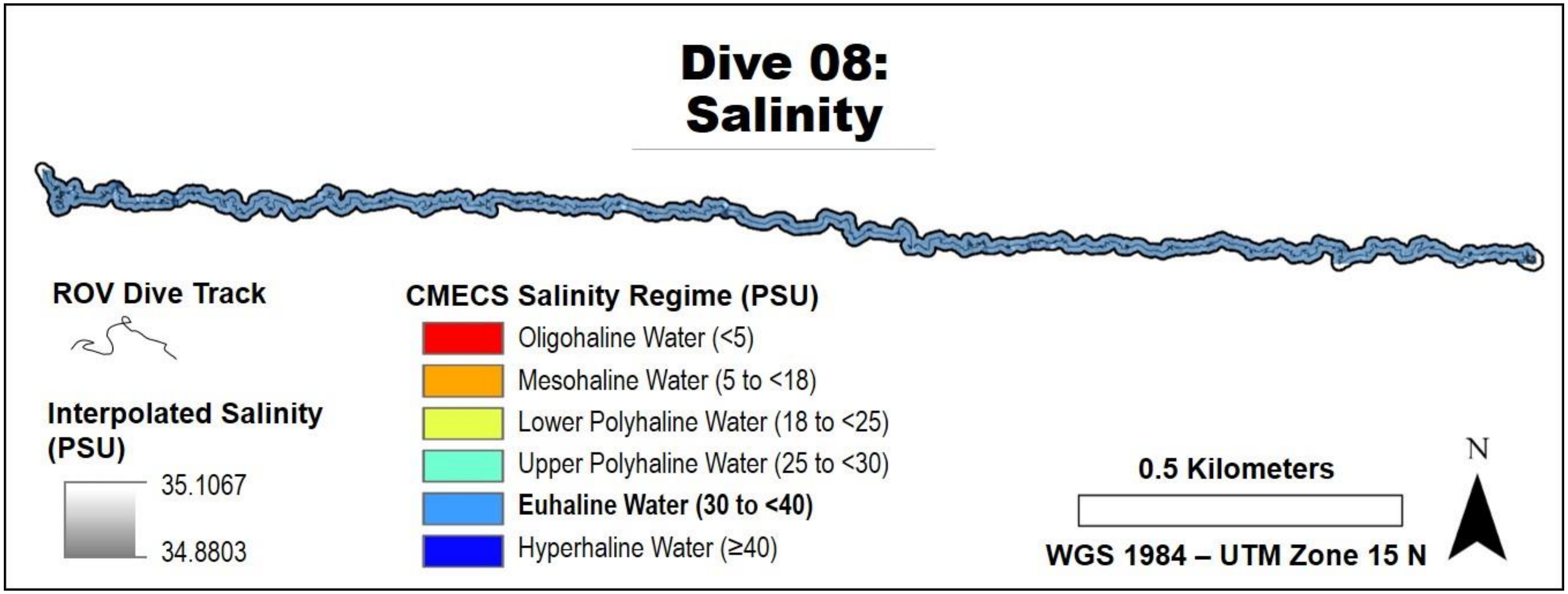

Figure C.22 Interpolated Salinity Concentration throughout Dive 08

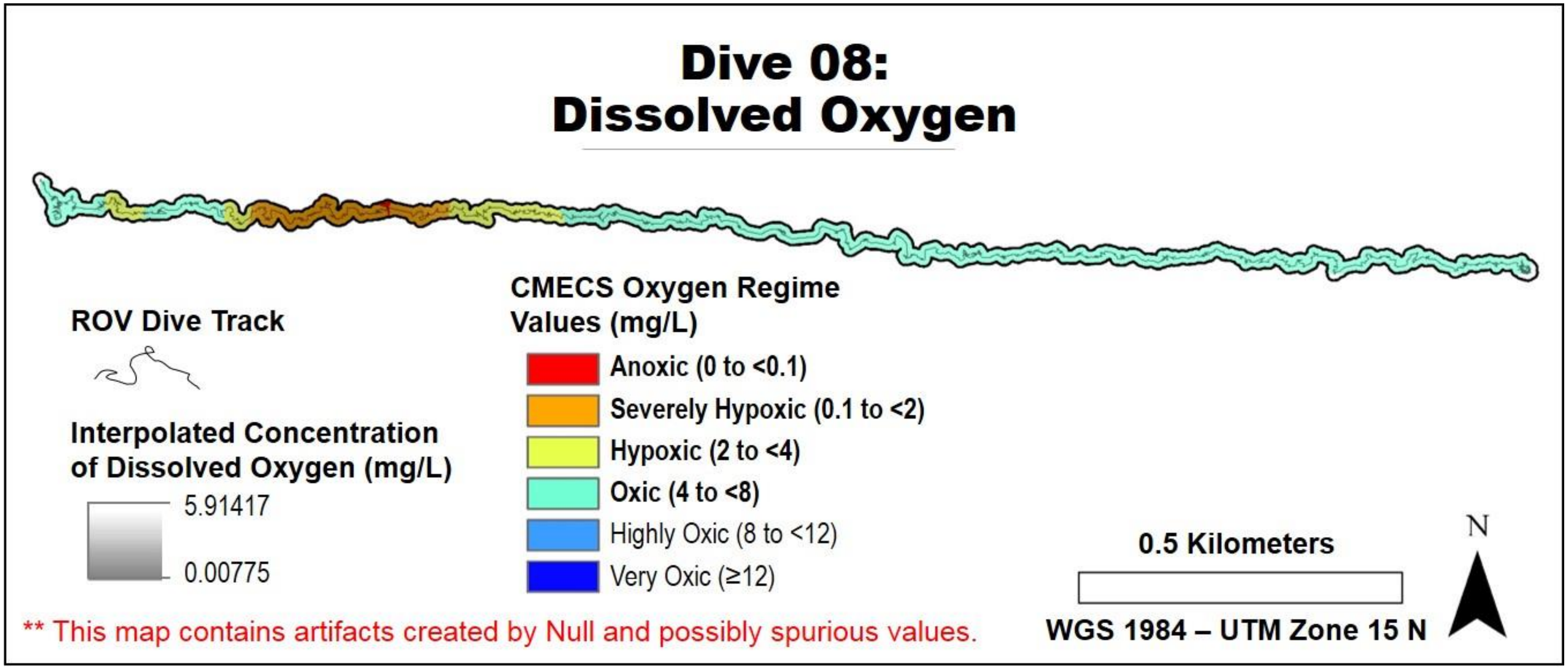

Figure C.23 Interpolated Dissolved Oxygen Concentration throughout Dive 08

This map contains artifacts created by Null and/or possibly spurious values.

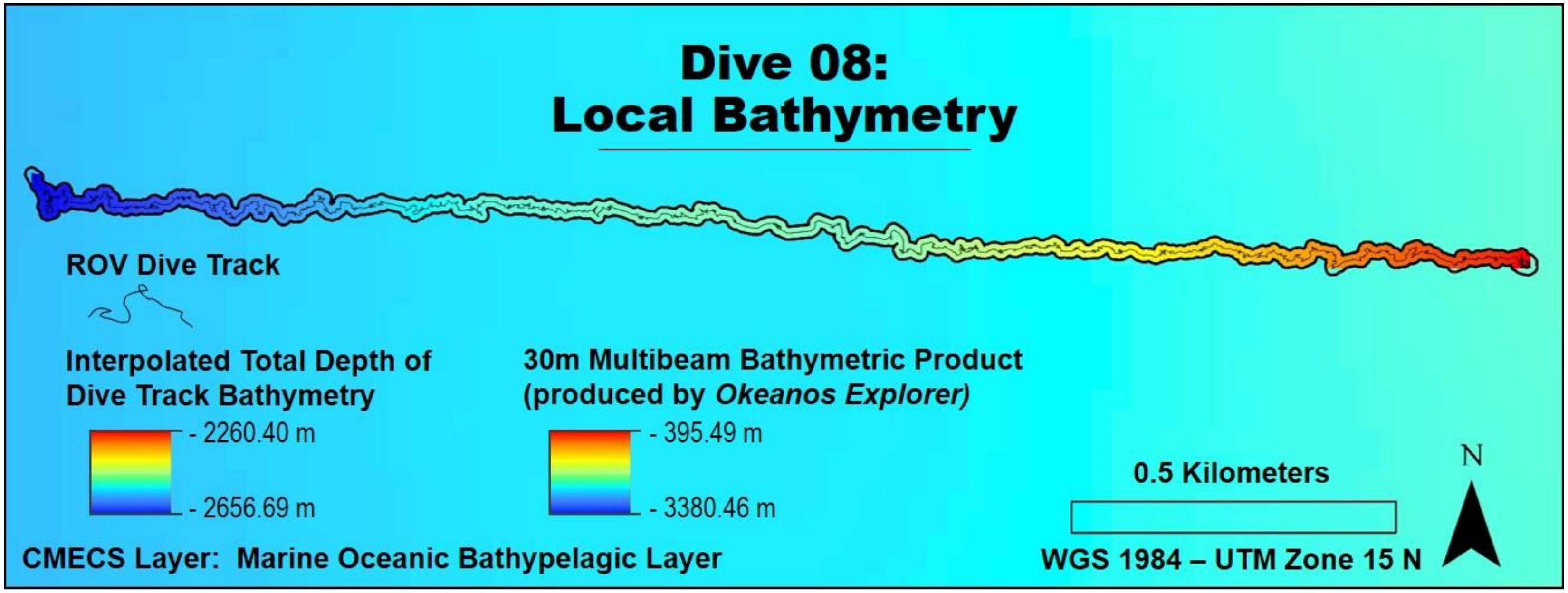

Figure C.24 Interpolated Total Depth of Seafloor throughout Dive 08

C.7 Dive 09

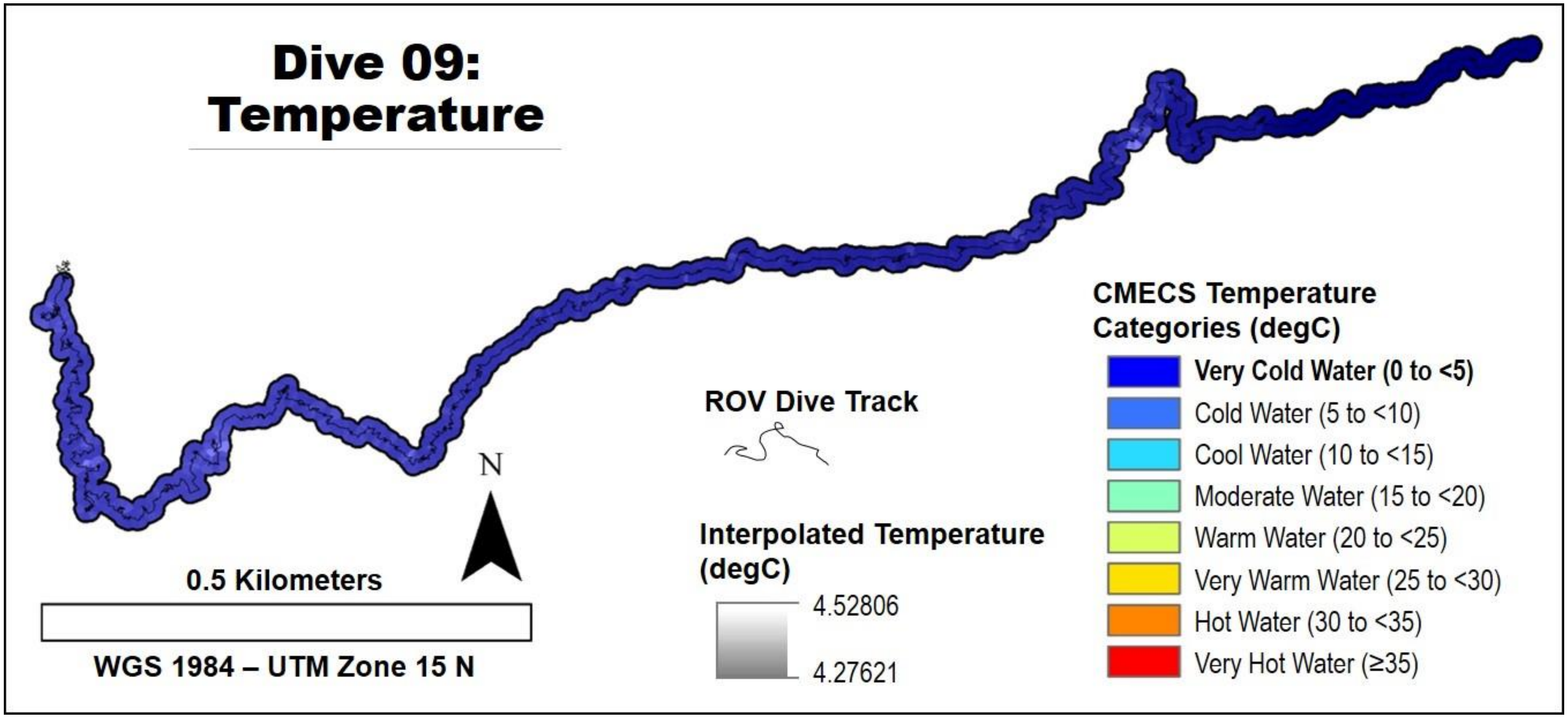

Figure C.25 Interpolated Temperature Gradient throughout Dive 09

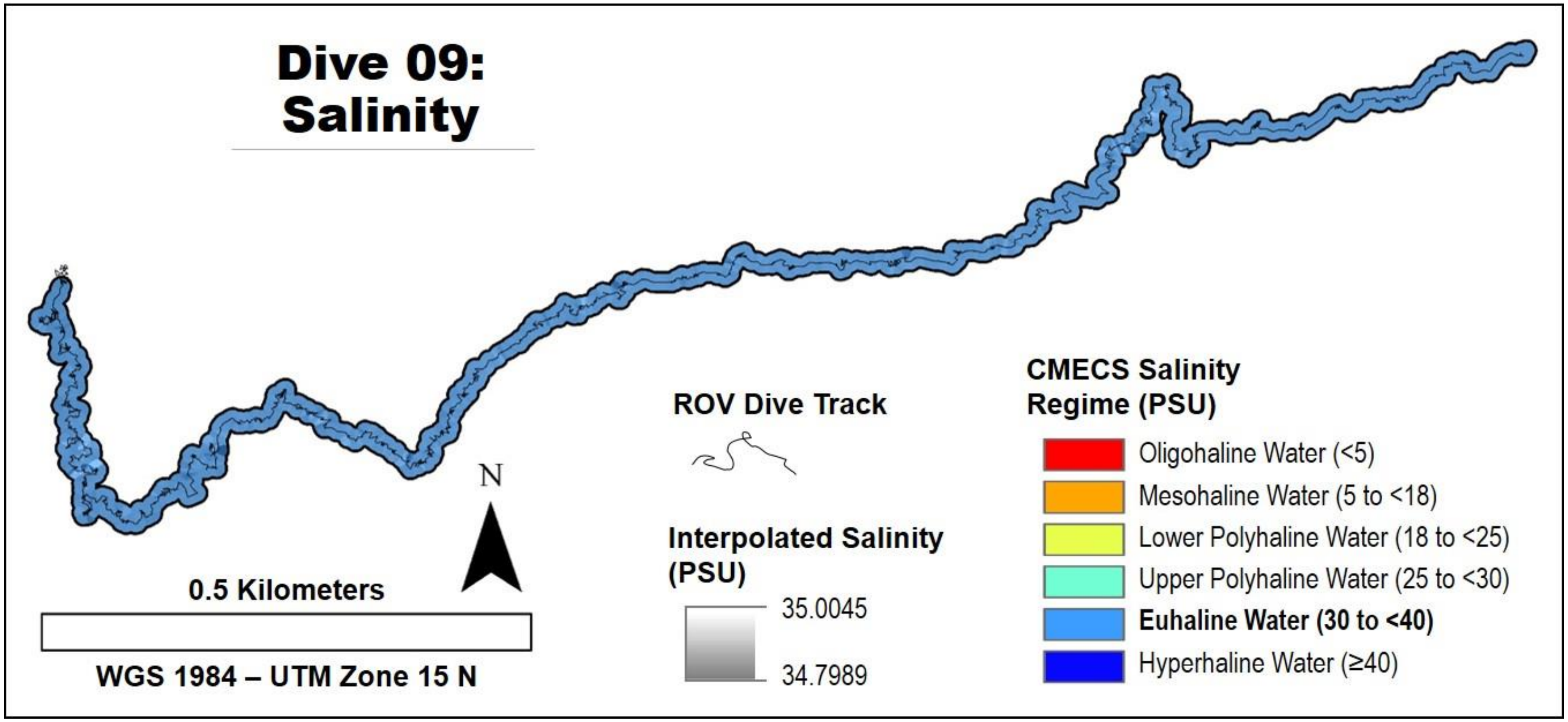

Figure C.26 Interpolated Salinity Concentration throughout Dive 09

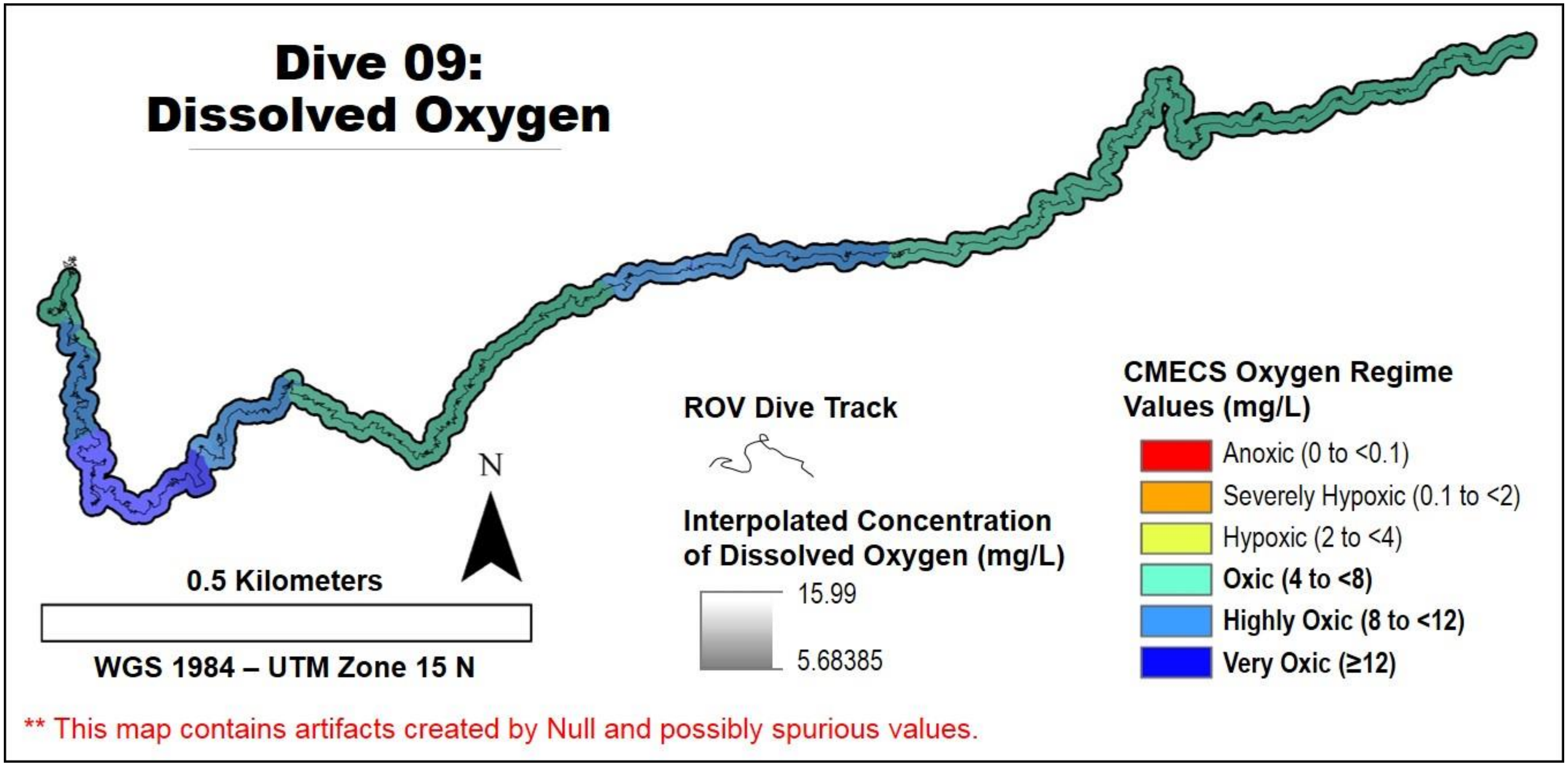

Figure C.27 Interpolated Dissolved Oxygen Concentration throughout Dive 09

This map contains artifacts created by Null and/or possibly spurious values.

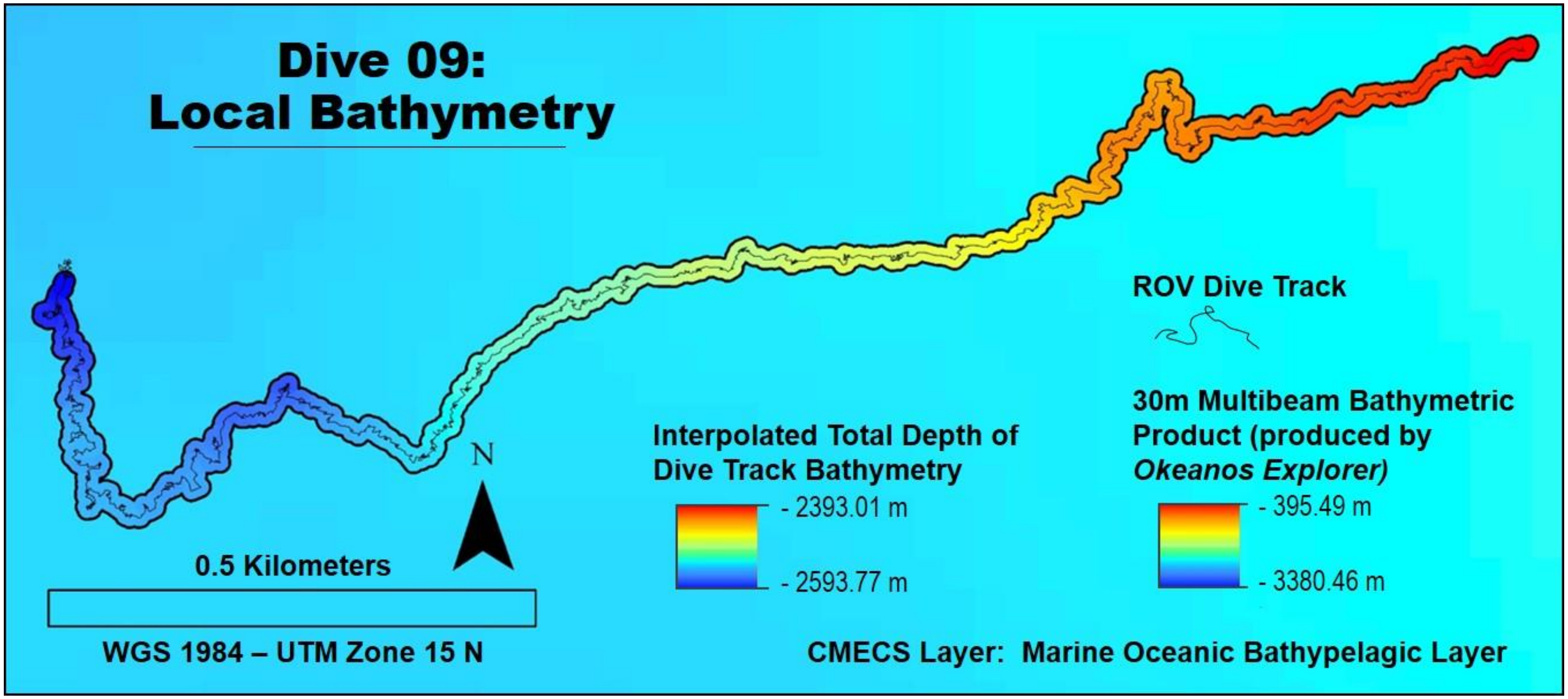

Figure C.28 Interpolated Total Depth of Seafloor throughout Dive 09

C.8 Dive 10

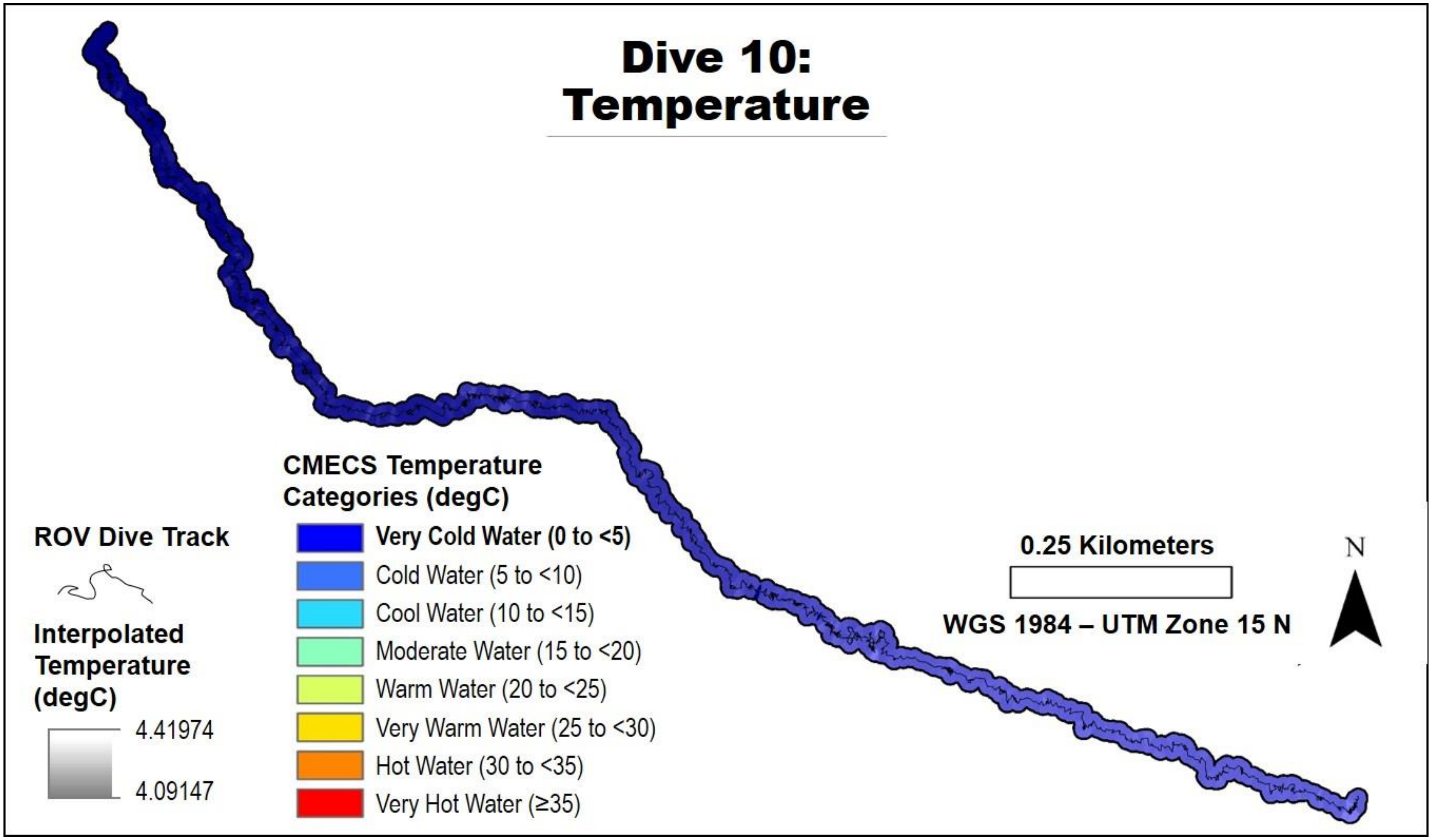

Figure C.29 Interpolated Temperature Gradient throughout Dive 10

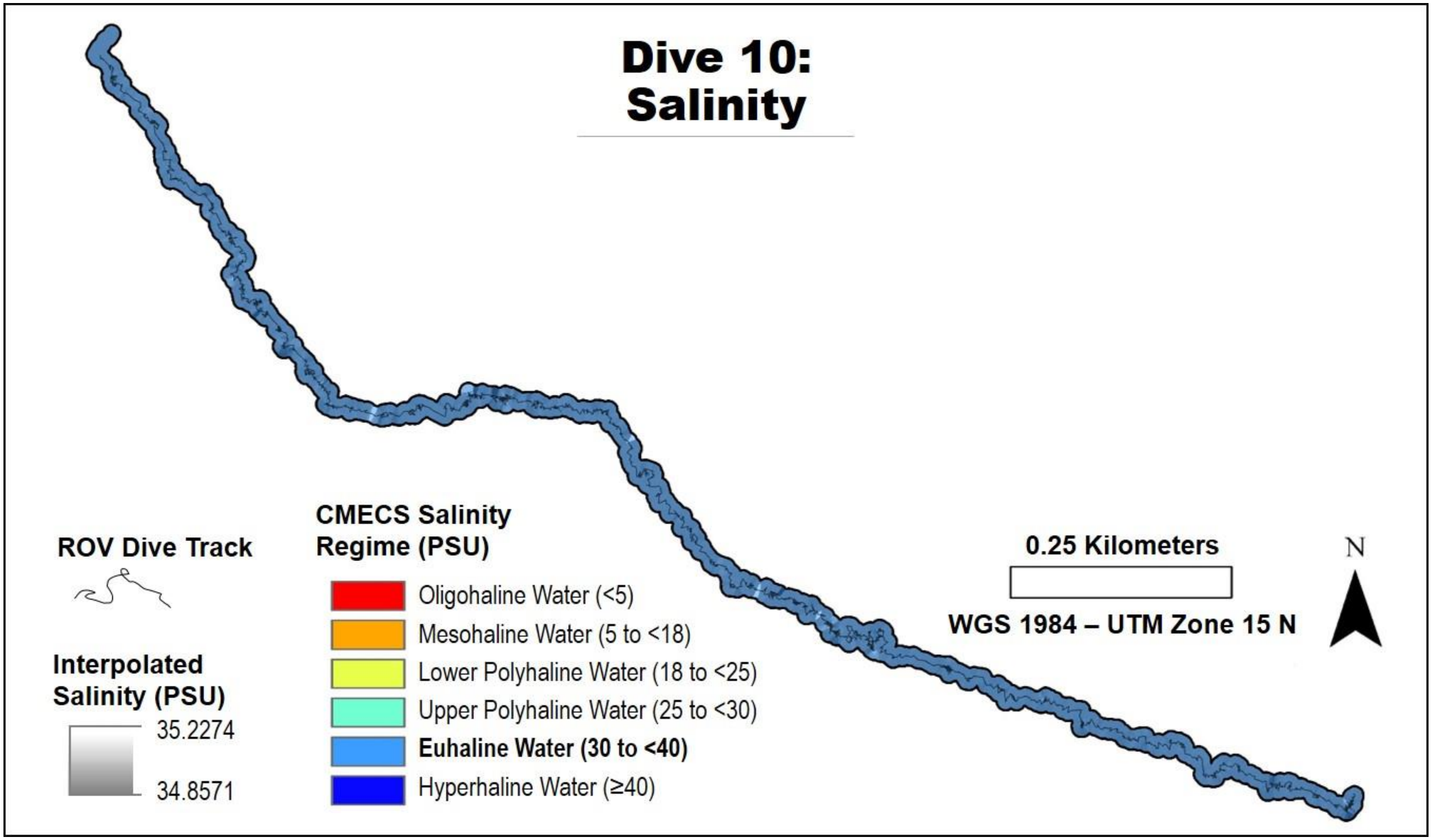

Figure C.30 Interpolated Salinity Concentration throughout Dive 10

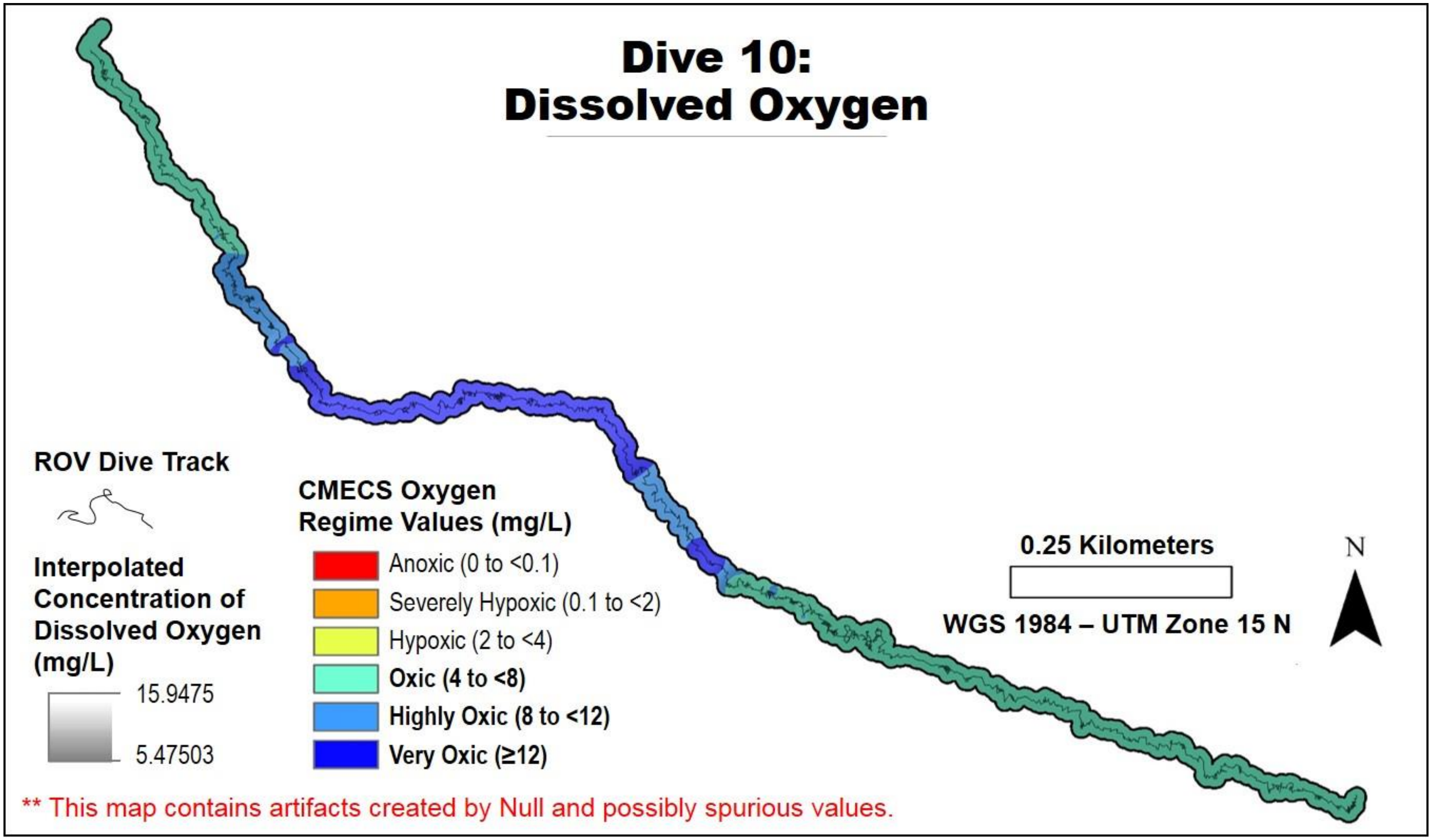

Figure C.31 Interpolated Dissolved Oxygen Concentration throughout Dive 10

This map contains artifacts created by Null and/or possibly spurious values.

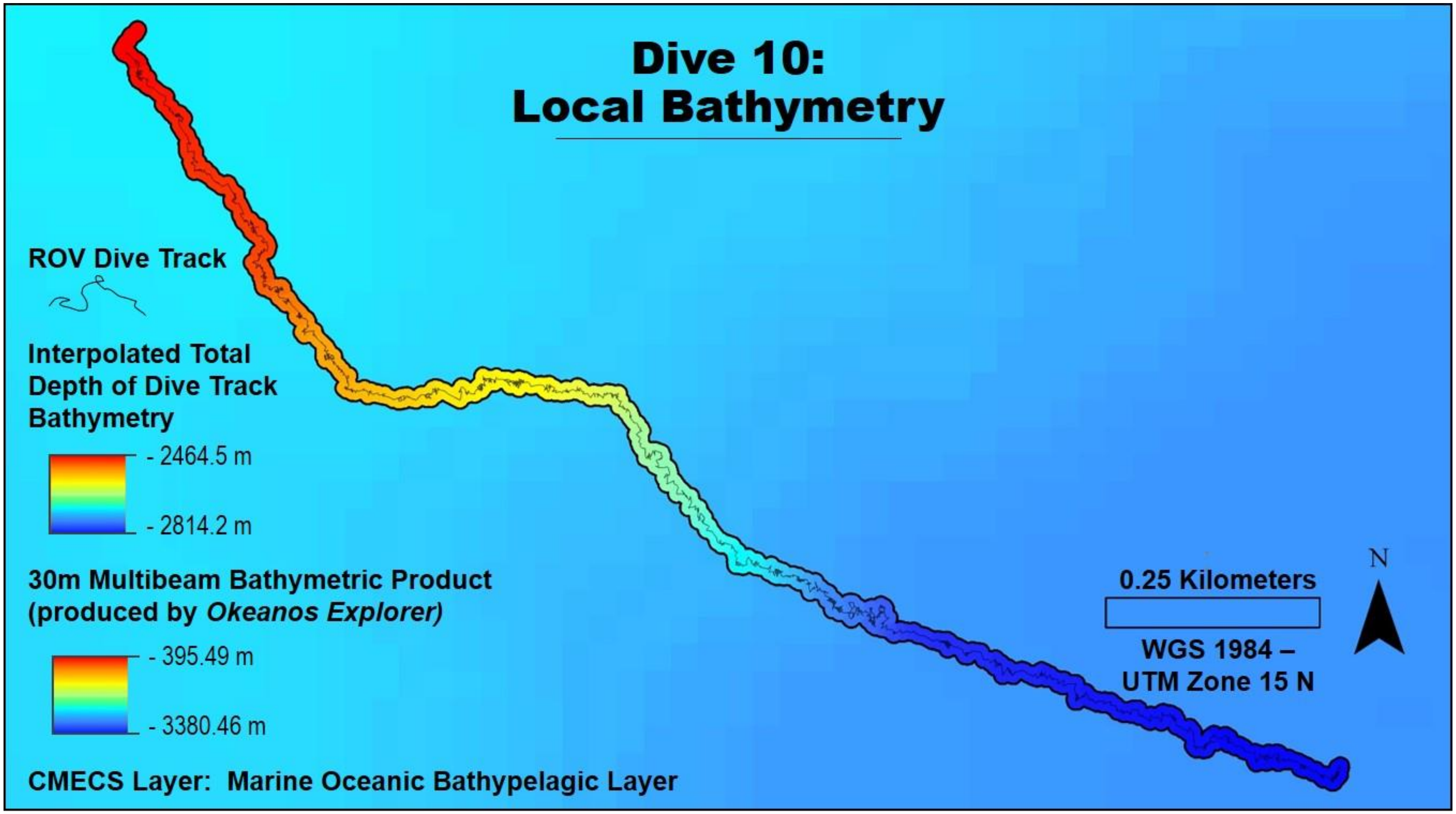

Figure C.32 Interpolated Total Depth of Seafloor throughout Dive 10

C.9 Dive 11

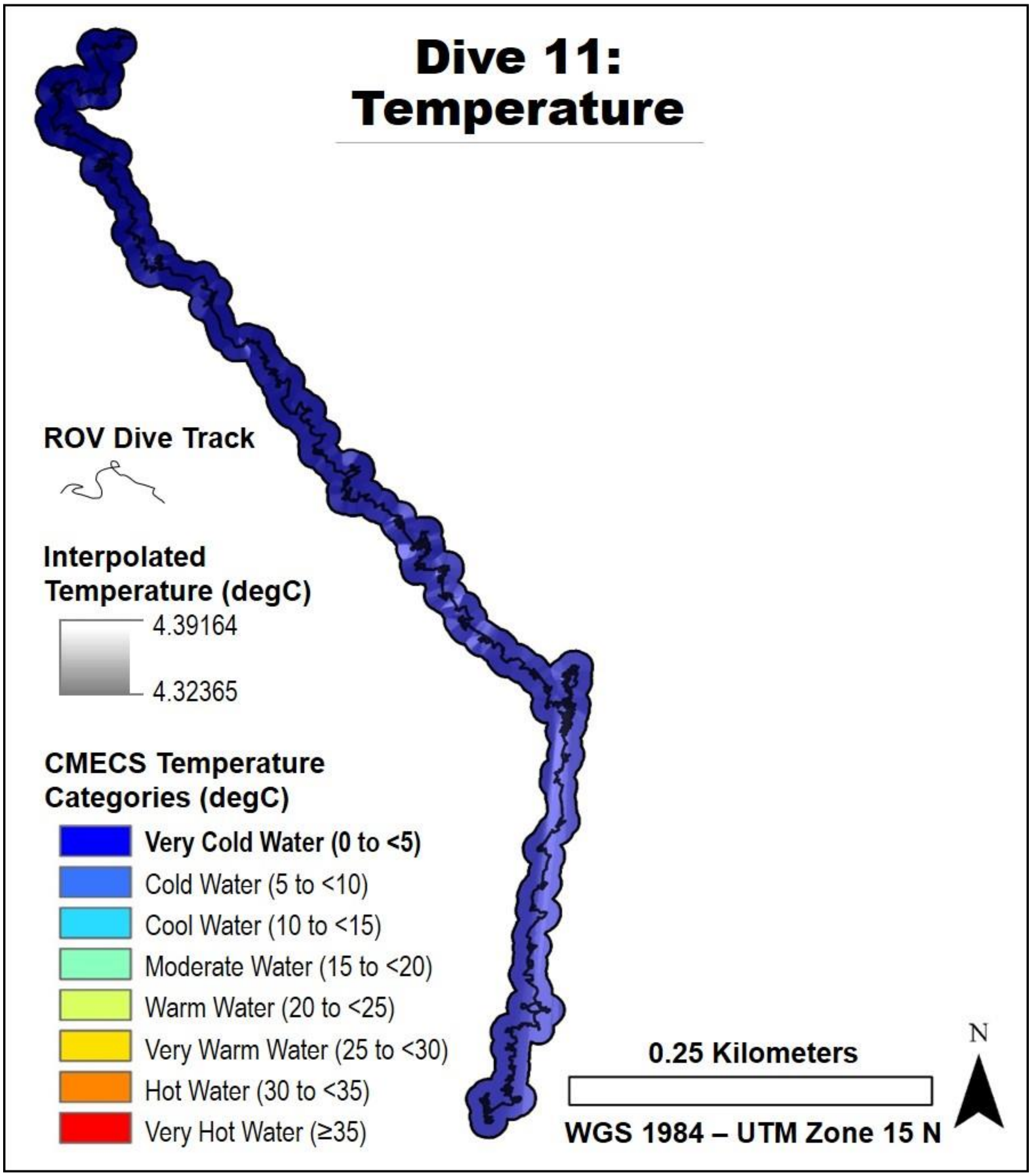

Figure C.33 Interpolated Temperature Gradient throughout Dive 11

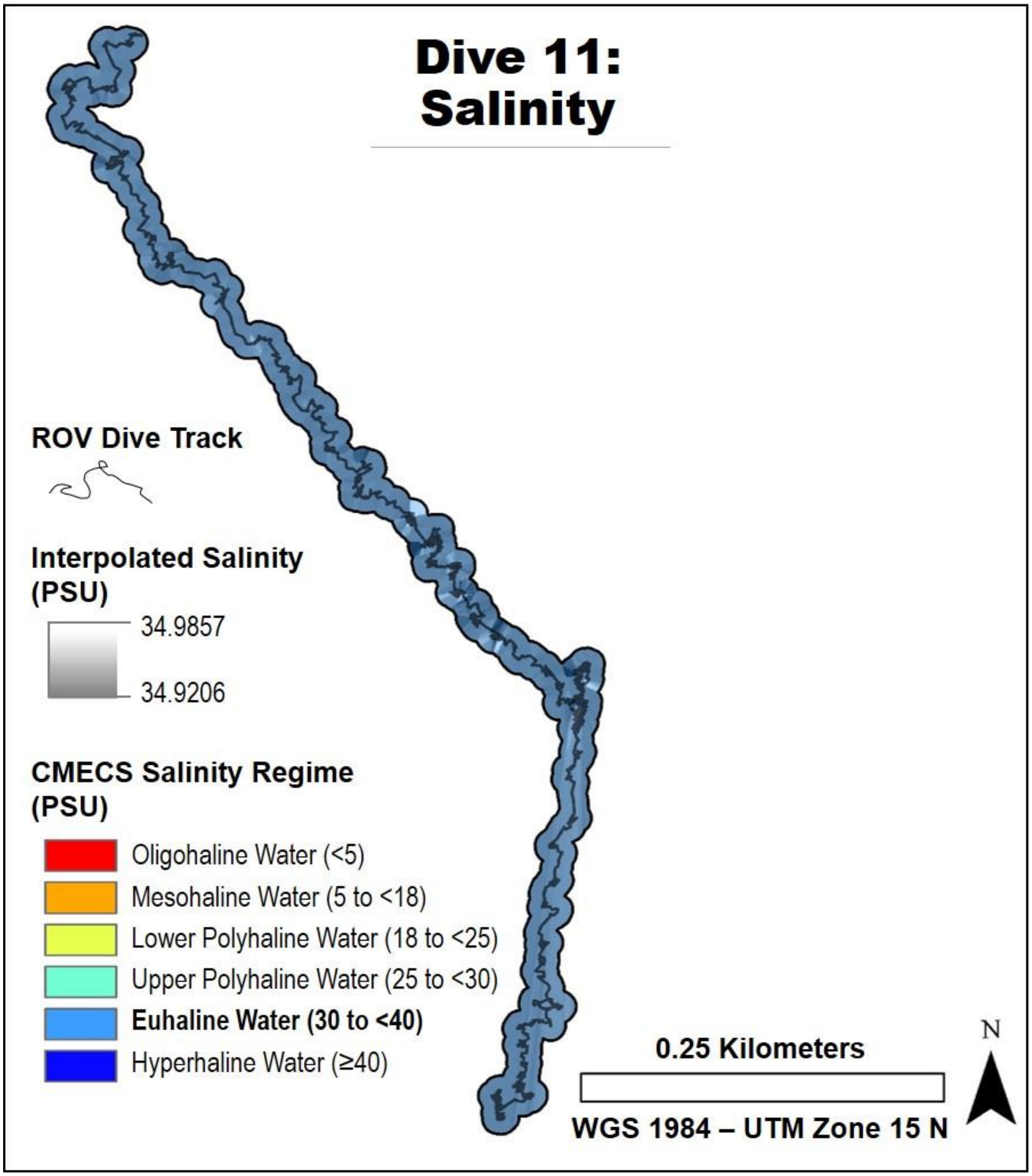

Figure C.34 Interpolated Salinity Concentration throughout Dive 11

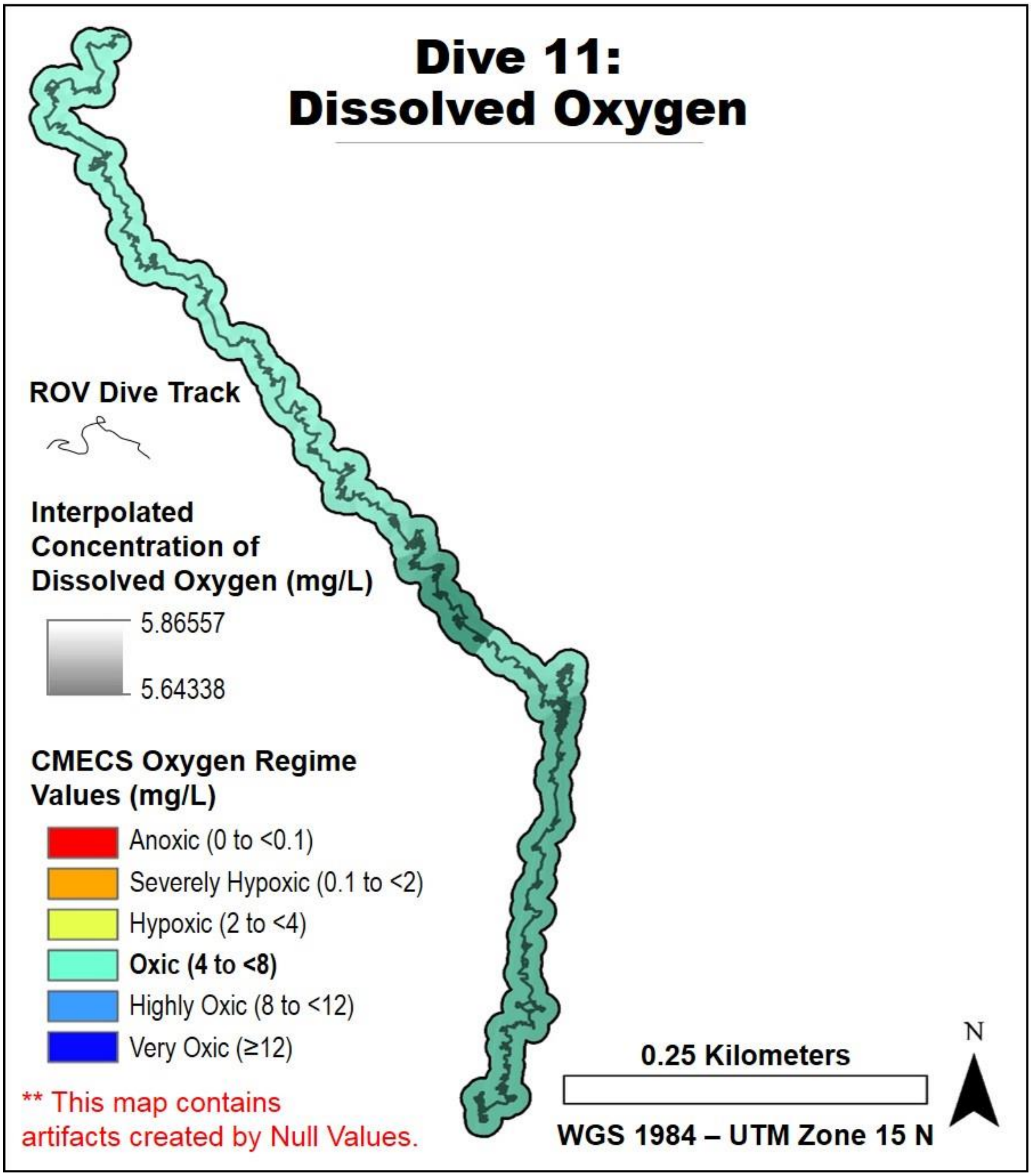

Figure C.35 Interpolated Dissolved Oxygen Concentration throughout Dive 11

This map contains artifacts created by Null and/or possibly spurious values.

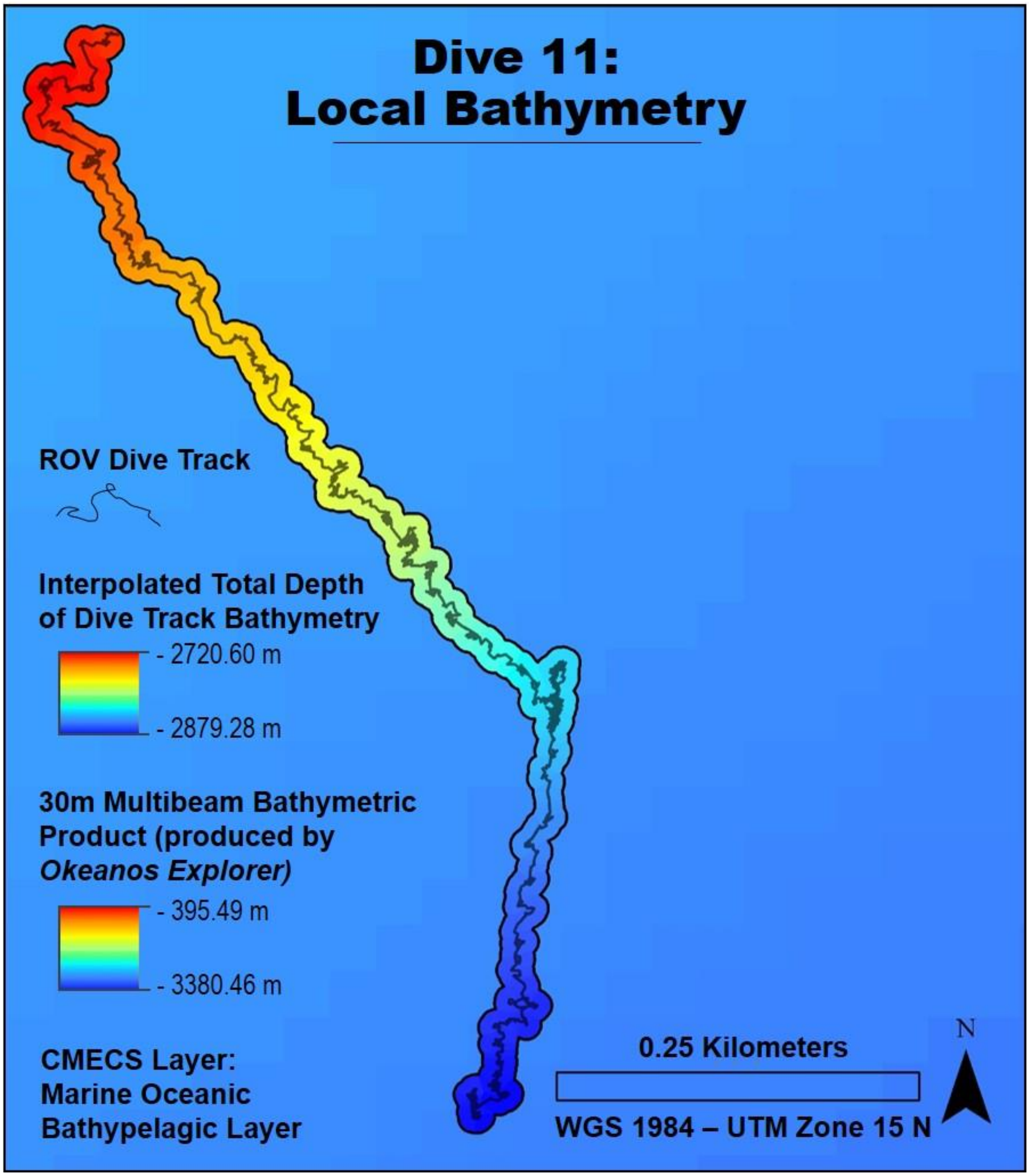

Figure C.36 Interpolated Total Depth of Seafloor throughout Dive 11

C.10 Dive 12

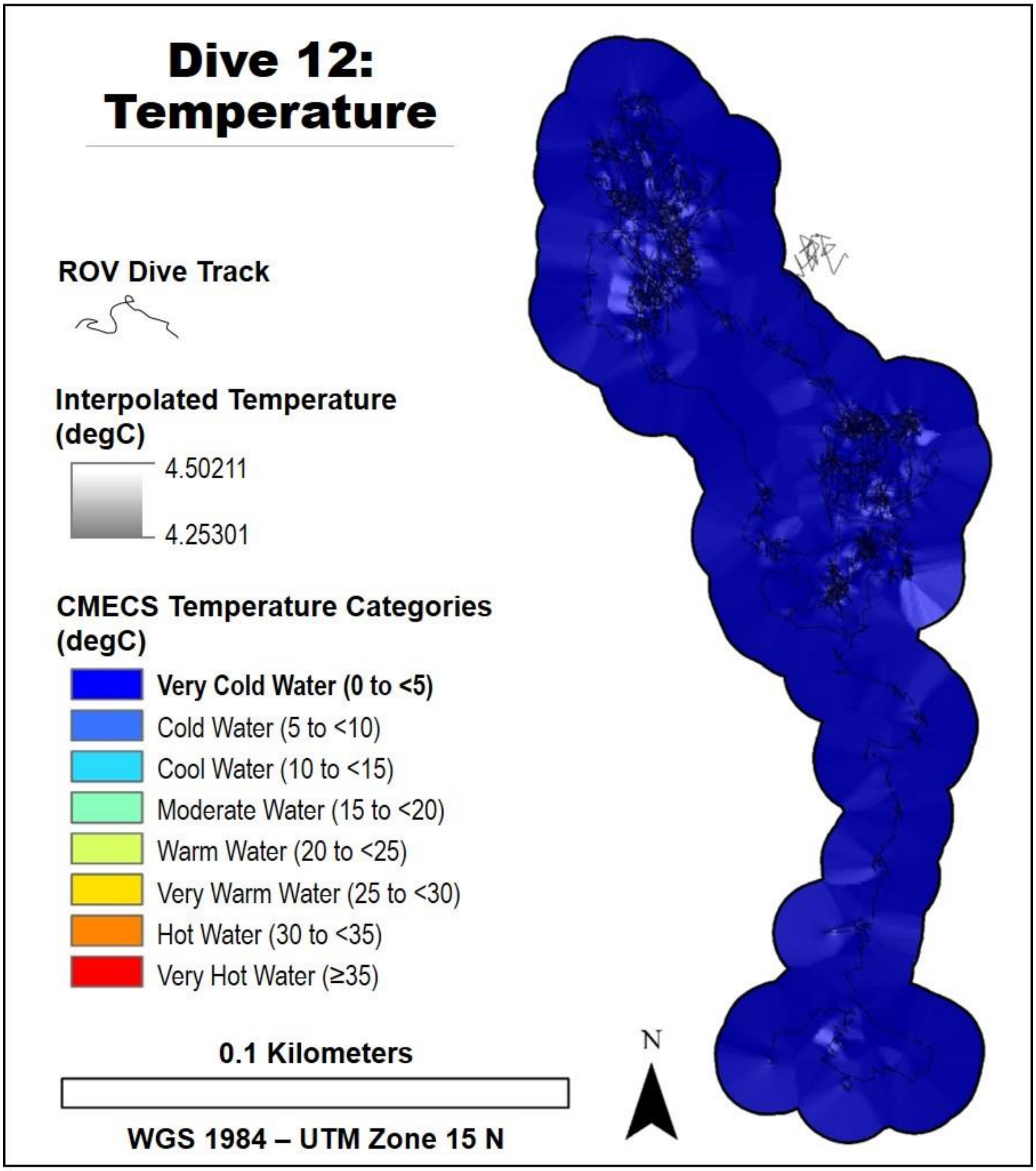

Figure C.37 Interpolated Temperature Gradient throughout Dive 12

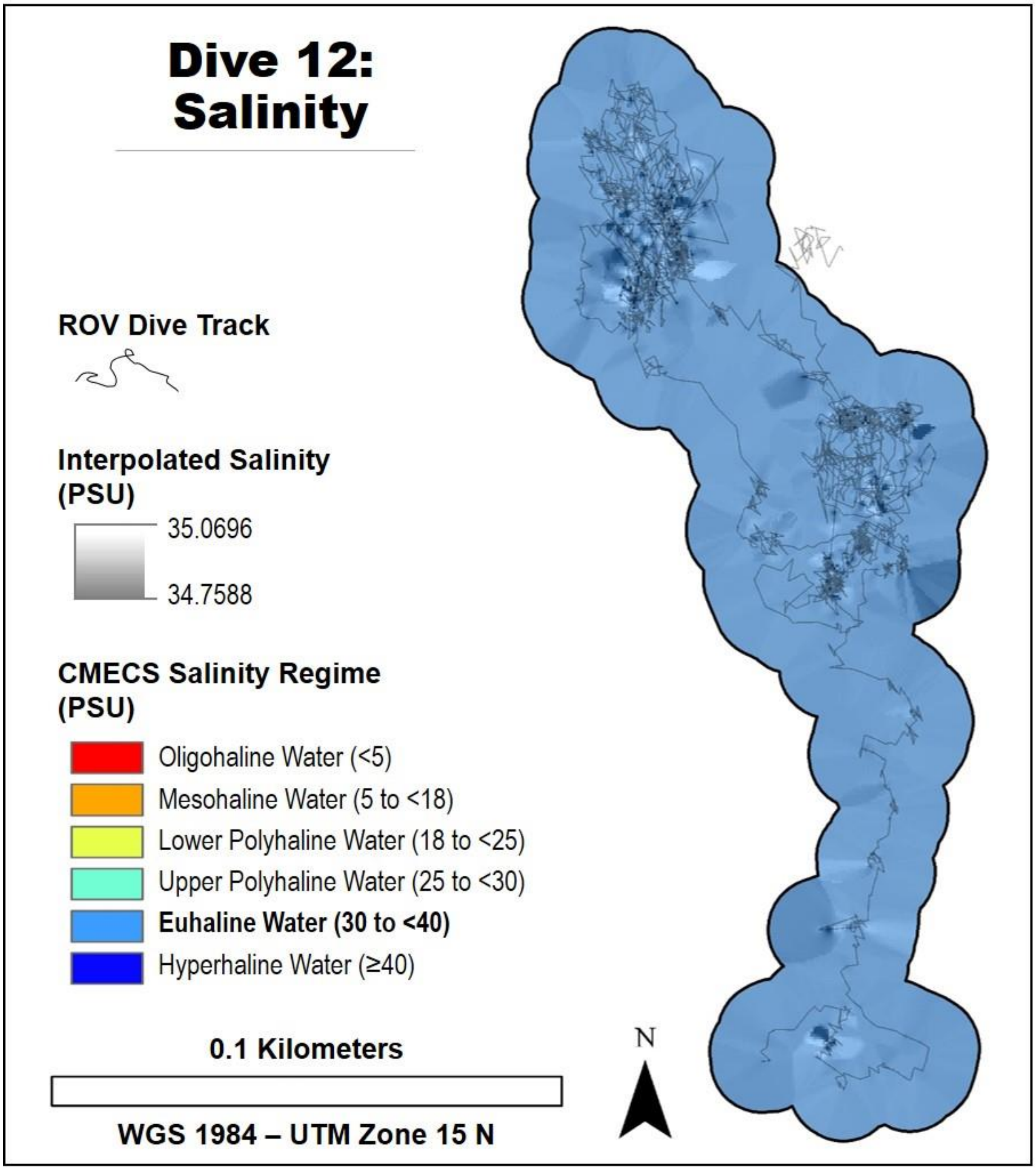

Figure C.38 Interpolated Salinity Concentration throughout Dive 12

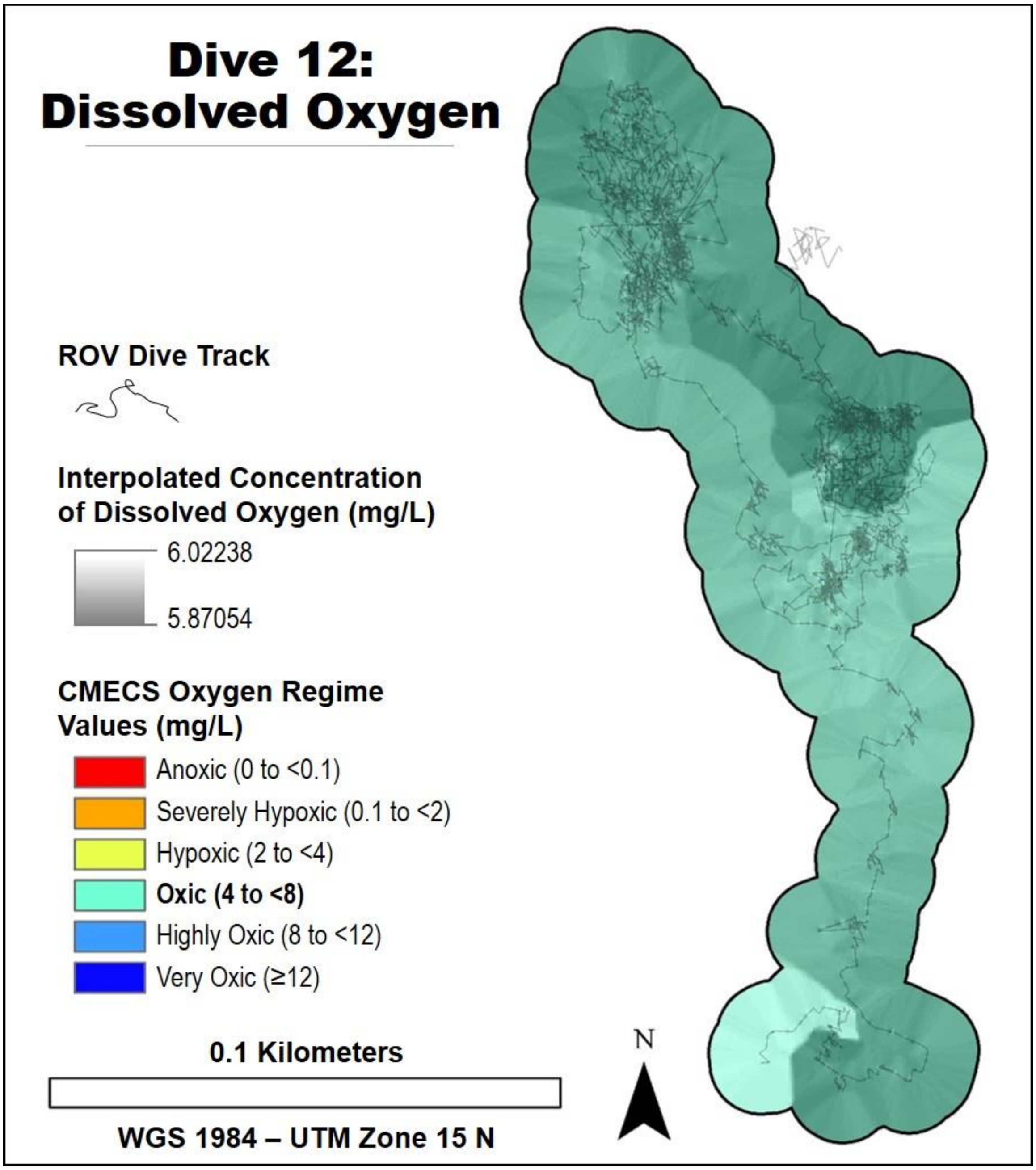

Figure C.39 Interpolated Dissolved Oxygen Concentration throughout Dive 12

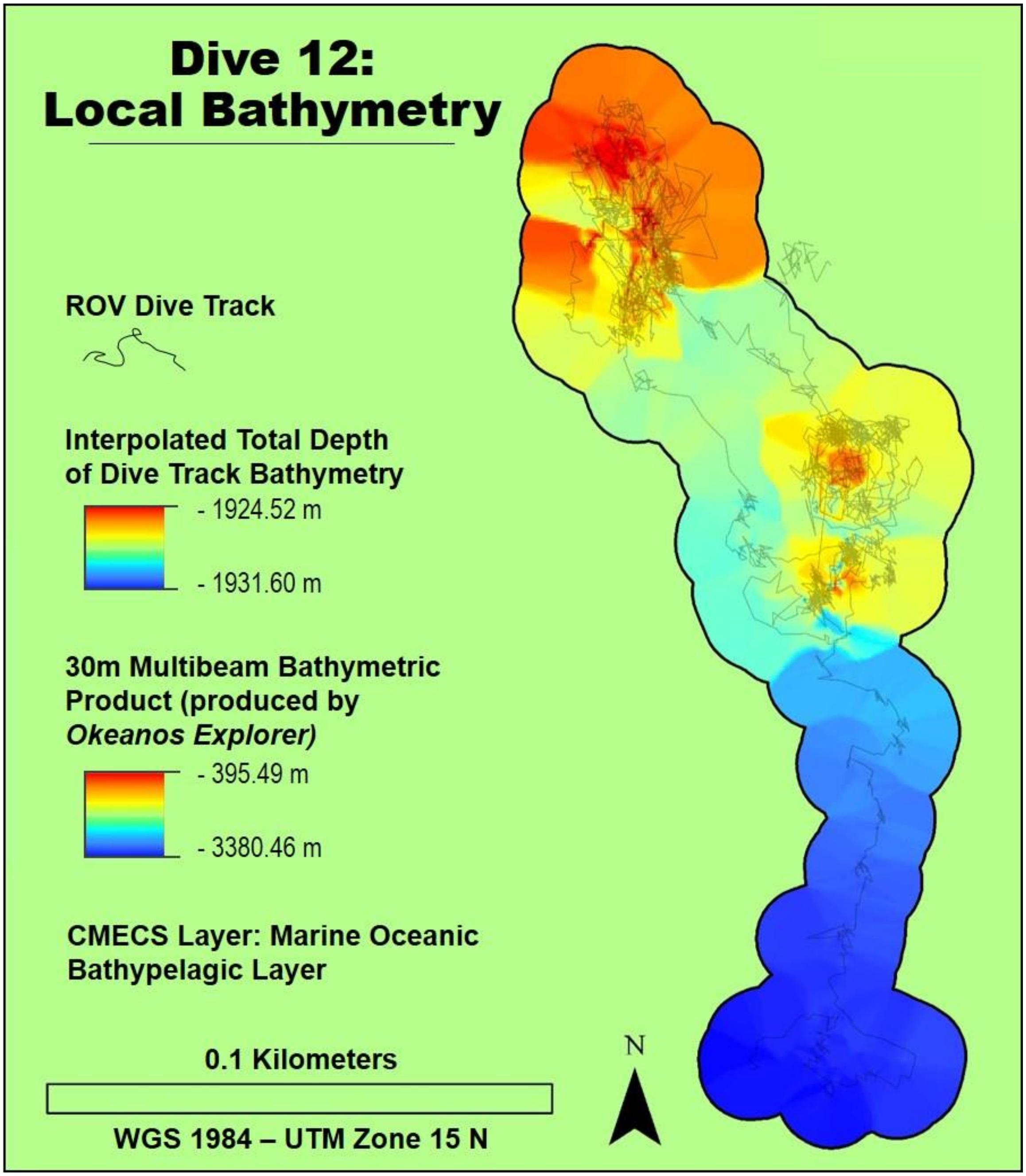

Figure C.40 Interpolated Total Depth of Seafloor throughout Dive 12

APPENDIX D

COMPARISONS OF CLASSIFIED HABITAT MAPS

D.1 Dive 01

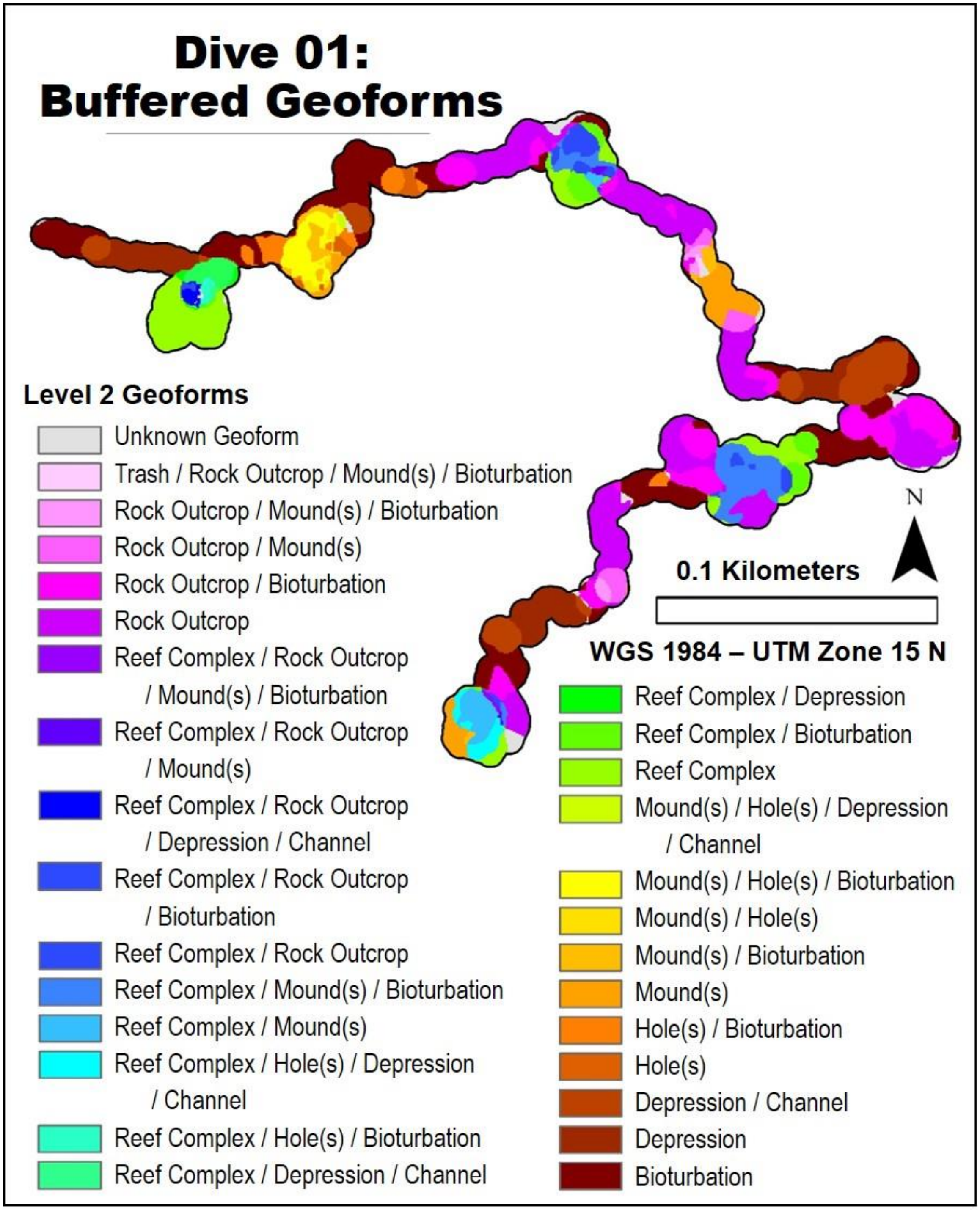

Figure D.1 Distribution of Level 2 Geoforms throughout Dive 01 using the Buffered Approach

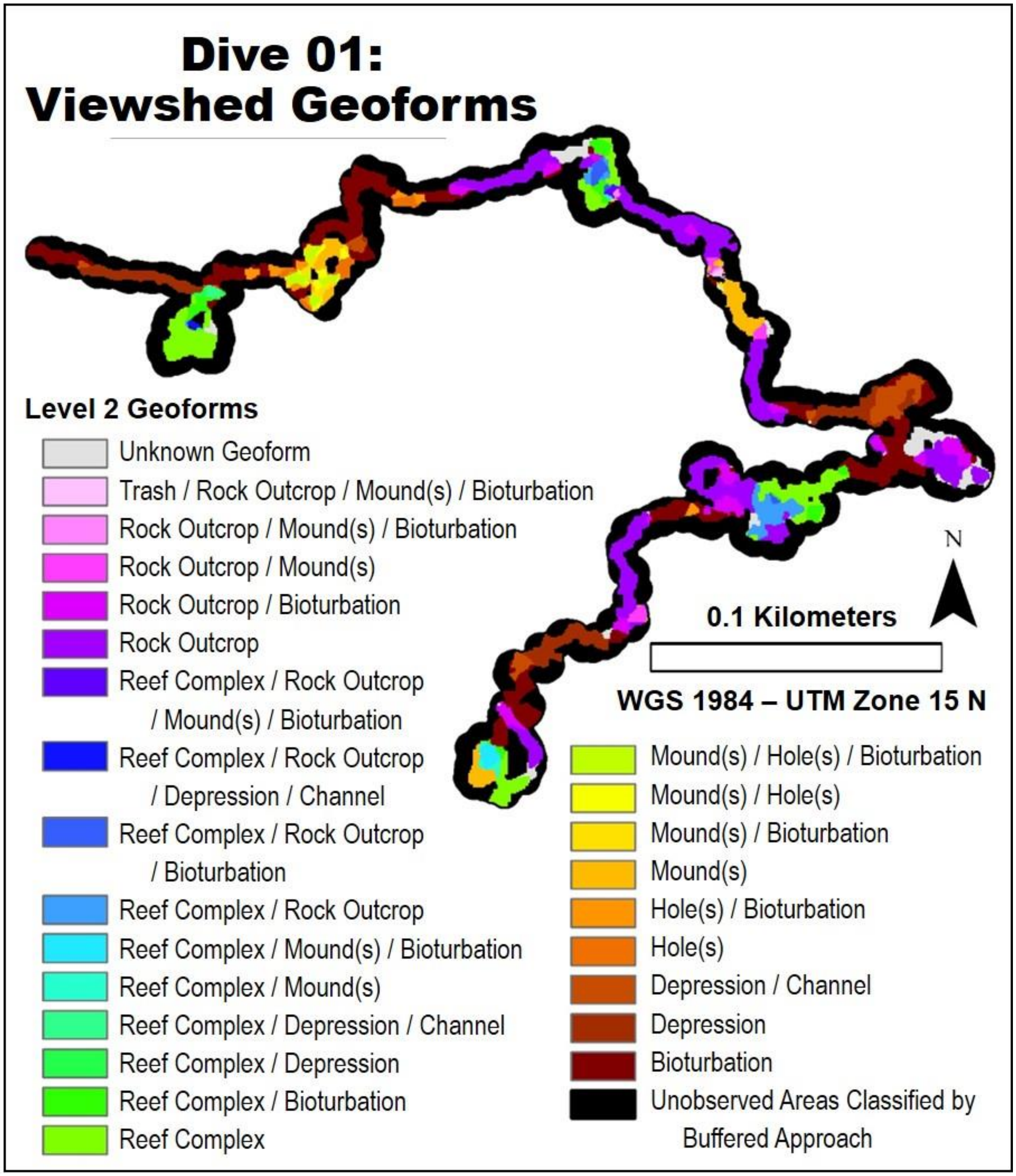

Figure D.2 Distribution of Level 2 Geoforms throughout Dive 01 using the Viewshed Approach

The viewshed approach eliminates three spurious classifications.

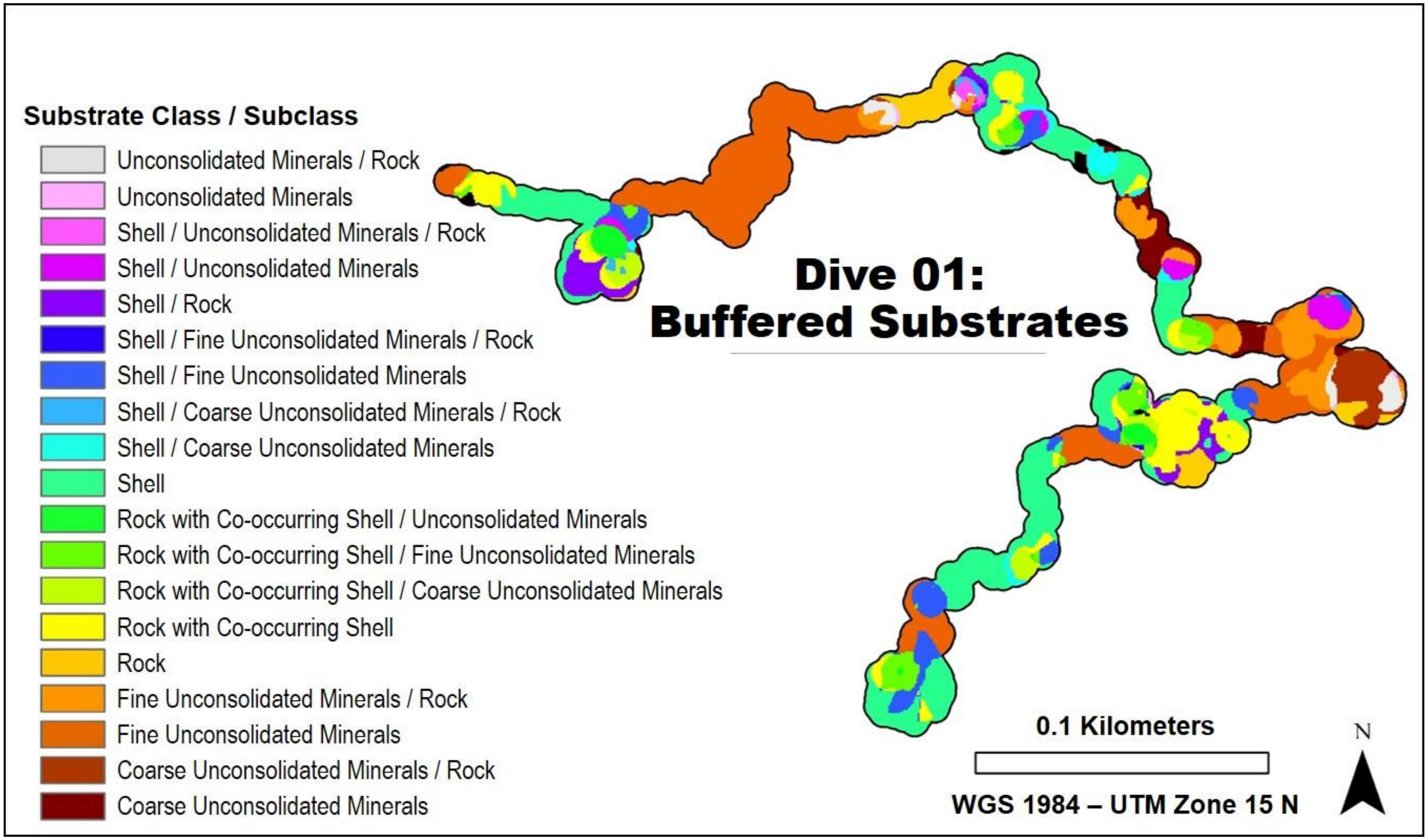

Figure D.3 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 01 using the Buffered Approach

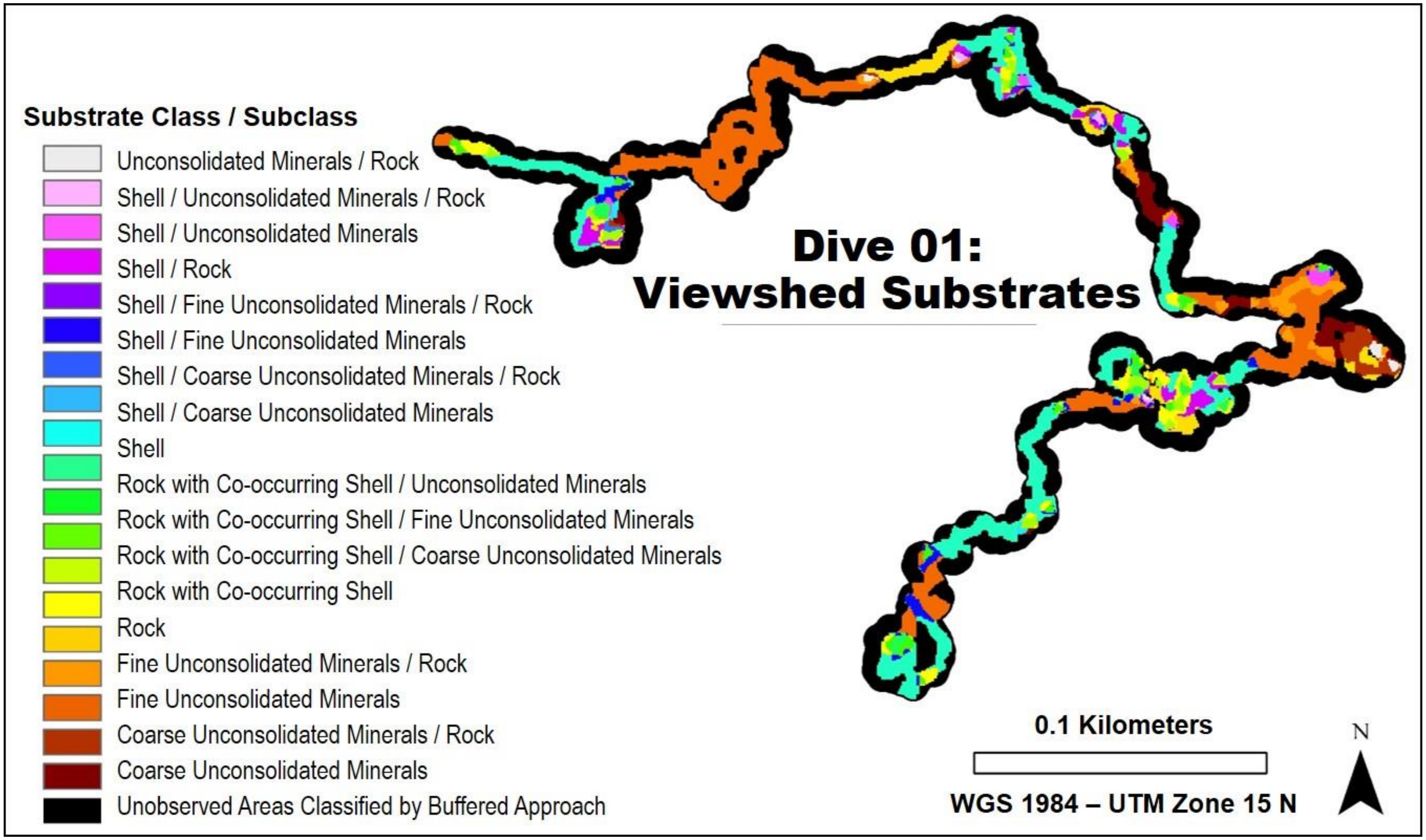

Figure D.4 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 01 using the Viewshed Approach

The viewshed approach eliminates one spurious classification.

D.2 Dive 02

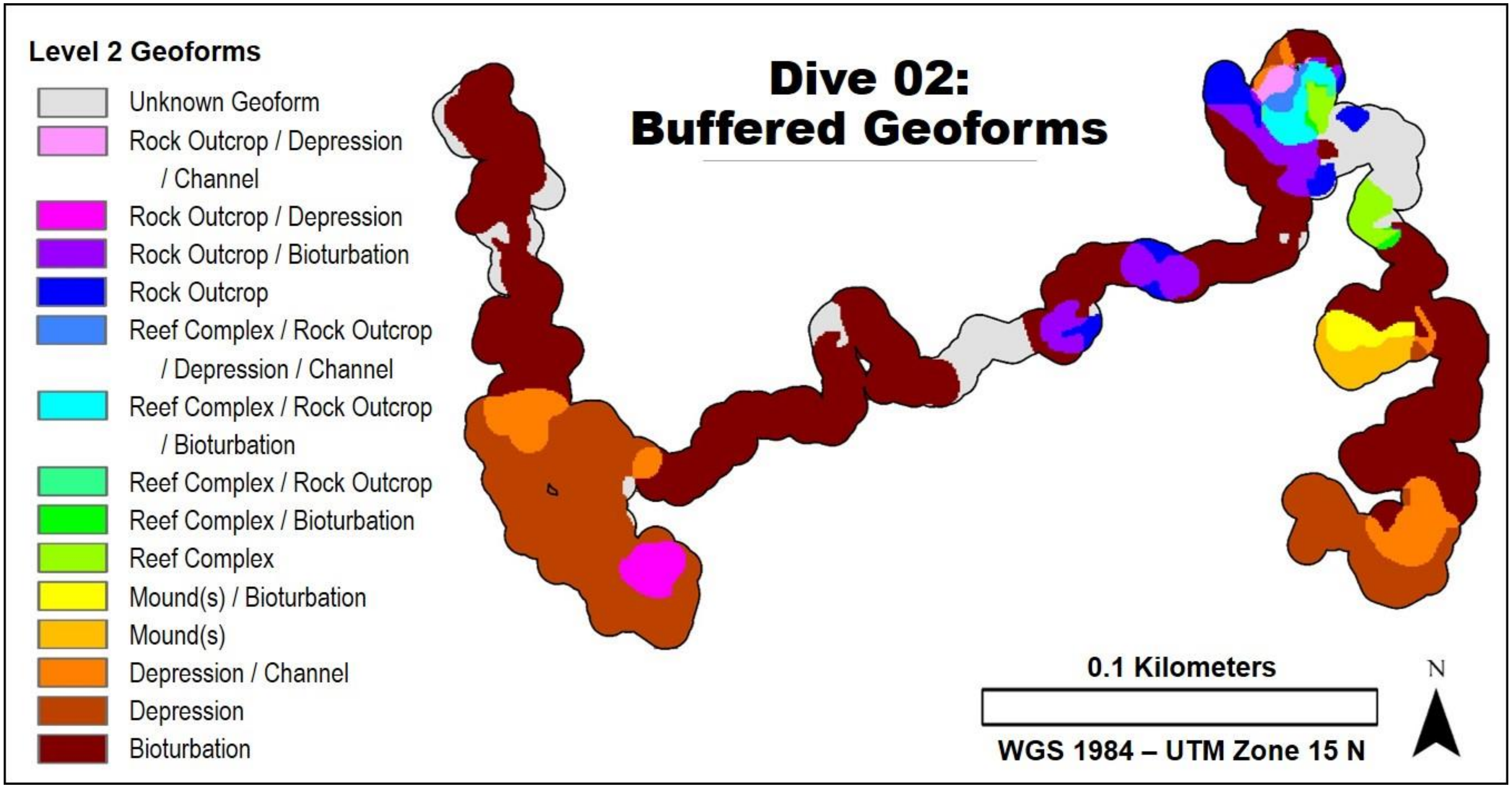

Figure D.5 Distribution of Level 2 Geoforms throughout Dive 02 using the Buffered Approach

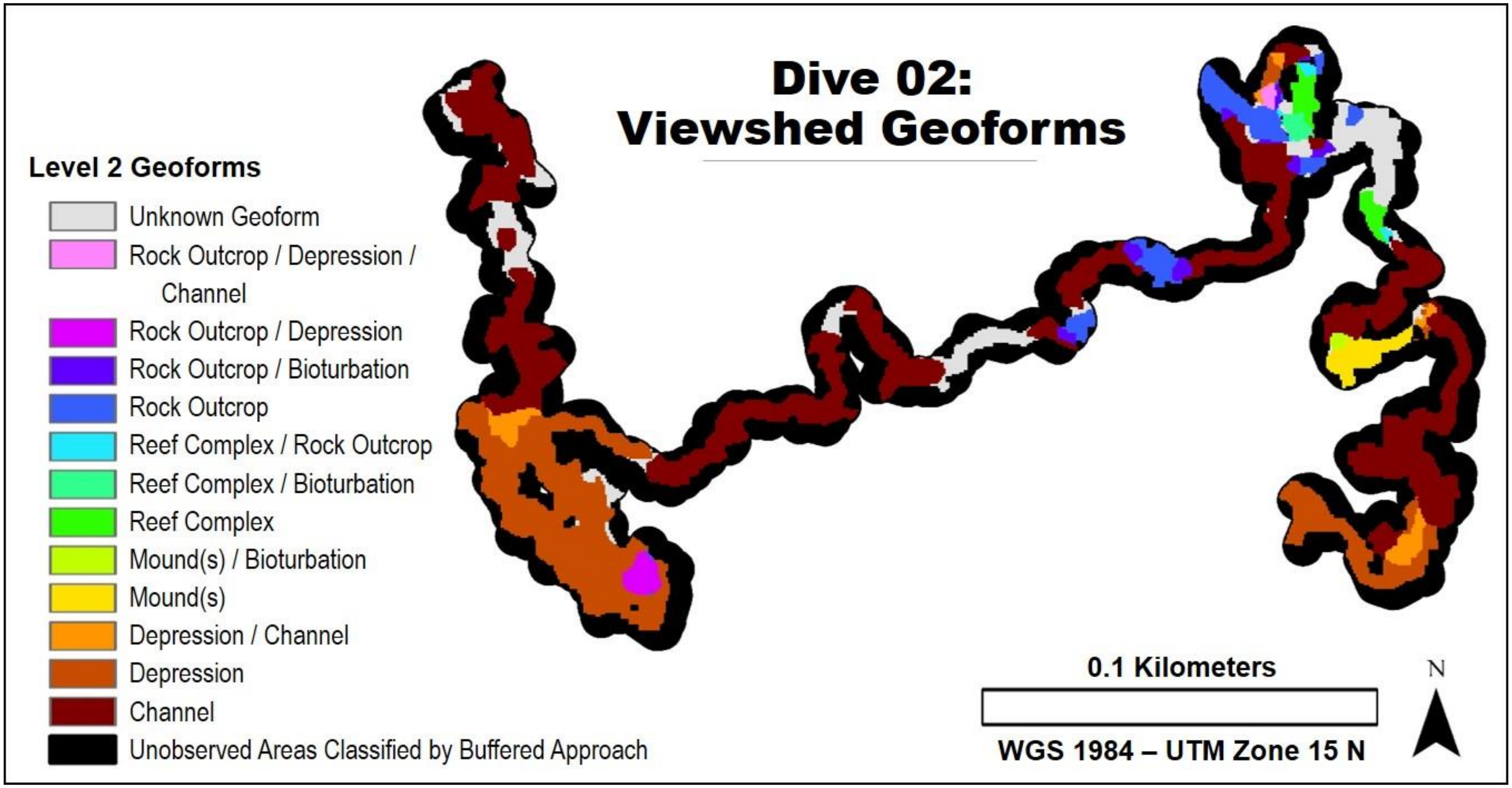

Figure D.6 Distribution of Level 2 Geoforms throughout Dive 02 using the Viewshed Approach

The viewshed approach eliminates two spurious classifications.

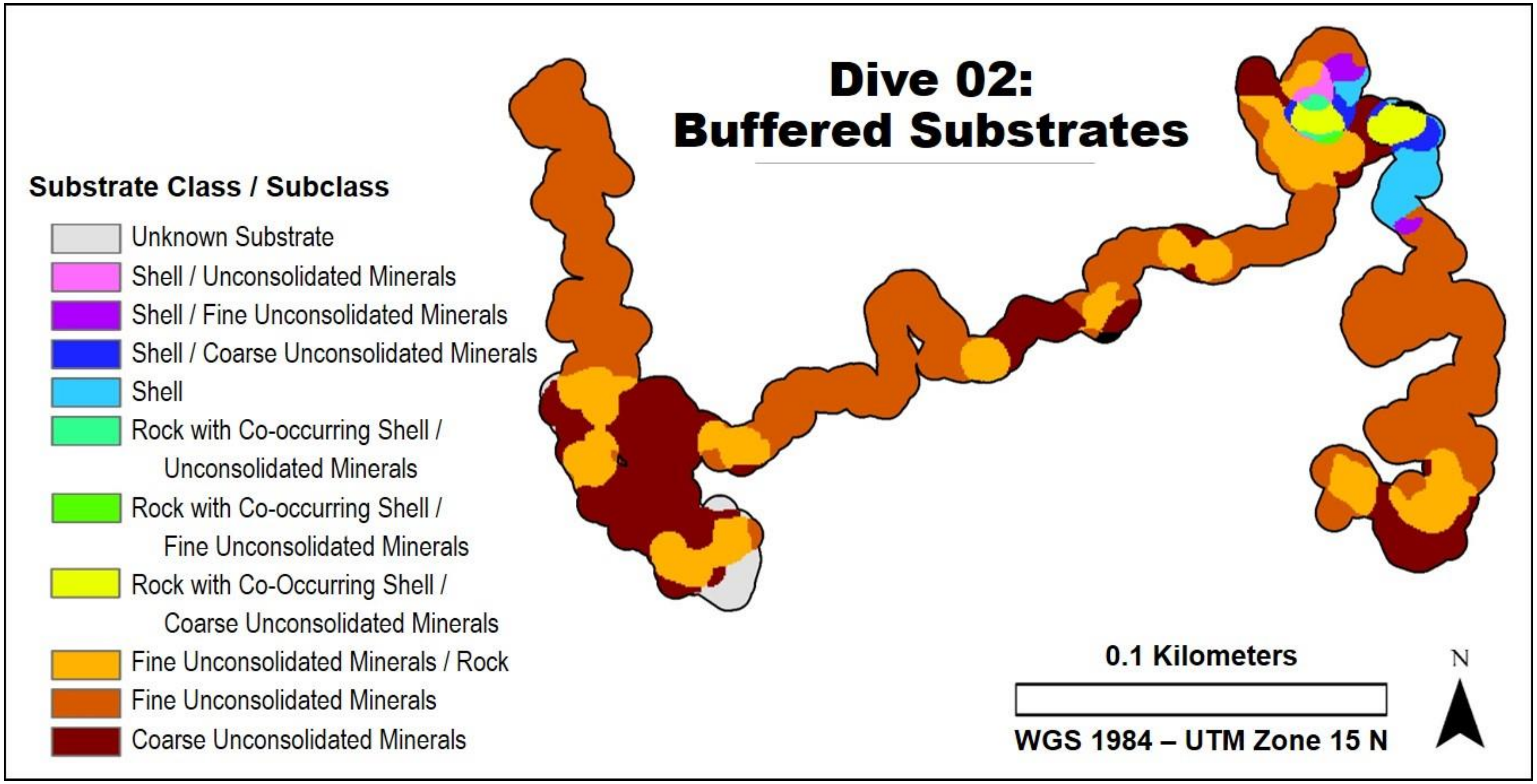

Figure D.7 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 02 using the Buffered Approach

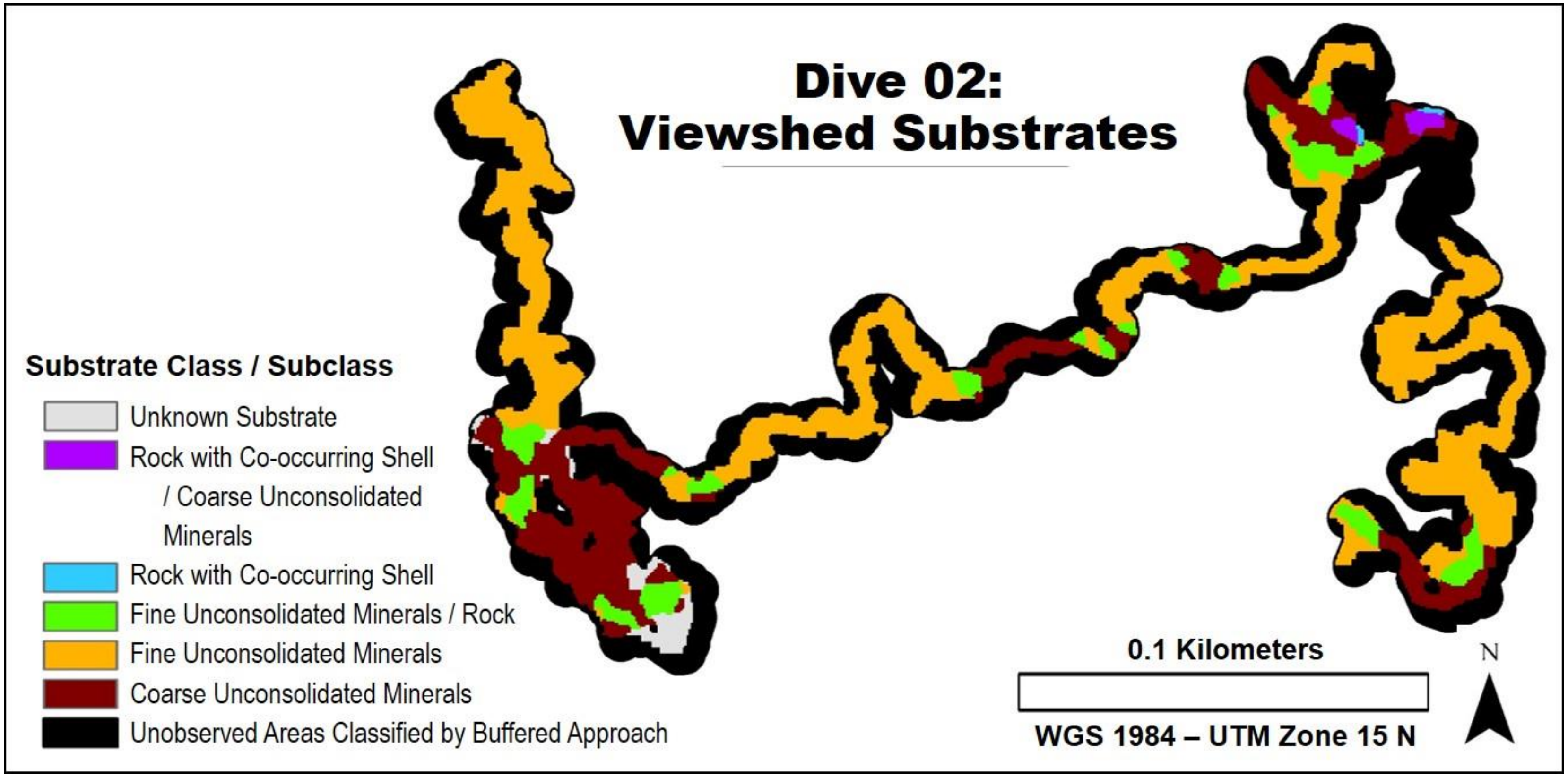

Figure D.8 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 02 using the Viewshed Approach

The viewshed approach eliminates three spurious classifications.

D.3 Dive 03

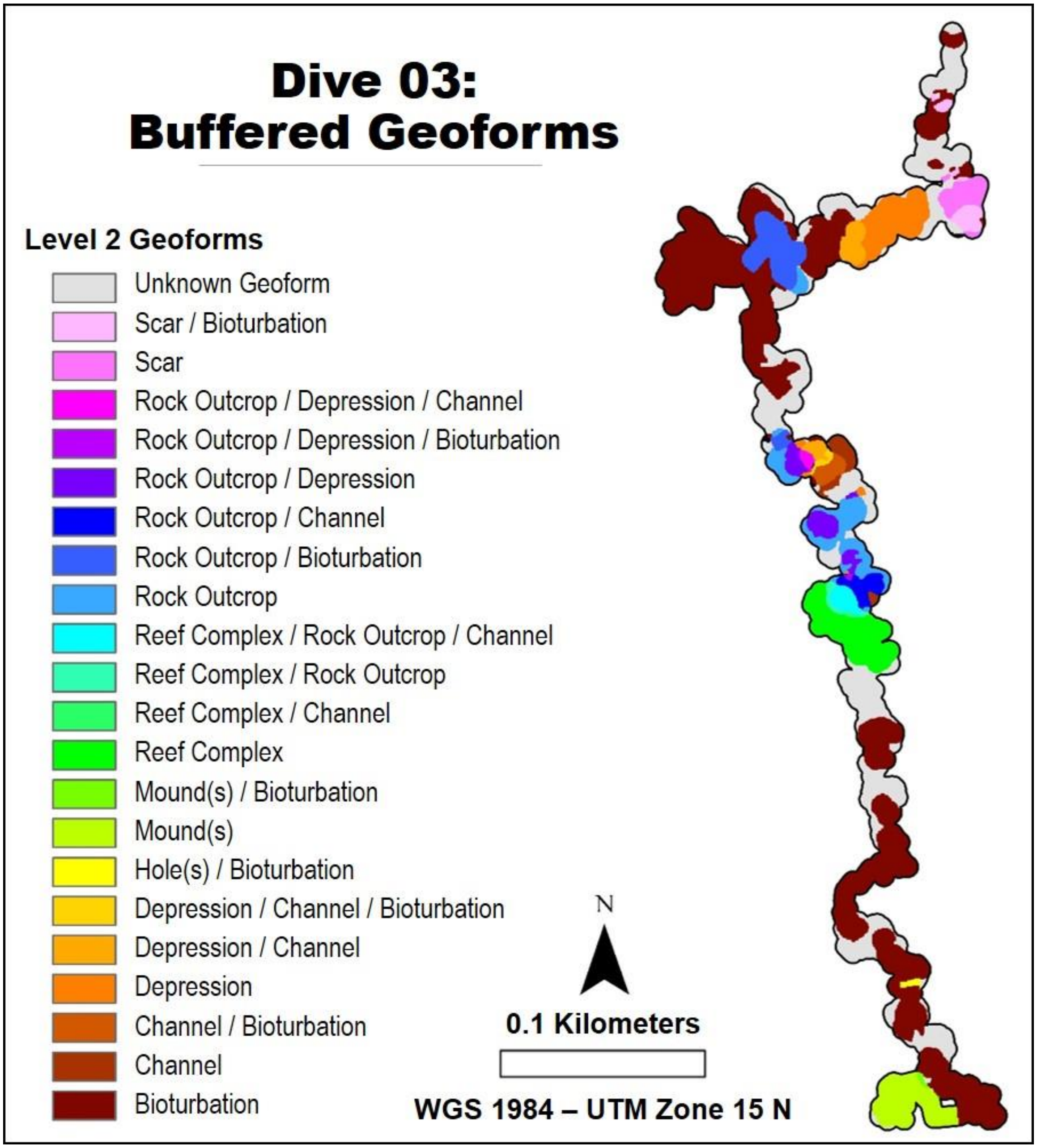

Figure D.9 Distribution of Level 2 Geoforms throughout Dive 03 using the Buffered Approach

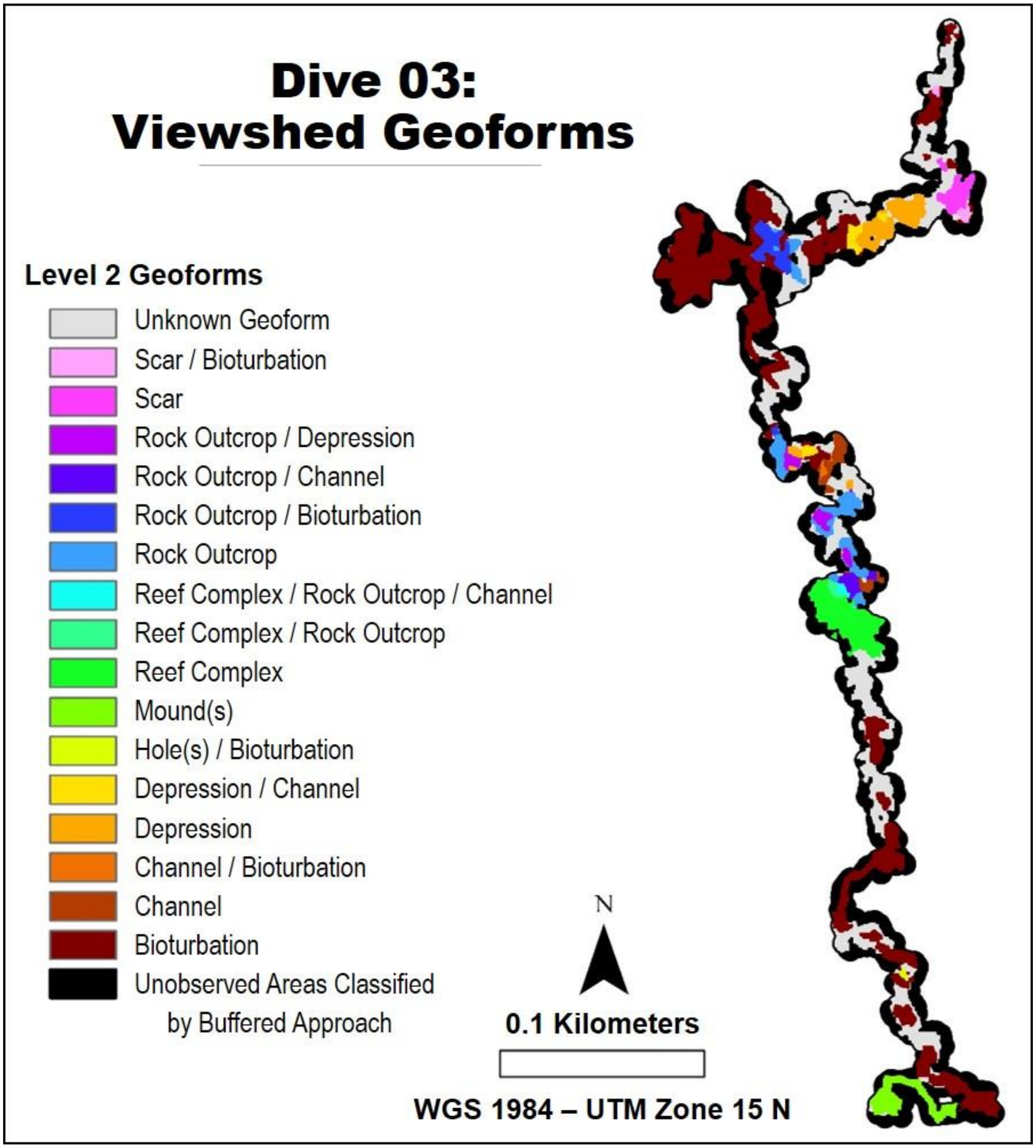

Figure D.10 Distribution of Level 2 Geoforms throughout Dive 03 using the Viewshed Approach

The viewshed approach eliminates five spurious classifications.

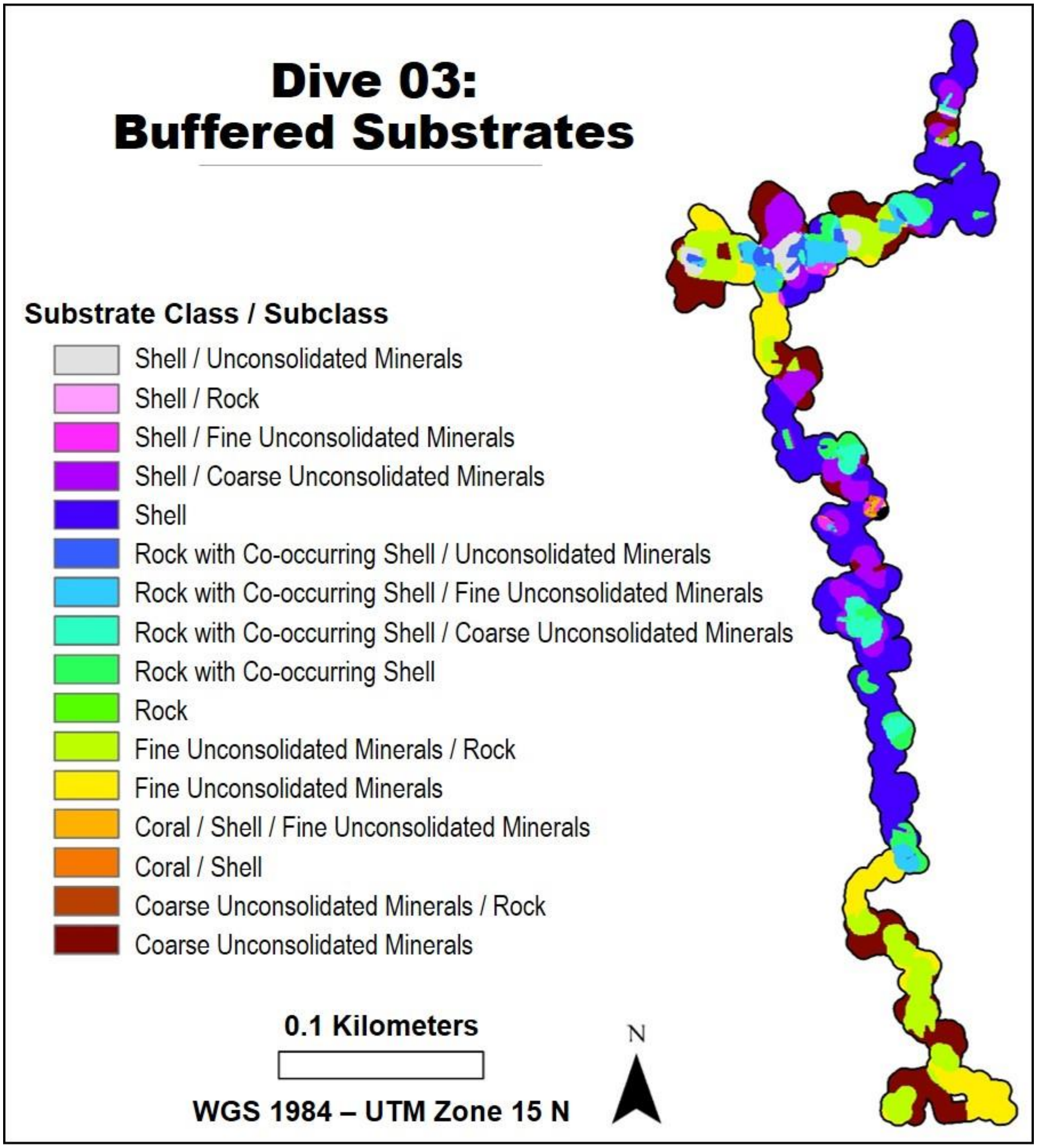

Figure D.11 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 03 using the Buffered Approach

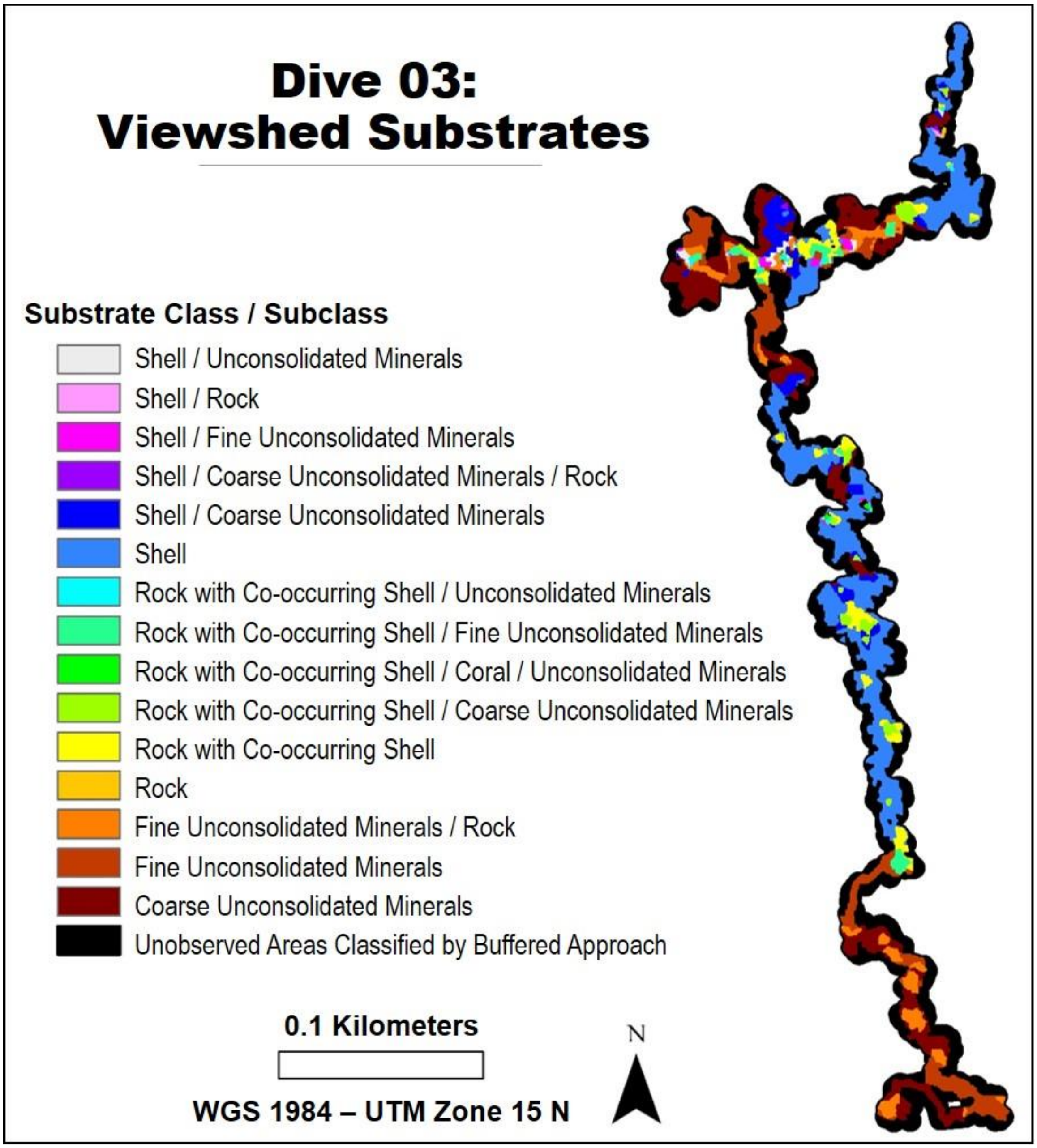

Figure D.12 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 03 using the Viewshed Approach

The viewshed approach eliminates one spurious classification.

D.4 Dive 04

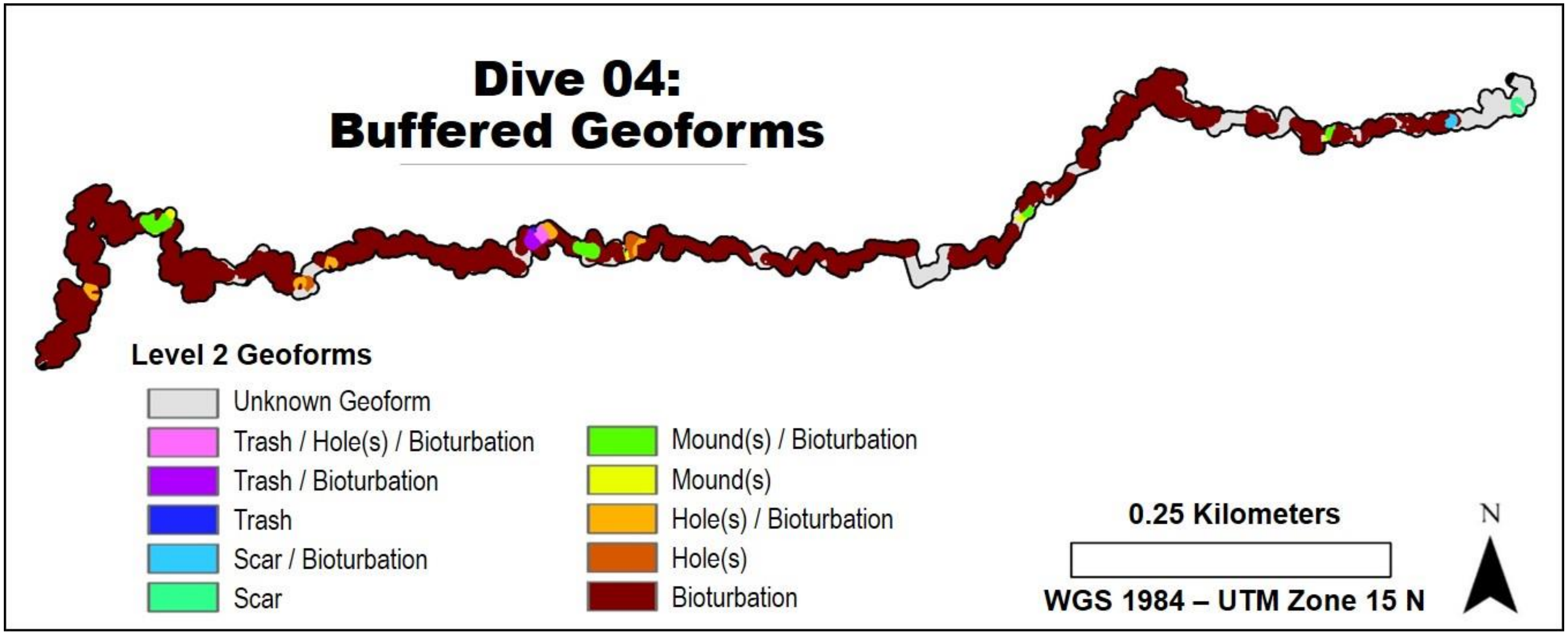

Figure D.13 Distribution of Level 2 Geoforms throughout Dive 04 using the Buffered Approach

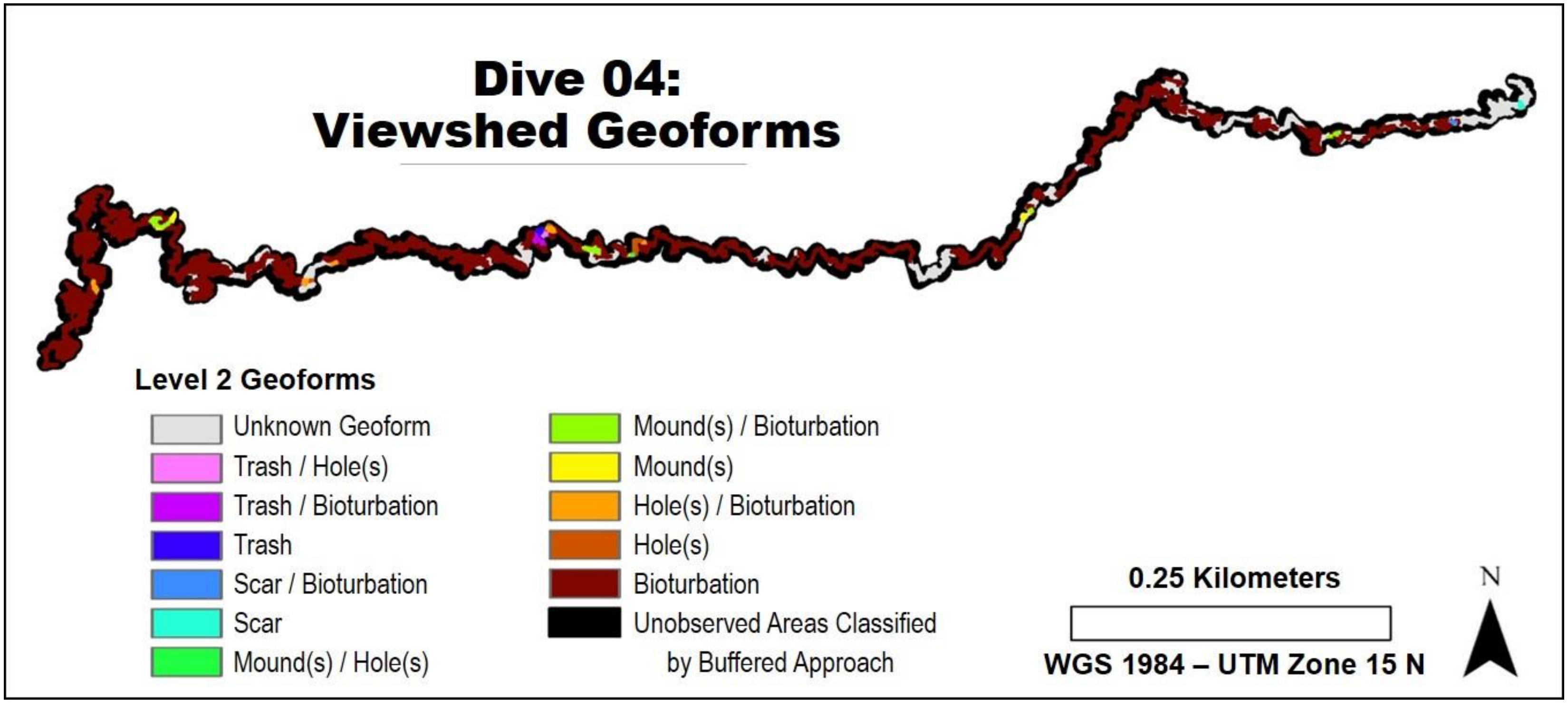

Figure D.14 Distribution of Level 2 Geoforms throughout Dive 04 using the Viewshed Approach

The viewshed approach adds one classification.

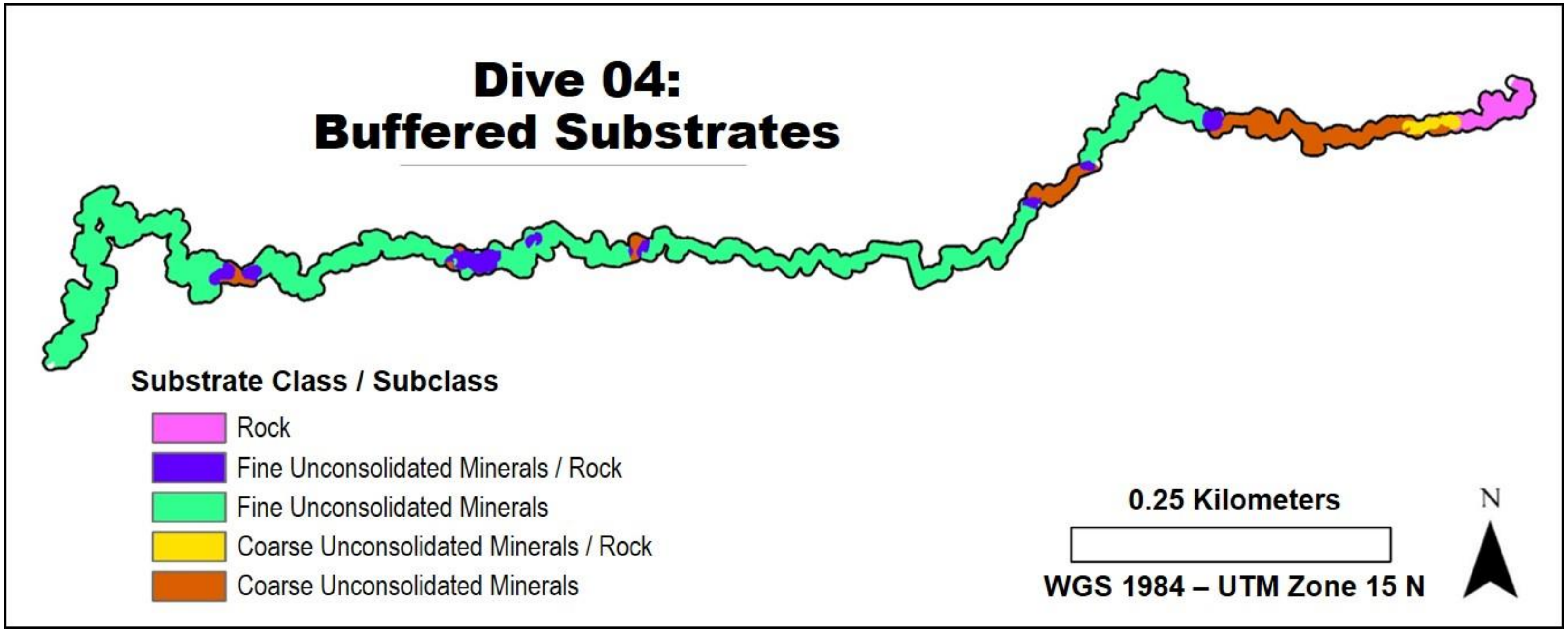

Figure D.15 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 04 using the Buffered Approach

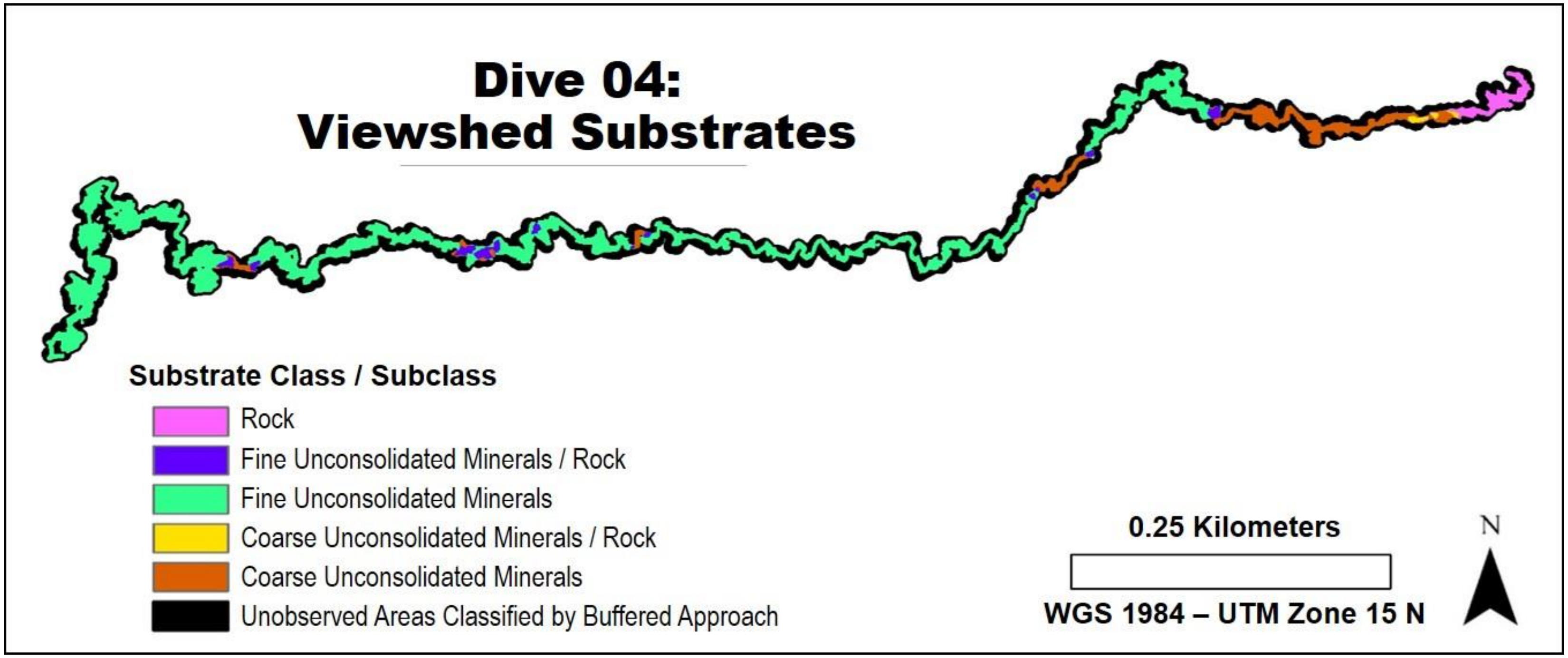

Figure D.16 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 04 using the Viewshed Approach

The number of classifications remained the same for both approaches.

D.5 Dive 06

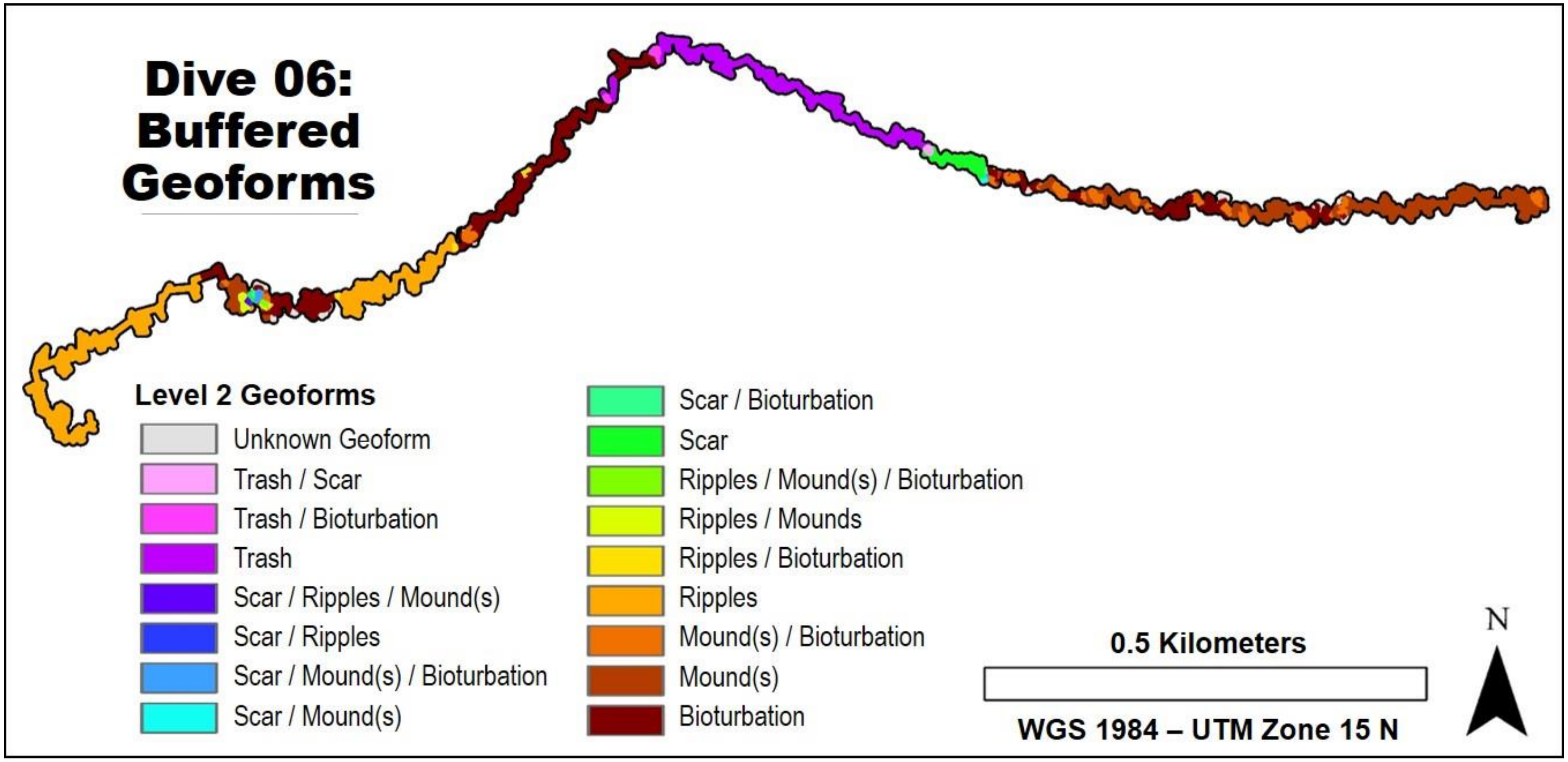

Figure D.17 Distribution of Level 2 Geoforms throughout Dive 06 using the Buffered Approach

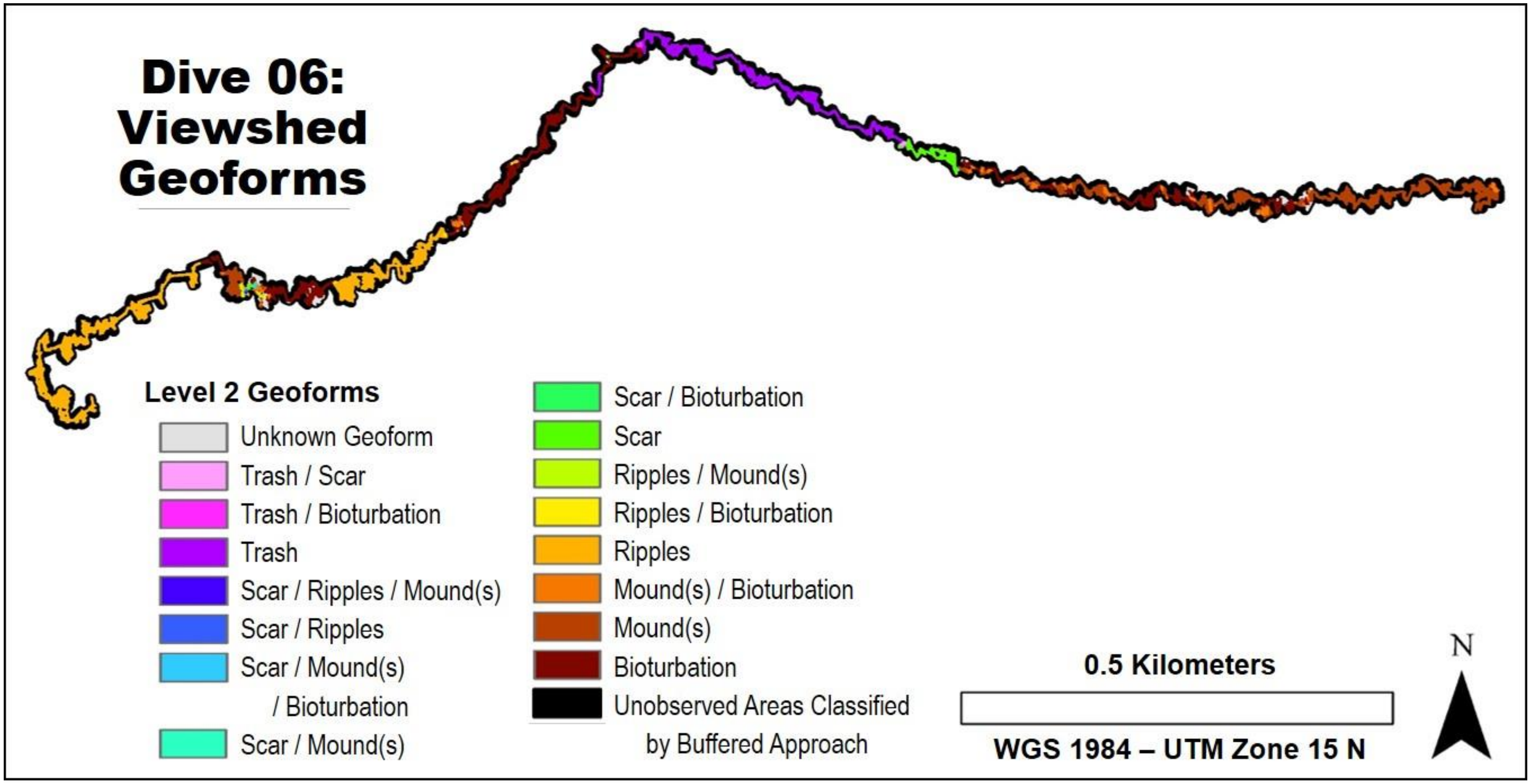

Figure D.18 Distribution of Level 2 Geoforms throughout Dive 06 using the Viewshed Approach

The viewshed approach eliminates one spurious classification.

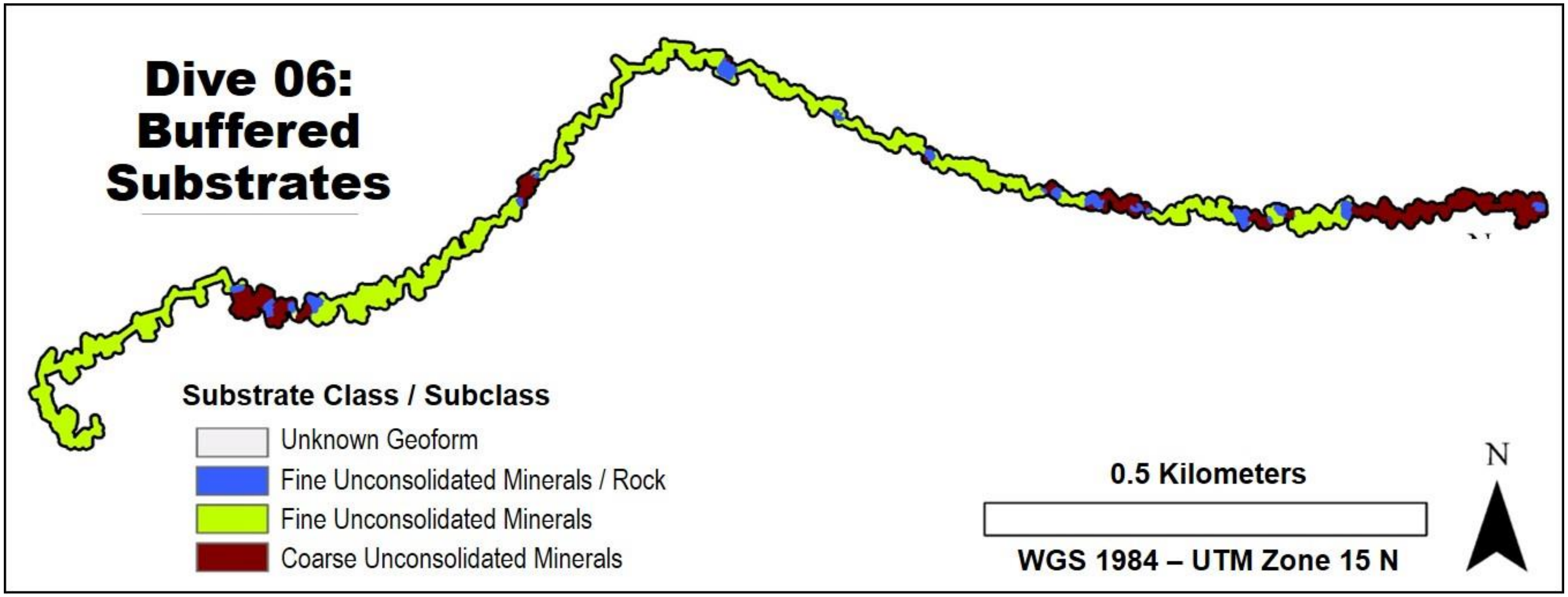

Figure D.19 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 06 using the Buffered Approach

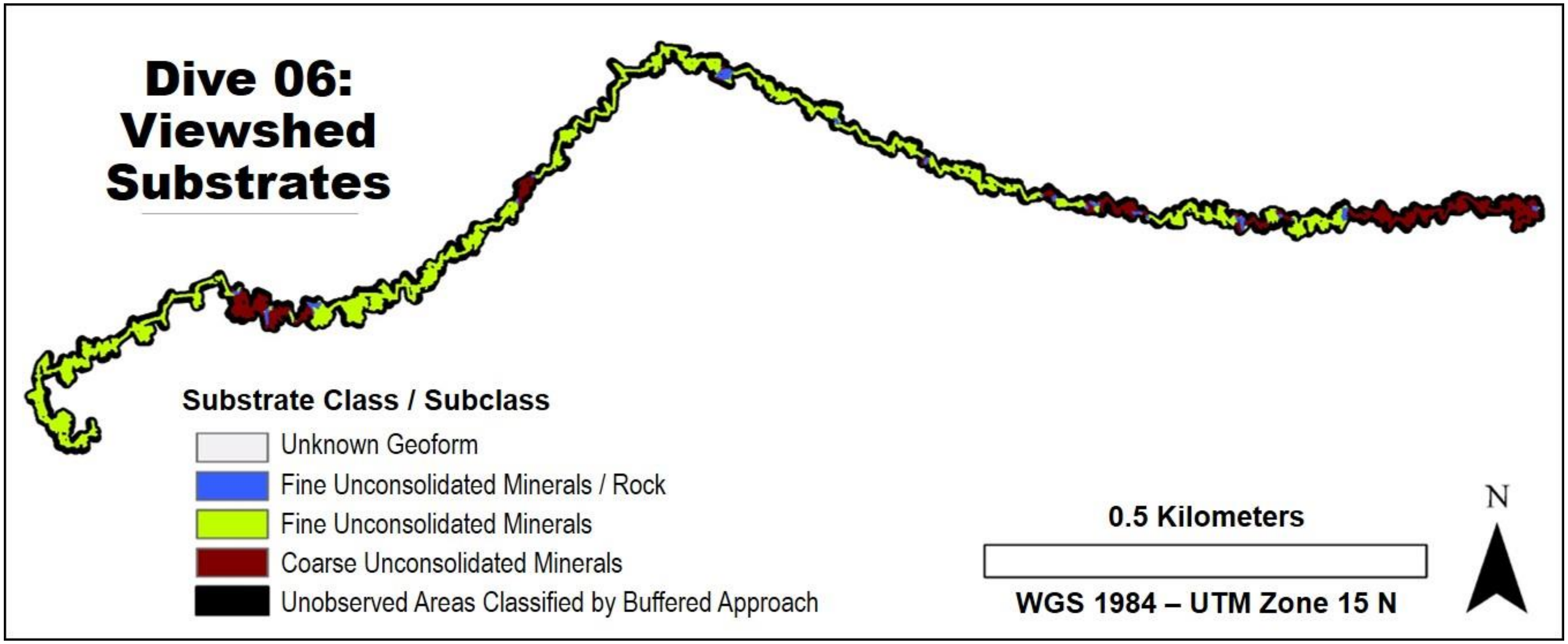

Figure D.20 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 06 using the Viewshed Approach

The number of classifications remained the same for both approaches.

D.6 Dive 08

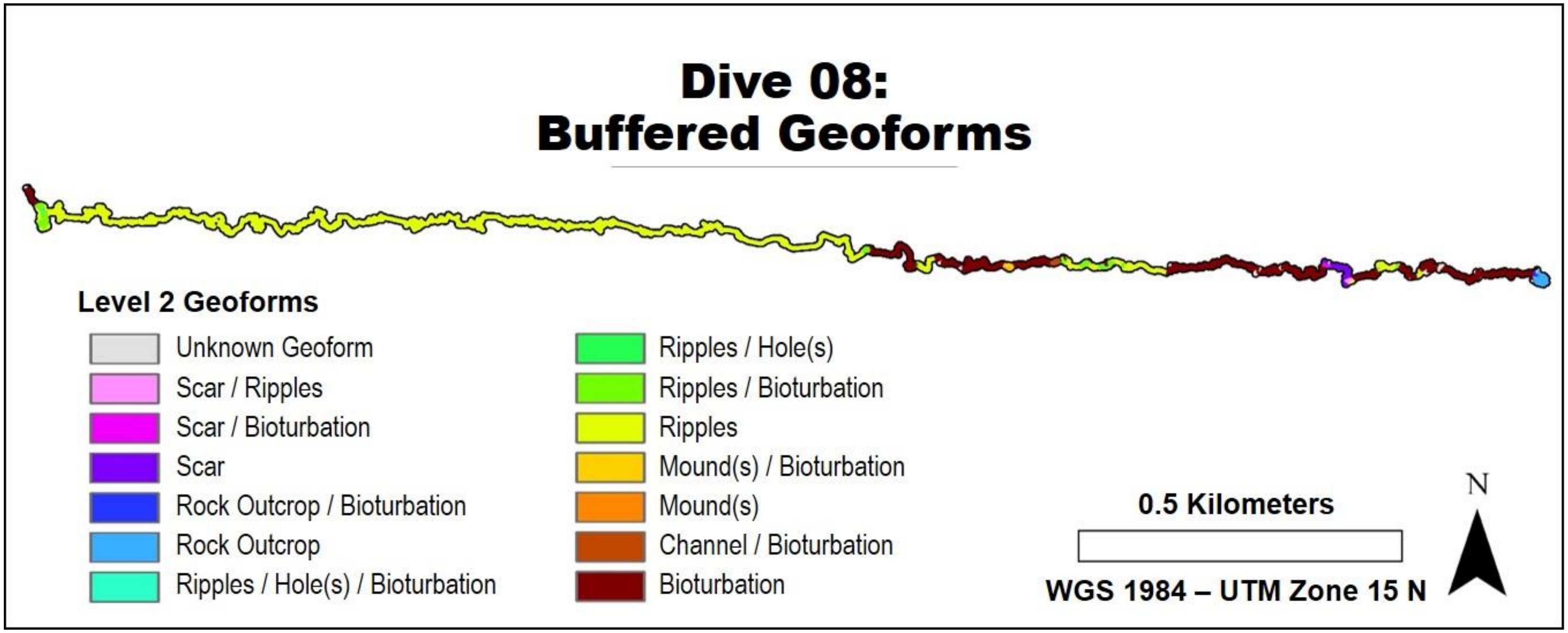

Figure D.21 Distribution of Level 2 Geoforms throughout Dive 08 using the Buffered Approach

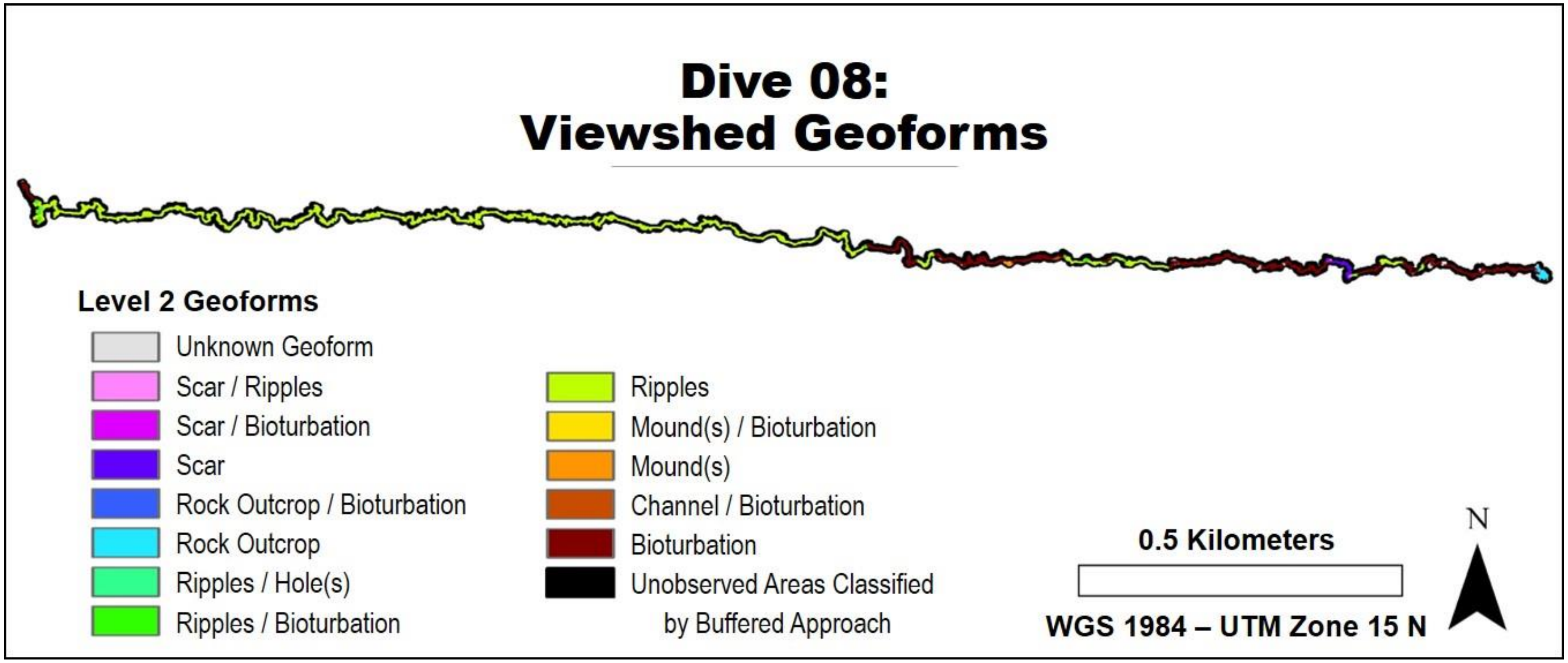

Figure D.22 Distribution of Level 2 Geoforms throughout Dive 08 using the Viewshed Approach

The viewshed approach eliminates one spurious classification.

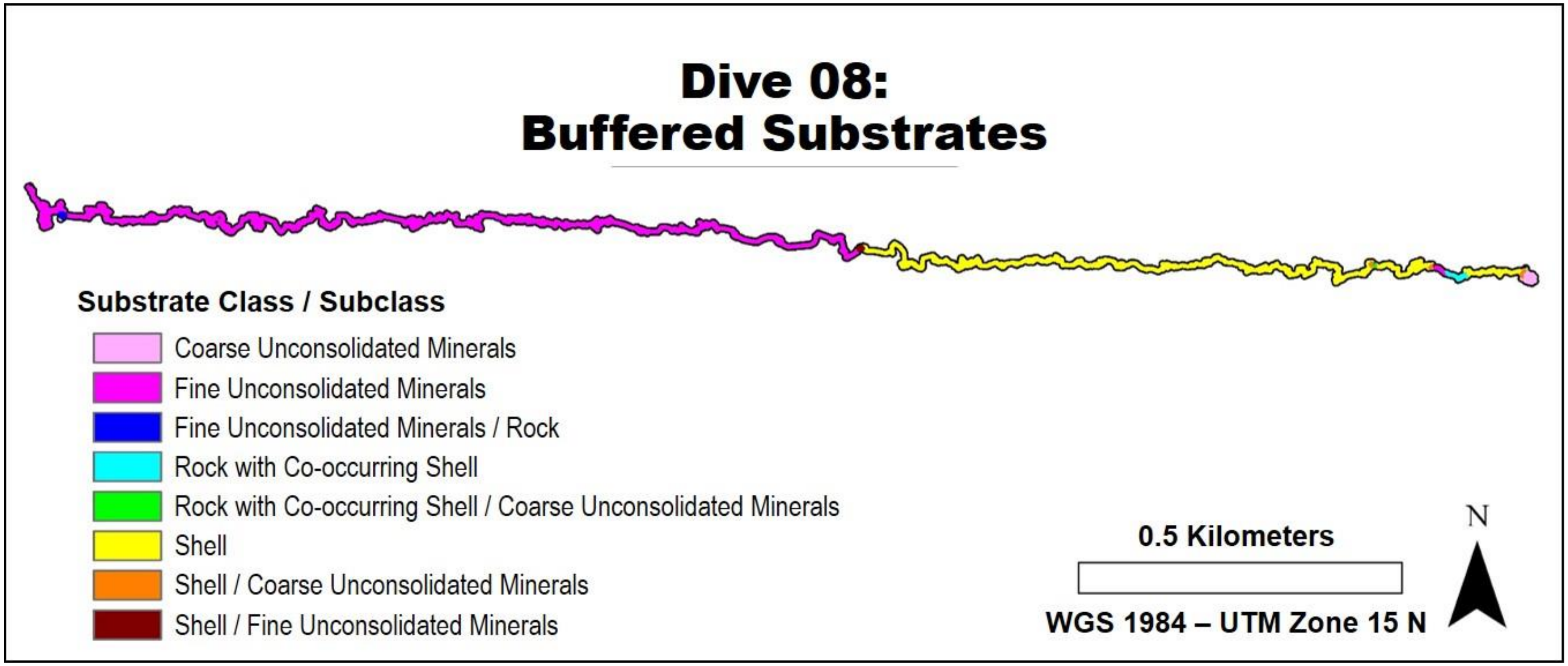

Figure D.23 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 08 using the Buffered Approach

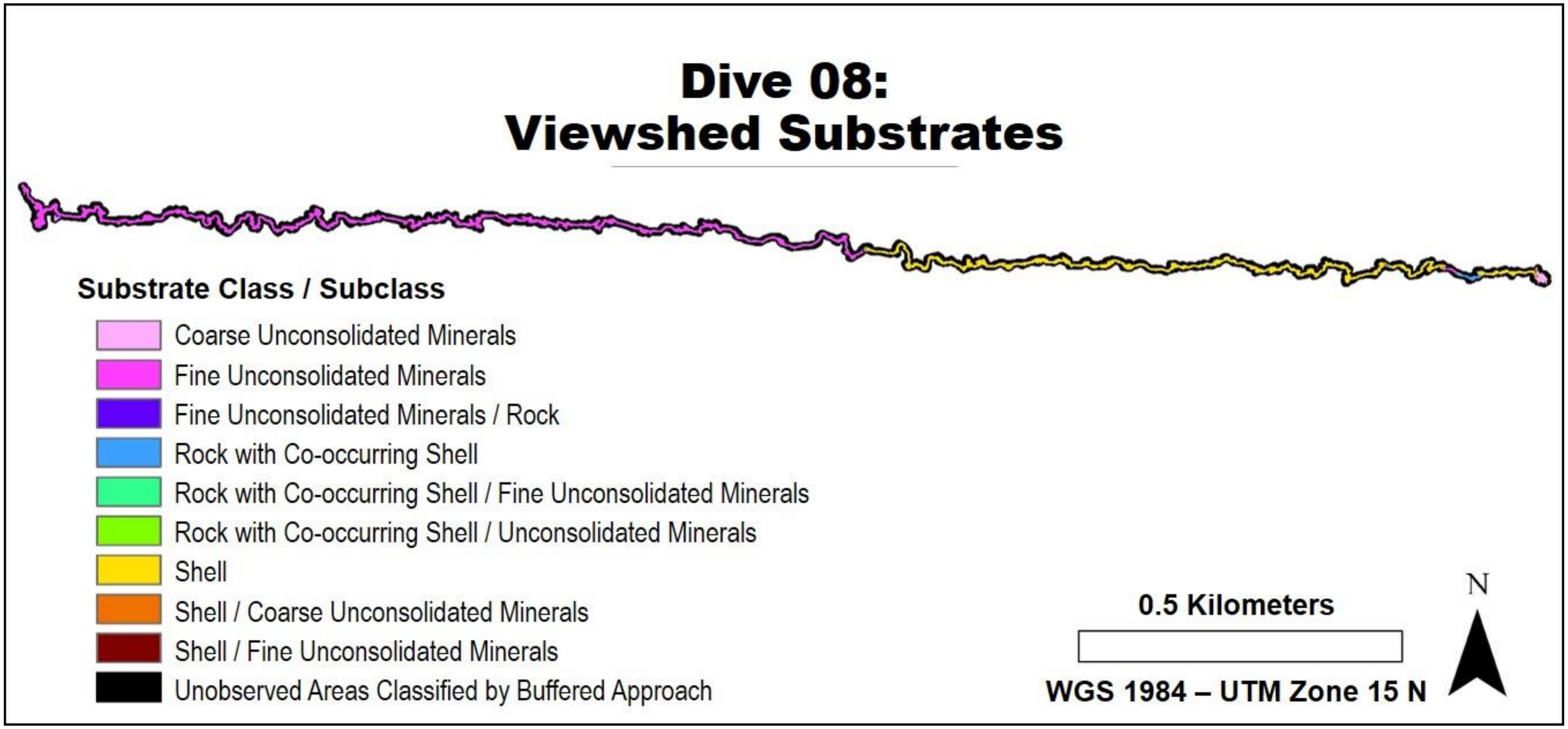

Figure D.24 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 08 using the Viewshed Approach

The viewshed approach adds one classification.

D.7 Dive 09

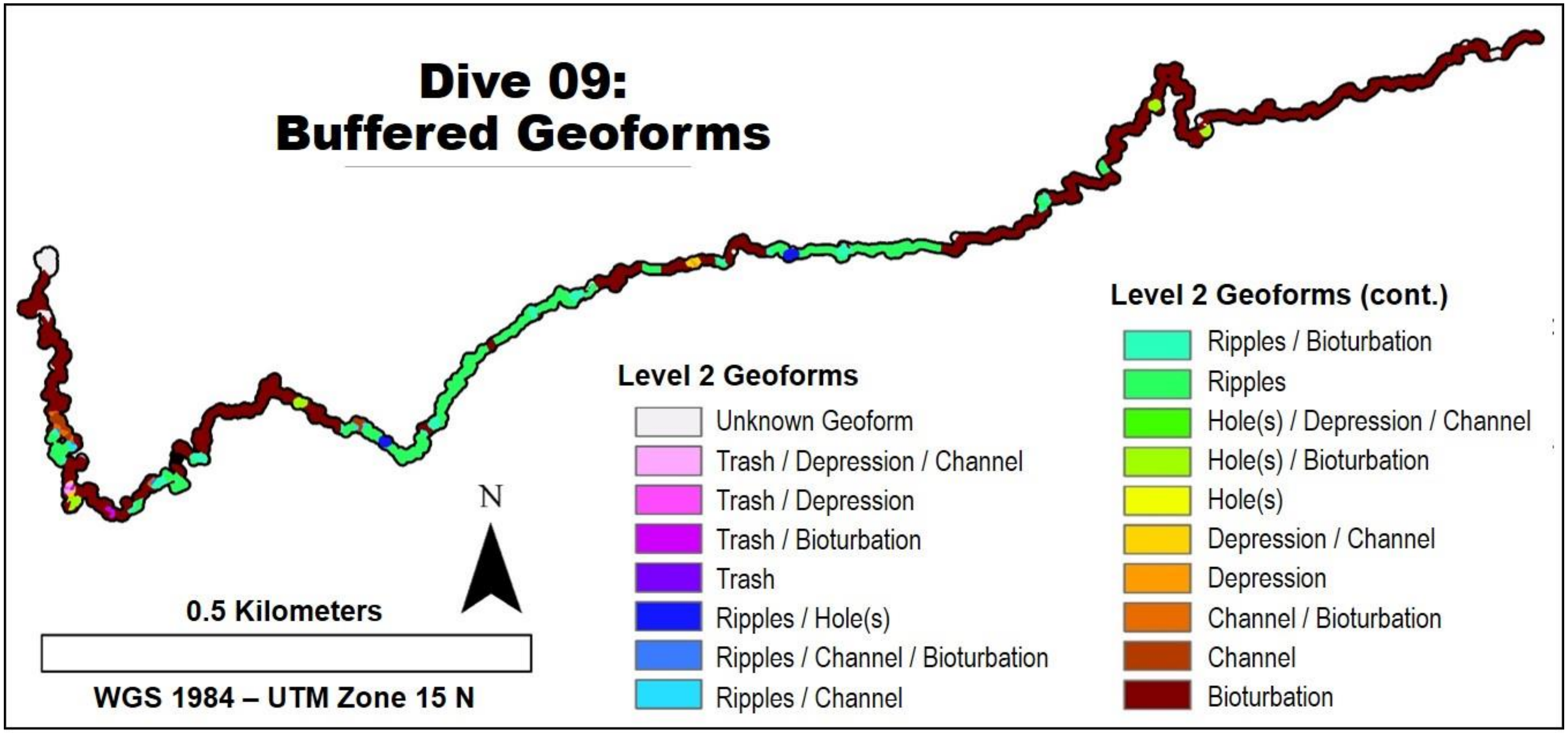

Figure D.25 Distribution of Level 2 Geoforms throughout Dive 09 using the Buffered Approach

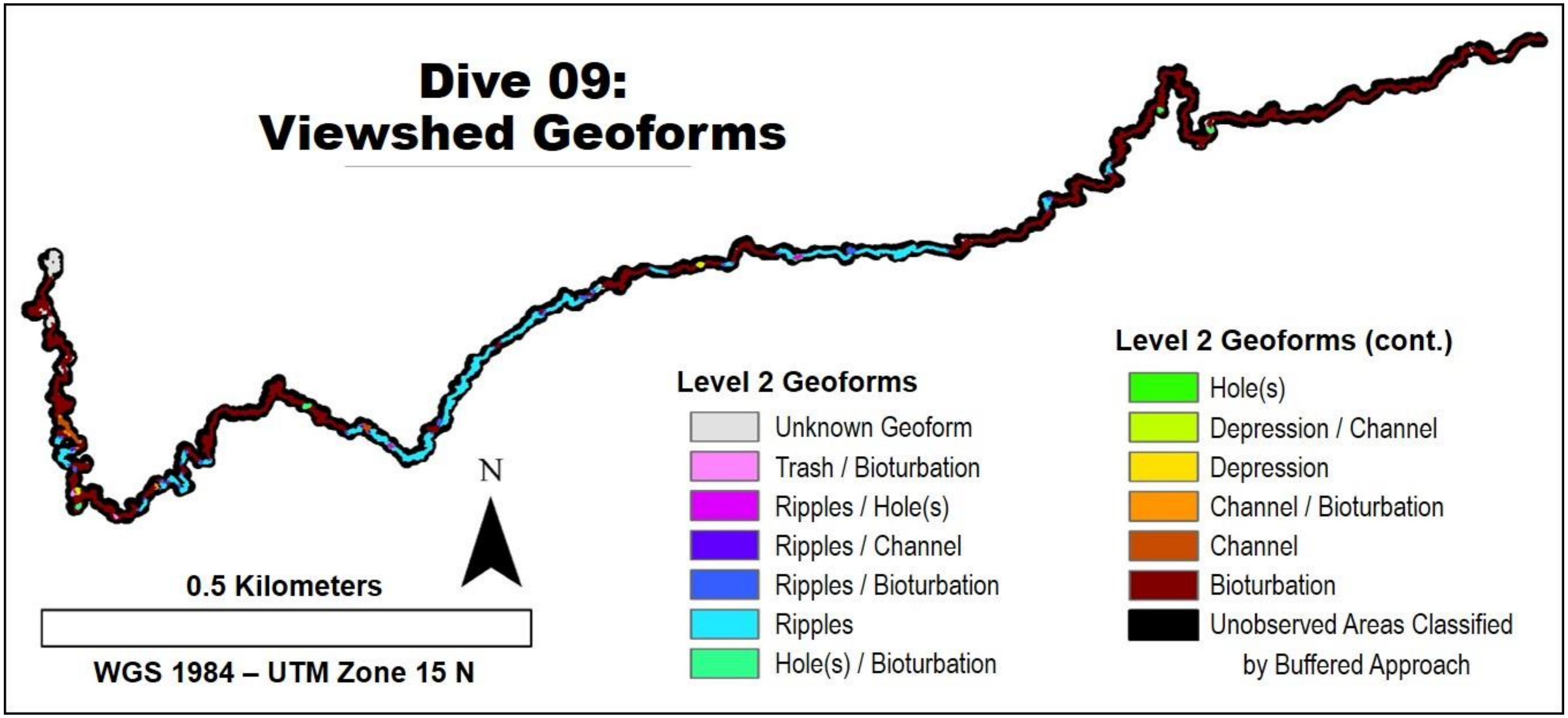

Figure D.26 Distribution of Level 2 Geoforms throughout Dive 09 using the Viewshed Approach

The viewshed approach eliminates five spurious classifications.

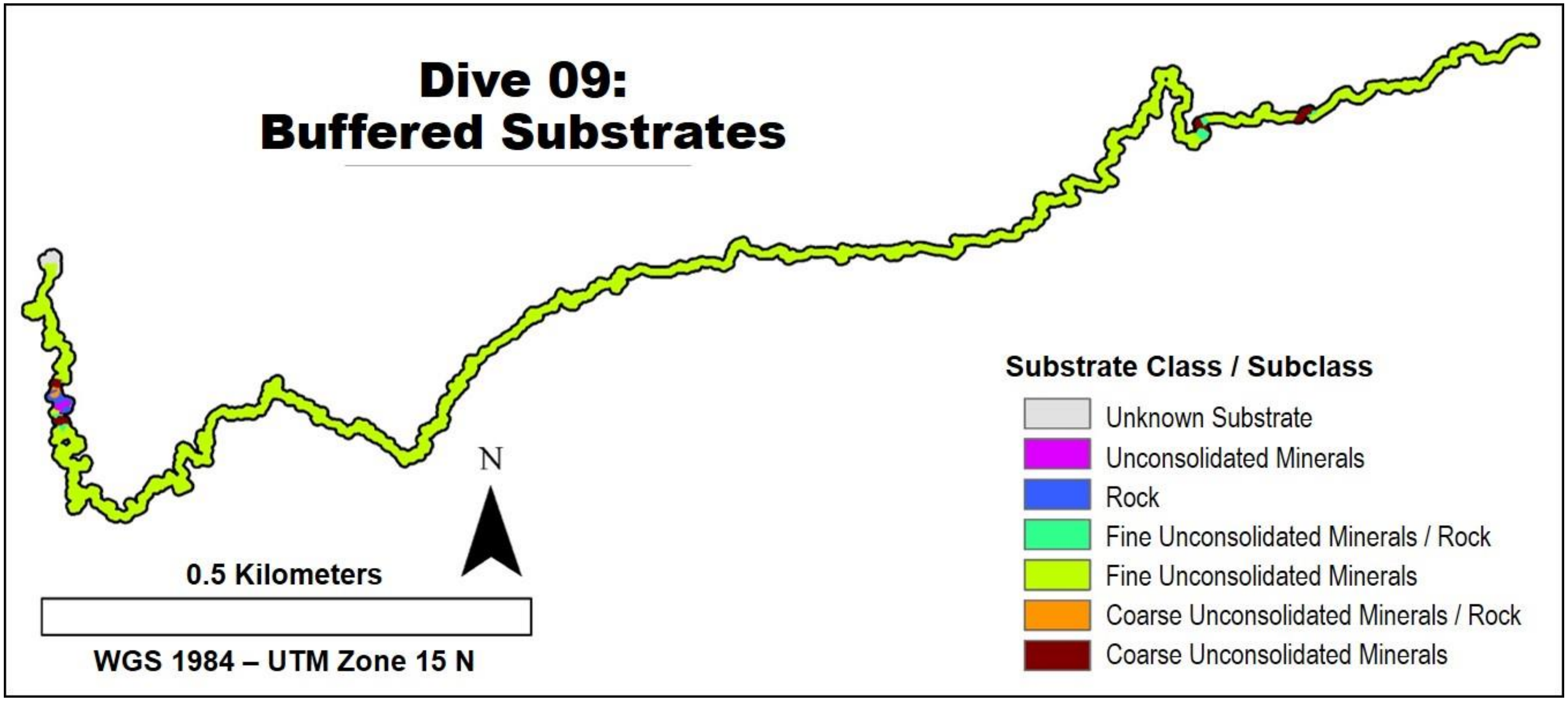

Figure D.27 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 09 using the Buffered Approach

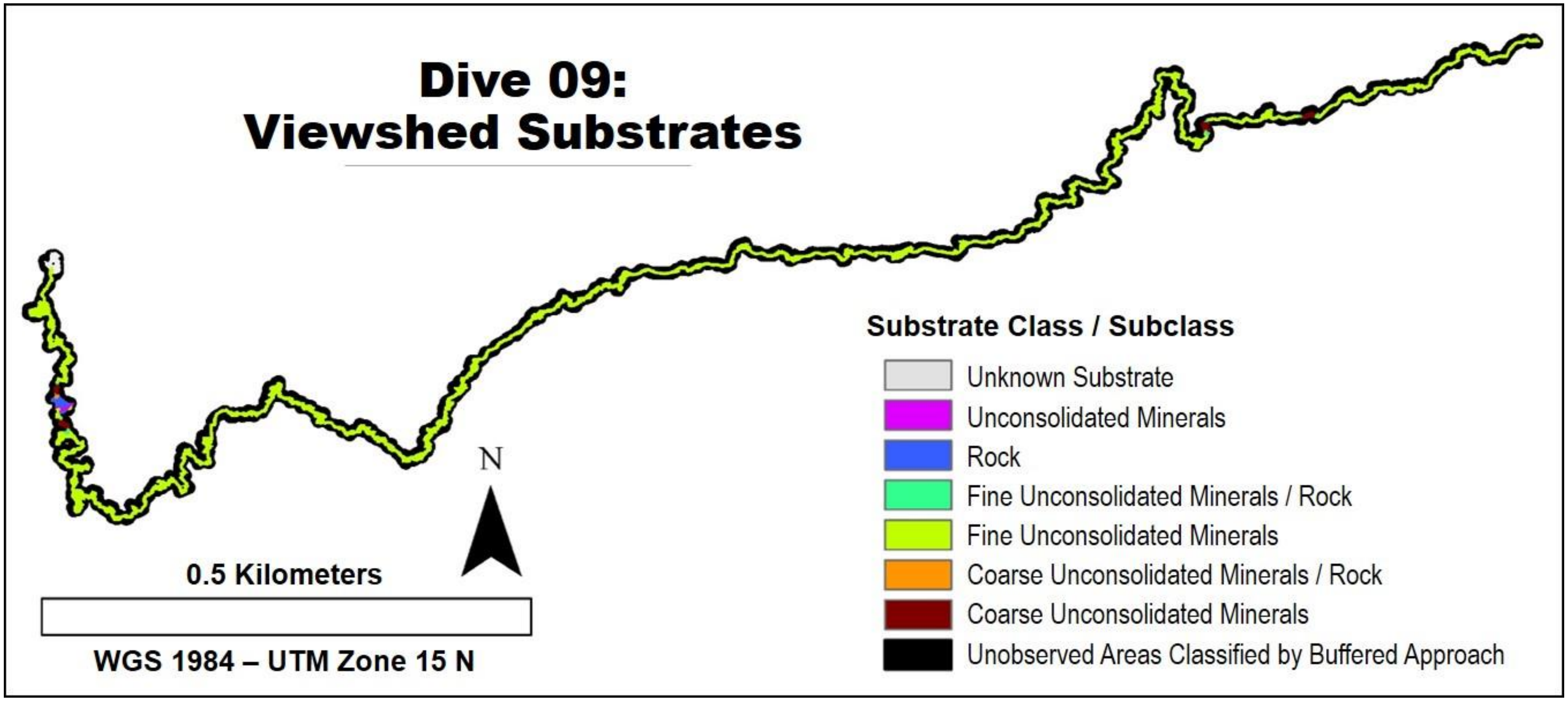

Figure D.28 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 09 using the Viewshed Approach

The number of classifications remained the same for both approaches.

D.8 Dive 10

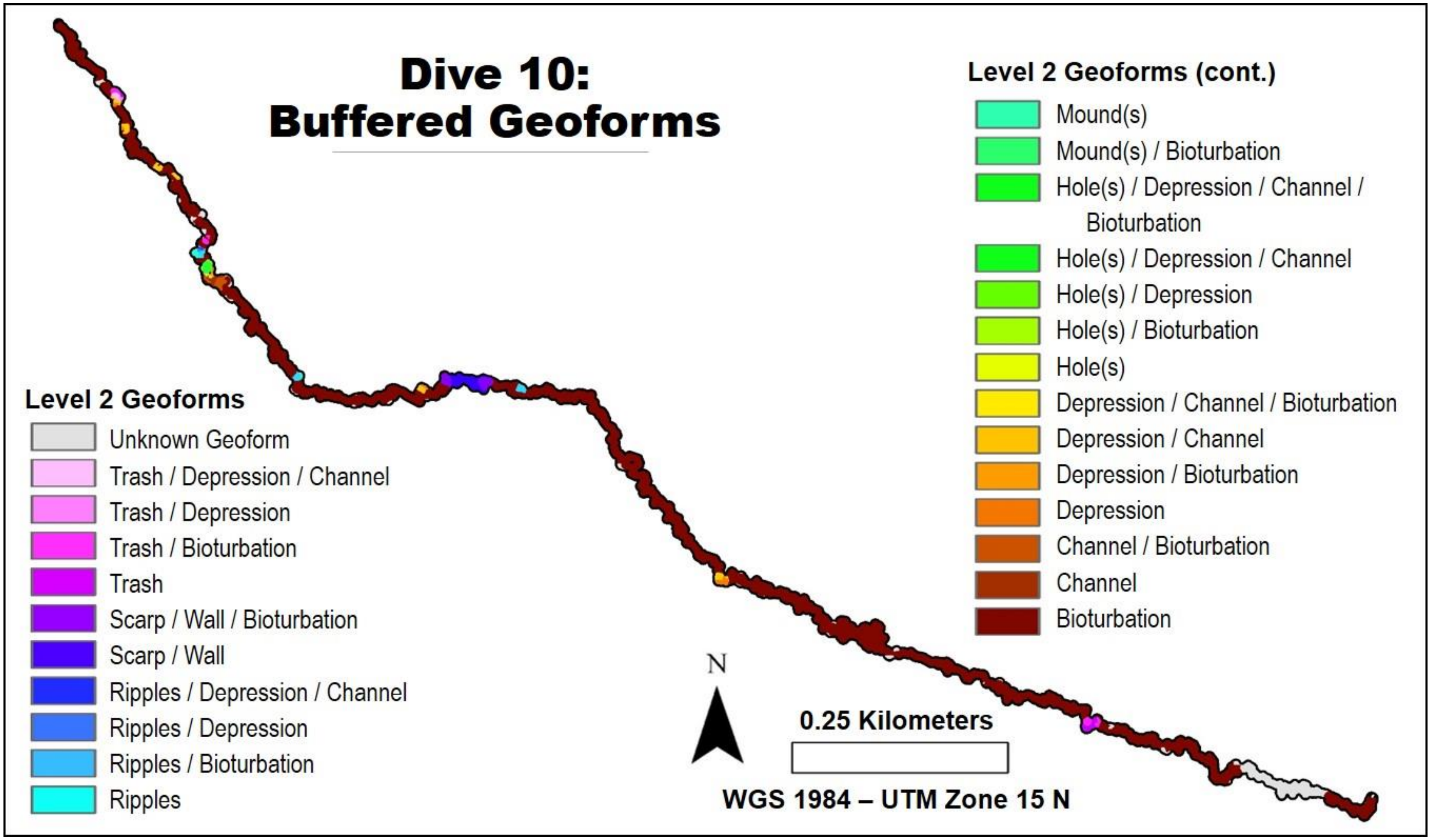

Figure D.29 Distribution of Level 2 Geoforms throughout Dive 10 using the Buffered Approach

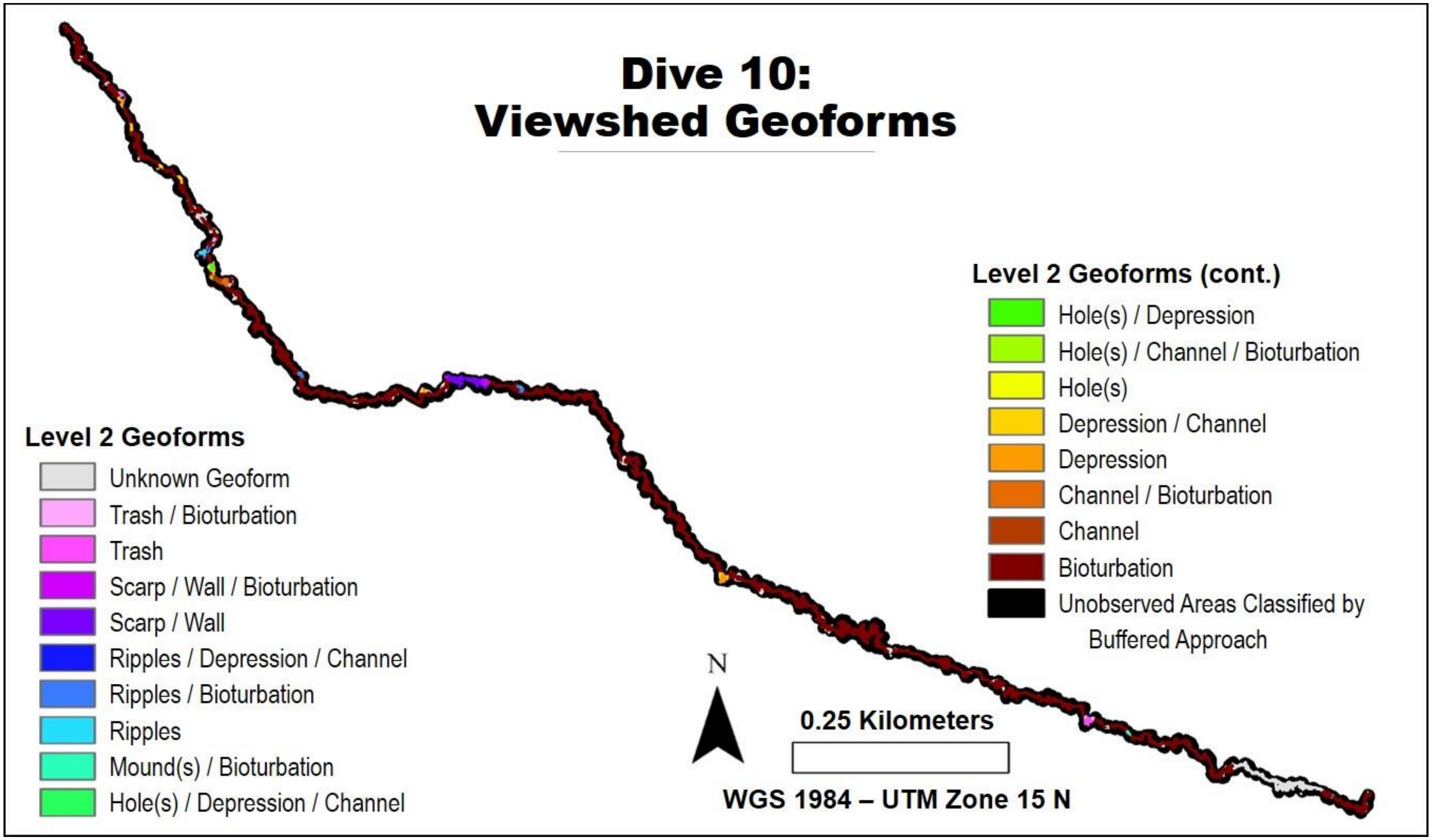

Figure D.30 Distribution of Level 2 Geoforms throughout Dive 10 using the Viewshed Approach

The viewshed approach eliminates six spurious classifications.

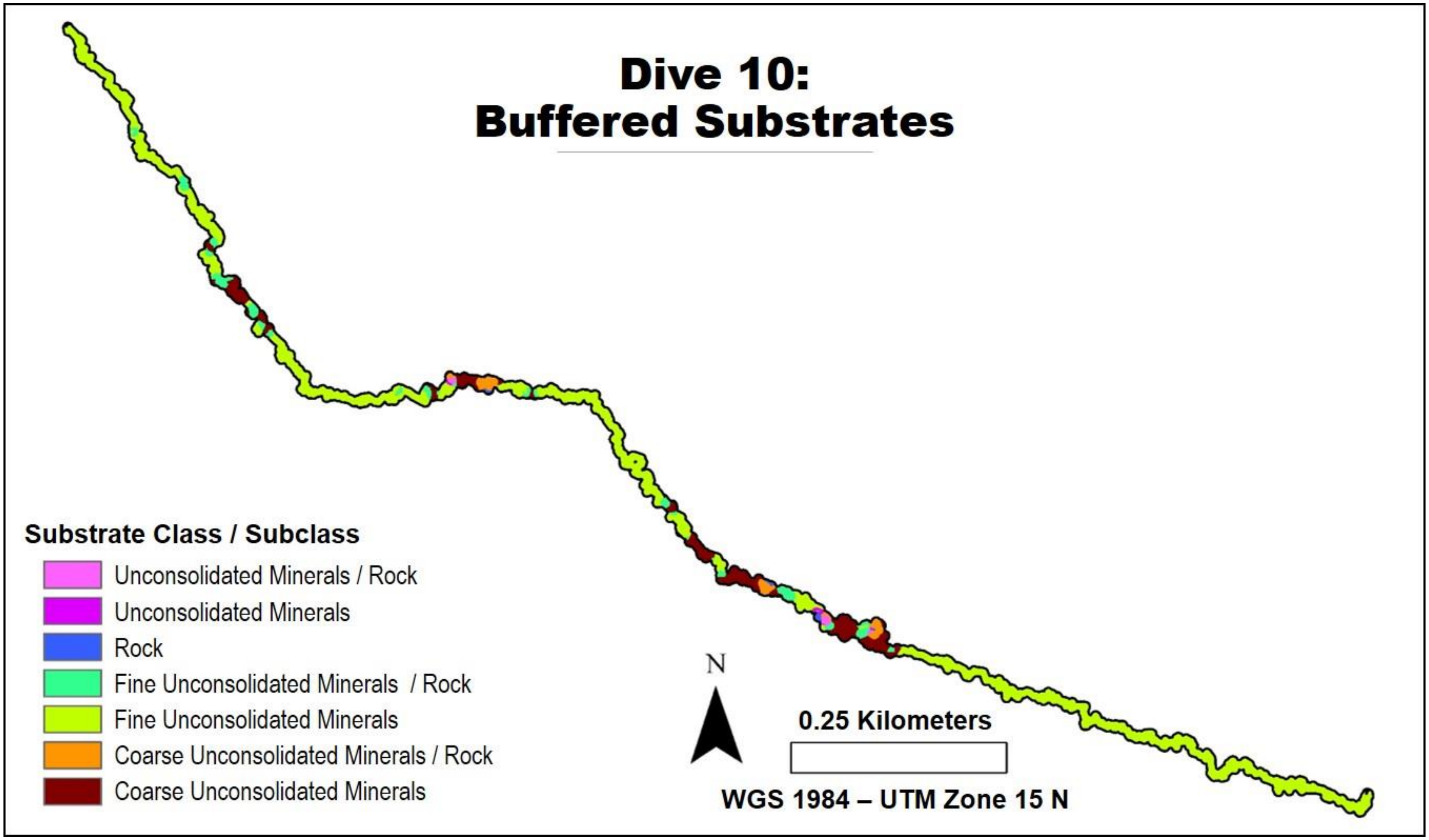

Figure D.31 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 10 using the Buffered Approach

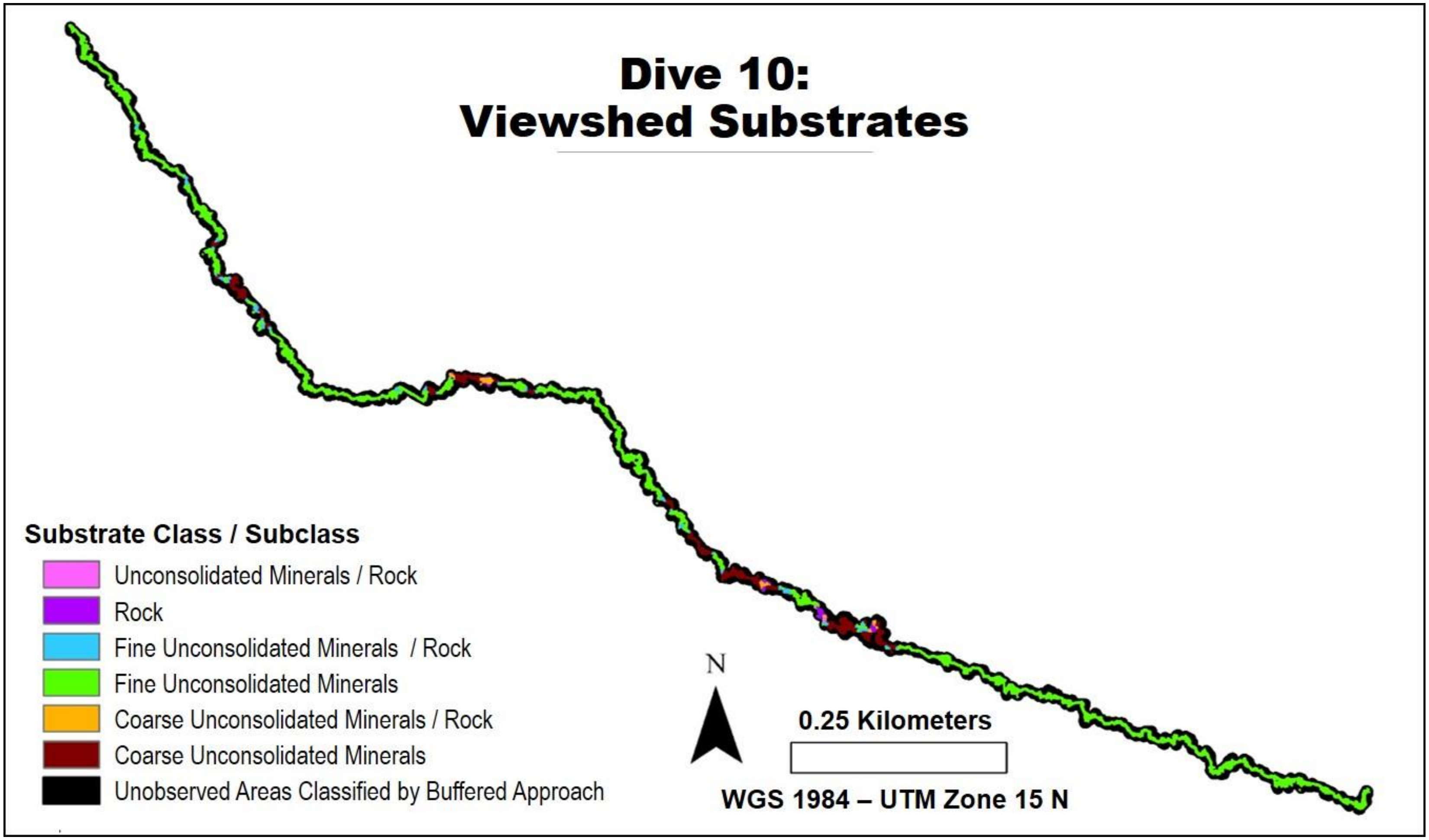

Figure D.32 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 10 using the Viewshed Approach

The viewshed approach eliminates one spurious classification.

D.9 Dive 11

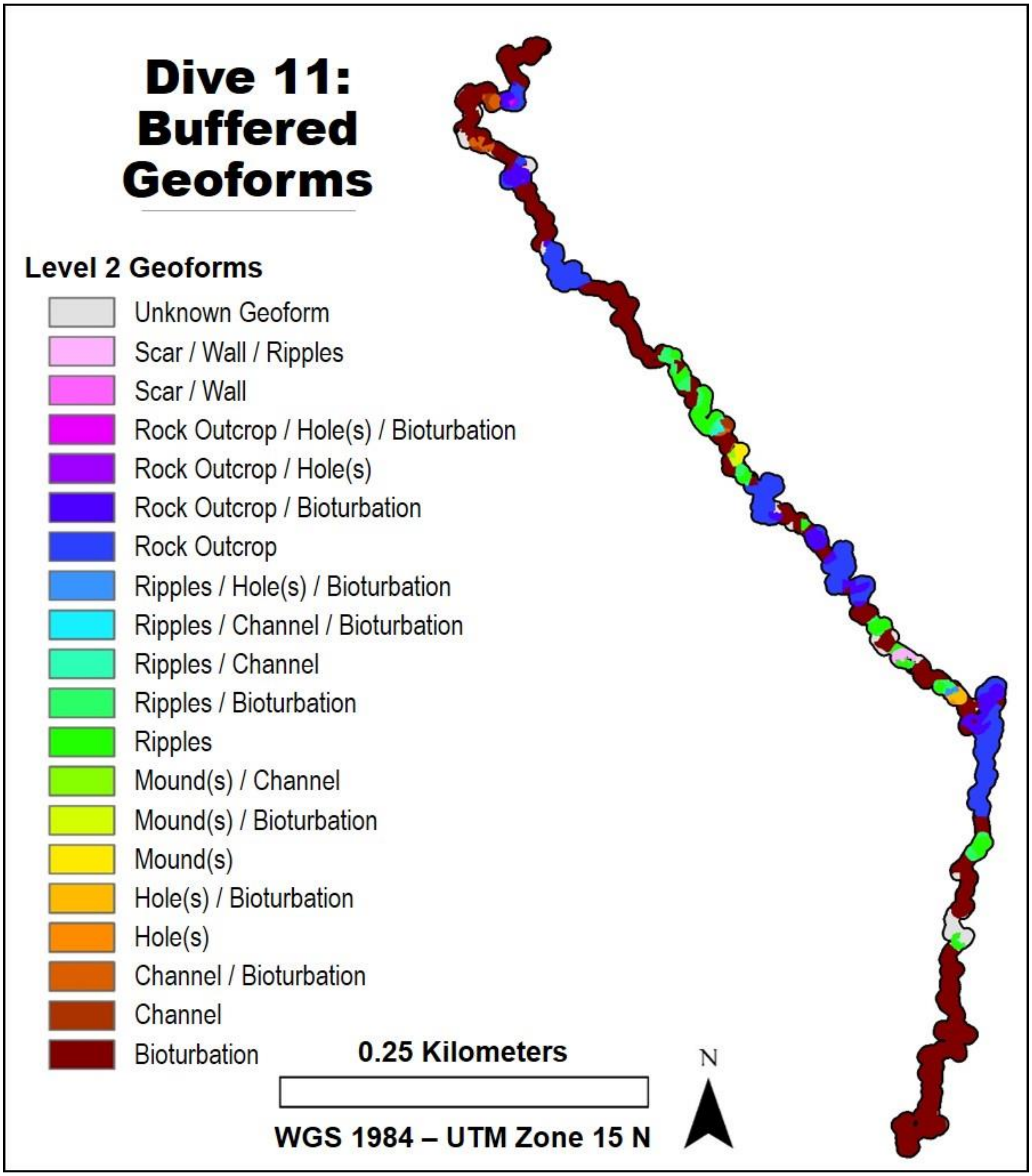

Figure D.33 Distribution of Level 2 Geoforms throughout Dive 11 using the Buffered Approach

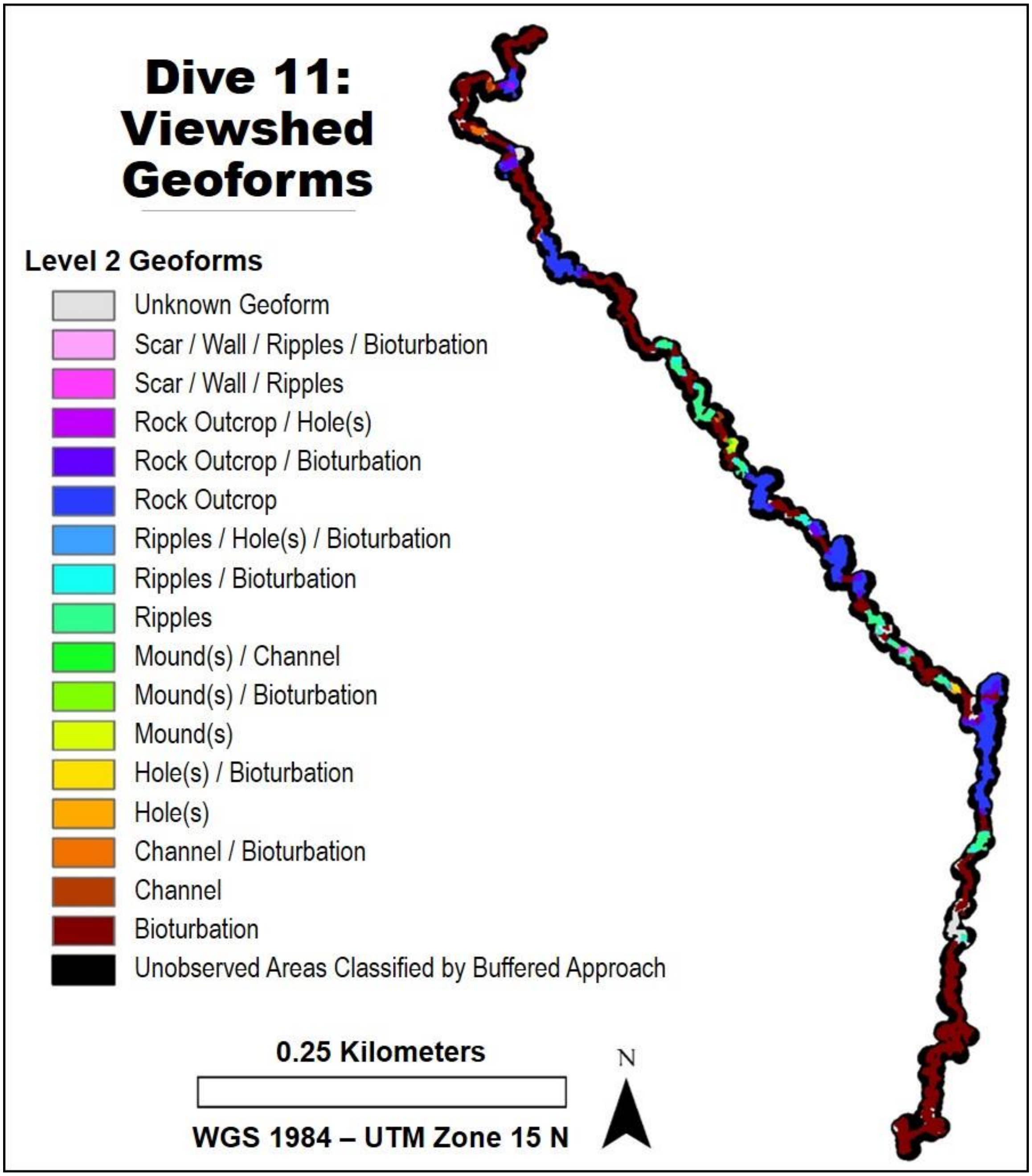

Figure D.34 Distribution of Level 2 Geoforms throughout Dive 11 using the Viewshed Approach

The viewshed approach eliminates three spurious classifications.

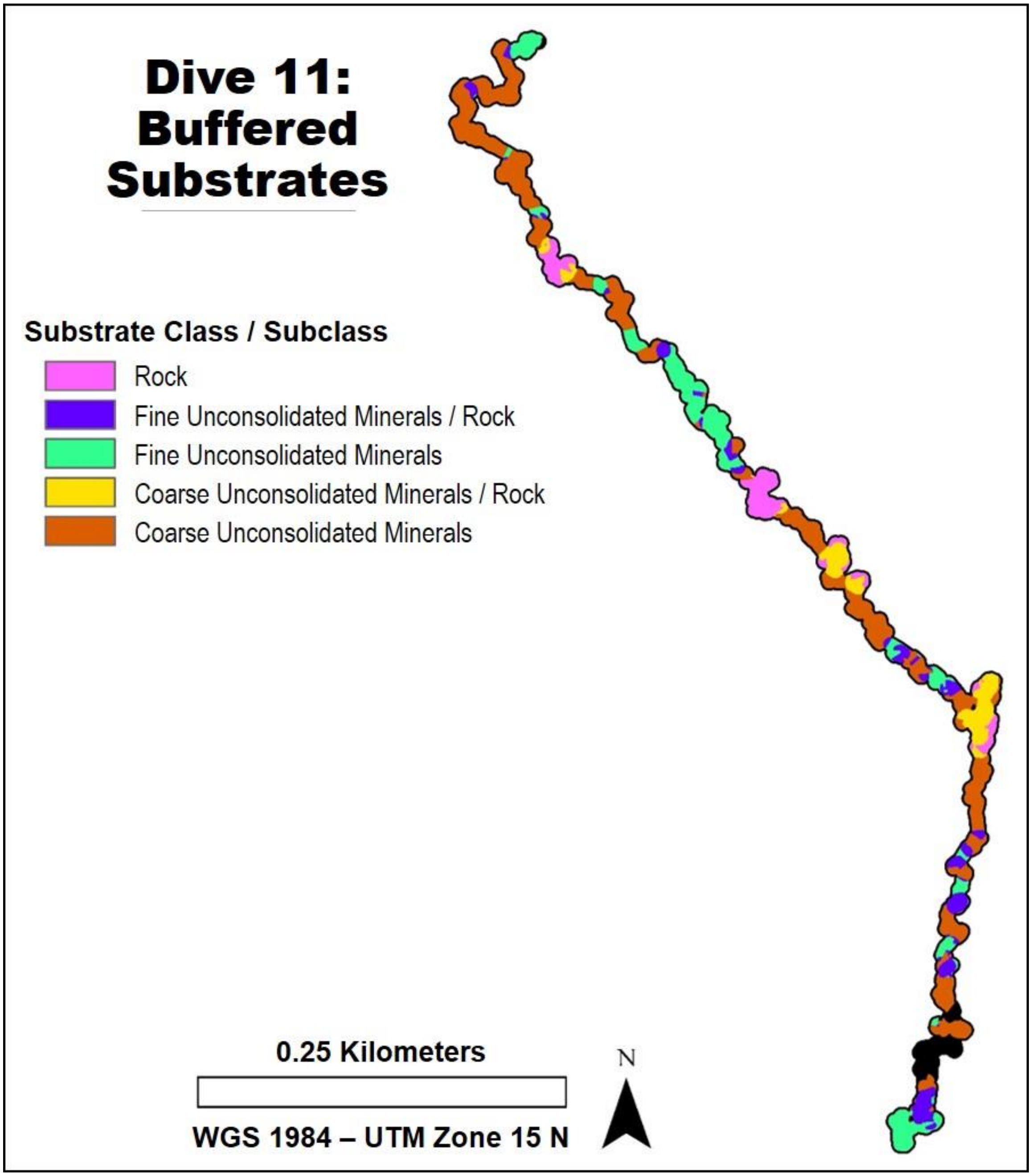

Figure D.35 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 11 using the Buffered Approach

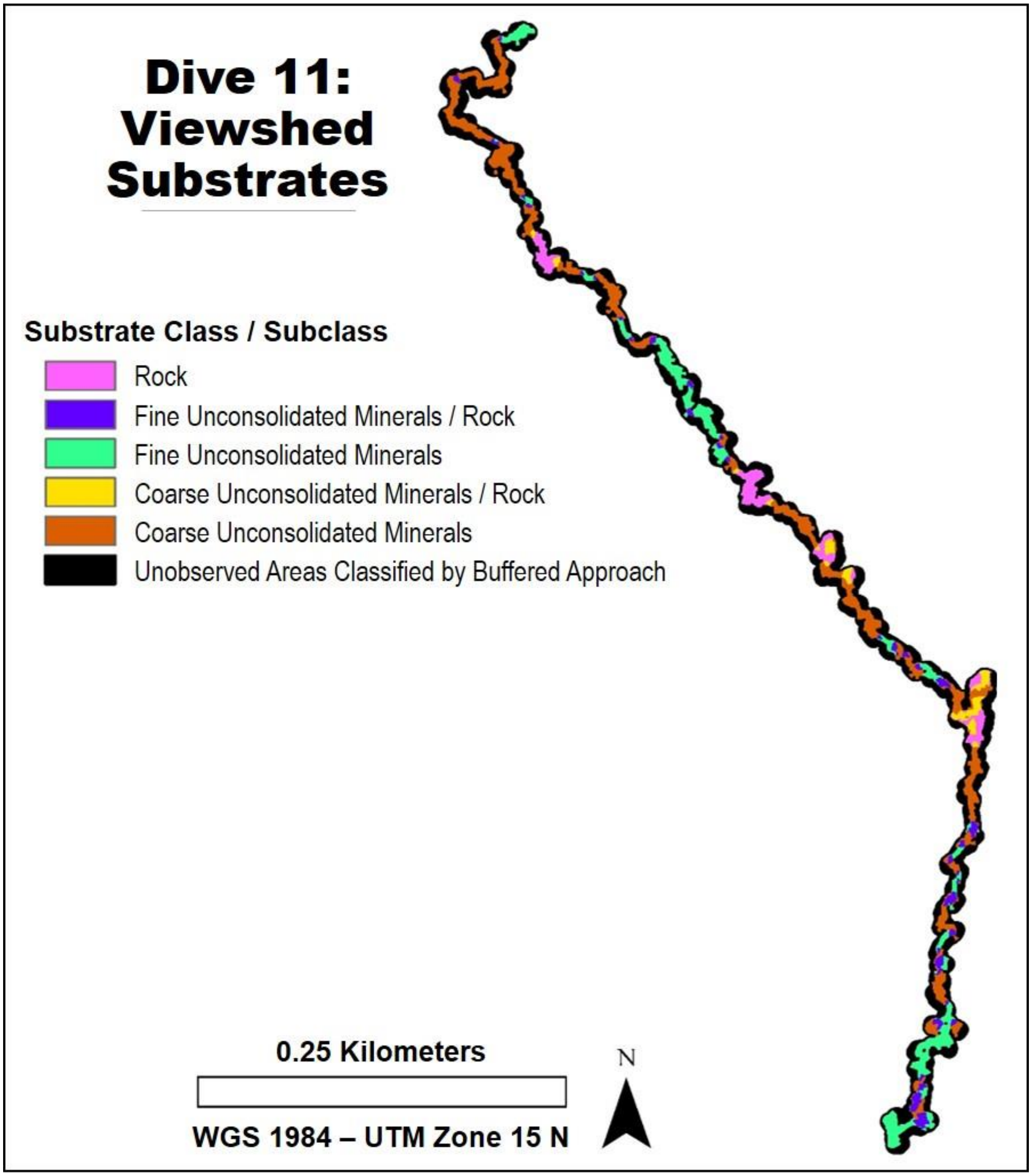

Figure D.36 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 11 using the Viewshed Approach

The number of classifications remained the same for both approaches.

D.10 Dive 12

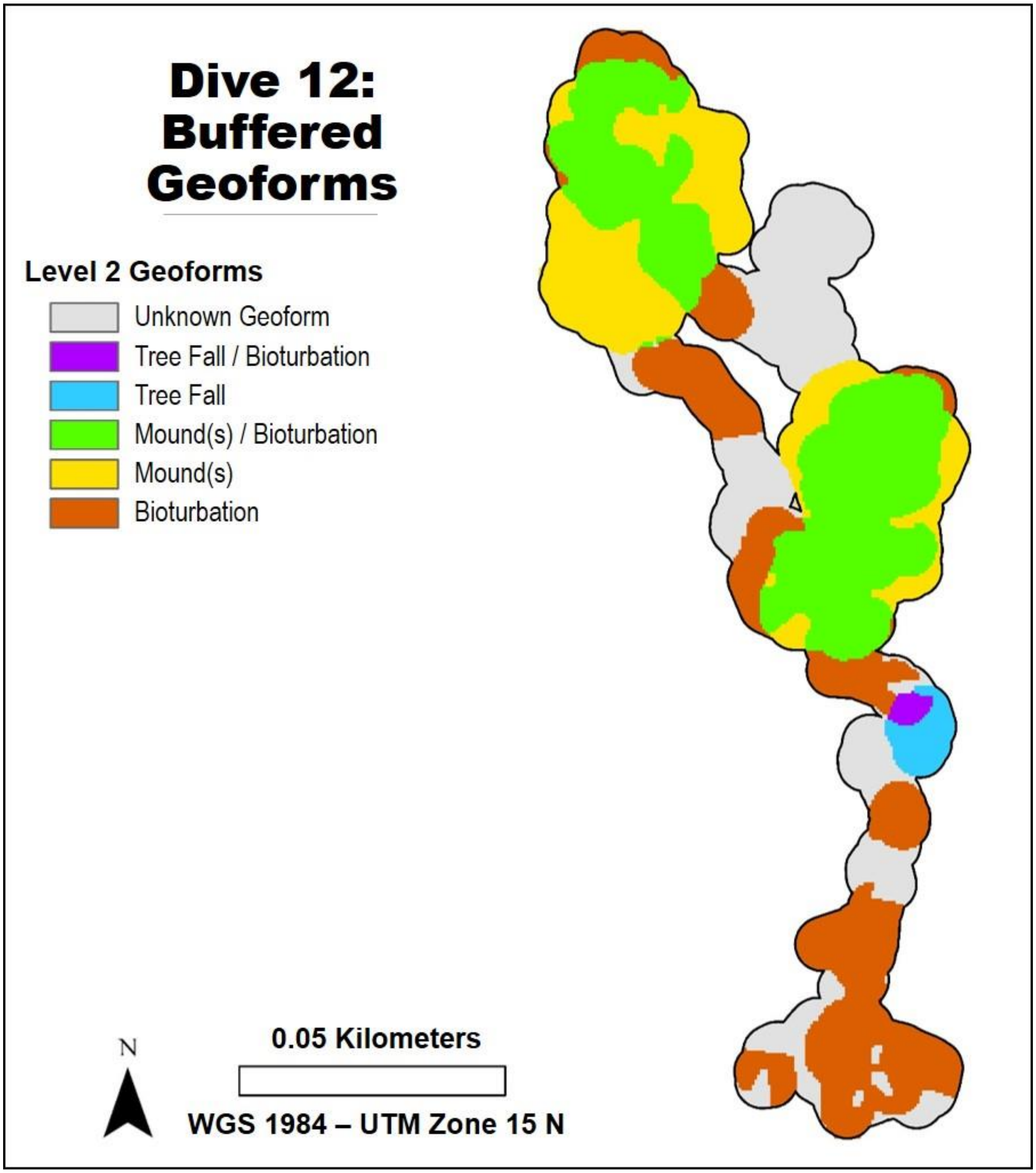

Figure D.37 Distribution of Level 2 Geoforms throughout Dive 12 using the Buffered Approach

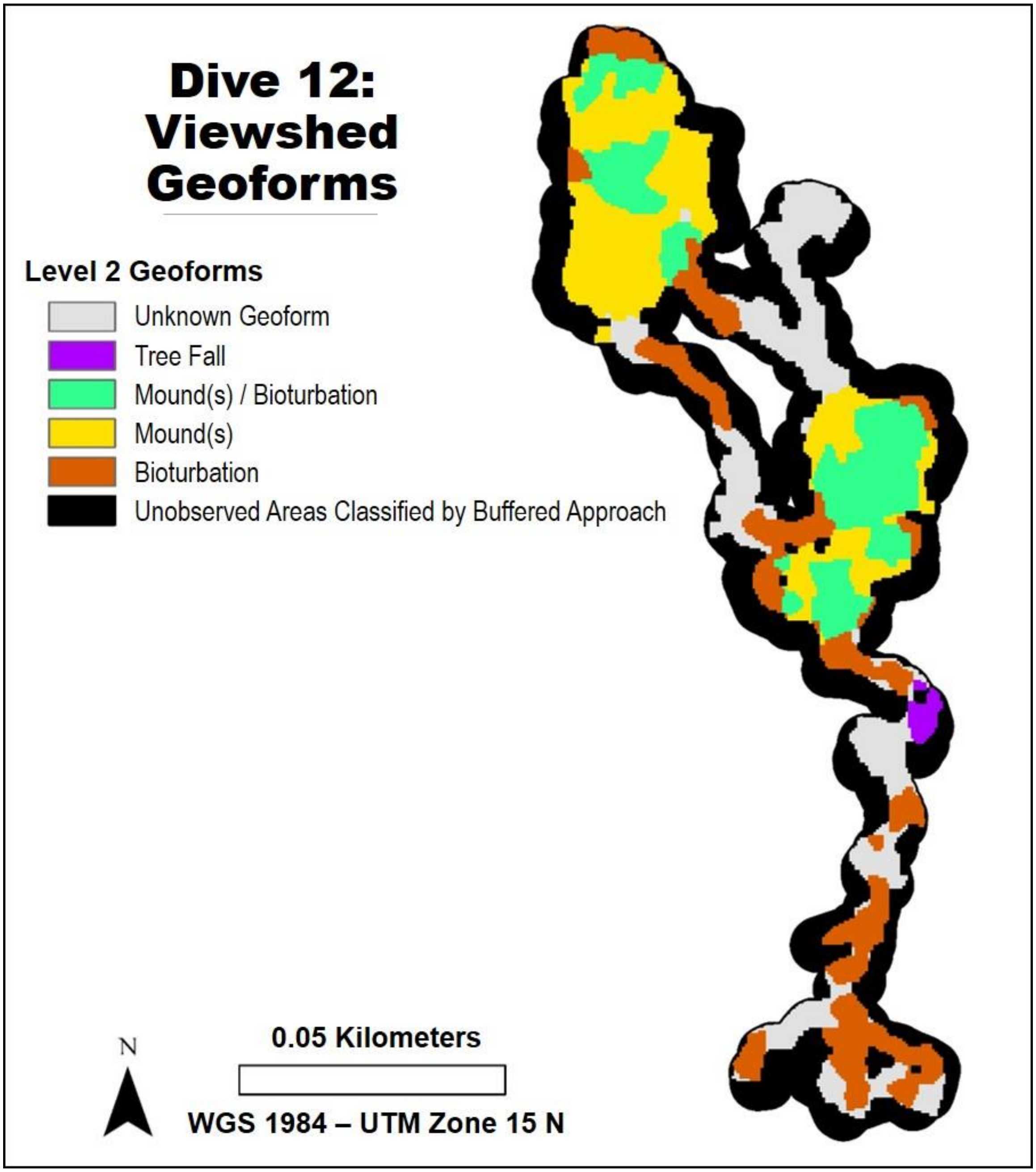

Figure D.38 Distribution of Level 2 Geoforms throughout Dive 12 using the Viewshed Approach

The viewshed approach eliminates one spurious classification.

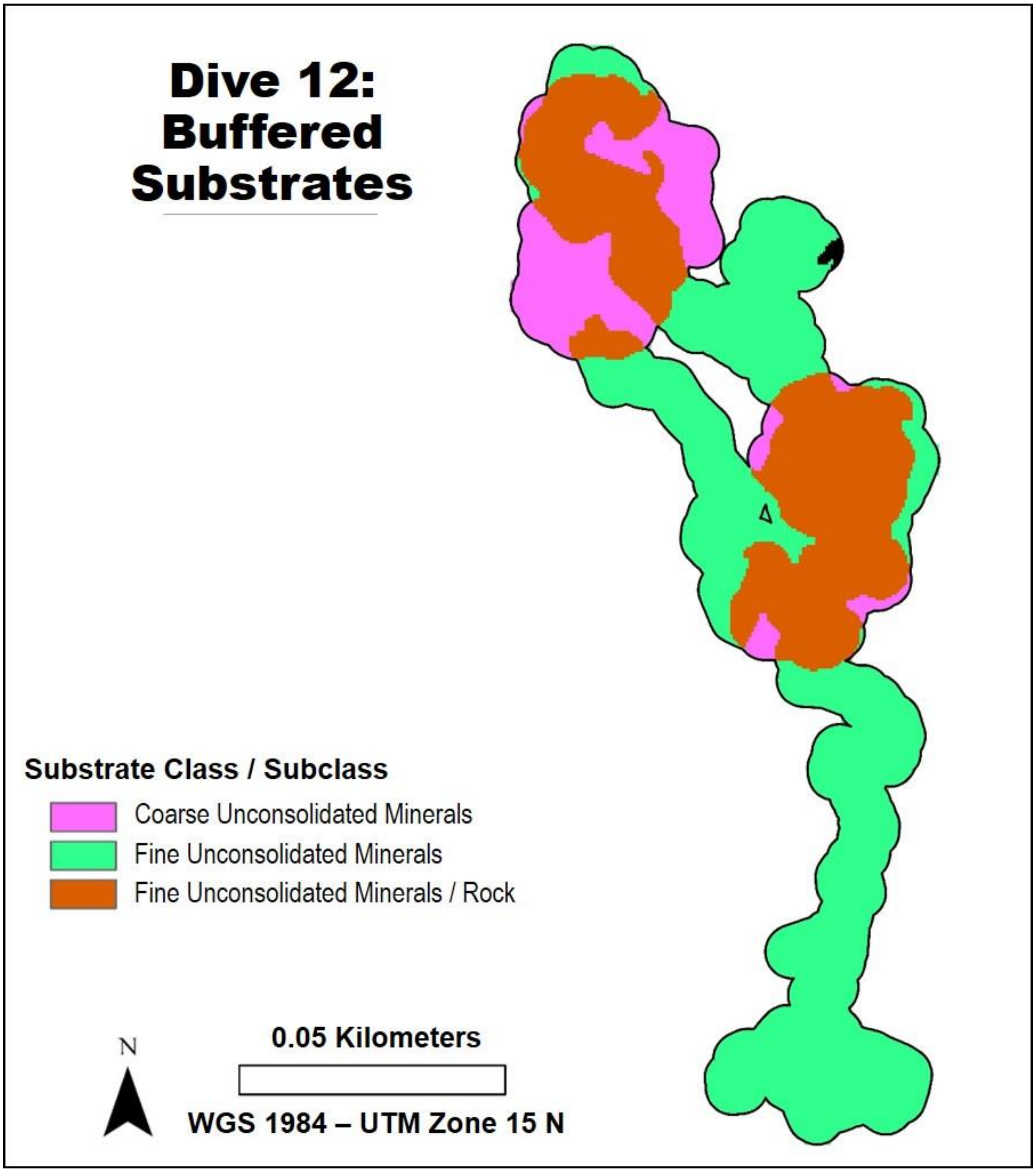

Figure D.39 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 12 using the Buffered Approach

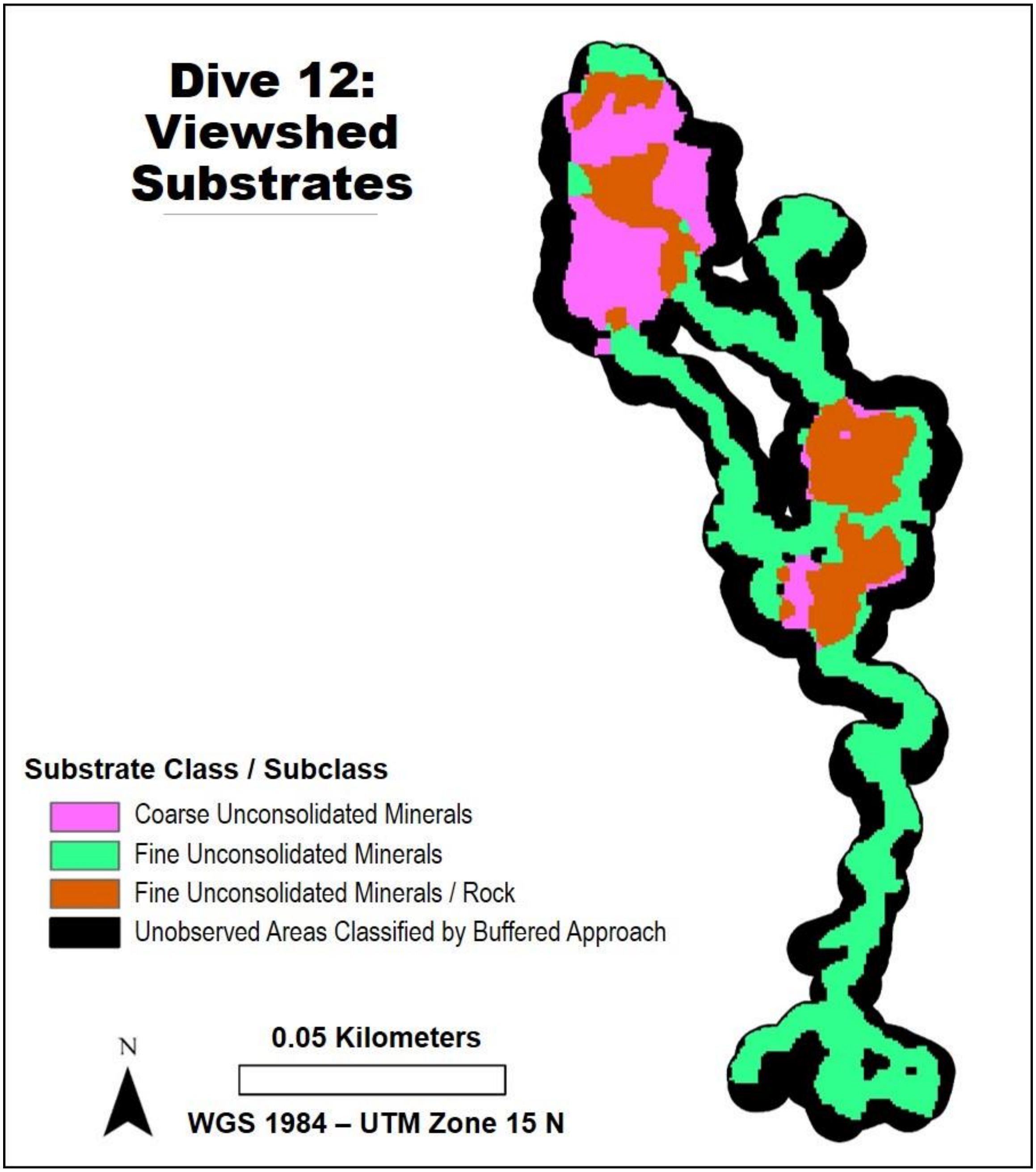

Figure D.40 Distribution of Classes, Subclasses, and Co-occurring Substrates throughout Dive 11 using the Viewshed Approach

The number of classifications remained the same for both approaches.