

Marco D’Emidio PhD research project (PhD in Earth Sciences)

Title:

Geological and morpho-acoustic characterization of marine benthic communities using Machine Learning

General objective:

The project focuses on developing innovative Machine Learning (ML) models to assist the interpretation of bathymetry data, with the main goal of mapping geological structures supporting mesophotic and deep-sea benthic communities.

Specific objectives:

The specific objectives of this research are to: 1. Train supervised ML models to recognize seafloor features from bathymetry, backscatter and imagery data; 2. Develop a user-friendly interface to automate seafloor mapping interpretation of benthic habitats; 3. Compare traditional interpretation methods with ML models in terms of time, effort, and cost.

State-of-the-art:

Study area: Despite being a passive continental margin, the Gulf of Mexico (GoM) is a complex geodynamic province, largely characterized by faulting, folding, seismic activity and other deformational processes related to the layering of thick sedimentary units over buoyant salt deposits. The continuous evolution of salt domes and connected salt withdrawal basins produces intricate faulting patterns that serve as conduits for migrating fluids, including gases and brines, from the deep oil reservoir resulting in a very complex seafloor topography [10]. The concurrent presence of rough terrain and natural gas leakage promotes the proliferation of benthic communities, including many coral reefs, even in very deep water (Fig. 1).

High resolution seafloor mapping: Over the past two decades, Autonomous Underwater Vehicles (AUVs) have radically changed deep-water seafloor mapping. AUVs are now equipped with Multibeam Echosounder (MBES), Sub Bottom Profiler (SBP), Side Scan Sonar (SSS), high-definition cameras, etc. Geomorphological information from AUV acoustic data is often combined with high-resolution visual data to provide powerful tools for characterizing the seabed and producing robust thematic maps. A prime example is the benthic habitat map, which is crucial for bolstering our ecological understanding of the seafloor by spatially representing its abiotic and biotic relationships and distributions as well as aiding in decision-making for future survey efforts and for marine conservation (Fig. 2) [8; 9]. After the 2010 BP oil spill there has been a significant effort in the GOM scientific community to assess the damage to impacted sites and deep benthic communities have been hard to fully evaluate due to the nature of the sites. AUV surveys offer the right resolution to assess the status of these communities and help refine various prediction models.

ML: ML, especially Deep Learning (DL) models, have significantly enhanced the abilities of marine scientists to extract quantitative geological and ecological information from acoustic and optical seafloor surveys. Deep Convolutional Neural Network (CNN) architectures such as ResNet, DenseNet, and EfficientNet now consistently achieve overall accuracies surpassing 92% in classifying sediment types using MBES backscatter data, making them highly applicable to the complex sedimentary environments of the GoM [7]. The ML workflow reduces weeks of manual

annotation into hours, enabling overnight processing of terabyte-scale sonar and video archives [4]; it eradicates inter-analyst subjectivity by applying identical decision rules throughout a survey [11]; modern CNNs learn discriminative texture and morphological cues directly from raw amplitude grids or unenhanced imagery, eliminating hand-crafted feature engineering [7]. The extreme class imbalance characteristic of deep-sea surveys still hampers rare-feature detection; generative-adversarial augmentation offers only partial relief [7]. Domain shift remains a chronic issue: models calibrated in one geological province often fail when confronted with differing lithologies or sensor settings, and robust cross-region adaptation strategies are still nascent [4]. Optical turbidity and acoustic noise further degrade input quality, while the power budget of battery-limited autonomous platforms constrains model complexity [11]. Despite these advancements, DL approaches face significant challenges related to limited availability of expertly annotated marine data, especially rare or ecologically important habitats such as mesophotic and deep coral communities. To address this constraint, transfer learning has been considered, leveraging pretrained CNN models (e.g., ImageNet-based ResNets) to enhance model accuracy with limited local datasets.

Research Activities:

Research methodology: This project is based on an extensive range of acoustic data collected in the GoM by the AUV *Eagle Ray* (ER) and multiple Remotely Operated Vehicle (ROV) videos and images collected by NOAA for the Gulf restoration plan. The ER collects MBES data, including bathymetry, backscatter, water column backscatter, along with SBP and magnetometer data (Fig. 3). Video annotations will be performed by NOAA scientists and used in this project for ground truthing the remote sensing data. ER data will be processed using a custom processing workflow (Fig. 3). Acoustic data interpretation will be based on morpho-bathymetric characterization (recognizing seafloor features such as pockmarks, mounds, faults' surface expressions, channelized structures, anthropogenic artifacts, etc.), backscatter intensity and acoustic facies analysis (sediment type classification), and subsequent correlation of these features with imagery and SBP data using specific GIS tools [1; 2]. Once the master geodatabase of the processed and interpreted data has been compiled, measured, and analyzed, the training of the ML model will begin. Deep CNNs, such as U-Net, will be trained on expertly annotated datasets using supervised machine learning techniques to enable the automated classification of seafloor habitats and the distribution of benthic communities (Fig. 4). Model performance will be rigorously evaluated by comparing automated outputs to expert manual interpretations, utilizing independent validation and test datasets and quantifying effectiveness with metrics such as accuracy, precision, recall, Intersection over Union (IoU), and F1-score. A comparative analysis will assess how ML and DL approaches enhance the localization and characterization of benthic habitats relative to traditional manual methods, documenting improvements in spatial resolution, mapping consistency, reproducibility, and the identification of ecologically significant features. Practical considerations, such as interpretation time, will also be evaluated to demonstrate the efficiency and scientific benefits of these automated approaches for habitat mapping and conservation management. Finally, validated models will be integrated into a scalable processing pipeline, enabling efficient deployment across large survey areas and supporting advanced habitat mapping and conservation efforts in complex marine environments.

Project innovation and impact: The proposed ML models will be able to: 1. Perform automated map interpretation from acoustic data and create a standardized geodatabase package that can be opened by any GIS-based software; 2. Design a user-friendly interface to provide easy access to data

(visualization, processing, exportation and clear metadata); 3. Build interdisciplinary bridges by including other researchers for collaboration/validation using their expertise (e.g. coral group, biologists); 4. Generate detailed article-like presentations ready for dissemination (e.g. cruise reports, press releases); 5. Incrementally refine the models with additional data and evaluation; 6. Potentially support the Marine Strategy Program and globally the Seabed 2030 Project.

Feasibility of the project: The project is primarily based on existing data, minimizing the risk associated with new data acquisition. The ML specific component will be conducted in close collaboration with the University of Louisiana Lafayette AI in Geoscience Lab, led by Dr. Gabriele Morra. The highly recognized expertise of the candidate in seafloor mapping will ensure the rapid transfer of knowledge to the ML group intended for model training.

Dissemination: The project will contribute to the NOAA Mesophotic Deep Benthic Communities mapping, ground-truthing and predictive habitat modeling group, participating in annual research meetings, conferences, and publications efforts. The geodatabase will be uploaded to the NOAA National Center Environmental Information database.

Education: The candidate will attend ML seminars at the University of Louisiana Lafayette (USA), relevant courses, summer schools, and seminars at La Sapienza.

International mobility:

The candidate will divide time between the University of Mississippi (USA) and La Sapienza, cooperating with the marine geology group. This arrangement provides a valuable opportunity to explore similar scientific questions across different ocean basins (e.g. southern Tyrrhenian margin). Mobility will be bidirectional, enabling active collaboration between Italy and the USA.

Time schedule:

This PhD project is structured around well-defined tasks aligned with the research objectives. The work plan follows a logical sequence, with each task building upon the outcomes of the previous one. However, due to the volume of the datasets, some phases will overlap. This approach also allows effective data validation and testing during model training (see the project's timeline on Fig. 5).

Figures:

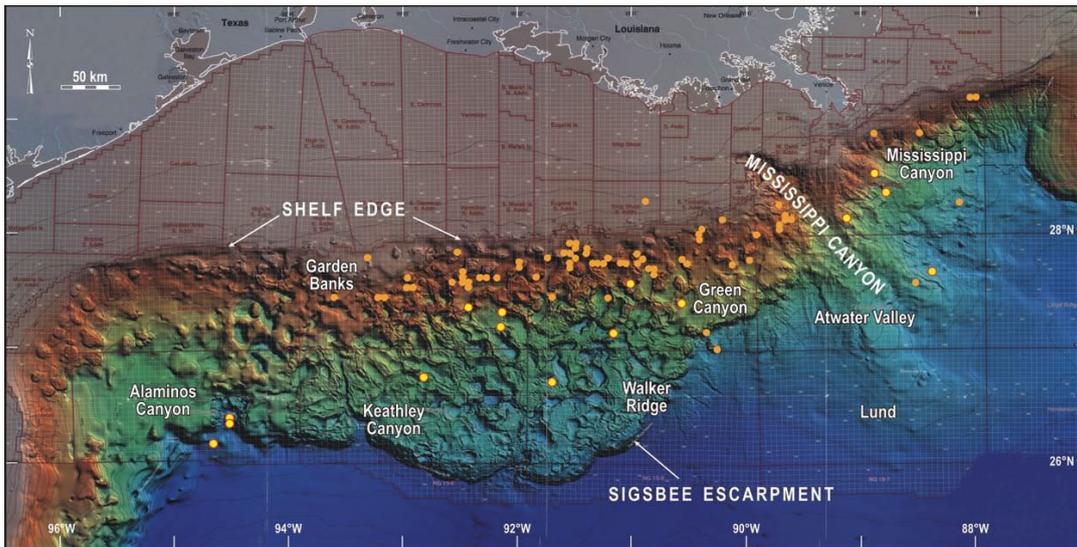


Figure 1. Multibeam bathymetric image of the northern Gulf of Mexico showing the location of all seep sites where seep-animal communities have been confirmed by ROV or manned submersible dives. [3]

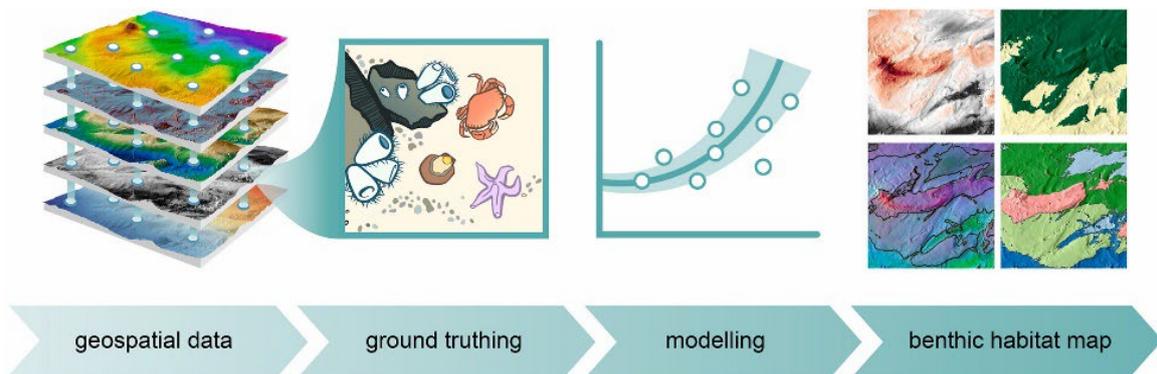


Figure 2: Generalized approach for producing benthic habitat maps [8].

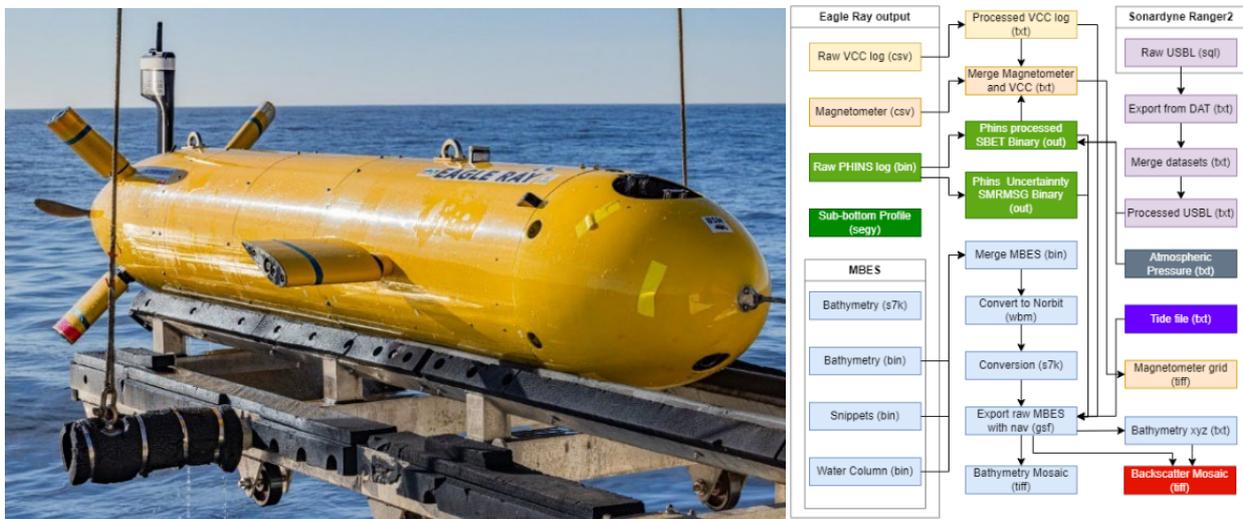


Figure 3: Eagle Ray AUV and its data processing workflow.

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