IN-SITU PRESERVATION OF DEEP-SEA SHIPWRECKS: UNDERSTANDING

BIOLOGICAL INTERACTIONS AND ENVIRONMENTAL IMPACTS

A Thesis

by

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ABSTRACT

Lack of research currently limits our understanding factors for preservation of shipwrecks along with the impact of these wrecks on the deep environment. Technology capable of assisting archaeologists in the study of these interactions exists, but lack of funding limits the opportunities to perform this research. As a result of lower deterioration rates of modern shipwrecks in the deep sea, shallow sites receive more attention. To draw some of the focus towards researching deep sea sites, this thesis discusses the deterioration factors shipwrecks face in the deep environment and why they need further study. *In-situ* conservation practices can surely cost archaeologists valuable cultural resources in the deep sea. Unburied parts of a shipwreck resting on the unconsolidated sediments of the deep-sea face several factors that eventually leads to their complete deterioration and the buried structures also face substantial risks. Increases in the understanding of these preservation factors should lead to an increase in effort to study sites on the bottom of the deep sea. This thesis also discusses the importance of limiting disturbances to shipwreck sites while performing archaeological research. Shipwrecks benefit the deep environment by becoming artificial reefs. Thus, increasing the biodiversity of the ecosystem. While some shipwrecks contain harmful substances that require recovery, the act of removing these wrecks may cause more unnecessary harm. Archaeologists should always consider the consequences of removing any shipwreck from the deep sea.

DEDICATION

I dedicate this thesis to both of my parents; Rhonda Rich, and Tim Frizzell and the rest of my family.

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CHAPTER I

INTRODUCTION

Continued exploration of the deep sea persists as an important component to many fields. Archaeologists, for example, may unlock secrets of the past by studying ships lost to the depths. Most shipwrecks occur in coastal waters, but several rest in the wide ranges of the deep sea. As discoveries of wrecks within the deep-sea increase, a need presents itself for a better understanding of deep-sea processes. Currently, due to a lack of research funding for deep-water sites and a focus on shallow-water sites, the relationship between the deep-sea environment and shipwrecks remains poorly understood.

This thesis describes currently understood processes involved with deep-sea site formation and the deterioration of shipwrecks. It also includes research on the influence of wrecks on the deep-sea environment. With the information gathered from several fields, this thesis will provide archaeologists with a better understanding of the state of deep-sea wrecks. Studying the processes allows archaeologists to grasp the risks associated with in situ preservation of significant deep-sea cultural sites. In order to properly conserve shipwrecks, researchers should strive to understand the formation of each site. Furthermore, studying the impact of individual wrecks on the deep environment will help determine whether their excavation is desirable. Increasing the understanding of deep-sea processes may lead to improved finical support for archaeological research.

Limited information on the deep sea within the field of archaeology alone requires information to be gathered from other sources including oceanography and marine biology. Fortunately, some of the preservation factors of wrecks in shallow-water sites overlap with those of the deep sea, but other aspects of deep-sea site formation processes remain unique and, therefore, require further study.[1] Physical, chemical, and biological interactions all contribute to the state of shipwrecks and each of these processes interacts with the others to either help or hinder preservation. In the deep sea, some of the deterioration of shipwrecks comes from physical damage and chemical reactions, while most decay results from the activity of marine organisms.[2] Shallow sites, on the other hand, usually incur more damage from the hydrodynamic environment. Meanwhile, human interactions play a key part in the loss of cultural artifacts from any site, including the deep sea.

Beyond the environmental impacts on the preservation state of shipwrecks, the risks and benefits each wreck provides to the environment also requires discussion. Shipwrecks

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This thesis uses *American Journal of Archaeology*.
[1] MacLeod 2016, 1-10.
[2] Laurea 2014, 129-141.

can provide valuable resources to marine life. Organisms rely on the presence of iron in the environment to survive and iron remains a limiting factor in the deep sea. Some parts of shipwrecks provide a more direct benefit by acting as a food source. The organic cellulose, hemicellulose, and lignin that gives wood its structure, provides nutrition to a variety of organisms. Most organisms that consume wood bore into it. Boring organisms exist anywhere with a supply of wood and oxygen. These boring organisms use the shipwrecks for protection and as a home. Several non-boring species such as corals even inhabit the surfaces of all types of shipwrecks and artifacts, creating artificial reef systems. Normally, the soft muddy bottom of the depths makes it difficult for corals to grow, as they need a substrate on which to attach and shipwrecks seem to work well.[3] Organisms growing directly on shipwrecks can encourage the growth of larger communities in the vicinity, which increases the biomass and biodiversity within the depths. Conversely, shipwrecks present hazards to the environment by introducing harmful chemicals that can alter the success rate of organisms.

Gathering data during archaeological research depends on the advancements of current technology. Most of the information gathered on marine sites in the past comes from excavations conducted by divers. However, an abundance of information waits outside of their reach. In order to solve this problem, it remains necessary to implement the various advancements in deep-sea technology. Some of the popular advancements

[3] Ballard 2007, 62-7; 2001, 607-23.

include Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), and human occupied vehicles (HOVs). Each of these incorporates different forms of remote sensing and scanning systems which can gather data from the seafloor. Additionally, systems utilizing sonar to make three-dimensional views of shipwrecks continue to evolve. Film and photography also benefit archaeologists by gathering otherwise unattainable visual data. Improvements in technology allow scientists to perform excavations on deep-water wrecks without divers in the water. Excavation of wrecks such as the *Mardi Gras* shipwreck demonstrate the capabilities of ROVs.[4] However, even with this new technology, problems persist in the depths that require continual innovation. For scientists to continue addressing these problems, they must understand the current technology available. Advancements from outside the field of archaeology will also provide necessary improvements. Archaeological exploration continues to grow with improved engineering.

As the first interdisciplinary study on archaeological remains in the deep sea, the Skerki Bank Project (1988) demonstrated the importance of the deep sea to archeological research.[5] Before this study, divers only studied sites of less than 100 meters. The average depth of the ocean is about 4000 meters with over 75 percent of the ocean reaching deeper than 1000 meters, thus, making prior exploration of the ocean by divers

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[4] Ford et al. 2010, 76-98.
[5] Ballard 2000, 1591-1620.

almost negligible.[6] Although coastal waters appear to contain more shipwrecks than deep water, deep water routes became more popular to sailors since they provided more safety from storms and pirates and the increased use resulted in a significant number of shipwrecks in deeper waters.[7]

The Skerki Bank Project, along with several others, discovered that the deep sea is not as calm and pristine as previously thought and natural physical processes such as water currents, erosion, pressure, and storms impact archaeological sites. The burial of artifacts due to some of these hydrodynamic forces can protect wrecks to some extent from chemical degradation and marine life, but the work of microorganisms in the sediment can still lead to deterioration. The chemical corrosion processes of metals continue in the deep sea, although at slower rates and with some differences from those of shallow sites. The existence of sulfate-reducing bacteria allows for the corrosion processes to occur even in the most anoxic environments and contributes to most corrosion. Concretions form differently as the environmental conditions vary in deeper waters and a unique type of concretion form, termed rusticles.

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[6] Ballard 2008, ix-x; see also Waller 2019.
[7] Wachsmann 2011, 202-31.

CHAPTER II

DEEP-SEA TECHNOLOGY

Most archaeologists rely on technology every day to study sites, especially when these sites are underwater. Archaeologists simply lack access to deep-water sites without the use of sophisticated equipment.[8] Some of the most essential pieces of technology to deep-sea archaeologists consists of those that gather accurate spatial data. Therefore, archaeologists favor geophysical tools that can map out a site and provide imaging, especially 3D imaging. Some of the data this equipment can provide, includes site boundaries, topography, structural components, and even data on artifacts within a site.[9] Archaeologists already significantly incorporate sonars, magnetometers, visual imaging systems and robotics into their study of underwater sites. In 1966 archaeologists already started to implement geospatial equipment into marine research.[10] Most of the deep-sea technology seen in archaeology complements survey work. These surveys rely heavily on the variety of remote sensing techniques. Also, these techniques require accurate navigation and GPS data.

[8] Warren et al. 2010, 1-11.
[9] Warren et al. 2010, 1-11.
[10] Blake 2010, 39-44.

Sonar

One of the most common yet useful tools for remote sensing remains sonar. In order to understand the various types of sonar equipment, the term requires a definition. The acronym SONAR stands for "Sound Navigation and Ranging" and in practice means the use of sound to detect objects and map the surroundings.[11] Archaeologists rely heavily on a variety of sonar equipment for surveying shipwrecks and other historical sites. Sonar originated in the US Navy and continues to improve in order to both meet military needs and the needs of researchers. The first listening device that led to sonar development appeared in 1906, when an American naval architect Lewis Nixon designed a system for detecting icebergs. Paul Langévin built the first passive sonar tasked with finding submarines in 1915 during World War I and by 1918, the British and the United States already starting using active sonars.[12] Passive sonar only detects sound coming from outside sources. However, active sonar requires sending out a signal and waiting for it to return. Archaeologists primarily rely on active systems to perform research underwater. Eventually, scientists began to mount sonars on the sides of vessels during the 1950s and at about the same time sonars became capable of gathering multiple echoes simultaneously from within a certain range.[13] Prior to this, sonar only measured echoes from a single point while locating large objects and measuring depth.

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[11] Hansen 2011, 3-38.
[12] Vegara 2019.
[13] Mazel 1985, 1.4.

In order to obtain measurements of distance, all sonar systems record the amount of time it takes for a sound pulse to return. By multiplying this time by the speed that sound travels through water (between 1405m/s to 1550m/s depending on conditions) and then dividing it by two will provide the distance of the target.[14] Dividing by two is required to get the distance since the sound pulse covers the distance twice within the measured amount of time.

Furthermore, every sonar system comes with a similar set of key components. These components consist of the transducer, the transmitter, the receiver, and the computer or control unit. The transducer converts energy for the system. Typically, transducers consist of a ceramic material referred to as Piezoelectric crystal. The material changes shape when an electric current is applied to it and conversely, it produces a current when it changes shape. Sonars utilize this function to create sound pulses when an oscillating electric current produced by the transmitter in the system induces vibrations in the material's shape. These vibrations produce sound by applying changes in pressure to the water. Then, once a sound pulse returns to the sonar system, the transducer produces an electric current from the vibration triggered by the wave. The receiver detects the new current produced by the transducer and amplifies it. Every step of the process requires monitoring and regulation with precise timing by an operating system. Usually, this operating unit or computer then displays the gathered data.[15]

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[14] Atherton 2011, 1.17; see also Mazel 1985, 1.1-3.24.
[15] Mazel 1985, 1.1-3.24; see also Atherton 2011, 1.5-2.45.

The display of data gathered by sonar systems or sonar imaging can be separated into two parts: range processing and beamforming. The calculations from the time required for the individual echoes to return results in the determination of range. Typically, the range data comes from the use of transmit waveforms. The original sonar systems utilized transmit waveforms or echoes referred to as pings. Pings are gated continuous-wave pulses which consist of a single tone. Some modern sonar systems now use phase-coded transmit signals, which are tones with changing pitch that typically rise in pitch for simplicity. The focusing of a signal collected from multiple receivers to a specific direction results in beamforming. Back-projection or Delay and Sum (DAS) serves as a form of beamforming that works by summing up the data gathered by the receivers and delaying it to a specific pixel in the imaging.[16]

Sonar equipment's diverse functions contribute to its widespread applications for archaeologists. There are multiple types of sonar that range from simple fish-finders to full-scale systems. Archaeologists can use inexpensive fish-finding sonars to find artifacts and shipwrecks in a defined survey area and to understand wildlife populations that might interfere with other sonar systems. Some of the slightly complicated types archaeologists rely on include sector-scanning sonar, and side-scanning sonar and sub-

[16] Hansen 2011, 3-38.

bottom profilers. While multibeam sonar, and synthetic aperture sonar are just a few of the more sophisticated options.

When using sonar data during surveys, archaeologists look for anomalies in the data that resemble shipwrecks and other artifacts. Larger objects will have large acoustic shadows that can be used to determine features of the ship.[17] However, the interpretation of sonar imaging shows bias in some cases and when done incorrectly can present problems in archaeology. During post-processing different signal "gains" or settings change the quality of the data. Archaeologists must maintain a strong understanding of the surroundings and environment during a survey as these factors can result in obstruction of the data. Surface reverberation caused by wave action or wind can distort parts of the image with horizontal and vertical motion of the equipment. Accurate sonar scanning relies on a consistently straight path. Changing the speed or direction of the survey vessel can affect the scale and range of the data or even lead to collisions with the seafloor or with objects on it. If the sonar equipment does strike a surface, the impact will create sounds overloading the data and the equipment could sustain damage. Another factor that impacts imaging occurs when another vessel comes within proximity during a survey. The vessel, along with its wake, may appear in the data. Even large structures in or above the water can appear in the data. Archaeologists

[17] Ballard 2008, 3-30; see also Morris 2019, 27-31.

need significant experience with sonar interpretations in order to correctly identify targets.[18]

Side-Scan Sonar

During the 1960s, side-scan sonars became commercially available for the first time and soon became an important aspect of archeological surveys.[19] Currently, researchers most commonly use this type of sonar due to its relative simplicity, affordability and applications.[20] This system sends out pulses from the side at a slight downward angle towards the seafloor. The smaller the angle the higher the resolution, but the shorter the range. In order to improve the total range of the system, usually researchers place the sonar on each side of a towed vessel. Since wider-beam angles remain unsuitable for obtaining high resolution, side-scan sonar requires the use of a horizontally narrow sound pulse which makes it difficult to place on a ship directly, as it requires maintaining accurate direction and the ship's unstable movement on the surface causes problems. To help solve this problem researchers typically place the sonar on a towfish (a small towed vessel or platform). They can also be placed on ROVs, HOVs and AUVs with the latter as the best option since it provides the most stability. AUVs also present a cheap alternative to using long tow cables, which researchers must lengthen for use in the deep sea in order to maintain a suitable distance from the seafloor.[21] As one example

[18] Atherton 2011, 1.5-46; see also Fish and Carr 1990; Morris 2019, 27-31.
[19] Shapreau 2001, 276-314.
[20] Hansen 2011, 3-38.
[21] Mazel 1985, 1.1-3.24; see also Bingham et al. 2010, 702-17.

showing the constraints of using a towfish over an AUV, the towfish Echo relies on a depressor weight to reduce the effect of heaving, or vertical movement of the ship.[22]

Scanning Sonar

Some archaeologists employ scanning sonars. This type of sonar relies on sound to produce a view in a circular or fan-like range. Often, the system rests on the seafloor mounted to a tripod and scans in a circular motion resembling a radar system.[23] Generally, one ping disperses at a time while the system rotates quickly. One standard use of this sonar comes from tracking divers as they explore a site. This set up works in a similar fashion to fish finders and can potentially achieve a full 360-degree view.[24] Even though some scanning sonars rest on the ocean floor, the geometry of the beam angles can gather more acoustic data than the seafloor alone.[25] Another application of scanning sonar comes from mounting the systems on the front of vessels in order to gather data along its path.[26] This hull mounting also applies to underwater vehicles, particularly AUVs. Scanning sonars mounted in this way are referred to as OAS or Obstacle Avoidance Sonar. These sonars originally served to provide aid to pilots attempting to avoid collisions when operating ROVs or HOVs and this still applies for

[22] Ballard 2008, 3-30.
[23] Atherton 2011, 3.7-62.
[24] Hansen 2011, 3-38.
[25] Atherton 2011, 3.7-62.
[26] Hansen 2011, 3-38.

AUVs today. ROVs and HOVs, on the other hand, now generally contain sonars solely for research purposes.[27]

Sub-Bottom Profilers

In addition to side-scan sonars, sub-bottom profilers also see consistent use in archaeology. Typically, sub-bottom profiling sonars emit lower frequency pings than side-scan sonars, despite being referred to as high-frequency seismic reflection systems. These lower frequencies penetrate the substrate to detect buried targets. Like side-scan sonar, the profilers often trail behind the ship. However, instead of casting pulses out to the side, sub-bottom sonars send a ping straight down. This process yields stratigraphic data based on the varied times for returns.[28]

An important example of the sub-bottom profiler's archaeological use comes from the study of Henry V's flagship, *Grace Dieu*.[29] Previously, researchers managed to only gather minimal data on the ship's lower structures since it remains buried. However, with the use of a high-resolution 3D acoustic sub-bottom chirp system with RTK-GPS archaeologists acquired images of the hull. They then created a 3D image of the buried remains of the *Grace Dieu* by selecting images from the acoustic data and combining them by means of a software program called *ShipShape*. The reconstruction from the

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[27] Atherton 2011, 1.5-2.45.
[28] Ballard 2008, 3-30
[29] Plets et al. 2009, 408-18.

combined vertical and horizontal imaging successfully provides a representation of the vessel. Although this model lacks the accuracy achievable by divers measuring the ship directly, this study showed that sub-bottom sonars can provide working 3D reconstructions of ships even when buried under sediment.[30]

Multibeam Bathymetric Sonar

One of the most useful pieces of equipment, multibeam-bathymetric sonar, provides archaeologists with more accurate positional data. By combining data from multibeam systems with visualization software, researchers can create 3D representations of sites.[31] Typically, archaeological surveys start with multibeam-bathymetric sonar or single-beam sonars to map out the area. A bathymetric system applies a swath of beams directly towards the seafloor, relying on hull-mounted transducers and receivers instead of using a towfish as in the case of side-scan sonar.[32] Multibeam-bathymetric sonar, which is connected to the bottom of the hull, sends multiple sound pulses creating a wide across-track swath with a narrow along-track beam width. With this set up, multibeam bathymetric sonar scans directly below the ship and outwards continuously within range. This means there is no gap in the data directly below the hull as with side-scan sonars.[33] In some cases, advanced pieces of this type of equipment allows for a resolution down to a centimeter scale.[34] General features of the sea floor mapped by this technology

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[30] Plets et al. 2009, 408-18.
[31] Warren et al. 2010, 1-11.
[32] Ballard 2008, 3-30.
[33] Foley et al. 2009, 269-305.
[34] Singh et al. 2000, 39-43.

provides crucial data necessary for the use of more detailed remote-sensing equipment.[35] Archeological projects including ScapaMap and The Rapid Archaeological Site Survey and Evaluation study (RASSE) provide excellent data gathered from multibeam sonar. The systems from the ScapaMap project show improvement over side-scan sonar records by reducing the obscuring of data caused by acoustic shadowing. This would be especially useful for objects standing high into the water column. The RASSE project took place in 2004 with the goal of further developing the use of geophysical technology for archeological sites. The project showed that multibeam sonar can accurately map shipwrecks in a timely fashion.[36]

Synthetic Aperture Sonar

The future for archeological surveys lies in SAS, or Synthetic Aperture Sonar. The setup of SAS systems resembles that of side-scan sonars and even shows the same nadir, or gap in data directly below the towfish in use. The images produced by SAS look like side-scan sonar images but with much higher resolution, obtainable over significantly larger ranges.[37] Even with ranges up to several hundred meters, SAS gathers data with resolution to a centimeter scale. The technological difference that allows SAS to provide a higher azimuth (along-track resolution) than other systems, resulting from syncing multiple pings to the same point rapidly. Several pulses create a large synthetic

[35] Ballard 2008, 3-30.
[36] Warren et al. 2010, 1-11.
[37] Ødegård et al. 2017, 1-13.

array with post-processing calculations. Just a single pixel contains data from a significant number of pings. Additionally, the resolution of SAS systems shows both range and frequency independence. Range independence comes from increasing the length of the synthetic array along with range. Frequency independence comes by increasing the length of the aperture when decreasing frequency. This range independence provides high resolution even with the longest of ranges. Furthermore, frequency independence from obtaining high resolution allows researchers to change the frequency for other reasons, such as using lower frequencies to penetrate surfaces.[38] The potential accuracy of SAS illustrated by the system PROSAS developed by Applied Signal Technology, Inc (AST) provides an excellent example. This system can detect objects within a $0.03m^2$ space at a 150m range. Furthermore, the accuracy even stays constant for the entire range of the scan, whereas traditional side-scan sonar loses resolution and warps images towards the ends of the system's range.[39]

Achieving results with high accuracy does not come without drawbacks. Even subtle movements of the system during the survey require calculated adjustments of the data, relying heavily on the accuracy of sensing equipment to detect these movements. Larger ranges see more impact from movements of SAS and increase the need for accurate navigation because the length of the aperture increases with range.[40] Additionally, the

[38] Hansen 2011, 3-38; see also Marx et al. 2000, 717-21.
[39] Lawrence 2010.
[40] Hansen 2011, 3-38; see also Caporale and Petillot 1-12; Ødegård et al. 2017, 1-13.

sheer amount of data SAS systems collect creates several issues. Large amounts of data require massive storage space. Furthermore, larger data files require higher computing power and can take a significant amount of time to process. Images created from overlapping data points will have massive file sizes that can become difficult to manage. Creating 3D models with synthetic aperture sonar would require even larger files. In order to combat these problems, researchers may cut out portions of the data and lose resolution. With long processing times and equipment cost, some researchers simply cannot afford to employ SAS in their surveys. However, because improvements in technology tend to reduce the cost and difficulty of research techniques, SAS may become a more affordable technique in the future. In some cases, the high-resolution results currently achievable with SAS may prove worth the costs. That said, there are interpretation issues when dealing with SAS data. SAS requires a flat landscape to function properly and tall objects can obscure data. Additionally, blooming effects, or scattered data points within images, occur with some objects and cloud the surrounding area of the image, especially when scanning artifacts with high reflective corners. Processing software struggles to deal with the blooming effect.[41]

[41] Morris 2019, 72-74.

Magnetometers

Magnetometers remain one of the most important tools for archaeologists in addition to sonars. In 1956, archaeologists applied magnetics in the field for the first time. Magnetometers became a crucial tool for identifying buried artifacts and shipwrecks.[42] Often magnetometer ("mag") data collected simultaneously with sonar data correlates well in identifying shipwrecks during survey work and archaeologists generally prefer this method. In order to gather data, magnetometers detect the magnetic field of the earth. While surveying, the equipment will detect anomalies or disruptions in the magnetic field caused by possible artifacts and shipwrecks.[43] Any magnetic object can disrupt the field as can changes in the sediment. Archaeologists either look for clusters of individual anomalies or large ones. Unfortunately, there exists some problems with mag data. For example, particularly magnetic substrates or surroundings can interfere with results. Also, mag data does not easily identify an object and often a visual search or a sonar scan follows the survey.[44] Even solar storms cause problems with data collection by creating spikes within the data that can resemble those produced by shipwrecks and artifacts. If researchers take note of geomagnetic storms occurring during surveys the impact decreases, but the anomalies can still cover up a possible target. For example, postprocessing of the data to remove anomalies caused by geomagnetic storms may inadvertently remove anomalies created by archaeological

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[42] Fassbinder 2017, 499-514.
[43] Ballard 2008, 3-30.
[44] Gearhart 2011, 90-113; see also Fassbinder 2017, 499-514.

sites.[45] This example shows why researchers often implement more than one survey technique at a time.

Photogrammetry

Another increasingly popular and important archeological tool with promising results is multi-image photogrammetry. The popularity of this method results from its low cost and automated processing. Multi-image photogrammetry takes several overlapping images of an object and combines them to make a point cloud. The points form a three-dimensional representation of the targeted object. The point cloud obtained resembles point clouds in laser scanning, except the points in photogrammetry maintain color detail. The density and accuracy of the point cloud depends on the number of images taken and their resolution. Additionally, processing software like PhotoScan by Agisoft make the process easier and increases accuracy. One of the most important components of the software includes the algorithm Scale-Invariant Feature Transform or SIFT. This algorithm permits researchers to take photos while not worrying about maintaining a constant distance and angle from an object for consistent scaling.[46] Previously, photogrammetry researchers used photo mosaicking or stereo photogrammetry. Images for stereo photogrammetry must come from a camera with a known lens geometry. The distance from the object model must stay constant, and the process requires a planar surface. Stereo photogrammetry can only combine two images at a time while

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[45] Carrier 2016, 1-14.
[46] McCarthy 2014, 175-85.

mosaicking can implement several but lacks accuracy.[47] The first use of stereo photogrammetry for studying a shipwreck took place in 1963 by George Bass.[48]

Thanks to modern software, anyone can incorporate photogrammetry into their research. Images taken with any camera can produce 3D representations of objects and terrain. However, this could present problems. The simplicity of photogrammetry can lead to inexperienced individuals producing subpar results. Professional archaeologists should apply high-resolution cameras and follow traditional guidelines to maintain accuracy.[49] Obtaining acceptable results requires adequate lighting, consistent angles, lack of obstructions and keeping the target stationary. Primarily because of sunlight, photogrammetry may prove more effective in shallow sites, but the use of artificial lighting allows for applying photogrammetry in deep sites. Furthermore, photogrammetry in the deep sea maintains greater potential than in shallow sites with the calmer environment of the depths containing less obstructions for the images and reduced water movement allows for more precision.[50]

Underwater Vehicles

Autonomous underwater vehicles (AUVs), remotely operated underwater vehicles, (ROVs) and human operated vehicles (HOVs) and submersibles, allow for the efficient

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[47] Ballard 2008, 30-41; see also McCarthy 2014, 175-85.
[48] Drap et al. 2015, 1-24; see also Bass 1970.
[49] Boehler 2004, 291-8.
[50] Bascom 1971, 261-9; 1972, 34-6; see also Ballard 2008, 1-41; Wachsmann 2011, 202-31.

gathering of data on deep shipwrecks. HOVs started seeing use in deep-sea research around the 1960s. Meanwhile, one of the first archeological studies that completely depended on the use of an ROV (named "Jason"), did not take place till 1989. This survey focused on a 4th-century AD merchant shipwreck at 800 meters. Fortunately, this expedition proved effective and opened the door for more ROV studies and scientific research. Today, some of the most valuable data comes from the implementation of this type of equipment.[51]

Archaeologists commonly utilize remote sensing and imaging equipment during their studies by mounting the equipment on the various types of underwater vehicles. At first, ROVs aided archaeologists in locating and studying shipwrecks.[52] Now, AUVs have become the best option for survey work, as the potential accuracy of surveys with AUV-mounted sonars far exceeds any other option. AUVs provide the best host for remote sensing equipment, and cameras when carrying out research in the deep sea. This is partly because AUVs can maintain constant altitude and straight, continuous paths better than other underwater vehicles. Furthermore, AUVs can maintain distances of 5m above the seafloor, considerably lower than towed vehicles. By hovering so low AUVs can collect greater spatial resolution.[53] For example, during the survey of the *Ewing Bank Wreck*, an AUV with a multibeam sonar collected data that showed sufficient resolution

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[51] Bingham et al. 2010, 702-17.
[52] Bingham et al. 2010, 702-17.
[53] Wynn 2014, 451-68; see also Roman and Mather 2010, 327-340.

to differentiate between copper sheathing, wood, and ballast. Survey of the 7,000 Ft-deep wreck demonstrated similar results with showing the differences in material and the sonar even picked up running rigging.[54]

Without the need for tethering, AUVs maintain distinct advantages over ROVs. AUVs navigate on their own by using sensors and following predetermined paths. Therefore, researchers can focus their attention on other tasks instead of the operation of the vehicle. In addition, one major disadvantage ROVs possess is that in the deep sea, the need for extensive lengths of tether can prove expensive and difficult to manage. For example, currents can push on the cables making control of an ROV difficult and this problem escalates with depth, as the total submerged surface area increases with a longer cable. Additionally, while being tethered to the ship, surface movements due to forces such as wave action, can affect the ROV's position, thus, requiring the use of sophisticated dynamic positioning systems.[55] Archaeologists can reduce this problem by attaching a downweight or an additional ROV system above the main ROV.[56] This technique proved successful with operating Jason with its partner ROV *Medea*.[57]

With more direct control than AUVs, modern ROVs present an advantage over AUVs when retrieving artifacts from the seafloor. HOVs hold this advantage over AUVs as

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[54] Warren et al. 2010, 1-11.
[55] Bingham et al. 2010, 702-17; see also Wynn 2014, 451-68.
[56] Søreide 2011, 3-22.
[57] Ballard 1993, 1673-87; 2002, 151-68.

well, but HOVs have limited bottom time and move slowly so they are well suited for small scale study and direct observation but not for more extensive surveys.[58] Numerous studies of deep-water wrecks demonstrate the artifact recovery capabilities of ROVs. For example, in 2003 an ROV removed artifacts from the *SS Republic,* which lies at depth of 500m.[59] Later on, the partial excavation of the *Mardi Gras* shipwreck depended significantly on a ROV. Several intact artifacts recovered from the wreck's depth of 1,220m provided substantial data.[60]

A recent discovery in the Baltic Sea, the *Ghost Ship*, provides an example of a ROV's potential in collecting sonar data and imaging.[61] However, this expedition also showed the difficulty in achieving results. The *Ghost Ship,* resting at 100 meters, remains in darkness and required significant lighting for adequate visual inspections of the entire vessel. In order to lower lighting between the masts of the ship, the survey vessel *Icebeam* held its position within a 0.2m accuracy. Thorough video recordings made by ROVs helped develop site plans of the shipwreck along with accurate data gathered with laser measurements. In addition to video and laser equipment, an ROV mounted with a multibeam echosounder surveyed the site. This echosounder penetrated the hull of the ship which led to the creation of a unique and accurate 3D model of the ship with cross-

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[58] Bingham et al. 2010, 702-17.
[59] Dobson and Gerth 2009, 1-44.
[60] Ford et al. 2010, 76-98.
[61] Eriksson and Rönnby 2012, 350–61; see also Dixelius et al. 2011.

sectional views. Archaeologists will find the model of the *Ghost Ship* a vital tool in understanding the traditions behind the ship's construction.[62]

Despite the distinct advantages of each type of underwater vehicle, they are often used in conjunction with each other during deep sea investigations. Take the *Mica* shipwreck project for example.[63] This expedition required the use of multiple ROVs, Texas A&M's deep-tow remote sensing equipment, the U.S. Navy research submarine NR-1 and AUVs in order to safely gather the necessary data.

Summary

Without the several advancements in technology we see today the possibility of deep-sea archaeology would not exist. Even with shallow-water sites, archaeologists rely on geophysical technology. Sonars including side-scan, multibeam echo sounders, and synthetic aperture sonar provide archaeologists with the means to locate abandoned or lost ships and artifacts. It appears that SAS shows the most promise for long range and high accuracy surveys. In order to find and study buried shipwrecks archaeologists need to apply sub-bottom profilers and magnetometers. This is especially useful in the deep sea as the unconsolidated sediments potentially hold vast numbers of artifacts waiting to be discovered. The best use of deep-sea technology remains the combination of different technologies and techniques. This includes combining AUVs and ROVs with

[62] Eriksson and Rönnby 2012, 350–61; see also Dixelius et al. 2011.
[63] Jones 2004, iii-48.

geophysical and visual equipment. Excavations of artifacts from deep sea wrecks without the presence of divers already occur with the help of ROVs and HOVs. Multibeam echo sounders mounted on ROVs and AUVs could achieve results that ordinarily require taking apart the hulls of ships.

CHAPTER III

SHIPWRECK PRESERVATION AND SITE FORMATION

As discoveries of wrecks in the deep-sea increase, a need for a better understanding of deep-sea processes presents itself. Currently, due to a lack of funding and a focus on shallow sites, the relationship between the deep-sea environment and shipwrecks remains poorly understood.[64] In order to properly research and conserve shipwrecks, archaeologists should strive to understand the formation of each wreck site. Fortunately, some shallow site preservation factors overlap with those in the deep sea, but other aspects of deep-sea site formation processes remain unique and, therefore, need further study.[65] Physical, chemical, and biological interactions all contribute to the preservation state of shipwrecks and each of these processes interacts with the others to either help or hinder preservation. In the deep sea, some of the deterioration of shipwrecks comes from physical damage and chemical reactions, but mostly from the activity of marine organisms.[66] Shallow sites, on the other hand, usually incur more damage from the hydrodynamic environment.[67] Meanwhile, human interactions play a key part in the loss of cultural artifacts from any site, including the deep sea.

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[64] Ballard 2008, ix-x; see also Wachsmann 2011 202-31.
[65] MacLeod 2016, 1-10
[66] Ward et al. 1999, 561-70.
[67] Wachsmann 2011, 202-31.

Physical Factors

The Sinking Event

From the initial sinking event, shipwrecks of the deep maintain a better chance of preservation than shallow sites.[68] Most of these wrecks were not involved with collisions with rocks and coral reefs and just filled up with water instead which means they stay mostly intact.[69] Wrecks in deep water also tend to settle upright on the bottom. This occurs as shipwrights naturally design ships as slightly bottom-heavy to increase stability when sailing. With extra time to reach the seafloor, sinking ships eventually correct themselves due to gravity.[70] When shipwrecks settle upright on the soft sediment of the deep sea, they will generally sink up to the waterline or deck and preserve better than wrecks in other positions.[71] When a ship rests in its naturally designed position, the structures support each other more efficiently and the burial of the main structural components keeps the ship together longer.[72]

Coinciding with settling upright, deep-water wrecks tend to sink into the soft, unconsolidated sediment, or muddy substrate of the ocean depths. The sediment provides an anoxic environment that can help protect shipwrecks from organisms or physical degradation.[73] Most of the burial of shipwrecks and other artifacts in the deep

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[68] Ballard 2000, 1591-1620; see also Church 2014, 27-40.
[69] Tolson 2009, 1-13; see also Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7; Church 2014, 27-40.
[70] Søreide 2011, 156-63.
[71] Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7; see also Church 2014, 27-40.
[72] Church 2014, 27-40.
[73] Søreide 2011, 156-63; see also Wachsmann 2011, 202-31; Church 2014, 27-40.

sea comes from the initial impact and their weight. A soft muddy bottom allows ships, especially the heavier iron and steel ships of modern wrecks, to sink deep into the bottom upon initial impact.[74] Over time, these deep-sea wrecks will sink further into the substrate. This rarely occurs for shallow marine sites with their hard or rocky substrates. Even sand does not give as much as deep-sea mud.[75]

Hydrodynamic Environment

Beyond the initial sinking event, naturally occurring physical interactions generally play the first, and probably the most obvious, role in the preservation of shipwrecks. When considering the stability of a site, archaeologists should remember that environments can change suddenly or vary over time. The differences in currents, tides, wave action, sediment movement, pressure, temperature, and weather make up the individual hydrodynamic environments that determines the stability of underwater cultural sites.[76] Shallow wrecks see the most damage from hydrodynamic forces while deep shipwrecks usually avoid some of the high energy hazards that devastate wrecks.[77] Wrecks below 100m in depth lie outside the influence of tides or wave action and, thus, take less damage from storms.[78] Most artifacts lay unbroken on the deep-sea floor because of this lack of intense wave action that shallow water presents.[79] However, even in the deepest

[74] Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7; see also Church 2014, 27-40.
[75] Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7.
[76] Ward et al. 1999, 561-70.
[77] Ward et al. 1999, 561-70.
[78] Søreide 2011, 156-60; see also Tolson 2009, 1-13.
[79] Ballard 2000, 1591-1620.

parts of the ocean, the physical environment still directly contributes to the state of lost ships. For example, storms still cause deterioration in the deep sea by changing the chemical concentration of the seawater, biological activity, and by reinforcing the problems caused by other hydrodynamic forces like currents.[80] Within the deep sea, shipwrecks face a hydrodynamic force that shallow sites avoid, pressure. While a ship sinks, movement through the water column creates a pressure wave behind the wreck which damages the ship. Pressure also causes artifacts and parts of a hull to collapse when they contain gaps or air pockets that do not fill with water immediately.[81] The pressure within the ocean increases by one atmosphere for every 10m.[82] The full potential impacts of pressure on wrecks in the deepest parts of the ocean still remains unknown.[83]

The main hydrodynamic force acting on non-coastal shipwrecks, especially in the deep sea, is water currents.[84] Currents carrying sediment or debris continuously erode the surfaces of ships and artifacts. Any surface remaining exposed could receive damage from intense currents. Even light currents containing sediment can deteriorate soft surfaces like the waterlogged wood of a shipwreck. Some fragile artifacts, such as glass, collapse under the added weight of sediment accumulation. However, even if an object receives erosion damage from currents carrying sediments initially, the eventual burial

[80]Ward et al. 1999, 561-70; see also Laurea 2014, 39-44, 129-135.
[81] Søreide 2011, 156-60.
[82] Miller and Wheeler 2012, 292; see also Søreide 2011, 156-60.
[83] Søreide 2011, 156-60.
[84] Laurea 2014, 39-44, 129-135.

under such sand and other debris generally offers the best protection from erosion.[85] The covering of the artifacts also puts them in an anoxic environment which reduces some of the activities of organisms and limits the chemical effects of the seawater. For artifact burial to occur, a soft and light substrate is necessary. Hard rocky sediment cannot shift easily with currents.[86] This provides yet another benefit to the ocean depths often consisting of a soft unconsolidated sediment. At the same time though, deep-sea currents move slowly and often not strong enough to bury the shipwrecks completely. Being far from rivers responsible for supplying fresh detritus and other materials into the ocean, as well as far from shores, the sedimentation rates remain low.[87] Even the *Gulfpenn* wreck site located in the Gulf of Mexico, which receives extensive sediment input from the Mississippi River, shows low sedimentation rates by resting in deeper waters.[88] Low sedimentation rates on shipwrecks also indicates a reduction in erosion processes and heavy disturbances.[89] There exist some regions in the deep sea that still experience strong currents. For example, the 500-meter wreck of the steamer *Republic,* sits in the gulf stream and experienced significant deterioration from the strong currents.[90]

[85] Laurea 2014. 39-44, 129-135
[86] Ward et al. 1999, 561-70.
[87] Ballard 2000, 1591-1620.
[88] Church et al. 2007, 90-93; 2009, 50-63.
[89] Ballard 2000, 1591-1620.
[90] Tolson 2009, 1-13.

Besides the erosion of object surfaces directly, ocean currents can cause other problems. Strong currents can shift artifacts from their original location. This can make it harder to locate them or increase the difficulty in studying the association between artifacts' original positions and their cultural significance or the origin of the associated ship. Archaeologists researching the deep sea worry less about this issue due to the generally weaker currents mentioned previously, especially for sites over 1,000m in depth,[91] but this still remains a problem as artifacts can separate from the wreck during sinking and currents during the long process can scatter the artifacts.[92] Also, the more continuous currents found in the deep-sea cause scouring issues and unburial. Scouring occurs when a vortex current forms around objects and removes sediment deposits on, around, and below the objects. In some cases, the sediment protecting objects can be completely displaced.[93] The scouring process can even remove protective corrosion layers and concretions.[94] These consist of protective accumulations of biological components, calcium carbonate, magnesium hydroxide, sand, and various corrosion products.[95] The removal of sediment and concretions leaves the artifacts more exposed to the environment.[96] If parts of a shipwreck lose support from sediment underneath, they may start to collapse and sustain more damage. This scouring seems to occur often in the deep sea. For example, most sites researched during the Skerki Bank project showed

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[91] Bascom 1971, 261-9; see also Drap et al. 2015, 1-24.
[92] Søreide 2011,156-63.
[93] Ballard 2000, 1591-1620; see also Ward et al. 1999, 561-70; Laurea 2014, 39-44.
[94] Tolson 2009, 1-13.
[95] Hamilton 1999, 38-88.
[96] Ward et al. 1999, 561-70; see also Laurea 2014, 39-135.

significant scouring. With help from the JASON system, researchers discovered amphoras around the *ISIS* wreck site resting in individually unique scouring pits that matched their shapes. The scouring appeared to take place over a long period of time with a constant current. Supporting this, pits were not formed around more recent objects found on the seafloor indicating that the pits located there do not form quickly or during impact.[97] Similar conditions, found on the *Tanit* and *Elissa* wrecks bolster the evidence of this scouring process.[98]

Chemical Deterioration

In the ocean, chemical deterioration separates into two parts that consist of the direct corrosion of objects in seawater and the indirect biochemical reactions with the surrounding environment. The mere presence of seawater causes preservation concerns for most artifacts, making this a problem for deep-water wrecks too.[99] Seawater consists of complex combinations of salts, silts, dissolved gases, living organisms, and decaying organic material.[100] Several chemicals lead to deterioration or preservation of all types of artifacts. Each chemical component of the seawater influences the corrosive effects of the others. This makes determining the influence on the exact corrosion rate of artifacts by the different seawater components difficult.[101] Deep shipwrecks do benefit somewhat more from variations of chemical concentrations than from those found in

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[97] Ballard 2000, 1591-1620.
[98] Ballard 2002, 151-68.
[99] Ward et al. 1999, 561-70.
[100] Venkatesan et al. 2002, 257-66.
[101] Ward et al. 1999, 561-70.

shallow water. For example, salinity levels drop with depth, exposing artifacts to lower concentrations of salts and even the slightest changes in salinity reduces corrosion rates.[102] Deep-water wrecks also benefit from other environmental conditions, such as temperature and light levels, although, some chemical processes become more prevalent in deeper environments.[103] As one beneficial condition, near-freezing temperatures in the depths reduce the rate of chemical reactions that lead to decay.[104] Furthermore, since deeper waters lack light, the direct deterioration from light exposure simply does not exist.[105] Reduced light levels indirectly improve conditions by inhibiting some activities of marine life.[106] Seawater's pH drops at depths creating means more acidic conditions that leads to lower diversity in marine life capable of degrading wrecks. Usually acidic conditions lead to higher corrosion rates of metal artifacts.[107]

As one of the most important factors to the preservation state of shipwrecks in the deep sea, the presence of oxygen contributes directly to the chemical deterioration of shipwrecks and influences other reactions. Therefore, anoxic conditions can lead to the greater preservation of sites.[108] Most deep-ocean environments maintain oxygenated conditions within the water column, only at lower levels than in the shallows, but the substrates in deep areas retains more anoxic conditions. Although, some parts of the

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[102] Søreide 2011, 160.
[103] Laurea 2014, 39-135.
[104] Bascom 1971, 261-9; see also Drap et al. 2015, 1-24; Søreide 2011, 160.
[105] Munro 2012.
[106] Søreide 2011, 159.
[107] Munro 2012.
[108] Ward et al. 1999, 561-70.

water column in the deep sea does become anoxic and maintains the best preservation.[109] A study near West Florida showed significantly lower oxygen levels nearing anoxic conditions around a depth between 400 and 500 meters then depths beyond 500 meters gradually become more oxygenated again.[110] This drop in oxygen level results from the end of the phototrophic zone. At this level the ability of photosynthesis to produce oxygen in organisms, such as algae, drops significantly. The consumption of detritus and decay of organisms, especially algae, at this level consumes oxygen at rates faster than it replenishes. Below this zone, biological activity and metabolic rates drop with higher pressure and lower temperatures, which means a reduction in oxygen consumption, and circulatory ocean currents bring in more oxygen.[111] These currents replenish oxygen in the deep when the saturated surface waters near the Artic cool and sink down to the depths. The cycle then continues by the deeper waters heating up and rising near the equator.[112]

Chemical Corrosion of Iron

Oxygen levels play a significant role in the deterioration of iron artifacts. Corrosion of iron and steel continues to occur in the deep sea similar in manner to the shallows, but at a slower pace. The chemical corrosion rate of steel could proceed roughly four times slower in deeper waters.[113] Electrochemical corrosion of iron contributes to the bulk of

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[109] Søreide 2011, 160-63.
[110] Munro 2012.
[111] Søreide 2011, 156-64; see also Munro 2012.
[112] Munro 2012; see also Venkatesan et al. 2002, 257-66.
[113] Venkatesan et al. 2002, 257-66.

the degradation processes and requires the presence of oxygen. The electrochemical corrosion of iron takes place faster in all marine sites than on land or in freshwater. Due to lower salinity in the deep sea, electrochemical corrosion occurs less aggressively than in shallow sites.[114] The various metal compounds and salts dissolved in seawater cause iron molecules to lose electrons, converting them to soluble ions. This results from iron's greater negative electrode potential, which causes it to act as an anode and lose electrons to solutions when in the presence of metals with more positive or less negative potential.[115]

Besides metals dissolved in the seawater, different parts of the same metal artifact can display different negative potential. For example, parts of iron under stress from bending or damage gain more negative potential. This results in electrochemical corrosion within the metal itself. Shipwrecks tend to receive plenty of stress during the sinking process making this a common issue.[116] Additionally, the pressure of the deep sea could potentially cause tremendous stress to parts of a wreck, especially hollow components not filled with water, which suggests that high pressure attributes to making parts of a wreck more anodic, allowing for increased corrosion.[117]

[114] Søreide 2011, 156-160
[115] Hamilton 1999, 38-88.
[116] Hamilton 1999, 38-88.
[117] Søreide 2011, 156-159.

The electrochemical corrosion of iron results in a series of corrosion steps that eventually repeats itself until the original metal completely corrodes away. When a metal loses electrons in the presence of water, hydroxides form by replacing one of the hydrogen atoms attached to the oxygen in a water molecule with the electron. Then sodium hydroxide forms in the presence of sodium ions. The act of electrons leaving the iron produces ferrous ions which combine with free chloride ions to produce the slightly acidic and hydrolyzing ferrous chloride.[118] Dissolved oxygen in seawater reacts directly with ferrous chloride corrosion compounds from the already corroding iron. The ferrous chlorides oxidize to ferric chloride and ferric oxide. Both ferrous chlorides and ferric chlorides dissolve in water and combine with sodium hydroxide to yield ferrous hydroxide. Newly formed ferrous hydroxide reacts with oxygen to make ferric hydroxide. This compound precipitates in alkaline or neutral conditions and the hydrated form may even form a protective layer on marine artifacts. Hydrated ferric hydroxide prevents oxygen from reaching the iron and corrosion layers beneath its surface. Below this layer and in anoxic conditions hydrated magnetite and black magnetite form from the ferrous hydroxides. In addition to forming ferrous hydroxide, ferrous chlorides and ferric chlorides combine with water to form hydrated chlorides, which then form ferric oxide and hydrochloric acid. Once hydrochloric acid forms it creates a cycle that continues until all non-corroded metal disappears by oxidizing metal to form more ferric and ferrous chlorides with water and hydrogen respectively.[119]

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[118] MacLeod 2016, 1-10; see also Hamilton 1999, 38-88.
[119] Hamilton 1999, 38-88.

Corrosion processes of iron eventually lead to the formation of concretions.[120] The amount of phosphorus within iron artifacts and concentrations of iron help determine the thickness of marine concretions.[121] Changes in pH during the corrosion of iron artifacts allow calcium carbonate and magnesium hydroxide to mix with marine life, sand, and the corrosion products consisting mostly of ferrous sulfide, ferrous hydroxide and magnetite. This concretion mix coats the entire surface of iron artifacts and forms a mold around it. Once the concretion forms, electrochemical corrosion stops since it separates the artifact from other metals and oxygen. This separation provides artifacts with protection from other sources of corrosion as well. Additionally, the hard shell protects artifacts from physical abrasions or erosion, but the artifacts still undergo anoxic corrosion processes.[122] Chlorides even seep in to satisfy electrical neutrality. In fact, the chloride concentration inside concretions could reach three times higher levels than in natural seawater. Chloride ions heavily corrode ferrous materials directly. Acids created during the decay of iron even dissolve calcareous minerals and form iron carbonates. Ferrous chlorides increase inside the concretions and lower the pH further. Therefore, archaeologists could analyze the rate of decay of artifacts by measuring the pH levels inside.[123]

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[120] Hamilton 1999, 38-88.
[121] MacLeod 2016, 1-10.
[122] Hamilton 1999, 38-88; see also González-Duarte et al. 2017, 301-10.
[123] MacLeod 2016, 1-10; see also Ward et al. 1999, 561-70; Bethencourt et al. 2018, 98–114.

The concretion-forming process occurs readily in shallow sites and can apply to some deep sites, but concretions often form somewhat differently in deeper waters. Levels of calcium carbonates diminish with depth, so the deep ocean absorbs carbonates instead of leaving them behind to form concretions.[124] As a key component of concretions, ferric hydroxide along with the calcium carbonates cannot precipitate in deeper waters easily with more acidic conditions. This presents part of the reason why certain types of steels do not form protective layers in deep waters.[125] As another factor, Iron (III) oxide-hydroxide or ferric oxyhydroxide stands as the most common form of corrosion found on mild steel in deep waters. Since it forms as a porous corrosion product, it allows for more unhindered corrosion compared to the those that form concretions. Even considering this lack of protection, the rate of corrosion for mild steel remains lower in deeper water.[126] Instead of the traditional concretion, in deep water rusticles form from the activity of marine microbes.[127] For more detail on this process see the end of the biological deterioration section further below.

Deterioration from Low Concentrations

As another source of chemical impacts, the deep sea lacks some minerals, such as calcium carbonates and other materials in comparison to shallow sites. This lack of minerals can harm archeological artifacts while also proving beneficial in other cases.

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[124] Wachsmann 2011, 202-31.
[125] Venkatesan et al. 2002, 257-66.
[126] Venkatesan et al. 2002, 257-66.
[127] Cultimore and Johnston 2008, 120-132.

For example, fewer chemically active components in the seawater reduces the amount of breakdown processes. However, the lack of dissolved minerals in deep water can lead to components leaching out of artifacts or even their complete disappearance.[128] Organic materials suffer the most from this process. Wooden artifacts contain some of these minerals naturally and lose them rapidly. Soluble substance in wooden artifacts already leach out in shallow sites but at depths the process could accelerate. The first components wood loses to seawater include starches and sugars. Cellulose in the cell walls disintegrates and lignin eventually breaks down in water, leaving wood more permeable to the water which leads to more leaching. Most of the structural support of wood after an extended submergence comes from water and any remaining lignin.[129]

Bones and calcium carbonate materials quickly dissolve in the deep sea because of the low carbonate concentrations and acidic conditions. Shells of marine organism in general will completely disappear.[130] Lower-quality ceramic materials suffer here as well. Depletion of carbonates play a role in applying stresses to the structure of pottery. Researchers encountered this problem during the Skerki Bank project when various pottery pieces were recovered. At first glance the pottery appeared normal, but once treated all ceramics recovered during the project showed solubilization, a loss in components due to partially dissolving in the seawater. When dried, the pottery softened

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[128] Søreide 2011, 162.
[129] Hamilton 1999, 38-88.
[130] Wachsmann 2011, 202-31.

and cracked easily while the surface seemed powdery as well. When pottery suffering from solubilization gets damp, it fractures and becomes sensitive to changes in humidity. Parts of the pottery submerged in the deep-sea mud at this site experienced increased dissolution of silica and other minerals. As a result of higher pH and further depletion of carbonates in the mud, the parts of the ceramics buried soften the most. Biozone fractures occur at the boundary level between the sediment and exposed areas inhabited by organisms. This boundary experiences different shrinkage rates and water saturation from the rest of the artifact, becoming an area of stress.[131]

Biological Deterioration

Interactions of marine organisms represents the most influential factor on the preservation of deep-sea shipwrecks, especially with wooden ones.[132] That said, both physical and chemical factors greatly influence the biological degradation of all cultural resources.[133] Because of the large circulation patterns of the world's oceans, the deep-sea oxygen levels can support marine growth. Unburied organic material is quickly consumed just as in shallow waters, although even buried artifacts remain at risk in the deep sea.[134] The hull of a ship generally disappears from the bottom up as organisms prefer to eat the portions of wrecks within one meter of the seabed. The process continues until no organic artifacts remain. Not even the calcium carbonate wastes and

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[131] Ballard 2000, 1591-1620.
[132] Ballard 2000, 1591-1620.
[133] Laurea 2014 39-135.
[134] Turner 1973, 1377-9; see also Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7; Bethencourt et al. 2018, 98–114.

burrows left by organism will survive long in the deep sea.[135] In the deep sea even iron wrecks see damage from marine organisms. Several species of organisms even inhabit the surfaces of all types of shipwrecks and artifacts causing damage without consuming them.[136]

Wood Consuming Organisms

The organic cellulose, hemicellulose and lignin that gives wood its structure provides nutrition to a variety of organisms. Most organisms that consume wood act as parasites that bore into it. Boring organisms appear anywhere with enough sources of wood and oxygen.[137] *Teredo* worms, devastate shallow water wrecks as the most commonly known organisms that bore into wood underwater and even attribute to some deterioration of deep wrecks.[138] Belonging to the family Teredinidae of mollusks, *Teredo* worms consist of over 65 different species. *Teredo navalis* or “shipworms” persists as the most infamous species and remain the most detrimental organism to wooden ships. *Teredo navalis* uses its specifically adapted shell to drill a tunnel into wood. The shells consist of two plates up to two cm long at the front end of its body and creates a long, circular tunnel. While making the tunnel, it creates shelter for itself within the wood with its limestone-based waste. *Teredo* worms prefer saltwater, but they can survive in salinities ranging from five to 30 percent. They even withstand a

[135] Wachsmann 2011, 202-31.
[136] Laurea 2014, 44-65.
[137] Ballard 2007, 62-7; 2001; 607-23.
[138] Søreide 2011, 160-164

wide range of temperatures from one to 30 °C but prefer temperatures between 11-25 °C. This preference comes from a reduction in growth and reproduction potential in cooler and hotter climates. *Teredo navalis* requires oxygenated conditions to survive but they can withstand anoxic zones for weeks using their preserved glycogen stores.[139] *Teredo* worms generally thrive above 100m but survive in greater depths too.[140]

The second most common organisms eating shallow water wrecks are gribbles. They belong to the order Isopoda, family Limnoridae with over 56 species. The title of most infamous gribbles belongs to *Limnoria Iignorum, L. tripunctata and L. quadripunctata*. Instead of drilling into wood, gribbles tunnel along the surface in long, shallow tunnels. They mainly inhabit colder regions like the North Atlantic and the northern zone of the Baltic Sea. Oddly enough, gribbles grow significantly faster on shipwrecks in warmer conditions even though they prefer colder regions.[141] This type of wood borer reaches depths of 500m so wrecks in deep water remain at risk from their activities.[142]

Mollusks remain the most significant boring organisms creating problems for the preservation of deep-sea wrecks, particularly *Xylophaga dorsalis* of the family Xylophagidae. *Xylophaga dorsalis* fulfills the same role in the deep sea as *Teredo* worms for shallower sites. It primarily lives in depths ranging from 150m to beyond

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[139] Laurea 2014, 44-65.
[140] Distel and Roberts 1997, 253-61; see also, Bascom 1971, 261-9; Turner 1973, 1377-9.
[141] Laurea 2014, 44-65.
[142] Søreide 2011, 162-63.

7000m.[143] Instead of drilling through the wood, it bores into wooden structures by using the shell as a cutting tool, resembling a shovel. The survival of this species in the deep sea, hinges on its ability to perform both sexual and asexual reproduction. It starts its life cycle as a male and can convert to a female later in life while maintaining the ability to self-fertilize. Because of this trait, populations of *X. dorsalis* can consist of dense groups of several types or only individuals.[144] Another part of its survival depends on how it consumes wood. In order to consume the wood, bacterial endosymbionts living in gill tissues of the *Xylophaga* break wood down into a suitable state for digestion. Ingested wood flakes get stored for future consumption within an out-pocketing of the stomach called a caecum. The morphology in this regard resembles that of the shipworms which shows they fulfill the same role.[145]

Despite the presence of *Xylophaga* in the deep, some ships at depths greater than 200 meters receive no damage from borers. For example, a Spanish wreck discovered by R, Marx off the coast of Florida at 400 meters remained untouched. This may result from variations in oxygen, nutrients, metallic ions and currents.[146] Even the soft muddy bottoms of the depths could cover the ship immediately during impact preventing organisms like *Xylophaga* from consuming the wreck. Some ships receive protection

[143] Distel and Roberts 1997, 253-61; see also Bascom 1971, 261-9; Turner 1973, 1377-9; Wachsmann 2011, 202-31.
[144] Laurea 2014, 44-65.
[145] Distel and Roberts 1997, 253-61; see also Bascom 1971, 261-9; Turner 1973, 1377-9; Wachsmann 2011, 202-31.
[146] Bascom 1971, 261-9.

from copper or covers like lead sheathing, tin, paint, and tar which poison organisms. Even tougher species of wood may prove more difficult for borers to damage.[147] Places like the Black Sea and the Baltic Sea present extreme environments in which borers and other organisms struggle. Conditions in the Black Sea become anoxic with depth below 320m as it lacks flow of oxygen from the global currents. Isolation of the Black Sea results from a shallow water sill connecting it to the Aegean Sea.[148] Oxygen levels drop in brackish places like the Baltic sea as well. For example, a 17th century Dutch *fluyt* named *The Ghost Ship* was found in nearly perfect condition lying at a 130m depth in the Baltic Sea. The wreck's preservation results largely from the cold deep waters of the Baltic and its lower salinity, which ranges between 0.06 and 0.15%.[149] The environment for both the Black Sea and the Baltic Sea effectively make it difficult for *Xylophaga,* shipworms and other organisms that speed up the decay of wood to thrive. The unique and harsh conditions may lead some to believe wrecks will last indefinitely in these environments, but the presence of microbes will still cause degradation.[150]

Even though microbes do not damage wrecks as quickly as the boring organism, they still cause significant decay.[151] Microbes drive a constant and slow form of decomposition and deterioration.[152] The main threat of microbes results from their

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[147] Bascom 1971, 261-9; see also Chen and Jakes 2001, 291-103.
[148] Ballard 2001, 607-23; see also Bascom 1971, 261-9.
[149] Eriksson and Rönnby 2012, 350–61; see also Fors and Björdal 2013, 36-45; National Geographic 2016.
[150] Ballard 2007, 62-7; 2008.
[151] Søreide 2011, 162-163.
[152] Laurea 2014, 44-65.

ability to adapt diversely to even the harshest environments. Even burial, or the formation of concretions, does not completely protect artifacts from microbial activity because their ability to survive in anoxic conditions. Some microbes even flourish more in anoxic zones.[153] The seafloor holds the most diverse and dense populations of microbes compared to any other environment due to the abundance of decaying material found there.[154] Most artifacts can experience degradation as a result of microbial activity as they even target inorganic structures.[155]

One type of microbe, fungi, readily consumes wood and other organics from both land and marine sites. There are three types of Lignicolous fungi that consume wood: Ascomycetes, Basidiomycetes, and Fungi Imperfecti. Basidiomycetes cause white-rot, or brown-rot degradation: (white-rot comes from the loss of lignin leading to lighter colors whereas brown-rot comes from the deterioration of hemicellulose and cellulose). This species mostly inhabits land environments and do not survive in deep sea environments. Ascomycetes and Fungi Imperfecti thrive in more diverse environments, including saltwater. These fungi introduce soft rot degradation to wooden artifacts both in marine and land environments. Some species of soft rot fungi can survive a temperature range of 0° C-65° C.[156] They can also survive in low-oxygenated environments, making them well suited for living in deep-sea sediment.[157] Even

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[153] Søreide 2011, 162-4; see also Laurea 2014, 44-65.
[154] Laurea 2014, 44-65; see also Cultimore and Johnston 2008, 120-132; Bethencourt et al. 2018, 98–114.
[155] Søreide 2011, 162-4.
[156] Laurea 2014, 44-65.
[157] Laurea 2014, 44-65; see also Søreide 2011, 162-4.

variations in pH levels do not significantly harm soft rot fungi.[158] Resulting from such high environmental adaptability, soft rot fungi represent the most aggressive and flexible wood-consuming fungi. The best-known species of soft rot fungi include *Aspergillus and Penicillium chyrsogenum*, which mainly consume cellulose and hemicellulose while ignoring the lignin in wood.[159]

Often found accompanying fungi on decomposing wood, bacteria play a more significant role in the preservation of artifacts found in the deep sea.[160] Out of all microbes, they survive in the widest range of environments and bacteria break down and consume the most extensive variety of materials. They can survive in conditions that macro-organisms and even fungi cannot.[161] The most anoxic conditions under the deep-sea sediment still support bacterial growth.[162] In other words, even the most buried artifacts will not likely avoid degradation from bacteria. They can even survive in extreme variations of temperature, humidity and pH levels.[163] The most diverse populations of bacteria live in seafloor sediment, and this remains true for the deep sea also.[164] Bacteria decompose the lignin and cellulose in wooden artifacts directly. There exist several different types of wood-consuming bacteria, including cavitation, tunneling, and erosion bacteria and the last organism survives better underwater than the

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[158] Laurea 2014, 44-65.
[159] Laurea 2014, 44-65; see also Bethencourt et al. 2018, 98–114.
[160] Laurea 2014, 44-65.
[161] Laurea 2014, 44-65; see also Søreide 2011, 160-164.
[162] Søreide 2011, 160-164.
[163] Laurea 2014, 44-65.
[164] Miller and Wheeler 2012, 292-366; see also Søreide 2011, 160-164.

others and can live in most environments. Erosion bacteria produce parallel channels along the cellulose in wood. These erosion channels encourage the growth of soft rot fungi by making it easier for them to attach, which explains why the two types of microbes often thrive together. While degrading the wood, erosion bacteria produce a slime substance that makes it easier for more bacteria and fungi to stick to the surface.[165]

Biological Deterioration of Metals

In addition to impacting organic material, bacteria contribute to the degradation of iron and other metals as well.[166] Marine organisms often suffer from a lack of iron in the ocean, essentially making it a limiting factor for survival. The pH of seawater naturally leans towards alkaline which makes iron (II) and iron (III) oxy-hydroxide insoluble.[167] Although, pH levels drop with depth, which could lead to more soluble iron.[168] Within concretions, the concentrations of dissolved iron increases over time. This increase provides an ideal source of nutrition for bacteria and other marine life. Iron artifacts also aid the growth of marine life when they consist of other materials such as iron phosphide. Anaerobic bacteria that thrive in concretions and deep-sea sediment can convert iron phosphide into a useable form of phosphine. This inevitably results in the deterioration of the artifacts, but concretions will thicken on iron alloys that contain more phosphorus.[169] The thicker concretions potentially protect the metal from

[165] Laurea 2014, 44-65; see also Bethencourt et al. 2018, 98–114.
[166] Ward et al. 1999, 561-70; see also Tolson 2009, 1-13; Hamilton 1999, 38-88.
[167] MacLeod 2016, 1-10.
[168] Munro 2012.
[169] MacLeod 2016, 1-10.

corrosion of outside sources. The growth rate of these organisms depends on currents that bring in other nutrients with stronger currents allowing for more corrosive bacteria.[170] Outside of concretions biofilms form with microbes including iron-oxidizing bacteria and iron-reducing bacteria. These two types of bacteria form a symbiotic bond and cause pitting in iron and steel artifacts by utilizing the iron for energy production.[171]

Another form of bacteria that leads to the degradation of iron, sulfate-reducing bacteria, exist as the most significant organic source of deterioration of iron in the deep sea. They contribute up to 60 percent of the total iron degradation in the ocean.[172] Sulfate-reducing bacteria including *Sporovibro desulphuricans* and *Desulphovibrio desulphuricans*, thrive in any aqueous environment with anaerobic conditions. Anoxic conditions of deep sediments and concretions present the perfect environment for this type of bacteria.[173] Without the presence of sulfate-reducing bacteria the corrosion of metals in anaerobic environments would cease.[174] When reducing sulfates, the bacteria utilize the hydrogen that builds up from iron corrosion processes. Normally, when iron separates from oxygen within concretions the built-up hydrogen reduces further corrosion. Once depleted, the corrosion process inhibited by hydrogen creating polarization of the cathode, allows the corrosion to freely continue.[175] Additionally, this type of bacteria

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[170] MacLeod 2016, 1-10; see also Cultimore and Johnston 2008, 120-132.
[171] Mugge et al. 2019, 1-17.
[172] Hamilton 1999, 38-88.
[173] Hamilton 1999, 38-88; see also Ward et al. 1999, 561-70; Enning and Garrelfs 2014, 1223-36.
[174] Ward et al. 1999, 561-70.
[175] Hamilton 1999, 38-88.

produces the byproduct hydrogen sulfide, which accelerates the corrosion process of all metals except gold. With iron artifacts, hydrogen sulfide reacts with ferrous ions producing the corrosion compounds ferrous sulfide and ferrous hydroxide.[176]

Sulfate-reducing bacteria also take part in another corrosion process that produces a unique form of concretion called rusticles, which consist of rust that appears to form in a shape resembling growing icicles as they cover the hulls of steel shipwrecks in the deep sea.[177] Rusticles lead to the rapid deterioration of deep-water wrecks, including the *Titanic*.[178] For the exact understanding of formation and process of rusticles in the deep sea, more research will need to occur, but we do know that numerous types of rusticles form and most maintain similar features. Each of the rusticles form into a crystalized structure that differs based on the presence of different concentrations of microbes in a complex way, but also depends on the type of material present and how the artifact has come to rest on the seafloor.[179] Multiple species of microbes thrive within rusticles and collaborate within the rusticles, forming a community that provides the basis of its formation. Some of these microbes include sulfate-reducing bacteria, acid-producing bacteria, heterotrophic bacteria, iron-related bacteria and denitrifying bacteria. While heterotrophic bacteria stand as the most active and abundant in rusticles, sulfate-reducing bacteria and iron related bacteria seem to grow within most, if not all,

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[176] Hamilton 1999, 38-88; see also Ward et al. 1999, 561-70.
[177] Little et al. 2016, 1-6.
[178] Tolson 2009, 1-13.
[179] Cultimore and Johnston 2008, 120-132.

rusticles.[180] Additionally, rusticles contain high levels of oxidized materials mostly consisting of iron. The core of rusticles crystalizes with ferric oxide and ferric oxyhydroxide as the main components while maintaining a porous structure with a high internal surface area allowing for permeation and flow of water.

The permeation is necessary as the growth of rusticles partially relies on the presence of oxygen, as the heterotrophic and other bacteria require it. Also, oxygen can tribute to the natural corrosion of iron by making it anodic.[181] This remains necessary for the negatively charged microbes to interact with iron. The formation of rusticles creates anoxic zones on the surface of iron that reduces the rate of electrochemical corrosion.[182] Sulfate-reducing bacteria thrive in these areas and remain the key component for the corrosion processes to continue. Some other microbes present may also affect the charges on iron and steel surfaces and further bypass the oxygen requirement for the electrochemical corrosion prosses.[183]

Studying the growth of rusticles can provide an ample source of information to archaeologists. Besides stripping metal artifacts directly, microbes within rusticles gather dissolved metals from the surrounding environment. Sampling rusticles provides archaeologists with information on the materials present on shipwrecks. Measuring the

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[180] Cultimore and Johnston 2008, 120-132; see also Little et al. 2016, 1-6.
[181] Hamilton 1999, 38-88.
[182] Cultimore and Johnston 2008, 120-132.
[183] Cultimore and Johnston 2008, 120-132; see also Hamilton 1999, 38-88.

concentrations levels of metals, or the size of the rusticles, can potentially aid researchers in calculating the deterioration rate of the metal artifacts. For example, if aluminum artifacts degrade within a steel wreck, the rusticles will absorb free aluminum products in correlation to the amount present.[184] Since other materials such as chemicals or recalcitrant materials including coal and glass fragments, can collect in rusticles, researchers can narrow down the different types of artifacts present on a shipwreck. One study already performed with rusticles, determined that it only took six years of exposure to deep-sea water near the RMS *Titanic* for rusticles to completely cover steel artifacts. The same study showed that the average rate of iron lost from steel roughly measures at 0.031 g/cm^2 a year when rusticles form. This rate appears to remain constant regardless of the type of steel involved. Instead, it may vary with the environmental conditions, but more research remains necessary to confirm this.[185] Change in currents presents one potential environmental change that could influence the growth rates of rusticles. Higher circulation of water and the porous structure of the rusticles allows the heterotrophic bacteria to dominate over other organism within rusticles thanks to their ability to utilize greater variations of organic compounds that seawater carries. Along with currents transporting in material, when organic artifacts such as wood rest near iron, the formation of rusticles and corrosion of iron increase further due to the extra nutrition provided for the use of bacteria.[186] Additionally,

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[184] Little et al. 2016, 1-6; see also Cultimore and Johnston 2008, 120-132.
[185] Cultimore and Johnston 2008, 120-132.
[186] Cultimore and Johnston 2008, 120-132.

shipwrecks located near hydrothermal vents should experience greater corrosion rates from sulfate-reducing bacteria since the sulfate concentrations in sea water increases at the vents. The wrecks will also experience an increased presence of sulfate-oxidizing bacteria and others, which could further impact the preservation state.[187]

The Human Element

Most archaeological sites see a reduction in preservation state due to impacts of humans and the deep sea presents little exception, apart from the most extreme environments. The most influential impacts include deep-sea fishing, treasure hunting or looting, industrial activities, pollution, and even the work of archaeologists.[188] Fishing remains one of the most widespread forms of human impact on deep shipwrecks and can even impact wrecks at over 1,000m.[189] The use of heavy trawling nets that scrape the seafloor can destroy brittle artifacts and shipwrecks when dragged across them. The nets get entangled on sturdier shipwrecks and cause more damage when left behind to sit on top of the site.[190] Some of these nets exceed 8-tons with widths of over 60 meters and contain heavy rollers that trample structures.[191] At this size, wrecks easily sustain significant damage. Several wrecks in the Black Sea bore witness to heavy damage from trawling and, as a result, remain in poor condition despite the significant preservation

[187] Miller and Wheeler 2012, 292-366.
[188] Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7; see also Laurea 2014, 44-65; Moore and Fergerson 2008, 994-997.
[189] Tolson 2009, 1-13.
[190] Ballard 2000, 1591-1620; 2001, 607-23; 2007, 62-7; see also Laurea 2014, 44-65.
[191] Tolson 2009, 1-13.

that occurs in the Black Sea environment.[192] Even during the Skerki Bank project the presence of nets interfered with the archaeological study.[193] Elsewhere, at a depth of 370 meters, over 75 percent of the Jacksonville *Blue China* wreck was destroyed from trawling activity.[194] The greatest problem with deep-sea fishing lies in the lack of regulations. Most deep-sea fishing sites lie in international waters and outside manageable zones. Some countries still lack policies to deal with deep-sea fishermen and international protection needs improvement.[195]

Looters present the next greatest human source of physical deterioration of cultural sites. Most treasure hunters gather the valuable artifacts as quickly as they can with no regard to the damage they cause to the hulls of ships and less valuable artifacts. Usually the hulls sustain heavy damage during salvage.[196] Even at depth, looting remains a significant problem. Better preservation of artifacts in the deep sea encourages looters because of the higher potential for profit. Fortunately, the depth of the ocean may also discourage looters due to the difficulty of removing artifacts. It takes advanced and expensive technology to salvage deep-water artifacts. The muddy substrate adds further protection with strong adhering properties keeping the artifacts buried. This, however, could lead to more destructive methods used during extraction.[197]

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[192] Brennan 2012, ii-100.
[193] Ballard 2000, 1591-1620.
[194] Tolson 2009, 1-13.
[195] Moore and Fergerson 2008, 994-997.
[196] Ballard 2000, 1591-1620.
[197] Ballard 2000, 1591-1620.

Organizations such as oil and gas companies potentially damage sites when they work in the deep sea. Most drilling or mining projects extend over large areas and can easily encompass unknown shipwrecks. Mining and oil operations require large platforms and underwater structures. Pipelines stretch over long distances and could lie directly across wrecks.[198] Laws in some regions requiring the survey of areas before the placement of these structures, reduces the possibilities of damage to wrecks, but does not eliminate it.[199] For example, the risk of placing structures on top of wreck sites increases in the depths if the sediment completely buries the wreck before preventative surveys take place. During the construction of underwater structures, large ships sometimes anchor on wrecks. Large industrial ships drag anchors across the bottom of some deep waters.[200] Ocean oil spills could also potentially cause unknown levels of damage to shipwrecks.[201] After the Deep Water Horizon oil spill, the corrosion rate of a German submarine, U-166, increased and studying this increase in deterioration revealed that it resulted from the increased activity of iron-reducing and oxidizing bacteria within biofilms.[202] As an indirect problem, pollution from the use of natural gases and oil leads to accelerated carbon dioxide pollution. Ocean acidification occurs when the sea absorbs carbon-dioxide from the atmosphere to form an equilibrium. The dissolved

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198 Laurea 2014, 65-76.
199 Søreide 2011, 165-68.
200 Laurea 2014, 65-76.
201 Mugge et al. 2019, 1-17; see also Laurea 2014, 65-76.
202 Mugge et al. 2019, 1-17.

carbon dioxide gradually changes the pH of seawater. Eventually more acidic conditions lead to greater corrosion and degradation of artifacts.[203]

Archaeologists remove artifacts from sites for study frequently and sometimes damage to remaining artifacts can occur.[204] Generally, archaeologists diligently avoid damaging the sites, but some artifacts prove difficult to manage. The interior of a shipwreck that remains intact generally gets left out of studies because damage occurs when trying to reveal inner components.[205] Sometimes researchers recover artifacts and rebury them later.[206] By recovering an artifact, archaeologists already expose it to a different environment and reburying it may no longer leave the artifact in a stable condition. Reburial of artifacts in the deep sea probably proves difficult, which can result in inadequate protection when done. Sometimes artifacts get reburied in different locations and because of the added difficulty in accessing sites, this may be worse for artifacts in the deep sea. Reburial often occurs to reduce the possibility of looting when the public knows the location of the site. Leaving an artifact in a new environment can lead to exposure of different types of organisms or other deterioration hazards causing unnecessary damage, especially when moving objects from deeper water to a shallower site.[207]

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[203] Munro 2012.
[204] Bethencourt et al. 2018, 98–114.
[205] Bethencourt et al. 2018, 98–114.
[206] Gregory et al. 2012, S139-48; see also Tolson 2009, 1-13.
[207] Bethencourt et al. 2018, 98–114.

Summary

As the deep sea holds sustainable levels of oxygen, biological activity contributes the most to the deterioration of shipwrecks in the depths, whereas in shallow sites, most of the deterioration comes from physical damage and chemical breakdown. This statement does not mean the exclusion of physical impacts on sites of the deep sea. The burial of artifacts during the initial sinking and with the help of currents persists as one of the most crucial aspects to shipwreck preservation in any environment. Even with complete burial and anaerobic conditions, the abundance of microorganisms in deep sediment still contribute to degradation of shipwrecks. The presence of these microbes speeds up the natural chemical breakdown of artifacts as well. Without sulfate-reducing bacteria, the corrosion of iron would nearly cease when concretions form. Rusticles in the deep sea presents a unique form of deterioration that requires more study. When physical processes, such as storms, occur concretions fall off and iron artifacts incur more stress. This increases their electrochemical corrosion potential while simultaneously allowing organisms to gain better access to surfaces. Even with all these processes considered, preservation in the deep sea remains potentially higher than in shallow-water sites.

CHAPTER IV

IMPACTS ON THE ENVIRONMENT

This section of the thesis discusses the impact of shipwrecks on the deep-sea environment. While the deterioration of shipwrecks in the deep sea remains poorly understood, the ecology of deep shipwrecks represents an even more challenging topic. For example, a 2015 archaeological study discovered an unexpectedly abundant community of the deep-water coral *Lophelia pertusa* on several World War II shipwrecks in the Gulf of Mexico.[208] If the success of a single species on a wreck in the deep-sea surprised archaeologists and biologists, efforts should increase.

Shipwrecks as Artificial Reefs

One of the most significant impacts of shipwrecks on the deep-sea environment occurs when a wreck forms an artificial reef system. Shipwrecks become artificial reefs and act as hotspots for marine life by adding nutrients to the ecosystem, providing structural support, and protection for organisms.[209] Marine conservators actively add artificial reefs to the open ocean to increase biodiversity and replace lost habitats.[210] Part of the reason that conservators implement artificial reefs comes from the loss of natural systems through destructive bottom trawling and pollution much like the dangers

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[208] Church et al. 2009, 50-63.
[209] González-Duarte et al. 2017, 301-10; see also Bethencourt et al. 2018, 98-114
[210] Lemoine et al. 2019, 1-9; see also Schutter et al. 2019, 1-13.

shipwrecks themselves face. Trawling activity destroy communities of corals along with the hard substrates they depend on for growth.[211] With the loss of these communities, artificial reefs provide significant benefit to the deep-sea environment from the lack in availability of hard surfaces for attachment due to most of the deep sea floor consisting of a soft muddy.[212] Much to the benefit of deep-water conservation, marine activity on the artificial reefs increases with depth, in part due to slower proliferation rates of algae groups that prevent settlement of other organisms. Additionally, growth rates of organisms that attach to shipwrecks in the depths benefit from the calm environment and receive less disturbances than shallow wreck sites.[213]

Platform for Growth

Like all artificial reefs, shipwrecks improve the biodiversity of the deep-water environment by providing a platform for growth. The presence of a hard surface in the deep sea increases the settlement rate of organisms in their early life states.[214] Colonization of substrates takes time and in shallow water sites shipwrecks deteriorate quickly, which leaves little time for growth to occur.[215] Since metal shipwrecks corrode much more slowly in deeper waters, they support this early growth over a longer period of time.[216] This type of support allows several organisms to thrive in the deep sea;

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[211] Schutter et al. 2019, 1-13; see also Laurea 2014, 65-76.
[212] Garcia and Barreiros 2017, 57-66.
[213] González-Duarte et al. 2017, 301-10.
[214] Schutter et al. 2019, 1-13.
[215] Schutter et al. 2019, 1-13.
[216] Venkatesan et al. 2002, 257-66.

sessile invertebrates that provide the foundation for thriving ecological communities in the ocean colonize shipwrecks in great numbers.[217] Corals, for example, need a hard surface for anchorage in order to grow properly. Species such as corals and sponges remain stationary, relying on ocean currents to carry in fresh supplies of nutrients so they can absorb or filter them from the water column.[218] Survival of deep-water corals can increase on shipwrecks compared to natural hard substrates by allowing the corals to sit higher and more exposed within the water column than they would on natural substrates, improving their potential to receive nutrition from water flow.[219] Additionally, some species of anemones act like Venus fly traps and need the elevated surface to trap their prey as it is carried in by the currents.[220] In order to grow, mollusks and other species also require hard surfaces for attachment.[221] Some microorganisms too, require a hard substrate on which to grow and shipwrecks prove quite favorable in this regard.[222]

Nutrition

Shipwrecks also support the growth of organisms by supplying more nutrients to the immediate environment, both directly and indirectly.[223] Corals thrive on shipwrecks due to the added supply of nutrients.[224] These nutrients come in several forms. Organic

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[217] Garcia and Barreiros 2017, 57-66.
[218] Roberts et al. 2005, 4-5.
[219] Larcom et al. 2014, 101-9.
[220] Ammons and Daly 2008, 1657-66.
[221] Turgeon et al. 2009, 711-44.
[222] Laurea 2014, 39-44.
[223] Balazy et al. 2019, 1-10.
[224] Larcom et al. 2014, 101-9.

compounds such as sugars, hydrocarbons, and organic phosphates come from the breakdown of materials including wood, food, cloths, leather, as well as human, and animal remains. Shipwrecks also provide inorganic compounds during deterioration, with iron, sulfates and phosphates being some of the most important.[225] Modern wrecks provide significant amounts of iron to the environment, and within iron and steel products there usually exists some level of phosphates.[226] A scarcity of iron and phosphates, however, can prove a limiting factor in marine ecosystems.[227] Organisms require phosphates for the production of lipids and DNA, making its presence vital.[228] Meanwhile, iron-reducing and oxidizing microbes utilize iron directly for energy production. Several microbial processes including ammonia oxidation, nitrate fixation, and light reactions, require the presence of iron to form the proteins responsible for the processes.[229] When researchers directly added iron to the environment during the Ocean Iron Experiment, an increase in the growth of microbes occurred, demonstrating that iron is a current limiting factor and showing the potential benefit shipwrecks add.[230] Other limiting factors, such as carbon and nitrogen can prevent the increase in iron and phosphates from improving marine growth in some cases. However, the deep-water environment contains plenty of this form of nutrition since it is re-supplied by the sinking decaying organic material from the water column above, while in comparison,

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[225] Redfield 1958, 205-21; see also Morel and Price 2003, 944-7; Miller and Wheeler 2012, 292-366.
[226] MacLeod 2016, 1-10.
[227] Morel and Price 2003, 944-7; see also Ammerman 1985, 1338-40; Miller and Wheeler 2012, 292-366.
[228] Miller and Wheeler 2012, 292-366.
[229] Morel and Price 2003, 944-7.
[230] Boyd et al. 2000, 695-702; see also Powell 2007; Yoon et al. 2018, 5847-89; Aumont and Bopp 2006, 1-15.

the phosphates get used up quickly as the decaying organic material sinks.[231] Microbial and planktonic life depends on the presence of phosphorous, nitrogen and carbon at a ratio of about 1:16:106.[232] Even the small amount of phosphorous added to marine environments by shipwrecks aids in creating this ideal ratio.

Food Web

By supporting growth of bacteria, coral, and other invertebrates, shipwrecks initiate a new ecological web. The organisms that grow directly on deep wrecks provide a home and act as a food source for other organisms. Several species of macrofaunal invertebrates rely on deep-water corals as their home. Some of these include chirostylid crabs, such as *Eumunida picta*; brittlestars, galatheoid crabs, the inflated spiny crab (*Rochinia crassa*), giant sea spiders (*Colossendeii bicinctata*), and certain stalked barnacles. A number of these species were found to live with the coral *Lophelia pertusa* and other deep-water corals growing on shipwrecks.[233] Even fish and larger predators rely on the reefs for their food supply.[234] Every ecosystem relies on the growth of the smaller life forms that lead to a cycle of energy by acting as a source of nutrition for larger organisms. The microbes that survive by gaining nutrition and energy from shipwrecks along with reefs create a new food chain.[235] They serve their purpose by providing nourishment to their predators, which in turn feed larger ones. Once the

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[231] Suttle 2007, 801-12
[232] Redfield 1958, 205-21; see also Miller and Wheeler 2012, 292-366.
[233] Church et al. 2007, 90-93.
[234] Tolson 2009, 1-13.
[235] Azam et al. 1983, 257-63; see also Biard et al. 2016, 504-19.

predatory organisms and even some of the microbes die, other forms of microbial life break down the decaying matter and their wastes, repeating the cycle.[236] This means that even after the shipwreck's supply of nutrients is depleted it still indirectly continues to benefit the environment. However, this cycle does not last forever, and the ecosystem will eventually require another source of nutrient input. If the cycle was continuous, the introduction of shipwrecks and artificial reefs would not prove as necessary to improve the biomass and biodiversity of the deep environment.

Protection

Even without the addition of nutrients, shipwrecks directly increase the success of smaller organisms by providing protection from predators.[237] Wood-boring organisms such as *Xylophaga*, use the wrecks as both a food source and a protective home.[238] Some species of fish use internal spaces and crevices of wrecks to hide from predators or as a haven for their eggs.[239] Aside from providing physical shelter to organisms, shipwrecks acting as artificial reefs provide indirect protection as valued cultural sites. Shipwrecks contain significant cultural importance and sites become protected areas.[240] Protected areas receive greater monitoring, which leads to lower levels of human impact by reducing fishing, poaching, polluting, construction, and general damage to the

[236] Azam et al. 1983, 257-63.
[237] Balazy et al. 2019, 1-10.
[238] Miller and Wheeler 2012, 292-366.
[239] Balazy et al. 2019, 1-10; see also Church et al. 2007, 90-93; González-Duarte et al. 2017, 301-10.
[240] Garcia and Barreiros 2017, 57-66.

environment.[241] With this added level of protection, the marine life maintains a better chance of survival than those of unobserved areas.

Comparisons to Natural Systems

By acting as artificial reefs, the nutrients shipwrecks add to the environment should be compared to natural biological hotspots within the deep sea, such as hydrothermal vents and whale carcasses. Whale falls, along with the carcasses of other large marine animals, directly increase biodiversity by providing food for grenadiers, deep-sea sharks, crabs, macrourid, hagfish, amphipods, microbes, and other benthic organisms. When the larger of these organisms disperse and defecate it allows for the spread of nutrients.[242] Since ships traversing the open ocean are often larger than whales, the amount of organic material a shipwreck provides to an ecosystem can exceed the concentration provided by whales, especially in the case of large wooden wrecks. Even modern iron and steel wrecks can provide significant amounts of organic materials.[243] Inorganic compounds can also exist in quantities within shipwrecks that compares to natural sources. Hydrothermal vents produce large quantities of the same metals found on shipwrecks.[244] The reason these localized hotspots remain important to biodiversity in the deep sea relies on the fact that without them, the environment rarely varies.[245] In a system with little variation and a lack of resources, the more poorly-adapted species within a niche

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[241] Garcia and Barreiros 2017, 57-66.
[242] Miller and Wheeler 2012, 309-317.
[243] Søreide 2011, 163.
[244] Miller and Wheeler 2012, 351-366.
[245] Søreide 2011, 159.

face extinction. This concept is referred to as the competition exclusion principal.[246] Shipwrecks can act as an additional small-scale environmental change that combats the competition exclusion principal, potentially making them as beneficial as whale falls and hydrothermal vents.

Since the communities of organisms that shipwrecks support differ from those of natural reefs, one can argue against the success of wrecks as artificial reefs.[247] Metal shipwrecks in particular, can support the growth of marine life differently than natural reefs and attract different types of fish. However, the abundance of fish found on metal shipwrecks can exceed those of rocky reefs and with greater biodiversity, thus, making the differences negligible in some cases.[248] Increases in the fish populations due to the presence of shipwrecks helps the environment and humans can benefit from the increased fishing potential.[249] Even in the presence of thriving natural reefs, such as in the Azores, the presence of artificial reefs still strengthens the biodiversity.[250] Shipwrecks can reduce the pressure on existing reefs, gradually improving the natural biodiversity.[251]

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[246] Miller and Wheeler 2012, 309-17.
[247] Lemoine et al. 2019, 1-9; see also Sanabria-Fernandeza et al. 2018, 190-99.
[248] Lemoine et al. 2019, 1-9.
[249] Carral et al. 2018, 1881-98.
[250] Garcia and Barreiros 2017, 57-66.
[251] Carral et al. 2018, 1881-98.

Harmful Shipwrecks

As beneficial as shipwrecks can be to the environment as artificial reefs, shipwrecks can also put fragile ecosystems at risk. Many wrecks, especially those from World War II, contain significant quantities of harmful substances including ammunitions or unexploded ordinances, oil, gas, chemical warfare agents, plastics, and other forms of pollutants.[252] Certain shipwrecks containing these substances do not currently expose them to the surrounding environment, but as they continue to deteriorate that separation disappears.[253] If the potential harmful effects of polluted wrecks outweigh the potential benefits the ships can provide, removal of these wrecks should take priority. Examples of harmful modern shipwrecks include shipwrecks that contain anti-fouling paints with chemicals such as organotin tributyltin (TBT) and copper compounds. TBT disrupts internal activities of shellfish and prevents organisms from growing directly on the wreck.[254]

Out of all the contaminants shipwrecks can contain, oil stands as one of the most well-known to harm the marine environment, yet there still exists a lack of understanding for the long-term impacts of oil in the deep environment.[255] Furthermore, some impacts of oil benefit the environment to some degree. Some microbes can consume and breakdown oil, which will lead to more growth. However, this extra growth disrupts the

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[252] Rogowska et al. 2010, 5775-83; see also Angel and Rice 1996, 915-26.
[253] Rogowska et al. 2010, 5775-83.
[254] Tornero and Hanke 2016, 17-38.
[255] Guidetti et al. 2000, 1161-1166; see also Mugge et al. 2019, 1-17.

natural concentrations of microbes, which may result in an unknown negative effect.[256] Even the methods implemented when cleaning up the oil may end up impacting the environment in unpredictable ways.[257] Archaeologists should continue to research oil and the rest the contaminants shipwrecks contain in order to fully comprehend the risks they pose to the deep-sea environment.

Salvaging Wrecks

When archaeologists or other professionals attempt to remove shipwrecks that act as artificial reefs, they must consider the implications carefully. Removing these wrecks can leave the dependent ecosystem without its structural and nutritional support. This sudden shock reduces the success and biodiversity in the immediate area. Fragile corrals will no longer support the localized ecosystem without a solid substrate. A significant number of organisms die immediately when removing a wreck in its entirety and the community may not recover. Even if the community survives the removal of the wreck, they still face other risks during the removal process. These risks were observed during the salvage of a shallow-water wreck, the *Costa Concordia*. Before the wreck was salvaged, platforms and grout bags were planted around the wreck which led to the dispersion of fine sediments. During the actual salvage process debris from the wreck spread out and damaged some communities. The salvage of the wreck led to losses in coral structures and reduced the diversity of organisms at the site. Since the impact

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[256] Mugge et al. 2019, 1-17; see also Guidetti et al. 2000, 1161-1166.
[257] Guidetti et al. 2000, 1161-1166.

studied at the *Costa Concodia* occurred in shallow water, the consequences may prove different in deeper waters. However, since the difficulty of salvage operations increase with depth, one can assume the potential for risks increases as well.[258] Another form of risk during salvage operations comes from the release of previously secured harmful substances from the wreck incurring damage during removal.[259]

Summary

Marine conservation studies show shipwrecks primarily benefit the environment by acting as artificial reefs. Shipwrecks provide an increase in solid substrate; this remains the most important benefit shipwrecks introduce. Even without the nutrition wrecks contain, shipwrecks increase biodiversity. The growth of marine microbes improves near modern shipwreck sites due to the increase in concentrations of iron and phosphorous. Whale falls, natural reef systems, and hydrothermal vents remain vital for maintaining the biodiversity of the deep-water ecosystem, but the presence of shipwrecks reduces some of the pressure on these natural hotspot ecosystems. Deep-water wrecks provide indirect and direct protection to a variety of organisms and serve as their home. While wrecks benefit the deep sea, some wrecks containing oil and biocides that put ecosystems at risk. However, recovering these wrecks and eliminating contaminants may introduce other problems.

[258] Casoli et al. 2017, 124-134.
[259] Rogowska et al. 2010, 5775-83.

CHAPTER V

CONCLUSIONS

In order to continue investigations on the preservation states of shipwrecks and the impacts of these wrecks on the deep-sea environment, researchers should employ a combination of equipment. AUVs provide potential for the continued monitoring of wreck sites while ROVs and HOVs allow for precision and the recovery of valuable samples. Since most wooden shipwrecks and organic artifacts deteriorate above the deep-sea sediment, sub-bottom profilers, and magnetometers benefit archaeologists with survey work. Creating accurate 3D models of wrecks with SAS systems, multibeam echo sounders, or photogrammetry can aid archaeologists in monitoring deterioration rates of wrecks and the growth rate of marine life. Sampling rusticles with ROVs helps with this monitoring as well.

In situ preservation of deep wrecks may cost archaeologists valuable cultural resources as the deterioration rates remain significant, albeit at slower rates than on shallow sites. Wave action, tides, and rocky outreaches that devastate shallow sites do not influence the state of deeper wrecks and the impact of storms reduces significantly. However, the increased pressure of the deep sea and the ever-present currents, pose risks on deep-sea sites. Barring the oxygen minimum zone and special environments like the Baltic and Black Seas, oxygen levels still negatively influence the condition of wrecks. The activity of wood borers, with *Xylophaga* as the most significant, leads to the loss of exposed wooden components. Electrochemical corrosion continues at a slower pace, but the protection provided from concretions decreases. Rusticles present another complicated form of degradation that quickly deteriorates modern iron and steel wrecks. The deterioration of all materials continues even in anoxic conditions under the seafloor sediment due to the activity of microbes. Sulfate-reducing bacteria contribute the most to anoxic degradation of iron artifacts. Even in waters over 1000 meters deep, humans negatively impact the preservation state of shipwrecks.

For the most part, shipwrecks benefit the environment greatly as artificial reefs. Wrecks provide a valuable replacement to the loss of rocky substrates and reef systems caused by the trawling activities of fishermen. By allowing the attachment and growth of key species at the bottom of the food chain and those that act as homes for others, ecological communities establish themselves on shipwrecks. The biodiversity of the deep sea, hinges on the formation of small communities. With this increase in biodiversity, wrecks help the ecosystem in a manner comparable to whale falls and hydrothermal vents. Nutrition in the form of iron, phosphorous and organic material provided by shipwrecks combats the limiting factors of the deep sea. The increase in abundance of life around shipwrecks, regardless of the slight differences in the type of species from natural systems, improves the environment and allows for more fishing by humans. By protecting shipwreck sites, the success of the immediate environment improves as a result of the limitations on local disturbances.

Since the benefits of shipwrecks to the environment exist, archaeologists should work to minimize disturbances by limiting the removal of wrecks and utilize the advances in technology to fully study important sites. With some of the current technology discussed in this thesis, certainly archaeologists can gather the necessary information needed for cultural discussion and for understanding the deterioration of deep-water sites without removing a wreck from the seafloor. However, *in situ* conservation of shipwrecks in the deep sea will eventually lead to the loss of these sites so the efforts to research wrecks needs increased.

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