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PRACTICE BRIDGE

Portholes into the deep: Exploring ocean memory of Lost City through art and science

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Ocean memory embraces the idea that the ocean retains, processes, and expresses information across a range of timescales, from moments to millennia. The Ocean Memory Project brings together scientists, artists, and scholars to investigate this notion from a transdisciplinary perspective, integrating empirical research with creative expression. Here, our scientific and artistic efforts center on the Lost City hydrothermal field, an otherworldly site on the deep Atlantic seafloor that offers rare insights into early Earth processes and the potential for life beyond our planet. In 2018, we sailed to Lost City and carried out our joint microbiological, geochemical, and artistic efforts. Our sampling revealed that the ultramafic rocks that underlie the field undergo reactions that support complex ecosystems dependent on interspecies cooperation to overcome extreme chemical limitations. These same rocks serve as a geologic sink for organic carbon carried with circulating seawater, a process likely active for as long as hydrothermal circulation has existed on Earth. These discoveries highlight the complex, evolving nature of subseafloor ecosystems and exemplify the ocean's capacity for memory. Alongside the science, the expedition supported an artist in residence, Anna Davidson, who created a body of work inspired by her time at sea. Her paintings, videos, photos, and mixed media sculptures, some incorporating physical samples and imagery from the dive footage, are not only aesthetic and conceptual reflections of Lost City but also educational resources. By integrating science and art, we argue in this paper for a broader epistemological framework in environmental research—one that recognizes the ocean not only as a site of data but as a dynamic, living archive of memories. Through interdisciplinary inquiry, we can deepen our understanding of the ocean and build more meaningful cultural narratives around its protection in the face of current mounting threats, including climate change and deep-sea mining.

Keywords: Art, Hydrothermal vents, Lost City, Deep-sea mining, Oceanography

What is ocean memory?

Does the ocean have memory? And if so, what form does it take? This central question, posed at an art-science conference (National Research Council, 2018), drives the Ocean Memory Project—an initiative that unites scientists, artists, and scholars from a wide range of fields and cultures. The goal is to explore this idea from a transdisciplinary perspective, blending insights from the sciences, humanities, and arts.

Ocean memory has been characterized as the capacity of the ocean's biological and physical systems to absorb, retain, and release information over timescales that range from hours to millennia—patterns that can shape the planet's future (Ocean Memory Project, 2023). Yet, because this concept emerges at the nexus of many disciplines and worldviews, it does not have a single, fixed definition. Instead, it represents a rich myriad of perspectives—ways of imagining the ocean as a vibrant, dynamic entity, capable of feedback loops that resemble memory in living beings. Merging the ideas of "ocean" and "memory" opens new paths for thought, creativity, and discovery. What unites the people working in this space is a shared desire to engage with the ocean as a vital, more-than-human system full of life and agency. Through this lens, we look to the ocean's past not only to understand it better, but to prepare ourselves more wisely for what lies ahead (Ocean Memory Project, 2023).

The first gathering for the Ocean Memory Project took place in 2017 at Friday Harbor Laboratories on San Juan Island, Puget Sound, WA. There oceanographer Dr. Susan Lang and artist-scientist Dr. Anna Davidson met and began a vibrant conversation centered around the enigmatic Lost City hydrothermal field ("Lost City"), a stunning deep-sea landscape of towering chimneys at the Mid-Atlantic Ridge, halfway between North America and Africa.

As Lang shared her scientific research questions, Davidson was struck by the conceptual and artistic depth of this fragile seafloor environment. Lost City is a landscape in

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need of research, protection, and visual storytelling. What role could an artist play in this world of deep-sea science? Could creative practices amplify scientific inquiry and help bridge the gap between scientists and public engagement? Could art extend the reach of scientific discoveries beyond academic circles and into the hearts of broader audiences? What is the result when an artist also has access to scientific tools, methods, a remotely operated vehicle and a scientific research vessel? Through these dialogs, Lang realized that broadening her focus beyond narrowly defined research goals could lead to new scientific insights, while also deepening the work's resonance beyond the scientific community. For Lang, this shift also meant seeing Lost City not solely as a site of scientific intrigue but also as a cultural treasure. To explore these questions, Lang invited Davidson to join the 2018 expedition to Lost City as an artist-in-residence. That invitation marked the beginning of a long-term collaboration rooted in mutual curiosity. It also engaged a vital interdisciplinary model—one that integrates artistic creativity and scientific exploration to tell the story of Lost City in new ways.

The art and science interface

In a rapidly changing world, the arts play an essential role in shaping our collective response to environmental crises. As we face climate change, extractivism, biodiversity loss, environmental destruction, and cultural disconnection, the arts help us not only to understand these challenges but also to process the emotional weight of them. The arts, often sidelined in scientific contexts, are an essential mode of inquiry in their own right. They offer more than science communication; they serve as tools for exploration, data collection, and meaning-making. Art functions not simply as a translator for science but as a complementary partner in the production of knowledge (Jung et al., 2025).

Art can strengthen our sense of connection to each other, to other species, and to the planet. In this sense, the arts are essential, and especially when combined with other disciplines like oceanography, climate science, and environmental activism, they create a powerful opportunity for learning and action. Artists are adept at working in open-ended contexts that benefit from new perspectives and unconventional ways of thinking. Operating free from the constraints of other disciplines, artists act as both provocateurs and instigators, challenging assumptions and norms. The artist's approach to creative thinking can help drive the interdisciplinary process toward a new set of questions leading to innovative solutions. As Gilbert and Cox (2019) note, to conduct science or art in a closed conversation within its own history, removed from the larger social and environmental context, no longer makes sense. Collaborative approaches that bring these fields together are therefore increasingly recognized as necessary.

Singh et al. (2021) point out that our ability to understand the ocean is unlikely to outpace the rate at which it is changing. Spalding (2023) further emphasizes that the ocean is shaped not only by biophysical processes but also by social meanings, values, and practices. Addressing this dual transformation requires an expanded epistemological framework that incorporates both scientific analysis and artistic modes of knowledge production.

Here, we present the scientific and artistic outcomes of the 2018 expedition to the Lost City hydrothermal field. We explore what happens when an artist is given access deep-sea landscapes—when creative practice becomes part of the inquiry itself. We reflect on how art and science, working in concert, can help us not only to understand the ocean but also to reimagine our human relationship with it.

What is Lost City and why is it significant?

The Lost City hydrothermal field is a beautiful seafloor formation with unique scientific and cultural value. It is a cluster of ghostly white chimneys growing on top of each other and forming a central spire the size of a 12-story tower, perched on a ledge just below the summit of a submarine mountain that rises 4 km from the surrounding seafloor. Many of the chimneys host thick mats of microbial communities, as well as microscopic animals, that feed on the warm fluids vented through the chimneys (Kelley et al., 2001; Kelley et al., 2005).

Lost City has been explored by several scientific expeditions since its discovery in 2000 and has been featured in documentaries such as James Cameron's Aliens of the Deep (2005) and Blue Planet 2 (2017). The Lost City hydrothermal system has attracted the interest of many differently trained scientists from geologists to chemists and biologists. It is studied as an important site for understanding fundamental geological, chemical, and biological processes, and as an example of a type of environmental system that could have hosted the origin of life on early Earth and could potentially support life on other planets and moons of our solar system.

In 2014, the Lost City hydrothermal field was proposed for special protection by the UNESCO World Heritage Centre and International Union for Conservation of Nature, although there is no enforcement of this protection due to the current lack of any legal framework for protection of the seafloor in international waters (Heffernan, 2018; Ngum and Rene, 2021). For example, a large tract of the seafloor including Lost City was included in an exploration mining permit awarded to Poland in 2017 by the United Nation's International Seabed Authority (Radziejewska et al., 2022). Subsequently, the Lost City chimneys have become a symbol of what can be lost to deep-sea mining activities and have been used to argue for meaningful regulations (Cuyvers et al., 2018; Johnson, 2019). Deep seabed mining presents substantial risks to ocean health, including irreversible harm to marine ecosystems, disruption of ecosystem services and cultural heritage, and possible species extinctions. The scientific knowledge gaps concerning the deep sea are significant and could take decades to address, leading many scientists and environmental organizations to advocate for a moratorium on deep-sea mining.

Although no mining activities are currently planned for the seafloor surrounding Lost City, multiple national and corporate interests are currently attempting to mine various sites, especially in the Pacific Ocean (Kröger et al., 2025). As we wrote this article, headlines emerged about the intentions of mining companies to seek mining approval from the United States to fast-track deep-sea mining, bypassing the United Nations and the International Seabed Authority despite global opposition. This effort to bypass is a result from President Trump's executive order signed on April 24, 2025, titled "Unleashing America's Offshore Critical Minerals and Resources" (Executive Order 14285, 2025), which aims to advance U.S. leadership in seabed mineral development by accessing, processing, and utilizing critical minerals found in offshore areas.

Discovery in 2000

The discovery of Lost City is often described as accidental or serendipitous. Indeed, the appearance of the ghostly white chimneys on a video screen aboard the R/V *Atlantis* in December 2000 was a surprise—not something that any of the geologists on board were expecting to see. At this point in time, the discovery of seafloor hydrothermal vents was already more than 20 years old, and it was well-established that large, actively venting hydrothermal chimneys were found only at seafloor spreading centers and other sites where large magmatic heat sources are near to the seafloor. Therefore, there was no reason to expect to find a cluster of warm chimneys reaching 60 m tall at a location 15 km away from the seafloor spreading center of the Mid-Atlantic Ridge.

Why, then, was a team of geologists exploring this part of the seafloor with the submersible Alvin as well as mapping and imaging equipment? They were searching for evidence that chunks of Earth's upper mantle were sometimes thrust from deep beneath the seafloor into the oceanic crust, a predicted consequence of seafloor spreading that could provide clues regarding the fundamental nature of Earth's mantle. These ideas had been developed in response to the discovery of the global mid-ocean ridge system after World War II, which resurrected the long-ridiculed idea of continental drift by providing a physical mechanism for the movement of the continents: they ride on thin plates of crust that are formed at mid-ocean spreading centers. The seafloor literally splits apart at these spreading centers, allowing new crust to be formed and pushing previously created crust out to where it will eventually collide with crust formed at other spreading centers. This discovery and its subsequent scientific revolution transformed the deep seafloor from a cold, dark place beyond the realm of human experience into the birthplace of both rocks and life.

By the 1990s, there was no longer any question regarding the validity of seafloor spreading and plate tectonics as a scientific theory, but geologists had many unanswered questions regarding the physical and chemical details of how it all worked. Is Earth's crust formed only by volcanic eruptions at the spreading centers? Are there other sources, such as slabs of rocky seafloor pulled up from deep beneath the seafloor? Does Earth's mantle contribute to the seafloor, or is it completely separated from the crust? Do mid-ocean ridges require a massive supply of magma to fuel seafloor spreading, or can plate tectonics continue to be active in the absence of magma? What physical features appear in regions of seafloor that have experienced rapid or slow spreading? Why is the Mid-Atlantic Ridge a chain of giant mountains, while other spreading centers are only small ridges?

These big-picture geological questions, among many more technical questions specific to their disciplines, were on the minds of the scientists aboard the R/V *Atlantis* when they discovered Lost City during the 2000 MARVEL Expedition. The main goal of this expedition was to gather evidence pertaining to the geologic origin of the Atlantis Massif, a submarine mountain roughly the same size as Mt. Rainier, WA. Their hypothesis was that the Atlantis Massif was not a volcano like Mt. Rainier, but rather a chunk of the lower crust or upper mantle that had risen to a weak spot in the seafloor created by the spreading of thin, newly formed crust. If so, the Atlantis Massif would provide an opportunity to study rocks that had formed not at a mid-ocean spreading center, but deep within the Earth, thereby giving geologists a rare glimpse into the nature of the lower crust and upper mantle. At the same time, they expected that the sudden intrusion of a mountain-sized chunk of mantle rock into the seafloor could trigger interesting chemical reactions, as these rocks from Earth's interior become exposed to water for the first time. The resulting hydration and oxidation of mantle rocks is known as serpentinization, due to the snakeskin-like texture that forms on the altered "serpentinite" rocks. Serpentinization was already known as a slow weathering reaction from the study of mantle-derived rocks that had been pushed (by plate tectonics) onto land and from a few examples of serpentinites that had been dredged from the seafloor. Serpentinization was expected to form very interesting minerals and perhaps cause the release of chemicals like hydrogen gas and methane into the ocean, but there was no expectation that serpentinites would be the place to find large fields of hot chimneys.

When a bright white chimney appeared in the monitor aboard the R/V *Atlantis*, captured by the towed camera sled Argo as it surveyed the Atlantis Massif, clearly it was something new and different. Not only was it located near the summit of a giant mountain 15 km away from the spreading center, but it looked very different from any previously observed hydrothermal vents. Samples of the chimneys collected during a subsequent dive with the manned submersible Alvin would show that the chimneys are composed of aragonite and calcite (calcium carbonate minerals) as well as brucite (magnesium hydroxide), a strong contrast to the dense metal sulfide deposits that form "black smoker" chimneys typically found at mid-ocean ridges. Furthermore, the chimneys were venting warm, alkaline fluids at temperatures less than 100°C, rather than the magmatically super-heated, acidic fluids of black smoker systems. Another immediately evident difference was the absence of giant tube worms or other large animals characteristic of vent fields with black smoker chimneys; instead, tiny mussels and amphipods were the most notable animals, while visible microbial biofilms covered the chimneys.

Geologists who had studied serpentinization, including participants on that 2000 discovery expedition, had suggested that it could release enough energy to create springs or seeps (Früh-Green et al., 1990; Kelley and Früh-Green, 1999), but they could not have predicted the towering spires of Lost City nor the biological communities living on them. Why the Lost City chimneys formed in this location remains an active topic of scientific inquiry (Blackman et al., 2002; Kelley et al., 2005; Lissenberg et al., 2024), but clearly a major source of energy fueling the chimneys is the heat of the mantle rocks that form the Atlantis Massif. In other words, the Atlantis Massif is still warm not because of ongoing magmatic activity but simply because the heat of deep rocks warms deeply circulating fluids.

The discovery of the Lost City chimneys also broadened our concepts of hydrothermal systems in terms of time. Typical black smoker chimneys are formed in months or years and can "die" just as quickly as their subseabed plumbing systems shift in accordance with their magmatic heat sources. Researchers revisiting their black smoker study sites may often find that venting has ceased, or that the field has been paved over by a volcanic eruption. Conversely, previously dormant sites can become reinvigorated. In stark contrast, the Lost City chimneys are fueled by a million-year-long tectonic uplift and appear to have been venting continuously for at least 100,000 years in the same location and probably longer (Früh-Green et al., 2004; Ludwig et al., 2011).

Nothing else quite like Lost City has been discovered yet, but white chimneys composed of carbonate minerals do occur elsewhere in the ocean (Postec et al., 2015; Lecoeuvre et al., 2021). Furthermore, chemical and biological products of serpentinization-associated reactions can be found in many kinds of hydrothermal systems on the seafloor and on land (Schrenk et al., 2013; Colman et al., 2025). Lost City may be unique, but it is only one particularly striking example of a widespread geological-chemical-biological phenomenon.

Therefore, rocks uplifted into the seafloor transfer their heat—a memory of their mantle origin—into seawater that flows through and alters them into new minerals and chemicals. The seawater circulating through these rocks also carries microbes, some of which are capable of colonizing and making a living in serpentinizing rocks and the chimneys that grow from them, perhaps because they had been living in a nearby seafloor environment also supplied with the products of serpentinization. In this way, we can imagine the continual intrusion of mantle rocks into the seafloor over geological time supporting a network of microbial communities that collectively retain the genetic memory for carrying out microbial activities fueled by the interaction between Earth's interior and its ocean.

Origin of life, chemosynthesis, and serpentinization

Many theories exist on how life emerged on Earth from a rocky solar system and its starting materials. A leading hypothesis was (and is) borne from the experiments of Miller and Urey that simulated lightning in an early Earth atmosphere (Miller, 1953). They showed that suites of organic molecules could be created from inorganic constituents, forming the earliest precursors to life. These small molecules could have accumulated in ponds on the surface of Earth and then, as the ponds evaporated, been brought into proximity to each other, allowing them to react with each other to generate more complex molecules.

The discovery of black smoker hydrothermal systems in 1977 upended the world view that all life on Earth was directly dependent on photosynthesis (Corliss et al., 1979). At the time, the deep sea was considered cold, dark, and inhospitable. The bacteria and animals surviving in the deep sea subsisted by scavenging food that sank from the surface ocean. The newly discovered hydrothermal systems were remarkable not just for their chimneys and heat but also for the diversity of life associated with them. Giant tube worms, clams, and other organisms hosted symbiotic chemosynthetic bacteria converting hydrogen sulfide and other chemicals in the vent fluids to biological energy. Complex ecosystems were built on the foundation of this chemosynthesis, rather than photosynthesis.

This discovery brought forth a new hypothesis for the origin of life: that it emerged from deep-sea hydrothermal vents, where the earliest steps may have been catalyzed by geochemistry and fueled by magmatic heat rather than lightning and a slow accumulation of organic materials in a pond (Corliss et al., 1981; Baross and Hoffman, 1985). At the time, some argued that black smoker hydrothermal vent fluids were so hot and acidic that organic molecules would quickly decompose, making them poor sites for the origin of life (Miller and Bada, 1988). A central concept of the hydrothermal origin hypothesis, however, is the formation of environmental gradients by the mixing of hydrothermal fluids with cold seawater (Baross and Hoffman, 1985), and others noted that some hydrothermal systems exist at lower temperatures (Russell et al., 1988). Indeed, lower temperature (<100°C) fluids were soon realized to vent from a large proportion of the basaltic and gabbroic oceanic crust, including near-subseafloor mixtures of hydrothermal fluids seawater circulating for kilometers through older crust far from spreading centers (German and Von Damm, 2006). Understanding hydrothermal vents as not only exotic, extreme environments but also manifestations of a global process that includes much of the world's ocean floor and connects these potential cradles of Earth's first life to the fundamental geological engines of seafloor spreading and plate tectonics.

The biological potential of these systems is evident from the incredible diversity of bacteria, archaea, and microbial eukaryotes that inhabit them (e.g., Orcutt et al., 2011), including hyperthermophilic archaea adapted to temperatures well in excess of 100°C (Takai et al., 2008). Nonetheless, the idea persisted that hydrothermal systems were unsuitable locations for the origin of life because they were too hot and too short-lived to allow the development of complex molecules, leading many to favor alternative hypotheses for life's origins (e.g., Bada, 2004).

The hypothesis that life may have emerged at hydrothermal systems fueled by the serpentinization reaction, which came to be known as the submarine alkaline vent theory, was proposed at a time when marine alkaline vents had not yet been discovered (MacLeod et al., 1994; Russell et al., 1994; Russell and Hall, 1997). In this scenario, hydrothermal circulation is hosted on ultramafic rocks rich in olivine and pyroxene rather than gabbros and basalts. These are the types of rocks that support serpentinization (described above), which can generate H_2, an excellent fuel for organic synthesis reactions. The resulting fluids are alkaline and, when mixed with seawater, create a proton gradient that may have provided a template for the evolution of the proton-driven energetic machinery common to all cellular life forms today (Russell et al., 2010; Krulwich et al., 2011; Schrenk et al., 2013).

Continental alkaline springs, rich in H_2 and CH_4 hosted in peridotites, had already been recognized in Oman (Barnes et al., 1978; Neal and Stanger, 1983), California (Barnes et al., 1978), and Italy (Cipolli et al., 2004). The discovery of the Lost City hydrothermal field in 2000, and subsequent work at the field, showed that the system had many of the necessary prerequisites including warm but not-too-hot temperatures (40–116°C), high H_2, alkaline pH (9–11), and abiotically synthesized organic compounds including short-chain hydrocarbons and formate (Kelley et al., 2001; Kelley et al., 2005; Proskurowski et al., 2008; Lang et al., 2010). Similar processes of serpentinization and generation of high H_2, alkaline fluids have been proposed to occur throughout the solar system (Glein et al., 2015; Vance and Daswani, 2020; Spiers and Schmidt, 2023). As a result, the Lost City hydrothermal field has become a model system to many researchers investigating what types of water-rock reactions and geochemical conditions may have led to the rise of life on Earth and other planetary bodies.

"Return voyage"

The 2003 expedition returned an immense amount of information on the geochemistry, geology, and biological properties of the Lost City system (Kelley et al., 2005; Proskurowski et al., 2006; Proskurowski et al., 2008; Bradley et al., 2009; Brazelton et al., 2010; Lang et al., 2010). Many key outstanding questions remained, however. Abundant metabolic energy is available in systems such as Lost City, and similar mantle rocks are distributed widely in the Atlantic, Arctic, and Indian Ocean. Microbial communities hosted by ultramafic-dominated systems could therefore represent a vast biome within the rocks below the ocean. There are significant potential limits on life's ability to thrive in these environments, however. The dual challenge of adapting to high pH (9–11) and elevated temperatures may be too great to overcome. The almost complete lack of dissolved inorganic carbon (total CO_2: $\sum CO_2 = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]$), an essential resource for primary chemosynthetic producers, represents a second, and possibly more significant, limitation to growth. To better understand the potential extent of serpentinite subsurface ecosystems, the goal of the 2018 expedition was to determine: what limits microbial activity in the serpentinite subsurface?

In September 2018, an international team of researchers boarded the R/V *Atlantis* and began a 5-day transit to the Lost City hydrothermal field. The multidisciplinary group included microbiologists, geologists, chemists, engineers, and a scientific artist (**Figure 1**). The team was brought together with the goal of combining diverse perspectives and approaches to better understand the factors that shape the distribution and limits of life in this extreme environment.

Before reaching the site, the team encountered the first of several hurricanes that would challenge the expedition. After delays to let the storms pass, the R/V *Atlantis* arrived at Lost City in calm seas. The remotely operated vehicle (ROV) *Jason* was loaded with sensors, water samplers, and specialized boxes designed to retrieve delicate chimney structures safely. Equipped with high-definition cameras, ROV *Jason* transmitted live footage to monitors installed throughout the ship's laboratories. The deep ocean is dark, but scientists and crew alike gathered around the screens as the ROV lights revealed chimneys in the distance (**Figure 2**).

With limited time available on station, the science and *Jason* teams quickly sprang into action to maximize their research efforts. Each time the ROV was deployed to depth it returned loaded with water and chimney samples, filters that trapped microorganisms, and sensor data. Between dives, all samples were removed and processed, and the samplers cleaned and turned around for *Jason*'s next deployment into the ocean. After 5 days on station, the weather conditions deteriorated and the R/V *Atlantis* headed back to port. Onboard were freezers of processed water and chimney samples and carefully preserved filters for DNA and RNA sequencing as well as ongoing incubation experiments.

In the years since the expedition, the science team has reported their findings in numerous peer-reviewed articles. One of the primary discoveries was that a few key species of archaea and bacteria likely play critical roles in the subseafloor microbial ecosystem (Brazelton et al., 2022). However, some of these microbes appear to require assistance in accessing $\sum CO_2$, which is scarce in the hydrothermal fluids. Notably, a dominant species of methane-producing archaea is predicted to use $\sum CO_2$ as its carbon source, based on its genetic content, but might rely on other microbial species, such as sulfate-reducing bacteria, to make $\sum CO_2$ available by oxidizing the small organic acid formate (Lang et al., 2018; McGonigle et al., 2020).

Additional significant findings included documentation of the multi-stage evolution of the fluids that supply the Lost City chimneys (Aquino et al., 2022), as well as the striking diversity of microbial communities that are shaped by (and shaping) the intricate mineralogy of the chimney structures (Aquino et al., 2024; Alain et al., 2025). Individual chimneys grow and disappear on time scales of months to thousands of years within a vent field that has been active hydrothermally for at least 100,000 years (Früh-Green et al., 2003; Ludwig et al., 2011). Each

Figure 1. Interdisciplinary team aboard the R/V *Atlantis* studying Lost City in 2018. Left-to-right: Jessica Frankle, Wee Shu Ying, Heather Lizethe Pendleton, Anna Davidson, Cameron Henderson, Susan Lang, David Butterfield, Karmina Aquino, Osama Alain, Shahrzad Motamedi, Tamara Baumberger, William Brazelton, Julia McGonigle, Aled Evans, Aaron Mau, Gretchen Früh-Green, Marvin Lilley, Sharon Walker, Elaina Thomas, Timothy D'Angelo, and Mitchel Elend. The remotely operated vehicle *Jason* appears in the background.

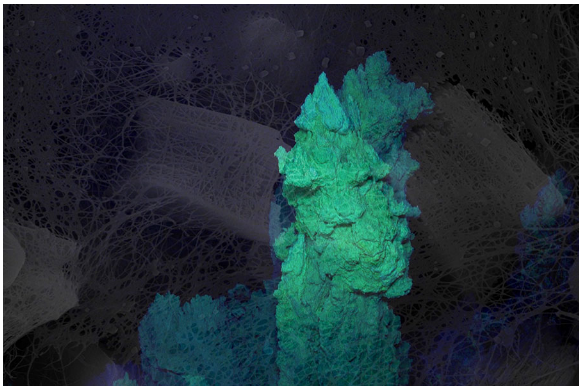

Figure 2. *Untitled*, 2023, by Anna Davidson: digital print of Lost City chimney rock overlaid on biofilms. Original images of the chimney rocks (bright colors in the foreground) were captured with underwater video by the ROV Jason provided by SQ Lang (U of SC / NSF / ROV *Jason* / 2018 © WHOI). Behind the rock is a scanning electron microscope image of a chimney and biofilm at an image size of approximately 11 µm by 13 µm, provided by TRR Bontognali (Space Exploration Institute, Neuchâtel, Switzerland), SQ Lang, and GL Früh-Green (Swiss Federal Institute of Technology, Zürich, Switzerland, Swiss National Science Foundation). Print size is 44 cm × 60 cm.

time a chimney begins to grow, it is colonized by microbial communities harboring the adaptations required for living within a constantly growing and evolving mineral matrix (Brazelton et al., 2010). These genetic memories surely preceded the birth of the Lost City hydrothermal field less than a million years ago and have been continually evolving throughout Earth's history in all the many locations where such minerals are formed by serpentinization and associated reactions (Colman et al., 2025).

Unexpected insights relating to time also emerged from geochemical analyses of the fluid samples. For example, the time required for seawater to travel downward from the deep ocean through the subseafloor rocks and back into the ocean through the chimneys appears to be surprisingly short—on the order of years rather than decades or millennia (Moore et al., 2021). Along this journey, the fluids become depleted in the highly refractory dissolved organic carbon ubiquitous in deep seawater, demonstrating for the first time that ultramafic rocks are a geologic sink for this important carbon pool (Lang et al., 2024). These organic molecules are mostly degradation products of biomass formed by living organisms that had lived perhaps hundreds or thousands of years ago, mostly in the surface ocean and on land. Therefore, results from this expedition have revealed that much of the deep-sea detritus of life, almost certainly including human remains and waste, is ultimately deposited for long-term storage in chunks of Earth's mantle. The same geologic transformations of seafloor that create cradles of life also provide a means for the storage and recycling of the remains of life.

Art of Lost City

During the 2018 voyage, Davidson began developing a body of work focused on Lost City—its architecture, its inhabitants, and eventually the threats posed by deep-sea mining. Daily activities ranged from painting, photography, video, and participating in the dives with *Jason.* For example, "Porthole Series" is a collection of 24 watercolor and ink paintings resulting from daily documentation of the seascape from the view of her porthole (**Figure 3**). These seascapes range from dark, cloud-filled skies during transit days to the calm, flat waters while on station, a visual representation of the weather to remember, in addition to numerical values on an excel spreadsheet.

In between dives Davidson assisted with the cameras and footage obtained from *Jason*. This footage was edited into an 8-minute video art piece projected in exhibitions (**Figure 4**). This piece provided viewers the opportunity to be immersed in the deep sea, to see what *Jason* and the scientists see. One lesson learned from this experience is that future expeditions should incorporate the artist at earlier stages of planning each dive, to ensure that the video captured during the dive satisfies both scientific and artistic needs. Satisfying artistic needs does not require scientists to sacrifice any dive time, only to plan and communicate, before and during the dive.

Captivated by the microbial biofilms found on site, Davidson printed scanning and transmission electron microscopy images of biofilms and microbes on fabric and wood and incorporated the results into mixed media sculptures post-voyage (**Figures 5**–**7**). Additionally, samples of chimney rocks (**Figure 6**) and venting fluids (**Figure 7**) were incorporated into wooden, chimney-shaped three-dimensional sculptures that also contained various materials including mirror and electronic wires, elements intended to evoke deep-sea mining.

The scanning and transmission electron microscopy images of biofilms and the architecture of the chimney rock were combined to create eight photographs that accompanied the sculptures. The fabric was used to create two large video installations, each containing multiple life-sized triangles representing the chimneys. These triangle forms were arranged to support one another while providing a "screen" for projection (**Figure 5**). The fabric was also used in a one-dimensional embroidery piece.

To help inform the public about the immediate threats of deep-sea mining, a large sculptural installation was created using canvas, ink, wire, sand, and real polymetallic nodules collected from the abyssal seafloor in the Clarion Clipperton Zone, central Pacific Ocean, by scientists from the U.S. Geological Service. The piece, simply titled "Deep-Sea Mining" (**Figure 8**), allows the viewers to see polymetallic nodules in person, which helps make the concept of deep-sea mining more tangible to the viewer.

The resulting body of work was featured in several exhibitions that underscored the dynamic interplay between art and science. The first, titled *The Lost City: Artwork by Anna Davidson*, was presented at the University of Utah in Salt Lake City, the academic home of microbiologist William Brazelton. Six sculptures and a video titled "Lost City" were shown in the center of the Marriot Library of the university.

The second exhibition, *Lost City: Between Art and Science*, was hosted at the McKissick Museum at the University of South Carolina in Columbia (**Figure 9**), where geochemist Susan Lang was based at the time of the expedition. Here, Davidson's artwork was interwoven with specimens collected during the expedition and research posters created by university students who had worked directly with Dr. Lang and who were part of the expedition. This dual curation fostered a genuine dialogue between artistic expression and scientific inquiry, illustrating how both disciplines can inform and elevate each other when presented

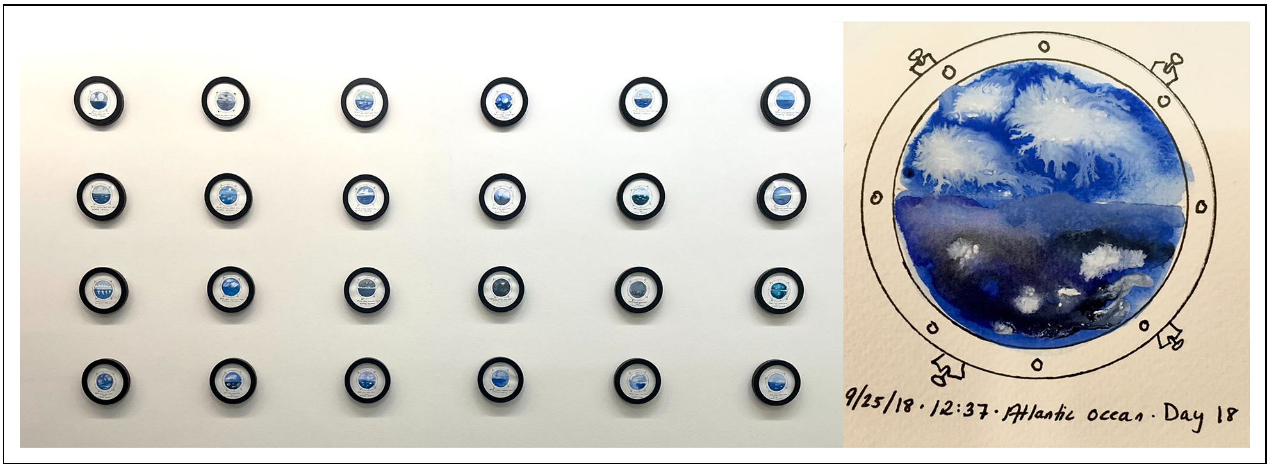

Figure 3. *Porthole Series,* 2018, by Anna Davidson: watercolor and ink on watercolor paper. Daily drawings of the seascape outside the artist's porthole of the research vessel *Atlantis*. Each drawing is on paper of approximately 15 cm diameter.

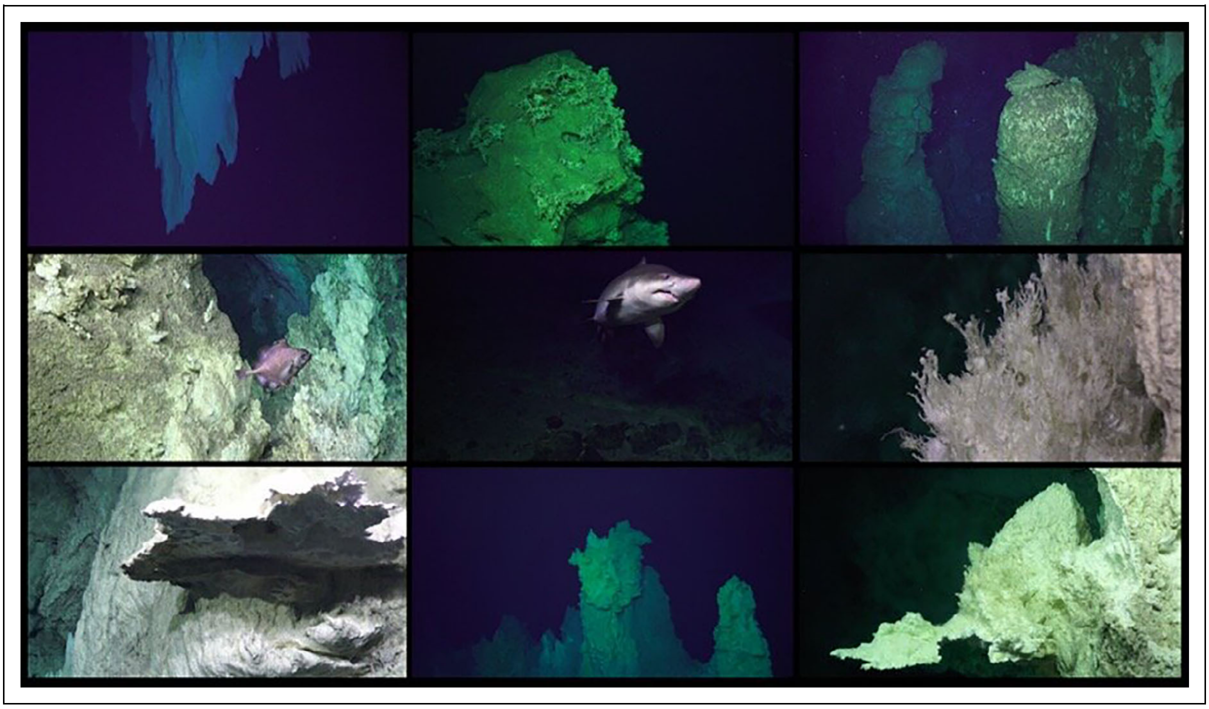

Figure 4. Multiple still images from the 8-minute video art piece, *Lost City,* 2018, by Anna Davidson. Images are of Lost City chimney rock with varying degrees of hydrothermal venting; two (unidentified) species of fish and shark are visible in middle left and center panels, respectively. Fields of view for upper panels, left to right, are approximately 1 m, 2 m, and 3 m; middle panels, left to right, approximately 1 m, 3 m, and 0.2 m; and lower panels, left to right, approximately 1.5 m, 5 m, and 4 m. The video was projected on a wall in a private viewing room during an exhibition at the McKissick Museum in Columbia, SC. Projection measured approximately 3 m × 4.2 m. Footage was provided by SQ Lang, U of SC / NSF / ROV Jason / 2018 © WHOI.

Figure 5. *Untitled*, 2023, by Anna Davidson: video installation. Video projection with scanning and transmission electron microscopy images of microbes printed on fabric and wood panels. The installation is approximately 1.8 × 2.4 × 1.5 m.

side by side. Additionally, at the opening both the artist and scientists gave public lectures about their work to complement what visitors experienced in the gallery. These presentations not only created a more robust story but also provided time for visitors to ask questions and for personal interaction among the scientists, artist, curators, and the public.

For visitors, the research posters offered a window into the scientific process: they revealed how data from Lost City were gathered, and how the research had evolved from questions derived from earlier findings at the site. They detailed the experimental methods used to pursue answers and offered new research findings. The posters allowed the viewer to zoom in on both the meticulous nature of the research and the complexity of the findings. Conversely, the artwork provided bigger pictures employing broader concepts while being informed by evidence-based research. Untethered from the constraints of the scientific method, the artist had the freedom to mix and match elements from the expedition using an array of materials to convey messages that may appeal to an alternative audience. The artwork provoked colorful discussions not only about Lost City but also the very fact that an artist was part of the expedition. Our hope is that this paper inspires more permanent artist residencies on research vessels similar to Schmidt's Artist at Sea Program on the R/V *Falkor* (Schmidt Ocean Institute, 2025).

Figure 6. *Deep-Sea Mining Threats*, 2022, by Anna Davidson: multi-component sculpture. Components include wire, mirror, chimney rock, digital photographs, and scanning and transmission electron microscopy images printed on wood. The piece is approximately 76 cm × 20 cm × 20 cm. Image of chimney was provided by SQ Lang, U of SC / NSF / ROV Jason / 2018 © WHOI.

Figure 7. *Poseidon*, 2022, by Anna Davidson: multi-component sculpture. Components include transmission electron microscopy images of microbes printed on sticker and applied to wood, plexiglass, and volumetric flasks containing venting fluids from Lost City. The sculpture is approximately 91 cm × 30 cm × 13 cm.

For the scientists, collaborating with Davidson offered a rare opportunity to see their work reimagined in sculptural, sometimes whimsical forms—breathing new life into

Figure 8. *Deep-Sea Mining*, 2023 by Anna Davidson: large, multi-component sculptural installation. Components include fabric, dye, paint, wire, sand, and polymetallic nodules. The installation is approximately 3.0 m × 1.2 m.

their data and discoveries. Her interpretations became an alternative visual narrative, complementing the traditional scientific outputs of graphs, charts, and technical reports. Perhaps science-based artwork has the potential to rekindle a sense of wonder in the researchers themselves, emphasizing the intrinsic beauty, uniqueness, and fragility of the natural systems they have devoted their careers to studying.

In 2023, select pieces from Davidson's body of work were exhibited at Cornell University in Ithaca, New York, and in 2024 at Winthrop University in Rock Hill, South Carolina, as part of the group show *Emergent Ecologies*. The work continues to circulate and evolve, especially as it engages with critical contemporary issues such as the potential risks posed by deep-sea mining—keeping the conversation between art, science, and culture very much alive.

Interdisciplinary models, progress, and lessons learned

A substantial body of literature documents the outcomes of collaborations between artists and scientists (Swanson, 2015; Eldred, 2016; Schnugg and Song, 2020; Leigh et al., 2021), and there is increasing institutional support for incorporating the arts and humanities into scientific contexts (Swanson, 2015). One manifestation of this trend has been the establishment of permanent artist- and humanities-in-residence programs at field stations. For example, the H.J. Andrews Experimental Forest, affiliated

Figure 9. Gallery view of the exhibit titled *Lost City: Between Art and Science.* View at the McKissick Museum at the University of South Carolina, Columbia, SC.

with Oregon State University, created the *Long-term Ecological Reflections Program: Arts, Humanities, and Science in Alliance* (PRAx, 2025). Modeled after the U.S. National Science Foundation's Long-Term Ecological Research program, the Long-Term Ecological Reflections initiative is notable for its commitment to interdisciplinarity, creativity, and collaborative exploration of environmental change over generations. The program's explicit goal is to foster sustained opportunities for reflection and creative expression, while building a 200-year archive of works (2003–2203). Internationally recognized writers such as Robin Wall Kimmerer (*Braiding Sweetgrass, 2013*) and Barry Lopez (*Arctic Dreams, 1986*) have participated in this residency.

Numerous other field stations and Long-Term Ecological Research sites in the U.S. host artist residencies, including Flathead Lake Biological Station (MT), Cedar Creek Ecosystem Science Reserve (MN), Hubbard Brook Experimental Forest (NH), Toolik Field Station (AK), Trout Lake Station (WI), multiple sites within the UC Natural Reserve System, and more. Some marine-focused programs include Friday Harbor Laboratories (WA), Shoals Marine Laboratory (ME), the Hawaiʻi Institute of Marine Biology, and the Hatfield Marine Science Center (OR).

In addition, artist residencies outside scientific institutions have invited scientists into their communities, fostering extended cohabitation and collaboration. A prominent example is *Scientific Delirium Madness* at the Djerassi Resident Artists Program in the Santa Cruz Mountains of northern California. An international example is the Arctic Circle Artist and Scientist Residency, which brings together a diverse group of creatives and scientists to explore the Svalbard Archipelago and Arctic Ocean aboard a specially outfitted icebreaker. Similarly, ship-based initiatives such as the Artist-at-Sea programs run by the Schmidt Ocean Institute, Ocean Exploration Trust, and Foundation Tara Océan demonstrate the expanding role of the arts in marine science.

Despite this progress, we argue that additional opportunities are needed for integrating the arts and humanities into science-based expeditions, particularly in the marine sciences. Our own experience highlights several lessons learned:

1. **Early inclusion of artists**. In our case, the artist's invitation to join the expedition was organic and last-minute. Therefore, the artist had not been included in the NSF grant writing and planning phases. We strongly recommend identifying and involving artists at the earliest stages to facilitate collaborative project design, generate interdisciplinary research questions, and ensure funding allocations for artistic contributions and post-expedition dissemination. Early involvement enhances richness, collaborative potential, and would help create an inclusive and welcoming environment for the artist while aboard the research vessel.

2. **Mutual knowledge exchange**. During transit to Lost City, all participants—scientists and the artist—shared presentations on their backgrounds and goals. This exchange was crucial for establishing mutual understanding of both the scientific and artistic work, and for articulating the value of artistic contributions to the expedition.
3. **Collaborative project design**. Although we worked largely in parallel during the expedition, our efforts were mutually informative. We recommend intentional planning of co-created projects where artists and scientists contribute equally to shared outcomes.
4. **Assessment**. The joint exhibition at the McKissick Museum, where artwork was displayed alongside scientific posters and artifacts, proved highly valuable. Future exhibitions would benefit from incorporating visitor surveys to qualitatively and quantitatively assess audience engagement and outcomes, a source of data that could be helpful in grant writing and institutional support for future opportunities. Survey data could also help evaluate the effectiveness of the exhibition to help guide the planning of future collaborative exhibitions.

Conclusion

By combining microbiological, geochemical, and artistic inquiry, the 2018 Lost City project not only advanced our scientific understanding of subseafloor life and carbon cycling but also illuminated the deeper philosophical, aesthetic, and cultural dimensions of the ocean as a living archive. The scientific findings from Lost City—ranging from the interdependent nature of microbial life in extreme environments to the finding that ultramafic rocks act as a sink for dissolved organic carbon—offer insights into the mechanisms by which the ocean retains and recycles information across geologic time. These findings expand our understanding of both Earth's biosphere and the potential for life on other worlds, situating Lost City as a vital analog for prebiotic conditions and evidence that the ocean indeed has a memory.

In parallel, the artworks served as alternative presentations of knowledge that could reach additional audiences. Through sculpture, video, photo, painting, and material experimentation, artist Anna Davidson reimagined data as narrative, sample as sculpture, and site as story—connecting audiences to the deep sea in emotional, visceral, and conceptual ways that science alone may not.

Together, the science and art of the Ocean Memory Project advocate for an expanded epistemology—one that acknowledges the ocean not only as a subject of study, but as an agent of memory and meaning. As the threats of deep-sea mining and climate change loom larger, this integrated approach offers a model for future ocean research and visual storytelling—one rooted in collaboration, imagination, and respect for the ocean.

Data accessibility statement

Data generated during the 2018 Lost City expedition are archived at the BCO-DMO page for project 658604: https://www.bco-dmo.org/project/658604. Artwork created from this project is available in this manuscript and at www.annadavidson.art.

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Competing interests

The authors declare no conflict of interest.

Author contributions

Contributed to conception and design: AMD, SQL, WJB.
Contributed to acquisition, analysis, and interpretation of data: SQL, WJB.
Contributed to artwork: AMD.
Drafted and revised the article: AMD, SQL WJB.
Approved submission for final publication: AMD, SQL, WJB.

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