Investigating the hidden ecosystems vibrant underneath hydrothermal vents and deepest oceanic trenches

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Abstract

The distinctive ecosystems and biodiversity linked to Mid-Ocean Ridge (MOR) hydrothermal venting networks starkly differ from adjacent Deepest Oceanic Trenches (DOT); however, both face escalating threats from modern activities, such as mining at enormous sulphide occurrences. Global warming can affect the DOT by raising bottom conditions, depleting oxygen levels, and altering DOT circulation patterns. Notwithstanding the possibility for significant impacts, the processes that allow these structures and their natural environments to endure, operate, and react to maritime, crustal, and anthropogenic stresses are inadequately comprehended. This is mainly attributable to technical obstacles and challenges in obtaining, watching, and tracking the DOT. During the 2000s, a DOT observatory was established to elucidate the interaction among sub-surface flows and oceanic and crustal environments and their impact on biological activities. DOT observatories yield extensive, interdisciplinary time-series information, including repeated surveys and samples at temporal precision ranging from seconds to years, utilizing a blend of cabled, portable, centrally operated, and autonomous measurement equipment. These observatories advocate for stewardship by establishing effective environmental surveillance, which includes characterizing natural and ecological baseline conditions, distinguishing changes due to natural variability from those resulting from human activities, and evaluating degradation, resiliency, and recuperation following disturbances. This underscores the potential of observatories as essential instruments for Ecological Impact Analysis (EIA) on climatic changes and other human activities, particularly ocean mines. This report presents an overview of scientific accomplishments facilitated by the three observatories over the past decade, along with suggestions to enhance future research through international cooperation and coherence. The suggested suggestions encompass: i) the establishment of universal scientific inquiries and the identification of Essentials Ocean Variables (EOVs) pertinent to MORs, ii) directives for the efficient utilization of observatory to inform policies affecting society, iii) methods for the growth of observatories facilities aimed at standardizing detectors, data types, and capacity, and iv) future technological requirements and unified sampling methodologies to address the most pressing contemporary questions.

Keywords: Hydrothermal Vents, Deep Sea, Oceanic Trenches, Ecosystems

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Introduction

In the last approximately 60 years, following the revolution in Earth and Ocean disciplines initiated by the validation of expanding seafloors and plates tectonics, technological difficulties, restricted access, and elevated costs related to Deepest Oceanic Trenches (DOT) research have resulted in considerable deficiencies in comprehending spatial and temporal variations linked to chemical, biological, and physical processes in the DOT (Du *et al.,* 2021). This particularly applies to seasonal dynamics that transpire across extensive geographical and time frames across the world's seas (Iyengar and Bhattacharya, 2024). DOT time-series studies have recorded significant climatic and ecological fluctuations from minutes to decades across multiple environments in bathyal and abyssal regions. The rising public's curiosity in DOT assets has led to an increasing acknowledgment of the urgent necessity for a thorough evaluation of the condition and vitality of DOT communities (Abel *et al.,* 2023).

Comprehensive ecological and biological starting points, along with a knowledge of their organic dynamics, are essential for evaluating and forecasting the effects and reactions of interrelated ecosystems to significant disturbances resulting from natural phenomena (e.g., seismic events and lava flows) and human activities (e.g., acidifying the oceans and rising temperatures, along with their climatic and ecological repercussions) (Saidova *et al.,* 2024; Abdi, 2017). Multi-decadal and transdisciplinary time-series analyses at varying time scales are crucial for distinguishing between anthropogenic effects and long-term ecological regular and episodic variation, enhancing the evaluation of environmental variables and their natural repercussions (Xiao *et al.,* 2025).

Mid-Ocean Ridges (MOR) and back-arc extending structures harbor distinctive habitats and biodiversity (Gollner *et al.,* 2021). Hydrothermal vents in these conditions facilitate substantial heat and chemical-based constituents transmission among the ocean's lithosphere as well as the surrounding hydrosphere, thereby regulating the thermo-mechanical evolution of the exterior, its development and stretching, rock change, and influencing elemental balances in the ocean (Beinart *et al.,* 2024). Unresolved inquiries persist concerning the temporal evolution of biotic groups, encompassing both non-directional and directional changes. Connected and automated DOT observatories can facilitate the long-term collection of multi-disciplinary time-series observations (e.g., geological history, physical, chemical-based, biological) with high temporal precision over years to centuries. Periodic submersible expeditions to research locations, alongside observatory upkeep, have recorded undersea lava flows and related alterations to hydrothermal vent systems.

Evolution of Biological Areas in the DOT

DOT, distinct from shallow marine animals, were gradually identified throughout the era of extensive oceanic

research (Jamieson and Onda, 2022). Accessing DOT habitats necessitates specialized equipment due to the extreme conditions present in these regions. After acquiring pertinent articles on DOT apparatus and biology, the study employed the VOS viewer to delineate the terms of the co-occurrence connection map. The minimal frequency for keyword occurrence was established at 25 instances due to the analysis of over 20k phrases. The research organized the top 98 terms for analysis based on their co-occurrence frequency to enhance the map's conciseness. The study encompassed several clusters, including organisms, environments, and equipment. Recent inquiries about DOT animals are progressively transitioning from species identification and habitat characterization to investigating ecosystems and their interconnections (Cheung, Wei and Levin, 2022).

Advancements in sample and in-situ monitoring technology have led to an increase in pioneering studies examining the adaptations of DOT creatures to extreme environments. Visualization tools and information storage methods were developed to comprehend the recently uncovered fauna's materials, framework, and purpose.

In laboratories, bioreactors can replicate the natural circumstances (elevated pressure, reduced temperatures, and high salinity) in which marine creatures thrive, facilitating studies on biodiversity and the natural adaptations of extremophiles. Generate novel bio-compounds and power that can be conducted responsibly inside the bioreactor without harming the ecosystem (Gladkova and Gladkov, 2021). In summary, enhanced studies on DOT ecosystems and their relationships with harsh conditions can be achieved through improved utilization of bioreactor technologies. In situ studies were facilitated by advancements in equipment.

Technological progress facilitates easier, deeper, and economical access to DOT ecosystems. Submarine technology combined with holography provides stereo imaging of the whole water structure. The dynamics of microbes and fauna in pristine deep-water regions have been assessed using high-resolution optical imagery and specimen examination combined with in situ DNA sequencing technologies. Since 2000, extensive distributions of extreme ecosystems, including cold seeps and hydrothermal vents, have been progressively uncovered through long-term submersible studies in deep-water environments. However, the restricted timeframe of dive research precludes a comprehensive assessment of rapid shifts and ongoing evolutionary characteristics. Long-term surveillance utilizing observatories to examine and track ongoing alterations in DOT environments was planned and executed (Ma *et al.,* 2024).

Studying the biological cycles in the deepest oceanic trenches has yielded insights into the evolution of specific creatures within their complicated oscillatory atmosphere, both directly and indirectly (Çiftçi, Ayas and Bakan, 2021). Significant previously undiscovered information regarding species in harsh habitats is revealed by advancing DOT capabilities.

Consequences for the Deepest Oceanic Trenches to Enhance Research on Abyssal Organisms

Recently, substantial advancements have been achieved in examining DOT environments from broad and deep viewpoints. Ongoing study of uncharted areas has led to the discovery of increasingly prosperous biological processes in the deep water. DOT ecosystems are inadequately comprehended, with merely around 1% of the seafloor being investigated by humans. Well-honed instruments yield superior results. Enhancing the efficiency of DOT equipment is essential for overcoming the limitations of the DOT creature study.

Delving Broader and Deeper into the Enigmatic Ecology

The environmental circumstances in the DOT ecosystem vary more than scientists previously anticipated. Historically, conducting in-situ surveys of marine habitats at depths over 40 m, beyond the capabilities of conventional scuba diving, has presented significant challenges due to the necessity for sophisticated equipment. A conventional desk-based study, which entails the analysis of photos and films captured by underwater camera equipment on vessels, leads scientists to perceive that they are examining virtual environments. Manned dives allow researchers to directly observe extreme surroundings, providing a more accurate assessment of the vastness of DOT environments and their interactions with environmental factors and organisms. The operational range of the supporting submarines is expanding to greater depths and widths. Researchers have successfully descended to the Challenger Deep in the Mariana Trench of the Pacific Seafloor. These diving vessels enable scientists to conduct meticulous observations, gather targeted specimens, and put, recover, or perform research on the deep ocean seabed. The number of researchers and the duration permitted for DOT investigations are significantly constrained.

Creating Extensive In-situ Conditions, Retaining Simulations

Living things in extreme habitats have evolved to the severe circumstances of the deep water, characterized by high pressure, high temperatures, poisonous surroundings, and restricted sustenance. Organismal parts, buildings, and gene regulation are altered during the transfer of creatures to the air atmosphere on the deck. The capacity of observation, identification, collection, and simulation apparatus to maintain in situ circumstances needs enhancement in future generations. In situ gene DNA sequencing has been suggested for nondestructive evaluation of DOT animals, providing a novel approach to investigate the genetic foundations of DOT life adaptability. Techniques for in-situ monitoring of chemical conditions, including underwater Raman imaging, DOT liquid chromatography, and various trace component analysis methods, can be created and combined to monitor environmental modifications in DOT habitats. Condition-controlled studies in the DOT facilitate microgram enrichment and acquiring ecological data, requiring advanced technologies for sensitive sensors, undersea positioning, continuous society, and directional collection. These new tools

will measure intricate reactions associated with elemental cycling in DOT habitats and enhance comprehension of the biogeochemical mechanisms involving DOT species.

Augmenting the Self-adaptive Capacity of the DOT Ecosystem

To comprehensively comprehend the biological processes in the DOT surroundings, it is essential to incorporate convenient, economical, and high-performance operational frameworks into future DOT gear. Relative to other kinds of equipment, soft design components will represent the future trajectory of manipulation systems, exemplified by soft robots emulating DOT fish and soft trapping gadgets prompted by human arms and legs, which enhance the efficiency of identifying and collecting delicate DOT organisms. Delicate organisms are abundant on the abyssal seafloor due to their skeletal and bodily structures evolving to be pliable in response to the extreme pressure of their habitat. DOT gear must adapt to extreme circumstances and environmental impacts to provide constant and reliable data regarding harsh conditions over extended durations. The observatories equipped with diverse imaging devices and sensors can function constantly in the deep ocean for extended durations, capturing three-dimensional ecological information to facilitate a thorough comprehension of the processes that occur inside ecosystems affected by worldwide shifts.

Engagement and Instruction

Current information and its corresponding archives represent an underutilized resource for educational goals and communication with the public. Hydrothermal vent environments are changing, and the various connections between biological and physical events should be incorporated into the academic curriculum at all levels. The accompanying annual cruises offer an unparalleled opportunity to develop outreach and educational programs. The extensive imagery save of hydrothermal vent structures can be utilized and presented to engage people's curiosity in these structures specifically, as well as in marine biology and DOT research broadly, while enhancing consciousness of the undiscovered and vulnerable ecosystems that the deep sea has yet to disclose to both the public and scientists fully. Given the rise in human activity, engaging with future generations and educating society on the findings, particularly regarding inaccessible regions, is imperative.

Over the past decade, numerous novel initiatives have been suggested across all three institutions to enhance public accessibility to science, personnel, and living aboard (Abbas *et al.,* 2024). The principal outreach initiatives pertain to upkeep excursions at the ocean at all three MORs (Box 3). Ocean Connections Canada facilitates broadcasting video, featuring comments from onboard crew, enabling viewers to observe Essential Ocean Variables (EOVs) excursions and on-deck activities aboard the study ship. The viewership of these broadcasts has significantly increased in the past few years due to a collaboration with the Ocean Exploring Respect (OER). It has regularly engaged the Investigative Ship

Nautilus, equipped with Hercules EOV, to conduct repairs at the Endeavour observatories. The Nemo Live programme attracts a substantial global audience, and the Education and Outreach personnel aboard the vessel possess expertise in conveying scientific concepts to the public, delivering real-time commentary during diving, and addressing inquiries from viewers on the internet. The Science Communications Scholarship and Science and Technology internship program enables teachers and pupils to collaborate with the outreach team at sea.

Various innovative initiatives have been established alongside live encounters during voyages, including participatory science and art & science programs. AbyssBox, the inaugural continuous open-air display of live DOT thermal fauna preserved at in situ pressure, represents a preliminary advancement in the year-round maintenance of diverse DOT fauna for academic and public interests.

The Deep Sea Spy (DSS) undertaking, established by Ifremer, enables societal participation in the scientific process by facilitating contributions to interpreting DOT hydrothermal vent data obtained from seafloor observatories. Over 1.5k citizens have analyzed around 52k photographs using the DSS platform, creating a repository of references for developing machine methods. The new methodology for studying ecosystems enhances public involvement and fosters scientific openness, thus augmenting the credibility and importance of the investigation method. The two radiophonic theater productions co-created by Ifremer researchers and the experienced theatre group encourage the audience to investigate the unknown and the imagined through active participation and immersive experiences. This method addressed the difficulty of engaging a distinct audience: individuals not inherently drawn to science or those residing far from the sea. More than 23k fans have attended one of the performances, with over 52 presentations anticipated in 2023. Going to the Eiffel Tower in an immersive setting through virtual eyewear offers a distinctive means to explore and understand an unreachable area (Box 3). This novel method of reaching the ocean's depths substantially enhances the capacity to elevate the general understanding of oceanic issues. Creating diverse outreach materials that engage all senses is imperative to reach a broad audience effectively. Collaborating with writers, artists, and performers, whose different perspectives enable exploration of the unknown in innovative ways, can facilitate the achievement of this purpose.

Although some of these programs originate from single or small group initiatives, a significant advancement could be realized by employing communication experts for each observatory to manage the available information. For instance, inside the European facilities, a communication service team is present; it is comprised of overburdened researchers and engineers and lacks a designated budget. The publicity staff facilitates outreach efforts throughout Nautilus trips and oversees at-sea engagement operations

during repair missions utilizing other boats and EOVs.

Conclusion

This paper provides a comprehensive framework to assist community-based studies in responding to specific occurrences and planning and coordinating observatory management and supplementary sampling during voyages. The study delineates the current advancements and outcomes facilitated by these observation structures, with the data, instruments, and architecture accessible to tackle scientific, technical, educational, and societal challenges. Data obtained over the past decade has significantly enhanced the comprehension of ridge and, more specifically, vent ecology. The last step is the integration of disciplines to improve the understanding of total DOT ecosystem operation, encompassing geological events and the location and reactions of biological populations. This can be accomplished by a collaborative endeavor to establish shared variables, detectors, and methods for complementary methodical sampling and data collection.

Science service organizations, such as those suggested by the network, can facilitate the dissemination of best practices for monitoring DOT environments from the seabed to the surface of the water and establish a global training initiative encompassing the handling of data and its availability. A substantial amount of data is collected through various observational projects and observations along the coastline and in international waters. An endeavor must be undertaken to correlate the data with adjacent measurements to achieve a comprehensive and multidisciplinary comprehension of ecosystem functionality at a regional level.

The suggested transdisciplinary initiatives are unique to regions to illustrate the viability of continuous DOT observation. Two suggested sites encompass the Azores Archipelago and the northern Pacific, extending from the Cascadian Marginal to the Juan de Fuca Peninsula. The execution of such projects facilitates the establishment of a community-oriented methodology for extensive cross-disciplinary investigations, positioning the ridge DOT ecosystem and its impact at the core of the worldwide oceans.

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