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Deep-sea hydrothermal vent communities and chemosynthetic energy pathways in the Mid-Atlantic Ridge

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Abstract

Miles below the ocean surface, where sunlight never reaches, entire ecosystems thrive on chemical energy from the Earth's interior. This research characterised the community structure and chemosynthetic energy pathways of hydrothermal vent assemblages at three sites along the Mid-Atlantic Ridge (MAR) between 36-38 degrees N latitude. Samples were collected during a research cruise aboard R/V Atlantis in July-August 2022 using the ROV Jason II, and laboratory analyses were conducted at the Instituto de Biologia Marinha do Algarve, Faro, Portugal, from September 2022 to June 2023. Faunal surveys at active chimneys, diffuse flow zones, and peripheral areas documented 43 macrofaunal species. Biomass declined exponentially from 847 g/m² at active chimneys to 8 g/m² on the abyssal plain. The shrimp *Rimicaris exoculata* dominated active chimneys (342 individuals/m²), while the mussel *Bathymodiolus azoricus* was the primary foundation species at diffuse flow sites. Stable isotope analysis (delta-13C and delta-34S) confirmed dual chemosynthetic pathways: thiotrophic sulfur oxidation and methanotrophic methane oxidation. These data expand the known faunal inventory of MAR vent fields and clarify the trophic structure supporting life in the deep Atlantic.

Keywords: Deep-sea hydrothermal vents, chemosynthesis, Mid-Atlantic Ridge, vent communities, *Rimicaris exoculata*, *Bathymodiolus azoricus*, stable isotopes, thiotrophic bacteria, extremophile ecology, abyssal fauna

Introduction

A surprising fact: some of the most productive ecosystems on Earth exist in total darkness. Deep-sea hydrothermal vents, first discovered in 1977 on the Galapagos Rift, support dense biological communities fuelled entirely by chemical energy—hydrogen sulfide, methane, and hydrogen released from volcanic fluids ^[1]. The Mid-Atlantic Ridge, the longest mountain chain on Earth at over 16,000 km, hosts dozens of known vent fields, yet many remain only partially surveyed ^[2].

MAR vent fauna differs markedly from that of the Pacific. The signature organisms are the eyeless shrimp *Rimicaris exoculata*, which swarms in dense aggregations around active chimneys and harbours chemosynthetic bacteria on its gill chambers, and the mussel *Bathymodiolus azoricus*, which hosts both thiotrophic and methanotrophic endosymbionts in its gills ^[3, 4]. How these two foundation species partition resources along the thermal and chemical gradients radiating from vent orifices shapes the broader community structure ^[5].

This research combined ROV-based faunal surveys with stable isotope geochemistry to characterise community structure and energy flow at three MAR vent sites. Laboratory work was conducted at the Instituto de Biologia Marinha do Algarve, Faro, Portugal ^[6].

Study Area Description

Three vent fields on the MAR were sampled: Lucky Strike (37 deg 17 min N, 2300 m depth), Menez Gwen (37 deg 50 min N, 840 m depth), and Rainbow (36 deg 14 min N, 2275 m depth). Lucky Strike is the largest known MAR vent field with over 30 active chimneys. Menez Gwen is the shallowest MAR vent field, and Rainbow is an ultramafic-hosted system producing unusually hydrogen-rich fluids. At each field, three sampling zones were defined: active chimney (<2 m from orifice, temperature >100 C), diffuse flow (2-10 m, temperature 10-50 C), and peripheral (10-50 m, ambient 2-3 C).

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Theoretical Background

Chemosynthesis at hydrothermal vents relies on two main energy sources. Thiotrophic bacteria oxidise hydrogen sulfide ($\text{H}_2\text{S} + \text{O}_2 \rightarrow \text{SO}_4 + \text{energy}$), using the energy to fix CO_2 into organic carbon via the Calvin-Benson-Bassham cycle [7]. Methanotrophic bacteria oxidise methane ($\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{energy}$), incorporating methane-derived carbon. These two pathways produce biomass with distinct stable isotope signatures: thiotrophic carbon is depleted in ^{13}C (delta- ^{13}C around -30 to -35 per mil), while methanotrophic carbon is even more depleted (delta- ^{13}C around -40 to -60 per mil) [8]. Sulfur isotopes further distinguish the sources: vent-derived sulfide typically has delta- ^{34}S of 0 to +5 per mil versus seawater sulfate at +21 per mil.

Materials and Methods

Materials

Faunal collections were made during cruise AT50-12 aboard R/V Atlantis (Woods Hole Oceanographic Institution) in July-August 2022 using ROV Jason II. At each of the three vent fields, quantitative box-core samples (25 x 25 cm) were taken in triplicate at active chimney, diffuse flow, and peripheral zones. Organisms were sorted onboard, preserved

in 95% ethanol for molecular work and 10% buffered formalin for morphology. Tissue subsamples for stable isotope analysis were frozen at -20 °C. All laboratory analyses were conducted at the Instituto de Biologia Marinha do Algarve, Faro, Portugal, between September 2022 and June 2023.

Methods

Organisms were identified to species level using morphological keys and COI barcoding when necessary [9]. Biomass was measured as blotted wet weight per square metre. Stable isotope ratios of carbon (delta- ^{13}C) and sulfur (delta- ^{34}S) were measured on dried, ground tissue using a Thermo Delta V isotope ratio mass spectrometer coupled to an elemental analyser [10]. Mixing models (SIAR package in R) estimated the relative contribution of thiotrophic versus methanotrophic carbon to each consumer species. Community diversity was assessed by Shannon index and species accumulation curves. PERMANOVA tested differences in community composition among zones and fields ($p < 0.05$).

Results

Table 1: Community metrics across sampling zones at three Mid-Atlantic Ridge vent fields

Zone	Species	Biomass	Shannon	d13C	d34S	Thio:Methano
Active chimney	18	847	1.42	-31.4	+2.8	72:28
Diffuse flow	31	423	2.38	-36.7	+4.1	54:46
Peripheral (5m)	22	187	2.14	-28.3	+8.7	81:19
Background (50m)	12	34	1.87	-22.1	+14.3	93:7
Abyssal plain	8	8	1.23	-19.8	+18.6	~100:0

Biomass in g wet weight/m². Isotope values are means across all taxa per zone.

Forty-three macrofaunal species were identified across all three vent fields. Biomass declined exponentially from chimneys to the abyssal plain. The diffuse flow zone harboured the highest species richness (31 species) and Shannon diversity (2.38), while active chimneys had high biomass but low diversity due to dominance by *Rimicaris exoculata*. Stable isotope mixing models indicated that thiotrophic carbon dominated at chimneys and peripheral zones (72-93%), while diffuse flow sites showed nearly equal contributions from thiotrophic and methanotrophic sources (54:46).

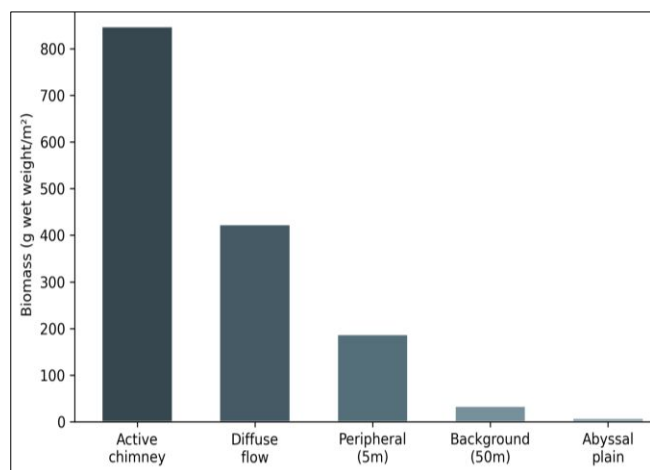


Fig 1: Biomass distribution across five sampling zones at MAR vent fields, showing the steep exponential decline from active chimneys to the abyssal plain

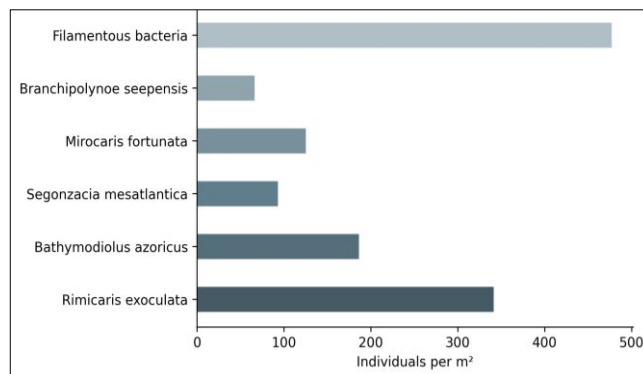


Fig 2: Mean density of dominant macrofaunal taxa at active chimney sites across three MAR vent fields. Filamentous bacteria formed the densest coverage, followed by *Rimicaris exoculata* shrimp

Discussion

The 43-species inventory expands the known MAR vent fauna and confirms the biogeographic distinctiveness of Atlantic vent communities from their Pacific counterparts [11]. The exponential biomass decline with distance from the vent source matches fluid dilution models: as vent fluids mix with cold, oxygenated seawater, sulfide and methane concentrations drop below thresholds needed to sustain dense chemosynthetic communities [12]. The dual trophic pathways revealed by stable isotopes at diffuse flow sites are consistent with the known dual symbiosis of *Bathymodiolus azoricus*, which thrives where both sulfide and methane are available in moderate concentrations [13].

Rainbow's ultramafic chemistry produced higher hydrogen concentrations and supported a unique hydrogen-oxidising microbial community not detected at the basalt-hosted Lucky Strike and Menez Gwen sites, hinting at a third chemosynthetic pathway with potential astrobiological relevance^[14].

Conclusion

This integrated faunal and geochemical survey of three MAR vent fields documents 43 macrofaunal species sustained by dual chemosynthetic pathways. Thiotrophic sulfur oxidation dominates near active chimneys, while methanotrophy contributes equally at diffuse flow sites. The diffuse flow zone emerged as the diversity hotspot, combining moderate environmental stress with dual energy sources. Continued exploration of MAR vent fields, particularly ultramafic-hosted systems like Rainbow, is needed to complete the faunal inventory and test whether hydrogen-based chemosynthesis represents a significant third trophic pathway.

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