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Editorial: From cold seeps to hydrothermal vents: geology, chemistry, microbiology, and ecology in marine and coastal environments

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Editorial on the Research Topic
From cold seeps to hydrothermal vents: geology, chemistry, microbiology, and ecology in marine and coastal environments

1 Background

This Research Topic compiles contemporary studies on cold seeps, hydrothermal vents, mud volcanoes, and related seafloor features that are associated with focused fluid emissions and the transfer of carbon, other chemical species, and sometimes heat from the geosphere to the ocean. Because these features sometimes tap fluids and gas originating kilometers below the seafloor, they provide an important window into deep processes that are otherwise inaccessible to scientists. At the shallow portion of their journey, migrating fluids nearing the seafloor contribute to a range of unique biological, physical, and chemical processes within the sediments themselves and at the sediment-water interface.

Seafloor fluid emissions play a critical role in global biogeochemical cycles, ocean chemistry, and possibly even climate change. Seafloor leakage points often emit hydrocarbon gases (especially methane and CO_2) and are sometimes the loci for deposition of seafloor minerals that have economic value. A burgeoning area of research focuses on natural products generated at these features, seeking compounds with potential pharmaceutical or other applications.

Multidisciplinary studies have become routine for characterization of seafloor fluid emission sites, attesting to the inseparability of geologic, physical, chemical, and biological processes in these settings. It is increasingly common for researchers to combine in a single research cruise: subbottom imaging and seafloor mapping; porewater and water column geochemistry and gas sampling; sediment retrieval for lithologic, biostratigraphic, and solid phase analyses; and studies of benthic and subseafloor communities at the microbial to

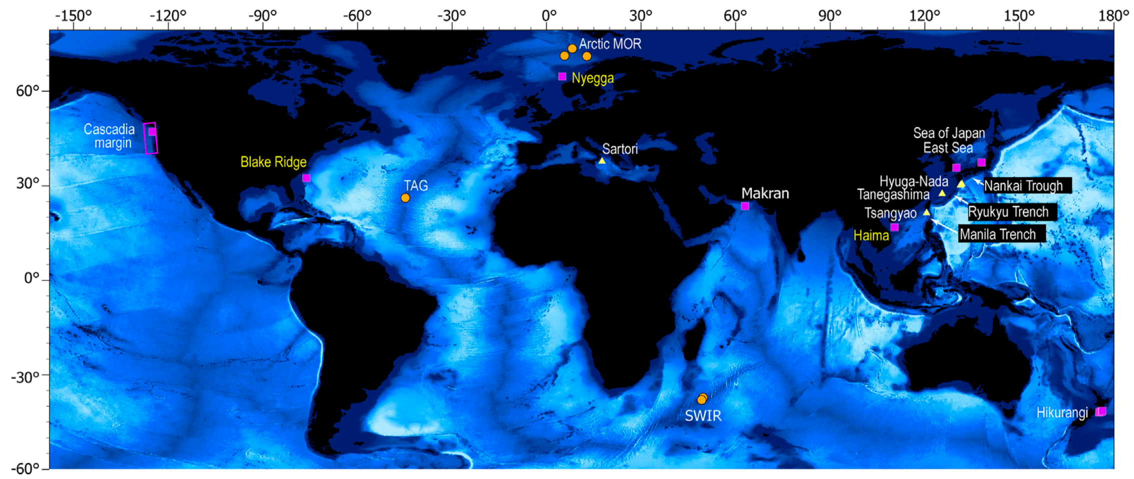

FIGURE 1
Geographic focus areas for studies included in the Research Topic. Purple squares and the box on the Cascadia margin mark cold seep sites, with yellow labels indicating those on passive margins (Blake Ridge, Nyegga, and Haima). Orange circles denote hydrothermal vent sites, and yellow triangles correspond to mud volcanoes. Seafloor fluid emission features have been recognized in all oceans, on most marine continental margins (active and passive), and near all types of plate boundaries. MOR denotes mid-ocean ridge; SWIR is the Southwest Indian Ridge; and TAG is the Trans-Atlantic Geotraverse hydrothermal area.

macrofaunal scales. This multidisciplinary approach has the advantage of ensuring the spatial and temporal coincidence of surveys and samples, an important factor at highly dynamic seafloor fluid emission sites. In addition, researchers often use remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), or human-occupied vehicles (HOVs) to record video of the seafloor, compile photomosaics, collect targeted samples, and survey with high-resolution geophysical near-seafloor systems, providing a degree of detail about seafloor fluid emission sites that is unprecedented compared to most areas of the deep ocean. While rarer, long-term cabled observatories or shorter-term deployments of portable observatories are also used at some loci for seafloor fluid flux and are particularly helpful for capturing temporal variations at these dynamic features.

Here we summarize the Research Topic's contribution to multidisciplinary seafloor emission studies in the categories of cold seeps, mud volcanoes, and hydrothermal vents. Figure 1 shows the geographic distribution of the studies in this Research Topic and key features referred to in this Introduction.

2 Cold seeps

Cold seeps derive their name from seafloor fluid emissions at temperatures similar to those of the overlying seawater. Cold seeps are found in a variety of settings, and deep-sea cold seeps often originate in areas characterized by a range of processes, including deep-seated fluid overpressures or dewatering sediments, degradation of gas hydrate above salt diapirs, and suboxic or anoxic sediments in which microbial methanogenesis exceeds methane oxidation in the shallow seabed. Methane (mostly microbial) is usually the predominant gas emitted at cold seeps, but CO_2 and light thermogenic hydrocarbons (ethane, propane) may also be present. Anaerobic oxidation of methane (AOM) with accompanying sulphate reduction usually cannot keep pace with rapid methane flux directly at seeps, and AOM in the surrounding sediments contributes to the formation of methane derived authigenic carbonates (MDAC). Beneath the sulphate reduction zone that extends into the sediments from the seafloor in locations slightly removed from the point of emission, gas hydrates are common. Hydrate deposits in high flux seeps can sometimes be massive, in contrast to the low saturation pore-filling hydrates common in much of the deep ocean. On the seafloor, cold seeps can be associated with pockmarks, MDAC outcrops, hydrate mounds, barite chimneys, or other features.

The widespread adoption of shipborne technologies that can rapidly detect water column gas plumes associated with active cold seeps has led to the discovery of cold seep provinces in every ocean and on most continental margins over the past 15 years. The cold seep studies included in this Research Topic highlight both active (Hikurangi, Cascadia, and Makran) and passive (Nyegga, Blake Ridge, and South China Sea) margins and encompass papers ranging from multidisciplinary investigations of cold seep processes to focused studies on microbial and benthic community characteristics.

The deliberately multidisciplinary approach for investigation of seafloor fluid emissions is epitomized in the study by Dupré et al., who explore processes associated with active seepage in the Nyegga pockmark field on the Norwegian margin. The researchers supplement seismic imagery, seafloor mapping, and sedimentologic data with ROV surveys. Their work reveals strong heterogeneity in seepage patterns, seafloor morphology, and dissolved methane concentrations across the pockmark field and uses the distribution of chemosynthetic fauna and microbial mats as markers for the vigor of gas seepage. They also offer a conceptual model for the migration of methane gas through the seabed hydrate stability zone to reach the overlying ocean as bubbles emitted at a seafloor seep.

Another type of multidisciplinary approach is adopted by Rudebusch et al. who focus on the geologic factors controlling the spatial distribution of cold seeps across the accretionary prism of the Cascadia convergent margin offshore the U.S. Pacific Northwest. More than 3,000 gas flares having been recognized in this geologically complex setting, and the researchers combine water column and seafloor data and geologic maps in a statistical approach focused on identifying the geomorphological and structural controls on seep distribution. Although some past studies have attributed concentrated seepage on this margin to degradation of gas hydrate near its landward limit of stability (e.g., Johnson et al., 2019), the province-wide analysis shows that seeps are primarily associated with deformation features (faults, anticlines) in the outer arc high, as well as with canyons and slope failures on the upper continental slope.

As evidence has emerged that cold seeps are far more widespread than had been previously known, determining their role in the marine carbon cycle has become more important. Seeps not only transfer methane carbon from below the seafloor into the ocean, but also play a critical role in transporting aged dissolved organic carbon (DOC) to ocean waters (Pohlman et al., 2011). A study by Law et al. adds to research estimating regional methane fluxes from cold seeps using the Hikurangi Margin offshore New Zealand as the study area. Instead of scaling up from bubble studies or analyses of methane plumes at individual seeps, the researchers adopt an oceanography-based approach that combines water column methane concentration measurements and constraints on ocean currents in local and regional hydrodynamic models. Their results also show that water column oxidation of emitted methane is not expected to significantly change pH or local concentrations of dissolved CO_2.

While water column studies have significantly advanced understanding of the fluxes of gases and other chemical constituents across the sediment-water interface at cold seeps, the associated sediments and porewaters hold critical secrets about fluid migration, seabed biogeochemical cycling, and the formation of MDAC. In the Makran accretionary wedge seep province offshore Pakistan, Chen et al. study sulphate, dissolved inorganic carbon (DIC), and cation concentrations and δ^{13}C-DIC in sediment porewaters at seeps and background sites. DIC flux is up to four times greater at the hydrate-bearing seep sites than at background sites, and the dominance of AOM leads to MDAC formation at the seeps. Kim et al. supplement porewater geochemical analyses with stable carbon, oxygen, and hydrogen isotopic data and petrological analyses of MDAC in cold seeps from southern Ulleung Basin in the East Sea. They infer massive gas hydrate accumulations beneath the seeps and demonstrate the influence of seawater carbonate in MDAC formation above the sulphate-methane transition.

Investigations of the synergy between microbial processes and geologic characteristics continue to be at the forefront of interdisciplinary research on cold seeps and now extend beyond the well-known connection between MDAC and AOM. Liang et al. describe significant microbial heterogeneity among cold seeps in the Haima area of the South China Sea and uncover a striking interplay between sediment mineralogy and microbial community structure. In that study, the sediment composition appears to be influencing microbial communities. Shiraishi et al. focus on the opposite relationship, in which microbial surfaces affect microdolomite deposition. Using X-ray and electron microscopy of samples from a hydrate-bearing sediment core retrieved at a pockmark in the Umitaka Spur, Sea of Japan, they demonstrate clear differences between microdolomite formed inorganically *versus* in association with microbes at different depths within the hydrate deposits.

Instead of the biology-physics link, Redick et al. explore the link between microbes and chemical compounds, namely, natural products associated with microbes or other living organisms and potentially useful for medicinal, antiseptic, or other purposes. Their study couples metabolomic and microbial community structure analysis of sediments collected at seeps and background locations on the Cascadia margin. The investigation demonstrates that the degree of microbial diversity and the range of associated natural products at a seep are related not only to vigor of fluid activity at the site, but also the age of the seep.

Studies of seep macrofauna have long been a cornerstone of interdisciplinary studies linking fluid migration and benthic community structure. At a large scale, Johnson et al. choose the well-known Blake Ridge seeps as the focus area for a seascape approach focused on determining the distances over which seeps affect deep sea communities. They find that seeps influence benthic taxa to distances of tens of meters, underscoring the concept that seeps are critical oases of life in the deep ocean. Other macrofaunal studies in this Research Topic describe new organisms discvered at seeps. Lin et al. discovered a new species of the genus *Catillopecten*, a deep-sea glass scallop, in the Haima cold seep area. Their work included morphological, anatomical, and molecular analyses to characterize the new species and to estimate its time of divergence from a known genus.

3 Mud volcanoes

Mud volcanoes (e.g., Mazzini and Etiope, 2017) are a special category of cold seeps associated with seafloor constructional edifices that form by the fluidization and expulsion of fine-grained sediments. They commonly emit methane-rich gases, which are sometimes of thermogenic origin, and exist both onshore and offshore and on both active and passive margins. Some mud volcanoes are associated with fluids warmer than ambient seawater but still colder than hydrothermal vents. While mud volcanoes are observed in some hydrocarbon basins (e.g., Gulf of Mexico), many of these features have formed in the accretionary wedges and forearcs of convergent margins, likely due to dewatering of wedge sediments. With one exception, studies on mud volcanoes in this Research Topic all focus on western Pacific subduction zones.

Asada et al. describe the discovery of mud volcanoes in the tectonically-complex Hyuga-Nada area east of Japan. The Kyushu-Palau Ridge is subducting beneath the Amur plate in this area (Yamamoto et al., 2013), which is just north of the junction of the Ryukyu and Nankai troughs. Fourteen mud volcanoes have been mapped in the Kumano forearc basin to the north, and the identification of 27 mud volcanoes in the Hyuga-Nada area in this study substantially expands the geographic extent of these features on this margin. The authors use geophysical data to characterize the Hyuga-Nada mud volcanoes and describe multiple bottom simulating reflections in some locations. They postulate that the Hyuga-Nada mud volcano field extends southward to the

Tanegashima area of the Ryukyu trench forearc, forming a large and continuous zone of sediment fluidization.

The Sartori mud volcano is on the accretionary wedge of the Calabrian subduction zone on the northern margin of the Mediterranean Sea is in a similar position relative to the trench as the Hyuga-Nada area. Doll et al. use geophysical data and sediment, porewater, and gas samples to unravel spatio-temporal variations in mud volcanism at the Sartori site. Their results imply that mud volcanism has been largely quiescent since 10 ka, and they conclude that recent fluid migration and release are dominated by diffusive methane flux fed by mixed microbial and thermogenic sources.

Porewater geochemistry is a powerful tool for analyzing fluid dynamics and microbial processes at seeps, and the large footprint and high fluid flux at mud volcanoes make it possible to capture strong lateral gradients in geochemical signatures and to search for the influence of fluids derived from deep in the sedimentary section. Chen et al. measure dissolved organic carbon (DOC) and volatile fatty acid profiles in sediment cores from the Tsangyao Mud Volcano Group, which is set in an accretionary setting in the forearc of the Manila trench south of Taiwan. Numerical modeling indicates that *in situ* organic matter degradation controls DOC patterns in most locations, with fluid migration processes becoming more important in influencing DOC characteristics at loci of known active flows. The models also suggest the co-existence of sulphate reduction and methanogenesis in the sediments in this dynamic setting. Ijiri et al. focus on mud volcanoes in the Tanegashima area of the Ryukyu trench forearc and use primarily porewater chloride concentrations and isotopic data to demonstrate that fluids feeding the mud volcanoes originate deep in the sediments and are affected by clay mineral dehydration reactions. They show that the most active mud volcanoes are associated with the strongest signals for deep fluids and also highlight a component of thermogenic methane in the gas emissions. Working in the same area, Mitsutome et al. couple porewater salinity data with measurements of boron and lithium concentrations and boron isotopes. Porewaters that were fresher than seawater, but that also contained higher concentrations of boron and lithium, originate kilometers beneath the mud volcanoes, and upward advection rates are inferred to be as high as 14 cm/yr.

4 Hydrothermal vents

Hydrothermal vents emit fluids at temperatures significantly higher than ambient seawater and are found in areas with active submarine magmatism or volcanism, including mid-ocean ridges and associated off-axis sites. While fluids emitted at these vents may be influenced by deep magmatic processes, water-rock interactions are often the primary source of gas and fluid emissions. CO_2 is typically the most important component of emitted gases in these settings. Seafloor structures (e.g., minerals) surrounding hydrothermal vents result from the reaction between migrating fluids and cooler seawater, which leads to precipitation of minerals at the seafloor.

Hydrothermal vents are often emphasized as the loci for the leakage of hot fluids. However, a study by Pelleter et al. highlights the role of both high-temperature and later low-temperature flux in the formation of seafloor massive sulfide (SMS) mineral occurrences at hydrothermal vents. Working at the famous Trans-Atlantic Geotraverse (TAG) hydrothermal field (Scott et al., 1974) on the slow-spreading northern Mid-Atlantic Ridge, the researchers use observations from HOV dives, sampling, and mapping to study SMS, which are increasingly being scrutinized as potential sources for metals critical to manufacturing and industrial processes. The study highlights the role of diffuse, lower temperature fluid flow at SMS for which high temperature flow has ceased and concludes that the grades of some of the newly-discovered SMS at TAG are lower than comparable onshore volcanogenic massive sulfide deposits with respect to key metals.

Yang et al. also study mineral occurrences associated with hydrothermal vents, focusing on ferromanganese crusts near the ultra-slow-spreading Southwest Indian Ridge. They discover two new hydrothermal fields and describe mineralization processes in those and other off-axis hydrothermal areas. The study demonstrates a mixed hydrogenetic (from seawater) and hydrothermal origin for the ferromanganese crusts. These crusts contain lower concentrations of cobalt and rare earth elements than typical purely hydrogenetic crusts forming far from hydrothermal activity.

Hydrothermal vent fields at the rarely-visited Arctic Mid-Ocean Ridge (MOR) are the focus of a study that links hydrothermal and cold seep processes. While microbial sulphate reduction is a key process in near-seafloor sediments near many cold seeps, reactive organic carbon is rarely available to fuel widespread sulphate reduction in the deep sea, far from continental margins. Roerdink et al. show that sulphate reduction rates are substantially elevated near both low- and high-temperature hydrothermal vents at the remote Arctic MOR. The zones of vigorous sulphate reduction are associated with cold-seep-like flux indicators such as microbial mats and seep chemosynthetic communities.

Mao et al. and an associated commentary by Chan et al. focus on the identification and analysis of deep-sea barnacles associated with hydrothermal vent settings. Mao et al. compare a shallow water barnacle with a barnacle species (Cirripedia, Scalpellomorpha) that inhabits hydrothermal vents to discern the evolutionary adaptations to the vent species' genome and transcriptome. The data show that the hydrothermal vent taxa have undergone selection towards refined mitochondrial energy production. The marker gene and genomic approach caried out by Chan et al. refine the species identification of the vent species analyzed by Mao et al.

Toki et al. provide insights into all the types of seafloor fluid emissions sites covered in this Research Topic. They measure dissolved methane and seawater environmental parameters along a transect from the continental shelf of the East China Sea to the Ryukyu trench. Their results reveal clear water column signatures over known cold seeps, mud volcanoes, and hydrothermal vents. However, they also detect methane anomalies that are uncorrelated with known features, implying that new seafloor emission sites may await discovery.

5 Conclusion

The original research papers summarized here provide a broad overview of the current state of science on seafloor emissions sites, as well as an introduction to some novel techniques and approaches.

While the papers are not exhaustive in covering every component of geological, physical, chemical, and biological processes, they set the stage for future work on a wide variety of global seafloor fluid emission features.

Author contributions

GS: Writing–original draft, Writing–review and editing. AT: Writing–original draft, Writing–review and editing. SD: Writing–original draft, Writing–review and editing. MK: Writing–original draft, Writing–review and editing. CR: Visualization, Writing–original draft, Writing–review and editing.

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