

Cold seeps: marine ecosystems based on hydrocarbons

Thousands of white crabs grazing on an extensive mussel bed at a cold seep off the coast of Pakistan

David Fischer takes us on a trip to the bottom of the sea to learn about cold seeps – their ecosystems, potential fuels, and possible involvement in global warming.

What are cold seeps?

Cold seeps are often oases for microbial and macrofaunal life on the sea floor – similar to hydrothermal vents, where hot water emerges under high pressure, several kilometres below the sea (see Little, 2010). In contrast to hydrothermal vents, however, cold seeps can occur at water depths of between a few metres and several kilometres, often along continental margins.

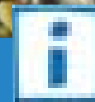
They are places where hydrocarbons – mostly methane but also ethane, propane, or even oil – seep from the sediment. Unlike at hydrothermal vents, the emanating fluids (gases and liquids) are no hotter than the surrounding seawater, and they are not necessarily under high pressure.

These hydrocarbons form up to several kilometres below the surface of the sediment when organic matter is degraded by either high temperatures or micro-organisms. When the hydrocarbons are produced in very large quantities, or where tectonic stress



Microbes covering cold seeps in an anoxic region, which does not support macrofauna

Image courtesy of MARUM, Bremen University



Glossary

Chemosymbiosis: a symbiotic association between a multi-cellular organism (the host), which provides a protected environment, and a bacterium that oxidises specific chemicals to obtain energy and synthesise organic carbon that is required by the host

Methanotrophic: a methanotrophic organism metabolises methane as its only source of energy and carbon

Pore water: the water that fills the space between individual grains of sediment

Thiotrophic: a thiotrophic organism oxidises sulphur compounds

Trophosome: a specialised internal organ in tube worms, hosting symbiotic bacteria

BACKGROUND

squeezes the sediments, the fluids rise to the sediment surface through cracks and fissures. The fluids may seep out at a continuous, low rate or the rate may vary.

Life at cold seeps: anybody home?

Some fascinating creatures can be found at deep-water cold seeps, including giant tube worms, mussels, clams and crabs. How are these ecosystems supported?

Almost the entire seabed is home to micro-organisms. However, to support significant levels of microfauna in deep water, where the sunlight does not reach, requires oxygen-rich water and an alternative energy source – such as hydrocarbons.

One such energy source is methane, released at cold seeps. The anaerobic oxidation of methane (AOM) is a metabolic process with sulphate as the final electron acceptor, mediated by a symbiosis of methane-oxidising (**methanotrophic**) archaeans and sulphate-reducing bacteria.



AOM takes place in anoxic marine sediments, wherever methane from deep down and sulphate from the seawater meet. The end products of AOM, bicarbonate and sulphide ions, are released into the surrounding sediment and **pore water** (see glossary for all terms in bold).

At locations where high methane concentrations are found close to the

surface of the sediment (as in cold seeps), the sulphide produced by the micro-organisms can fuel an entire ecosystem. Microbial or faunal colonies at cold seeps can be between 100 cm² and several hundred square metres in diameter. Where the sulphide-rich pore water escapes from the sea floor, the seep site will be colonised concentrically around these spots: closest to them will be those organisms which tolerate the highest concentrations of otherwise toxic sulphide (see upper image on page 62).

At the basis of these ecosystems are methanotrophic and **thiotrophic** bacteria. Some of them live in **chemosymbiosis** with mussels (methanotropic bacteria), clams and



- ✓ Biology
- ✓ Chemistry
- ✓ Earth science
- ✓ Marine environments
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- ✓ Climate change
- ✓ Ages 15+

If you are curious about the extremes of life on Earth, this is the article for you. David Fischer reports on exotic biological communities living at the bottom of the sea and on the exploration of these environments.

The language is easy enough to understand, with a glossary for technical terms. The article can be used in different subjects (biology, earth science, chemistry) to address a whole range of topics, such as: ecosystems, energy metabolism, food chains, natural resources, sedimentary rocks, non-renewable energy sources, marine environments and biodiversity, air pollution and the greenhouse effect, oceanographic research, hydrocarbons, clathrates, or redox reactions. Some of these topics (e.g. ecosystems, energy sources) are particularly suitable for an interdisciplinary approach.

The text also provides valuable background reading to introduce the origin of life at the bottom of the sea, for example with a comparison to hydrothermal vents.

In addition, the article provides references to content-rich websites (MARUM, NOAA) where the reader can find further information and resources (including teaching materials) on the topic. Therefore, I suggest completing the teaching unit with an activity from one of the cited web resources.

The article can also be used as a comprehension exercise. Possible questions include:

In AOM

- a) sulphate is oxidised to sulphide
- b) sulphide is reduced to sulphate
- c) methane is reduced to bicarbonate
- d) methane is oxidised to bicarbonate.

Gas hydrates

- a) consist of water molecules surrounded by gas molecules
- b) consist of gas molecules surrounded by water molecules
- c) are formed under high-temperature and low-pressure conditions
- d) are formed under high-temperature and high-pressure conditions.

Giulia Realdon, Italy

Image courtesy of BGR, after Sahling et al. (2002)

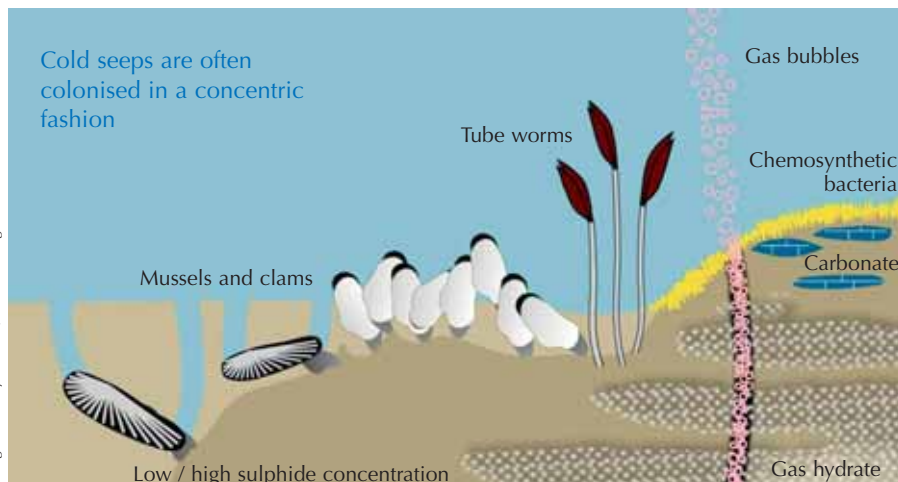
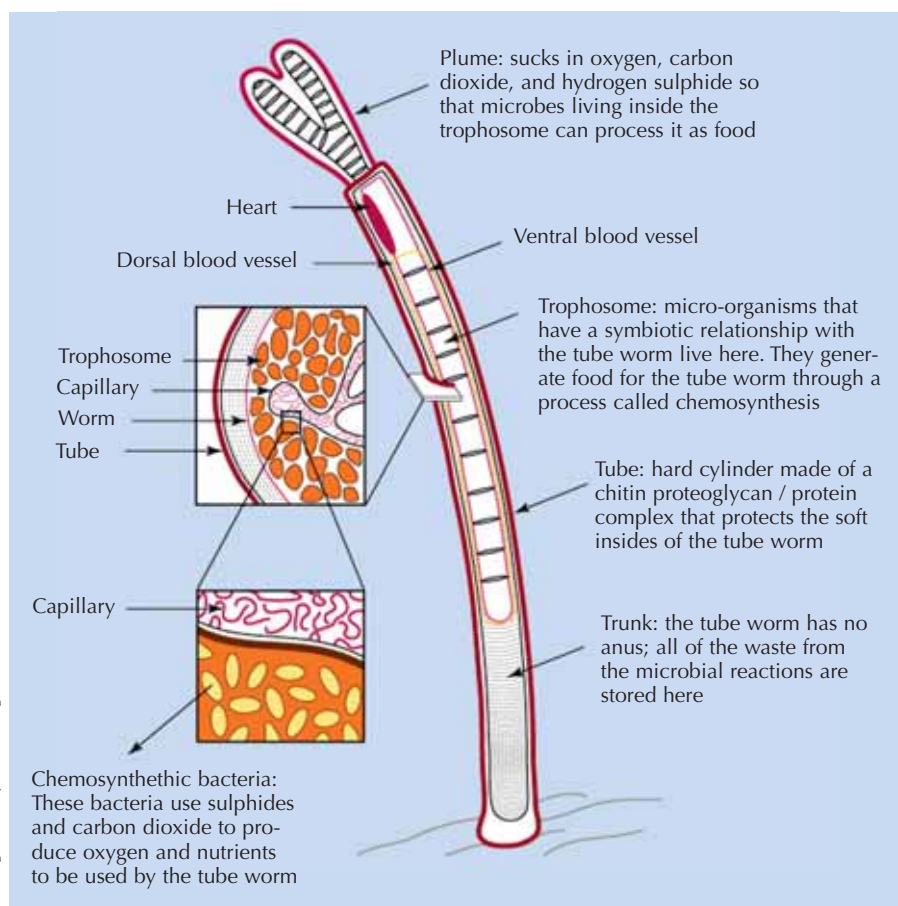


Image courtesy of Enduring Resources for Earth Science Education (ERESE)



Tube worms host chemosymbiotic bacteria in their trophosome. This is a cross-section of *Riftia pachyptila*, which is found at hydrothermal vents

tube worms (thiotrophic bacteria). The mussels and clams harbour the bacteria in their gills, whereas the tube worms shelter the bacteria in their **trophosome**; the bacteria, in return, supply their host with organic carbon (see image above).

The formation and fate of gas hydrates

Cold seeps are not only interesting because of the ecosystems they host: they could be important contributors to climate change and valuable new sources of hydrocarbons, to satisfy

our increasing energy demands. Cold seeps generally indicate large amounts of hydrocarbons below the seabed, and they are comparably easy to identify because of their typical colonisation by specialised organisms.

Most interesting in this respect are gas hydrates. In these ice-like crystalline compounds, water molecules form a cage structure called a clathrate around individual gas molecules (see image on page 63) – in natural gas hydrates, this is mostly methane. Gas hydrates form where pore water is saturated with methane gas, within a narrow window of low-temperature and high-pressure conditions found only in deep permafrost soils – and in marine sediments at depths below about 400 m (see lower image on page 63). At atmospheric pressure, gas hydrates are unstable and rapidly decompose into water and free gas.

Gas hydrates store large amounts of chemically bound energy: because of the specific molecular structure, one litre of gas hydrate holds 0.8 l of water and 164 l of methane gas. The total energy resources in gas hydrates on Earth are estimated to be greater than those of all other known fossil fuels combined – ever.

Several countries, including the USA, Japan, South Korea, India and China, are exploring ways to harvest gas hydrates – safely, which is not a trivial matter. More importantly, however, it is essential to stop the gas hydrates from melting. Global warming is increasing the oceans' temperatures, and this could cause a large-scale melting of gas hydrates in the sediment.

If they were to melt, the methane released into the atmosphere would react with atmospheric oxygen to form CO₂, very efficiently enhancing the greenhouse effect. Left undamaged, gas hydrates act as stabilising agents for the continental slopes. If they were to melt, the slopes could destabilise, resulting in huge submarine landslides and tsunamis.

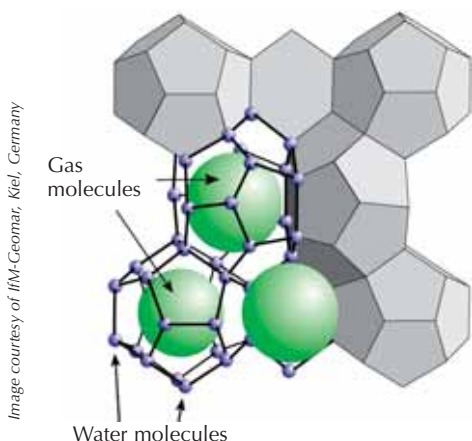


Image courtesy of IfM-Geomar, Kiel, Germany

Clathrate structure of gas hydrates



Burning gas hydrates



White gas hydrates consolidate sea floor sediments

Images courtesy of MARUM, Bremen University

How do we study cold seeps?

Studying cold seeps is obviously a big challenge for scientists: how can gases, water, sediment and organisms be sampled up to several kilometres below the sea surface? First, you have to reach your sampling location – this may take several days by ship, even for cold seeps on the continental shelf, and maintaining such a research vessel costs several tens of thousands of Euros a day. And when you get there, how do you reach the sea floor? Until the 1990s, the only way was to lower special tools on the end of a long steel cable, and recover them as soon as

they had filled with sample material. This of course made it very difficult to have any visual control of where the tools hit the ground.

Matters have improved dramatically with the development of sophisticated underwater technology, such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), equipped with an array of cameras, lamps and sampling devices. MARUM^{w1} has its own workshop to develop such tools and robots for ocean research. Researchers use them to investigate cold seeps by either having them dive to individual spots

to collect samples or taking photos of a larger area to provide an overall picture of a cold seep location.

There is still a lot of research to be done into the development and stability of cold seeps over time, and little is known about the organisms colonising them. Yet the most important question about cold seeps is how much methane is transferred into the ocean and subsequently into our atmosphere, where it will contribute to global warming. For me, it is very exciting to take part in this research.

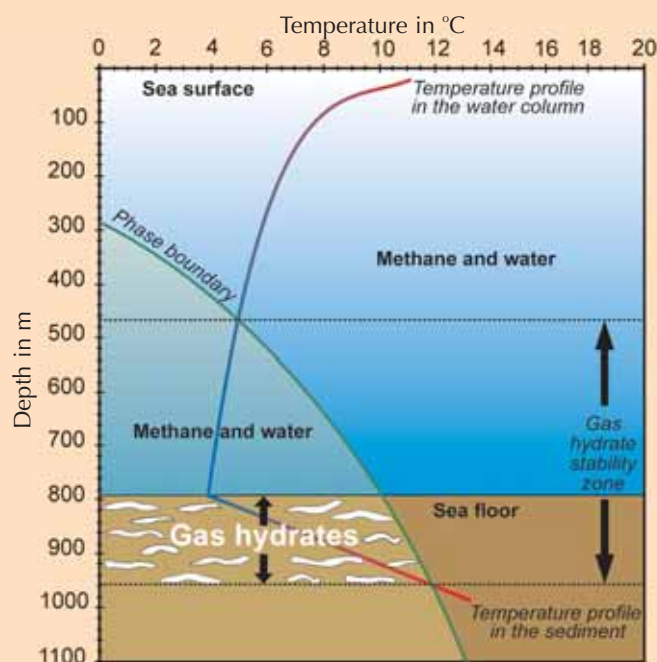


Image courtesy of David Fischer, MARUM

Under specific combinations of high pressure (water depth) and low temperature, methane can crystallise with water to form gas hydrates, as indicated by the phase boundary line. At higher temperatures or shallower depths, methane will instead dissolve in water.

In the ocean, there are additional complications: in the water column, temperature decreases with increasing water depth, whereas in the sediment, temperature increases with increasing depth. The points at which these temperature profiles cross the theoretical phase boundary determine the depths at which gas hydrates may be found (the gas hydrate stability zone).

Furthermore, it is mostly in the sediment that methane concentrations are high enough to form gas hydrates (marked in white) – they have seldom been observed in the water column.

Note that the scale in this diagram is an example and can vary depending on conditions



MARUM-QUEST 4000m, an ROV suitable for depths of up to 4000 m, equipped with a large number of cameras, spotlights, corers and other tools to collect samples from the sea floor as small as single organisms only a few millimetres long



Close-up photograph of the symbiotic vestimentiferan tube worm *Lamellibrachia luymesii* from a cold seep at 550 m depth in the Gulf of Mexico. The tubes of the worms are stained with a blue chitin stain to determine their growth rates. Approximately 14 months of growth is shown by the staining here

clams found at cold seeps. See <http://www.marum.de/marumTV.html>

The US National Oceanic and Atmospheric Administration (NOAA) offers a number of lesson plans and downloadable teaching activities on cold seeps for all ages, plus background information. See the NOAA website (<http://oceanexplorer.noaa.gov>) or use the direct links:
<http://tinyurl.com/36zuhfb> ('Windows to the Deep')
<http://tinyurl.com/32f6me6> ('Expedition to the Deep Slope 2006')
<http://tinyurl.com/35g3qrk> ('Expedition to the Deep Slope 2007')

For some general information about gas hydrates, see the MARUM website (www.marum.de) or use the direct link:

<http://tinyurl.com/3xzzpj>

For more information on hydrocarbons, including gas hydrates, see: van Dijk M (2009) Hydrocarbons: a fossil but not (yet) extinct. *Science in School* 12: 62-69.

www.scienceinschool.org/2009/issue12/energy

If you enjoyed reading this article, you might like to browse our other articles on science topics in *Science in School*: www.scienceinschool.org/sciencetopics

Born in Jülich, Germany, David Fischer has always been fascinated by science and the sea. After graduating in physical geography, marine geology and biology from the University of Bremen, he is now working towards a PhD in marine geology at MARUM, investigating the biogeochemistry of cold seeps. He has participated in a number of research expeditions to the North Sea, the Baltic Sea, the Arabian Sea, the central east Atlantic, and the Southern Ocean near the Antarctic Peninsula.



Acknowledgements

The author would like to thank Dr Pape (MARUM^{W1}) for valuable comments, particularly about gas hydrates. Moreover, *Science in School* and the author thank the publisher Inter-Research for permission to reuse the image from Sahling et al. (2002).

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The article can be downloaded free of charge from the Inter-Research website: www.int-res.com

Web reference

- w1 – To learn more about MARUM – the Center for Marine Environmental Sciences, an independent DFG-funded research facility at the University of Bremen, Germany, see: www.marum.de

Resources

MARUM offers a large selection of German-language resources and activities for teachers and school students, including videos and articles on research topics, a large selection of workshops for both primary- and secondary-school students in the MARUM teaching lab, workshops for primary-school teachers, experimental science theatre workshops for primary-school children, and much more. See: www.marum.de/en/entdecken.html

MARUM has produced a wonderful (English-language) video on cold seeps and methane hydrates. See www.marum.de/marumTV.html

In addition, MARUM has produced, in co-operation with the Deutsche Forschungsgemeinschaft, a 12-episode series of films about its research (DFG Science TV). Episode six (German only) tells the story of