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Expedition to the Deep Slope 2007

One Tough Worm
[adapted from the 2002 Gulf of Mexico Expedition]

Focus
Physiological adaptations to toxic and hypoxic environments

Grade Level
7-8 (Life Science)

Focus Question
How can aerobic organisms cope with environments containing little oxygen and an abundance of respiratory poisons?

Learning Objectives
Students will be able to explain the process of chemosynthesis.

Students will be able to explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps.

Students will be able to describe three physiological adaptations that enhance an organism's ability to extract oxygen from its environment.

Students will be able to describe the problems posed by hydrogen sulfide for aerobic organisms, and explain three strategies for dealing with these problems.

Materials
- ❐ Copies of "Comparative Functional Characteristics of Polychaete Gills," one copy for each student group
- ❐ Copies of "Metazoans in Extreme Environments," one copy for each student group (download from or refer students to http://asgsb.indstate.edu/bulletins/v13n2/vol13n2p13-24.pdf

Audio/Visual Materials
None

Teaching Time
One 45-minute class period for first part of activity, plus one-half to one additional 45-minute class period for group reports and discussion

Seating Arrangement
Groups of four students

Maximum Number of Students
20

Key Words
Cold seeps
Methane hydrate ice
Chemosynthesis
Brine pool
Vestimentifera
Trophosome
Fick's equation
Hemoglobin
Hydrogen sulfide
Mitochondria
Aerobic
Anaerobic
Gill

Background Information
Cold seeps are areas of the ocean floor where gases (such as methane and hydrogen sulfide)

and oil seep out of sediments. These areas are commonly found along continental margins, and are home to many species of organisms that have not been found anywhere else on Earth. Unlike biological communities in shallow-water ocean habitats, cold-seep communities do not depend upon sunlight as their primary source of energy. Instead, these communities derive their energy from chemicals through a process called chemosynthesis (in contrast to photosynthesis in which sunlight is the basic energy source). Some chemosynthetic communities have been found near underwater volcanic hot springs called hydrothermal vents, which usually occur along ridges separating the Earth's tectonic plates. Visit http://www.pmel.noaa.gov/vents and http://www.divediscover.whoi.edu/vents/index.html for more information and activities on hydrothermal vent communities.

Typical features of the cold seep chemosynthetic communities that have been studied so far include mounds of frozen crystals of methane and water called methane hydrate ice that are home to polychaete worms. Brine pools, containing water four times saltier than normal seawater, have also been found. Researchers often find dead fish floating in the brine pool, apparently killed by the high salinity. The base of the food chain in cold seep communities is chemosynthetic bacteria that are able to obtain energy from some of the chemicals seeping out of the ocean floor. Bacteria may form thick bacterial mats, or may live in close association with other organisms.

One of the most conspicuous associations exists between chemosynthetic bacteria and large tubeworms that belong to the group Vestimentifera (formerly classified within the phylum Pogonophora; recently Pogonophora and Vestimentifera have been included in the phylum Annelida). Pogonophora means "beard bearing," and refers to the fact that many species in this phylum have one or more tentacles at their anterior end. Tentacles of vestimentiferans are bright red because they contain hemoglobin (like our own red blood cells). Vestimentiferans can grow to more than 10 feet long, sometimes in clusters of millions of individuals, and are believed to live for more than 100 years. They do not have a mouth, stomach, or gut. Instead, they have a large organ called a trophosome that contains chemosynthetic bacteria. Hemoglobin in the tubeworm's blood absorbs hydrogen sulfide and oxygen from the water around the tentacles, and then transports these raw materials to bacteria living in the trophosome (the tentacles also absorb carbon dioxide, which is also transported to the bacteria). The bacteria produce organic molecules that provide nutrition to the tubeworm. Similar relationships are found in clams and mussels that have chemosynthetic bacteria living in their gills. A variety of other organisms are also found in cold-seep communities, and probably use tubeworms, mussels, and bacterial mats as sources of food. These include snails, eels, sea stars, crabs, isopods, sea cucumbers, and fishes. Specific relationships between these organisms have not been well-studied.

Recently, increasing attention has been focused on cold seeps in the Gulf of Mexico, an area that produces more petroleum than any other region in the United States. Responsibility for managing exploration and development of mineral resources on the Nation's outer continental shelf is a central mission of the U.S. Department of the Interior's Minerals Management Service (MMS). In addition to managing the revenues from mineral resources, an integral part of this mission is to protect unique and sensitive environments where these resources are found. MMS scientists are particularly interested in finding deep-sea chemosynthetic communities in the Gulf of Mexico, because these are unique communities that often include species that are new to science and whose potential importance is presently unknown. In addition, the presence of these communities often indicates the presence of hydrocarbons at the surface of the seafloor.

The 2006 Expedition to the Deep Slope was focused on discovering and studying the sea floor communities found near seeping hydrocarbons on hard bottom in the deep Gulf of Mexico. The sites visited by the Expedition were in areas where energy companies will soon begin to drill for oil and gas. A key objective was to provide information on the ecology and biodiversity of these communities to regulatory agencies and energy companies. Dives by scientists aboard the research submersible ALVIN revealed that hydrocarbons seepage and chemosynthetic communities were present at all ten sites visited by the Expedition. The most abundant chemosynthetic organisms seen were mussels and vestimentiferan tubeworms. Expedition to the Deep Slope 2007 is focused on detailed sampling and mapping of four key sites visited in 2006, as well as exploring new sites identified from seismic survey data.

This activity focuses on some of the physiological adaptations that allow cold seep organisms to survive conditions that would be deadly to many other species. Polychaete "ice worms" received a lot of attention when they were first discovered at Gulf of Mexico cold seeps in 1997, because they were found living inside chunks of frozen methane. Another polychaete belonging to the family Orbiniidae (previously unknown to science) is often found living among mussel beds that are one of the most conspicuous features of these cold-seep communities. These polychaetes are aerobic animals, which means they require oxygen for their metabolism. Yet, these worms live in areas where oxygen is in extremely short supply, and often can't be detected in the water at all. To make matters worse, sediments around the mussel beds contain large quantities of hydrogen sulfide, which is similar to cyanide in its toxicity. Hydrogen sulfide interferes with cytochrome molecules that are essential to aerobic metabolism, as well as hemoglobin that is used by many organisms to transport oxygen within living tissues. So our cold-seep polychaete has two big problems: getting oxygen to support aerobic metabolism, and avoiding the toxic effects of hydrogen sulfide.

There are several strategies that organisms may use to improve their ability to obtain oxygen from their surrounding environment. Three of the most common strategies are anatomical adaptations that increase an organism's surface area in contact with a source of oxygen, thin membranes between the interior of the organism and an oxygen source, and internal circulatory systems that transport oxygen within the organism. These strategies are related by Fick's equation which describes the passive diffusion of gas molecules across a membrane:

$$F = \frac{A \bullet P \bullet c}{D}$$

where

F = gas flow
A = membrane surface area
P = pressure difference on the two sides of the membrane
c = a mathematical constant
D = distance over which diffusion takes place (at the minimum, thickness of the membrane)

So, gas flow across a membrane will be increased by increasing the membrane's surface area, reducing the membrane's thickness, and/or increasing the pressure difference across the membrane. "Pressure difference" is related to the difference in concentration of a gas on one side of the membrane compared to the other side. If there is no difference, then there will be no net flow of gas (according to Fick's equation, if P = 0 then F = 0). An organism can't do much about the concentration of gas in the external environment, but if it has a way to move gas away from the membrane as the gas diffuses in, a pressure difference can be maintained. A circulatory system is a well-known adaptation for maintaining this kind of pressure difference. If the circulatory system includes molecules that can bind the gas as it diffuses in (like hemoglobin binds oxygen) this also helps maintain the pressure gradient.

Three major strategies are common among organisms that must deal with potentially toxic sulfides. The first is to switch from aerobic metabolism to anaerobic metabolism that does not require oxygen. Many invertebrates are capable of doing this for varying periods of time. Another strategy is to bind the sulfide with another material that keeps it from interacting with sensitive molecules involved with aerobic metabolism. Tubeworms from hydrothermal vents are known to have specialized forms of hemoglobin that bind with sulfide and keep it away from metabolically critical areas. The third strategy is to convert the sulfide molecules to something else that is not toxic to the organism. This strategy has been found in a variety of animals that have mitochondria that are able to oxidize sulfide to thiosulfate (which is relatively nontoxic).

Learning Procedure

1. To prepare for this lesson, visit http://oceanexplorer.noaa.gov/explorations/07mexico/welcome.html for information about Expedition to the Deep Slope 2007. You may want to visit http://www.bio.psu.edu/cold_seeps for a virtual tour of a cold-seep community, and http://www.bio.psu.edu/hotvents for a virtual tour of a hydrothermal vent community.

2. Lead a discussion of deep-sea chemosynthetic communities. Contrast chemosynthesis with photosynthesis. Point out that there are a variety of chemical reactions that can provide energy for chemosynthesis.

   Review the problem of oxygen scarcity that challenges the survival of the Orbiniid polychaete. Discuss adaptations that enhance an organism's ability to extract oxygen from its environment. Be sure students understand the terms in Fick's equation, and how an increase or decrease in each parameter would affect gas flow across a respiratory membrane. Students should realize that gills are a common adaptation in aquatic animals for increasing respiratory surface area (alveoli serve a similar function in lungs of humans and other animals). Discuss the role of hemoglobin in obtaining and transporting oxygen.

3. Distribute a copy of "Comparative Functional Characteristics of Polychaete Gills" to each student group. Assign one or more species to each group, and have the group calculate gas flow across their species' gills using Fick's equation and assuming that c and P are the same for each species, but that neither c nor P is equal to zero. The point here is to have students recognize the factors that affect gas transport in gills and similar biological structures, and how anatomical differences between deep-sea and shallow-water species may affect the efficiency with which these species are able to extract oxygen from their environment.

4. Have each group discuss their results, and what these results imply about the environment occupied by each species. Students should recognize that polychaetes from hydrothermal vent and cold seep communities have gills with larger surface area and thinner diffusion membranes, which means that gills of these species are much more efficient at extracting oxygen from their environment than the shallow-water species. Students should also recognize that these data are very limited and do not provide a solid basis for reliable conclusions; but this is the nature of "preliminary studies" that lead to testable hypotheses, which in turn can be the focus of more rigorous experiments with larger sample sizes, replicates, and controls. The results of such experiments can lead to conclusions that are much more reliable.

The Bridge Connection

www.vims.edu/bridge/vents.html

The "Me" Connection

Have students write a short essay on what physiological adaptations would be required to allow them to live near a hydrothermal vent or cold-seep, including a description of a day spent in one of these extreme environments.

Connections to Other Subjects

English/Language Arts, Earth Science

Assessment

Have students prepare individual written statements of their conclusions prior to oral presentations in Step #4.

Extensions

1. Visit http://oceanexplorer.noaa.gov/explorations/07mexico/welcome.html to keep up to date with the latest Expedition to the Deep Slope 2007 discoveries.

2. Distribute copies of "Metazoans in Extreme Environments" or refer students to http://asgsb.indstate.edu/bulletins/v13n2/vol13n2p13-24.pdf. Have each group prepare a written report on the problems posed by hydrogen sulfide for inhabitants of hydrothermal vent and cold-seep communities, and what strategies are used by organisms in these communities to cope with these problems. This article deals with several other problems of "extreme environments" besides sulfide. You may want to direct students to the sulfide section alone, or alternatively, have them address the other problems as well, perhaps assigning one additional problem to each group.

   Lead a discussion based on student groups' reports. Students should realize that adaptations that favor oxygen extraction can also increase an organism's exposure to hydrogen sulfide. The problem is even trickier for organisms that have a symbiotic relationship with chemosynthetic bacteria that use hydrogen sulfide as an energy source: These organisms must live close to a source of hydrogen sulfide to provide their symbiotic bacteria with this necessary raw material, but must simultaneously avoid being poisoned by the same material. Students should identify the three alternative strategies discussed in the "Background" section for dealing with this problem.

Multimedia Learning Objects

http://www.learningdemo.com/noaa/ Click on the links to Lessons 3, 5, 6, 11, and 12 for interactive multimedia presentations and Learning Activities on Deep-Sea Corals, Chemosynthesis and Hydrothermal Vent Life, Deep-Sea Benthos, Energy from the Oceans, and Food, Water, and Medicine from the Sea.

Other Relevant Lessons from the Ocean Exploration Program

Let's Go to the Video Tape! (11 pages; 327kb PDF) (from the Cayman Islands Twilight Zone 2007 Expedition) http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/videotape.pdf

Focus: Characteristics of biological communities on deep-water coral habitats (Life Science)

In this activity, students will recognize and identify some of the fauna groups found in deep-sea coral communities, infer possible reasons for observed distribution of groups of animals in deep-sea coral communities, and discuss the meaning of "biological diversity." Students will compare and contrast the concepts of "variety" and "relative abundance" as they relate to biological diversity, and given abundance and distribution data of species, will be able to calculate an appropriate numeric indicator that describes the biological diversity of a community.

Treasures in Jeopardy (8 pages; 278kb PDF) (from the Cayman Islands Twilight Zone 2007 Expedition) http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/edu/media/treasures.pdf

Focus: Conservation of deep-sea coral communities (Life Science)

In this activity, students will compare and contrast deep-sea coral communities with their shallow-water counterparts and explain at least three benefits associated with deep-sea coral communities. Students will also describe human activities that threaten deep-sea coral communities and describe actions that should be taken to protect resources of deep-sea coral communities.

Come on Down! (6 pages, 464k) (from the 2002 Galapagos Rift Expedition) http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr7_8_l1.pdf

Focus: Ocean Exploration

In this activity, students will research the development and use of research vessels/vehicles used for deep ocean exploration; students will calculate the density of objects by determining the mass and volume; students will construct a device that exhibits neutral buoyancy.

Living by the Code (5 pages, 400k) (from the 2003 Deep Sea Medicines Expedition) http://oceanexplorer.noaa.gov/explorations/03bio/background/edu/media/Meds_LivingCode.pdf

Focus: Functions of cell organelles and the genetic code in chemical synthesis (Life Science)

In this activity, students will be able to explain why new drugs are needed to treat cardiovascular disease, cancer, inflammation, and infections; infer why sessile marine invertebrates appear to be promising sources of new drugs; and explain the overall process through which cells manufacture chemicals. Students will also be able to explain why it may be important to synthesize new drugs, rather than relying on the natural production of drugs.

Mapping Deep-sea Habitats in the Northwestern Hawaiian Islands (7 pages, 80kb) (from the 2002 Northwestern Hawaiian Islands Expedition) http://oceanexplorer.noaa.gov/explorations/02hawaii/background/education/media/nwhi_mapping.pdf

Focus: Bathymetric mapping of deep-sea habitats (Earth Science - This activity can be easily modified for Grades 5-6)

In this activity, students will be able to create a two-dimensional topographic map given bathymetric survey data, will create a three-dimensional model of landforms from a two-dimensional topographic map, and will be able to interpret two- and three-dimensional topographic data.

Life is Weird (8 pages, 268k) (from the 2006 Expedition to the Deep Slope) http://oceanexplorer.noaa.gov/explorations/06mexico/background/edu/GOM%2006%20Weird.pdf

Focus: Biological organisms in cold-seep communities (Life Science)

In this activity, students will be able to describe major features of cold-seep communities, and list at least five organisms typical of these communities. Students will also be able to infer probable trophic relationships among organisms typical of cold-seep communities and the surrounding deep-sea environment, and describe the process of chemosynthesis in general terms, and will be able to contrast chemosynthesis and photosynthesis.

It's a Gas! Or Is It? (12 pages, 276k) (from the 2006 Expedition to the Deep Slope) http://oceanexplorer.noaa.gov/explorations/06mexico/background/edu/GOM%2006%20Gas.pdf

Focus: Effects of temperature and pressure on solubility and phase state (Physical Science/Earth Science)

In this activity, students will be able to describe the effect of temperature and pressure on solubility of gases and solid materials; describe the effect of temperature and pressure on the phase state of gases; and infer explanations for observed chemical phenomena around deep-sea volcanoes that are consistent with principles of solubility and phase state.

Other Links and Resources

The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

http://oceanexplorer.noaa.gov/explorations/07mexico/welcome.html – Follow Expedition to the Deep Slope 2007 daily as documentaries and discoveries are posted each day for your classroom use.

http://www.bio.psu.edu/People/Faculty/Fisher/fhome.htm – Web site for the senior biologist on Expedition to the Deep Slope 2007

http://www.rps.psu.edu/deep/ – Notes from another expedition exploring deep-sea communities

http://www-ocean.tamu.edu/Quarterdeck/QD5.3/macdonald.html – Article on cold-seep communities

http://nai.arc.nasa.gov/news_stories/news_detail.cfm?ID=86 – "Cafe Methane," another article on cold-seep communities

Paull, C.K., B. Hecker, C. Commeau, R.P. Feeman-Lynde, C. Nuemann, W.P. Corso, G. Golubic, J. Hook, E. Sikes, and J. Curray. 1984. Biological communities at Florida Escarpment resemble hydrothermal vent communities. Science 226:965-967 – Early report on cold-seep communities.

http://www.divediscover.whoi.edu/vents/index.html – "Dive and Discover: Hydrothermal Vents;" another great hydrothermal vent site from Woods Hole Oceanographic Institution

http://asgsb.indstate.edu/bulletins/v13n2/vol13n2p13-24.pdf – Article on adaptations to life in hydrothermal vent and cold-seep communities

http://www.accessexcellence.org/BF/bf01/arp/bf01p1.html – Verbatim transcript of a slide show on coping with toxic sulfide environments

Hourdez, S., L.A. Frederick, A. Schernecke, and C.R. Fisher. Functional respiratory anatomy of a deep-sea orbiniid polychaete from the Brine Pool NR-1 in the Gulf of Mexico. Invertebrate Biology 120:29-40. – Technical journal article upon which this activity is based.

National Science Education Standards

Content Standard A: Science As Inquiry
- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Content Standard B: Physical Science
- Properties and changes in matter

Content Standard C: Life Science
- Structure and function in living systems
- Diversity and adaptations of organisms

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.
The Earth has one big ocean with many features.
Fundamental Concept h. Although the ocean is large, it is finite and resources are limited.

Essential Principle 3.
The ocean is a major influence on weather and climate.
Fundamental Concept f. The ocean has had, and will continue to have, a significant influence on climate change by absorbing, storing, and moving heat, carbon and water.

Essential Principle 5.
The ocean supports a great diversity of life and ecosystems.

Fundamental Concept c. Some major groups are found exclusively in the ocean. The diversity of major groups of organisms is much greater in the ocean than on land.

Fundamental Concept d. Ocean biology provides many unique examples of life cycles, adaptations and important relationships among organisms (such as symbiosis, predator-prey dynamics and energy transfer) that do not occur on land.

Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

Essential Principle 6.
The ocean and humans are inextricably interconnected.

Fundamental Concept b. From the ocean we get foods, medicines, and mineral and energy resources. In addition, it provides jobs, supports our nation's economy, serves as a highway for transportation of goods and people, and plays a role in national security.

Fundamental Concept g. Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Essential Principle 7.
The ocean is largely unexplored.

Fundamental Concept a. The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation's explorers and researchers, where they will find great opportunities for inquiry and investigation.

Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.

Fundamental Concept d. New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.

Fundamental Concept f. Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

Send Us Your Feedback

We value your feedback on this lesson.
Please send your comments to:
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Student Handout

Comparative Functional Characteristics of Polychaete Gills

(modified from Hourdez, et al., 2001)

Species	Habitat	Gill Surface Area	Minimum
		(cm2/g Diffusion Distance	(µm)
		body wet weight)	
Branchipolynoe symmytilida	vent	14.2	10
Branchipolynoe seepensis	vent	10.3	9
Paralvinella grasslei	vent	47	4
Alvinella pompejana	vent	12	1-3
Arenicola marina	shallow mud	4	8-14
Undescribed Orbiniidae	seep	8	4