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2006 Gulf of Mexico Expedition

This Life Stinks

(adapted from the 2003 Windows to the Deep Expedition)

Focus
Methane-based chemosynthetic processes

Grade Level
9-12 (Physical Science)

Focus Question
How do organisms in cold seep communities obtain energy from methane?

Learning Objectives
Students will be able to define the process of chemosynthesis, and contrast this process with photosynthesis.

Students will be able to explain the process of methane-based chemosynthesis.

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

Materials
❒ None

Audio/Visual Materials
❒ None

Teaching Time
One-half 45-minute class period for introduction, plus one-half 45-minute class period for discussion; approximately 1-2 hours for research outside of class

Seating Arrangement
Classroom style

Maximum Number of Students
32

Key Words
Cold seeps
Methane hydrate
Chemosynthesis
Ice worm
Vestimentifera
Trophosome

Background Information
On August 28, 2005, Hurricane Katrina swept across the Gulf of Mexico, gathering strength to become a Category 3 storm that proved to be the most costly—and one of the most deadly—hurricanes in U.S. history. Four days later, the Department of the Interior's Minerals Management Service (MMS) reported that oil production in the Gulf of Mexico had been reduced by over 90 percent, and that natural gas production had been reduced by more than 78 percent. In the weeks that followed, fuel shortages and soaring prices underscored the importance of the Gulf of Mexico to petroleum supplies in the United States.

In fact, the Gulf of Mexico produces more petroleum than any other region in the nation, even though its proven reserves are less than those in Alaska and Texas. The San Francisco *Chronicle* reports that oil companies are spending billions to find more crude oil and drill more wells. Even with the threat of more hurricanes, the Gulf of Mexico has advantages: oil workers are not in danger of being kidnapped by armed insurgents as is the case in Nigeria; no foreign president threatens to raise oil companies' taxes, as has happened in Venezuela; and OPEC doesn't control oil production in the Gulf of Mexico. As of August 1, 2005, a total of 41,188 wells had been drilled in the Gulf, and 1,259 petroleum fields had been discovered.

Much of this new exploration is focussed on some of the deepest regions of the Gulf, made possible by improved technology and increasing crude oil prices (which have doubled in the last three years). In addition to new petroleum fields, this exploration has led to other discoveries as well. Some of the same conditions responsible for petroleum deposits also provide the basis for biological communities that receive energy from chemicals through a process called chemosynthesis (in contrast to photosynthesis that provide energy to terrestrial and shallow-water communities through processes in which sunlight is the basic energy source).

The first chemosynthetic communities were discovered in 1977 near the Galapagos Islands in the vicinity of underwater volcanic hot springs called hydrothermal vents, which usually occur along ridges separating the earth's tectonic plates. Hydrogen sulfide is abundant in the water erupting from hydrothermal vents, and is used by chemosynthetic bacteria that are the base of the vent community food chain. These bacteria obtain energy by oxidizing hydrogen sulfide to sulfur:

$$CO_2 + 4H_2S + O_2 > CH_2O + 4S + 3H_2O$$

(carbon dioxide plus sulfur dioxide plus oxygen yields organic matter, sulfur, and water). Visit http://www.pmel.noaa.gov/vents/home.html for more information and activities on hydrothermal vent communities.

Chemosynthetic communities in the Gulf of Mexico were found by accident in 1984. These communities are similar in that they are based upon energy produced by chemosynthesis; but while energy for the Galapagos communities is derived from underwater hot springs, deep sea chemosynthetic communities in the Gulf of Mexico are found in areas where hydrocarbon gases (often methane and hydrogen sulfide) and oil seep out of sediments. These areas, known as cold seeps, are commonly found along continental margins, and (like hydrothermal vents) are home to many species of organisms that have not been found anywhere else on Earth. Typical features of 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.

Where hydrogen sulfide is present, large tubeworms (phylum Annelida) known as vestimentiferans are often found, sometimes growing in clusters of millions of individuals. These unusual animals do not have a mouth, stomach, or gut. Instead, they have a large organ called a trophosome that contains chemosynthetic bacteria. Vestimentiferans have a structure called a plume that consists of filaments (sometimes referred to as "tentacles") that extend into the water. The tentacles are bright red due to the presence of hemoglobin which can absorb hydrogen sulfide and oxygen which are transported to the bacteria in the trophosome. The bacteria produce organic molecules that provide nutrition to the tube worm. A similar symbiotic relationship is found in clams and mussels that have chemosynthetic bacteria living in their gills. Bacteria are also found living independently from other organisms in large bacterial mats. 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, starfish, crabs, lobsters, isopods, sea cucumbers, and fishes. Specific relationships between these organisms have not been well-studied.

Deepwater chemosynthetic communities are fundamentally different from other biological systems, and there are many unanswered questions about the individual species and interactions between species found in these communities. These species include some of the most primitive living organisms (*Archaea*) that some scientists believe may have been the first life forms on Earth. Many species are new to science, and may prove to be important sources of unique drugs for the treatment of human diseases. Because their potential importance is not yet known, it is critical to protect these systems from adverse impacts caused by human activities.

Ironically, one of the most likely sources of such impacts is the same activity that led to the discovery of these systems in the first place: exploration and development of petroleum resources. MMS has the dual responsibility of managing these resources as well as protecting the environment from adverse impacts that might result from development activities. In 1988, MMS issued regulations specifically targeted toward protecting deepwater chemosynthetic communities. An essential part of the protection strategy requires identification of seafloor areas that could support chemosynthetic communities. These areas must be avoided by drilling, anchoring, pipeline installation, and other activities that involve disturbing the seafloor. Developing better ways to locate deepwater biological communities, evaluating their sensitivity to impacts from human activities, and understanding more about the ecological relationships of organisms that inhabit these communities are key objectives of the 2006 Gulf of Mexico Expedition.

In this lesson, students will investigate and describe the overall chemical processes involved in using methane and hydrogen sulfide to synthesize organic material.

Learning Procedure

1. To prepare for this lesson, review
   - Introductory essays for the 2006 Gulf of Mexico Expedition at http://oceanexplorer.noaa.gov/explorations/06mexico/

2. Lead a discussion of deep-sea chemosynthetic communities. Contrast chemosynthesis with photosynthesis: In both processes, organisms build sugars from carbon dioxide and water. This process requires energy; photosynthesizers obtain this energy from the sun, while chemosynthesizers obtain energy from chemical reactions. Be sure students understand that there are a variety of chemical reactions that can provide this kind of energy. Contrast hydrothermal vent communities with cold-seep communities. Visit http://www.bio.psu.edu/cold_seeps for a virtual tour of a cold seep community. Point out that until recently it was well-accepted that photosynthesis was the basis of all major biological communities on Earth. Recognition of chemosynthetic communities has changed this view dramatically; indeed, many biologists now favor the idea that life on Earth may have begun in chemosynthetic communities like those found near hydrothermal vents and cold seeps.

   Discuss the importance of the Gulf of Mexico to U.S. petroleum resources, as well as the potential importance of deepsea biological communities that might be adversely affected by exploration and development of petroleum resources. Ask students to brainstorm steps that might be taken to avoid adverse impacts. Briefly describe MMS regulations that require petroleum development companies to locate potentially sensitive biological communities and avoid these during exploration and development activities. Tell students that the overall purposes of the 2006 Gulf of Mexico Expedition are to develop ways to more easily locate such communities, and to learn more about how these communities work.

3. Tell students that their assignment is to describe the overall chemical processes involved in using methane and hydrogen sulfide to synthesize organic material. You may choose to have students complete this assignment individually or in small groups. Have each student or student group write a brief report in which they:
   - Identify the basic oxidation-reduction reactions;
   - State which reactants are oxidized and which ones are reduced; and
   - Explain whether or not these "chemosynthetic" reactions are totally independent of photosynthesis.

   The Web sites listed under "Resources" may be helpful for this assignment.

4. Lead a discussion of student reports. Students should recognize that chemosynthetic organisms using hydrogen sulfide oxidize this substance to form sulfur:
   $CO_2 + 4H_2S + O_2 > CH_2O + 4S + 3H_2O$
   (carbon dioxide plus hydrogen sulfide plus oxygen yields organic matter, sulfur, and water). Sulfur may be subsequently oxidized to form sulfate. The oxygen molecules in these reactions are reduced.

   The process appears to be a little more complicated for methane-based chemosynthesis. Despite numerous attempts, the organisms responsible for anaerobic methane oxidation have not yet been identified. Research has shown that maximum anaerobic methane oxidation rates coincide with maximum rates of sulfate reduction. Scientists have hypothesized that at least two different organisms are involved in the process: one that oxidizes methane, and one or more others that reduce sulfate. The overall equation for the process is:
   $CH_4 + SO_4^{2-} > HS^- + HCO_3^- + H_2O$
   (methane plus sulfate yields sulfide plus organic matter plus water)

   Preliminary investigations of chemosynthetic mussels on the Blake Ridge (the dominant invertebrate fauna) suggest that methane-oxidizing bacteria are accompanied by other bacteria that oxidize sulfide.

   Students should realize that while these reactions occur in anaerobic environments in the absence of sunlight, they probably are not totally independent of photosynthesis. This is because both methane and hydrogen sulfide are formed as a result of reactions involving organic carbon (buried in the sediments) much of which was produced by "ancient" photosynthesis. Moreover, most of the oxygen dissolved in seawater (needed for sulfide oxidation) is also a product of photosynthesis.

The Bridge Connection

www.vims.edu/bridge/vents.html and www.vims.edu/bridge/geology.html

The "Me" Connection

Have students write a brief essay on how processes involving chemosynthesis could affect them personally.

Connections to Other Subjects

English/Language Arts, Biology, Chemistry

Assessment

Written reports may be scored according to a rubric based on points identified in Step #3. Thoroughness of research (e.g., inclusion of references not provided by the instructor) may be added to this rubric if desired.

Extensions

1. Visit http://oceanexplorer.noaa.gov/explorations/06mexico/ for daily logs and updates about discoveries on the 2006 Gulf of Mexico Expedition.

2. Couple this lesson with "What's the Big Deal?" [http://oceanexplorer.noaa.gov/explorations/03windows/background/education/media/03win_bigdeal.pdf] and/or "Life

is Weird" explorations/06mexico/background/edu/edu.html to give students opportunities to explore the significance of methane hydrates and chemosynthetic biological communities in greater detail.

Resources

NOAA Learning Objects

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

Other Relevant Lesson Plans from the Ocean Exploration Program

Biochemistry Detectives (8 pages, 480k)) (from the 2002 Gulf of Mexico Expedition) [http://oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_biochem.pdf]

Focus: Biochemical clues to energy-obtaining strategies (Chemistry)

Students will be able to explain the process of chemosynthesis, explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps, and describe three energy-obtaining strategies used by organisms in cold-seep communities. Students will also be able to interpret analyses of enzyme activity and $\delta^{13}C$ isotope values to draw inferences about energy-obtaining strategies used by organisms in cold-seep communities.

This Old Tubeworm (10 pages, 484k)) (from the 2002 Gulf of Mexico Expedition) [http://oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_oldtube.pdf]

Focus: Growth rate and age of species in cold-seep communities

Students will be able to explain the process of chemosynthesis, explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps, and construct a graphic interpretation of age-specific growth, given data on incremental growth rates of different-sized individuals of the same species. Students will also be able to estimate the age of an individual of a specific size, given information on age-specific growth in individuals of the same species.

Hot Food (4 pages, 372k) (from the 2003 Gulf of Mexico Deep Sea Habitats Expedition) [http://oceanexplorer.noaa.gov/explorations/03mex/background/edu/media/mexdh_hotfood.pdf]

Focus: Energy content of hydrocarbon substrates in chemosynthesis (Chemistry)

Students will compare and contrast photosynthesis and chemosynthesis as processes that provide energy to biological communities, and given information on the molecular structure of two or more substances, will make inferences about the relative amount of energy that could be provided by the substances. Students will also be able to make inferences about the potential of light hydrocarbons as an energy source for deep-water coral reef communities.

Cool Corals (7 pages, 476k) (from the 2003 Life on the Edge Expedition) [http://oceanexplorer.noaa.gov/explorations/03edge/background/edu/media/cool.pdf]

Focus: Biology and ecology of *Lophelia* corals (Life Science)

Students will describe the basic morphology of *Lophelia* corals and explain the significance of these organisms, interpret preliminary observations on the behavior of *Lophelia* polyps, and infer possible explanations for these observations. Students will also discuss why biological communities associated with *Lophelia* corals are the focus of major worldwide conservation efforts.

Submersible Designer (4 pages, 452k) (from the 2002 Galapagos Rift Expedition)
[http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9-12_l4.pdf]
Focus: Deep Sea Submersibles

Students will understand that the physical features of water can be restrictive to movement; students will understand the importance of design in underwater vehicles by designing their own submersible; Students will understand how submersibles such as ALVIN and ABE, use energy, buoyancy, and gravity to enable them to move through the water.

The Benthic Drugstore (4 pages, 360k) (from the 2003 Deep Sea Medicines Expedition)
[http://oceanexplorer.noaa.gov/explorations/03bio/background/edu/media/Meds_Drugstore.pdf]

Focus: Pharmacologically active chemicals derived from marine invertebrates (life science)

Students will be able to identify at least three pharmacologically active chemicals derived from marine invertebrates, describe the disease-fighting action of at least three pharmacologically active chemicals derived from marine invertebrates, and infer why sessile marine invertebrates appear to be promising sources of new drugs.

How Diverse is That? (6 pages, 552k) (from the 2003 Windows to the Deep Expedition)
[http://oceanexplorer.noaa.gov/explorations/03windows/background/education/media/03win_hdiverse.pdf]

Focus: Quantifying biological diversity (Life Science)

Students will be able to discuss the meaning of "biological diversity" and will be able to compare and contrast the concepts of "variety" and "relative abundance" as they relate to biological diversity. Given abundance and distribution data of species in two communities, students will be able to calculate an appropriate numeric indicator that describes the biological diversity of these communities.

What's the Difference? (15 pages, 1Mb) (from the 2003 Mountains in the Sea Expedition)
[http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts_difference.pdf]

Focus: Identification of biological communities from survey data (Life Science)

Students will be able to calculate a simple similarity coefficient based upon data from biological surveys of different areas, describe similarities between groups of organisms using a dendrogram, and infer conditions that may influence biological communities given information about the groupings of organisms that are found in these communities.

Living in Extreme Environments (12 pages, 1Mb) (from the 2003 Mountains in the Sea Expedition)
[http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts_extremeenv.pdf]

Focus: Biological Sampling Methods (Biological Science)

Students will understand the use of four methods commonly used by scientists to sample populations; students will understand how to gather, record, and analyze data from a scientific investigation; students will begin to think about what organisms need in order to survive; students will understand the concept of interdependence of organisms.

Cut-off Genes (12 pages, 648k) (from the 2004 Mountains in the Sea Expedition)
[http://oceanexplorer.noaa.gov/explorations/04mountains/background/edu/media/MTS04.genes.pdf]

Focus: Gene sequencing and phylogenetic expressions (Life Science)

Students will be able to explain the concept of gene-sequence analysis; and, given gene sequence data, students will be able to draw inferences about phylogenetic similarities of different organisms.

What was for Dinner? (5 pages, 400k) (from the 2003 Life on the Edge Expedition) [http://oceanexplorer.noaa.gov/explorations/03edge/background/edu/media/dinner.pdf]

Focus: Use of isotopes to help define trophic relationships (Life Science)

Students will describe at least three energy-obtaining strategies used by organisms in deep-reef communities and interpret analyses of $\delta^{15}N$, $\delta^{13}C$, and $\delta^{34}S$ isotope values.

Other Resources and Links

http://www.gomr.mms.gov/index_common.html – Minerals Management Service Web site

http://www.gomr.mms.gov/homepg/lagniapp/chemcomp.pdf – "Chemosynthetic Communities in the Gulf of Mexico" teaching guide to accompany a poster with the same title, introducing the topic of chemosynthetic communities and other ecological concepts to middle and high school students.

http://www.gomr.mms.gov/homepg/lagniapp/lagniapp.html – Kids Page on the Minerals Management Service Web site, with posters, teaching guides and other resources on various marine science topics

http://www.coast-nopp.org/ – Resource Guide from the Consortium for Oceanographic Activities for Students and Teachers. Contains modules, guides, and lesson plans related to oceanography and coastal processes

http://cosee-central-gom.org/ – Web site for The Center for Ocean Sciences Education Excellence: Central Gulf of Mexico (COSEE-CGOM)

http://www.energybulletin.net/4901.html – Article "Out of Gas: Sediments in Northern Gulf of Mexico Not Right for Methane Gas Hydrate Formation, Study Shows" published by Georgia Research Tech News, 21 Mar 2005

http://www.ridge2000.org/eo/index.html – Links to other deep ocean exploration Web sites

http://www-ocean.tamu.edu/education/oceanworld-old/resources/general_links.htm – links to other ocean-related Web sites

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://dbhs.wvusd.k12.ca.us/webdocs/ChemTeamIndex.html – Web site for help with basic chemical concepts including oxidation-reduction reactions

http://www.geol.ucsb.edu/faculty/valentine/Valentine%202002.pdf – Review of methane-based chemosynthetic processes

Van Dover, C.L., et al. 2003. Blake Ridge methane seeps: characterization of a soft-sediment, chemosynthetically based ecosystem. Deep-Sea Research Part I 50:281–300. (available as a PDF file at http://www.geomar.de/projekte/sfb_574/abstracts/vanDover_et_al_2003.pdf)

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

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

- Chemical reactions
- Interactions of energy and matter

Content Standard C: Life Science

- Matter, energy, and organization in living systems

Content Standard D: Earth and Space Science

- Energy in the Earth system
- Origin and evolution of the Earth system

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 4.
The ocean makes Earth habitable.

- *Fundamental Concept b.* The first life is thought to have started in the ocean. The earliest evidence of life is found in the ocean.

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

- *Fundamental Concept b.* Most life in the ocean exists as microbes. Microbes are the most important primary producers in the ocean. Not only are they the most abundant life form in the ocean, they have extremely fast growth rates and life cycles.
- *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 f.* Ocean habitats are defined by environmental factors. Due to interactions of abiotic factors such as salinity, temperature, oxygen, pH, light, nutrients, pressure, substrate and circulation, ocean life is not evenly distributed temporally or spatially, i.e., it is "patchy". Some regions of the ocean support more diverse and abundant life than anywhere on Earth, while much of the ocean is considered a desert.
- *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 e.* Humans affect the ocean in a variety of ways. Laws, regulations and resource management affect what is taken out and put into the ocean. Human development and activity leads to pollution (such as point source, non-point source, and noise pollution) and physical modifications (such as changes to beaches, shores and rivers). In addition, humans have removed most of the large vertebrates from the ocean.
- *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 c.* Over the last 40 years, use of ocean resources has increased significantly, therefore the future sustainability of ocean resources depends on our understanding of those resources and their potential and limitations.
- *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.

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We value your feedback on our lesson plans. Please send your comments to:
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