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Thunder Bay Sinkholes 2008

This Life Stinks
(adapted from the 2003 Windows to the Sea 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

Audiovisual 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
30

Key Words
Cold seeps
Methane hydrate
Clathrate
Chemosynthesis
Ice worm
Vestimentifera
Trophosome

Background Information
In June, 2001, the Ocean Explorer Thunder Bay ECHO Expedition was searching for shipwrecks in the deep waters of the Thunder Bay National Marine Sanctuary and Underwater Preserve in Lake Huron. But the explorers discovered more than shipwrecks: dozens of underwater sinkholes in the limestone bedrock, some of which were several hundred meters across and 20 meters deep. The following year, an expedition to survey the sinkholes found that some of them were releasing fluids that produced a visible cloudy layer above the lake bottom, and the lake floor near some of the sinkholes was covered by conspicuous green, purple, white, and brown mats.

Preliminary studies of the mats have found that where water is shallow (≤ 1.0 m) the mats are composed of green algae. In deeper (about 18 m) waters, mats are formed by filamentous purple cyanobacteria. Mats near the deepest (93 m) sinkholes are white or brown, but their composition is presently unknown. The appearance of mats near the deepest sinkholes is very similar to mats observed in the vicinity of cold seeps and hydrothermal vents in the deep ocean, which are often formed by chemosynthetic bacteria. These bacteria are able to obtain energy from inorganic chemicals, and are a food source for a variety of other organisms that inhabit cold seep and vent communities. Biological communities whose primary energy source comes from chemosynthesis are distinctly different from more familiar biological communities in shallow water and on land where photosynthetic organisms convert the energy of sunlight to food that can be used by other species. Hydrothermal vent and cold seep communities are home to many species of organisms that have not been found anywhere else on Earth, and the existence of chemosynthetic communities in the deep ocean is one of the major scientific discoveries of the last 100 years.

Scientists hypothesize that the source of the fluids venting from the Lake Huron sinkholes is the Silurian-Devonian aquifer beneath the lake's sediments. Aquifers are rocks and sediments that contain large amounts of water. Between 350 and 430 million years ago, during the Paleozoic era, shallow seas covered what is now the border between Canada and the United States between Minnesota and New York. Over thousands of years, sand, minerals, and sediments accumulated on the seafloor, and were gradually compressed to form sandstone, limestone and shale. About 1.8 million years ago, the Great Ice Age of the Pleistocene epoch began and continued until about 10,000 years ago. During this time, four major periods of glaciation occurred, separated by three interglacial periods. As the final glacial period came to a close, retreating glaciers along the U.S.-Canadian border revealed five huge lakes that we now know as the Laurentian Great Lakes. In the Great Lakes region, aquifers are found in deposits of sand and gravel left by glaciers, as well as in porous bedrocks (limestone and sandstone) that were formed much earlier in geologic time. Five major aquifers are recognized in this region: one near the land or lake floor surface (the surficial aquifer) and the others in deeper bedrock named for the geologic time periods when they were formed (the Cambrian-Ordovician, Silurian-Devonian, Mississippian, and Pennsylvanian aquifers). The bedrock that forms the Silurian-Devonian aquifer is primarily limestone and mineral formations from evaporating seawater. Both fresh and saline water are found in the Silurian-Devonian aquifer.

Sinkholes are common features where limestone is abundant, because limestone rocks are soluble in acid. Atmospheric carbon dioxide often dissolves in rainwater to form a weak acid (carbonic acid). Rainwater flowing over land surfaces may also pick up organic acids produced by decaying leaves and other once-living material. The resulting weak acid can slowly dissolve limestone rocks to form caves, springs, and sinkholes. Sinkholes on land are known recharge areas for the Silurian-Devonian aquifer (areas where water flows into the aquifer). But very little is known about the chemistry, geology, and biology of submerged sinkholes that may serve as vents for groundwater in the aquifer. Water samples collected near these sinkholes is very different from the surrounding lake, with much higher concentrations of sulfate, phosphorus, and particulate organic matter, as well as ten times more bacteria compared to nearby lake water. These observations suggest that submerged sinkholes may be biogeochemical "hot spots" inhabited by unusual and possibly unknown life forms. At the same time, water flow through submerged sinkholes depends upon recharge from land. This means that sinkhole ecosystems are likely to be very sensitive to changes in rainfall patterns that may accompany climate change, as well as human alterations of these landscapes surrounding recharge areas. These factors make understanding sensitive sinkhole ecosystems an urgent necessity.

Learning Procedure

1. To prepare for this lesson:
   Review introductory essays for the Thunder Bay Sinkholes 2008 Expedition at http://oceanexplorer.noaa.gov/explorations/08thunderbay/welcome.html

2. Briefly introduce the Thunder Bay Sinkholes Expedition, highlighting the discovery of fluids emerging from sinkholes on the lake floor, and the variety of mats found in the vicinity of these sinkholes. Be sure students understand the concept of an aquifer, and that the mats are likely to be living organisms (algae and/or bacteria) that can serve as food for many other organisms. Point out that very little is known about the mats in Lake Huron or the biological communities they may support; but since their appearance is very similar to mats found in some deep ocean habitats, these habitats may provide clues for explorations of the Thunder Bay sinkholes.

3. Review, compare, and contrast chemosynthesis and photosynthesis. Be sure students understand that both are processes used by organisms to obtain energy needed for life functions (reproducing, locomotion, synthesizing tissues, etc.). Energy in living organisms is stored and transported in the form of adenosine triphosphate (ATP) molecules. The energy used to produce ATP comes from reactions that transfer electrons from an electron donor molecule to an electron acceptor molecule. When these reactions take place, the molecule that loses an electron is said to be "oxidized" and the molecule that gains an electron is said to be "reduced." One basic way to distinguish chemosynthesis from photosynthesis is the source of these electrons.

   In photosynthesis, light energy absorbed by pigments (e.g., chlorophyll) is transferred to electrons in the pigment molecule, and these electrons are transferred to other molecules in a series of oxidation-reduction reactions. What happens to the chlorophyll molecule that loses its electron? In some cases, the electron is eventually recycled to the chlorophyll molecule; a process called "cyclic photophosphorylation." In an alternative process called "noncyclic photophosphorylation" the electron is replaced by splitting another molecule through a process called "photolysis" (which means "light splitting"). The general equation for photosynthetic photolysis is

   $$H_2X + 2 \text{ photons} > 2e^- + 2H^+ + X$$

   "X" may be one of several elements. In the most familiar form of photosynthesis, "X" is oxygen, and the photosynthetic photolysis of water produces oxygen gas. In some purple bacteria, however, hydrogen sulfide is oxidized and particles of sulfur are produced. Note that while photosynthesis is often explained as noncyclic photophosphorylation and photolysis of water, some photosynthetic organisms use other pathways.

   In chemosynthesis, electrons are also transferred between molecules to provide the energy needed for ATP production. The key difference is that light does not play a part in these reactions. A variety of electron donors are found in chemosynthetic systems; hydrogen sulfide is common in chemosynthetic organisms associated with hydrothermal vents, while methane is often the electron donor in cold seep communities.

   In both photosynthetic and chemosynthetic communities, a significant amount of the energy captured as ATP is used to synthesize organic molecules (note that highly simplified descriptions of photosynthesis imply that light energy is used to combine carbon dioxide and water to form glucose in a single reaction; but the reality is that many reaction sequences are involved).

4. Lead a discussion of deep-sea chemosynthetic communities. Contrast hydrothermal vent com-

munities with cold-seep communities. Visit http://www.bio.psu.edu/cold_seeps and http://www.bio.psu.edu/hotvents for virtual tours of cold seep and hydrothermal vent communities. Point out that until recently, it was well-accepted that photosynthesis was the basis of all major biological communities on Earth. Recognition of these 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.

Hydrothermal vents are underwater volcanic hot springs, which usually occur along ridges separating the Earth's tectonic plates. Cold seeps are areas where gases (such as methane and hydrogen sulfide) and oil seep out of sediments. Both communities are home to many species of organisms that have not been found anywhere else on Earth.

Hydrothermal vent communities are often inhabited by large tubeworms known as vestimentiferans, sometimes growing in clusters of millions of individuals. At present, vestimentiferans are generally considered to be part of the phylum Annelida, but they are sometimes grouped as a separate phylum (Pogonophora).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 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.

Typical features of cold seep communities that have been studied so far include mounds of frozen crystals of methane and water called methane hydrate ice, that are home to polychete 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.

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.

5. 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.

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

6. 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 sulfur dioxide 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).

   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

http://www2.vims.edu/bridge/noaa/ – The NOAA collection of education resources on a variety of science topics including oceanography, climate, coral reefs, fishes, and exotic species

The "Me" Connection

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

Connections to Other Subjects

English/Language Arts, Biology, Chemistry

Assessment

Have students submit records of their observations and their written interpretation of these observations.

Extensions

1. Visit http://oceanexplorer.noaa.gov/explorations/08thunderbay/welcome.html to keep up to date with the latest Thunder Bay Sinkholes Expedition discoveries, and to find out what researchers are learning about these ecosystems.

Multimedia Learning Objects

http://www.learningdemo.com/noaa/ Lesson 5 for interactive multimedia presentations and Learning Activities on Chemosynthesis and Hydrothermal Vent Life.

Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

Designing Tools for Ocean Exploration

http://oceanexplorer.noaa.gov/explorations/deepeast01/background/education/dehslessons1.pdf
(14 pages, 80k) (from the 2001 Deep East Expedition)

Focus: Ocean Exploration

In this activity, students will understand the complexity of ocean exploration, learn about the technological applications and capabilities required for ocean exploration, discover the importance of teamwork in scientific research projects; and will develop the abilities necessary for scientific inquiry.

Finding the Way

http://oceanexplorer.noaa.gov/explorations/deepeast01/background/education/dehslessons4.pdf
(10 pages, 628k) (from the 2001 Deep East Expedition)

Focus: Underwater Navigation (Physical Science)

In this activity, students will describe how the compass, Global Positioning System (GPS), and sonar are used in underwater explorations, understand how navigational tools can be used to determine positions and navigate in the underwater environment.

Living in Extreme Environments

http://oceanexplorer.noaa.gov/explorations/deepeast01/background/education/dehslessons5.pdf
(13 pages 140k) (from the 2001 Deep East Expedition)

Focus: Biological Sampling Methods (Biological Science)

In this activity, students will be introduced to four methods commonly used by scientists to sample populations, learn how to gather, record, and analyze data from a scientific investigation, consider what organisms need in order to survive; and understand the concept of the interdependence of organisms.

Submersible Designer

http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9-12_l4.pdf
(4 pages, 452k) (from the 2002 Galapagos Rift Expedition)

Focus: Deep Sea Submersibles

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

Rock Eaters of the Gulf of Alaska

http://oceanexplorer.noaa.gov/explorations/02alaska/background/edu/media/rock_eaters9_12.pdf
(8 pages, 104k) (from the 2002 Exploring Alaska's Seamounts Expedition)

Focus: Chemosynthetic microbes in basalt rocks (Chemistry, Biology, Earth Science)

In this activity, students will be able to compare and contrast the processes of photosynthesis and chemosynthesis, identify and describe sources of energy used by various organisms for chemosynthesis, and predict what chemosynthetic reactions might be possible in selected "extreme" environments.

Calling All Explorers. . . .

http://oceanexplorer.noaa.gov/explorations/02fire/background/education/media/ring_calling_explorers_9_12.pdf
(14 pages, 124k) (from the 2002 Submarine Ring of Fire Expedition)

Focus: Ocean Exploration - Recent explorers of deep-sea environments and the relationship between science and history

In this activity, students will learn what it means to be an explorer, both modern and historic; recognize that not all exploration occurs on land; understand the importance of curiosity, exploration, and the ability to document what one studies; gain insight into the vastness of unexplored places in the deep sea; and gain appreciation of science mentors and role models.

Mystery of the Megaplume
http://oceanexplorer.noaa.gov/explorations/02fire/background/education/media/ring_mystery_9_12.pdf
(7 pages, 104k) (from the 2002 Submarine Ring of Fire Expedition)
Focus: Hydrothermal vent chemistry (Chemistry, Earth Science, Physical Science)

In this activity, students will be able to describe hydrothermal vents and characterize vent plumes in terms of physical and chemical properties, describe tow-yo operations and how data from these operations can provide clues to the location of hydrothermal vents, and interpret temperature anomaly data to recognize a probable plume from a hydrothermal vent.

Candy Chemosynthesis
http://oceanexplorer.noaa.gov/explorations/02fire/background/education/media/ring_candy_chemo_9_12.pdf
(10 pages, 208k) (from the 2002 Submarine Ring of Fire Expedition)

Focus: Biochemistry of hydrothermal vents (Biology, Chemistry)

In this activity, students will differentiate between requirements for life in extreme environments and other environments and will use models to create a visual image of chemicals involved in autotrophic nutrition.

From the Gulf of Mexico to the Moons of Jupiter
http://oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_moons.pdf
(6 pages, 46468k) (from the 2002 Gulf of Mexico Expedition)

Focus: Adaptations to unique or "extreme" environments (Earth Science)

In this activity, 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 will be able to compare physical conditions in deep-sea "extreme" environments to conditions thought to exist on selected moons of Jupiter. Students will also discuss the relevance of chemosynthetic processes in cold seep communities to the possibility of life on other planetary bodies.

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

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

In this activity, 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 ^{13}C isotope values to draw inferences about energy-obtaining strategies used by organisms in cold-seep communities.

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

Focus: Growth rate and age of species in cold-seep communities (Life Science)

In this activity, 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.

Where Did They Come From?

http://oceanexplorer.noaa.gov/explorations/05galapagos/background/edu/media/05galapagos_biogeography.pdf
(7 pages, 196k) (from the 2005 GalAPAGoS: Where Ridge Meets Hotspot Expedition)

Focus: Species variation in hydrothermal vent communities (Life Science)

In this activity, students will define and describe biogeographic provinces of hydrothermal vent communities, identify and discuss processes contributing to isolation and species exchange between hydrothermal vent communities, and discuss characteristics which may contribute to the survival of species inhabiting hydrothermal vent communities.

The Benthic Drugstore

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

Focus: Pharmacologically-active chemicals derived from marine invertebrates (Life Science)

In this activity, 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.

Watch the Screen!

http://oceanexplorer.noaa.gov/explorations/03bio/background/edu/media/Meds_WatchScreen.pdf
(5 pages, 428k) (from the 2003 Medicines from the Deep Sea Expedition)

Focus: Screening natural products for biological activity (Life Science)

In this activity, students will be able to explain and carry out a simple process for screening natural products for biological activity, and will be able to infer why organisms such as sessile marine invertebrates appear to be promising sources of new drugs.

C.S.I. on the Deep Reef (Chemotrophic Species Investigations, That Is)

http://oceanexplorer.noaa.gov/explorations/03mex/background/edu/media/mexdh_csi.pdf
(6 pages, 444k) (from the 2003 Gulf of Mexico Deep Sea Habitats Expedition)

Focus: Chemotrophic organisms (Life Science/Chemistry)

In this activity, students will describe at least three chemotrophic symbioses known from deep-sea habitats and will identify and explain at least three indicators of chemotropic nutrition.

My Wet Robot

http://oceanexplorer.noaa.gov/explorations/06greece/background/edu/media/wet_robot.pdf
(7 pages, 260 kb) (from the PHAEDRA 2006 Expedition)

Focus: Underwater Robotic Vehicles

In this activity, students will be able to discuss the advantages and disadvantages of using underwater robots in scientific explorations, identify key design requirements for a robotic vehicle that is capable of carrying out specific exploration tasks, describe practical approaches to meet identified design requirements, and (optionally) construct a robotic vehicle capable of carrying out an assigned task.

The Roving Robotic Chemist

http://oceanexplorer.noaa.gov/explorations/06greece/background/edu/media/robot_chemist.pdf
(14 pages, 440 kb) (from the PHAEDRA 2006 Expedition)

Focus: Mass Spectrometry (Chemistry)

In this lesson, students will be able to explain the basic principles underlying mass spectrometry, discuss the advantages of in-situ mass spectrometry, explain the concept of dynamic re-tasking as it applies to an autonomous underwater vehicle, and develop and justify a sampling strategy that could be incorporated into a program to guide an AUV searching for chemical clues to specific geologic features.

Where's My 'Bot?

http://oceanexplorer.noaa.gov/explorations/08bonaire/background/edu/media/wheresbot.pdf
(17 pages, 492kb) (from the Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies Expedition)

Focus: Marine Navigation (Earth Science/ Mathematics)

In this activity, students will estimate geographic position based on speed and direction of travel, and integrate these calculations with GPS data to estimate the set and drift of currents.

Outta Gas (from the 2007: Exploring the Inner Space of the Celebes Sea Expedition)
http://oceanexplorer.noaa.gov/explorations/07philippines/background/edu/media/outtagas.pdf
(10 pages, 300 kb)

Focus: Gas Laws (Chemistry/Physics)

In this activity, students will define Boyle's Law, Charles' Law, Gay-Lussac's Law, Henry's Law, and Dalton's Law and will be able to solve practical problems related to SCUBA diving.

Other 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/08thunderbay/welcome.html – Follow the Thunder Bay Sinkholes 2008 Expedition daily as documentaries and discoveries are posted each day for your classroom use

http://celebrating200years.noaa.gov/edufun/book/welcome.html#book – A free printable book for home and school use introduced in 2004 to celebrate the 200th anniversary of NOAA; nearly 200 pages of lessons focussing on the exploration, understanding, and protection of Earth as a whole system

http://oceanexplorer.noaa.gov/projects/thunderbay01/thunderbay01.html – Web site for the 2001 Ocean Explorer Expedition to survey "Shipwreck Alley" in Thunder Bay, Lake Huron

http://gvsu.edu/wri/envbio/biddanda/sinkhole.htm – 1 minute ROV video clip of conspicuous white benthic mats interspersed with the brownish mats characterizing the lake floor in the vicinity of the sinkhole, and a dark cloudy nepheloid-like plume layer prevailing just over the site of submarine groundwater seepage

ftp://ftp.glerl.noaa.gov/eos/El_Cajon_Boils_Short.wmv – Underwater video of El Cajon "boils"

ftp://ftp.glerl.noaa.gov/eos/Purple_Mats_40_sec.wmv – Underwater video of the purple benthic mats from the Middle Island Sinkhole

Biddanda, B. A., D. F. Coleman, T. H. Johengen, S. A. Ruberg, G. A. Meadows, H. W. VanSumeren, R. R. Rediske, and S. T. Kendall. 2006. Exploration of a submerged sinkhole ecosystem in Lake Michigan. Ecosystems 9:828-842. Available online at http://www.glerl.noaa.gov/pubs/fulltext/2006/20060020.pdf

Ruberg, S.A., D.F. Coleman, T.H. Johengen, G.A. Meadows, H.W. VanSumeren, G.A. LANG, and B.A. Biddanda. 2005. Groundwater plume mapping in a submerged sinkhole in Lake Huron. Marine Technology Society Journal 39(2):65-69. Available online at http://www.glerl.noaa.gov/pubs/fulltext/2005/20050038.pdf

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

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

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

Tunnicliffe, V., 1992. Hydrothermal-vent communities of the deep sea. American Scientist 80:336-349.

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 3.

The ocean is a major influence on weather and climate.

Fundamental Concept e. The ocean dominates the Earth's carbon cycle. Half the primary productivity on Earth takes place in the sunlit layers of the ocean and the ocean absorbs roughly half of all carbon dioxide added to the atmosphere.

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 4.

The ocean makes Earth habitable.

Fundamental Concept a. Most of the oxygen in the atmosphere originally came from the activities of photosynthetic organisms in the ocean.

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 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 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:
oceanexeducation@noaa.gov

For More Information

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