Aegean and Black Sea 2006 Expedition

I Can't Breathe!

Focus
Anoxic ocean environments

Grade Level
9-12 (Life Science/Earth Science)

Focus Question
What causes hypoxic conditions that produce the "dead zone" in the ocean?

Learning Objectives
Students will be able to explain how nutrient enrichment in aquatic habitats can result in anoxic (no oxygen) conditions.

Students will be able to explain a plausible hypothesis that explains the existence of the "dead zone" in the northeastern Gulf of Mexico.

Students will be able to design an experiment to test their hypothesis.

Materials
❒ Copies of "Guidance Questions for Investigating Anoxic Ocean Environments" worksheet, one copy for each student or student group
❒ (Optional) Computers with internet access; if students do not have access to the internet, download copies of materials cited under "Learning Procedure" and provide copies of these materials to each student or student group

Audio/Visual Materials
None

Teaching Time
One or two 45-minute class periods, plus time for student research; additional time will be needed if students are to carry out their planned experiments

Seating Arrangement
Groups of 3-4 students

Maximum Number of Students
30

Key Words
Black Sea
Anoxia
Eutrophication
Stratification
Nutrient enrichment
Gulf of Mexico Dead Zone
Pycnocline

Background Information
The geographic region surrounding the Aegean and Black Seas has been the stage for many spectacular performances in Earth's geologic and human history. Human activities on the region's stage began during Paleolithic times; artifacts discovered near Istanbul are believed to be at least 100,000 years old. Well-known Aegean cultures include the Minoans (ca 2,600 – 1,450 BC), Mycenaeans (ca 1,600 – 1,100 BC), Ancient Greeks (776 – 323 BC), and Hellenistic Greeks (323 – 146 BC). Istanbul—"the only city that spans two continents"—has been a crossroads of travel and trade for more than 26 centuries.

Mariners have traveled the Aegean and Black Seas since Neolithic ("Stone Age" times; 6,500 – 3,200 BC), probably for a combination of purposes, including trading, exploration, and warfare.

Interactions between these cultures and many others were often violent and destructive. So, too, were interactions with geological processes. One of the most dramatic and destructive events was the eruption of a volcano in a small group of Aegean islands called Thera (also known as Santorini), sometime between 1,650 and 1,450 BC. Estimated to be four times more powerful than the Krakatoa volcano of 1883, the eruption left a crater 18 miles in diameter, spewed volcanic ash throughout the Eastern Mediterranean, and may have resulted in global climactic impacts. Accompanied by earthquakes and a tsunami, the volcano destroyed human settlements, fleets of ships, and may have contributed to the collapse of the Minoan civilization on the island of Crete, 110 km to the south.

Interactions with other geological processes may have been equally disastrous. In 1997, geologists William Ryan and Walter Pitman published a theory in which the Black Sea was inundated around 5,600 BC by flood waters from the Mediterranean passing through the Straits of Bosporus at Istanbul. Such a deluge, if it occurred, would have been disastrous for human settlements along the Black Sea shoreline and might have provided an origin for accounts of cataclysmic floods in Christianity and other cultures. Subsequent research has neither proved nor disproved the "Black Sea deluge theory," but in 2000, Robert Ballard discovered remains of a wooden structure that may have been part of an ancient seaport 95 meters below the surface of the Black Sea. This may be one of the best places in the world to look for remains of ancient civilizations, because the deep waters of the Black Sea contain almost no oxygen, so the biological organisms that normally attack such relics cannot live in this environment.

The Black Sea is the world's largest water body in which the bottom waters never mix with shallower waters (a condition known as "meromictic"). As a result, the deeper waters are completely anoxic (devoid of oxygen). Seawater flows into the Black Sea basin from the Mediterranean via the Straits of Bosporus, while freshwater enters from several European rivers including the Danube. As a result, salinity gradually increases with depth from about 18 ppt at the surface to about 22 ppt in deeper waters. A water mass known as the Cold Intermediate Layer (CIL) separates surface waters from deeper waters, and is the major reason for deep-water isolation. Below about 200 m, bacterial decomposition of biomass sinking from shallow water consumes all available oxygen, while the anaerobic metabolism of other bacteria causes the formation of hydrogen sulfide.

While such conditions are not favorable for many biological species, they are excellent for preserving human artifacts from normal processes of degradation. The discovery of what may have been an ancient shoreline 95 m below the present surface of the Black Sea may support Ryan and Pitman's suggestion that a catastrophic flood transformed the Black Sea from a freshwater lake to its present condition. Additional support for the idea comes from radiocarbon dating of the shells of freshwater molluscs sampled at the "ancient shoreline" site. These analyses show the age of the freshwater molluscs to be about 7,500 years, while saltwater species from the same area appeared about 6,900 years ago. In other words, the transition from fresh to saline conditions was fairly rapid. More recent analyses of other data conclude that while this flood did occur, it was not as catastrophic as suggested by Ryan and Pitman, and a more severe flooding event took place 16,000 - 13,000 years ago (see http://gsa.confex.com/gsa/2003AM/finalprogram/abstract_58733.htm). Notwithstanding debate about the relative significance of ancient floods, the anoxic waters of the Black Sea may still reveal a great deal about seafaring activities of "Stone

Age" peoples. Finding well-preserved archaeological sites, studying ancient maritime trade, and exploring the history of the Theran volcano are the primary goals of the Ocean Explorer Aegean and Black Sea 2006 Expedition.

In this lesson, students will investigate the causes of anoxia in benthic environments, develop hypotheses for the probable cause of anoxic conditions in the Gulf of Mexico, and design an experiment to test their hypothesis.

Learning Procedure

NOTE: Portions of this lesson are adapted from the National Ocean Service's Discovery Classroom; see http://oceanservice.noaa.gov/education/classroom/)

1. To prepare for this lesson, review the background essays for the Aegean and Black Sea 2006 Expedition at http://oceanexplorer.noaa.gov/explorations/06blacksea/welcome.html. You may also want to review information at some of the Web sites listed in Step 3, as well as the discussion of the "Guidance Questions for Investigating Anoxic Ocean Environments" worksheet in Step 4.

   You should also consider whether or not to place constraints on proposed student investigations (e.g., are laboratory simulations acceptable, or should investigations be confined to field measurements), as well as whether students will be required to actually carry out their proposed investigations.

2. If necessary, briefly review the significance of dissolved oxygen in aquatic environments. Be sure students understand the customary units for reporting dissolved oxygen concentration in water (mg/L or parts-per-million), and the normal values for dissolved oxygen in water (freshwater at 25°C is saturated with dissolved oxygen at a concentration of about 8.3 mg/L; seawater at 25°C is saturated with dissolved oxygen at a concentration of about 6.9 mg/L). You may also want to point out that the solubility of oxygen decreases as temperature increases, and also decreases as salinity increases. Portions of the National Ocean Service Estuary Discovery Kit (http://oceanservice.noaa.gov/education/kits/estuaries) dealing with temperature and dissolved oxygen provide a useful overview of these topics (see oceanservice.noaa.gov/education/kits/estuaries/media/supp_estuar10a_temp.html, and http://oceanservice.noaa.gov/education/kits/estuaries/media/supp_estuar10d_disolvedox.html.

3. Briefly introduce the Aegean and Black Sea 2006 Expedition, emphasizing some of the reasons that scientists are interested in the Black Sea. Tell students that there are other places in Earth's ocean where there is little or no dissolved oxygen, and that such conditions are called "anoxic." Say that that their assignment is to research these areas and prepare a report that includes:
   - Background on anoxic ocean environments, including answers to questions on the worksheet;
   - An hypothesis for the probable cause of the "Gulf of Mexico Dead Zone;" and
   - A design for an experiment to test this hypothesis.

   You may want to provide one or more of the following references:
   - http://disc.gsfc.nasa.gov/oceancolor/scifocus/oceanColor/dead_zones.shtml;
   - http://blacksea.orlyonok.ru/blacksea.shtml;
   - http://www.ncddc.noaa.gov/ecosystems/hypoxia;
   - http://toxics.usgs.gov/hypoxia/;
   - http://www.smm.org/deadzone/;
   - http://www.epa.gov/msbasin/;
   - http://www.ducks.org/news/deadzone.asp;
   - http://www.nwrc.usgs.gov/climate/hypoxia.pdf (2 pages, 184 kb); and/or
   - http://www.seaweb.org/resources/briefings/dead_zone.php.

   Alternatively, you may wish to have students discover these (or other) resources on their own.

4. Lead a discussion of the results of students' research. Key points should include:
   - The usual cause of anoxic conditions in ocean environments is excessive amounts of organic matter (particularly phytoplankton) produced near the surface of the ocean. When this material sinks to the bottom, it is broken down by bacteria that consume dissolved oxygen. Anoxic conditions occur when dissolved oxygen is consumed at a rate that exceeds the rate of oxygen replenishment (by the circulation of shallower waters containing oxygen produced by photosynthesis). If productivity near the surface is enhanced, more organic matter is produced, and more oxygen will be consumed when dead organisms sink to the bottom. If water circulation is restricted, the natural replenishment of oxygen in deeper waters is reduced, which may result in oxygen depeletion.
   - "Creeping dead zones" are areas in the ocean where it appears that phytoplankton productivity has been enhanced, or natural water flow has been restricted, leading to increasing bottom water anoxia.
   - Human activities can contribute to the development of anoxic conditions by enhancing shallow water productivity (e.g., by adding nutrients from agricultural activities or sewage treatment facilities), and/or by reducing the circulation of oxygenated waters to deeper waters.
   - Disasters such as hurricanes can intensify conditions that deplete oxygen in deeper waters when extensive flooding caused by heavy rains carry nutrients from dead animals, flooded animal waste ponds, fertilized agricultural areas, sewage systems, and other sources to coastal waters, leading to increased production of organic matter.
   - Naturally occurring anoxic basins include the Cariaco Basin, near the coast of Venezuela; Saanich Inlet on Vancouver Island, Canada; and the Black Sea.
   - A pycnocline is a density boundary where the water density changes abruptly.
   - The largest anoxic basin on Earth is the Black Sea.
   - Anoxic conditions in the Black Sea are the result of limited seawater input to the Black Sea from the Mediterranean through the narrow Straits of Bosporus, while freshwater input comes from several large European rivers. Because freshwater inflow from rivers is less dense than seawater, all of the mixing between freshwater and seawater takes place in the upper 150 meters. Below the pycnocline, the water column is entirely anoxic.
   - The Black Sea could have been a freshwater lake during the last Ice Age when sea levels were lower than at present (a suggestion supported by the discovery of freshwater molluscs in Black Sea sediments). As sea levels rose due to glacial melting, a flood of seawater could have broken through the Straits of Bosporus and entered the Black Sea basin to create the density difference that prevents vertical mixing.
   - Anoxic conditions are favorable to marine archaeology because of the slow rate at which artifacts are degraded by biological processes.

5. Have each student group present their hypothesis for the probable cause of the "Gulf of Mexico Dead Zone," and describe their planned experiment to test their hypothesis.

   Based on their research, students should identify nutrient enrichment (eutrophication) as the most probable cause, though alternative hypotheses should be allowed if they are supported by a plausible line of reasoning. Scientific investigations of the Gulf of Mexico Dead Zone have confirmed that influx of fertilizer and animal waste from the Mississippi River watershed, coupled with seasonal stratification of Gulf waters, are the most probable cause of these conditions. This watershed drains 41% of the continental United States, including some of the major U.S. agricultural regions. There is evidence that hypoxic conditions occasionally occurred in the same area before modern agriculture, but such conditions were much less common than they have been since the 1970's.

Seasonal stratification occurs when surface waters are heated during warmer months, and consequently become less dense than colder, deeper waters. This is a relatively stable condition (warm, less dense water on top of colder, more dense water), and tends to suppress the exchange of water between the surface and deeper waters. Without vertical mixing, it is much more difficult for oxygen from the atmosphere to replenish oxygen consumed in deeper water. When decomposing algae increase the rate of oxygen consumption in deeper waters, unusually low oxygen concentrations can result. Stratified conditions are temporary in the Gulf of Mexico, in contrast to areas such as the Black Sea where they have persisted for hundreds of years.

Key points that should be included in students' experimental designs are:

- The hypothesis should relate to potential causes of oxygen depletion that are substantiated by students' literature research.
- If the hypothesis involves fertilizers and/or animal wastes from agricultural activities, the experimental test should use fertilizers or waste that might actually be involved with such activities.
- There should be appropriate controls for each different factor being tested.
- There should be at least two replicates of each test and control.

You may also want to have students describe the statistical tests that will be used to analyze their experimental data, since the intended statistical approach is a key consideration in experimental design.

6. If you plan to have students actually conduct their experiments, refer to the following examples for equipment ideas and safety considerations:
   - http://ei.cornell.edu/watersheds/Eutrophication_Experiments.pdf (6 pages, 32KB) – Eutrophication experiments from Cornell University's Institute on Science and the Environment for Teachers
   - http://www.zoo.utoronto.ca/able/volumes/vol-23/13-bennett.pdf (16 pages, 64KB) – Eutrophication - A Project Lab for Multi-Section Lab Courses by Virginia Bennett, Department of Biology, Georgia Southern University
   - http://www.stormwatercoalition.org/pdf/Lesson%20Plans/lesson05-07.pdf (5 pages 108KB) – Eutrophication activity from Salt Lake County Storm Water Quality Education Lesson and Activity Plans

The Bridge Connection

http://www.vims.edu/bridge/archive1099.html/ – "The Dead Zone: A Marine Horror Story;" includes information on the causes and implications of the dead zone. Includes maps and data and invites students to find ways to fix the problem.

The "Me" Connection

The Gulf of Mexico Dead Zone is a dramatic example of how activities in one locale can have far-reaching impacts elsewhere. Have students write a brief essay describing how one or more activities with which they are personally involved could have an effect (positive or negative) on ecosystems in other locations.

Connections to Other Subjects

English/Language Arts, Chemistry, Social Studies

Assessment

Student research, hypotheses, and (optionally) experiments (Steps 4, 5, and 6) provide opportunities for assessment.

Extensions

1. Have students visit http://oceanexplorer.noaa.gov/explorations/06blacksea/ to keep up with the latest discoveries from the Aegean and Black Sea 2006 Expedition.

2. Visit the following Web sites for additional activities related to the "Gulf of Mexico Dead Zone:"

http://lamer.lsu.edu/classroom/deadzone/index.htm – "On Again, Off Again – The Dead Zone;" Louisiana Sea Grant Dead Zone Mapping Activity

http://www.lpb.org/education/classroom/ntti/cdpdf2003/6jmHyp.pdf (8 pages, 80KB) – "Hypoxia and the Dead Zone in the Gulf of Mexico: Is It the Mississippi River's Fault?" activity by Janiece Mistich, from the National Teacher Training Institute

http://www.epa.gov/msbasin/index.htm – EPA Web page on the Mississippi River Basin and hypoxia in the Gulf of Mexico, including information on subbasins, hypoxia, culture and history of the area, strategies for reducing the frequency of hypoxic events and links to other resources

http://www.epa.gov/gmpo/ – "The Gulf of Mexico Watershed" provided by the U.S. Environmental Protection Agency, Gulf of Mexico Program; follow links from "Educator and Student Resources" to "Kid's Stuff" for facts, figures and maps of the Gulf watershed.

Resources

NOAA Learning Objects

http://www.learningdemo.com/noaa/ – Click on the links to Lessons 1, 2, and 4 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Mid-Ocean Ridges, and Subduction Zones.

Other Relevant Lessons from the Ocean Exploration Program

What's Eating *Titanic*?
http://oceanexplorer.noaa.gov/explorations/04titanic/edu/media/Titanic04.Rusticles.pdf
(5 pages, 408k) (from the *Titanic* 2004 Expedition)

Focus: Biodeterioration processes (Physical Science/Biological Science)

In this activity, students will be able to describe three processes that contribute to the deterioration of the *Titanic*, and define and describe rusticles, explaining their contribution to biodeterioration. Students will also be able to explain how processes that oxidize iron in *Titanic's* hull differ from iron oxidation processes in shallow water.

Designing Tools for Ocean Exploration
http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_l1.pdf
(13 pages, 496k) (from the 2002 Galapagos Rift 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 develop the abilities necessary for scientific inquiry.

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

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.

Mapping the Canyon

http://oceanexplorer.noaa.gov/explorations/deepeast01/background/education/dehslessons2.pdf
(10 pages, 72k) (from the 2001 Deep East Expedition)

Focus: Hudson Canyon Bathymetry (Earth Science)

In this activity, students will be able to compare and contrast a topographic map to a bathymetric map; investigate the various ways in which bathymetric maps are made; and learn how to interpret a bathymetric map.

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; and understand how navigational tools can be used to determine positions and navigate in the underwater environment.

Other Resources and Links

http://oceanexplorer.noaa.gov/explorations/06blacksea – Web site for the Aegean and Black Sea 2006 Expedition

http://www.immersionpresents.org/ – Immersion Presents Web site; click on "Ancient Eruptions!" for more information about the Aegean and Black Sea 2006 Expedition, images, and educational activities

http://www.ngdc.noaa.gov/paleo/ctl/clihis10k.html –Timeline for last 10,000 years from NOAA's Paleoclimatology Web site

http://pubs.usgs.gov/pdf/planet.html – "This Dynamic Planet," map and explanatory text showing Earth's physiographic features, plate movements, and locations of volcanoes, earthquakes, and impact craters

http://disc.gsfc.nasa.gov/oceancolor/scifocus/oceanColor/dead_zones.shtml – Web page from NASA about "Creeping Dead Zones," including SeaWIFS satellite imagery

http://news.nationalgeographic.com/news/2000/12/122800blacksea.html – National Geographic Web site, "Ballard Finds Traces of Ancient Habitation Beneath Black Sea"

http://blacksea.orlyonok.ru/blacksea.shtml – Web site of the Living Black Sea Marine Environmental Education Program in the Russian Federal Children Center Orlyonok

Friedrich, W. L.. 2000. Fire in the Sea. The Santorini Volcano: Natural History and the Legend of Atlantis. Translated by Alexander R. McBirney. Cambridge University Press. 258 pp.

Ryan, W. and W. Pitman. 1999. Noah's Flood: The New Scientific Discoveries About the Event That Changed History. Simon and Schuster. New York.

Yanko-Hombach, V. 2003. "Noah's Flood" and the late quaternary history of the Black Sea and its adjacent basins: A critical overview of the flood hypotheses. Paper presented at the Geological Society of America Annual Meeting, November 2–5, 2003, Seattle, WA (abstract available online at http://gsa.confex.com/gsa/2003AM/finalprogram/abstract_58733.htm).

http://ina.tamu.edu/ub_main.htm – Web site with information about the excavation of a Bronze Age shipwreck at Uluburun, Turkey

http://projectsx.dartmouth.edu/history/bronze_age/ – Dartmouth University Web site, "Prehistoric Archaeology of the Aegean," with texts, links to other online resources, and numerous bibliographic references

http://www.ncddc.noaa.gov/ecosystems/hypoxia – Hypoxia Watch System for the Gulf of Mexico

http://toxics.usgs.gov/hypoxia/ – Web site on hypoxia in the Gulf of Mexico and related activities of the US Geological Survey

http://www.nps.gov/miss/features/factoids/ – General information and "factoids" about the Mississippi River and its watershed from the Mississippi National River and Recreation Area Web site

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico. Washington, DC; available online at http://www.epa.gov/msbasin/taskforce/pdf/actionplan.pdf (6.4MB).

http://www.nwrc.usgs.gov/climate/hypoxia.pdf (2 pages, 184 kb) – Fact sheet from the U.S. Geological Survey, National Wetlands Research Center.

http://www.epa.gov/msbasin/ – Web page from the U.S. Environmental Protection Agency with information on hypoxia, the relationship between the Mississippi River Basin and the Gulf of Mexico, and links to scientific reports

http://www.smm.org/deadzone/ – Web site from the Science Museum of Minnesota about the Gulf of Mexico Dead Zone with interactive activities, links, maps and video in English and Spanish

http://www.seaweb.org/resources/briefings/dead_zone.php – SeaWeb briefing book, including a recommended reading list.

Diaz, R. J. 2001. Overview of Hypoxia around the world. Journal of Environmental Quality. 30:275-281; available online at http://jeq.scijournals.org/cgi/content/abstract/30/2/275 (369K)

National Science Education Standards

Content Standard A: Science As Inquiry

- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Content Standard C: Life Science

- Interdependence of organisms

Content Standard D: Earth and Space Science

- Geochemical cycles

Content Standard F: Science in Personal and Social Perspectives

- Personal and community health
- Natural resources
- Environmental quality
- Natural and human-induced hazards
- Science and technology in local, national, and global challenges

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.

The Earth has one big ocean with many features.

- *Fundamental Concept d*. Sea level is the average height of the ocean relative to the land, taking into account the differences caused by tides. Sea level changes as plate tectonics cause the volume of ocean basins and the height of the land to change. It changes as ice caps on land melt or grow. It also changes as sea water expands and contracts when ocean water warms and cools.

- *Fundamental Concept g*. The ocean is connected to major lakes, watersheds and waterways because all major watersheds on Earth drain to the ocean. Rivers and streams transport nutrients, salts, sediments and pollutants from watersheds to estuaries and to the ocean.

Essential Principle 2.
The ocean and life in the ocean shape the features of the Earth.

- *Fundamental Concept b*. Sea level changes over time have expanded and contracted continental shelves, created and destroyed inland seas, and shaped the surface of land.
- *Fundamental Concept e*. Tectonic activity, sea level changes, and force of waves influence the physical structure and landforms of the coast.

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

- *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.

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

- *Fundamental Concept a*. The ocean affects every human life. It supplies freshwater (most rain comes from the ocean) and nearly all Earth's oxygen. It moderates the Earth's climate, influences our weather, and affects human health.
- *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 c*. The ocean is a source of inspiration, recreation, rejuvenation and discovery. It is also an important element in the heritage of many cultures.
- *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 f*. Coastal regions are susceptible to natural hazards (such as tsunamis, hurricanes, cyclones, sea level change, and storm surges).
- *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

Guidance Questions for Investigating Anoxic Ocean Environments

1. What is the usual cause of anoxic conditions in ocean environments?

2. What are "creeping dead zones?"

3. How can human activities contribute to the development of anoxic conditions?

4. How can disasters such as hurricanes intensify conditions that deplete oxygen in deeper waters?

5. List two naturally-occurring anoxic basins.

6. What is a pycnocline?

7. What is the largest anoxic basin on Earth?

8. What causes anoxic conditions in the Black Sea?

9. How might the Black Sea have changed from a freshwater lake to an anoxic marine basin?

10. Why are anoxic conditions favorable to marine archaeology?