New Zealand American Submarine Ring of Fire 2007

Going to Extremes

Focus
Archaea

Grade Level
9-12 (Biology)

Focus Question
What are Archaea, and what is their potential significance in hydrothermal communities of the Kermadec Arc?

Learning Objectives
Students will be able to define "lipid biomarkers," and explain what the presence of certain biomarkers signifies.

Students will be able to describe Archaea, and explain why these organisms are often considered to be unusual.

Students will be able to compare and contrast Archaea with bacteria and eukaryotes.

Students will be able to define methanogen and methanotroph, and explain the relevance of these terms to Archaea.

Students will be able to discuss the potential significance of Archaea in hydrothermal communities of the Kermadec Arc.

Materials
❒ Copies of "Going to Extremes Worksheet," one copy for each student or student group

Audio/Visual Materials
❒ (Optional) Equipment for viewing online or downloaded video of vent communities

Teaching Time
One or two 45-minute class periods, plus time for student research

Seating Arrangement
Classroom style if students are working individually, or groups of two to four students

Maximum Number of Students
30

Key Words
Kermadec Arc
Hydrothermal field
Archaea
Prokaryote
Eukaryote
Methanogen
Methanotroph
Chemoautotroph

Background Information
The Submarine Ring of Fire is an arc of active volcanoes that partially encircles the Pacific Ocean Basin, including the Kermadec and Mariana Islands in the western Pacific, the Aleutian Islands between the Pacific and Bering Sea, the Cascade Mountains in western North America, and numerous volcanoes on the western coasts of Central America and South America. These volcanoes result from the motion of large pieces of the

Earth's crust known as tectonic plates. This volcanic activity releases immense quantities of heat, minerals, gases and other substances, and often produces "hydrothermal systems" or seafloor hot springs. These processes influence the entire ocean, and support unique biological communities. Many species in these communities are new to science, and have a high potential for developing important new natural products for industrial and medical applications. In addition, fluids produced by volcanic activity often have high concentrations of metals that quickly precipitate in cold ocean waters, and may be directly linked to the formation of ores and concentrated deposits of gold and other precious and exotic metals.

The junction of two tectonic plates is called a "plate boundary," and three major types of plate boundary are produced by tectonic plate movements. If two tectonic plates collide more or less head-on they form a convergent plate boundary. Usually, one of the converging plates will move beneath the other, which is known as subduction. The junction of two tectonic plates that are moving apart is called a divergent plate boundary. Magma rises from deep within the Earth and erupts to form new crust along submarine mountain ranges called oceanic spreading ridges. The third type of plate boundary occurs where tectonic plates slide horizontally past each other, and is known as a transform plate boundary. As the plates rub against each other, huge stresses are set up that can cause portions of the rock to break, resulting in earthquakes.

The volcanoes of the Submarine Ring of Fire result from the motion of several major tectonic plates. The Pacific Ocean Basin lies on top of the Pacific Plate. To the east, along the East Pacific Rise, new crust is formed at the oceanic spreading center between the Pacific Plate and the western side of the Nazca Plate. Farther to the east, the eastern side of the Nazca Plate is being subducted beneath the South American Plate, giving rise to active volcanoes in the Andes. Similarly, convergence of the Cocos and Caribbean Plates produces active volcanoes on the western coast of Central America, and convergence of the North American and Juan de Fuca Plates causes the volcanoes of the Cascades in the Pacific Northwest.

On the western side of the Pacific Ocean, the Pacific Plate converges against the Philippine Plate and Australian Plate. Subduction of the Pacific Plate creates the Mariana Trench (which includes the Challenger Deep, the deepest known area of the Earth's ocean) and the Kermadec Trench. As the sinking plate moves deeper into the mantle, new magma is formed as described above, and erupts along the convergent boundary to form volcanoes. The Mariana and Kermadec Islands are the result of this volcanic activity, which frequently causes earthquakes as well. The movement of the Pacific Ocean tectonic plate has been likened to a huge conveyor belt on which new crust is formed at the oceanic spreading ridges, and older crust is recycled to the lower mantle at the convergent plate boundaries of the western Pacific. For more information on plate tectonics, visit the NOAA Learning Objects Web site (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.

Since they were discovered in 1977, hydrothermal vent communities associated with divergent plate boundaries have been extensively studied. In contrast, much less is known about hydrothermal systems near convergent plate boundaries like those of the Mariana and Kermadec Arcs. Beginning in 2002, Ocean Exploration expeditions have undertaken systematic mapping and study of hydrothermal systems in previously-unexplored areas of the Submarine Ring of Fire. Visit

- http://oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain/;
- http://www.oceanexplorer.noaa.gov/explorations/03fire/;
- http://www.oceanexplorer.noaa.gov/explorations/04fire/;

- http://www.oceanexplorer.noaa.gov/explorations/05fire/; and
- http://oceanexplorer.noaa.gov/explorations/06fire/welcome.html

for more information about the many discoveries, as well as still and video imagery, from these expeditions. The New Zealand American Submarine Ring of Fire 2007 Expedition is focused on detailed exploration of hydrothermal systems at Brothers Volcano in the Kermadec Arc, an area where tectonic plates are converging more rapidly than any other subduction zone in the world.

When seawater penetrates the permeable ocean crust in the vicinity of volcanoes, increased heat and pressure cause a variety of gases, metals and other materials to dissolve into the water from the surrounding rock. This process causes many metals to be concentrated by a thousand to a million times their concentration in normal seawater. When the fluid is vented into cold ocean water, some dissolved substances precipitate out of solution, forming metal deposits, "chimneys," and "black smokers." Dissolved gases may react to form other materials. At NW Rota Volcano, for example, dissolved sulfur dioxide forms sulfuric acid and elemental sulfur. At NW Eifuku Volcano, 1,600 meters below the sea surface, the 2004 Ring of Fire Expedition found buoyant droplets of liquid carbon dioxide, probably formed from degassing of a carbon-rich magma.

Hydrothermal fluids also provide an energy source for a variety of chemosynthetic microbes that in turn are the basis for unique food webs associated with hydrothermal vents. Many of these microbes have specific adaptations to extreme conditions; scientists found evidence for microbes living in hot spring fluids on NW Rota with a pH of 2.0 or less. At another extreme, cold springs on mud volcanoes on the Mariana Arc (also formed by subduction of the Pacific Plate beneath the Philippine Plate) have been found to have a pH of 12.5, and microbial populations dominated by Archaea. These microbes obtain energy from methane in the cold spring fluid, and may be key primary producers in biological communities associated with these volcanoes. Other new and unique microbes are expected to be found in association with extreme vent fluids as other sites are identified and explored along the Kermadec Arc.

In this lesson, students will investigate some of the strangest and most fascinating of these microbes: the Archaea, whose specialty is living in some of the most extreme environments on Earth.

Learning Procedure

1. To prepare for this lesson, review the introductory essays for the New Zealand American Submarine Ring of Fire 2007 Expedition at http://oceanexplorer.noaa.gov/explorations/07fire/welcome.html.

   You may also want to review background information on lipid biomarkers and Archaea at http://exobiology.arc.nasa.gov/ssx/biomarkerlab/index.html and http://www.ucmp.berkeley.edu/archaea/archaea.html.

2. Briefly review:
   (a) The concepts of plate tectonics, being sure that students understand the processes that take place at convergent and divergent boundaries, and why these boundaries are often the site of volcanic activity; and
   (b) Hydrothermal vents, cold seeps, and the Submarine Ring of Fire, emphasizing distinctions between the characteristics and origin of vented fluids. Point out that each of these habitats is associated with distinct living communities, and that they are all based on chemoautotrophic organisms that are able to thrive in conditions that would be lethal for most species and are also able to use substances in vent fluids as energy sources for the synthesis of essential compounds needed by living organisms.

3. This lesson may be undertaken as an individual student activity or by small groups of 2 - 4 students. Because the assignment requires significant student research and potentially novel concepts, the group approach provides an opportunity to distribute the work effort and for students to help each other master these concepts.

   Provide each student or student group with a copy of "Going to Extremes Worksheet" and say that their assignment is to prepare a brief report containing answers to questions on the worksheet. Encourage students to use diagrams where these would clarify their answers. You may also want to provide addresses to the resources referenced above as a starting point for student research.

4. Lead a discussion of students' answers to worksheet questions. The following points should be included:
   - Lipid biomarkers are lipid molecules that are found only in specific groups of organisms. Detection of these molecules signifies the presence of their corresponding organisms. Since lipids are major constituents of all living cells and include a wide range of biomolecules there are many potential biomarkers. Since some of these molecules can remain almost intact for billions of years, lipid biomarkers can be used to detect the presence of various groups of organisms in the fossil record.

   - Large quantities of ether-linked lipids and lesser quantities of hopanoids in extracts from crushed samples of carbonate chimneys suggest the presence of large numbers of Archaea and lesser numbers of prokaryotic organisms (bacteria).

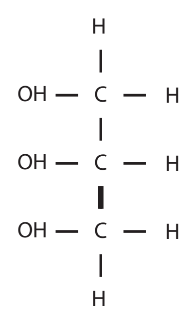
   - Archaea are microorganisms that superficially resemble bacteria, in that they are prokaryotic (they have no nucleus or internal cell membranes). But archaeal DNA is so profoundly different from other organisms that it merits classifying Archaea as an entirely separate group. Life on Earth is now classified into three "domains:" Bacteria, Eukaryota, and Archaea.

   - Archaea are often considered to be unusual because many of them are "extremophiles;" that is, they prefer environmental conditions that would be considered extreme for most organisms. These environments include Archaeans in deep-sea hydrothermal vents where temperatures are well above 100 degrees Centigrade, extremely alkaline or acid waters, extremely saline waters, and even petroleum deposits deep underground. But Archaea are not confined to "extreme" environments; they are found in many other locations, including marshes, soils, and among the plankton of the open ocean. They are also found in the digestive tracts of many animals including humans (but are not known to cause human disease).

     Archaea are also unusual in that most archaeal DNA is completely different from that of bacteria and eukaryotes. Sometimes this is referred to as "junk" DNA; but the fact is we just don't know what it does.

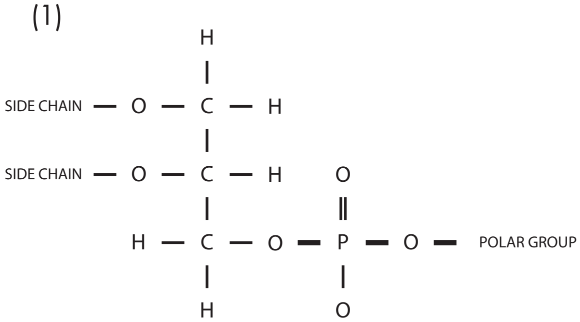
   - Key structures of archaeal cells are chemically distinct from bacteria and eukaryotes. In particular, archaeal cell membranes are distinct in four ways.

The basic "building block" for cell membranes is the phospholipid. The "backbone" of a phospholipid is a molecule of glycerol:

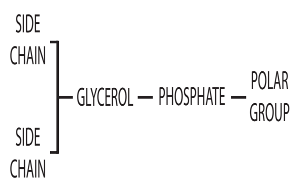


with two side chains attached at one end and a phosphate group coupled to one of various polar groups at the other end:

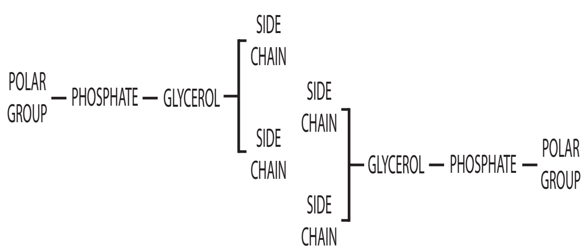
(1)



To simplify things, we can diagram this arrangement as



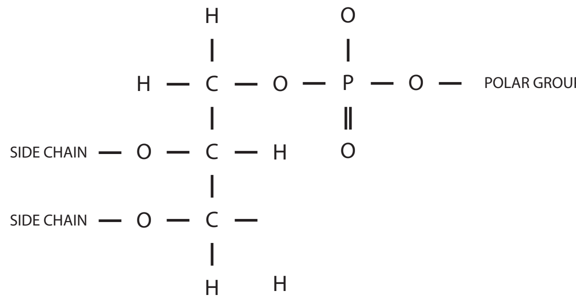
When multiple phospholipids are put together to form a cell membrane, they form a double layer with the side chains sandwiched in the middle and the glycerol and phosphate components oriented toward either side of the membrane:



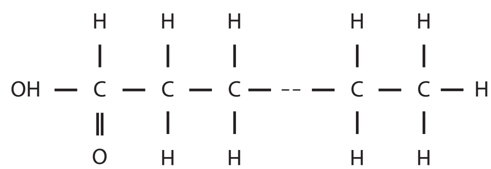
This arrangement provides a chemical barrier around the cell and helps regulate substances that move in and out of the cell's interior (note that cell membranes also contain proteins and carbohydrates; the phospholipids are just the foundation).

The **first way** that archaeal cell membranes differ from those of bacteria and eukaryotes is that the glycerol in archaeal phospholipids is a stereoisomer (mirror image) of the glycerol found in cell membranes of other organisms. So instead of the arrangement shown in diagram (1), which is typical of bacteria and eukaryotes, phospholipids of Archaea would be diagrammed as:

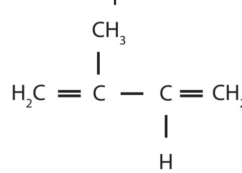
(2)



The **second way** that archaeal cell membranes are different is that the side chains in phospholipids of bacteria and eukaryotes are fatty acids, which are long unbranched chains, usually of 16 to 18 carbon atoms with a carboxyl group at one end:



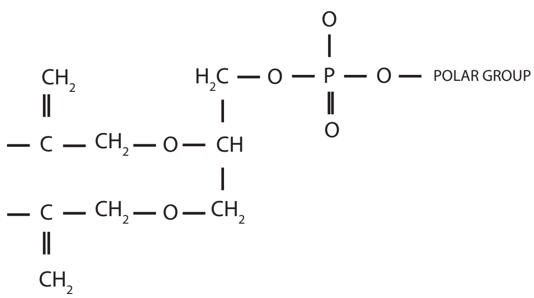
Phospholipid side chains in archaea, however, are not fatty acids, but instead are 20-carbon chains built from isoprene:



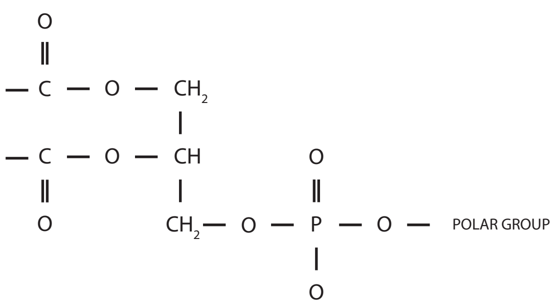
Isoprene molecules can be joined in many ways, and are used to make many synthetic products (including vitamin A, synthetic rubber, and steroid hormones) and are the most common hydrocarbon in the human body.

The branching side chains of the isoprene "building block" are the **third distinctive feature** of archaeal cell membranes. These branches give archaeal cell membranes some interesting properties, including the ability to form carbon rings within the membrane structure. These rings are believed to provide structural stability to the membranes, since such rings are more common in species that tolerate high temperatures.

The **fourth distinctive feature** of archaeal cell membranes is that the side chains are joined to the glycerol portion of the phospholipid by an ether bond:



while the fatty acid side chains in bacterial and eukaryotic phospholipids are joined with ester bonds:



This also gives the archaeal phospholipid different chemical properties than the membrane lipids of other organisms.

- Methanogens are organisms that produce methane from other chemicals.
- Methanotrophs are organisms that consume methane.
- Archaea can be methanogens as well as methanotrophs. While it is not clear that an single species of Archaea may produce methane as well as consume it, there is some evidence that this may happen. Studies at the Lost City Hydrothermal Field (see http://ocean-explorer.noaa.gov/explorations/05lostcity/welcome.html) indicate that Archaea are actively producing methane, probably from hydrogen, and possibly in association with sulfate-reducing bacteria.
- The abundance of Archaea in mud volcanoes on the Mariana Arc suggests that these organisms may be the primary chemoautotrophs in the associated biological community, and as such provide the primary source of nutrition for many other organisms present. Just how they do this, and how much methane is produced by Archaea compared to that produced by inorganic processes are two of the many questions that remain to be answered by further exploration.

The Bridge Connection

www.vims.edu/bridge/ – In the "Site Navigation" menu on the left, click "Ocean Science Topics," then "Habitats," then "Deep Sea" for links to resources about hydrothermal vents.

The "Me" Connection

Have students write a brief essay describing how Archaea might be personally important or significant.

Connections to Other Subjects

English/Language Arts, Chemistry, Earth Science

Assessment

Students reports prepared in response to worksheet questions provide opportunities for assessment.

Extensions

Have students visit http://oceanexplorer.noaa.gov/explorations/07fire/welcome.html to keep up to date with the latest New Zealand American Submarine Ring of Fire 2007 Expedition discoveries, and find out what scientists are learning about hydrothermal systems in the vicinity of Brothers Volcano.

Multimedia Learning Objects

http://www.learningdemo.com/noaa/ – Click on the links to Lessons 1, 2, 4, and 5 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Mid-Ocean Ridges, Subduction Zones, and Chemosynthesis and Hydrothermal Vent Life.

Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

Where Did They Come From? [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.WhereFrom.pdf] (10 pages; 296 k) (from the Submarine Ring of Fire 2006 Expedition)

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

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.

Hydrothermal Vent Challenge [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.VentChallenge.pdf] (9 pages; 288 k) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Chemistry of hydrothermal vents (Chemistry)

Students will be able to define hydrothermal vents and explain the overall processes that lead to their formation; explain the origin of mineral-rich fluids associated with hydrothermal vents; explain how "black smokers" and "white smokers" are formed; and hypothesize how properties of hydrothermal fluids might be used to locate undiscovered hydrothermal vents.

Roots of the Mariana Arc [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.Roots.pdf] (11 pages; 312 k) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Seismology and geological origins of the Mariana Arc (Earth Science)

Students will be able to explain the processes of plate tectonics and volcanism that resulted in the formation of the Mariana Arc and will be able to describe, compare, and contrast S waves and P waves. Students will also be able to explain how seismic data recorded at different locations can be used to determine the epicenter of an earthquake and will infer a probable explanation for the existence of ultra-low velocity zones.

Mystery of the Megaplume [http://www.oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.Megaplume.pdf] (11 pages; 324 k) (from the Submarine Ring of Fire 2006 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.

The Big Balancing Act [http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_balancing.pdf] (9 pages, 383Kb) (from the Submarine Ring of Fire 2006 Expedition)

Focus: Hydrothermal vent chemistry at subduction volcanoes (Chemistry/Earth Science)

Students will be able to define and describe hydrothermal circulation systems; explain the overall sequence of chemical reactions that occur in hydrothermal circulation systems; and compare and contrast "black smokers" and "white smokers." Given data on chemical enrichment that occurs in hydrothermal circulation systems, students will be able to make inferences about the relative significance of these systems to ocean chemical balance compared to terrestrial runoff.

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.

oceanexplorer.noaa.gov – Web site for NOAA's Ocean Exploration program

http://www.pmel.noaa.gov/vents/index.html – NOAA's hydrothermal vent Web site

http://pubs.usgs.gov/publications/text/dynamic.html#anchor19309449 – On-line version of "This Dynamic Earth," a thorough publication of the U.S. Geological Survey on plate tectonics written for a non-technical audience

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://www.pbs.org/wgbh/nova/teachers/activities/2609_abyss.html – Nova Teachers Web site, Volcanoes of the Deep Classroom Activity to research and classify symbiotic relationships between individual organisms of different species.

Mottl, M. J., S. C. Komor, P. Fryer, and C. L. Moyer. 2003. Deep-slab fluids fuel extremophilic Archaea on a Mariana forearc serpentine mud volcano: Ocean Drilling Program Leg 195. Geochemistry Geophysics Geosystems 4(11):9009

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

Committee on Reference Materials for Ocean Science, National Research Council. 2002. Chemical Reference Materials: Setting the Standards for Ocean Science.

National Science Education Standards

Content Standard A: Science as Inquiry

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

Content Standard C: Life Science

- The cell
- Interdependence of organisms
- Matter, energy, and organization in living systems

Content Standard D: Earth and Space Science

- Geochemical cycles

Content Standard E: Science and Technology

- Understandings about science and technology

Content Standard F: Science in Personal and Social Perspectives

- Natural resources
- Science and technology in local, national, and global challenges

Content Standard G: History and Nature of Science

- Nature of scientific knowledge

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.

The Earth has one big ocean with many features.

Fundamental Concept a. The ocean is the dominant physical feature on our planet Earth—covering approximately 70% of the planet's surface. There is one ocean with many ocean basins, such as the North Pacific, South Pacific, North Atlantic, South Atlantic, Indian and Arctic.

Fundamental Concept b. An ocean basin's size, shape and features (such as islands, trenches, mid-ocean ridges, rift valleys) vary due to the movement of Earth's lithospheric plates. Earth's highest peaks, deepest valleys and flattest vast plains are all 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 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

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Student Handout

Going to Extremes Worksheet

1. What are lipid biomarkers?

2. Suppose scientists found large quantities of ether-linked lipids and lesser quantities of hopanoids in extracts of crushed rock samples from a hydrothermal site. What would these observations suggest (see Table 1)?

3. What are Archaea?

4. Why are Archaea often considered to be unusual?

5. How are Archaea different from bacteria and eukaryotes?

6. What are methanogens?

7. What are methanotrophs?

8. Are Archaea methanogens or methanotrophs?

9. Mottl et al. (2003) studied mud volcanoes on the Mariana Arc, and found “a microbial community operating at pH 12.5, made up overwhelmingly of Archaea.” What is the potential significance of Archaea at this site?

Student Handout

Table 1
Examples of Microbial Biomarkers and Potential Source Organisms

(source: Committee on Reference Materials for Ocean Science, National Research Council; see "Resources")

Biomarker	Potential Source Organism(s)
Tetrapyrroles	
Divinyl chlorophylls $_a$ and $_b$	*Prochlorococcus* spp.
Monovinyl chlorophyll $_b$	Chlorophytes, prasinophytes
Chlorophylls $_{c1}$, $_{c2}$ and $_{c3}$	Chromophyte microalgae
Bacteriochlorophyll $_a$	Anoxygenic photosynthetic bacteria
Carotenoids	
Peridinin	Dinoflagellates
Fucoxanthin	Diatoms
19′-butanoyloxyfucoxanthin	Pelagophytes
19′-hexanoyloxyfucoxanthin	Haptophytes
Alloxanthin	Cryptophytes
Prasinoxanthin	Prasinophytes
Lutein	Chlorophytes
Zeaxanthin	Cyanobacteria, chlorophytes
C_{20} isoprenoids	
Phytol	Photoautotrophs
All $_{trans}$-retinal	*Proteobacteria*
Ether-linked lipids	*Archaea*
Sterols	
Dinosterol	Dinoflagellates
24-methylcholesta-5,22E-dien-3β-ol	Diatoms, Haptophytes
24-methylcholesta-5,24(28)-dien-3 β-ol	Diatoms
24-methyl cholest-5-en-3β-ol	Chlorophytes
Hopanoids	
Diploptene, hopanoic acids	Prokaryotes, including cyanobacteria
Lipopolysaccharides (LPS)	
β-hydroxy-acids	Gram-negative bacteria
Polar lipid fatty acids	
Branched-chain C_{15} and C_{17} acids	Bacteria, especially *Bacillus* spp.
Peptidoglycan	
D-amino acids	Bacteria, mainly gram-positive strains