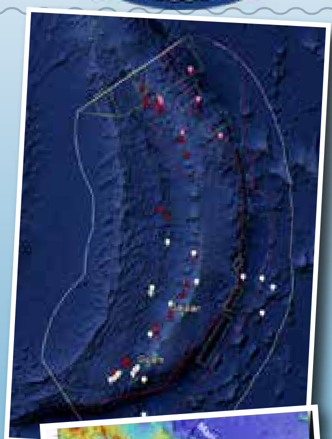
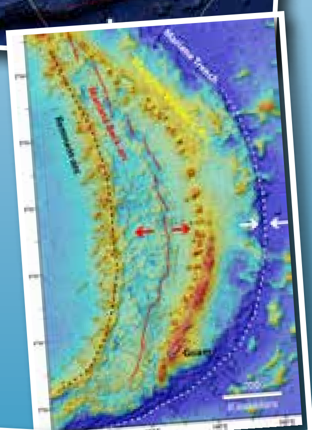
2016 Deepwater Exploration of the Marianas

Serpentine Volcanoes





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lesson plan

Focus
Serpentine mud volcanoes

Grade Level
9-12 (Earth Science)

Focus Question
What are serpentine mud volcanoes and what geological and chemical processes are involved with their formation?

Learning Objectives
- Students will describe serpentinization and explain its significance to deep-sea ecosystems.

Materials
- ❑ Copies of *Mud Volcano Inquiry Guide*, one copy for each student group

Audio-Visual Materials
- ❑ (Optional) Interactive whiteboard

Teaching Time
One or two 45-minute class periods

Seating Arrangement
Groups of two to four students

Maximum Number of Students
30

Key Words
Mariana Arc
Serpentine
Mud volcano
Mariana Trench
Serpentinization
Peridotite
Tectonic plate

Background Information

NOTE: Explanations and procedures in this lesson are written at a level appropriate to professional educators. In presenting and discussing this material with students, educators may need to adapt the language and instructional approach to styles that are best suited to specific student groups.

The Marina Trench is an oceanic trench in the western Pacific Ocean that is formed by the collision of two large pieces of the Earth's crust known as tectonic plates. These plates are portions of the Earth's outer crust (the lithosphere) about 5 km thick, as well as the upper 60 - 75 km of the underlying mantle. The plates move on a hot, flexible mantle layer called the asthenosphere, which is several hundred kilometers thick.

The Pacific Ocean Basin lies on top of the Pacific Plate. To the east, new crust is formed by magma rising from deep within the Earth. The magma erupts along boundaries between the Pacific Plate and the North American and South American Plates. The Pacific Plate slowly moves westward, away from the North American and South American Plates. Because the plates are moving apart, their junction is called a divergent plate boundary.

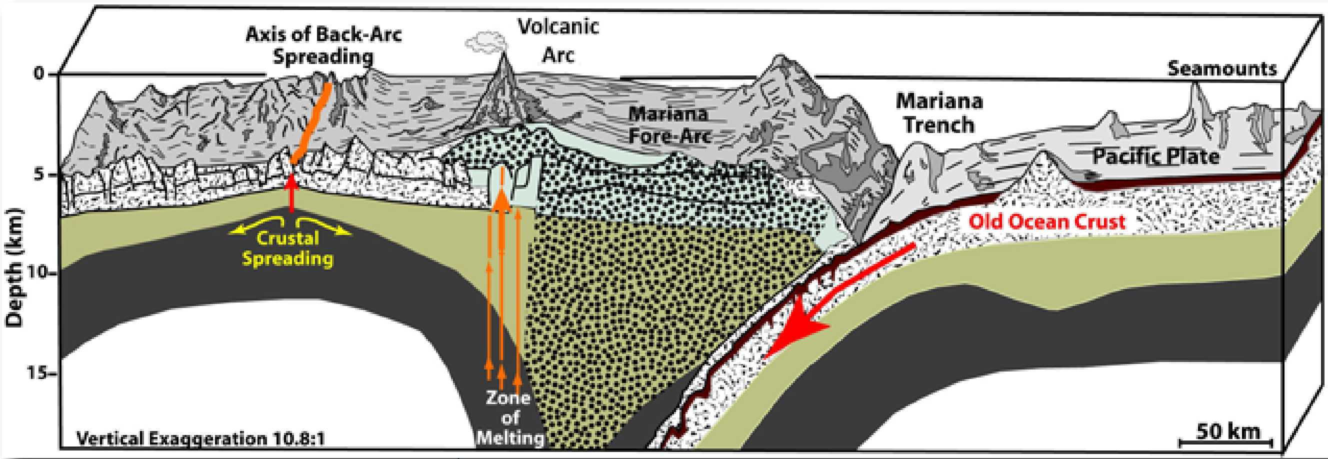
At the Mariana Trench, the west-moving Pacific Plate converges against the Phillipine Plate (this type of plate junction is called a convergent plate boundary). The Pacific Plate is forced beneath the Philippine Plate. As it descends, the edge of the Phillipine Plate becomes more dense and pulls the plate down, causing the plate's overall westward movement. As the sinking plate moves deeper into the mantle, fluids are released from the rock causing the overlying mantle to partially melt. The new magma (molten rock) rises and may erupt violently to form volcanoes, often forming arcs of islands along the convergent boundary. The Mariana Islands are the result of this volcanic activity. The subduction processes that produce volcanoes can also cause major earthquakes. 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 off the western coasts of North and South America, and older crust is recycled to the lower mantle at the convergent plate boundaries of the western Pacific. The Mariana Trench includes the Challenger Deep, the deepest known area of Earth's ocean (10,916 meters; 35,814 feet deep).

Images from Page 1 top to bottom:
This Google Earth map shows the operating area of the 2016 Deepwater Exploration of the Marianas Expedition. Image courtesy of the NOAA Office of Ocean Exploration and Research, 2016 Deepwater Exploration of the Marianas.
http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/plan/media/map.html

Map showing the locations of the Mariana Trench (white dashed line), Volcanic Arc (yellow dashed line), and back-arc spreading center (red line) and remnant arc (black dashed line). Image courtesy of Bill Chadwick.
http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/geology/media/fig2.html

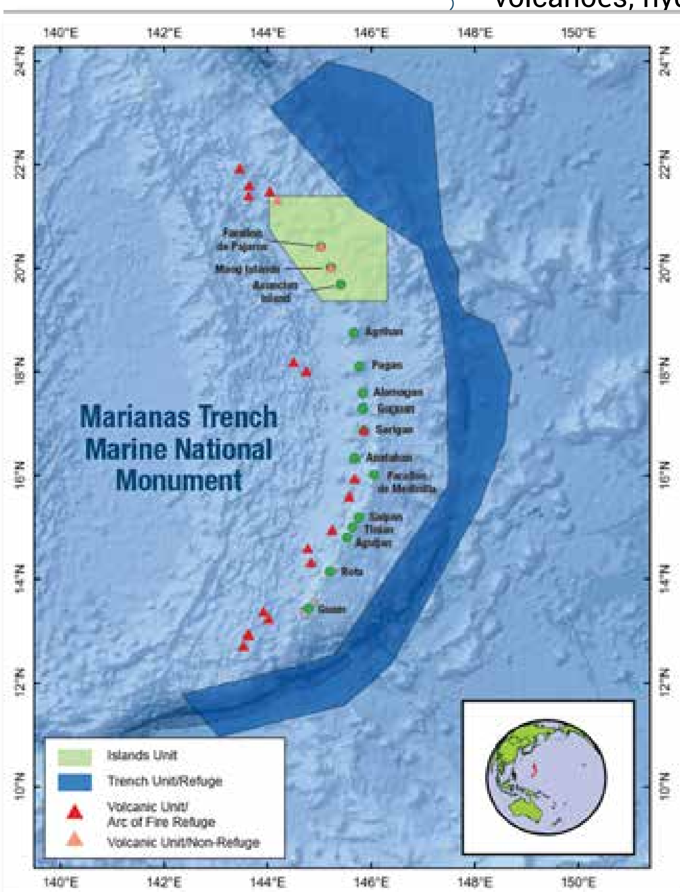
ROV *Deep Discoverer* (D2) will be used to conduct daily dives from 250 to 6,000 meters on Legs 1 and 3 of the 2016 Deep. Image courtesy of the NOAA Office of Ocean Exploration and Research.
http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/plan/media/d2.html

NOAA Ship *Okeanos Explorer* uses telepresence technology to transmit data in real time to a shore-based hub where the video is then transmitted to a number of Exploration Command Centers located around the country as well as to any Internet-enabled device. Access to the video combined with a suite of Internet-based collaboration tools allow scientists on shore to join the operation in real-time, and allows the general public to follow the expedition online. Image courtesy of the NOAA Office of Ocean Exploration and Research.
http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/plan/media/telepresence.html



Cross-section of the Mariana subduction zone, showing the relationship between the Trench, Forearc, Volcanic Arc, and Back-Arc. Image adapted from Hussong and Fryer, 1981.
http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/geology/media/fig1-hires.jpg

In 2009, the Marianas Trench Marine National Monument (MTMNM) was established to protect biological and geological resources associated with volcanoes, islands, and deepwater habitats in the vicinity of the Mariana Trench. These resources include subduction systems in the trench; submerged volcanoes; hydrothermal vents; coral reef, chemosynthetic, and hydrothermal ecosystems; and deep-sea coral and sponge communities.

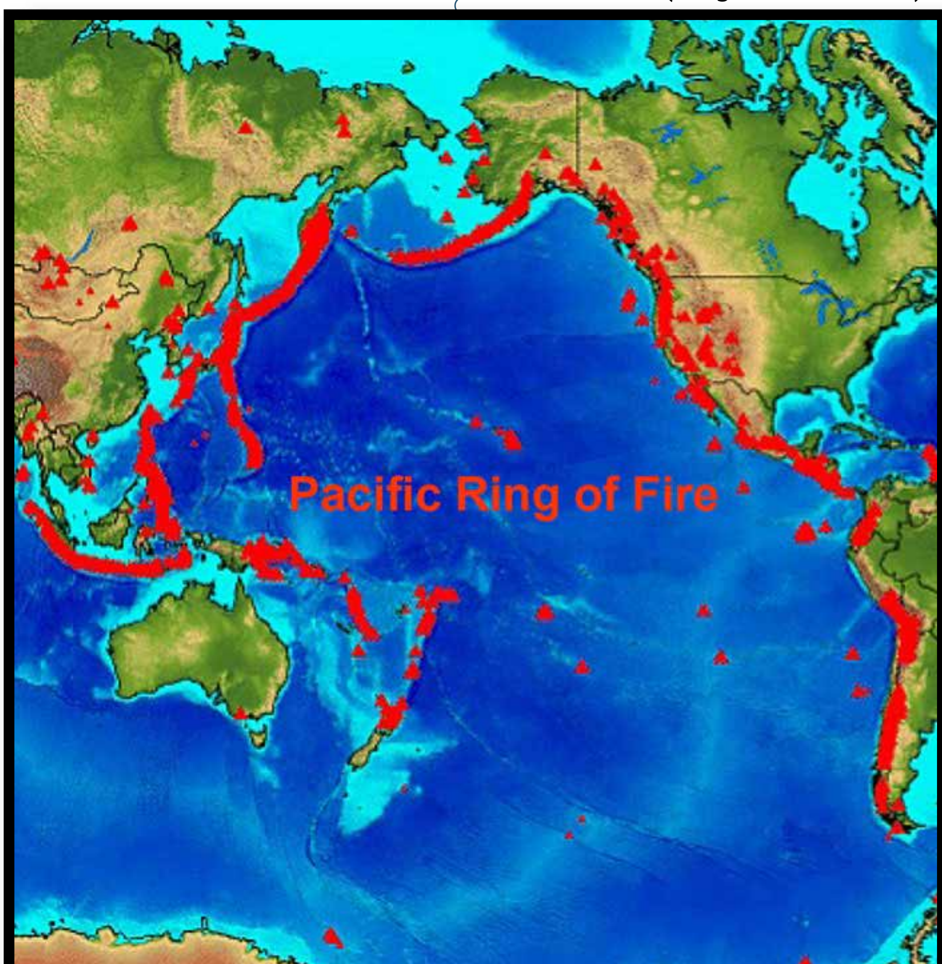


Management designations within the Marianas Trench Marine National Monument. The green points denote islands. Image courtesy of the Marianas Trench Marine National Monument.
http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/mtmnm/media/map.html

NOAA's Ocean Explorer program has a long history of explorations in the vicinity of the Mariana Trench. In 2003, the Ocean Exploration Ring of Fire Expedition surveyed more than 50 volcanoes along the Mariana Arc, and discovered that ten of these had active hydrothermal systems (visit *http://oceanexplorer.noaa.gov/explorations/03fire/welcome.html* for more information on these discoveries). The 2004 Submarine Ring of Fire Expedition focused specifically on hydrothermal systems of the Mariana Arc volcanoes, and found that these systems are very different from those found along mid-ocean ridges (visit *http://oceanexplorer.noaa.gov/explorations/04fire/welcome.html* for more information). The 2006 Submarine Ring of Fire Expedition is focused on interdisciplinary investigations of the hydrothermal and volcanic processes on the submarine volcanoes of the Mariana Arc. In 2007, 2012, and 2014, Ocean Explorer expeditions visited other areas on the Submarine Ring of Fire. In 2015, NOAA and other partners began a multi-year science effort named CAPSTONE (Campaign to Address Pacific monument Science, Technology, and Ocean Needs) focused on deepwater areas of U.S. marine protected areas in the central and western Pacific.

The 2016 Deepwater Exploration of the Marianas Expedition continues the CAPSTONE program, focusing specifically on deepwater habitats in and around the Marianas Trench Marine National Monument (MTMNM) and the Commonwealth of the Northern Mariana Islands (CNMI). The purpose of the expedition is to provide information about these unexplored and poorly known habitats. This information is essential to understanding and managing deepwater resources associated with Earth's deepest oceanic trench.

The MTMNM is part of a larger region known as the Submarine Ring of Fire, named for the numerous volcanoes that result from the movements of tectonic plates in the region. While the best-known volcanoes are those that involve eruptions of molten rock (magma volcanoes), the MTMNM also includes mud volcanoes. Mud volcanoes are found around the world, and are commonly produced when a viscous mixture of water and sediment (that we commonly call "mud") beneath the land or seafloor surface becomes pressurized and erupts to the surface to form a pool that often is surrounded by a cone similar to the cone we associate with magma volcanoes.



Map of the all the volcanoes around the Pacific (red triangles) making up the Ring of Fire. Image courtesy of Submarine Ring of Fire 2014 - Ironman, NOAA/PMEL, NSF. http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/history/media/fig1.html

A different process, however, forms mud volcanoes in the Mariana region. The mud volcanoes here form only in the zone between the trench and the active volcanic arc. This area is called the "forearc" region. Here, movement of tectonic plates brings mantle rocks into contact with seawater. When this happens, numerous chemical reactions occur between fluids driven off of the subducting Pacific Ocean plate and minerals in the mantle rock (a process called serpentinization, producing a new type of rock called serpentinite). Serpentine is less dense than the surrounding mantle rock, and it is very soft so is easily crushed. There are many faults in the forearc area and fluids from the subducting plate tend to find their way to sea floor springs along the fault planes. When earthquakes occur, the rocks on either side of a moving fault plane grind up the soft serpentinized rock, thus rising fluids mix with the ground-up rock to form serpentinite mud. When the serpentinite muds ooze out of the fault up to the seafloor they can build large mounds that may be up to 50 km in diameter and 2.6 km high. These serpentinite mud volcanoes produce new habitats for living organisms, but have not been well-explored, so we know very little about mud volcano ecosystems.

In this lesson, students will investigate mud volcanoes and their relationship to the motion of tectonic plates.

Learning Procedure

1. To prepare for this lesson:
   a. Review background information about the 2016 Deepwater Exploration of the Marianas Expedition. [*http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/welcome.html*]

   b. Review "The Geology of the Mariana Convergent Plate Region" by Bill Chadwick and Patty Fryer [*http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/background/geology/welcome.html*].

   c. Review the Multimedia Discovery Mission, Plate Tectonics (Lesson 1) [*http://oceanexplorer.noaa.gov/edu/learning/welcome.html#lesson1*]. Decide whether your students will be able to understand this presentation on their own, or whether you want to use the slides with your own narration and explanations.

   d. You may also want to review "Mud Volcanoes of the Marianas" (see Resources section on Page 8).

2. Briefly introduce:
   - The NOAA Ship *Okeanos Explorer*, which is the only U.S. ship whose sole assignment is to systematically explore Earth's largely unknown ocean for the purposes of discovery and the advancement of knowledge;
   - The Mariana Trench region and the Submarine Ring of Fire;
   - Marine national monuments, and the variety of biological, geological, and cultural resources found in the MTMNM;

and

• The 2016 Deepwater Exploration of the Marianas Expedition.

3. If necessary, review the concept of tectonic plate movements. You may want to show video from the Multimedia Discovery Mission about Plate Tectonics (Lesson 1), or your own presentation about this topic. Make sure students understand the distinction between convergent and divergent plate junctions, and why there are so many active volcanoes along the Submarine Ring of Fire.

4. Provide each student group with a copy of *Mud Volcano Inquiry Guide*, and the URL for "The Geology of the Mariana Convergent Plate Region" by Bill Chadwick and Patty Fryer (or a copy of the latter if internet resources are not available). Students will also need Internet or library resources to answer the last two questions on the *Inquiry Guide*. Briefly discuss the types of models that can be used for Step 6. These may include physical replicas, diagrams, drawings, dramatizations, or other student-generated ideas for representations that you approve.

5. Lead a discussion of students' answers to questions on the *Inquiry Guide*. The following points should be included:

• Peridotites are the most common type of rock in Earth's upper mantle, and are composed primarily of olivine and pyroxene. The introduction of fluids from the subducting plate into fault zones in the forearc region converts portions of the forearc mantle to serpentine. These changes cause the peridotite rock to become serpentinite rock. The overall process is known as serpentinization.

• The subduction of the Pacific Plate beneath the Phillipine Plate on the Mariana forearc produces conditions that allow serpentinite to form as described above. Serpentinite is less dense than peridotite, and tends to rise along fault lines. The subduction also produces fluids from "distillation" as the descending rocks are subjected to increasing pressure. When fluids rise along the fault planes, they can carry ground up serpentinite to the seafloor surface, and produce the huge serpentinite mud volcanoes found along the Mariana forearc.

- Fluid seeps at the Mariana serpentinite mud volcanoes contain high concentrations of hydrogen and methane if carbon is present in the fluid. The Mariana serpentinite mud volcanoes have the highest pH (12.5) measured in the world's ocean.

- According to Ohara *et al.* (2011), serpentinization of peridotite produces hydrogen-rich fluids that can react with dissolved carbon dioxide to form methane which provides a source of energy for some chemoautotrophic organisms. Anaerobic oxidation of methane generates hydrogen sulfide, which is the food source for sulfide-oxidizing bacteria that are symbiotic with chemosynthetic organisms.

- Student models to illustrate how tectonic processes form mud volcanoes and magma volcanoes should include:
  - the convergent plate junction formed by the Pacific Plate and Mariana Plate;
  - subduction of the Pacific Plate beneath the Mariana Plate;
  - faulting associated with plate movements bringing mantle rock (peridotite) into contact with fluids derived from the subducted plate;
  - metamorphism of peridotite to form serpentinite;
  - release of fluids from the descending plate as it is subducted, which rise along fault planes and carry ground up serpentinite to the seafloor surface to form mud volcanoes;
  - partial melting of mantle rock overlying the descending plate to form magma, which rises and erupts to form magma volcanoes

  Discuss how these processes that form mud volcanoes involve both constructive forces as well as destructive mechanisms. 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 off the western coasts of North and South America, and older crust is recycled to the lower mantle at the convergent plate boundaries of the western Pacific.

The BRIDGE Connection

www.vims.edu/bridge/ – Enter "Mariana" in the search bar to access resources about the Mariana Arc and other volcanic regions.

The "Me" Connection

Have students write a brief essay speculating on how knowledge of mud volcanoes could be of personal importance.

Connections to Other Subjects

English/Language Arts, Social Studies

Assessment

Participation in class discussions provides opportunities for assessment.

Extensions

Visit *http://oceanexplorer.noaa.gov/okeanos/explorations/explorations.html* for links to individual voyages of discovery by NOAA Ship *Okeanos Explorer*.

Other Relevant Lessons from NOAA's Ocean Exploration Program

Please note that while serpentinization is a key geologic process at both the Lost City and Mariana mud volcano sites, there are important differences that make direct comparison of these sites inappropriate. In particular, (a) the Mariana mud volcano processes involve fluids from the subducting plate (which are NOT seawater); (b) Lost City serpentinization is happening on the seafloor, not in the underlying mantle as is the situation at the Mariana mud volcanoes; and (c) while both sites have chemoautotrophic communities, the organisms are different between these sites.

Lost City Chemistry Detectives (Grades 9-12))
from the Lost City 2005 Expedition
[*http://oceanexplorer.noaa.gov/explorations/05lostcity/background/edu/media/lostcity05_chemdetect.pdf*]

Focus: Chemistry of the Lost City Hydrothermal Field (Chemistry/Earth Science)

Students compare and contrast the formation processes that produce black smokers and the Lost City hydrothermal field, describe the process of serpentinization and how this process contributes to formation of chimneys at the Lost City hydrothermal field, and describe and explain the chemical reactions that produce hydrogen and methane in Lost City hydrothermal vent fluids.

Where's Dinner? (Grades 9-12)
from the Lost City 2005 Expedition
[*http://oceanexplorer.noaa.gov/explorations/05lostcity/background/edu/media/lostcity05_dinner.pdf*]

Focus: Trophic relationships in biological communities of the Lost City Hydrothermal Field (Life Science)

Students compare and contrast primary production in biological communities and cold seeps and hydrothermal vents, describe and discuss probable primary production processes in biological communities of the Lost City Hydrothermal Field, and infer probable trophic relationships among macrofauna of the Lost City Hydrothermal Field.

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/okeanos/edu/welcome.html – Web page for the NOAA Ship *Okeanos Explorer* Education Materials Collection

http://oceanexplorer.noaa.gov/edu/learning/welcome.html – Multimedia Discovery Missions, a series of 14 interactive multimedia presentations and learning activities that address topics ranging from Chemosynthesis and Hydrothermal Vent Life and Deep-sea Benthos to Food, Water and Medicine from the Sea

Fryer, P. 1992. Mud Volcanoes of the Marianas. *Scientific American* 266(2):46-52

Ohara Y, Reagan MK, Fujikura K, Watanabe H, Michibayashi K, Ishii T, Stern RJ, Pujana I, Martinez F, Girard G, Ribeiro J, Brounce M, Komori N, Kino M (2011) A serpentinite-hosted ecosystem in the Southern Mariana Forearc. Proc Natl Acad Sci USA 109(8):2831-2835.

Next Generation Science Standards

The primary purpose of this lesson is to assist educators with incorporating information about the Deepwater Exploration of the Marianas Expedition into their instructional program. While they are not intended to target specific Next Generation Science Standards, activities in this lesson may be used to address specific NGSS elements as described below.

HS-ESS2 Earth's Systems

Performance Expectation

HS-ESS2-1. Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.

[Clarification Statement: Emphasis is on how the appearance of land features (such as mountains, valleys, and plateaus) and sea-floor features (such as trenches, ridges, and seamounts) are a result of both constructive forces (such as volcanism, tectonic uplift, and orogeny) and destructive mechanisms (such as weathering, mass wasting, and coastal erosion).]

[Assessment Boundary: Assessment does not include memorization of the details of the formation of specific geographic features of Earth's surface.]

Science and Engineering Practices

Developing and Using Models

- Develop a model based on evidence to illustrate the relationships between systems or between components of a system.

Disciplinary Core Ideas

ESS2.A: Earth Materials and Systems

- Earth's systems, being dynamic and interacting, cause feedback effects that can increase or decrease the original changes.

Crosscutting Concepts

Stability and Change

- Change and rates of change can be quantified and modeled over very short or very long periods of time. Some system changes are irreversible.

Common Core State Standards Connections:

ELA/Literacy –

SL.11-12.5 Make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in presentations to enhance understanding of findings, reasoning, and evidence and to add interest.

Mathematics –

MP.2 Reason abstractly and quantitatively.
MP.4 Model with mathematics.

HSN-Q.A.1 Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.

HSN-Q.A.2 Define appropriate quantities for the purpose of descriptive modeling.

HSN-Q.A.3 Choose a level of accuracy appropriate to limitations on measurement when reporting quantities.

Ocean Literacy Essential Principles and Fundamental Concepts

Essential Principle 1.
Earth has one big ocean with many features.

Fundamental Concept h. Although the ocean is large, it is finite, and resources are limited.

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

Fundamental Concept e. Tectonic activity, sea level changes, and the force of waves influence the physical structure and landforms of the coast.

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

Fundamental Concept b. The ocean provides food, medicines, and mineral and energy resources. It supports jobs and national economies, serves as a highway for transportation of goods and people, and plays a role in national security.

Fundamental Concept d. 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 (point source, nonpoint source, and noise pollution), changes to ocean chemistry (ocean acidification), and physical modifications (changes to beaches, shores, and rivers). In addition, humans have removed most of the large vertebrates from the ocean.

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

Essential Principle 7.
The ocean is largely unexplored.

Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, experimentation, and discovery are required to better understand ocean systems and processes. Our very survival hinges upon it.

Fundamental Concept c. Over the last 50 years, use of ocean resources has increased significantly; the future sustainability of ocean resources depends on our understanding of those resources and their potential.

Fundamental Concept f. Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, physicists, animators, and illustrators. And these interactions foster new ideas and new perspectives for inquiries.

Send Us Your Feedback

In addition to consultation with expedition scientists, the development of lesson plans and other education products is guided by comments and suggestions from educators and others who use these materials. Please send questions and comments about these materials to: *oceanexeducation@noaa.gov*.

For More Information

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Credit

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Mud Volcano Inquiry Guide

1. What are:
   Peridotite ______
   Olivine ______
   Pyroxene ______
   Serpentinite ______

2. What is the relationship between these substances, and movements of tectonic plates?

3. What is the relationship between these substances and serpentinite mud volcanoes found on the Mariana forearc?

4. Patty Fryer states that fluid seeps at mud volcanoes have extreme chemical compositions. In what way are the chemical compositions of these seeps extreme?

5. Ohara *et al.* (2011) report the discovery of a serpentinite-hosted ecosystem in the Southern Mariana forearc. How does serpentinite, a mineral, "host" an ecosystem?

6. The Mariana forearc is part of the "Submarine Ring of Fire," so-named because of the large number of magma volcanoes associated with convergent plate junctions around the Pacific Plate. These volcanoes are distinctly different from mud volcanoes, yet both are associated with tectonic plate movements. Develop a model that illustrates how tectonic processes form these volcanic features, and how both constructive and destructive forces are involved. This model may be a physical replica, diagram, drawing, dramatization, or other form approved by your teacher.