



## 2006 Submarine Ring of Fire

# Roots of the Mariana Arc

*(adapted from the 2002 Northwestern Hawaiian Islands Expedition)*

### Focus

Seismology

### Grade Level

9-12 (Earth Science)

### Focus Question

How can scientists obtain information on geological processes deep within the Earth?

### Learning Objectives

Students will be able to explain the processes of plate tectonics and volcanism that resulted in the formation of the Mariana Arc Islands.

Students will be able to describe, compare, and contrast S waves and P waves.

Students will be able to explain how seismic data recorded at different locations can be used to determine the epicenter of an earthquake.

Students will be able to infer a probable explanation for the existence of ultra-low velocity zones

### Materials

- Meter stick
- Stopwatches (3)
- Masking tape
- Drawing compasses
- Ruler
- Graph paper
- Colored pencils
- Copies of "Time-Distance Data Sheet" and "6m x 6m Grid," one for each student group

### Audio/Visual Materials

- Marker board or overhead transparency projector

### Teaching Time

Two 45-minute class periods

### Seating Arrangement

Groups of 4-5 students

### Maximum Number of Students

32

### Key Words

Tectonic plate  
Mantle  
Asthenosphere  
Lithosphere  
Magma  
Rift  
Subduction  
Hotspots  
P wave  
S wave  
Ultra-low velocity zone  
Ring of Fire  
Mariana Arc

### Background Information

The Submarine Ring of Fire is an arc of active volcanoes that partially encircles the Pacific Ocean Basin and results from the motion of 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 flowing mantle layer called the asthenosphere, which is several hundred kilometers thick. Heat within the asthenosphere creates convection currents (similar to the currents that can be seen if food coloring is added to a heated container of water) that cause the tectonic plates to move several centimeters per year relative to each other.

If tectonic plates are moving apart their junction is called a divergent plate boundary; if they slide horizontally past each other they form a transform plate boundary; and if they collide more or less head-on they form a convergent plate boundary. 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 and erupting at divergent plate boundaries between the Pacific Plate and the North American and South American Plates. These eruptions form submarine mountain ranges called oceanic spreading ridges. While the process is volcanic, volcanoes and earthquakes along oceanic spreading ridges are not as violent as they are at convergent plate boundaries.

To the west, the Pacific Plate converges against the Philippine Plate. The Pacific Plate is forced beneath the Philippine Plate, creating the Marianas Trench (which includes the Challenger Deep, the deepest known area of the Earth's ocean). 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, 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 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.

Volcanic activity is often associated with "hydrothermal systems" or seafloor hot springs, where heat and chemicals from the interior of volcanoes are vented into the ocean. This process supports unique biological communities. 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 focussed specifically on hydrothermal systems of the Mariana Arc volcanoes, and found that these systems are very different from those found along mid-ocean ridges. On April 1, 2004, scientists exploring the NW Rota #1 volcano reported the first-ever direct observations of a submarine volcanic eruption (visit <http://oceanexplorer.noaa.gov/explorations/04fire/welcome.html> for more information). The 2006 Submarine Ring of Fire Expedition is focussed on interdisciplinary investigations of the hydrothermal and volcanic processes on the submarine volcanoes of the Mariana Arc.

Most people are at least vaguely familiar with seismometers that can record earthquakes (and other vibrations in the solid parts of the Earth). This activity focuses on how these instruments can also provide information about the deep structure of the Earth.

### Learning Procedure

1. To prepare for this lesson:
  - Read the introductory essays for the 2006 Submarine Ring of Fire Expedition at <http://oceanexplorer.noaa.gov/explorations/06fire/background/edu/edu.html>;
  - Review the NOAA Learning Object on Plate Tectonics at <http://www.learningdemo.com/noaa/>;
  - Review procedures in Steps 3 and 4, below.
2. Introduce (or review) the concept of plate tectonics and the processes that result in volcanic activity. Introduce the Submarine Ring of Fire,

and point out that this is a volcanically active region. Tell students that the focus of the 2006 Submarine Ring of Fire Expedition is to learn more about hydrothermal and volcanic systems on the submarine volcanoes of the Mariana Arc.

3. Introduce the overall concept of seismology. Tell the students that most earthquakes occur because of movements of the Earth's tectonic plates. Point out that an earthquake produces vibrations that travel away from the source in all directions. Vibrations that travel on the Earth's surface are Rayleigh waves or Love waves (named after the scientists who first described them).

This activity is concerned with vibrations that pass through the Earth's interior. These vibrations are called body waves, and are grouped into two categories:

Compressional waves (also called P waves), in which the vibration is parallel to the direction in which the wave is travelling. Imagine a long spring (like a spring used to close a screen door) stretched between two people. If one person pushes one end of the spring in the direction of the other person, a compression wave moves along the spring. This is analogous to a P wave.

Shear waves (also called S waves), in which the vibration is parallel to the direction in which the wave is travelling. Imagine a length of rope stretched between two people. If one person lifts and lowers one end of the rope, a "ripple" wave is generated that travels toward the other end of the rope. This is analogous to an S wave.

P waves and S waves can travel along many different paths within the Earth, and may be reflected one or more times from the Earth's surface or core. These waves are divided into additional categories depending upon the path that they travel. If you have a device that can

detect these vibrations located somewhere on the Earth's surface, each path will be associated with a characteristic travel-time; the time required for the vibration to travel from the source (an earthquake), along its specific path, to the detecting device (such as a seismograph). This means that a recording of the vibrations will show a series of waves: those with the shortest travel-times will arrive at the seismograph first, followed by waves with progressively longer travel-times.

Tell students that they will do two activities that demonstrate how specific types of information can be obtained from seismic waves. The first activity illustrates how the source of an earthquake can be determined. The second activity illustrates how seismic waves can give clues about the type of material present in the deep interior of the Earth. These activities are based on activities developed by L. W. Braile and S. J. Braile (<http://www.ics.purdue.edu/~braile/edumod/walk-run/walkrun.htm>).

4. In the first activity, students will simulate the motion of two seismic waves travelling through the Earth at different speeds, construct a travel-time/distance graph for these waves, and use this graph to locate the source of a simulated earthquake.
  - a. Clear a space about 8m x 8m in the room where students will do the activity, and mark off a 6m line on the floor with masking tape. Place marks at 2m and 4m along the line. Assign three students as timekeepers, three students to simulate S waves and three other students to simulate P waves. Assign one student as data recorder.
  - b. Station students with stopwatches at 2m, 4m and 6m along the line.
  - c. Tell students who will simulate S and P waves that they each will walk the 6m line at an

assigned pace, and time keepers will record the times at which the students pass the 2m, 4m, and 6m marks. Students simulating S waves will walk heel-to-toe, while students simulating P waves will walk with a normal stride. Have the first student stand at the beginning of the 6m line, and say "Go" when you are ready to begin. You should establish a cadence by counting "one banana, two banana, three banana..." Each time you say "banana" the student should take one step; either a heel-to-toe step or a normal stride, depending upon which type of wave the walker is simulating. After a student has walked the entire 6m line, the data recorder should record the times in the appropriate spaces on the "Time-Distance Data Sheet." Repeat this procedure until all six students have walked the 6m line.

- d. Have data recorder average the travel-times to 2m, 4m, and 6m and record the averages on the "Time-Distance Data Sheet." List these averages on a marker board or overhead transparency.
- e. Have each student group construct a graph with distance in meters on the x-axis and time in seconds on the y-axis. Each group should plot points corresponding to 2m, 4m, and 6m for average S wave time, average P wave time, and for (average S wave time) - (average P wave time). Draw a straight line that best fits each set of data points. Use different colors or symbols for S wave times, P wave times, and (S wave time) - (P wave time).
- f. Ask students to calculate the speed of the simulated S and P waves (simulated S wave speed should be approximately 0.3 m/sec and simulated P wave speed should be approximately 1.0 m/sec). Compare these speeds to the speed of actual S and P waves (3,500 - 4,500 m/sec and 6,000 - 8,000 m/sec respectively).

- g. Mark the corners of a 6m x 6m square. Have students who will represent S and P waves (three students for each wave type) agree on a location within the square that will be the epicenter of a simulated earthquake. Station three timekeepers at different locations on the perimeter of the square, and mark these positions with masking tape. Tell students that these timekeepers represent seismograph stations.
- h. Have the six students who are simulating S and P waves stand on the selected epicenter. Assign one P wave simulator and one S wave simulator to each of the three timekeepers. When you say "Go," all six wave simulators should begin walking toward their assigned timekeeper. P wave simulators should walk with a normal stride, S wave simulators should walk heel-to-toe. Establish a cadence by saying "One banana, two banana . . ." as before. This represents the propagation of S and P waves from the site of an earthquake to various sensing stations around the world. Be sure students realize that these waves are actually propagated in all directions, but we are simplifying the simulation by using only enough wave simulators to reach the three sensing stations (timekeepers). Have timekeepers start their stopwatches when the P wave arrives and stop their stopwatches when the S wave arrives to measure the length of time between the arrival of the P wave and the arrival of the S wave.
- i. Record the (S wave time) - (P wave time) measured by each of the three sensing stations on a marker board or overhead transparency.
- j. Have each student group determine the distance from the sensing station to the epicenter using the graph they constructed in step #3e by:

- (1) locating the (S wave time) - (P wave time) on the y-axis;
  - (2) drawing a horizontal line to the point of intersection with the graphed line representing (average S wave time) - (average P wave time); and
  - (3) drawing a vertical line from the intersection point to the x-axis, and reading the distance on the x-axis scale.
- k. Have each student group construct a map of the 6m x 6m area on the "6m x 6m Grid." Students should mark the positions of the sensing stations on the perimeter, and use a compass to draw a circle around each sensing station location. The center of the circle should be the sensing station location, and the radius should be the distance from the sensing station to the epicenter inferred in step #3i. The point at which the three circles intersect is the inferred epicenter location (all three circles may not intersect precisely because of plotting errors). Measure the actual distances on the 6m x 6m area laid out in Step 3g, and compare these distances to those calculated by Step 3i.
5. The second activity illustrates how seismic waves can give clues about the type of material present in the deep interior of the Earth.
- a. Select 12 students, and have them stand side-by-side in two groups of six. Have one group stand with their shoulders and upper arms touching. Have the other group link their arms at the elbow. Say that the students with linked arms represent solid rock, and the students whose arms are just touching represent liquid which could be water or liquid rock (magma).
  - b. Say that P waves are compression waves whose vibration moves in the direction in which the wave travels. Demonstrate this by gently pushing the end person in the linked-arm line toward the next person in line. The disturbance (vibration) will eventually travel the entire length of the line. Repeat this process for the line of students whose arms are just touching. Again, the disturbance will eventually travel the entire length of the line. Students should infer that P waves will move through liquid as well as solid rock.
  - c. Say that S waves are shear waves whose vibration moves in a direction that is perpendicular to the direction in which the wave travels. Demonstrate this on the linked-arm line by gently pushing the shoulders of the end person forwards and backwards. Eventually the disturbance will travel the entire length of the line. Next, repeat this process for the line of students whose arms are just touching. This time, the disturbance does not travel the entire length of the line because the liquid particles slip past each other. Students should infer that S waves will move through solids, but not through liquids.
6. Tell students that seismologists can identify S waves that are reflected from the region in the Earth where the mantle meets the Earth's core. Recently, scientists have discovered that parts of this region cause dramatic reductions in the velocity of S waves; these areas are called "ultra-low velocity zones." Ultra-low velocity zones have recently been discovered beneath Hawaii and Iceland. Ask students to infer an explanation for why the velocity of S waves might be reduced using their knowledge of S wave propagation in different media. Students should suggest that the mantle or core might be partially liquid in the ultra-low velocity zones, which would be expected to reduce the propagation of S waves. Actual observations show that the velocity of P waves is reduced as well, though not nearly as much as is the case for S waves.

## The Bridge Connection

[www.vims.edu/bridge/pacific.html](http://www.vims.edu/bridge/pacific.html)

## The “Me” Connection

Have students write a short essay about their personal exposure to natural hazards, and whether their potential exposure to such hazards would affect their choices of places to live.

## Connections to Other Subjects

English/Language Arts, Geography, Biology, Physics

## Assessment

Develop a grading rubric that includes the graphs constructed in Step 3g and the map constructed in Step 3k. You may also choose to have students prepare individual written responses to questions posed in Steps 5 and 6 prior to discussion of these questions by the entire class.

## Extensions

1. Visit <http://oceanexplorer.noaa.gov/explorations/06fire/welcome.html> for daily logs and updates about discoveries being made by the 2006 Submarine Ring of Fire Expedition.
2. Visit these sites for many more activities and links related to plate tectonics, earthquakes and seismology:  
<http://www.ldeo.columbia.edu/~mwest/WS4instructors/primer.html>  
<http://facstaff.gpc.edu/~pgore/seismic2.htm>  
[http://mae.cee.uiuc.edu/K-12/teacher\\_resources.html](http://mae.cee.uiuc.edu/K-12/teacher_resources.html)

## Resources

### 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 the Ocean Exploration Program

**The Big Balancing Act** [http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05\\_balancing.pdf](http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_balancing.pdf) (9 pages, 1.3Mb) (from the New Zealand American Submarine Ring of Fire 2005 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; compare and contrast “black smokers” and “white smokers;” and make inferences about the relative significance of hydrothermal circulation systems to ocean chemical balance from data on chemical enrichment that occurs in these systems.

**What’s the Difference?** [http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05\\_difference.pdf](http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_difference.pdf) (7 pages, 720k) (from the New Zealand American Submarine Ring of Fire 2005 Expedition)

Focus: Volcanic processes at convergent and divergent tectonic plate boundaries (Earth Science)

Students will be able to compare and contrast volcanoes at convergent and divergent plate boundaries; identify three geologic features that are associated with most volcanoes on Earth; and explain why some volcanoes erupt explosively while others do not.

**Where There’s Smoke, There’s . . .** [http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05\\_smoke.pdf](http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_smoke.pdf) (6 pages, 680k) (from the New Zealand American Submarine Ring of Fire 2005 Expedition)

Focus: Hydrothermal vent chemistry at subduction volcanoes (Chemistry)

Students will be able to use fundamental relationships between melting points, boiling points, solubility, temperature, and pressure to develop plausible explanations for observed chemical phenomena in the vicinity of subduction volcanoes.

**It Looks Like Champagne** [http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05\\_champagne.pdf](http://www.oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_champagne.pdf) (7 pages, 736k) (from the New Zealand American Submarine Ring of Fire 2005 Expedition)

Focus: Deep ocean carbon dioxide and global climate change (Chemistry/Earth Science)

Students will be able to interpret phase diagrams, and explain the meaning of “critical point” and “triple point;” define “supercritical fluid;” and will be able to describe two practical uses of supercritical carbon dioxide; and discuss the concept of carbon dioxide sequestration.

**The Galapagos Spreading Center** [http://www.oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal\\_gr9\\_12\\_12.pdf](http://www.oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_12.pdf) (8 pages, 480k) (from the 2002 Galapagos Rift Expedition)

Focus: Mid-Ocean Ridges (Earth Science)

Students will be able to describe the processes involved in creating new seafloor at a mid-ocean ridge; will investigate the Galapagos Spreading Center system; and will understand the different types of plate motion associated with ridge segments and transform faults.

**Thar She Blows!** [http://www.oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal\\_gr9\\_12\\_13.pdf](http://www.oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_13.pdf) (5 pages, 456k) (from the 2002 Galapagos Rift Expedition)

Focus: Hydrothermal vents

Students will demonstrate an understanding of how the processes that result in the formation of hydrothermal vents create new ocean floor; students will demonstrate an understanding of how the transfer of energy effects solids and liquids.

**Chemosynthesis for the Classroom** [http://www.oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom\\_chemo\\_gr912.pdf](http://www.oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_chemo_gr912.pdf) (6 pages, 464k) (from the 2002 Gulf of Mexico Expedition)

Focus: Chemosynthetic bacteria and succession in chemosynthetic communities (Chemistry/Biology)

Students will observe the development of chemosynthetic bacterial communities and will recognize that organisms modify their environment in ways that create opportunities for other organisms to thrive. Students will also be able to explain the process of chemosynthesis and the relevance of chemosynthesis to biological communities in the vicinity of cold seeps.

#### Other Links and Resources

<http://www.oceanexplorer.noaa.gov/explorations/04fire/background/marianaarc/marianaarc.html> – Virtual fly-throughs and panoramas of eight sites in the Mariana Arc

<http://www.oceanexplorer.noaa.gov/explorations/02fire/logs/magic-mountain/welcome.html> – Magic Mountain Virtual Web site, featuring animations and videos of the Magic Mountain hydrothermal field

<http://oceanexplorer.noaa.gov/explorations/03fire/logs/subduction.html> and <http://oceanexplorer.noaa.gov/explorations/03fire/logs/ridge.html> – Animations of the 3-dimensional structure of a mid-ocean ridge and subduction zone

<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.pmel.noaa.gov/vents/nemo/education.html> – Web site for the New Millennium Observatory Project, a long-term study of the interactions between geology, chemistry, and biology on Axial Seamount, an active volcano on the Juan de Fuca Ridge that is part of the mid-ocean ridge system

<http://vulcan.wr.usgs.gov/> – USGS Cascades Volcano Observatory, with extensive educational and technical resources

<http://volcano.oregonstate.edu/> - Volcano World magazine Web site

<http://nationalzoo.si.edu/publications/zoogoer/1996/3/lifewithout-light.cfm> – “Life without Light: Discoveries from the Abyss,” by Robin Meadows; Smithsonian National Zoological Park, Zoogoer Magazine, May/June 1996

<http://www.ngdc.noaa.gov/mgg/image/2minrelief.html> – Index page for NOAA’s National Geophysical Data Center combined global elevation and bathymetry images (<http://www.ngdc.noaa.gov/mgg/image/2minsurface/45N135E.html> includes the Mariana Arc)

<http://volcano.oregonstate.edu/earthquakes-and-volcanoes> - lessons about earthquakes and volcanoes

<http://www.guam.net/pub/sshs/depart/science/mancuso/marianas/intromar.htm> – Web site with background information on 15 of the Mariana Islands.

<http://www.extremescience.com/DeepestOcean.htm> – Extreme Science Web page on the Challenger Deep

<http://oceanexplorer.noaa.gov/explorations/05galapagos/welcome.html> – Web page for the 2005 Galapagos Spreading Center Expedition

[http://www.divediscover.whoi.edu/ventcd/vent\\_discovery](http://www.divediscover.whoi.edu/ventcd/vent_discovery) – Dive and Discover presentation on the 25th anniversary of the discovery of hydrothermal vents

[http://seawifs.gsfc.nasa.gov/OCEAN\\_PLANET/HTML/ps\\_vents.html](http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML/ps_vents.html) – Article, “Creatures of the Thermal Vents” by Dawn Stover

[http://seawifs.gsfc.nasa.gov/OCEAN\\_PLANET/HTML/ps\\_vents.html](http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML/ps_vents.html) – “Creatures of the Thermal Vents,” article on hydrothermal vent organisms

Corliss, J. B., J. Dymond, L.I. Gordon, J.M. Edmond, R.P. von Herzen, R.D. Ballard, K. Green, D. Williams, A. Bainbridge, K. Crane, and T. H. Andel, 1979. Submarine thermal springs on the Galapagos Rift. *Science* 203:1073-1083. – Scientific journal article describing the first submersible visit to a hydrothermal vent community

Shank, T. M. 2004. The evolutionary puzzle of seafloor life. *Oceanus* 42(2):1-8; available online at [http://www.whoi.edu/cms/files/dfino/2005/4/v42n2-shank\\_2276.pdf](http://www.whoi.edu/cms/files/dfino/2005/4/v42n2-shank_2276.pdf).

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



Van Dover, C. L. Hot Topics: Biogeography of deep-sea hydrothermal vent faunas; available online at <http://www.divediscover.whoi.edu/hottopics/biogeo.html>

## National Science Education Standards

### Content Standard A: Science as Inquiry

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

### Content Standard B: Physical Science

- Structure and properties of matter
- Interactions of energy and matter

### Content Standard D: Earth and Space Science

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

### Content Standard E: Science and Technology

- Understandings about science and technology

### Content Standard F: Science in Personal and Social Perspectives

- Natural and human-induced hazards

## Ocean Literacy Essential Principles and Fundamental Concepts

### Essential Principle 2.

**The ocean and life in the ocean shape the features of the Earth.**

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

### Essential Principle 6.

**The ocean and humans are inextricably interconnected.**

- *Fundamental Concept f.* Coastal regions are susceptible to natural hazards (such as tsunamis, hurricanes, cyclones, sea level change, and storm surges).

### 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.

## For More Information

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Problem links updated May 2011.

### Student Handout

<b>1</b>			
<b>2</b>			
<b>3</b>			
<b>average</b>			

### Student Handout

**6m x 6m Grid**  
**each square = 0.5m**

