



## The Galápagos Rift Expedition 2011

# Hot Maps



### Focus

Multibeam sonar exploration for hydrothermal vent systems

### Grade Level

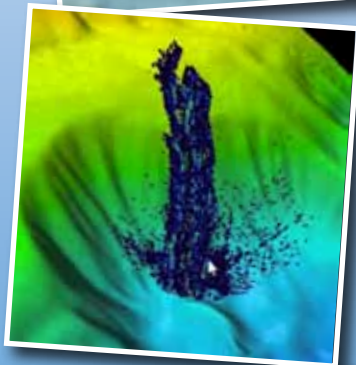
9-12 (Earth Science/Physical Science)

### Focus Question

How does multibeam sonar help explore Earth's deep ocean?

### Learning Objectives

- Students will describe multibeam sonar.
- Students will discuss the advantages of multibeam sonar bathymetry compared to two-dimensional topographic bathymetry.
- Students will interpret three-dimensional multibeam bathymetric data from the vicinity of the Galápagos Spreading Center.



### Materials

- Copies of *Introduction to Multibeam Imagery Worksheet*, one for each student group

### Audio-Visual Materials

- Interactive white board, video projector, or large screen monitor for showing downloaded videos (see Learning Procedure, Step 3)



### Teaching Time

One or two 45-minute class periods

### Seating Arrangement

Groups of 3-4 students

### Maximum Number of Students

32

### Key Words

Galápagos Rift  
Galápagos Spreading Center  
Hydrothermal vent  
Multibeam sonar  
Bathymetric survey

Image captions/credits on Page 2.

# lesson plan



The first photograph of a black smoker vent published on the cover of *Science* magazine. The blackened water is jetting out at 1–5 meters per second and is 380°C, hotter than a pizza oven. Image courtesy Spiess, Macdonald, *et al.*, 1980. [http://oceanexplorer.noaa.gov/explorations/05galapagos/logs/hires/macdonald\\_hires.jpg](http://oceanexplorer.noaa.gov/explorations/05galapagos/logs/hires/macdonald_hires.jpg)

#### Images from Page 1 top to bottom:

An overview of the Galápagos Islands. They are produced by volcanic activity caused by magma upwelling at the Galápagos hotspot. Green to white indicates the coastline, outside this is below sea level. Image produced by Ken Macdonald using GeoMapApp courtesy of Lamont Doherty Earth Observatory.

[http://oceanexplorer.noaa.gov/explorations/05galapagos/background/hotspots/media/Galapagos\\_IS\\_Topo\\_600.html](http://oceanexplorer.noaa.gov/explorations/05galapagos/background/hotspots/media/Galapagos_IS_Topo_600.html)

Multibeam image of Mendocino Ridge Plume taken with the Kongsberg EM302 multibeam bathymetric mapping system. Image courtesy INDEX-SATAL 2010 Expedition.

[http://oceanexplorer.noaa.gov/oceanos/media/movies/mendocino\\_ridge\\_plume\\_video.html](http://oceanexplorer.noaa.gov/oceanos/media/movies/mendocino_ridge_plume_video.html)

Close-up imagery showing a type of gooseneck barnacle, shrimp and a scaleworm on Kawio Barat submarine volcano. Image captured more than 1,850 meters deep by the *Little Hercules* ROV on August 3, 2010. Image courtesy of NOAA *Okeanos Explorer* Program, INDEX-SATAL 2010.

[http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/slideshow/ex\\_july\\_highlights/gallery/hires/barnacle\\_zoom\\_hires.jpg](http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/slideshow/ex_july_highlights/gallery/hires/barnacle_zoom_hires.jpg)

Doug Jongeward, a highly skilled IT Specialist, works in the control room of the *Okeanos Explorer* managing the enormous amounts of video and data that is collected each day on board the ship. Image courtesy of NOAA *Okeanos Explorer* Program.

[http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/hires/8\\_doug\\_jongeward\\_hires.jpg](http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/hires/8_doug_jongeward_hires.jpg)

## 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.*

On Feb. 17, 1977, scientists exploring the seafloor near the Galápagos Islands made one of the most significant discoveries in modern science: large numbers of animals that had never been seen before were clustered around underwater hot springs flowing from cracks in the lava seafloor. Similar hot springs, known as hydrothermal vents, have since been discovered in many other locations where underwater volcanic processes are active.

These processes are often associated with movement of the tectonic plates, which 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. These 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). Movement of convection currents causes tectonic plates to move several centimeters per year relative to each other.

Where tectonic plates slide horizontally past each other, the boundary between the plates 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. Places where these breaks occur are called faults. A well-known example of a transform plate boundary is the San Andreas Fault in California. View animations of different types of plate boundaries at:

[http://www.seed.slb.com/flash/science/features/earth/livingplanet/plate\\_boundaries/en/index.html](http://www.seed.slb.com/flash/science/features/earth/livingplanet/plate_boundaries/en/index.html).

A convergent plate boundary is formed when tectonic plates collide more or less head-on. When two continental plates collide, they may cause rock to be thrust upward at the point of collision, resulting in mountain-building (the Himalayas were formed by the collision of the Indo-Australian Plate with the Eurasian Plate). When an oceanic plate and a continental plate collide, the oceanic plate moves beneath the continental plate in a process known as subduction. Deep trenches are often formed where tectonic plates are being subducted, and earthquakes are common. 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. These island arcs are always landward of the neighboring trenches. View the three-dimensional



A black smoker chimney named 'Boardwalk' emitting 644°F (340°C) hydrothermal fluids in the northeastern Pacific Ocean at a depth of 7,260 feet (2,200 m). Microbes grow within and on the surface of such mineral formations. Image courtesy of James F. Holden, University of Massachusetts, Amherst.

[http://oceanexplorer.noaa.gov/oceanos/explorations/10index/background/hires/boardwalk\\_black\\_smoker\\_hires.jpg](http://oceanexplorer.noaa.gov/oceanos/explorations/10index/background/hires/boardwalk_black_smoker_hires.jpg)



Hydrothermal vents on Kawio Barat submarine volcano spew white smoke. Image captured more than 1,850 meters deep by the *Little Hercules* ROV on August 3, 2010. Image courtesy of NOAA *Okeanos Explorer* Program, INDEX-SATAL 2010.

[http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/slideshow/ex\\_july\\_highlights/gallery/hires/white\\_plumes\\_hires.jpg](http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/slideshow/ex_july_highlights/gallery/hires/white_plumes_hires.jpg)

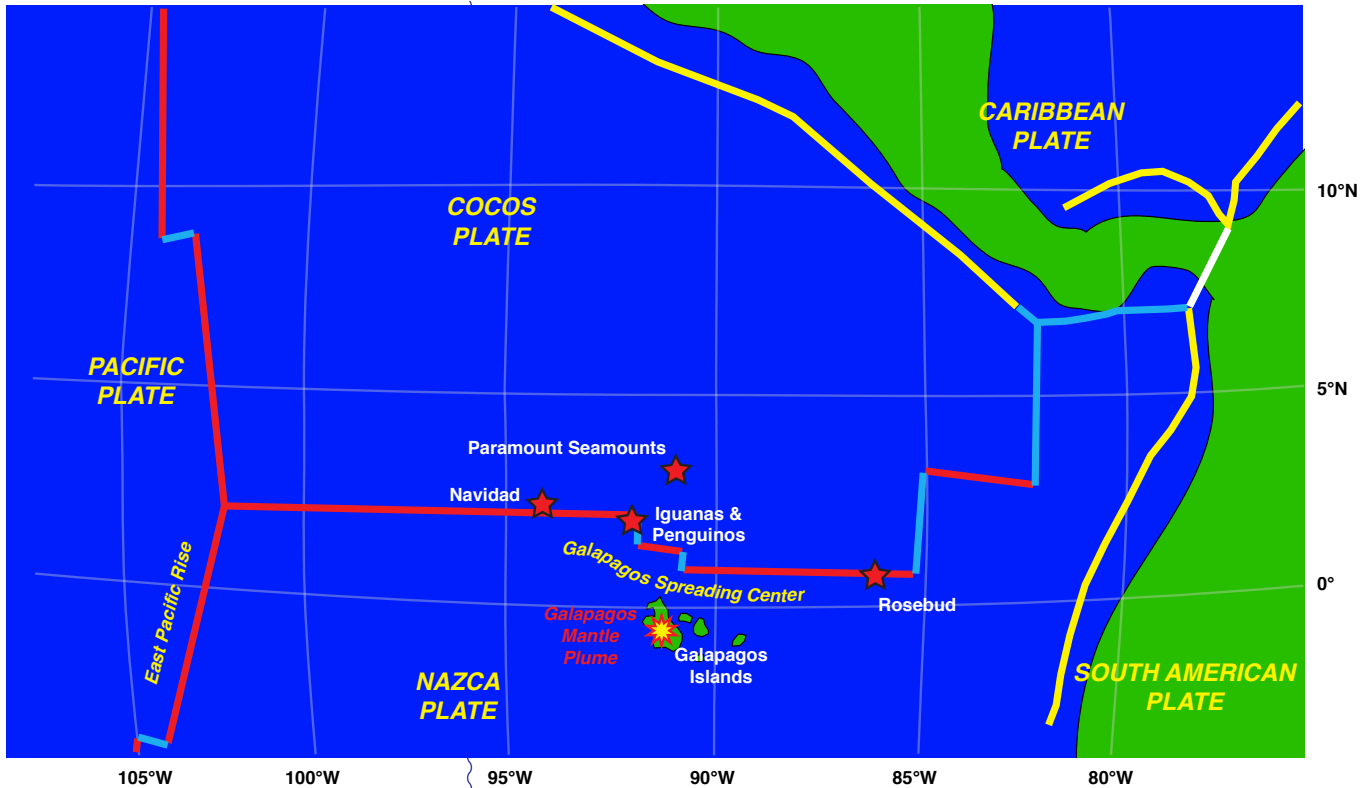
structure of a subduction zone at: <http://oceanexplorer.noaa.gov/explorations/03fire/logs/subduction.html>.

Where tectonic plates are moving apart, they form a divergent plate boundary. At divergent plate boundaries, magma rises from deep within the Earth and erupts to form new crust on the lithosphere. Most divergent plate boundaries are underwater (Iceland is an exception), and 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. View the three-dimensional structure of a mid-ocean ridge at: <http://oceanexplorer.noaa.gov/explorations/03fire/logs/ridge.html>.

Volcanic activity can also occur in the middle of a tectonic plate, at areas known as hotspots, which are thought to be natural pipelines to reservoirs of magma in the upper portion of the Earth's mantle. The volcanic features at Yellowstone National Park are the result of hotspots, as are the Hawaiian Islands. As the Pacific tectonic plate moves over the Hawaiian hotspot, magma periodically erupts to form volcanoes that become islands. The oldest island is Kure at the northwestern end of the archipelago. The youngest is the Big Island of Hawaii at the southeastern end. Loihi, east of the Big Island, is the newest volcano in the chain and may eventually form another island.

The Galápagos region is geologically complex (see Figure 1 on page 4). The Galápagos Islands were formed by a hotspot called the Galápagos Mantle Plume (GMP), which continues to produce active volcanoes (the Sierra Negra volcano erupted on October 22, 2005). These islands are formed on the Nazca Plate, which is moving east-southeast. On the western side of the Nazca Plate, this motion produces a divergent plate boundary with the Pacific Plate. This boundary is called the East Pacific Rise. On the northern side of the Nazca Plate, just north of the Galápagos archipelago, another divergent plate boundary exists with the Cocos Plate. This boundary is known as the Galápagos Spreading Center (GSC). A convergent boundary exists on the eastern side of the Nazca Plate, which is being subducted beneath the South American and Caribbean Plates. This subduction has caused some of the oldest seamounts formed by the GMP to disappear beneath the South American and Caribbean Plates, so it is not certain exactly how long the GMP has been active in its present position (for additional discussion and illustrations about these processes, see "This Dynamic Earth" available online from the U.S. Geological Survey at <http://pubs.usgs.gov/publications/text/dynamic.pdf>).

When the movement of tectonic plates causes deep cracks to form in the ocean floor, seawater can flow into these cracks. As the seawater moves deeper into the crust, it is heated by molten rock. As the



**Figure 1. Galápagos Tectonic Setting.**

Red plate boundaries are divergent; yellow plate boundaries are convergent; blue plate boundaries are transform; white plate boundaries are undetermined. Navidad, Iguanas and Pinguinos are locations where black smokers were discovered in 2005. Paramount Seamounts are an exploration target for Galápagos Rift Expedition 2011. For more information see the Galapagos Rift Expedition 2011 Expedition Education Module (<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1103/background/edu/edu.html>). Credit: UNAVCO (tectonic boundaries); NOAA (hydrothermal sites)

temperature increases, sulfur and metals such as copper, zinc, and iron dissolve from the surrounding rock into the hot fluid. Eventually, the mineral-rich fluid rises again and erupts from openings in the seafloor. The temperature of the erupting fluid may be as high as 400°C, and contains hydrogen sulfide, which is toxic to many species. When the hot hydrothermal fluid meets cold (nearly freezing) seawater, minerals in the fluid precipitate. The precipitated mineral particles give the fluid a smoke-like appearance, so these vents are often called black smokers or white smokers, depending upon the types of minerals in the fluid. Precipitated minerals may also form chimneys that can be several meters high.

Hydrothermal vent communities and other deepwater chemosynthetic ecosystems are fundamentally different from other biological systems on Earth, and there are plenty of unanswered questions about the individual species and interactions between species found in these communities. Many of these species are new to science, and include primitive living organisms (Archaea) that some scientists believe may have been the first life forms on Earth. Although much remains to be learned, useful products have already been discovered in hydrothermal vent organisms. At present, almost all drugs produced from natural sources come from terrestrial plants, but marine animals produce more drug-like substances than any group of organisms that live on land. Some chemicals from microorganisms found around hydrothermal vents (the exopolysaccharide HE 800 from *Vibrio diabolicus*) are promising for the treatment of bone injuries and diseases, while



Port view of the *Okeanos Explorer*.

[http://oceanexplorer.noaa.gov/okeanos/media/slideshow/gallery/ex2010/hires/port\\_view\\_hires.jpg](http://oceanexplorer.noaa.gov/okeanos/media/slideshow/gallery/ex2010/hires/port_view_hires.jpg)

### The NOAA Ship *Okeanos Explorer*

Formerly: USNS *Capable*  
 Launched: October 28, 1988  
 Transferred to NOAA: September 10, 2004  
 Commissioned: August 13, 2008  
 Class: T-AGOS  
 Length: 224 feet  
 Breadth: 43 feet  
 Draft: 15 feet  
 Displacement: 2,298.3 metric tons  
 Berthing: 46 (19 Mission/science)  
 Speed: 10 knots  
 Range: 9600 nm  
 Endurance: 40 days

### Systems and Instrumentation:

Kongsberg EM302 Multibeam rated to 7,000 m  
 SBE 911plus CTD  
 ROVs -  
*Little Hercules* - 4,000 m depth rating;  
 USBL tracking; depth, altitude, attitude/heading sensors; Seabird SBE 49 FastCat CTD; HD camera and HMI lights  
 Camera platform with depth/altitude/heading sensors, HD camera and HMI lights.  
 Telepresence

### Operations:

Ship crewed by NOAA Commissioned Officer Corps and civilians through NOAA's Office of Marine and Aviation Operations; Mission equipment operated by NOAA's Office of Ocean Exploration and Research

For more information, visit <http://oceanexplorer.noaa.gov/okeanos/welcome.html>.



Aft view of the *Okeanos Explorer*.

[http://oceanexplorer.noaa.gov/okeanos/media/slideshow/gallery/ex2010/hires/aft\\_view\\_hires.jpg](http://oceanexplorer.noaa.gov/okeanos/media/slideshow/gallery/ex2010/hires/aft_view_hires.jpg)

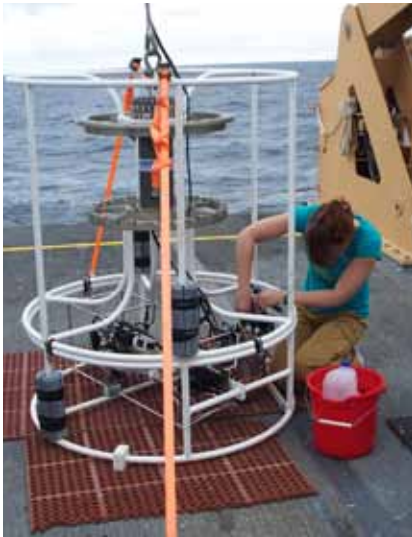
similar chemicals may be useful for treating cardiovascular disease. Other examples of useful products include a protein from *Thermus thermophilus*, which is a microorganism that is adapted to live under extremely high temperature conditions near hydrothermal vents. One of these adaptations is the protein Tth DNA polymerase that can be used to make billions of copies of DNA for scientific studies and crime scene investigations. Another microorganism (genus *Thermococcus*) produces a type of protein (an enzyme called pullulanase) that can be used to make sweeteners for food additives.

In 2002 and 2005, NOAA's Office of Ocean Exploration and Research sponsored expeditions to the Galápagos Rift (see <http://oceanexplorer.noaa.gov/explorations/02galapagos/welcome.html> and <http://oceanexplorer.noaa.gov/explorations/05galapagos/welcome.html> for more information about these expeditions). A major objective of the 2002 expedition was to revisit a hydrothermal vent site named Rose Garden to investigate changes that might have occurred in the community of living organisms around the vent since it was discovered in 1977. Scientists found that significant changes had indeed taken place: Rose Garden had completely disappeared! In its place was a fresh sheet of lava that had apparently buried the vent and all of the surrounding organisms. About 300 meters away, a new vent field (which the scientists named Rosebud) was discovered with typical hydrothermal vent species beginning to colonize cracks in recently-formed lava. These discoveries underscored a growing awareness that the deep ocean environment can change much more quickly than was previously believed. The 2005 expedition focused on a portion of the GSC that had never been explored for hydrothermal vents. Scientists hoped that they would find black smokers, because at that time high temperature (several hundred degrees C) vents had not been found in the Galápagos region; only vents whose temperatures were less than 50°C. Using chemical and physical clues, explorers eventually made the first discovery of black smokers on the Galápagos Rift!

These discoveries set the stage for the Galápagos Rift Expedition 2011, which will use the state-of-the-art exploration capabilities of the NOAA Ship *Okeanos Explorer* to obtain detailed information about the biology and geology of Galápagos hydrothermal ecosystems, and determine whether different ecosystems are found at different vent fields within the Galápagos region. A major objective of the Expedition is to survey and map known hydrothermal vent sites, and to search for new hydrothermal vents in unexplored regions of the Galapagos Rift.

Ocean exploration aboard *Okeanos Explorer* typically involves four key technologies:

- Multibeam sonar mapping system;
- CTD (an instrument package that measures conductivity, temperature, and depth) and other electronic sensors to measure



Senior Survey Technician Elaine Stuart works on the CTD while the altimeter battery recharges. Water sampling bottles, which are often attached to the rosette frame, have been removed for tow-yo operations. Sensors are mounted in the lower part of the frame where SST Stuart is working. Image courtesy of NOAA *Okeanos Explorer* Program.

[http://tethys.gso.uri.edu/OkeanosExplorerPortal/ex1103l1/news-articles/update-for-june-25-2011/image/image\\_view\\_fullscreen](http://tethys.gso.uri.edu/OkeanosExplorerPortal/ex1103l1/news-articles/update-for-june-25-2011/image/image_view_fullscreen)



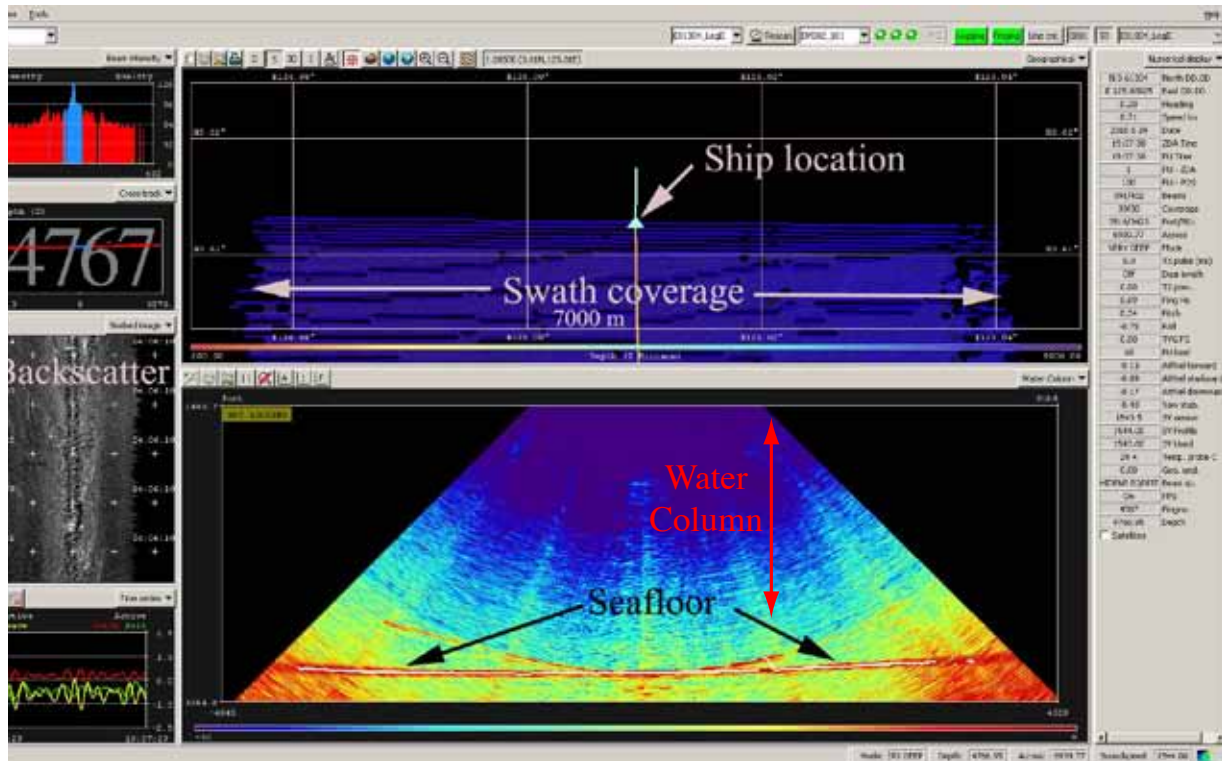
A CTD with water sampling bottles attached to the rosette frame. Image courtesy of NOAA *Okeanos Explorer* Program.

- chemical and physical seawater properties;
- A Remotely Operated Vehicle (ROV) capable of obtaining high-quality imagery and samples in depths as great as 6,000 meters; and
- Advanced broadband satellite communication that provides the foundation for “telepresence,” which allows people to observe and interact with events at a remote location so that scientific expertise can be brought to the exploration team as soon as discoveries are made, and at a fraction of the cost of traditional oceanographic expeditions. See the Galápagos Rift Expedition 2011 Expedition Education Module for additional information about *Okeanos Explorer* exploration technologies.

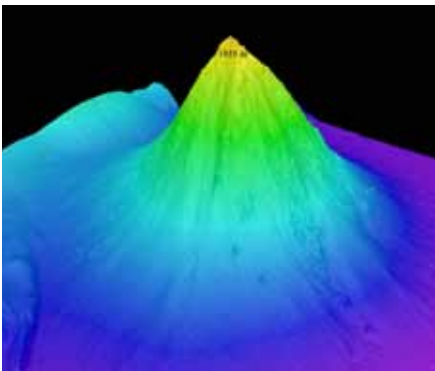
To search for hydrothermal vents, scientists raise and lower a CTD through several hundred meters near the bottom as the ship slowly cruises over the area being surveyed. This repeated up-and-down motion of the towed CTD resembles the movement of a yo-yo, so this process is called tow-yo operations. Because hydrothermal vents cause changes to the chemistry and physical characteristics of surrounding seawater, these vents are often surrounded by masses of seawater that are distinctly different from normal seawater. These water masses are called plumes, and can be detected by instruments carried on the CTD. During tow-yo operations, scientists also make maps of the seafloor using multibeam sonar. When CTD data show evidence of a possible plume from a hydrothermal vent, scientists use these maps to plan dives of *Okeanos Explorer*'s remotely operated vehicle (ROV). The ROV gathers video images, and hopefully provides the first look at newly discovered vents!

Sonar (which is short for SOund NAVigation and Ranging) systems are used to determine water depth, as well as to locate and identify underwater objects. In use, an acoustic signal or pulse of sound is transmitted into the water by a sort of underwater speaker known as a transducer. The transducer may be mounted on the hull of a ship, or may be towed in a container called a towfish. If the seafloor or other object is in the path of the sound pulse, the sound bounces off the object and returns an “echo” to the sonar transducer. The time elapsed between the emission of the sound pulse and the reception of the echo is used to calculate the distance of the object. Some sonar systems also measure the strength of the echo, and this information can be used to make inferences about some of the reflecting object's characteristics. Hard objects, for example, produce stronger echoes than softer objects. This is a general description of “active sonar.” “Passive sonar” systems do not transmit sound pulses. Instead, they “listen” to sounds emitted from marine animals, ships, and other sources.

Multibeam sonar is one of the most powerful tools available for modern deep sea exploration. A multibeam system uses multiple transducers



**Data acquisition screen:** There is a lot of information to keep track of when standing watch at the multibeam acquisition station. Each piece of information provides unique and valuable details about the seafloor, which are used in the exploration decision-making process: swath coverage is used to determine the spacing of consecutive passes of the ship over an area being surveyed to ensure that the area is completely mapped; the water column allows us to visualize the detected seafloor and water mass above it in order to identify features on the seafloor or above; and the backscatter imagery shows the relative hardness or softness of the seafloor, which helps identify targets such as shipwrecks and deep water coral reefs. Image courtesy of NOAA *Okeanos Explorer* Program, INDEX-SATAL 2010. [http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/hires/june26fig3\\_hires.jpg](http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/hires/june26fig3_hires.jpg)



This is a perspective view of the Kawio Barat (West Kawio) seamount looking from the northwest acquired with multibeam sonar. The underwater volcano rises around 3800 meters from the seafloor. Image courtesy of NOAA *Okeanos Explorer* Program, INDEX-SATAL 2010. [http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/hires/june26fig1\\_hires.jpg](http://oceanexplorer.noaa.gov/oceanos/explorations/10index/logs/hires/june26fig1_hires.jpg)

pointing at different angles on either side of a ship to create a swath of signals. The *Okeanos Explorer* is equipped with a Kongsberg Simrad EM 302 multibeam system that can produce up to 864 depth soundings in a single swath, and over 10 swaths per second. The time interval between signal transmission and return echo arrival is used to estimate depth over the area of the swath. In some systems, the intensity of the return echo is also used to infer bottom characteristics that can be used for habitat mapping. In addition to high-resolution maps, multibeam data can be used to create three dimensional models or even “fly-by” videos that simulate a trip across the area being mapped. For a fascinating example of this, see <http://oceanexplorer.noaa.gov/explorations/02fire/logs/jul08/media/sm2k.html>. This 3D fly-through movie shows the seafloor in the Magic Mountain area of Explorer Ridge (near the coast of Vancouver, British Columbia ) where there are active hydrothermal vents. To see what the vents look like, you can view other fly-throughs of the same area at <http://oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain>. Recently, a new generation of multibeam sonars has been developed that are able to map features in the water column as well as the seafloor. This ability will potentially allow multibeam sonars to map the location of fishes and marine mammals, as well as a wide range of physical oceanographic processes. For more information about sonar systems, see <http://oceanexplorer.noaa.gov/technology/tools/sonar/sonar.html>.

An important technique for studying multibeam images uses a three-dimensional data visualization system called Fledermaus (which is the German word for “bat,” and is pronounced “FLEE-der-mouse”). This lesson introduces students to multibeam technology and simple analysis of multibeam data using free viewing software for multibeam imagery in the Fledermaus file format. In the future, students will have the opportunity to apply their analytic skills to investigate new multibeam images as the *Okeanos Explorer* continues its voyages of discovery in Earth’s deep ocean.

[Note: mention of proprietary names does not imply endorsement by NOAA.]

### Learning Procedure

[NOTE: Depending upon available time and instructional objectives, educators may want to have students complete the topographic mapping exercise described in “Mapping the Deep Ocean Floor” (<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/mapping.pdf>). In this exercise, students construct a three-dimensional topographic model from bathymetric soundings. The resulting model has much less detail than the multibeam image used in this lesson, which underscores the value of multibeam technology and illustrates the extent to which this technology has enhanced our ability to explore the deep ocean.]

1. To prepare for this lesson:
  - (a) Review introductory essays for the Galápagos Rift Expedition 2011 at <http://oceanexplorer.noaa.gov/okeanos/explorations/ex1103/welcome.html>
  - (b) If students are not familiar with hydrothermal vent communities, you may want to have students complete the background portion of the *Hydrothermal Vent Plume Inquiry Guide* (<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/plume.pdf>) which guides student inquiries about hydrothermal vents and plumes.
  - (c) Review background information on multibeam sonar technology and questions on the *Introduction to Multibeam Imagery Worksheet*. Depending upon time, instructional objectives, and students’ abilities, you may want to do Step 5 as a group activity, or just provide the estimated CTD positions for the remaining steps.
  - (d) Download the iView4D software from <http://www.ivs3d.com/products/iview4d/>, and the **galapagos\_mb\_11\_6\_24.sd** file from [http://oceanexplorer.noaa.gov/okeanos/edu/resources/media/galapagosmb\\_11\\_6\\_24.sd](http://oceanexplorer.noaa.gov/okeanos/edu/resources/media/galapagosmb_11_6_24.sd), and install these on computers that students will be using to complete the *Worksheet* activity. Alternatively, you may have students download these resources onto their own computer systems.



(e) Download or bookmark the video ([http://ccom.unh.edu/NOAA\\_oceanexploration/PlumePoints2.mov](http://ccom.unh.edu/NOAA_oceanexploration/PlumePoints2.mov)) referenced in Step 2.

- Briefly introduce the Galápagos Rift Expedition 2011, and 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. Be sure students understand that discoveries of deep sea chemosynthetic communities during the last 30 years are major scientific events that have changed many assumptions about life in the ocean and have opened up many new fields of scientific investigation.

Briefly discuss hydrothermal vent communities, or have students complete the activity referenced in Step 1b. Say that a primary purpose of the Galápagos Rift Expedition 2011 is to search for new hydrothermal vents in unexplored regions of the Galápagos Rift, and describe the exploration strategy discussed above. Be sure students understand why hydrothermal vents produce plumes, and how ocean explorers search for plumes to locate hydrothermal vents.

- Ask students what they know about sonar, and provide additional information as necessary. Be sure students understand that sonar uses acoustic signals or pulses of sound that are transmitted into the water by a transducer, which may be mounted on the hull of a ship or towed in a container called a towfish. If the seafloor or other object is in the path of the sound pulse, the sound bounces off the object and returns an "echo" to the sonar transducer. The time elapsed between the emission of the sound pulse and the reception of the echo is used to calculate the distance of the object. Multibeam sonar systems use multiple transducers pointing at different angles on either side of a ship to create a swath of signals.

Tell students that on June 24, 2011, the *Okeanos Explorer* was conducting tow-yo operations near the Galápagos Rift. Early in the morning of June 25, sensors on the CTD indicated the possible presence of plumes that might be produced by hydrothermal vents (for more information and activities about this discovery, see the *We've Got Plumes!* lesson). Point out that the only way to be certain that vents are present is to survey the area with video equipment carried by the ship's ROV, and that the ROV team always wants as much information as possible about target dives sites. This is where multibeam sonar comes in.

- Provide each student group with a copy of the *Introduction to Multibeam Imagery Worksheet*, and ensure that students have access to the software and file referenced in Step 1d. Tell students that this activity is intended to familiarize them with multibeam imagery and how it can be manipulated to answer basic questions about features

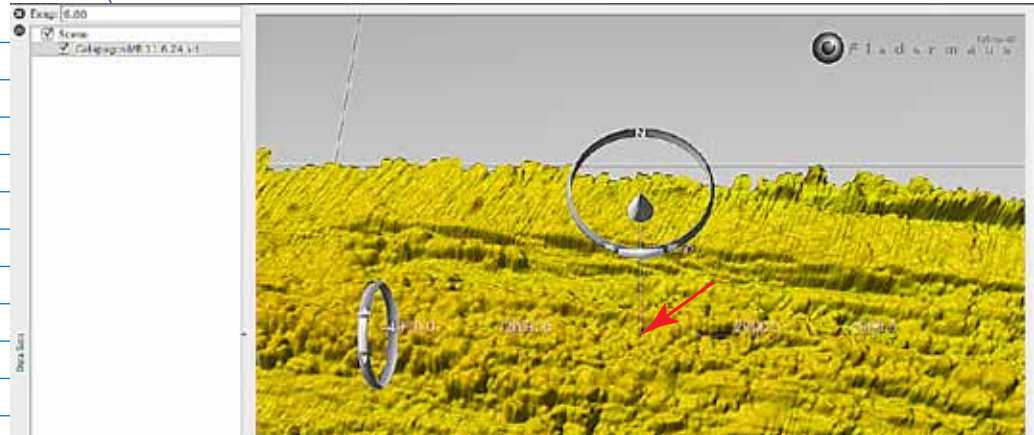


*Okeanos Explorer* crew launch the ROV *Little Hercules*. Image courtesy of NOAA *Okeanos Explorer* Program, INDEX-SATAL 2010.  
<http://oceanexplorer.noaa.gov/okeanos/explorations/10index/background/rov/media/launch.html>

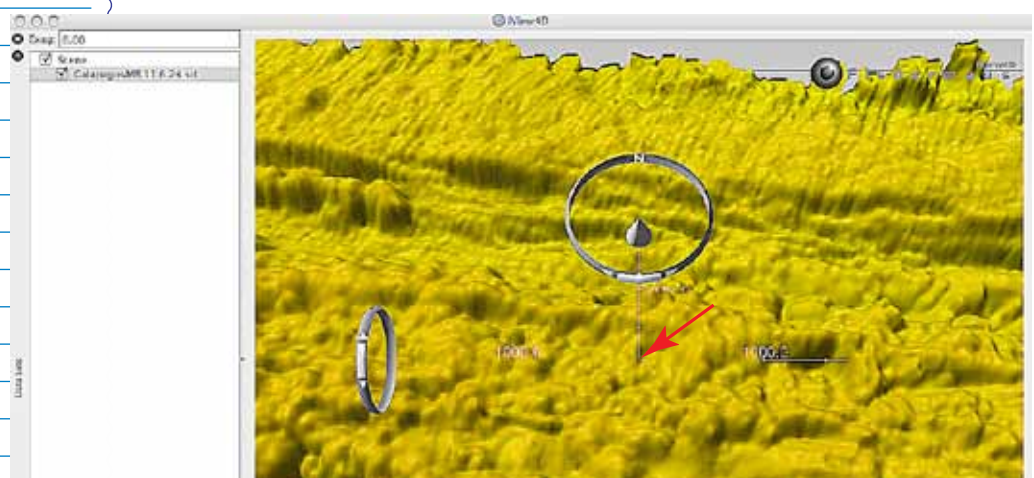
on the ocean floor. You may also want to mention that this skill will allow them to investigate additional images that will be available from future *Okeanos Explorer* missions. If students are not familiar with the concepts of latitude and longitude, you may wish to review these using information in Appendix A.

5. When students have answered questions on the *Worksheet*, lead a discussion of their results. This discussion should include:
- Depth in the vicinity of  $0^{\circ} 46' 55.0''$  North latitude,  $88^{\circ} 47' 57.00''$  West longitude is about 1819.38 meters.
  - Students should use the Pythagorean theorem to calculate the CTD setbacks. According to this relationship, the square of "Wire Out" is equal to the sum of the squares of "CTD Depth" and "Setback." So, "Setback" is equal to the square root of "Wire" squared minus "Depth" squared. At 01:45 the setback was 2371 m; at 02:02 the setback was 2357 m. Note that the distance from the sea surface to the ship's deck is negligible and is ignored in this calculation.
  - One online calculator for distance and bearing between latitude/longitude points can be found at <http://www.movable-type.co.uk/scripts/latlong.html>. Scroll down the page to the "Destination point given distance and bearing from start point" heading, and enter the latitude and longitude for the ship's position, bearing of the CTD from the ship (which is  $180^{\circ}$  opposite the ship's heading), and setback distance in km. The calculator provides the solution in degree-minute-second format. At 01:45 the estimated position of the CTD was  $0^{\circ} 45' 14''$  N;  $88^{\circ} 32' 22''$  W; at 02:02 the estimated position of the CTD was  $0^{\circ} 45' 13''$  N;  $88^{\circ} 31' 53''$  W.
  - The two points calculated in Step 5 are approximately in the center of the Galapagos Rift.
  - The location calculated for the plume signal detected at 01:45 appears to be near the bottom of a shallow crater (see Figures 6 and 7). The seafloor depth at this point is about 1,911 m.
  - The location calculated for the plume signal detected at 02:02 appears to be near the bottom of a crater that is somewhat larger than the other location (see Figures 8 and 9). The maximum depth inside this crater is about 1,955 m.
  - Currents are the primary source of possible error in calculating the probable location of vents that produced the plumes, and could move the plume away from the vent location, as well as displace the CTD from its calculated position. During ROV operations, a CTD is carried aboard the *Serios* vehicle (see the Galápagos Rift Expedition 2011 Expedition Purpose for additional information

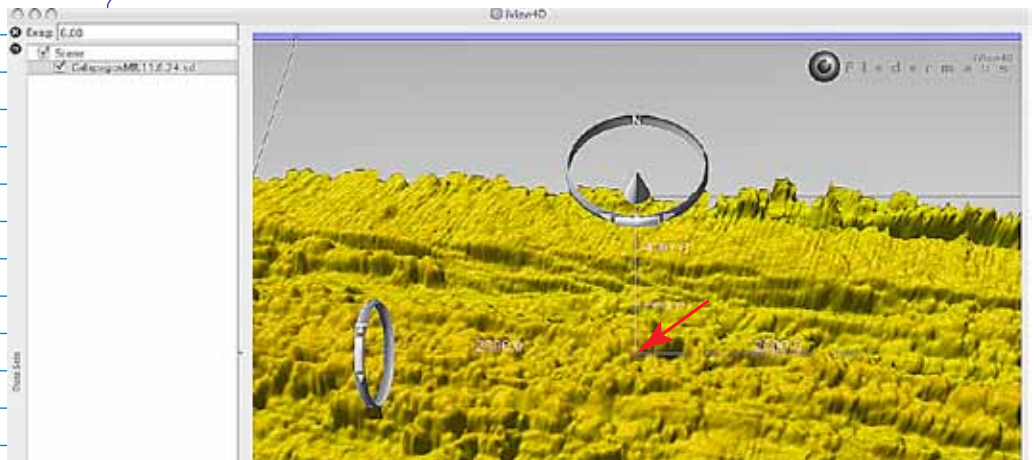
**Figure 6.** Approximate location  
(red arrow) of position  $0^{\circ} 45' 14''$   
N;  $88^{\circ} 32' 22''$  W



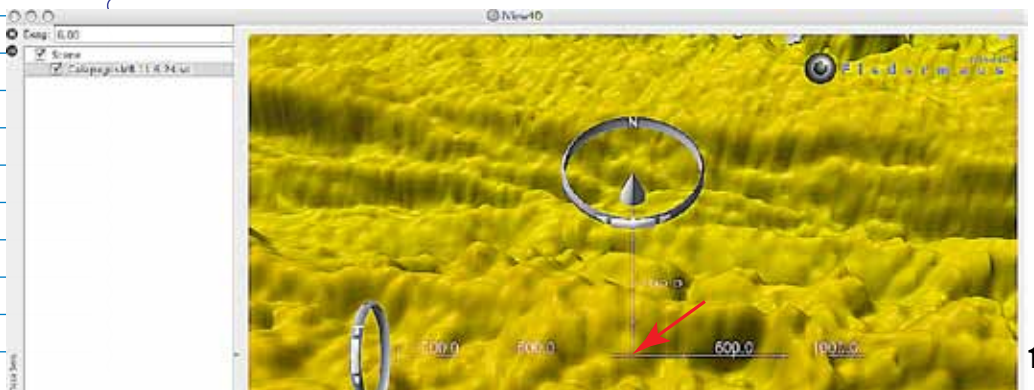
**Figure 7.** Same as Figure 6,  
zoomed



**Figure 8.** Approximate location  
(red arrow) of position  $0^{\circ} 45' 13''$   
N;  $88^{\circ} 31' 53''$  W



**Figure 8.** Same as Figure 8,  
zoomed



about the *Okeanos Explorer's* ROV system). This allows the ROV team to follow the plume to its source before beginning video surveys with the *Little Hercules* vehicle.

### The BRIDGE Connection

[www.vims.edu/bridge/](http://www.vims.edu/bridge/) – Click on “Ocean Science Topics” in the menu on the left side of the page, then “Habitats” then select “Deep Ocean” for activities and links about deep ocean ecosystems.

### The “Me” Connection

Have students write a brief essay describing a backpacking trip across a landscape having the topography shown in the multibeam image used for the *Worksheet* activity.

### Connections to Other Subjects

English/Language Arts, Social Studies

### Assessment

Students answers to *Worksheet* questions and class discussions provide opportunities for assessment.

### Extensions

1. Visit <http://oceanexplorer.noaa.gov/okeanos/explorations/ex1103/welcome.html> for more information about the expedition and to check out the Daily Updates.
2. Visit the *Okeanos Explorer* Digital Atlas ([http://www.ncddc.noaa.gov/website/google\\_maps/OkeanosExplorer/mapsOkeanos.htm](http://www.ncddc.noaa.gov/website/google_maps/OkeanosExplorer/mapsOkeanos.htm)) and Web page (<http://oceanexplorer.noaa.gov/okeanos/welcome.html>) for reports, images, and other products from *Okeanos Explorer* cruises.

### Multimedia Discovery Missions

<http://oceanexplorer.noaa.gov/edu/learning/welcome.html> – Click on the links to Lessons 1, 5, and 6 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Chemosynthesis and Hydrothermal Vent Life, and Deep-Sea Benthos.

### Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

#### Tools of Exploration – Remotely Operated Vehicles

(from the INDEX-SATAL 2010 Expedition)

<http://oceanexplorer.noaa.gov/okeanos/explorations/10index/background/edu/media/multibeam.pdf>

Focus: Technology for deep ocean exploration: Remotely Operated Vehicles (Earth Science/Physical Science)

Students describe systems and capabilities of science-class remotely operated vehicles, typical applications and limitations of imagery obtained with ROVs, and use ROV imagery to make inferences about deep ocean habitats.

### **To Explore Strange New Worlds**

(Grades 7-8; adaptations for Grades 5-6 & 9-12) (from the *Okeanos Explorer Education Materials Collection, Volume 2: How Do We Explore?*)  
[http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe\\_78\\_toexplore.pdf](http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe_78_toexplore.pdf)

Focus: Strategies for exploring unknown areas on Earth (Life Science/Physical Science/Earth Science)

Students describe requirements for explorations of unknown areas on Earth; discuss factors that influenced exploration strategies of the Lewis and Clark and *Challenger* Expeditions; describe the overall exploration strategy used aboard the NOAA Ship *Okeanos Explorer*; and describe how fractal geometry models natural systems, and how scale influences exploration strategy and results.

### **Wow, That Hertz!**

(from the *Okeanos Explorer Education Materials Collection, Volume 2: How Do We Explore?*)  
[http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe\\_912\\_hertz.pdf](http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe_912_hertz.pdf)

Focus: Communications physics (Physical Science/Physics)

Students explain the concept of energy transfer through wave propagation, and how this process is used to support telepresence and scientific communications aboard the *Okeanos Explorer*; define an electric current, and describe the relationship between current, voltage and resistance using Ohm's Law; identify resistors, capacitors, and inductors, and explain how each of these influences the flow of electric current; and identify and describe the function of the five basic electronic building blocks that make radios work.

### **Watching in 3-D**

(from the *Okeanos Explorer Education Materials Collection, Volume 2: How Do We Explore?*)  
[http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe\\_912\\_3d.pdf](http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe_912_3d.pdf)

Focus: Multibeam sonar

Students describe multibeam sonar and explain why the velocity of sound in water must be measured before maps can be created with

the *Okeanos Explorer's* multibeam sonar system; and interpret three-dimensional multibeam data of underwater features mapped by the *Okeanos Explorer*.

### **Through Robot Eyes**

(from the *Okeanos Explorer Education Materials Collection, Volume 2: How Do We Explore?*)

[http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe\\_912\\_roboteyes.pdf](http://oceanexplorer.noaa.gov/okeanos/edu/lessonplans/media/hdwe_912_roboteyes.pdf)

Focus: Image analysis (Physical Science/Technology)

Students describe typical applications and limitations of imagery obtained with remotely operated vehicles (ROVs); demonstrate how lasers may be used to calibrate images for size and distance measurements; and analyze ROV imagery from the *Okeanos Explorer* to make inferences about deep ocean habitats.

### **The Ridge Exploring Robot**

(from the INSPIRE: Chile Margin 2010 Expedition)

<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/robot.pdf>

Focus: Autonomous Underwater Vehicles/Marine Navigation (Earth Science/Mathematics)

Students explain a three-phase strategy that uses an autonomous underwater vehicle (AUV) to locate, map, and photograph previously undiscovered hydrothermal vents; design a survey program to provide a photomosaic of a hypothetical hydrothermal vent field; and calculate the expected position of the AUV based on speed and direction of travel.

### **Reduced Fare**

(from the INSPIRE: Chile Margin 2010 Expedition)

<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/reducedfare.pdf>

Focus: Deep-Sea Reducing Environments (Life Science)

Students describe oxidation and reduction; explain the meaning of "reducing environment;" give at least three examples of deep-sea reducing environments; and demonstrate a flow of electric current produced by a redox reaction.

### **The Chemosynthetic Cafe**

(from the INSPIRE: Chile Margin 2010 Expedition)

<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/cafe.pdf>

Focus: Biochemistry of hydrothermal vents (Life Science)

Students compare and contrast food web energy sources in hydrothermal vent and aerobic environments, and use models to explain the overall chemistry of autotrophic nutrition.

### **The Big Balancing Act**

(from the New Zealand American Submarine Ring of Fire 2005 Expedition)

[http://oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05\\_balancing.pdf](http://oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_balancing.pdf)

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

Students 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 use data from hydrothermal circulation systems to make inferences about their significance to ocean chemical balance.

### **Hydrothermal Vent Challenge**

(from the Submarine Ring of Fire 2006 Expedition)

<http://oceanexplorer.noaa.gov/explorations/06fire/background/edu/media/ROF06.VentChallenge.pdf>

Focus: Chemistry of hydrothermal vents (Chemistry)

Students 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.

### **Survivors on the Ocean Ridge**

(from the 2002 Galapagos Rift Expedition)

[http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal\\_gr9\\_12\\_l5.pdf](http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_l5.pdf)

Focus: Inheritance of genetic traits and the effect of environmental pressures on the expressed traits (Life Science)

Students investigate the history of explorations of the hydrothermal vent systems; design a new shrimp species based on the introduction of a new gene form from migrating shrimp populations along the rift

systems; assess the viability of the new shrimp species; and develop a model for the establishment of a population of a new species of shrimp.

### 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/oceanos/explorations/ex1103/welcome.html> – Web site for Galápagos Rift Expedition 2011, with links to lesson plans, career connections, and other resources

<http://oceanexplorer.noaa.gov/oceanos/edu/welcome.html> – Web page for the NOAA Ship *Okeanos Explorer* Education Materials Collection

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

<http://oceanexplorer.noaa.gov/explorations/02galapagos/welcome.html> – Web site for the 2002 Galápagos Rift Expedition

<http://oceanexplorer.noaa.gov/explorations/05galapagos/welcome.html> – Web site for the 2005 GalAPAGoS: Where Ridge Meets Hotspot Expedition

<http://oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain/welcome.html> – Links to virtual fly-throughs and panoramas of the Magic Mountain hydrothermal vent site on Explorer Ridge in the NE Pacific Ocean, where two tectonic plates are spreading apart and there is active eruption of submarine volcanoes

<http://www.pmel.noaa.gov/vents/nemo/index.html> – Web site for NOAA's New Millennium Observatory (NeMO), a seafloor observatory at an active underwater volcano near the spreading center between the Juan de Fuca and Pacific tectonic plates

<http://www.nationalgeographic.com/xpeditions/lessons/07/g35/seasvents.html> – National Geographic Xpeditions lesson plan, *We're in Hot Water Now: Hydrothermal Vents*, includes links to *National Geographic* magazine articles and video with an emphasis on geography and geographic skills

<http://www.divediscover.who.edu/vents/index.html> – Woods Hole Oceanographic Institution's Dive and Discover Web site about



hydrothermal vents includes details about vent formation, education resources, and the story of the discovery of the first hydrothermal vent in 1977.

### National Science Education Standards

#### Content Standard A: Science As Inquiry

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

#### Content Standard E: Science and Technology

- Abilities of technological design
- Understandings about science and technology

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

- Natural resources
- Environmental quality
- 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 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 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 5.

##### The ocean supports a great diversity of life and ecosystems.

*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

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](mailto:oceanexeducation@noaa.gov).

### For More Information

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### Acknowledgements

This lesson was developed and written for NOAA's Office of Ocean Exploration and Research (OER) by Dr. Mel Goodwin, Science and Technology Consultant to OER's Education Team.

Design/layout: Coastal Images Graphic Design, Mt. Pleasant, SC.

### Credit

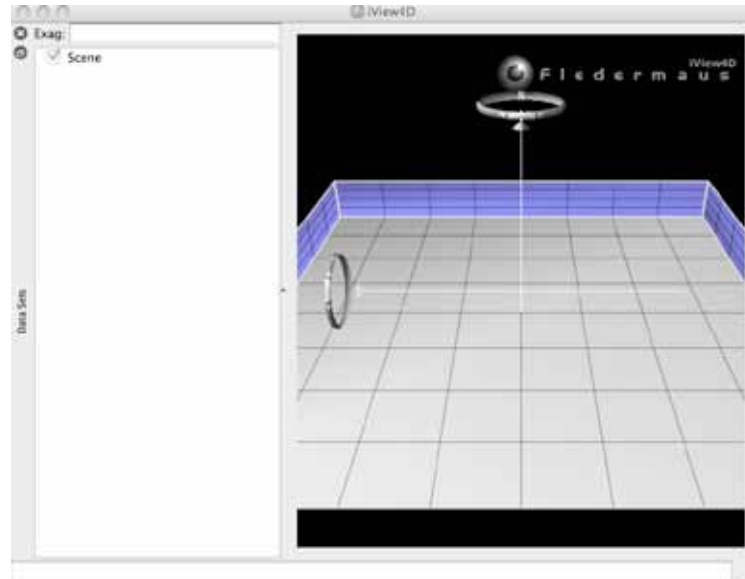
If reproducing this lesson, please cite NOAA as the source, and provide the following URL: <http://oceanexplorer.noaa.gov>

## Hot Maps

# Introduction to Multibeam Imagery Worksheet

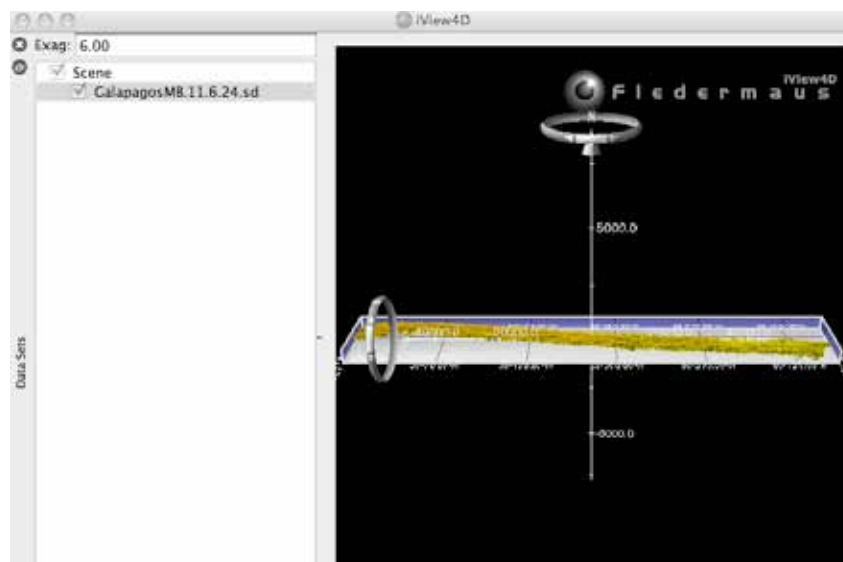
1. Launch the iView4D software. Your screen should resemble Figure 1. Note the Rotation Control Rings near the top center and mid-left side of the screen. If your screen doesn't look like Figure 1, be sure "Bounds" is checked under the "View" drop-down menu.

Figure 1



2. Open the file, **galapagos\_mb\_11\_6\_24.sd**. Now your screen should resemble Figure 2. This is a multibeam sonar image of the ocean floor along the Galapagos Ridge made aboard the *Okeanos Explorer* on June 24, 2011. Make the window as large as possible by clicking on the lined triangle in the lower right corner, then dragging down and to the right.

Figure 2



The ocean floor is shown as a three-dimension image. The x-axis represents longitude, the y-axis represents latitude, and the z-axis represents depth. Some of the numbers may not be clear at this point, but we will fix that shortly.

When you move the cursor over the image, the window near the bottom of the screen shows the geo coordinates (x, y, and z) for the location beneath the cursor. The x-coordinate is latitude, the y-coordinate is longitude and the z-coordinate is depth.

The Rotation Control Ring near the top allows you to rotate the image around the vertical axis, and the Rotation Control Ring on the left allows you to rotate the image around the horizontal axis. Alternatively, you can left-click (simple click on a Macintosh platform) and drag up or down to rotate the image around the horizontal axis, or left-click and drag left or right to rotate the image around the vertical axis. As you rotate the image, the numbers on the axes will probably become easier to read.

You can zoom the image by right-clicking (or control-clicking on a Macintosh platform) in the middle of the image then dragging to zoom in or out.

To change the center of the image, place the cursor over the point that you want to center upon, then right-click (control-click on a Macintosh platform). This allows you to move the image up and down or side to side.

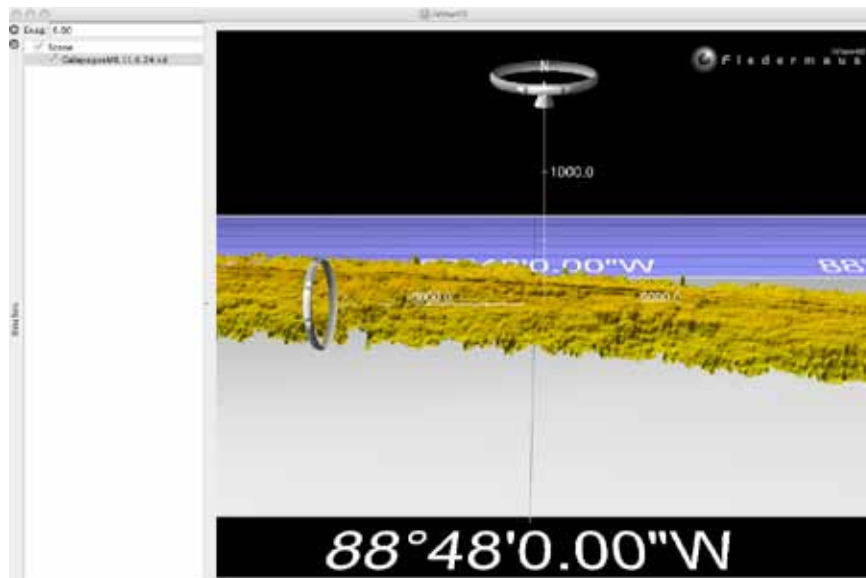
Some images use “vertical exaggeration” to show features more clearly. This means that the vertical scale is larger than the horizontal scale so vertical features are magnified. You can control the amount of vertical exaggeration by clicking and dragging the cone shaped object on the vertical scale line near the middle of the image. Numbers on the scale lines show the relative horizontal and vertical scales. The amount of vertical exaggeration is also shown in the “Exag” box at the upper left. The number is how many times the vertical scale is exaggerated relative to the horizontal scale. “6,” for example, means the vertical scale is 6 times larger than the horizontal scale.

Experiment with these controls to find out how they allow you to manipulate the image. If you want to return to the original view, select “Reset Camera” from the Camera menu, or click “escape.” When you have finished experimenting, reset the image to the original view.

3. Let’s look a little more closely at a portion of the image. Put the cursor on the yellow part of the image around longitude  $88^{\circ} 48' 0.00''$ , then right-click (control-click on a Macintosh platform) to center the view on this spot. Now zoom in until your screen resembles Figure 3. The dark horizontal line is the Galapagos Rift, where the Nazca Plate is diverging from the Cocos Plate. Use the Rotation Control Ring on the left to rotate the image around the horizontal axis so you can more clearly see the bottom of the Rift. What is

the depth in the vicinity of  $0^{\circ} 46' 55.0''$  North latitude,  $88^{\circ} 47' 57.00''$  West longitude?

Figure 3



4. During tow-yo operations, a CTD is raised and lowered through several hundred meters near the bottom as the ship slowly cruises over the area being surveyed (Figure 4). This raising and lowering is accomplished by using a winch to reel in a cable attached to the CTD, then allowing the cable to spool back out until the CTD has reached the desired depth. The position of the ship is precisely determined with GPS equipment, but the exact position of the CTD is somewhere behind the ship, depending upon how much cable has been released from the winch. The distance between the CTD and the ship is called setback. To help calculate the CTD's position during tow-yo operations, technicians keep a record of how much cable has been released when the CTD is at the shallowest and deepest parts of the tow-yo cycle (Figure 5).

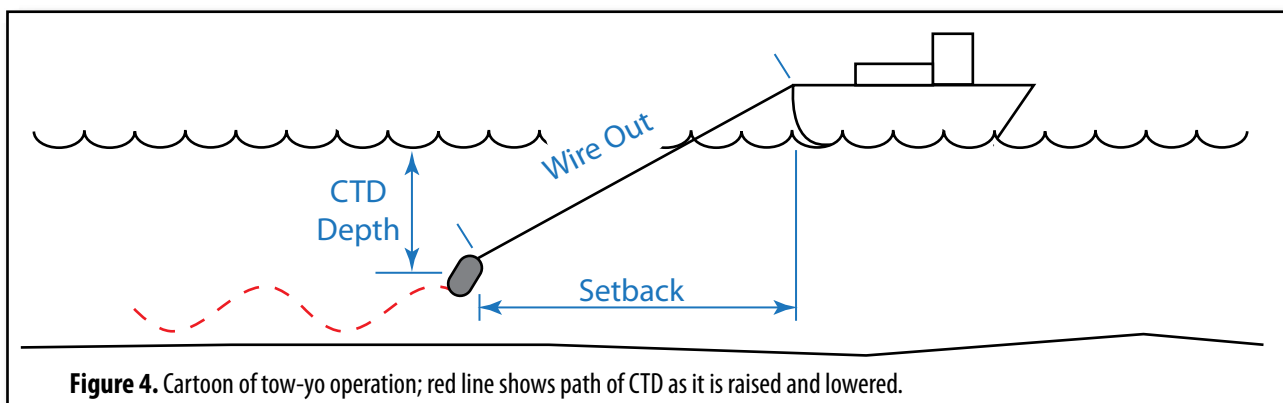


Figure 4. Cartoon of tow-yo operation; red line shows path of CTD as it is raised and lowered.

Early in the morning of June 25, 2011, tow-yo operations aboard *Okeanos Explorer* discovered plumes that might mean hydrothermal vents are nearby. From the information in Table 1, calculate the setback of the CTD when these two plumes were discovered.

**Figure 5.** Example of CTD navigation log during a tow-yo operation. (Scanned and emailed from the *Okeanos Explorer*. Recreated due to legibility issues.)

Julian Day	Time (UTC)	Ship Position ° Lat.	Ship Position ° Long.	CTD Depth	Wire Out (or range)	Altitude	Setback	Comments
174	21:02:08	0° 47.2510	89° 16.2040	1678.48	2371.37	19.78	1675	
*	21:08:21	0° 47.2480	89° 16.0540	1391.5144	2078.93	200	1537	
*	21:15:57	0° 47.2450	89° 15.8600	1676.622	2405.2	21.564	1725	
*	21:22:03	0° 47.2430	89° 15.7120	1399.2042	2107.17	200	1576	increased speed to 1.7 knots
*	21:33:14	0° 47.2400	89° 15.4010	1690.5664	2499.69	19.438	1841	
*	21:39:10	0° 47.2380	89° 15.2290	1399.1416	2200.16	200	1699	
*	21:48:39	0° 47.2340	89° 14.9320	1676.9136	2552.52	18.901	1951	

- Table 1 lists the ship's position and heading when the two plumes were discovered. Using this information and your setback calculations, estimate the latitude and longitude of the CTD when the plumes were discovered. Hint: Use an online calculator to determine distance and bearing between latitude/longitude points.
- On the **galapagos\_mb\_11\_6\_24.sd** image, place the cursor in the approximate location of the two points calculated in Step 5. Where are these points located relative to the Galápagos Rift?
- Place the cursor on the location calculated for the plume signal detected at 01:45. The easiest way to do this is to start with the view zoomed out (hit the escape key), then place the cursor in the approximate location of the desired point. Right-click (control-click on a Macintosh platform) to center the view on this spot. Zoom in a little, then reposition the cursor so it is closer to the desired position. Center the view on this spot, then zoom in some more. Repeat this process until you have the cursor positioned within 0.5" of the position. Describe the appearance of the seafloor at this location. About how deep is the seafloor at this location?
- Repeat the procedure used in Step 7 to examine the location calculated for the plume signal detected at 02:02. Describe the appearance of the seafloor at this location. About how deep is the seafloor at this location?
- The locations calculated in Step 5 are estimates. What factors might cause errors in calculating the probable location of vents that produced the plumes?

**Table 1. Navigation Data for Plumes Detected on June 25, 2011**

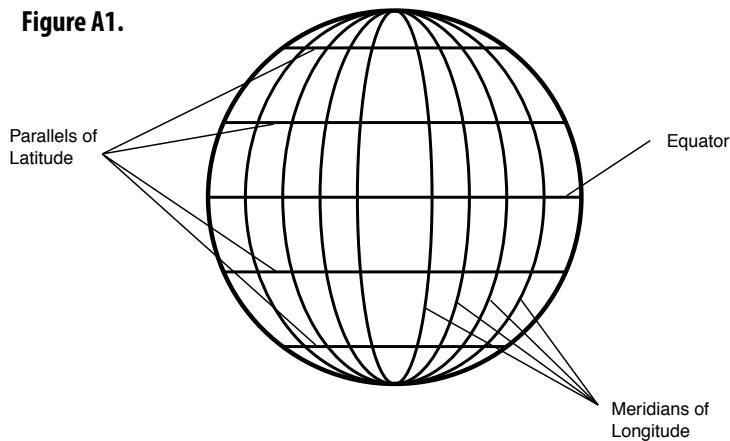
Time (UTC)	Ship Latitude	Ship Longitude	Ship Heading	CTD Depth (m)	Cable Out (m)	Setback (m)
01:45	0° 45' 8.496" N	88° 31' 5.304" W	094°	1883.206	3028	_____
02:02	0° 45' 7.415" N	88° 30' 36.936" W	094°	1871.047	3009	_____

## Appendix A

# Latitude and Longitude

All nautical charts are based on a system of geographic coordinates that can be used to describe a specific location on a body of water. One of the best-known and most widely used set of geographic coordinates is the latitude - longitude system. This system is based on two sets of imaginary circles on the Earth's surface. One set includes circles that pass through the north and south poles. These circles are known as "meridians of longitude." The other set includes circles that would lie on plane surfaces cutting through the Earth perpendicular to the polar axis (and therefore perpendicular to meridians of longitude). This second set of circles is known as "parallels of latitude" (see Figure A1).

**Figure A1.**



Geographic coordinates using the latitude - longitude system are measured in terms of degrees. The reference point for all measurements of longitude is the meridian passing through Greenwich, England; this

meridian is called the "prime meridian," and is represented by 0 degrees. The meridian of longitude that passes through any position on Earth is described in terms of how many degrees that meridian is to the east or west of the prime meridian. The maximum in either direction is 180 degrees. Sometimes, meridians to the west of the prime meridian are given a negative sign to distinguish them from meridians to the east of the prime meridian. Parallels of latitude are measured in terms of how many degrees a given parallel is north or south from the equator (which is assigned a latitude of 0 degrees). Fractions of degrees are expressed in minutes (there are 60 minutes in one degree) and seconds (there are 60 seconds in one minute). Minutes and seconds are sometimes divided decimally for very precise descriptions of geographic location. Each degree of latitude corresponds to sixty nautical miles, so one minute of latitude corresponds to one nautical mile (a nautical mile is equal to about 6,076 ft, or about 1.15 statute miles).