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New Zealand American Submarine Ring of Fire 2007

Where There's Smoke...

Focus
Hydrothermal vent chemistry at subduction volcanoes

Grade Level
9-12 (Chemistry)

Focus Question
How can unusual chemical phenomena near hydrothermal vents be explained in terms of melting points, boiling points, solubility, temperature, and pressure?

Learning Objectives
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.

Materials
- ❒ Copies of "Brimstone Pit Challenge Worksheet," one copy for each student or student group

Audio/Visual Materials
- ❒ (Optional) Computer projection facilities to show photographs and video

Teaching Time
Two or three 45-minute class periods, plus time for student research

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

Maximum Number of Students
30

Key Words
Melting point
Boiling point
Solubility
Temperature
Pressure
Ring of Fire
Asthenosphere
Lithosphere
Magma
Fault
Transform boundary
Convergent boundary
Divergent boundary
Subduction
Tectonic plate

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

Tectonic plates are of 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). These convection currents cause the tectonic plates to move several centimeters per year relative to each other.

The junction of two tectonic plates is called a "plate boundary." Three major types of plate boundaries are produced by tectonic plate movements. If two tectonic plates collide more or less head-on they form a convergent plate boundary. Usually, one of the converging plates will move beneath the other, which is known as subduction. 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. For a 3-dimensional view of a subduction zone, visit: http://oceanexplorer.noaa.gov/explorations/03fire/logs/subduction.html.

The junction of two tectonic plates that are moving apart is called a divergent plate boundary. Magma rises from deep within the Earth and erupts to form new crust 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 3-dimensional structure of a mid-ocean ridge at: http://oceanexplorer.noaa.gov/explorations/03fire/logs/ridge.html.

The third type of plate boundary occurs where tectonic plates slide horizontally past each other, and is known as a transform plate boundary. As the plates rub against each other, huge stresses are set up that can cause portions of the rock to break, resulting in earthquakes. Places where these breaks occur are called faults. A well-known example of a transform plate boundary is the San Andreas Fault in California. See animations of different types of plate boundaries at: http://www.seed.slb.com/en/scictr/watch/living_planet/plate_boundaries/plate_move.htm.

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

On the western side of the Pacific Ocean, the Pacific Plate converges against the Philippine Plate and Australian Plate. Subduction of the Pacific Plate creates the Marianas Trench (which includes the Challenger Deep, the deepest known area of the Earth's ocean) and the Kermadec Trench. As the sinking plate moves deeper into the mantle, new magma is formed as described above, and erupts along the convergent boundary to form volcanoes. The Mariana and Kermadec Islands are the result of this volcanic activity, which frequently causes earthquakes as well. The movement of the Pacific Ocean tectonic plate has been likened to a huge conveyor belt on which new crust is formed at the oceanic spreading ridges, and older crust is recycled to the lower mantle at the convergent plate boundaries of the western Pacific. For more information on plate tectonics, visit the NOAA Learning Objects Web site (http://www.learningdemo.com/noaa/). Click on the links to Lessons 1, 2 and 4 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Mid-Ocean Ridges, and Subduction Zones. See the satellite and sonar survey animation of the Mariana Arc Volcanic Chain at: http://oceanexplorer.noaa.gov/explorations/04fire/background/marianaarc/media/sat_em_islands_video.html.

Beginning in 2002, Ocean Exploration expeditions have undertaken systematic mapping and study in previously-unexplored areas of the Submarine Ring of Fire. Visit

- http://oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain/;
- http://www.oceanexplorer.noaa.gov/explorations/03fire/;
- http://www.oceanexplorer.noaa.gov/explorations/04fire/;
- http://www.oceanexplorer.noaa.gov/explorations/05fire/; and
- http://oceanexplorer.noaa.gov/explorations/06fire/welcome.html

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

On April 1, 2004, scientists exploring the NW Rota #1 Volcano reported that the ROPOS remotely operated vehicle (ROV) had been engulfed by balls of molten sulfur while investigating a portion of the volcano known as Brimstone Pit. The scientists also reported that plumes of hydrothermal fluids extended for several kilometers over and around the volcano's summit. These fluids were unusual, in that they contained the highest concentrations of particulate aluminum ever recorded, as well as high concentrations of sulfur, iron, and manganese. In this lesson, students will develop explanations for these and other observed phenomena based on relationships between melting points, boiling points, solubility, temperature, and pressure.

Learning Procedure

1. To prepare for this lesson, review:
   - Introductory essays for the New Zealand American Submarine Ring of Fire 2007 Expedition at http://oceanexplorer.noaa.gov/explorations/07fire/welcome.html;
   - Submarine Ring of Fire 2004 daily logs for March 30 and April 1 (http://oceanexplorer.noaa.gov/explorations/04fire/logs/march30/march30.html and http://oceanexplorer.noaa.gov/explorations/04fire/logs/april01/april01.html); and
   - April 24, 25, and 29 logs from the Ring of Fire 2006 Expedition, which Includes first-ever images of live red lava erupting from a submarine volcano.

   You may also want to print copies of the photographs and/or download the video vista of Brimstone Pit.

2. Briefly review the concepts of plate tectonics and continental drift and how they are related to underwater volcanic activity and hydrothermal vent systems. You may want to use resources from NOAA's hydrothermal vent Web site (http://www.pmel.noaa.gov/vents/index.html) and NOAA Learning Objects 1, 2, and 4 (http://www.learningdemo.com/noaa/) to supplement this discussion. Introduce the Ring of Fire, and describe the processes that produce the island arcs.

3. Show students photographs and videos of Brimstone Pit, or direct them to the Ocean Explorer Web site. Provide each student or student group with a copy of the "Brimstone Pit Challenge Worksheet," and have each student or student group develop explanations for observed phenomena as directed. Tell students that they are to use specific numeric information (such as solubility data) or chemical reac-

tions where possible. Background essays from the 2004 and 2006 Ring of Fire expeditions may be helpful in developing appropriate explanations.

4. Lead a discussion of students' results. Students should realize that sulfur dioxide can react with water to form sulfuric acid and elemental sulfur:

$3SO_2 + 2H_20 > 2\ H_2SO_4 + S$

Sulfur melts at 113°C and boils at 444°C. Brimstone Pit is about 555 meters deep. This would correspond to a pressure of 56.5 bar:

1 bar (surface pressure) + (555 meters depth • 1 bar/10 meters depth) = 56.5 bar

The boiling point graph shows that the boiling point of seawater would be over 250°C; so seawater could easily be hot enough to melt sulfur produced by the above reaction, and create the observed molten "blobs." Sulfuric acid produced by this reaction would account for the low pH observed in the area.

Low pH values would also help explain the high concentrations of particulate aluminum, iron, and manganese in the hydrothermal fluids. These metals are dissolved into the acidic hydrothermal fluid, but precipitate as the fluid mixes with cooler seawater.

The scientists in the submersible are working at a pressure of 30 bar:

300 meters depth • 1 bar/10 meters depth = 30 bar

This means that gas in the tube will expand 30 times when the pressure is reduced to one bar, assuming the temperature remains constant. So the scientists should only collect one inch of gas in the cylinder to avoid losing any gas on the way to the surface.

The Bridge Connection

www.vims.edu/bridge/ – Click on "Ocean Science Topics" then "Habitats," then "Deep Sea" for links to information and activities about hydrothermal vents.

The "Me" Connection

Have students write a brief essay describing how the chemical phenomena observed at Brimstone Pit might be of personal importance.

Connections to Other Subjects

Earth Science

Assessment

Worksheets and class discussions provide opportunities for assessment.

Extensions

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

2. Lieu, 1996 (see "Resources") has directions for a simple demonstration of phase changes of carbon dioxide.

Multimedia Learning Objects

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

Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

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

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

In this activity, students will define and describe biogeographic provinces of hydrothermal vent communities, identify and discuss processes contributing to isolation and species exchange between hydrothermal vent communities, and discuss characteristics which may contribute to the survival of species inhabiting hydrothermal vent communities.

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

Focus: Chemistry of hydrothermal vents (Chemistry)

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

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

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

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

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

Focus: Hydrothermal vent chemistry (Chemistry, Earth Science, Physical Science)

In this activity, students will be able to describe hydrothermal vents and characterize vent plumes in terms of physical and chemical properties, describe tow-yo operations and how data from these operations can provide clues to the location of hydrothermal vents, and interpret temperature anomaly data to recognize a probable plume from a hydrothermal vent.

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

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

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

Other Links and Resources

The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.

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

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

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

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

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

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
- Chemical reactions
- Interactions of energy and matter

Content Standard D: Earth and Space Science
- Energy in the Earth system
- Geochemical cycles
- Origin and evolution of the Earth system

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

Content Standard G: History and Nature of Science
- Nature of scientific knowledge

Ocean Literacy Essential Principles and Fundamental Concepts

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

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

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

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

Fundamental Concept b. Most life in the ocean exists as microbes. Microbes are the most important primary producers in the ocean. Not only are they the most abundant life form in the ocean, they have extremely fast growth rates and life cycles.

Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

Essential Principle 7.
The ocean is largely unexplored.

Fundamental Concept a. The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great

frontier for the next generation's explorers and researchers, where they will find great opportunities for inquiry and investigation.
Fundamental Concept b. Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.
Fundamental Concept d. New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.
Fundamental Concept f. Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

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Student Handout

Brimstone Pit Challenge Worksheet

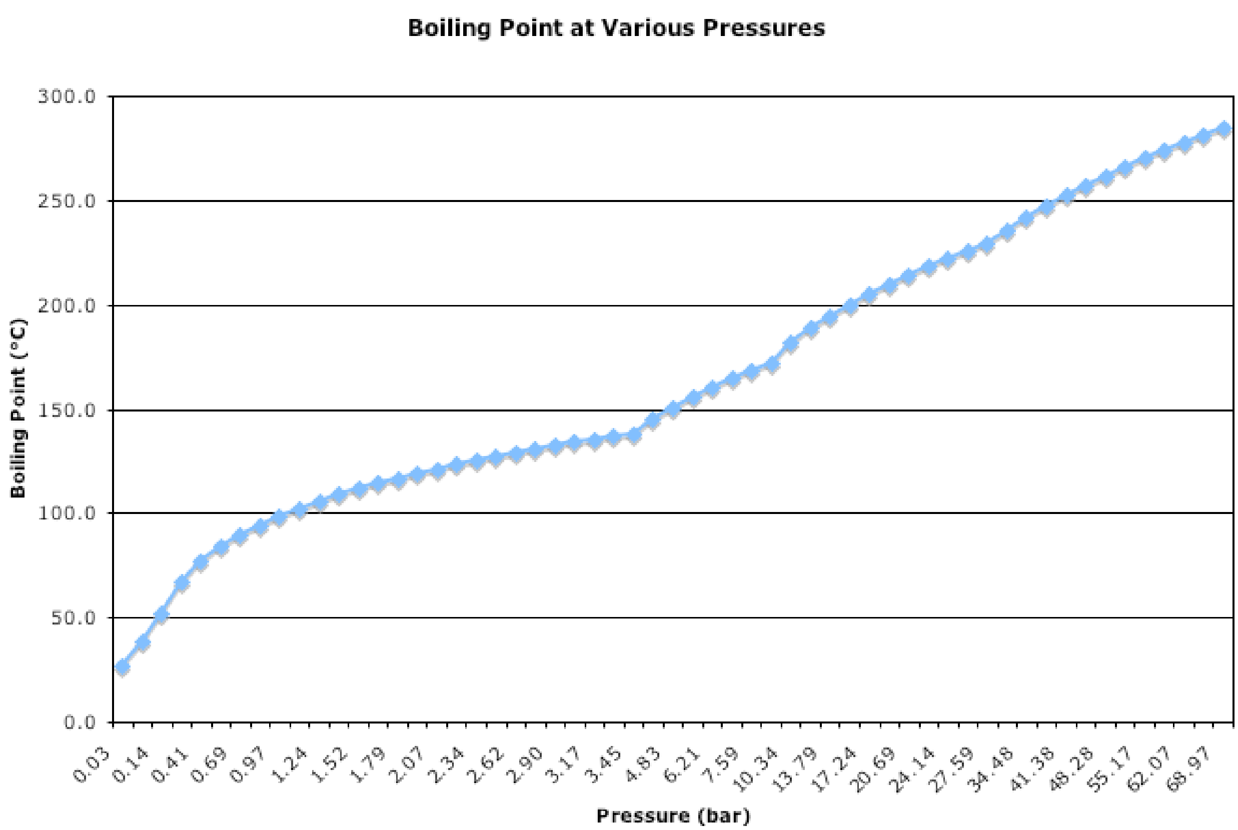
On April 1, 2004, scientists exploring the NW Rota #1 Volcano reported that the ROPOS remotely operated vehicle (ROV) had been engulfed by balls of molten sulfur while investigating a portion of the volcano known as Brimstone Pit. The scientists also reported that plumes of hydrothermal fluids extended for several kilometers over and around the volcano's summit. These fluids were unusual, in that they contained the highest concentrations of particulate aluminum ever recorded, as well as high concentrations of sulfur, iron, and manganese.

Your challenge is to use information about simple chemical reactions, melting points, boiling points, solubility, temperature, and pressure to provide reasonable explanations for:

1. The blobs of molten sulfur that splattered over the ROPOS ;
2. The low pH (about 2) observed in water samples collected from Brimstone Pit; and
3. The high concentrations of particulate aluminum, iron, and manganese in hydrothermal fluid plume over NW Rota #1 volcano.

Hints and other useful information:

- Sulfur dioxide is a common volcanic gas released from magma.
- The solubility of many metals, including aluminum, iron, and manganese increases at low pH values.
- Here is a boiling point curve for seawater. The graph shows that the temperature at which seawater boils increases as the pressure increases. The critical point is the point at which the properties of the gas phase and liquid phase become identical.



- You can find information about the depth of Brimstone Pit at http://oceanexplorer.noaa.gov/explorations/04fire/logs/march30/march30.html.
- The pressure at the surface of the ocean is one atmosphere (one bar in the metric system).
- Pressure in the ocean increases by one atmosphere (one bar) with every 10 meter increase in depth.

Extra Challenge:

Scientists inside a manned submersible at 300 m depth on a submarine volcano north of New Zealand observe gas bubbles coming out of a vent. The only thing they have available to collect the gas bubbles is a plastic cylinder that is open on one end and capped on the other end. They intend to collect bubbles by holding the cylinder with over the gas bubbles with the open end downward. The plastic cylinder is 30″ long. The scientists know that the gas bubbles will expand as the submarine rises. What is the maximum amount of gas (in inches) that the scientists can collect in their cylinder without losing any gas as the submarine rises to the sea surface (assume the temperature in the cylinder remains constant)?

[provided by John Lupton, a NOAA scientist]