2005 Lost City Expedition

Towers of the Lost City

Focus
pH, buffers, and chemistry of the Lost City hydrothermal chimneys

Grade Level
7-8 (Physical Science/Earth Science)

Focus Question
What chemical processes are involved in forming the Lost City hydrothermal chimneys?

Learning Objectives
Students will be able to define a buffer, and explain in general terms the carbonate buffer system of seawater.

Students will be able to define pH, and contrast the pH of hydrothermal vent fluids at Lost City with those associated with "black smokers."

Students will be able to describe the process through which hydrothermal chimneys are formed at Lost City, and identify the primary chemicals involved in this process.

Materials
- ❒ Copies of the Buffer Properties of Seawater Worksheet; one copy for each student group
- ❒ Protective goggles and gloves; one set for each student and one for the teacher
- ❒ 100 ml glass beaker; one for each student group
- ❒ 100 ml graduated cylinder; one cylinder may be shared by several student groups, but have separate cylinders for distilled water and seawater
- ❒ 500 ml glass beaker
- ❒ 2 - 1 liter beakers or Erlenmeyer flasks for mixing solutions
- ❒ Plastic washbottle, 500 ml capacity
- ❒ Glass stirring rod; one for each student group
- ❒ Sodium hydroxide pellets, approximately 50 grams (see Learning Procedure, Step 1)
- ❒ Solid citric acid (to neutralize sodium hydroxide spills); approximate 450 grams
- ❒ Distilled water; approximately 150 ml for each student group, plus 1.5 liters for making solutions (see Learning Procedure, Step 1)
- ❒ Artificial seawater; approximately 150 ml for each student group, plus approximately 250 ml for demonstration
- ❒ pH test paper, wide range; one roll for each student group
- ❒ Dilute acetic acid solution in dropper bottles; one bottle containing approximately 50 ml for each student group (see Learning Procedure, Step 1)
- ❒ 0.1 M sodium hydroxide solution in dropper bottles; one bottle containing approximately 50 ml for each student group (see Learning Procedure, Step 1)
- ❒ (Optional) modeling clay, two colors (see Learning Procedure, Step 6)

Audio/Visual Materials
- ❒ Marker board or overhead projector with transparencies

Teaching Time
One or two 45-minute class periods

Seating Arrangement

Groups of two to four students

Maximum Number of Students

30

Key Words

Lost City
Hydrothermal vent
Peridotite
Buffer
pH
Calcium carbonate

Background Information

In 1977, scientists in the deep-diving submersible Alvin made the first visit to an oceanic spreading ridge near the Galapagos Islands, and made one of the most exciting discoveries in 20th century biology. In the middle of deep, cold ocean waters, they found hot springs and observed black smoke-like clouds billowing from chimneys of rock; and nearby were communities of animals that no one had ever seen before.

These hot springs came to be known as hydrothermal vents, and since that first discovery, more than 200 similar vent fields have been documented in the world's ocean. These systems are formed when seawater flowing through cracks in the seafloor crust enters magma-containing chambers beneath a spreading ridge. Intense heat from the molten rock causes a variety of chemical changes and many substances from the rocks become dissolved in the fluid. The heated fluid becomes less dense, rises upward, and emerges onto the sea floor to form a hydrothermal vent. When the heated fluid is cooled by cold water of the deep ocean, many of the dissolved materials precipitate, creating black clouds and chimneys of rock-like deposits. The hydrothermal fluid emerging from the vents is rich in sulfide, which is used as an energy source by chemosynthetic bacteria to produce essential organic substances. These autotrophic bacteria are the base of a diverse food web that includes large tubeworms (vestimentiferans), clams, mussels, limpets, polychaete worms, shrimp, and crabs.

In 2000, a different sort of vent field was serendipitously discovered on an underwater mountain called the Atlantis Massif near the Mid-Atlantic Ridge. This new field also had hot fluids venting from rocky chimneys. But these chimneys towered as much as 200 feet above the seafloor, much larger than chimneys found in other vent fields. In fact, the vent field was located 15 kilometers away from the spreading axis of the Mid-Atlantic Ridge and the chimneys looked so much like towers and spires of a fantastic city that the new vent field was named "Lost City." And the fluids emerging from the chimneys, as well as the surrounding biological communities, were unlike any other known hydrothermal system. Subsequent investigations have shown that the newly-discovered hydrothermal fields are not formed by seawater reacting with molten magma. Instead, these fields are formed when seawater reacts with solid mantle rocks. These rocks, called peridotites, are formed deep inside the Earth, but a unique type of faulting can bring them close to the seafloor. Cracks in the seafloor can allow seawater to percolate down to the up-lifted peridotites. When this happens, numerous chemical reactions occur between seawater and minerals in the rock (a process called serpentinization). These reactions produce a large amount of heat that causes the fluids to rise and eventually vent at the surface of the seafloor. Mixing between the heated fluids and cold surrounding seawater causes additional reactions that include precipitation of calcium carbonate (limestone), which forms the towering chimneys of Lost City. Because the reactions of seawater with peridotites are essential to these formations, the Lost City is called a "peridotite-hosted ecosystem."

In contrast to the abundant biological communities of hydrothermal vents formed by volcanic activity, the Lost City Hydrothermal Field (LCHF) initially appeared to be devoid of living organisms. But when scientists took a closer look at the surface of the chimneys (they actually vacuumed the surface), they found large numbers of tiny shrimps and crabs. Because most of these animals are less than one centimeter in size, transparent or translucent, and tend to hide in small crevices, they were easily overlooked when the LCHF was first discovered. While the total biomass around the LCHF vents appears to be less than at other hydrothermal vents, scientists believe there is just as much diversity (variety of different species). Like previously discovered vent communities, the LCHF ecosystem is based on microorganisms that are able to use chemicals in the vent fluids as an energy source for producing complex organic compounds that are used as food by other species (chemosynthesis). But again, the LCHF differs in that the fluids emerging from the chimneys has very little of the hydrogen sulfide and metals that are typical in hydrothermal fluids of other vent. Instead, LCHF vent fluids contain high concentrations of methane and hydrogen, and these chemicals appear to provide the energy source for chemosynthetic microbes.

In this lesson, students will investigate some properties of the ocean's carbonate buffer system, and make inferences about the chemical reactions that form the towering chimneys at LCHF.

Learning Procedure

1. To prepare for this lesson:
    - Visit the Lost City expedition's Web pages (http://oceanexplorer.noaa.gov/explorations/05lostcity/welcome.html; http://www.lostcity.washington.edu/; and http://www.immersionpresents.org) for an overview of the expedition and background essays.

    - Prepare solutions for student demonstration and experiment:

      (a) 4 M sodium hydroxide solution: Dissolve 40 g NaOH in 100 mL water, then dilute to 250 ml. Transfer the solution to a plastic wash bottle.

      (b) 0.1 M sodium hydroxide solution: Dilute 25 ml of 4 M sodium hydroxide solution to a volume of 1 liter. Transfer the solution to dropper bottles, one bottle for each student group.

      [**NOTE: Be careful!** Concentrated sodium hydroxide is dangerous. Use goggles and protective rubber gloves when working with solid chemicals and solutions, and be sure the surfaces of gloves and bottles are dry to avoid accidental slippage when bottles are handled. Any chemical that contacts the skin should be immediately washed off with copious quantities of water. Then apply dilute vinegar solution to neutralize traces of the alkali. Spills of alkalis should be diluted as above before mopping up. For large spills, solid citric acid should be used as a neutralizer.]

      (c) Dilute acetic acid solution: Transfer white vinegar to dropper bottles, one bottle for each student group.

      (d) Artificial Seawater: Follow directions on package to prepare required quantity (see Materials; typically, 1 liter will require about two tablespoons of the dry powder).

2. Briefly review the concepts of plate tectonics, being sure that students understand the processes that take place at convergent and divergent boundaries, and why these boundaries are often the site of volcanic activity. Briefly review the discovery of hydrothermal vents, and describe the general appearance of hot fluids venting from chimneys or cracks in the seafloor. You may want to show video clips from some of the sites referenced in Step 1 to supplement this discussion. Be sure students understand that these vent communities were produced by seawater reacting with molten magma.

   Tell students that in the year 2000 a different type of vent community was discovered in which heat results from reactions between seawater and solid rock (peridotite) that has been brought close to the surface by faulting. These reactions occur because the peridotite was originally formed deep inside the Earth's mantle, and has a chemical structure that is not stable in the presence of water.

Review the concept of acids and bases, and pH, and be sure students understand that vent fluids produced by reactions between seawater and molten magma are very acidic, while the vent fluids at LCHF are extremely basic. Describe (or show images of) the chimneys that give Lost City its name, and tell students that some of these are much higher than the chimneys associated with black smokers.

3. Tell students that they are going to conduct an experiment and observe a demonstration that will help them make some inferences about how the LCHF chimneys are formed. Provide each student group with a copy of the "Buffer Properties of Seawater Worksheet" and the materials listed on the worksheet.

4. When students have completed the procedures described on the worksheet, lead a discussion of their results. Students should have found that seawater is much more resistant to changes in pH than distilled water, and consequently is a good buffer. Write the following equation on a marker board or overhead transparency so that it is visible to all students:

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \leftrightarrows \underset{\text{carbonic acid}}{H_2CO_3} \leftrightarrows \underset{\text{hydrogen ion}}{H^+} + \underset{\text{bicarbonate ion}}{HCO_3^-} \leftrightarrows \underset{\text{hydrogen ion}}{H^+} + \underset{\text{carbonate ion}}{CO_3^{2-}}$$

Tell students that this equation describes the carbonate buffer system of seawater. The equation shows that carbon dioxide dissolves in seawater to form carbonic acid, a weak acid. Most of the carbonic acid normally dissociates to form hydrogen ions, bicarbonate ions, and carbonate ions. Be sure students understand that carbon dioxide, carbonic acid, bicarbonate ions, and carbonate ions are all present in normal seawater, although not in the same concentrations (bicarbonate and carbonate concentrations are much higher than carbon dioxide and carbonic acid). When these chemicals are in equilibrium, the pH of seawater is about 8.1 – 8.3 (slightly basic).

Remind students of Le Chatelier's Principle: If a system that is in equilibrium is changed, the system will react in such a way as to undo the effect of the change. Ask students to predict what will happen if hydrogen ions are added to normal seawater. Considering Le Chatelier's Principle, students should realize that the system will react in a way that tends to remove hydrogen ions from solution, so the reactions will proceed to the left. Next, ask students to predict what will happen if a very basic solution (which tends to remove hydrogen ions from solution) is added to normal seawater. Students should predict that the system will react in a way that tends to add more hydrogen ions, and so the reactions will proceed to the right.

5. Tell students that you are going to demonstrate what happens when a strongly basic solution is added to seawater. Pour about 200 ml of artificial seawater into a 500 ml beaker. Place the tip of the washbottle containing 4 M sodium hydroxide solution beneath the surface of the seawater, and slowly squeeze the washbottle. As the sodium hydroxide solution enters the seawater a flaky white precipitate should form.

Ask students to infer what has taken place, and how this might help explain the formation of white towers at Lost City. From the discussion in Step 4, they should infer that the reactions of the buffer system have proceeded to the right, adding more hydrogen ions to the solution, as well as more carbonate ions. If necessary, prompt students to speculate about what produced the precipitate. Since more carbonate ions were produced by the buffer system in response to the basic solution, they may infer that these ions might be involved in forming the precipitate. You may need to remind students that seawater is a mixture of many different chemicals; in fact there are more than 70 elements dissolved in normal seawater, but only 6 account for more than 99% of all dissolved substances. These six (which all occur as ions) are: chloride (Cl^-), sodium (Na^+), sulfate (SO_4^{2-}), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+). This should lead to speculation that the white precipitate may be carbonate ions combined with one or more of the positively charged ions normally present in seawater. Tell students that hydrothermal vent fluids at Lost City are enriched with calcium, and that calcium carbonate is a white, rock-like substance. This should lead students to infer that the white chimneys at Lost City may be composed of calcium carbonate precipitated when the highly basic and calcium enriched vent fluids encounter seawater.

6. Tell students that calcium carbonate deposits at Lost City have been seen in a variety of shapes other than the spectacular chimneys. These shapes range from arrays of delicate fingerlike crystals to masses resembling beehives that are tens of centimeters across. In some areas, calcium carbonate deposits form massive walls on steep sides of the mountain-like Atlantis Massif. Ask students to speculate on the processes through which these deposits are formed. You may need to remind students that the chemical reactions that produced the highly basic vent fluid are the result of reactions between seawater and rocks that have been uplifted from deep in the mantle by faulting. You can illustrate an imaginary fault by making a two-layer hamburger-size cake from modeling clay, with the lower layer representing the peridotite in the mantle and the upper layer representing the Earth's crust. Simulate a fault by pushing, pulling, or twisting the cake so that part of the lower layer protrudes through the surface of the upper layer (at this point no one is sure about the exact faulting process, except that it is incredibly powerful). This should make it clear that cracks in the crust can take many forms other than vertical channels. Hydrothermal fluids escaping through these cracks could emerge as a narrow stream (like the washbottle) or as a much more diffuse flow which would cause the calcium carbonate deposits to have a variety of shapes.

The Bridge Connection

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

The "Me" Connection

Have students write a brief essay describing how buffer systems are of personal benefit. If you need to "jump-start" the creative process, remind students that the chemistry of their blood is very similar in many ways to seawater, and that most organisms (including humans) do not tolerate large fluctuations in pH.

Connections to Other Subjects

English/Language Arts, Life Sciences

Evaluation

Experimental work in Step 3 and subsequent discussions provide opportunities for assessment.

Extensions

Have students visit http://oceanexplorer.noaa.gov/explorations/05lostcity/welcome.html to keep up to date with the latest Lost City Expedition discoveries.

Resources

http://oceanexplorer.noaa.gov/explorations/05lostcity/welcome.html – Web site for the 2005 Lost City expedition.

Kelley, D. S. and S. P. Sylva. 2005. A serpentinite-hosted ecosystem: The Lost City Hydrothermal Field. Science 307:1428-1434 – The technical journal article on which this lesson is based

http://www.oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain/welcome.html – Virtual tour of Magic Mountain, a hydrothermal vent site located on Explorer Ridge in the NE Pacific Ocean, about 150 miles west of Vancouver Island, British Columbia, Canada.

http://oceanexplorer.noaa.gov/explorations/03fire/logs/ridge.html – 3-dimensional structure of a "mid-ocean ridge," where two of the Earth's tectonic plates are spreading apart

http://www.bio.psu.edu/hotvents – Virtual tour of hydrothermal vent communities

http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML.ps_vents.html – Links to many other Web sites with information about hydrothermal vents

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

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
- Properties and changes of properties in matter

Content Standard D: Earth and Space Science
- Structure of the Earth system

Content Standard F: Science in Personal and Social Perspectives
- Populations, resources, and environments
- Science and technology in society

Content Standard G: History and Nature of Science
- Nature of science

For More Information

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Acknowledgements

This lesson plan was produced by Mel Goodwin, PhD, The Harmony Project, Charleston, SC for the National Oceanic and Atmospheric Administration. If reproducing this lesson, please cite NOAA as the source, and provide the following URL:
http://oceanexplorer.noaa.gov

Buffer Properties of Seawater Worksheet

A buffer is a solution that tends to resist changes in pH. In this experiment, you will investigate the buffer system in seawater.

Materials

Distilled water, approximately 150 ml
Artificial seawater, approximately 150 ml
pH test paper
Dilute acetic acid solution in dropper bottle
0.1 M sodium hydroxide solution in dropper bottle
100 ml glass beaker
100 ml graduated cylinder
Glass stirring rod

Procedure

1. **Wear eye protection and gloves throughout this experiment! Wash your hands thoroughly when you are finished! Do not eat, drink, or chew anything while you are in the laboratory!**
2. Measure 50 ml of distilled water into a 100 ml glass beaker. Test the pH by dipping a strip of pH test paper into the water and comparing the color of the paper to the chart on the test paper container. Record the pH on the data chart below.
3. Add one drop of dilute acetic acid to the beaker, stir with a glass stirring rod, test the pH, and record the result on the data chart.
4. Repeat step 3 until 20 drops of dilute acetic acid have been added, testing and recording the pH after each drop.
5. Rinse the beaker, then repeat Steps 2 through 4 using seawater instead of distilled water. Be sure to use a separate graduated cylinder for measuring the seawater.
6. Rinse the beaker and repeat Steps 1 through 4 with distilled water and seawater (use a different graduated cylinder for each!), but use 0.1 M sodium hydroxide solution instead of dilute acetic acid.
7. Wash your hands thoroughly!
8. What do your data suggest about the buffer system of seawater compared to distilled water?

Buffer Properties of Seawater Chart

Drops Dilute Acetic Acid	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
pH Distilled Water																					
pH Seawater																					

Drops 0.1 M NaOH	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
pH Distilled Water																					
pH Seawater																					