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PHAEDRA 2006:

Partnership for Hellenic-American Exploration in the Deep Regions of the Aegean

The Roving Robotic Chemist

Focus

Underwater mass spectrometry

Grade Level

9-12 (Physical Science)

Focus Question

How can real-time mass spectrometry be used on an autonomous underwater vehicle to locate underwater volcanoes and other geological features?

Learning Objectives

Students will be able to explain the basic principles underlying mass spectrometry.

Students will be able to discuss the advantages of in-situ mass spectrometry, and explain the concept of "dynamic re-tasking" as it applies to an autonomous underwater vehicle.

Students will be able to develop and justify a sampling strategy that could be incorporated into a program to guide an AUV searching for chemical clues to specific geologic features.

Materials

- ☐ Copies of "Guidance Questions for Researching the Principles of Mass Spectrometry," one copy for each student or student group
- ☐ Copies of the "AUV Survey Tracking Sheet" and "Methane Concentration Contour Map" copied onto plain paper, and the "Plume Location Grid" copied onto an overhead projector transparency; at least one copy of each for each student group

Audio/Visual Materials

- ☐ None

Teaching Time

One 45-minute class period, plus time for student research

Seating Arrangement

Groups of 3-4 students

Maximum Number of Students

30

Key Words

Mass spectrometer
Underwater volcano
Cold seep
AUV
Robotic vehicle
Dynamic re-tasking
Underwater archaeology

Background Information

"Man hoisted sail before he saddled a horse. He poled and paddled along rivers and navigated the open seas before he traveled on wheel along a road. Watercraft were the first of all vehicles." Thor Heyerdahl, *Early Man and the Ocean* (Doubleday, 1979)

Mariners have travelled the Aegean Sea since Neolithic times (the Stone Age: 6,500 – 3,200 BC). Motives for their voyages ranged from trading to exploration to warfare, making seafaring prominent in the history of cultures that include the Minoans (ca 2,600 – 1,450 BC), Mycenaeans (ca 1,600 – 1,100 BC), Ancient Greeks (776 – 323 BC), and Hellenistic Greeks (323 – 146 BC). Remnants of ancient ocean voyages (i.e., shipwrecks) can provide information about trading patterns, sociopolitical networks, technological development and many other unique insights into these cultures, but a variety of factors makes it difficult to find such remnants. One problem is that interactions between cultures were not always peaceful, and destroying important shipping assets would have been an obvious step toward conquering an opponent.

Another obstacle is the same feature that makes ancient shipwrecks so valuable: their age. In addition to increasing the severity of deterioration by biological and chemical processes, the passage of time also increases the likelihood that ancient shipwrecks will be impacted by natural disasters. The southern Aegean region has experienced numerous severe volcanic events and tsunamis, including the eruption of a volcano near a small island called Thera (also known as Santorini), sometime between 1,650 and 1,450 BC. This eruption is estimated to have been four times more powerful than the Krakatoa volcano of 1883, left a crater 18 miles in diameter, spewed volcanic ash throughout the Eastern Mediterranean, and may have resulted in global climatic impacts. Coupled with earthquakes and a tsunami, the volcano destroyed human settlements, fleets of ships, and may have contributed to the collapse of the Minoan civilization. More recently, the 1650 AD eruption of the Columbo volcano—7 km to the northeast of Thera—produced ash, pumice, toxic gases, and a tsunami that devastated the coasts of surrounding islands.

Even if ancient shipwrecks survive natural disasters (and those caused by humans), finding, exploring and scientifically studying these sites are complicated by the fact that much of the Aegean Sea is relatively deep. Total darkness and an environment that is extremely hostile to humans have, until recently, been obstacles that are virtually insurmountable. Technological advances over the past decade, though, have made deepwater archaeology a much more feasible endeavor. The PHAEDRA 2006 Expedition will use the SeaBED Autonomous Underwater Vehicle to search for deepwater shipwrecks, as well as conduct precise geological and chemical surveys in the vicinity of underwater volcanoes in the Aegean Sea. "Autonomous Underwater Vehicle" (AUV) means that this is a self-contained underwater robot that operates without a physical cable or tether such as those used on remotely operated vehicles (ROVs). SeaBED is designed specifically to provide precise maps and high-resolution three-dimensional color images of seafloor features, as well as to carry equipment for measuring physical and chemical properties of the surrounding seawater. Using SeaBED to map and document survey sites frees archaeologists from tedious measuring and sketching tasks and allows them to concentrate on interpreting survey results. For more information about SeaBED, visit http://www.whoi.edu/institutes/doei/general/news_seabed.pdf.

This expedition is an unusual collaboration between four U.S. research institutions and the Greek Ephorate of Underwater Antiquities (Hellenic Ministry of Culture) and Hellenic Centre for Marine Research. Scientists from Woods Hole Oceanographic Institution, Massachusetts Institute of Technology, Franklin W. Olin College of Engineering, and Johns Hopkins University will work with their Greek counterparts to use underwater robots to make detailed archaeological surveys of two ancient shipwrecks in deep water. One of these is believed to be the wreck of a Classical or Hellenistic ship that lies in a depth of about 500 m off the island of Hythnos in the central Aegean Sea. The other is believed to be the remains of a Byzantine period vessel that sank in 110 m of water off Porto Kuofo in the northern Aegean.

A third survey area will focus on a portion of the Aegean seafloor that scientists believe was unaffected by the Theran eruption and may consequently contain very ancient shipwrecks that have not yet been discovered. This area is close to the Columbo volcano, but has never been explored. To learn more about volcanic processes in this area, surveys will precisely map the seafloor and gather chemical data that will provide clues about volcanic activity as well as unusual geologic features such as cold seeps and volcanic vents.

The Gemini mass spectrometer that will be used in this expedition is unusual in that it makes measurements as soon as water samples are collected, in about 10 seconds. In contrast, other surveys that have used mass spectrometers for similar purposes have had to wait until water samples were transported back to laboratories for analysis, sometimes several weeks after the samples were collected, and usually long after scientists had left the area that was sampled. A big advantage of in-situ measurements is the fact that these are "real-time" measurements that can warn of dangerous geologic activity (e.g., volcanic eruptions). In addition, real-time measurements can provide the basis for "dynamic re-tasking," which means that an AUV can deviate from its programmed task list if certain chemicals are detected. This means that an AUV could be instructed to automatically seek the source of chemicals that might be emitted from underwater volcanoes, cold seeps, hydrothermal vents, or other interesting features.

Students will investigate the principles of mass spectrometry, and challenge other students in a game that models dynamic re-tasking of an AUV.

LEARNING PROCEDURE

1. To prepare for this lesson, review the background essays for the PHAEDRA 2006 Expedition at http://oceanexplorer.noaa.gov/explorations/06greece/. If students do not have access to the internet, make copies of relevant materials on underwater robotic vehicles from the Web site referenced above.
2. Introduce the PHAEDRA 2006 Expedition, emphasizing the role of the SeaBED AUV. Highlight the types of information that the AUV will collect, including photographic images as well as chemical data. One of the challenges about investigating unexplored areas is deciding what kinds of information to collect. In this case, there is good reason to suppose that there may be undiscovered shipwrecks as well as unusual geologic activity in the same general area, so it makes sense to collect data that can help locate both types of features. Briefly discuss the Gemini mass spectrometer. Tell students that their assignment is to research the basic principles upon which mass spectrometers operate, and then compete in a contest that models one of the ways in which an AUV might use real-time mass spectrometry data.
3. Provide each student group with a copy of the "Guidance Questions for Researching the Principles of Mass Spectrometry." There are numerous sources on the internet and in encyclopedias that describe these principles, so students should have little difficulty locating answers to the questions.
4. Discuss students' answers to the guidance questions, which should include:
   - The four major steps in mass spectrometry are:
     a. Ionization – Atoms of a substance being analyzed are vaporized, and bombarded with electrons from a heated plate (also known as an "electron gun"), causing one or more electrons to be knocked off, leaving the atoms with a positive charge (which makes them ions).
     b. Acceleration – Ions are accelerated by a positively charged plate (called an "ion repeller" which repels the positive ions) and negatively charged grids (which attract the ions).
     c. Deflection – The ions move through a magnetic field which causes the path of the ions to bend.

d. Detection – A metal plate is placed in the path of the ions so that only those ions whose path has been bent by a certain amount will strike the plate. Ions that strike the plate gain an electron from the metal which causes a current to flow through a circuit connected to the plate. This current is proportional to the number of ions that strike the plate. Information about the strength of the magnetic field (which corresponds to a certain amount of deflection) provides a measure of the size of the ions. Measurement of the current flowing through the metal plate provides a measure of the relative number of ions. By varying the magnetic field, different-size ions can be detected and their relative concentrations compared.

- The amount of deflection depends on the mass of the ion (lighter ions are deflected more easily than heavier ones) and the charge on the ion (ions that have lost two or more electrons are deflected more than ions that have lost only one electron).

- Ionic mass and charge are combined into the mass/charge ratio, abbreviated "m/z" or "m/e."

- Mass spectrometers need to operate in a vacuum because if air (or other) molecules were present, they would severely interfere with the path of ions.

You may want to use the cannon ball analogy if students have difficulty grasping the idea behind mass spectrometry: imagine a cannon ball is flying past you and you want to deflect its path with a jet of water from a garden hose. Obviously, the force from the hose won't have much effect. But suppose the object flying past is a tennis ball instead of a cannon ball. Now, the force of the water will have a much greater impact on the path of the ball. If you measured the force of the water, the amount of deflection, and the velocity of the ball, you could calculate the ball's mass. This is the concept behind mass spectrometry.

Discuss advantages of in-situ mass spectrometry, and highlight the concept of "dynamic re-tasking" as it applies to an AUV.

5. Tell students that they are about to compete with each other to locate the source of a deepwater plume of dissolved methane that may be coming from an undiscovered cold seep (if students are unfamiliar with cold seeps you may want to briefly discuss these; see http://www.bio.psu.edu/cold_seeps for more information). Explain that one group will control the movements of an imaginary AUV that is searching for the plume, and another group will control the location of the plume in the survey area and provide data on dissolved methane to the survey group.

   Pair each student group with another group, and assign the role of "Surveyor" or "Plume Locator" to each group. Provide each Surveyor group with a copy of the "AUV Survey Tracking Sheet." Provide each Plume Locator group with a copy of the "Plume Location Grid" and the "Methane Concentration Contour Map." Explain the ground rules for the Dynamic Re-Tasking Game:

   a. This game takes place inside a 10 x 10 grid that corresponds to an area of sea bottom being surveyed by an AUV. The survey may begin at any corner of the grid (cell 0,0; 0,9; 9,0; or 9,9), and the AUV may move to any adjacent grid cell. Because of limited battery power and time constraints, the AUV may cross no more than 50 grid cells, and may sample no more than 16 of these cells.

   b. Prior to the start of each game, the Plume Locator group will place the transparent "Plume Location Grid" on top of the "Methane Concentration Contour Map." The Methane Concentration Contour cells can match up with any cells on the Location Grid, and it is not necessary for all of the Methane Concentration Contour cells to be included on the Location Grid; but the "12 nmol/kg" cell must be somewhere on the grid.

c. To begin a game, the Survey group states the coordinates of the starting cell, and then states the coordinates of each cell that the AUV moves across. When the AUV crosses a cell that the Survey group wishes to sample, the Surveyors will say "Sample!" and the Plume Locator group will state the dissolved methane concentration for that cell. If a Location Grid cell does not correspond with a Methane Concentration Contour cell, the Plume Locator group says, "Trace" (i.e., the concentration is too low to quantify). The Survey group will write the dissolved methane concentration in the corresponding grid cell on the "AUV Survey Tracking Sheet," and then move to the next cell. The object of the game is to locate the source of the plume (which is indicated by a dissolved methane concentration of 12 nmol/kg) using the smallest possible number of moves by the imaginary AUV. When the 12 nmol/kg cell is located, record the number of cells crossed by the AUV. This is the Survey group's score. If 50 cells are crossed or 16 samples are collected before the 12 nmol/kg cell is discovered, the Survey group gets no score (they lose).

After the first game has been played, Survey groups become Plume Locator groups and vice versa, new "AUV Survey Tracking Sheets," "Plume Location Grids," and "Methane Concentration Contour Maps" are distributed, and a second game is played. The group with the lowest score wins.

6. Say that the AUV must be programmed prior to beginning the survey, so each group should discuss their sampling strategy, then write down their "program." Remind students of the constraints on AUV movement (it may cross no more than 50 grid cells and sample no more than 16 cells). You may want to suggest that the survey should begin by sampling every third cell or so, then have a plan for how to proceed if methane is detected. Alternatively, you may decide to let them work this out for themselves.

7. Lead a discussion about the most successful strategies for "dynamic re-tasking." A reasonable strategy would be to plan to cross the survey grid with a zig-zag pattern, sampling every third grid cell (see Figure 1). Once methane is detected, the pattern could change to a circle until the methane concentration increases (Figure 2), and then move in the direction of increasing concentration.

Figure 1. Zigzag search pattern, beginning cell 0,0

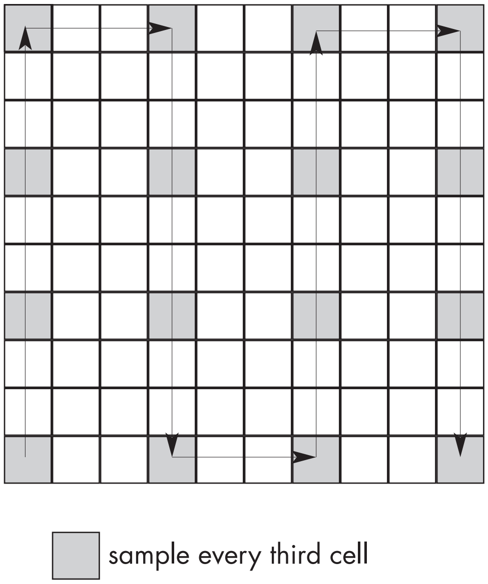
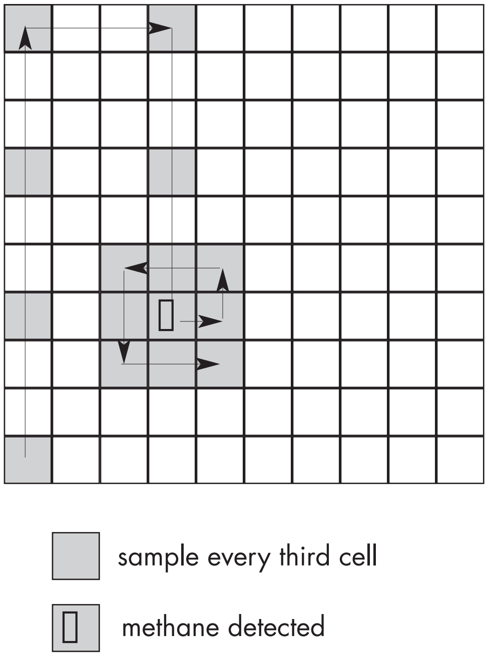


Figure 2. Zigzag search pattern, modified to circular search pattern when methane is detected in 3,3



Students may complain that "too much luck is involved," since the number of samples is heavily influenced by where the survey starts compared to where the plume is positioned within the survey grid. Ask students whether they think that luck is a factor in real underwater surveys (it is). For purposes of scoring the game, you can reduce the "luck problem" by only counting the number of moves after methane is first detected.

The Bridge Connection

www.vims.edu/bridge/ – In the "Site Navigation" menu on the left, click "Ocean Science Topics," then "Human Activities," then "Technology" for links to resources about submersibles, ROVs, and other technologies used in underwater exploration.

The "Me" Connection

Have students write a brief essay describing how a mass spectrometer might provide information that is personally important.

Connections to Other Subjects

English/Language Arts, Social Studies

Assessment

Answers to guidance questions (Step 3), survey strategies (Step 6) and participation in class discussions provide opportunities for assessment.

Extensions

1. Have students visit http://oceanexplorer.noaa.gov/explorations/06greece/ to keep up with the latest discoveries from the PHAEDRA 2006 Expedition.

2. Visit http://genesismission.jpl.nasa.gov/educate/sims_mini_mod.pdf for a lesson plan based on NASA's Genesis solar wind expedition, including a mass spectrometer simulation activity.

Resources

NOAA 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 Lessons from the Ocean Exploration Program

Lost City Chemistry Detectives

http://oceanexplorer.noaa.gov/explorations/05lostcity/background/edu/media/lostcity05_chemdetect.pdf

6 pages, 411k) (from the Lost City 2005 Expedition)

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

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

The Big Balancing Act

http://oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_balancing.pdf
(9 pages, 1.3Mb) (from the New Zealand American Submarine Ring of Fire 2005 Expedition)

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

In this lesson, students will be able to define and describe hydrothermal circulation systems, explain the overall sequence of chemical reactions that occur in hydrothermal circulation systems, compare and contrast “black smokers” and “white smokers,” and use data on chemical enrichment in hydrothermal circulation systems to make inferences about the relative significance of these systems to ocean chemical balance compared to terrestrial runoff.

Where There’s Smoke, There’s ...

http://oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_smoke.pdf
(6 pages, 680k) (from the New Zealand American Submarine Ring of Fire 2005 Expedition)

Focus: Hydrothermal vent chemistry at subduction volcanoes (Chemistry)

In this lesson, 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.

Do You Have a Sinking Feeling?

http://oceanexplorer.noaa.gov/explorations/06blacksea/background/edu/media/06blacksea_sinking.pdf
(from the Aegean and Black Sea 2006 Expedition)

Focus: Marine archaeology (Earth Science/Mathematics)

In this activity, students plot the position of a vessel given two bearings on appropriate landmarks, draw inferences about a shipwreck given information on the location and characteristics of artifacts from the wreck, and explain how the debris field associated with a shipwreck gives clues about the circumstances of the sinking ship.

What’s the Difference?

http://oceanexplorer.noaa.gov/explorations/06blacksea/background/edu/media/06blacksea_difference.pdf
(from the Aegean and Black Sea 2006 Expedition)

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

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

I, Robot, Can Do That!

http://oceanexplorer.noaa.gov/explorations/06blacksea/background/edu/media/06blacksea_robot.pdf
(from the Aegean and Black Sea 2006 Expedition)

Focus: Underwater Robotic Vehicles for Scientific Exploration

In this activity, students will be able to describe and contrast at least three types of underwater robots used for scientific explorations, discuss the advantages and disadvantages of using underwater robots in scientific explorations, and identify robotic vehicles best suited to carry out certain tasks.

Designing Tools for Ocean Exploration

http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_l1.pdf
(13 pages, 496k) (from the 2002 Galapagos Rift Expedition)

Focus: Ocean Exploration

Students will understand the complexity of ocean exploration; learn about the technological applications and capabilities required for ocean exploration; discover the importance of teamwork in scientific research projects; and develop the abilities necessary for scientific inquiry.

The Puzzle of the Ice Age Americans

http://oceanexplorer.noaa.gov/explorations/02fire/background/education/media/ring_puzzle_9_12.pdf
(8 pages, 100k) (from the 2002 Submarine Ring of Fire Expedition)

Focus: Anthropology, Earth Science - Origin of the first humans in the Americas

Students will be able to describe alternative theories for how the first humans came to the Americas and explain the evidence that supports or contradicts these theories, explain how exploration of a submerged portion of the North American west coast may provide additional insights about the origin of the first Americans, and describe the role of skepticism in scientific inquiry.

OTHER RESOURCES AND LINKS

http://oceanexplorer.noaa.gov/explorations/06greece/ – Web site for the PHAEDRA 2006 Expedition

http://genesismission.jpl.nasa.gov/educate/sims_mini_mod.pdf – Lesson plan from NASA's Genesis solar wind expedition, including a mass spectrometer simulation activity

http://www.bio.psu.edu/cold_seeps – Pennsylvania State University Department of Biology Web site on cold seeps

Bohm, H. and V. Jensen. 1998. Build Your Own Programmable Lego Submersible: Project: Sea Angel AUV (Autonomous Underwater Vehicle). Westcoast Words. 39 pages.

Bohm, H. 1997. Build your own underwater robot and other wet projects. Westcoast Words. 148 pages.

http://ina.tamu.edu/vm.htm – The Institute of Nautical Archaeology's Virtual Museum

http://projectsx.dartmouth.edu/history/bronze_age/ – Dartmouth University Web site, "Prehistoric Archaeology of the Aegean," with texts, links to other online resources, and numerous bibliographic references

http://newton.physics.wwu.edu:8082/jstewart/scied/earth.html – Earth science education resources

http://www.sciencegems.com/earth2.html – Science education resources

http://www-sci.lib.uci.edu/HSG/Ref.html – References on just about everything

NATIONAL SCIENCE EDUCATION STANDARDS

Content Standard A: Science As Inquiry
- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Content Standard B: Physical Science
- Structure of atoms
- Structure and properties of matter
- Interactions of energy and matter

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

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
- Natural and human-induced hazards
- Science and technology in local, national, and global challenges

Content Standard G: History and Nature of Science

- Science as a human endeavor
- Nature of scientific knowledge

OCEAN LITERACY ESSENTIAL PRINCIPLES AND FUNDAMENTAL CONCEPTS

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 6.

The ocean and humans are inextricably interconnected.

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

Essential Principle 7.

The ocean is largely unexplored.

- *Fundamental Concept a.* The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation's explorers and researchers, where they will find great opportunities for inquiry and investigation.
- *Fundamental Concept b.* Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.
- *Fundamental Concept d.* New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.
- *Fundamental Concept f.* Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

SEND US YOUR FEEDBACK

We value your feedback on this lesson.
Please send your comments to:
oceanexeducation@noaa.gov

FOR MORE INFORMATION

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Student Handout
Guidance Questions for Researching the Principles of Mass Spectrometry

1. Mass spectrometry involves four major steps. There are many different types of "mass specs," but this is the basic process. Briefly describe what happens in each step:
   a. Ionization

   b. Acceleration

   c. Deflection

   d. Detection

2. The amount of deflection experienced by an ion in a mass spectrometer depends upon what two properties of the ion?

3. These two properties are combined on a mass spectrograph as what unit?

4. Why do mass spectrometers need to operate in a vacuum?

Student Handout
Guidance Questions for Researching the Principles of Mass Spectrometry
(Teacher Answer Key)

1. Mass spectrometry involves four major steps. There are many different types of "mass specs," but this is the basic process. Briefly describe what happens in each step:

   a. Ionization
   Atoms of a substance being analyzed are vaporized, and bombarded with electrons from a heated plate (also known as an "electron gun"), causing one or more electrons to be knocked off, leaving the atoms with a positive charge (which makes them ions).

   b. Acceleration
   Ions are accelerated by a positively charged plate (called an "ion repeller" which repels the positive ions) and negatively charged grids (which attract the ions).

   c. Deflection
   The ions move through a magnetic field which causes the path of the ions to bend.

   d. Detection
   A metal plate is placed in the path of the ions so that only those ions whose path has been bent by a certain amount will strike the plate. Ions that strike the plate gain an electron from the metal which causes a current to flow through a circuit connected to the plate. This current is proportional to the number of ions that strike the plate. Information about the strength of the magnetic field (which corresponds to a certain amount of deflection) provides a measure of the size of the ions. Measurement of the current flowing through the metal plate provides a measure of the relative number of ions. By varying the magnetic field, different-size ions can be detected and their relative concentrations compared.

2. The amount of deflection experienced by an ion in a mass spectrometer depends upon what two properties of the ion?
   The amount of deflection depends the mass of the ion (lighter ions are deflected more easily than heavier ones) and the charge on the ion (ions that have lost two or more electrons are deflected more than ions that have lost only one electron).

3. These two properties are combined on a mass spectrograph as what unit?
   Ionic mass and charge are combined into the mass/charge ratio.

4. Why do mass spectrometers need to operate in a vacuum?
   Mass spectrometers need to operate in a vacuum because if air (or other) molecules were present, they would severely interfere with the path of ions.

Student Handout

AUV Survey Tracking Sheet

0,9	1,9	2,9	3,9	4,9	5,9	6,9	7,9	8,9	9,9
0,8	1,8	2,8	3,8	4,8	5,8	6,8	7,8	8,8	9,8
0,7	1,7	2,7	3,7	4,7	5,7	6,7	7,7	8,7	9,7
0,6	1,6	2,6	3,6	4,6	5,6	6,6	7,6	8,6	9,6
0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5
0,4	1,4	2,4	3,4	4,4	5,4	6,4	7,4	8,4	9,4
0,3	1,3	2,3	3,3	4,3	5,3	6,3	7,3	8,3	9,3
0,2	1,2	2,2	3,2	4,2	5,2	6,2	7,2	8,2	9,2
0,1	1,1	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1
0,0	1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0

Student Handout

Methane Concentration Contour Map
(nmol/kg)

trace	trace	trace	2	trace	trace	trace
trace	trace	2	8	2	trace	trace
trace	2	8	10	8	2	trace
2	8	10	12	10	8	2
trace	2	8	10	8	2	trace
trace	trace	2	8	2	trace	trace
trace	trace	trace	2	trace	trace	trace

Student Handout

Plume Location Grid

0,9	1,9	2,9	3,9	4,9	5,9	6,9	7,9	8,9	9,9
0,8	1,8	2,8	3,8	4,8	5,8	6,8	7,8	8,8	9,8
0,7	1,7	2,7	3,7	4,7	5,7	6,7	7,7	8,7	9,7
0,6	1,6	2,6	3,6	4,6	5,6	6,6	7,6	8,6	9,6
0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5
0,4	1,4	2,4	3,4	4,4	5,4	6,4	7,4	8,4	9,4
0,3	1,3	2,3	3,3	4,3	5,3	6,3	7,3	8,3	9,3
0,2	1,2	2,2	3,2	4,2	5,2	6,2	7,2	8,2	9,2
0,1	1,1	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1
0,0	1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0