Unit 4
Volcano Hazards

In this unit, you will

• Examine records of historical volcanoes.
• Use the Volcanic Explosivity Index (VEI) to categorize volcanoes.
• Investigate the effects of major eruptions on climate.
• Explore the effects of the most explosive volcanoes in history.

Mt. St. Helens viewed from the north, showing Spirit Lake and the new summit crater. The lateral blast from the May 18, 1980 eruption damaged or destroyed over four billion board feet of usable timber, enough to build 150,000 homes.
Warm-up 4.1

Location map

The tragedy of Mont Pelée

After reading the account of the volcanic eruption that destroyed the town of St. Pierre on the island of Martinique in 1902 (pages 93–97), list and describe all of the volcano-related hazards discussed. Feel free to add other hazards from your previous knowledge or experience with volcanoes.

Volcano hazards

1. 
2. 
3. 
4. 
5. 
6. 
7. 
8.

Volcano hazard examples (optional)

If you have access to a computer, you can see examples of these and other volcanic hazards. Be sure to add any new hazards you find to your list.

Launch ArcMap, and locate and open the ddde_unit_4.mxd file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.
In the Table of Contents, right-click the **Geological Hazards** data frame and choose Activate.

Expand the **Geological Hazards** data frame.

To see examples of other volcano hazards:

- Turn on the **Hazard Links** layer.
- Select the **Hazard Links** layer.
- Using the Hyperlink tool, click on each of the brown volcano hazard symbols (brown volcanoes) on the map.
- Read the caption for each picture, then close its window. There may be more than one picture for each link.

**Questions**

1. In St. Pierre, which of the hazards you listed caused the greatest amount of damage and cost the most lives?

2. Do you think anything could have been done to reduce the loss of life and property in St. Pierre? Explain.

3. What warning signs did the people of St. Pierre have of the coming eruption? Why do you think so many people ignored the signs?

4. Why do you think people build farms and cities so close to volcanoes?

5. Would you rebuild the city of St. Pierre? Explain why or why not.

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The tragedy of Mont Pelée
Eyewitness accounts

The Destruction of St. Pierre, 1902

Volcanoes in the Caribbean

The islands of the Lesser Antilles are the surface expression of a volcanic arc above a subduction zone. For the past 40 million years, the Atlantic plate has been slowly plunging beneath the Caribbean plate, building this chain of tropical islands.

The rock and sediment of the ocean floor contain significant amounts of water. As the Atlantic plate carries these rocks downward into the mantle, the increasing heat and pressure releases the trapped water. At a depth of about 100 km (60 mi), this combination of heat, pressure, and water vapor cause the subducting plate to melt. The molten rock — magma — is much lighter than the surrounding mantle, so it rises toward the surface. Near the surface, the magma accumulates in reservoirs known as magma chambers. Occasionally, the pressure in the chamber increases, forcing magma to the surface in a volcanic eruption.

The shape and explosive nature of these volcanoes is a direct result of the magma’s chemical content. At subduction zones, minerals with relatively low melting points such as silica (quartz) melt, whereas minerals with higher melting points remain solid. Magmas high in silica are very viscous; that is, they do not flow easily. Rather, the water vapor and other gases in the magma tend to build pressure until it is released explosively. This type of eruption forms steep-sided cones called stratovolcanoes that can reach thousands of meters in elevation. Mt. Rainier (outside Seattle), Mt. Fuji (in Japan), Popocatépetl (towering over Mexico City), and Mt. Etna (on the island of Sicily) are all stratovolcanoes, and all are located above subduction zones.

The tropical islands of the West Indies are a series of stratovolcanoes that occasionally erupt with spectacular violence. The first recorded eruption in the West Indies occurred about 1660 on the island of Montserrat. Since that time, dozens of eruptions have been observed and activity continues with regularity today. The deadliest eruption of the 20th century occurred in the West Indies on the island of Martinique.

Mt. Pelée and the island of Martinique

The island of Martinique sits at the midpoint of the Lesser Antilles island arc. For several hundred years the island had been a stopping point for pirates and buccaneers, but by the start of the 20th century it was home to over 160,000 residents. The largest city, the port of St. Pierre, was a thriving community of over 25,000. Spread out along a gently curving beach at the foot of cone-shaped Mont Pelée, it billed itself as the “Paris of the West Indies.” Famous for its rum, St. Pierre had a distillery filled with barrels of the potent spirit.

Mont Pelée, rising several miles to the north of St. Pierre, was draped in a thick cover of jungle. At its summit, a bowl-shaped crater held a lake, Lac des Palmistes. Below the summit was a second crater, breached by a V-shaped canyon aimed like a rifle sight at St. Pierre, 6 km (3.8 mi) away. Though it was well known that Mont Pelée was a volcano, having produced minor eruptions in 1792 and 1851, the 1300-m (4265-ft) peak was assumed by...
most to be dormant and therefore harmless. In fact, it was considered by many to be the island’s benevolent “protector.”

**Mt. Pelée awakens**

In late January 1902, Mont Pelée began to show signs that it was awakening from its long slumber. Smoke and steam began to puff from the summit. For the people of St. Pierre, it was more a source of wonder than alarm. This activity, called **fumarole** activity, gradually increased through the spring. Citizens occasionally noted the smell of sulfur, and on many days the mountain’s summit was covered with an ashen fog.

On April 23rd the townsfolk heard a loud explosion, and the summit of Mont Pelée billowed gray ash skyward in a minor eruption. Over the next few days, there were numerous explosions and tremors, and several times St. Pierre was dusted with fine volcanic ash. Conditions for the citizens of the town deteriorated; several times clouds of sulfurous gases, smelling of rotten eggs, permeated the city. The increasing activity of Mont Pelée caused the wildlife of the mountain to seek safer surroundings, while deadly snakes and swarms of insects invaded St. Pierre and surrounding villages in search of food. Reports from diaries and letters described how livestock screamed as red ants and foot-long centipedes bit them. Many livestock and an estimated 50 people, mostly children, died from snakebites.

On May 5th the water in the crater lake was heated to a boil and the crater rim failed. The hot water rushed down the canyon towards St. Pierre, mixing with the recently fallen ash to create a volcanic mudflow called a **lahar**. The lahar destroyed everything in its path, including the premiere distillery where 23 workers were swept away and killed. When the lahar reached the ocean it created a local tsunami that flooded low-lying areas around the waterfront.

Obviously, life in the shadow of Mont Pelée was becoming unbearable. People were trying to leave the island, but passage aboard ships was difficult to secure. The cathedral was crowded with people waiting to make confessions. Seeking to comfort the populace, the governor sent a team to the summit to assess the danger. Only one scientist, the local high school science teacher, was in the group. The team delivered a positive report to the governor stating, “There is nothing in the activity of Mt. Pelée that warrants a departure from St. Pierre,” and concluded that “the safety of St. Pierre is absolutely assured.”

Unfortunately, the report was not accurate. On May 7th Pelée continued to be rocked with explosions, and people noted that two fiery “eyes” appeared near the summit. Above the summit hung a gray ash cloud filled with lightning. Marino Leboff, captain of the Italian merchant ship *Orsolina*, knew what was coming. His home port was Naples, which lies in the shadow of Mt. Vesuvius, a volcano that erupted with deadly force in A.D. 79, completely burying the cities of Pompeii and Herculaneum. Leboff ordered the *Orsolina* to leave port only half loaded with cargo and noted, “I know nothing of Mont Pelée, but if Vesuvius were looking the way your volcano looks this day, I’d get out of Naples; and I’m going to get out of here.” Threatened with arrest for leaving port without clearance papers, Leboff replied, “I’ll take my chance of arrest, but I won’t take any chances on that volcano.”
The eruption on May 8th

Shortly before 8:00 a.m. on May 8th a series of violent explosions rocked Mont Pelée. Thus began a huge volcanic eruption, first sending a plume of gases and ash skyward, followed by a lateral eruption that sent a deadly superheated cloud of gases through the V-notch directly towards St. Pierre. The eruption that went upward created a huge mushroom cloud that blocked out the early morning sun and was pierced by flashes of lightning. People 30 km from the volcano were immersed in darkness, and could not see even an arm’s length away. This cloud reached an elevation of nearly 9 km (30,000 ft) in a matter of a few minutes.

Although spectacular, the vertical plume of ash was not the deadliest messenger from Mont Pelée. The lateral eruption of superheated gases roared toward St. Pierre at over 160 km per hour (100 mph). The shock wave flattened brick buildings and ripped branches from trees. “Rubble walls three feet in thickness had been torn to pieces as if made of dominoes or kindergarten blocks.” Not a single roof remained attached. It was reported that a 3-ton cast-iron statue was thrown 15 m (50 ft) from its pedestal. The nuée ardente, or “fiery cloud” of superheated gases and debris, glowed red, searing everything in its path and igniting fires throughout the city. At the distillery, rocks propelled by the cloud pierced centimeter-thick iron storage tanks with holes as large as 30 cm (1 ft) in diameter.

Thousands of barrels of rum exploded, sending flaming rivers down the streets of the city and out to sea.

The eruptions were immediately followed by torrential rains. The runoff mixed with volcanic ash to form lahars that swept down river valleys, filling them with debris and burying or sweeping houses off their foundations. The lahars flowed into the sea so suddenly that they generated large waves — tsunamis — that were observed around the Caribbean.

When the eruption finally subsided, more than 29,000 people had been killed. Only two residents of St. Pierre were reported to have survived, making this eruption the deadliest of the 20th century.

Stories of survivors

The force of the eruption was not limited to the city. In the harbor, the shock wave capsized steamships, and raining pyroclastic debris set ships afame. Chief Officer Ellery Scott of the Canadian steamship Roraima later told about his experience. Below is a translation of his account.

Chief Officer Ellery Scott

According to Scott, “The ship arrived at St. Pierre at 6 a.m. on the 8th. At about 8 o’clock, loud rumbling noises were heard from the mountain overlooking the town, the eruption taking place immediately, raining fire and ashes; lava running down the mountainside with a terrific roar, sweeping trees and everything in its course. I went at once to the forecastle-head to heave anchor. Soon after reaching there, there came a terrible downpour of fire, like hot lead, falling over the ship and followed immediately by a terrific wave which struck the ship on the port side, keeling her to starboard, flooding ship, fore and aft, sweeping away both masts, funnel-backs and everything at once.

“I covered myself with a ventilator standing nearby, from which I was pulled out by some of the stevedores, and dragged to the steerage apartment forward, remaining there for some time, during
which several dead bodies fell over and covered me. Shortly after, a downfall of red hot stones and mud, accompanied by total darkness, covered the ship. As soon as the downfall subsided, I tried to assist those lying about the deck injured, some fearfully burnt. Captain Muggah came to me, scorched beyond recognition. He had ordered the only life boat left to be lowered; but it was too badly damaged. From that time, I saw nothing of the captain; but was told by a man that the captain was seen by him to jump overboard. The man followed him in the water, and succeeded in getting the captain on a raft floating nearby, where he died shortly after.

“I gave all help possible to passengers and others lying about the deck in dying condition, most of whom complained of burning in the stomach. I picked up one little girl lying in the passageway dying, covered her over with a cloth, and took her to a bench nearby, where I believe she died. About 3 p.m. a French man-of-war’s boat, the Suchet, came alongside and passed over the side about twenty persons, mostly injured, and myself and other survivors were taken to Fort de France. I afterwards saw the Roddam steaming out to sea, with her stern part on fire. The Roraima caught fire and was burning when I left her in the afternoon, the town and all shipping destroyed.”

Overall, 48 of the 68 crew members and passengers died in the horrible ordeal, while on other ships the casualty rate was even higher.

Ciparis

Although only two people survived the eruption in St. Pierre, several people lived in the surrounding communities and chronicled some remarkable tales. The most amazing story was that of Louis Auguste Sylbaris, also known as Ciparis. Ciparis was a robust 25-year-old who had a passion for drinking and brawling. In early April, he was arrested and jailed for wounding one of his friends with a sword during an argument. Jail time meant that Ciparis was required to labor in the service of the city, and he soon tired of the regimented life. Near the end of April, he escaped and partied all night with friends.

In the morning he turned himself in to the authorities, who sentenced him to one week of solitary confinement in the dungeon. The dungeon was next to a steep hillside, totally isolated from the outside world. On the morning of May 8, while Ciparis was waiting for his breakfast to be delivered, his cell became very dark. Gusts of hot air and steaming ash came through the cracks in his cell door. The heat became unbearable and he held his breath as long as he could. Finally, the heat began to subside and he slumped to the floor. He was horribly burned, but had some water in the cell to drink.

Ciparis managed to survive for four days before being rescued. An American journalist interviewed him shortly after his rescue and stated, “He had been more frightfully burned, I think, than any man I had ever seen.” Ciparis eventually recovered, and was pardoned for his crimes on the basis of the miracle of his survival. Later, he joined the Barnum and Bailey Circus, and he was billed as the “Lone Survivor of St. Pierre.”

Aftermath of the eruption

News of the deadly eruption was telegraphed to the world, and soon aid and supplies were rushed to Martinique. Along with this aid came scientists to study the volcano including Alfred Lacroix, often called the “father of modern volcanology.” It was Lacroix who coined the phrase nuée ardente, which he described as a “lateral blast propelled down-slope by gravity.”
On May 20th, 1902 Mont Pelée exploded again with a giant eruption, probably larger than that of May 8th. No one died in this event, mostly because there was no one left. Throughout the summer and fall there were many small eruptions, and on August 3rd another nuée ardente destroyed the village of Morne Rouge southeast of St. Pierre, killing 1000 to 2000 people.

In October 1902 a lava dome began to rise out of the crater floor. This dome formed an imposing obelisk that has been described as the most impressive lava dome ever produced; it was 100 – 150 m (325 – 500 ft) thick at its base and soared to 358 m (1175 ft) above the crater rim. At times it rose at the remarkable rate of 15 m per day! This obelisk, nicknamed “the tower of Pelée,” glowed an incandescent red at night until it finally became unstable and collapsed into a pile of rubble in March of 1903.


For a detailed account of the events surrounding the 1902 eruption, see *The Day the World Ended* by Gordon Thomas and Max Morgan Witts. (New York: Stein and Day, 1969.)

View of the obelisk, or spire, rising 358 meters above the crater rim.
The tragedy of Mont Pelée
Investigation 4.2  

**Deadly volcanoes**

Volcanoes have the potential for affecting much larger areas and numbers of people than earthquakes. Mudflows generated by an eruption can travel hundreds of kilometers, and ash can be carried by atmospheric currents all the way around the world.

In this activity, you will investigate different types of volcanic hazards and their effects on people and the landscape.

- Launch ArcMap, and locate and open the *ddde_unit_4.mxd* file.
- Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

**Historical volcanoes**

The *Volcanoes* layer shows the locations of all volcanoes that are known to have been active in the past 10,000 years. The *Volcanic Eruptions* layer contains information about known volcanic eruptions since 10,000 B.C. These data are primarily gathered through written historical accounts as well as field investigations by geoscientists. The data are reliable for those regions where written history was preserved and sparse where oral history was the tradition.

- Use the Zoom In tool and the Pan tool to closely examine the relationship between volcanoes and plate boundaries.

1. With which type of plate boundary are the volcanoes most strongly associated?

- Click the Full extent button to view the entire map.
- Turn off the *Volcanoes* and *Plate Boundaries* layers.
- Select the *Volcanic Eruptions* layer.
- Click the Open Attribute Table button.
- Read the total number of volcanic eruptions at the bottom of the table (your answer will be different than the example shown below).

```
Deadly volcanoes
99
```
2. How many volcanic eruptions have been recorded since 10,000 B.C.?

☐ Close the attribute table.

**Volcanic Explosivity Index (VEI)**

No single feature describes the size of a volcanic eruption. To compare the energy of eruptions, volcanologists developed a magnitude scale called the Volcanic Explosivity Index (VEI). The calculation factors in the height of the eruption plume, the distance ejected materials traveled, the duration of the blast, and the volume of material erupted. A VEI difference of 1 represents a difference in energy of approximately 10 times. For historical eruptions, VEIs range from 0 – 7, with 7 being the most explosive.

**Which one’s the biggest?**

The only eruption in recent history with a VEI of 7 was the April 18, 1815 eruption of Mt. Tambora in Indonesia. To see a table of other historic eruptions and their intensities, click the Media Viewer button and choose VEI Index Table.

Now you will examine the largest historical eruptions.

☐ Click the Select By Attributes button.

☐ To display volcanic eruptions with a VEI 5 or greater, query the Volcanic Eruptions layer for (“VEI” > 4) as shown in steps 1 – 6 on the following page:
If you have difficulty entering the query statement correctly, refer to the **QuickLoad Query** described at left.

Close the Select By Attributes window.

The volcanic eruptions with a VEI 4 or greater should now be highlighted on your map.

Click the Open Attribute Table button.

Read the number of major eruptions at the bottom of the table (your answer will be different than the example shown below).

1. How many major eruptions (VEI 4 or greater) have there been since 10,000 B.C.?

2. What percentage of the total eruptions were major ones (VEI 4 or greater)? Report your answer to the nearest tenth of a percent (see example at left).

3. If an average of 250 volcanic eruptions occur each decade, how many eruptions would have a VEI greater than 4 in that same period?
Historical records: a window to the future?

Scientists routinely use records of the past to make educated guesses about events in the future.


Historical data are often used to calculate recurrence intervals of major geologic hazards in a region. These are then used to estimate future levels of hazards. Recurrence can be calculated by dividing the number of years over which an event is repeated by the number of times the event occurred.

Next you will examine the recurrence interval of Mt. St. Helens eruptions with VEI ratings of 3 or greater.

- Click the Select By Attributes button.
- To determine the recurrence interval of VEI 3 eruptions or greater of Mt. St. Helens, query the Volcanic Eruptions layer using the following query statement:

  \((\text{VEI} \geq 3) \land (\text{NAME} = \text{'St. Helens'})\)

- Click New.

- Click OK.
- Click New.

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  \((\text{VEI} \geq 3) \land (\text{NAME} = \text{'St. Helens'})\)

- Click New.
- If you have difficulty entering the query statement correctly, refer to the QuickLoad Query described at left.
- Close the Select By Attributes window.
- Click the Open Attribute Table button.
- The number of eruptions found by your query is shown at the bottom of the table (your answer will be different than the example shown below).
Click the **Selected** button at the bottom of the table to view only the highlighted records. Use the table to answer the following questions.

7. How many times has Mt. St. Helens erupted with a VEI of 3 or greater? Over what time interval did those eruptions occur? (Hint: The database lists eruptions through the year 2004.)

8. What is the recurrence interval for eruptions of VEI greater than or equal to 3 by Mt. St. Helens? How would you use this information in managing the future development and use of the area surrounding the volcano?

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Close the attribute table.

Click the Clear Selected Features button.

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**Range of volcanic hazards**

On May 18, 1980 Mt. St. Helens erupted with a blast of VEI = 5 that deposited a blanket of ash over areas as far away as 400 km (250 mi). Lahars flowed down river valleys as far as 30 km (19 mi). Spokane, Washington was significantly affected by the event. What would be the impact of a similar eruption at Mt. Rainier near Seattle, Washington?

To figure this out:

- Turn off the **Volcanic Eruptions** layer and turn on the **Volcanoes** layer.
- Turn on the **Cities** layer.
- Select the **Cities** layer.
- Use the Zoom In tool to zoom in on the Seattle area. (See locator map, left.) The black circle shows the area within a radius of 100 km of Mt. Rainier.
- Using the Select Elements tool, click on the circle to select it. Small black “handles” or a dashed line will appear around the circle when it is selected.
- Click the Select by Graphics button to select the cities within 100 km of Mt. Rainier. They will be highlighted.
- Click the Statistics button.

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**Finding Seattle**

Seattle, Washington is located near Puget Sound, on the U.S. west coast.
In the Statistics window, calculate statistics for only selected features of the Cities layer, using the Total Population field.

Click OK. Be patient while the statistics are calculated.

The number of people affected by an eruption of Mt. Rainier is given as the Total.

9. How many people living within 100 km of Mt. Rainier would be significantly affected if it erupted like Mt. St. Helens?

Close the Statistics window.

Click the Clear Selected Features button.

In 1991 Mt. Pinatubo in the Philippines erupted, causing widespread damage. The eruption was similar to the Mt. St. Helens eruption of 1980, only larger. With a VEI of 6, this larger blast affected an area around the volcano within a radius of about 500 km.

Click the Full extent button to view the entire map.

Use the locator map at the left to zoom in on Mt. Pinatubo in the Philippines. Repeat the Select by Graphics and Statistics procedures above to determine how many people would be affected by another eruption of Mt. Pinatubo.

10. How many people would be significantly affected by another eruption of Mt. Pinatubo?

Close the Statistics window.

Click the Clear Selected Features button.

Quit ArcMap and do not save changes.
Volcanic hazards

Volcanoes are capable of affecting much larger areas and numbers of people than are earthquakes. Fortunately, they often provide warning signs of upcoming eruptions, allowing people to evacuate to safety. Still, there have been 35 volcanic eruptions in the past 500 years in which 300 or more people were killed.

Volcanic hazards fall into two categories.

- **Direct effects** — eruption clouds, shock waves from the eruption blast, lava and pyroclastic flows, and volcanic gases.
- **Indirect effects** — lahars (mud flows of volcanic ash), flooding, tsunamis, and post-eruption starvation.

**Eruption clouds**

Explosive eruptions blast rock fragments, or tephra, and superheated gases into the air with tremendous force. The distance these fragments travel depends on their size — smaller particles go farther than larger fragments. Volcanic bombs, the largest fragments, generally land within 3 km of the vent. Particles less than 2 mm (0.08 in) across, called volcanic ash, can rise high into the air forming a huge, billowing eruption cloud or column.

Eruption columns grow rapidly and can reach heights of more than 20 km (12 mi) in less than 30 minutes. Large eruption clouds extend hundreds of miles downwind, resulting in ashfall over broad areas. Ash from the 1980 eruption of Mt. St. Helens covered more than 50,000 km² (20,000 mi²). Heavy ashfall can damage or collapse buildings. Even minor ashfalls can damage crops, electronics, and machinery.

Volcanic ash clouds also pose a serious hazard to air travel. Each year, thousands of aircraft fly routes over volcanically active areas. During the past 15 years, about 80 commercial jets have been damaged by accidentally flying into ash clouds. Several have nearly crashed when ash clogged the engines and caused them to fail. The drifting cloud can carry the hazard far from its source. In 1992, Chicago’s O’Hare airport was forced to close.
for several hours due to a drifting ash cloud from Alaska’s Mt. Spurr volcano, which is nearly 5000 km (3000 mi) from Chicago!

**Volcanic gases**

At depth and under high pressure, magma can hold large amounts of dissolved gases. As the magma rises toward the surface and the pressure decreases, the gases bubble out and escape. This is similar to what happens when you open a can of soda.

Near the surface, the magma interacts with the surrounding rocks and ground- or surface water to generate more gases. These gases may be released suddenly in explosions or seep slowly to the surface through cracks in the overlying rock.

The behavior of magma is related to the amount of silica and water it contains. Magmas with a high silica content are generally more explosive.

<table>
<thead>
<tr>
<th>Location</th>
<th>Source</th>
<th>% Silica</th>
<th>Explosivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot spots</td>
<td>lower mantle</td>
<td>50%</td>
<td>low</td>
</tr>
<tr>
<td>divergent boundaries</td>
<td>upper mantle</td>
<td>50%</td>
<td>low</td>
</tr>
<tr>
<td>convergent boundaries</td>
<td>upper mantle and crust</td>
<td>60-70%</td>
<td>medium to high</td>
</tr>
</tbody>
</table>

The table below shows magma temperatures and volcanic gas compositions (by percent) from three types of volcanic sources.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Kilauea hot spot 1170°C</th>
<th>Erta’Ale divergent plate 1130°C</th>
<th>Momotombo convergent plate 820°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water vapor (H₂O)</td>
<td>37.1</td>
<td>77.2</td>
<td>97.1</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>48.9</td>
<td>11.3</td>
<td>1.44</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>11.8</td>
<td>8.34</td>
<td>0.50</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>0.49</td>
<td>1.39</td>
<td>0.70</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>1.51</td>
<td>0.44</td>
<td>0.01</td>
</tr>
<tr>
<td>Hydrogen sulfide (H₂S)</td>
<td>0.04</td>
<td>0.68</td>
<td>0.23</td>
</tr>
<tr>
<td>Hydrogen chloride (HCl)</td>
<td>0.08</td>
<td>0.42</td>
<td>2.89</td>
</tr>
<tr>
<td>Hydrogen fluoride (HF)</td>
<td>-</td>
<td>-</td>
<td>0.26</td>
</tr>
</tbody>
</table>

As you can see, much of the gas released by volcanoes is water vapor. Some water is dissolved in the magma itself, but most water vapor is produced when the magma comes in contact with groundwater.

Carbon dioxide is denser than air, causing it to accumulate in low areas. High concentrations of CO₂ (above 10%) are poisonous, but even lower concentrations can be deadly because CO₂ displaces oxygen required for respiration.

At California’s Mammoth Mountain, the accumulation of CO₂ in the soil and in low areas is killing trees and small animals and poses a threat to humans unaware of the danger.

Lake Nyos, in Cameroon, west-central Africa, sits in a large volcanic caldera. A caldera is a large depression at the summit of a volcano; formed when magma erupts or withdraws from a subsurface reservoir, causing the overlying rock to collapse. Groundwater carries large amounts of dissolved CO₂ from the underlying magma into the bottom of the lake. Over time, the water becomes over-saturated with CO₂. If a disturbance...
causes some of this water to rise, the decreased pressure allows bubbles of CO\textsubscript{2} to form. The rising bubbles further disturb the water, triggering a chain reaction, resulting in a sudden, massive release of CO\textsubscript{2}.

In 1986 a tremendous amount of CO\textsubscript{2} suddenly escaped from the depths of the lake, formed a cloud, and flowed down a valley toward a nearby village. Before the dense gas dissipated, it had killed more than 1700 people as well as livestock up to 25 km (16 mi) from the lake. This is not a unique event — similar cases have occurred elsewhere and will continue to occur.

**Air pollution — vog and laze**

Constant eruptions, like those that occur at Hawaii’s Kilauea volcano, can be significant sources of local air pollution. Under the right conditions, erupting sulfur dioxide (SO\textsubscript{2}) gas combines with water vapor to form tiny sulfuric acid droplets. These interact with other volcanic gases, dust, and sunlight to produce volcanic smog, or vog. Vog reduces visibility, causes health problems, damages crops, and corrodes metals.

When molten lava comes in contact with seawater, the intense heat produces clouds of lava haze, or laze, which is more complex than simple clouds of steam. Heat breaks down the salt to form hydrochloric acid (HCl). The resulting cloud has a pH of 1.5 – 2.5 and can create significant health problems for downwind populations.

**Pyroclastic flows**

Pyroclastic flows — sometimes called \textit{nuées ardentes} (French for “fiery clouds”) — are hot, often glowing mixtures of volcanic fragments and gases that flow down the slopes of volcanoes. These flows can reach temperatures of 800 °C (1500 °F) and move at speeds up to 725 km/hr (450 mph), flattening and burning everything in their path.

The eruption of Mt. St. Helens on May 18, 1980 produced a sideways “lateral blast” that destroyed an area of 600 sq km (230 sq mi). Trees were mowed down like blades of grass as far as 24 km (15 mi) from the volcano.
St. Helens grew to a height of about 300 meters (1000 feet). Lava domes seldom pose risks to humans.

### Landslides

Volcanic landslides range from small surface movements of loose debris to collapses of the entire summit or sides of a volcano. These landslides are triggered when eruptions, heavy rainfall, or large earthquakes cause material to break free and move downhill.

Landslides are particularly common on **stratovolcanoes**, which are steep volcanoes often built up of layers of loose volcanic rock fragments. Heavy precipitation or groundwater can turn volcanic rocks into soft, slippery clay minerals, reducing the energy needed to trigger a slide.

The largest volcanic landslide in historical time occurred at the start of the May 18, 1980 Mt. St. Helens eruption. Over 2.3 km³ (0.55 mi³) of the mountain were transported as far as 24 km (15 mi) downhill at speeds over 240 km/hr (150 mph). The slide left behind a **hummocky** (lumpy) deposit with an average thickness of 45 m (150 ft). For years, geologists were puzzled by a similar strange, hummocky landscape north of Mt. Shasta in northern California (shown above right).

After witnessing the eruption of Mt. St. Helens, with its tremendous landslide and the hummocky terrain it left behind, they could then make sense of Mt. Shasta. A massive landslide occurred there about 350,000 years ago when nearly the entire volcano collapsed. Debris traveled almost 50 km (30 mi) from the volcano in an enormous landslide nearly 20 times larger than the Mt. St. Helens landslide.

### Lahars

**Lahar** is an Indonesian term for a mixture of water and rock fragments flowing down a volcano or river valley. These flows can rush down valleys and stream channels at speeds of 30 – 60 km per hour (18 – 37 mph) and can travel more than 60 km (37 mi). As lahars pick up debris and water, they can easily grow to more than 10 times their initial size.

Some lahars contain so much rock debris (60 – 90 percent by weight) that they look like fast-moving rivers of wet concrete. Close to their source, these flows are powerful enough to rip up and carry trees, houses, and huge boulders miles downstream. As slopes level out and the flows lose energy, they entomb everything in their path in mud.

Historically, lahars have been one of the deadliest volcanic hazards. In 1985, Colombia’s Nevado...
del Ruiz volcano produced a relatively modest, VEI 3 eruption. The pyroclastic flow melted about 2.5 km² (1 mi²) of snow and glacial ice on the mountain. Meltwater mixed with volcanic ash rushed down river valleys at speeds up to 60 km/hr (37 mph), stripping away rocks, soil, and vegetation.

Two hours later, a 5-m (16-ft) wall of hot mud and debris slammed into the town of Armero, Colombia, 74 km (46 mi) from the volcano, killing nearly 23,000 people and destroying 5000 homes. Surprisingly, Armero had previously been devastated by lahars in 1595 and again in 1845, only to be rebuilt on the same spot.

**Volcanic resources**

These short-term hazards of volcanoes are balanced by many long-term benefits to humanity. In many places, fertile volcanic soils make it profitable to live near volcanoes. Volcanic materials are used in construction and other industries. Heat energy from young volcanic systems may be harnessed to produce electricity. Most volcanoes are located near oceans, and many are found in mild climates. Because these volcanoes can lie dormant for long periods of time, people often consider them harmless.

The challenge to volcanologists is to minimize the risks associated with volcanic hazards, so that society may continue to enjoy volcanism’s long-term benefits. They must continually improve their ability to predict eruptions and provide sound information to decision makers and the public.

**Climate change**

Major eruptions like the June 15, 1991 eruption of Mt. Pinatubo inject huge amounts of sulfur dioxide gas (SO₂) into the stratosphere. There, SO₂ combines with water to form tiny droplets of sulfuric acid (H₂SO₄) as in the diagram (below). These droplets, called **aerosols**, scatter sunlight, lowering Earth’s average surface temperature for long periods of time. The satellite images on the following page show the spread of aerosols from the Pinatubo eruption.

For two years after the Pinatubo eruption, global temperatures were about 0.6 °C (1.1 °F) lower than...
normal. Sulfuric acid also contributes to the destruction of the ozone layer.

These aerosols may persist for months or years, until they eventually settle out of the atmosphere or are “scrubbed” out by precipitation or other processes. Historically, periods of rapid global cooling have occurred after the largest eruptions.
Questions

1. Why do volcanoes at hot spots erupt less violently than volcanoes near subduction zones?

2. What is tephra, and how does it cause damage?

3. Why is carbon dioxide gas (CO₂) a dangerous eruptive product?

4. In 1985, a relatively mild, VEI = 3 eruption of Colombia’s Nevado del Ruiz volcano destroyed the town of Armero, nearly 80 km (50 mi) away. What eruptive product or process destroyed the town, and what warnings did the inhabitants have that this type of event was possible?

5. Describe three ways in which volcanoes benefit humans.
6. How does sulfur dioxide gas (SO$_2$) from major volcanic eruptions cause global cooling of Earth’s climate?

7. How long does the cooling effect from SO$_2$ typically last?
Volcanoes and climate

In this part of your investigation of volcanoes, you will look at some of the major eruptions occurring since A.D. 1450 and explore the relationship between these eruptions and changes in Earth’s climate.

- Launch ArcMap, and locate and open the ddee_unit_4.mxd file.
- Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.
- In the Table of Contents, right-click the Volcano Hazards data frame and choose Activate.
- Expand the Volcano Hazards data frame.
- Turn off all layers except Topography and Countries.

Major Eruptions and the Volcano Explosivity Index (VEI)

How often do major volcanic eruptions occur? You will look at the historical record over the last several hundred years to answer this question.

- Turn on and select the Major Eruptions (1450 – 2000 AD) layer.
- Select the Major Eruptions (1450 – 2000 AD) layer.

This layer shows the largest volcanic eruptions occurring since A.D. 1450. To determine the number of major eruptions of VEI category 5:

- Click the Select By Attributes button.
- To determine the number of VEI 5 eruptions, query the Major Eruptions (1450 – 2000 AD) layer for (“VEI” = 5) as shown in steps 1 – 6 on the following page. Your query will actually read: (“MAJVEI” = 5)
Data Detectives: Dynamic Earth

Unit 4 – Volcano Hazards

If you have difficulty entering the query statement correctly, refer to the QuickLoad Query described at left.

Close the Select By Attributes window.
Click the Open Attribute Table button.
Read the number of major eruptions at the bottom of the table (Your answer will be different than the example shown below.)

1. Record the number of eruptions with a VEI of 5 in the table below.

<table>
<thead>
<tr>
<th>VEI Value</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of eruptions of this VEI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of years covered in data set</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recurrence interval (average years between eruptions)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Close the attribute table.
Repeat the query process above for VEI = 6 and VEI = 7, and record the number of eruptions of each magnitude in the table.
If you have difficulty entering any of the query statements correctly, refer to the QuickLoad Queries described at left.
Close the Select By Attributes window when you are finished.
Click the Open Attribute Table button.
Read the number of major eruptions for each query at the bottom of the table.

2. Record the number of VEI 6 and VEI 7 eruptions in the table.
Next you will determine how many years the data set covers.

Examine the years listed for each major eruption in the Year column of the attribute table. They are in chronological order, starting with the oldest eruption at the top of the table.

3. How many years are covered by the Major Eruption data set? Record this number in the table on the previous page. (The number is the same for all three columns in your table.)

The recurrence interval for eruptions of a particular VEI is the average number of years between eruptions of that magnitude.

4. Calculate the VEI recurrence interval by dividing the number of years by the number of eruptions in that VEI category. Record the recurrence intervals in the table.

5. What problem might there be with the recurrence interval you calculated for the largest VEI categories? Does it represent a full recurrence interval?

6. As the VEI increases, what happens to the number of eruptions and the recurrence interval?

Close the attribute table.

Major eruptions and Northern Hemisphere climate

In this section, you will look at a graph recently published in the science journal *Nature* that shows changes in atmospheric temperature in the Northern Hemisphere over the last 600 years.

Scientists cannot measure past temperatures directly, but they can infer temperatures indirectly by measuring the spacing of growth rings in trees. Closely spaced rings indicate poor growing conditions such as cold weather or low rainfall, and widely spaced rings indicate warmer temperatures and more rainfall.
The scientists were looking for large anomalies, or irregularities, in the data, which reflect years when the temperature was much lower than normal. You will examine the graph to identify these major atmospheric cooling events, then use ArcMap to determine which volcanic eruption triggered each event.

Click the Media Viewer button and choose Volcanoes and Climate from the list.

The graph shows how the average temperature varied from normal over a 600-year period. The bottom portion of the graph shows the VEI intensity of volcanic eruptions over the same time period. Six temperature anomalies — major atmospheric cooling events — are marked with yellow dots. They are the same as those in the following table. (Note: If needed, use the Zoom In tool to examine the graph in more detail.)

7. For each event, read the temperature anomaly on the right-hand axis of the graph and record it in the table below.

<table>
<thead>
<tr>
<th>Year of anomaly</th>
<th>Temperature anomaly (°C)</th>
<th>Name of volcano</th>
<th>Year of eruption</th>
<th>VEI of eruption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1453</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1601</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1816-1818</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1884</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1912</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Close the Media Viewer window.

Click the Open Attribute Table button.

Scroll down the table and look for volcanoes with high VEI values (VEI > 4) that erupted in the same year as (or the year before) each temperature anomaly you recorded.

8. Use the Major Eruptions (1450 – 2000 AD) attribute table to complete the table. Fill in the name, date of eruption, and VEI for each eruption.

9. How well do the years of the temperature anomalies match the dates of the corresponding eruptions? What might account for differences between the two dates?
10. According to the graph, how is the VEI of an eruption related to the degree of atmospheric cooling following the event, as indicated by the temperature anomaly? Give examples to support your answer.

- 

Close the attribute table.

**The big ones — prehistoric VEI 7 & 8 eruptions**

You’ve seen that the 1815 Tambora eruption was a big one. The only VEI 7 eruption of the last 550 years, Tambora cooled the Northern Hemisphere by an average of 0.5 °C for several years. In fact, 1816 has been called “the year without a summer.” The Northeastern U.S. was hit particularly hard, with snow in June and killing frosts from June through September. Beginning in 1817, large numbers of people started leaving northern New England for warmer climates.

The most recent powerful eruption was the VEI 6 eruption of Mt. Pinatubo in the Philippines in 1991. The eruption produced a global cooling of around 0.3 °C. In terms of total material ejected, Tambora was nearly 20 times greater than Pinatubo and about 500 times greater than the 1980 Mt. St. Helens eruption.

- Turn off the **Major Eruptions (1450 – 2000 AD)** layer.
- Turn on the **Ashfall Events** layer.
- Select the **Ashfall Events** layer.
- Turn on the **Ashfall Sources** layer.

In the not so distant past, geologically speaking, there have been tremendous VEI 8 eruptions that dwarf those of Tambora and Pinatubo. What exactly is the difference between an eruption with a VEI of 7 and one with a VEI of 8? In this next section you will compare some of the larger eruptions in human history with some of the biggest eruptions in geologic history by comparing the areas and volumes of their ashfall deposits.

The **Ashfall Events** layer shows the distribution of ash from several historic and prehistoric volcanic eruptions. Notice how the ash plumes overlap, particularly in what is now the United States.

- Click the QuickLoad button 🔄.
Select Spatial Bookmarks, choose Eastern Hemisphere Plumes from the list, and click OK.

The volcanoes that produced the plumes are labeled by name in the figure at left. To select the ashfall plumes for Vesuvius and Pinatubo, you will probably have to zoom in even closer.

Click the Open Attribute Table button.

11. Find the VEI of each eruption and the area of the plume it produced, and record them in the table below.

Close the attribute table.

Using the Measure tool, click on the source (the purple triangle), drag across to the farthest extent of each plume, and double-click to find the distance. The distance in kilometers is displayed in the lower-left corner of the map.

12. Record the distance in the table below. (Round it to the nearest 100 km.)

<table>
<thead>
<tr>
<th>Volcano name</th>
<th>Eruption VEI</th>
<th>Area of ashfall plume $\text{km}^2$</th>
<th>Maximum distance from volcano $\text{km}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>data source:</td>
<td>attribute table</td>
<td>attribute table</td>
<td>measure</td>
</tr>
<tr>
<td>Vesuvius</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinatubo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tambora</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toba</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Now, consider the Indonesian volcano Toba, which erupted about 74,000 years ago. Toba deposited ash over an estimated 1 percent of Earth’s surface, left telltale chemical traces in the ice caps of Greenland and Antarctica, and produced a prolonged period of cold and darkness that severely stressed humankind’s ancestors. Genetic evidence suggests that the human population may have declined significantly due to Toba’s effects, and that our species survived only by finding refuge in isolated pockets of tropical warmth. Scientists estimate that the Toba eruption caused global cooling of $3 - 5 \, ^\circ\text{C} (5 - 9 \, ^\circ\text{F})$ for a period of up to seven years, with summertime temperatures in some areas dropping by as much as $15 \, ^\circ\text{C} (27 \, ^\circ\text{F})$. 
13. Consider the effects that the 0.5 °C cooling from the Tambora eruption had on society. How might an eruption similar in magnitude to Toba affect society today?

On a human time scale, VEI 8 eruptions are rare, occurring once or twice every 100,000 years. Geologically speaking, however, VEI 8 eruptions are relatively common. Next, you will look at three of the biggest eruptions to occur in the United States over the past 2 million years, the Yellowstone Caldera eruptions.

The Yellowstone Caldera eruptions

Occupying the northwest corner of Wyoming is a spectacular area of geysers, hot springs, and abundant wildlife. This region was so unusual and notable for its geological and biological wonders that it was protected back in 1869 as the United States’ first national park. Called Yellowstone, the park today is considered one of the three “crown jewels” of the National Park System, and receives about 3 million visitors per year.

Many visitors are unaware that Yellowstone is a giant collapsed volcano, or caldera, that produced three gargantuan eruptions within the past 2 million years. Next, you will take a closer look at this slumbering volcanic giant.

- Click the Full extent button to view the entire map.
- Use the Zoom In tool to zoom in on the continental United States.

You should be able to see several overlapping ashfall plumes across the middle and southwestern parts of the U.S. Three of these plumes were produced by volcanic activity at Yellowstone; the fourth plume was created by another massive eruption from the Long Valley Caldera in California.

To highlight the Yellowstone ashfall plumes:

- Click the Select By Attributes button.
- Click the QuickLoad Query button inside the Select By Attributes window.
- Select the Yellowstone Caldera Deposits query and click OK.
- Click New.
- Close the Select By Attributes window.
Now the Yellowstone ashfall plumes should be outlined on your map. Next you will use the **Ashfall Events** attribute table to obtain information about each eruption.

1. Click the Open Attribute Table button.

14. Complete the following table with information about the three Yellowstone ashfall deposits. List them in order from oldest to youngest.

<table>
<thead>
<tr>
<th>Name of deposit</th>
<th>Age years before present</th>
<th>Area of deposit km²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

15. Estimate the area in square kilometers that the ashfall from the next Yellowstone Caldera eruption might cover. You can do this by calculating the average area of the three historical ashfall deposits.

2. Close the attribute table when you are finished.

Finally, calculate the recurrence interval. You can use the recurrence interval to predict when the next major eruption from the Yellowstone Caldera might occur.

- Subtract the youngest (most recent) age from the oldest age in the table above.
- Divide by the number of times the original eruption was repeated; in this case, divide by 2.

16. What is the recurrence interval for the Yellowstone Caldera?

17. Use the most recent eruption and the recurrence interval to estimate when the next eruption might take place.

3. Quit ArcMap and do not save changes.