### Where are they?

Most of these volcanoes are located along the Aleutian Arc that extends 2,500 kilometers (1,550 miles) westward from central Alaska along the Alaska Peninsula, then out along the Aleutian Islands toward eastern Russia. The arc forms the northern portion of the Pacific "Ring of Fire." Other volcanoes that have been active during the last few thousand years are found in southeastern Alaska and in the Wrangell Mountains. Smaller volcanoes, some active within the last 10,000 years, are found in interior Alaska and in western Alaska as far north as the Seward Peninsula.

### Why are they there?

Most volcanic activity in Alaska is the result of *subduction*, the process in which one crustal plate slides beneath another. In the Aleutian Arc, the northward-moving Pacific Plate dives beneath the North American Plate at a rate of 6 to 7.5 centimeters (2.5 to 3 inches) per year (see *Plate Tectonics*, right). As the Pacific Plate slowly grinds beneath the Alaska portion of the North American Plate, stress and strain are stored and then released in great earthquakes. In fact, about one-quarter of all earthquake energy released on earth is released in Alaska, and three of the ten largest earthquakes since 1900 took place in Alaska. During this century alone, Alaska has had nearly 70 earthquakes of magnitude 7 or greater. These large earthquakes and thousands of smaller ones occur at the boundary of the Pacific and North American plates. They form a narrow curtain of activity which deepens northward from the Aleutian trench and is about 100 kilometers (60 miles) deep underneath the Aleutian Arc volcanoes.

As the plate descends into the *mantle* (dense rock that underlies the earth's crust), it undergoes a series of chemical and physical changes caused by increasing pressure and temperature. First, the water that is stored in subducted sediments and in the oceanic crust is released. Then, at greater depths, water-bearing minerals (such as hornblende) change into non-water-bearing minerals (such as *pyroxene*). Water given off by this process, along with dissolved impurities, rises into the overlying mantle. The addition of water to the mantle lowers its melting point and is one of the primary processes that leads to the production of magma. Magma also forms as the mantle, stirred by the motion of the descending Pacific Plate, rises to a position beneath the volcanoes (see Formation of Subduction Zone Volcanoes).

The magma that results from these processes is less dense than the surrounding *mantle* and rises toward the surface of the earth. When it reaches the continental crust, which is less dense than mantle and the mantle-derived magma, it pools and begins to change in character. First it heats, then melts, and then mixes with the surrounding crust or country rock. As the magma cools, it begins to crystallize and the crystals that form differ in composition from the magma. This is important because the crystals separate from the liquid, which changes the magma's composition still further; it becomes richer in those chemical components not concentrated in the crystals. This process is called fractional crystallization, or fractionation.

The most fundamental change that results from the fractional crystallization of magma is the increase in silica. Throughout the fractionation process magma changes from the initial basalt to andesite and then to dacite. As the silica content of the magma increases, the magma continually becomes less and less dense until it reaches a point where it is lighter than the crust that surrounds it and then resumes its rise toward the surface. Depending on the magma's rate of ascent, it can continue to crystallize, fractionate, and assimilate with the surrounding crust producing, in extreme cases, rhyolite with up to 76 percent silica.

When the magmas finally reach the surface, if they are relatively poor in dissolved gases, they erupt nonexplosively and form lava flows or domes. If they are rich in dissolved gases, they explode violently (like a shaken soda bottle) and form columns of *volcanic ash* that can reach more than 15 kilometers (45,000 feet) into the atmosphere.

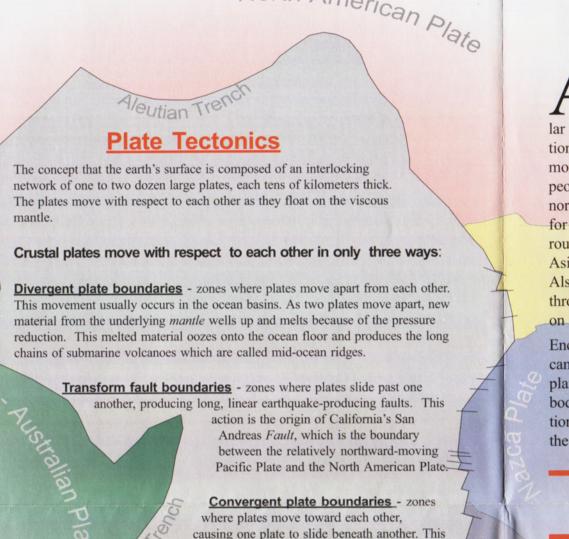
The processes outlined above are a thumbnail sketch of the complicated processes that form the volcanoes of the Aleutian Arc. Current models sug-

Area of Block Diagram

gest that the Wrangell volcanoes in Alaska formed in a very similar way and are associated with a small sliver of the Pacific Plate that is thrust northeastward beneath central Alaska. Several of the Wrangell volcanoes are among the most voluminous *andesite* volcanoes in the world—several times the volume of Mt. Rainier.

There are two major types of volcanoes in Alaska not directly tied to the Aleutian subduction zone. The first type is a series of small craters (and one larger one, Mt. Edgecumbe near Sitka) scattered throughout southeastern Alaska. These small volcanoes may result from the intense shearing along many strike-slip transform faults that are caused by the northward movement of the Pacific Plate. Deep crustal fractures such as these faults may allow magma to rise and volcanoes to form in areas where magma could not normally reach the surface.

The second type of non-subduction volcanoes form the basalt fields of western Alaska. These fields typically consist of many basaltic cinder cones and lava flows, each of which formed over the course of only a few weeks or months. It has been suggested that at least some of these fields formed where tension in the earth produced deep fractures and thinning within the crust. The origin of these fields is not well understood, but they are analogous to the cinder cone fields northwest of the Japanese volcanoes in Southeast Asia, eastern China, and Korea.



process is called *subduction*, and produces the

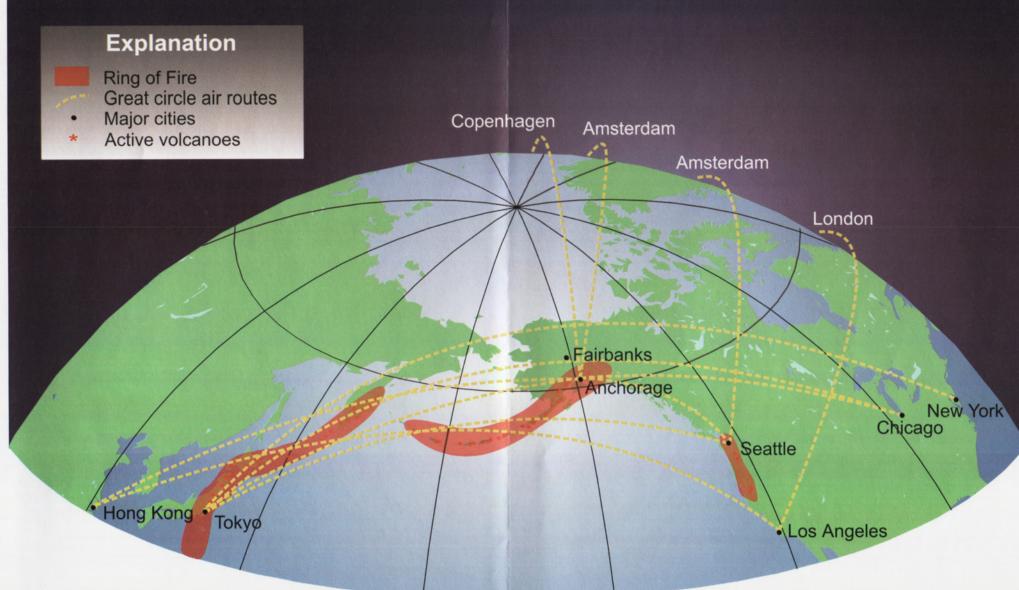
deep submarine trenches around the margins of the

Pacific Ocean, and produce the volcanoes that

make up the Pacific "Ring of Fire."

# Formation of Subduction Zone **Volcanoes** Pacific Plate 100 km These arrows show the movement of the mantle as it is stirred by the descending asthenospheric mantle Pacific Plate

# Ash & Aircraft – A Special Alaska Hazard



laska airspace is extremely busy with long-range, wide-body aircraft as well as bush planes and smaller aircraft. The Anchorage International Airport handles more international air freight (in dollar value) than any other airport in the United States; the Fairbanks International airport, located in Alaska's interior, is ninth on the list and handles more and more freight each year. More than 60,000 aircraft and 10,000 people each day fly over or very near Alaska volcanoes as they travel the north Pacific (NOPAC) and Russian far east (RFE) air routes. The reason for all the activity is Alaska's unique geographic location. All direct air routes between the United States (even Los Angeles and New York) and Asian cities such as Tokyo and Hong Kong pass along the NOPAC routes. Also, most of the aircraft carrying freight between Europe and Asia come through Anchorage for refueling. A considerable percent of all air freight on earth passes near Alaska's many volcanoes.

Encounters between aircraft and volcanic ash are serious because the ash can cause severe damage to the engines as well as other parts of the airplane. Two processes damage jet engines, particularly long-range, widebody airplanes such as DC-10s and Boeing 747s that are used for international transport. The first damaging process is the mechanical abrasion of the moving parts in a jet engine, such as the compressor and turbine blades.

This abrasion reduces the efficiency of the engine but does not typically cause engine failure. Another process with potentially more dangerous consequences is the introduction of ash into the hot parts of an aircraft's engines. Jet engines, particularly those on large airplanes used on international routes, operate near the melting temperature of volcanic ash. Ingestion of ash can clog fuel nozzles, combuster, and turbine parts causing surging, flame out, immediate loss of engine thrust, and engine failure.

In the past 16 years more than 80 jet airplanes have been damaged by volcanic ash worldwide. Seven of those encounters actually resulted in engine failure, although all seven eventually managed to restart enough engines to land without loss of life. In Alaska, potentially lethal ash clouds put aircraft at risk an average of four days per year.

To address these hazards, the Alaska Volcano Observatory (AVO) is continually upgrading and expanding its real-time seismic network to extend its coverage of Alaska's more than 40 active volcanoes. From its inception in 1988, AVO has gone from actively monitoring four Alaska volcanoes to 18 in 1998; it continues to find new and more efficient ways of reporting and predicting volcanic activity likely to pose a significant hazard to aircraft or local populations.

# Recent or Notable Eruptions

ince the early 1900s, one to two Alaska volcanoes have erupted every year. While not all of them have directly impacted local populations, some of the more spectacular and recent eruptions have shown that volcanic hazards do exist, particularly in light of the ever-growing air freight industry in Alaska.

### Okmok Volcano—1997

Okmok volcano began a strombolian eruption on the morning of February 13, 1997, that continued through the next six weeks, abruptly declining in late March of the same year. Since AVO does not seismically monitor Okmok volcano, the eruption was first observed as a "hot spot" on a February 13th thermal-infrared band (AVHRR) satellite image. The eruption produced lava fountains, multiple spatter-fed and effusive lava flows that nearly crossed the caldera floor, frequent ash bursts to heights of up to 5 kilometers (16,000 feet) above sea level (ASL), and at least one steam and ash plume reported to have risen as high as 9 kilometers (30,000 feet ASL).

Okmok is a 10-kilometer-wide (6-mile-wide) caldera that forms the northeastern end of Umnak Island, 120 kilometers (75 miles) southwest of Dutch Harbor in the central Aleutian Islands. The volcano has had several historic major eruptions and a dozen minor events. The nearest settlements are Nikolski, population about 35, located 72 kilometers (45 miles) west of the volcano, and a small number of ranchers at the abandoned Fort Glenn military base situated 16 kilometers (10 miles) east of the caldera.

## Pavlof Volcano—1996

With virtually no precursory seismic activity, Pavlof volcano began a vigorous strombolian eruption in mid September 1996 that continued into January 1997. Historically the most active volcano in the Aleutian volcanic arc, Pavlof has erupted about every 3-8 years since the mid 1700s. Pavlof last erupted between April 1986 and May 1988 and, like the current episode, the eruption was characterized by steam and ash emissions, strombolian lava fountaining at the summit, spatter-fed lava flows, and derivative lahars down the northwestern and southeastern flanks of the volcano.

Located 965 km southwest of Anchorage beneath the heavily-traveled North Pacific jet air routes, Pavlof presents a serious potential threat to aviation safety. In answer to this hazard, AVO installed six seismic stations near Pavlof in July 1996, just in time to monitor its most recent eruption. This new instrumentation at Pavlof significantly improved AVO's ability to monitor the course of the 1996 eruption and to disseminate information on potential hazards to air traffic.

Mount Spurr—1992 On June 27, 1992, following 39 years of inactivity, Crater Peak vent on the south flank of Mount Spurr volcano burst into eruption at 7:04 a.m. Alaska daylight time (ADT). This and subsequent eruptions on August 18 and September 16 and 17 lasted about four hours and lofted ash about 15 kilometers (50,000 feet) into the atmosphere. The June, August, and September eruptions released 44, 52, and 56 million cubic meters (56, 66, and 71 million cubic yards) of andesitic tephra.

The August eruption caused the most far-reaching effects when it deposited up to 3 millimeters (one tenth of an inch) of ash on Anchorage, 125 kilometers (77 miles) east of the volcano. During the August and September eruptions, pyroclastic flows surged down the flanks of Crater Peak.

Real-time seismic monitoring tracked the 10-month buildup of precursory earthquakes and allowed timely warning of the increasing unrest to state

and federal government officials, the military, air carriers, and local citizens. This monitoring was augmented with other types of observations and provided the basis for accurate eruption advisories that minimized economic

The Anchorage and the Matanuska-Susitna Valley communities, which together make up the state of Alaska's center of population and economic activity, suffered \$5–8 million in unavoidable losses from the August ashfall, and additional but unevaluated costs were incurred from flight delays in large North American airports to the south and east of the volcano. The fact that no jet airplanes were damaged can be attibuted to AVO's ash-cloud warning system and a new awareness within the aviation community of the hazards of ash clouds.

## Redoubt Volcano—1989

The 1989-1990 eruption of Redoubt Volcano, located 177 kilometers (110 miles) southwest of Anchorage, began on December 14, 1989. After less than 24 hours of unusual seismicity, a huge cloud of ash heralded the volcano's fourth and most damaging eruption of this century. Volcanic ash generated by the 23 individual explosive episodes between December 1989 and April 1990 caused severe damage to aircraft, severely disrupted air traffic above southern Alaska, and caused local power outages and school closures. Some disruption to air traffic was even experienced by aircraft as far south as Texas.

The explosions produced hot, fast-moving clouds of ash, rock debris, and gas that swept across Redoubt's heavily glaciated north flank. In the Drift River valley, these events triggered massive debris flows that threatened an oil tanker terminal near the river's mouth. Partial flooding of the terminal compound on two occasions forced authorities to modify its operating procedures and temporarily halted oil production from 10 platforms in Cook Inlet. The total losses from the eruption were about \$160 million, making it the second most costly volcanic eruption in the history of the United States.

### Novarupta—1912

The world's largest 20th-century eruption and the largest *rhyolite* eruption in recorded history occurred in the Katmai region on the Alaska Peninsula. The eruption started at 1:00 p.m. on June 6, 1912. During the next 60 hours of continuous explosive activity some 30 cubic kilometers (7 cubic miles) of ash and *pyroclastic flows* erupted. About half the material was dispersed as windblown ash which fell as thick as 30 centimeters (12 inches) on the town of Kodiak, 170 kilometers (105 miles) away, fouled water supplies, and damaged buildings. The other half of the material formed an ashflow sheet some 200 meters (650 feet) thick, that filled a glacier-carved valley and formed the Valley of Ten Thousand Smokes, appropriately named because the cooling ash sheet contained thousands of fumaroles that vented hot steam and gases until the late 1920s. The vent from which the magma erupted is now filled by Novarupta dome, which formed at the end of the

This eruption was originally attributed to Mount Katmai, because during the eruption from Novarupta, the summit of Mount Katmai collapsed, forming a 5-square-kilometer (2-square-mile) caldera which now contains a lake. The collapse of Mount Katmai, a *stratocone* 10 kilometers (6 miles) away from Novarupta, simultaneous with the eruption led early workers to mistakenly believe Mount Katmai was the source vent for the eruption. More than 50 years after the eruption, scientists found that virtually all the magma that erupted came from the Novarupta vent.

# **Volcanic Hazards and Benefits**

because they convey information about geological processes

occurring deep beneath the surface. They are one

**T**olcanoes erupt a few tenths to a few tens of cubic kilometers (a few hundredths to a few cubic miles) of lava at temperatures of 750 to 1,150 degrees centigrade (1,400 to 2,100 degrees Fahrenheit). These eruptions pose a variety of hazards, both near the volcano and far downwind. Lavas with relatively low silica contents are fluid and often form lava flows, which are rivers of molten rock that flow quickly down slopes and through tubes. Lavas with higher silica contents are stickier (have higher viscosity) and erupt either explosively or form domes that perch on top of the volcanic vent. As these domes grow they become oversteepened and fail, causing avalanches of hot rock and dust which sweep swiftly down the flanks of the volcanoes and form pyroclastic flows.

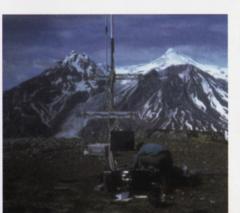
The eruption of hot lava and volcanic ash onto snow and glacier covered surfaces causes rapid melting of the ice, creating additional flood-related hazards. The resulting meltwater then mixes with the fragmented lava to form lahars, which are slurries of hot mud and water. Lahars can flow considerable distances down existing river drainages, inundating low lying areas with volcanic and other debris.

Explosive eruptions can loft volcanic ash 15 kilometers (50,000 feet) or more into the air. These eruptions pose a special hazard to aircraft (see section entitled Ash and aircraft - A Special Alaska Hazard). Volcanic plumes that are energetic enough to carry volcanic ash, water, and chemical aerosols (principally sulfur-based) into the *stratosphere* can alter local and even global climate for the few years that they are in circulation around the earth. Volcanoes can also erupt corrosive and poisonous gases that can harm local plant and animal life.

Volcanoes also have a beneficial side. Magma moving toward the surface can produce geothermal resources which may be used to generate low-cost, environmentally clean electricity. That same heat makes deep groundwater percolate through the volcano and surrounding areas and generates certain types of economically important ore deposits. Rich agricultural soils are often associated with volcanic landscapes.

Volcanoes in repose form beautiful mountains and are the central attractions of many national parks. Volcanoes in eruption are enthralling in their power and grandeur and demonstrate unequivocally that the earth below the atmosphere and biosphere is not static. Scientifically they are thrilling

# Volcano Monitoring



As magma moves beneath a volcano prior to an eruption, it often generates earthquakes, causes the surface of the volcano to swell, and causes the amount of gases emitted by the volcano to increase. By monitoring these changes, scientists are often able to anticipate eruptive activity and issue warnings of possible hazards. While not all of these changes are observed before every eruption, combining ob-

servations of each of these precursors often allows scientists to forecast

Often the first indication of an impending eruption is an increase in earthquake activity. Generally, a network of six to eight seismometers are positioned around a volcano. Readings from each seismometer are continuously radioed to a central recording site where scientists determine the locations, sizes, numbers, and types of earthquakes. In the weeks or days prior to an eruption the number, size and type of earthquakes that occur beneath the volcano will often increase. In many cases, the earthquakes will move to progressively shallower depths beneath the volcanic vent. At some volcanoes, low-frequency earthquakes and a continuous seismic disturbance called tremor will occur shortly before an eruption.

As magma moves to shallower depths it can cause the surface of the volcano to swell. Scientists monitor the deformation of the ground surface using a variety of surveying techniques and instruments. Electronic distance meters (EDM) bounce infrared light off of targets on the volcano's surface to accurately determine the distance between the EDM and the target. Repeated measurements allow the displacement of the target to be measured. Scientists may also use the global positioning system (GPS, a network of precise navigational satellites) to monitor changes in the ground's surface. In some cases, instruments called tiltmeters are cemented to a volcano's sides. These instruments operate much like a carpenter's level and record the amount the volcano's surface bulges or tilts. Data from both tiltmeters and GPS receivers can be transmitted from the volcano to a central recording site for real-time analysis.

As magma nears the ground's surface it releases several types of gas. These include water (steam), carbon dioxide, and sulfur dioxide. Sulfur dioxide is the easiest of these to monitor. Measurements of sulfur dioxide concentrations are made using an instrument called a correlation spectrometer (COSPEC) which can measure the absorption of sunlight by sulfur dioxide. The COSPEC can be used from the ground or mounted in an airplane or helicopter that then circles the volcano.

AVO also observes volcanoes in Alaska and on the Kamchatka Pennisula in Russia using the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-12 and NOAA-14 satellites. The images are received at a ground station at the Geophysical Institute, University of Alaska Fairbanks, and are analyzed daily to detect volcanic eruption clouds and thermal anomalies at volcanoes in the north Pacific region. This important tool allows AVO scientists to keep an eye on the many volcanoes not yet monitored by the current seismic network. The Okmok eruption of 1997 is a prime example of the importance of this rapidly expanding technology.

Geologic studies of the deposits of past eruptions are an important component in identifying hazards at a given volcano. Frequently a given volcano will develop a characteristic eruptive style and size that will remain approximately the same for thousands of years. Identifying the types and sizes of past eruptions allows estimates of the areas and types of hazards that may be expected in the event of a future eruption at a given volcano.

Decades of monitoring many restless volcanoes around the world have shown that each volcano is different. Some reawakening volcanoes, such as Mount Spurr, show increased earthquake activity for many months before they erupt, while others, like Redoubt Volcano, may have less than a day of increased seismic activity. Some volcanoes will deform visibly, as at Mount St. Helens, and some will not. Other volcanoes, like Augustine, vent large quantities of gas before they erupt.

To successfully predict eruptions, scientists consider information from all the monitoring techniques. This information is generally analyzed on a highspeed system of networked computers. Once patterns emerge that suggest an eruption may be imminent, a warning will be issued. Advance warnings were made for a number of eruptive events during the 1989-90 eruptions of Redoubt Volcano, as well as two of the three eruptions of Mount Spurr in

Volcanic Processes

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with respect to each other. At depths of 100-350 kilometers (60-210 miles), the mantle is plastic and weak, and forms the layer on which plates move. Pleistocene – The period of time extending from the beginning of the Holocene (about 10,000 years ago) to about 1.64 million years ago.

Glossary

Andesite - Volcanic rock, magma, or lava with between 53 and 63 weight percent silica.

Basalt – Volcanic rock, magma, or lava with less than 53 weight percent silica. Basalt is

Caldera – Large, semicircular depression in the summit of a volcano, many times larger

than a single vent produced by a very large eruption. In Alaska, volcanic calderas are

Continental Crust - Uppermost layer of the earth composed of relatively light (low

density) rocks. Continental crust forms land masses and large islands and is com-

posed of rock types like sandstone, schist, granite, and andesite. Oceanic crust forms

Between basalt and dacite in silica content.

typically 5–10 kilometers (3–6 miles) across.

the floors of the ocean basins and is made of basalt

Debris flow/avalanche - See Volcanic Processes figure for description.

**B.P.** – Years before the present.

fluid (has low viscosity) and usually forms lava flows.

**Pyroclastic flow** – See *Volcanic Processes* figure for description.

Pyroxene – A mineral made mostly of silica, iron, magnesium, and calcium, that does

"Ring of Fire" - The nearly continuous chain of volcanoes that circle the Pacific Ocean. All these volcanoes are formed by subduction of oceanic plates beneath continental Rhyolite - Volcanic rock, magma, or lava with more than 72 weight percent silica.

Rhyolite is very viscous (thick) and eruptions of this material are often very explo-Seismicity – Shaking of the earth caused by movement along faults or by movement of

gases and magma within volcanoes.

Seismometer - Instrument that detects earthquakes by measuring the shaking of the

Shearing – Movement resulting from stresses that cause rock bodies to slide past each other. In the brittle upper crust this usually results in earthquakes along faults. Shield volcano - A broad volcano with low surface slope composed mostly of lava flows erupted from a single vent or a few closely spaced vents. Forms over a period

of hundreds of thousands of years. Silica – Chemical compound composed of two oxygen atoms for every silicon atom. Oxygen and silicon are the most common elements in the earth's crust.

Stratocone - Steep-sided volcano composed of many layers of lava flows, ash, and pyroclastic flows produced by eruptions from a single vent or a few closely-spaced vents. Forms over a period of hundreds of thousands of years; also known as strato-

**Stratosphere** – The outer layer of the atmosphere that is from 10–20 kilometers (6–12 miles) above the Earth's surface. Strombolian eruption – A type of volcanic eruption characterized by jetting clots or

"fountains" of fluid, basaltic lava from a central crater. Tephra - See Volcanic Processes figure for description.

Volcanic ash – See Volcanic Processes figure for description.

Volcanic field - A closely-spaced collection of small cinder cones and lava flows, each of which are produced by individual eruptions of days to months duration.

Volcano - A roughly circular opening in the earth's surface through which magma erupts. Also the landform produced by erupted material that accumulates around the vent.

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of the fascinating facets of the geologic evolution of the planet Earth that can be studied on a human timescale.