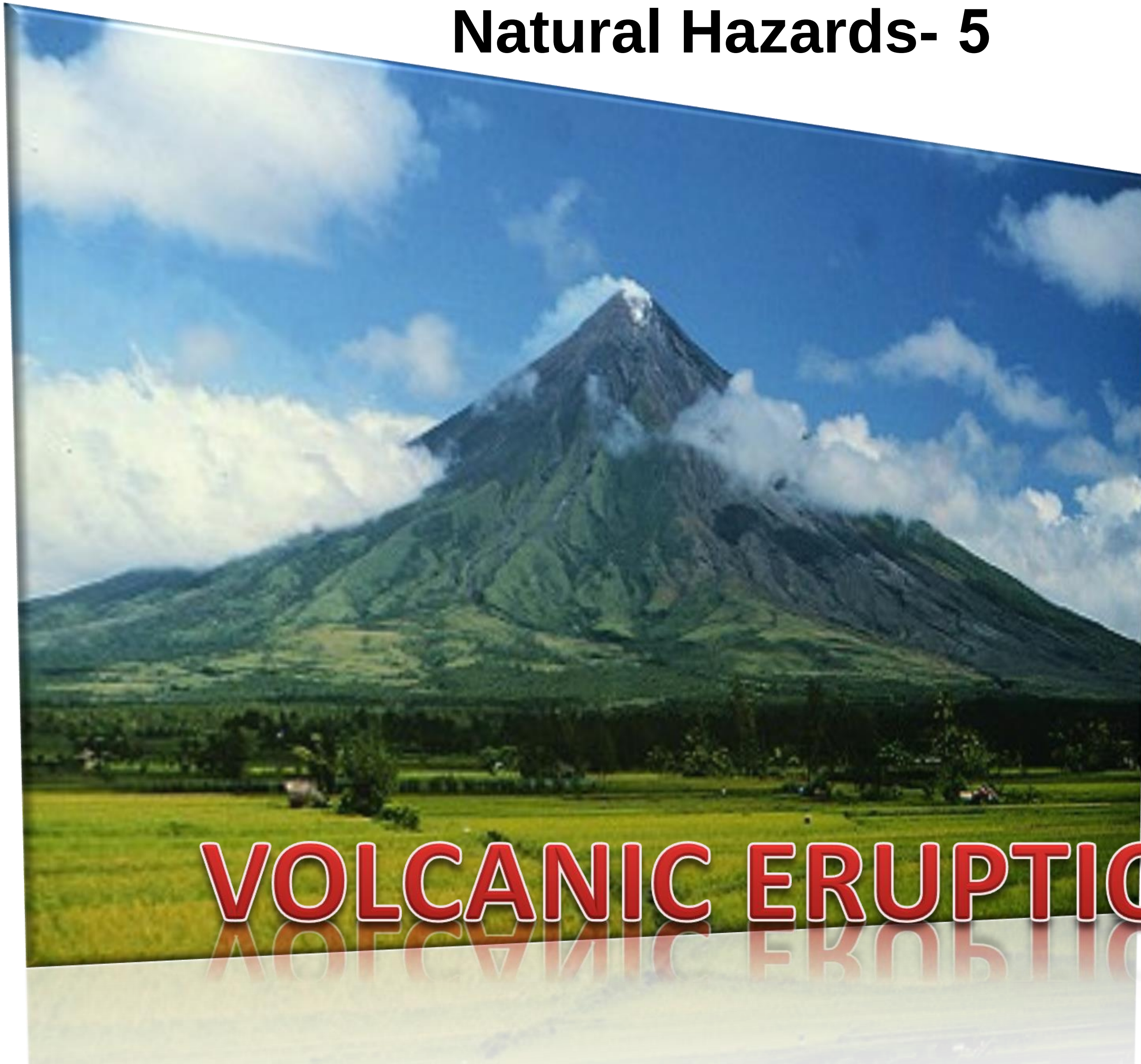
Natural Hazards- 5



VOLCANIC ERUPTIONS

Volcanoes and Magma

Volcano

is a vent from which magma and gases erupt.

The term **volcano** comes from **Vulcan**, the ***Roman god of fire***.

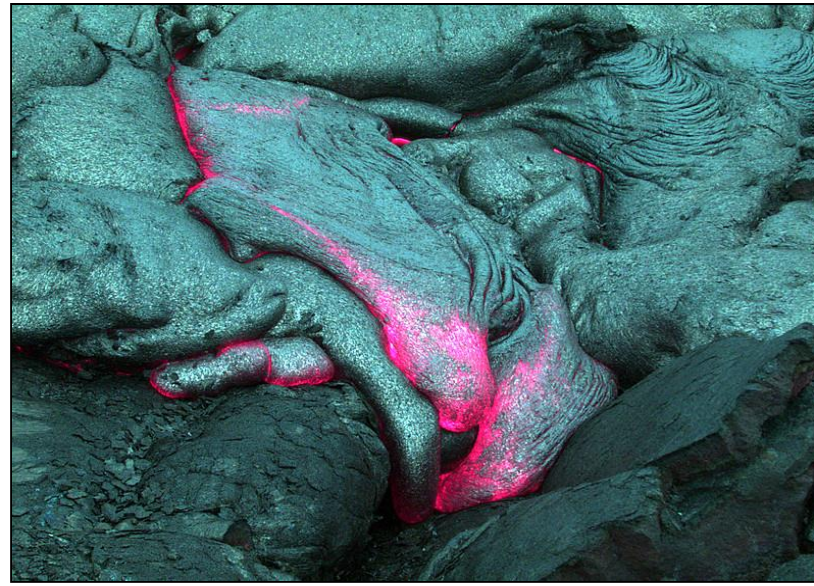
Magma

is ***molten rock*** that forms when temperatures rise sufficiently high for melting to occur in the Earth's crust or mantle.

Lava

is ***magma*** that reaches the Earth's surface through a ***volcanic vent*** and pours out over the ***landscape***.

Characteristics of Magma



The **characteristics of magma** have a significant influence on the **style** and the **explosiveness** of **volcanic eruptions**.

- **Composition**
- **Dissolved Gases**
- **Temperature**
- **Viscosity**

Composition

The most abundant component of magma is the **silica (SiO_2)**.

The most common types of magma are:

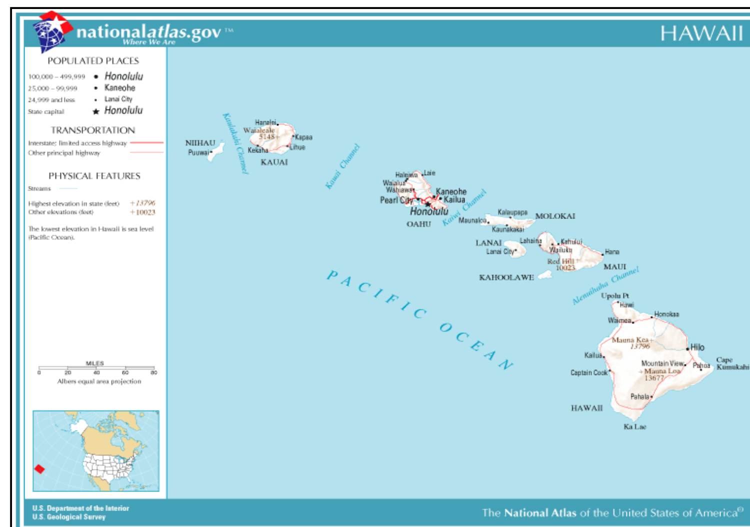
1. **Basaltic Magma**
2. **Andesitic Magma**
3. **Rhyolitic Magma**

Plutonic rocks form from magmas that never make it to the surface of the Earth, instead cooling and crystallizing more slowly underground.

1. Basaltic Magma

Contains about **50%** SiO_2

Forms about **80%** of all magma erupted by volcanoes

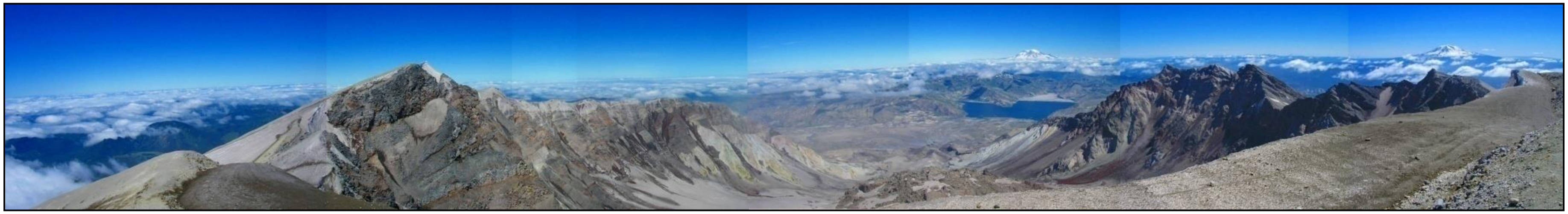


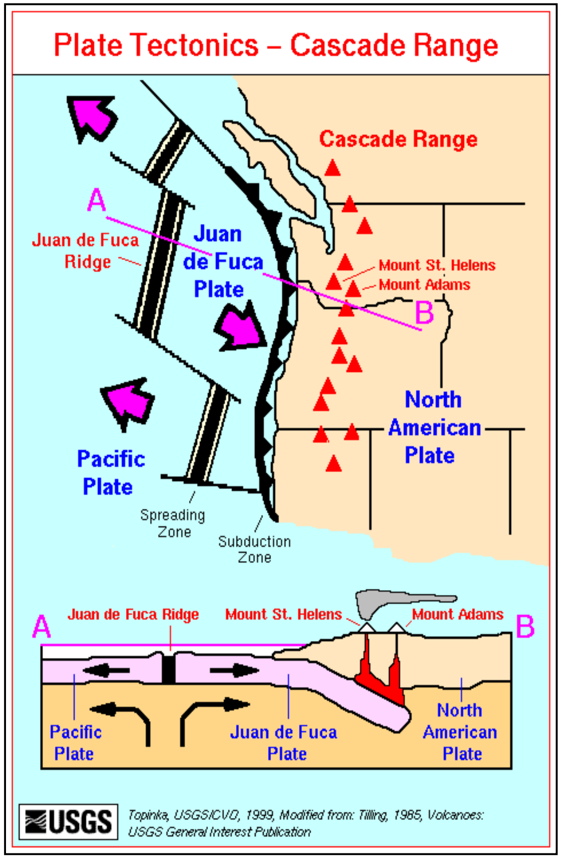
The **extrusive (volcanic)** rock type corresponding to this magma is **Basalt**

The **intrusive (plutonic)** rock type corresponding to this magma is **Gabbro**

Such as the Hawaiian volcanoes such as Mauna Loa

2. Andesitic Magma





The **extrusive (volcanic)** rock type corresponding to this magma is **Andesite**

The **intrusive (plutonic)** rock type corresponding to this magma is **Diorite**

Such as Mount St. Helens

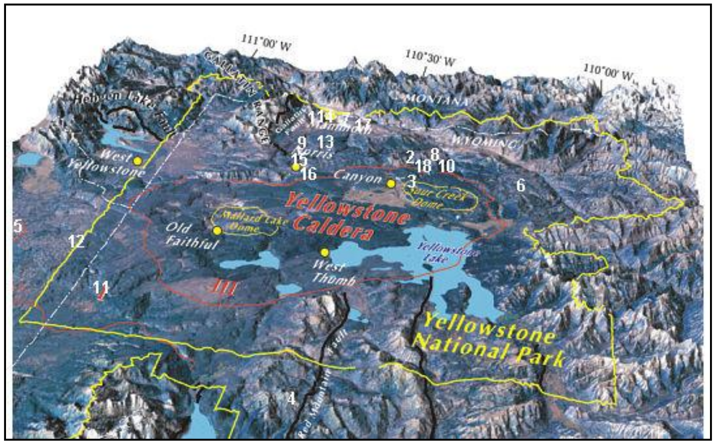
Contains about **60%** SiO_2

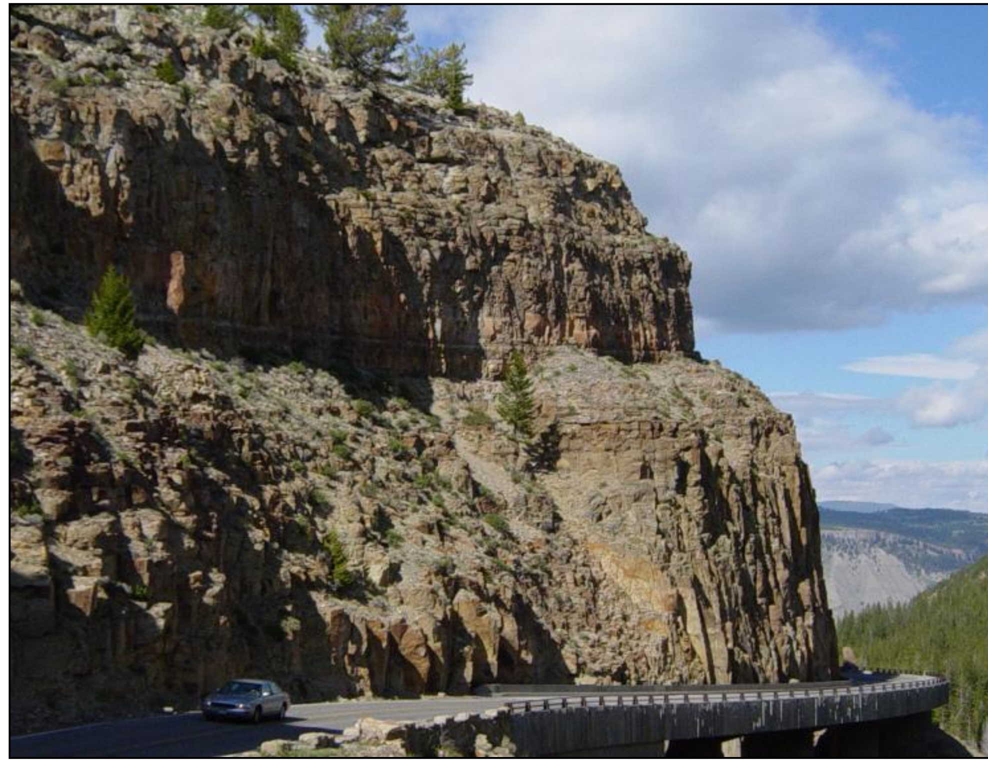
Forms about **10%** of all magma erupted by volcanoes

3. Rhyolitic Magma

Contains about **70%** SiO_2

Forms about **10%** of all magma erupted by volcanoes





The **extrusive (volcanic)** rock type corresponding to this magma is **Rhyolite**

The **intrusive (plutonic)** rock type corresponding to this magma is **Granite**

Such as the volcanoes at Yellowstone National Park

Dissolved Gases

Small amounts of gas (**0.2 to 3.0 percent by weight**) are dissolved in all magmas.

Even though they are present in very low abundance, these gases can strongly influence the properties of the magma, which in turn influence the style and explosiveness of the eruption.

The principal volcanic gas is **water vapor**, which, together with **carbon dioxide**, accounts for more than **98%** of all gases emitted from volcanoes.

Other volcanic gases include **nitrogen**, **chlorine**, **sulfur**, and **argon**, which are rarely present in amounts exceeding **1%**.

Throughout geologic history, **volcanic gas emissions** have been the primary mechanism whereby the Earth has released the volatile material from its interior.

The ***chemical evolution of the atmosphere*** and the ***origin of the oceans*** are intimately linked to this outgoing process.

Temperature

It is **difficult** to measure the **extrusion temperature of magma**, but it can be done **during volcanic eruption**.

Magma temperatures during eruptions of volcanoes such as **Kilauea in Hawaii** and **Mount Vesuvius in Italy** have been recorded as ranging from **800** to **1200ºC**.

Experiments on **synthetic magmas in the laboratory** suggest that under some conditions magma temperatures might be as high as **1400ºC**.

Viscosity

Viscosity of a substance is the ***degree to which a substance is resistant to flow***.

The **more viscous** a substance, the **less fluid** it is.

The **viscosity** of a magma depends on

Temperature → **Composition (Silica)** → **Dissolved Gases**

Low-silica basaltic lava moving down a steep slope on Mauna Loa in Hawaii has been clocked at **64 km/h**, indicating a very **low viscosity**.

High-silica rhyolitic lava flows so slowly that its movement can hardly be detected.

The **higher the temperature** and, in general, the **higher the gas content**, the **lower the viscosity** and the more readily the magma flows.

A **very hot magma** erupted from a volcano may **flow readily**, but it soon begins to **cool**, becomes **more viscous**, and eventually **comes to a halt**.

Volcanic Eruptions

It is **impossible** to produce a ***strict classification of volcanic eruptions***.

During most eruptive episodes the **types of activity** and the **nature of the materials ejected** from the volcano change, sometimes **gradually** (over weeks, months, or years) and sometimes from **one day to the next** or even from **hour to hour**.

volcanic eruptions can be classified based on

- volcanoes **eruptive style**
- **types of materials erupted**
- **type of landform built**

Materials Ejected During an Eruption

- Gases
- Tephra
- Lava

Factors Influencing Eruptive Styles

Pressure

Magma is **less dense than the solid rock** from which it is formed.

the lower density magma exerts upward **pressure** on the enclosing higher density rock and slowly forces its way up.

The rising mass of magma is facing a pressure that is created by the weight of the overlying rock.

This **pressure is proportional to depth**

The amount of gas a magma can dissolve (More gas at high P, Less at low P)

Dissolved Gases

Gas dissolved in an upward-moving magma comes out of solution and forms bubbles.

Viscosity

The **viscosity** of the magma will determine the **behavior of the bubbles**

People tend to view **active volcanoes** as **dangerous places** that should be avoided. However, geologists have discovered that **some volcanoes are safe** and relatively **easy to study**.

Nonexplosive eruptions, such as those we can witness in Hawaii, are relatively safe compared to violent, **explosive eruptions** like the 1980 eruption of Mount St. Helens in Washington, the 1982 eruption of El Chichon in Mexico, and the 1991 eruption of Mount Pinatubo in the Philippines, each of which caused substantial destruction and loss of life.

When **little or no dissolved gas** is present, a magma will be erupted as a **lava flow regardless of its composition**.

If **dissolved gas** is present, it must escape somehow.

Nonexplosive Eruptions:

Low-viscosity basaltic magmas rise rapidly. Hence, the pressure also decreases rapidly. Thus, gas bubbles out of solution so fast that spectacular fountaining occurs. When fountaining dies down, hot, fluid lava emerging from the vent flows rapidly downslope.

Explosive Eruptions:

In **high-viscosity andesitic or rhyolitic magmas** gas bubbles can rise only very slowly because they are held back by the viscosity of the fluid. As the rising magma approaches the surface, rapid decompression causes the dissolved gases to expand and escape explosively.

low-viscosity magmas

low dissolved-gas contents

→ **Non-explosive eruptions**

high-viscosity magmas

High dissolved-gas contents

→ **Non-explosive eruptions**

The higher the viscosity, the more difficult it is for the gas to form bubbles and the greater the likelihood the escaping gas bubbles' causing an explosive eruption.

Tephra and Pyroclastic Rocks

A **fragment of rock ejected during a volcanic eruption** is called a **pyroclast** (from the Greek words *pyro*, meaning heat or fire, and *klastos*, meaning broken; hence, *hot, broken fragments*).

Rocks formed from pyroclasts are **pyroclastic rocks**.

Geologists also commonly refer to pyroclasts as **tephra**, a Greek word for *ash*. **Tephra** is employed as a **collective term for all airborne pyroclasts** (i.e., a **loose assemblage of pyroclasts**).

Abundant tephra is characteristic of violent, explosive eruptions.

Volcanologists are fond of saying that **tephra** is **igneous** on the way up but **sedimentary** on the way down.

The pyroclasts are ejected from the volcano in a molten state and solidify as igneous rocks in midair, but are deposited on the ground in the form of sedimentary fragments.

As a result, **pyroclastic rocks** are a **transitional form** between **igneous** and **sedimentary** rocks.

The names of pyroclastic rocks are keyed to the size of the mineral grains of which they are composed.

Names for Tephra and Pyroclastic Rock

Average Particle Diameter (mm)	Tephra (Unconsolidated Material)	Pyroclastic Rock (Consolidated Material)
>64	Bombs	Agglomerate
2-64	Lapilli	Lapilli Tuff
<2	Ash	Ash Tuff

Pyroclastic rocks are called agglomerates when the tephra particles are large (i.e., bomb sized), and tuffs when they are smaller, either lapilli or ash sized.

Volcanic Landforms

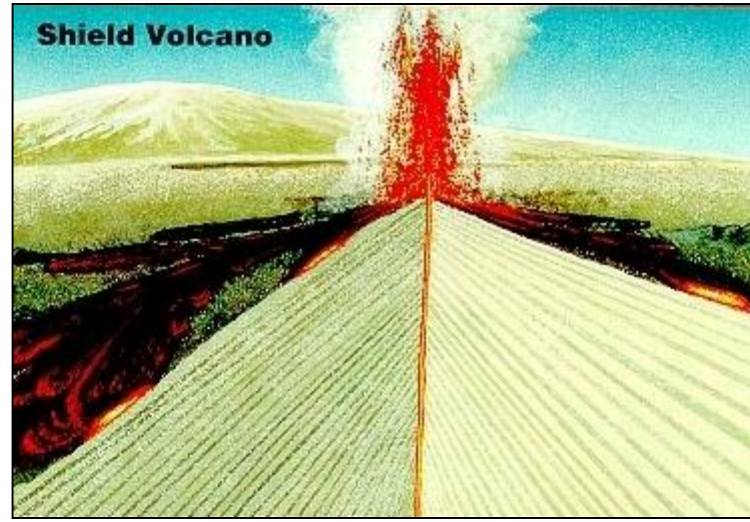
During its lifetime a volcano builds up a **volcanic landform** whose shape is determined by

the composition and characteristics of the volcanic materials

the types of eruptions that have occurred

Shield Volcanoes

Shield volcano is a volcano that **emits fluid lava** and **builds a broad, dome-shaped edifice**.



The **shield volcano** is built up of **successive flows of fluid lava**.

Such lavas are capable of flowing great distances down gentle slopes, forming thin sheets of nearly uniform thickness.

Eventually the pile of lava builds up a shield volcano, a broad formation, resembling a shield lying horizontally, with an average slope of only a few degrees.

Shield volcanoes are characteristically formed by the eruption of basaltic lava; the proportions of ash and other tephra are small.

The slope of a shield volcano is slight near the summit (less than 5^o) because the magma is hot and very fluid; it will readily run down even a very slight slope.

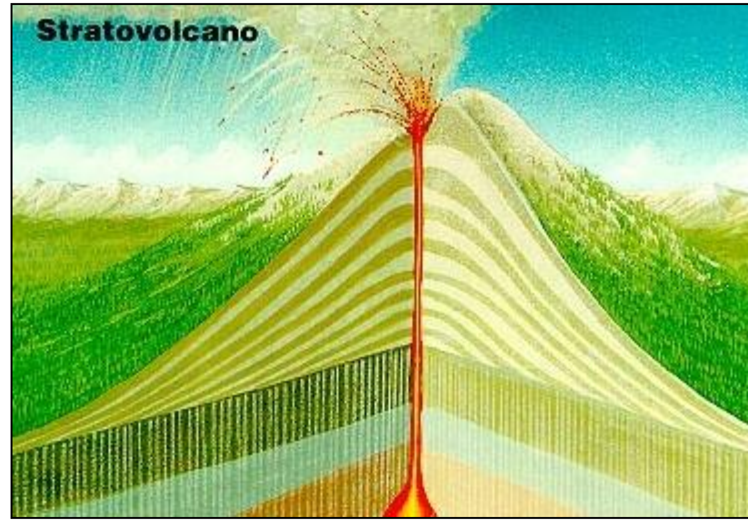
The farther the lava flows down the volcano's flanks, the cooler and more viscous it becomes and the steeper the slope (about 10o) must be in order for it to flow.

Hawaii, Tahiti, Samoa, the Galapagos, and many other oceanic islands are actually the upper portions of large shield volcanoes.

The Mauna Kea, a shield volcano on the island of Hawaii with a light dusting of snow

Stratovolcanoes (Composite Volcanoes)

Startovolcanoes emit both **tephra** and **viscous lava** and build up steep, conical mounds of **interlayered lava and pyroclastic deposits**.



They are most often composed of **andesitic material**.

The **volume of tephra** in a stratovolcano may **equal or exceed** the **volume of the lava**.

The **slopes** of stratovolcanoes are **steep**. Near the summit the slope is typically about **30º**, whereas toward the base the slope flattens to about **6º** to **10º**.

The steep slope near the summit is due in part to the **short, viscous lava flows** that are erupted, and in part to the **tephra**.

Virtually all major continental volcanoes are stratovolcanoes.

In general, **stratovolcanoes** are **much smaller than** the great oceanic **shield volcanoes**.

For example, the total volume of **Mauna Loa**, the Earth's largest shield volcano, is more than **300 times** that of **Mount Fuji** in Japan, one of the most voluminous of all stratovolcanoes.

Other Features of Volcanoes

When active volcanism finally ceases, the rock in an old magma chamber may remain hot for hundreds of thousands of yeas.

Descending groundwater that comes into contact with the hot rock near the magma chamber of a volcano, is heated and rises to the surface along rock fractures, forming a **thermal spring**.

Thermal springs at volcanic sites in **Italy**, **Iceland**, **Japan**, and **New Zealand**, as well as many other locations, have become famous health spas.

Green Dragon Spring in Yellowstone National Park, USA

Hot Springs

Geyser

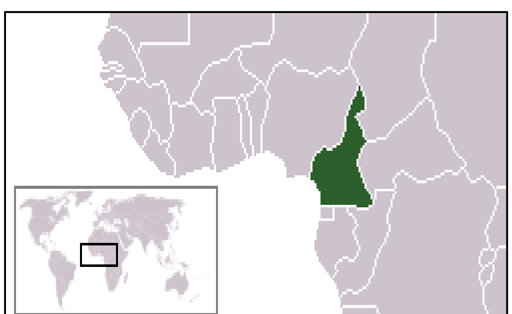
A ***thermal spring equipped with a natural system of plumbing and heating that causes intermittent eruptions of water and steam*** is a **geyser**.

The name comes from the Icelandic word *geysir*, meaning to gush, for **Iceland** is the home of many geysers.

Most of the world's geysers outside Iceland are located in **New Zealand** and in **Yellowstone National Park** in the United States.

Vixen Geyser in Yellowstone National Park, USA

Near the summit of most volcanoes is a **crater**, a ***funnel-shaped depression opening upward, from which gases, tephra, and lava are ejected***.



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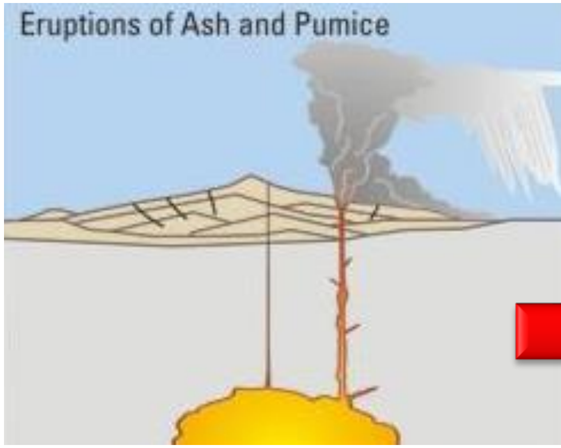
Caldera

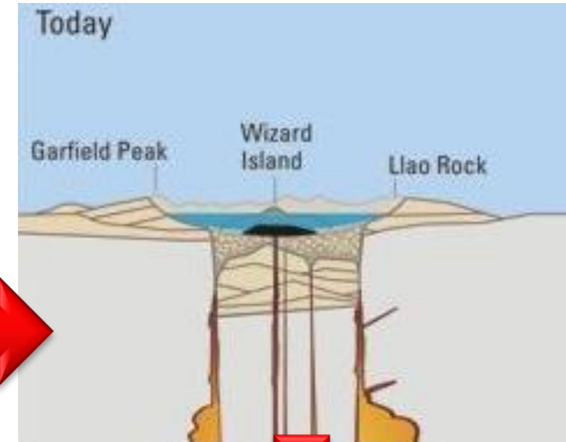
However, many volcanoes, both shield and stratovolcanoes, have a much larger depression known as a **caldera**, a ***roughly circular, steep-walled basin that may be several kilometers or more in diameter***.

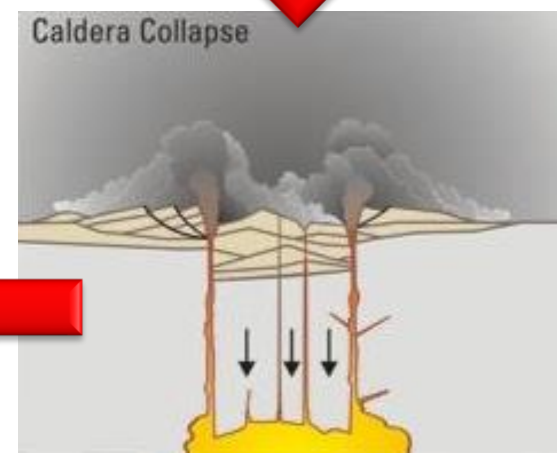
Calderas are formed as a result of the partial emptying of a **magma chamber**. Rapid ejection of magma during a large lava or tephra eruption can leave the magma chamber empty. The unsupported roof of the chamber then collapses under its own weight dropping downward on a ring of steep vertical fractures.

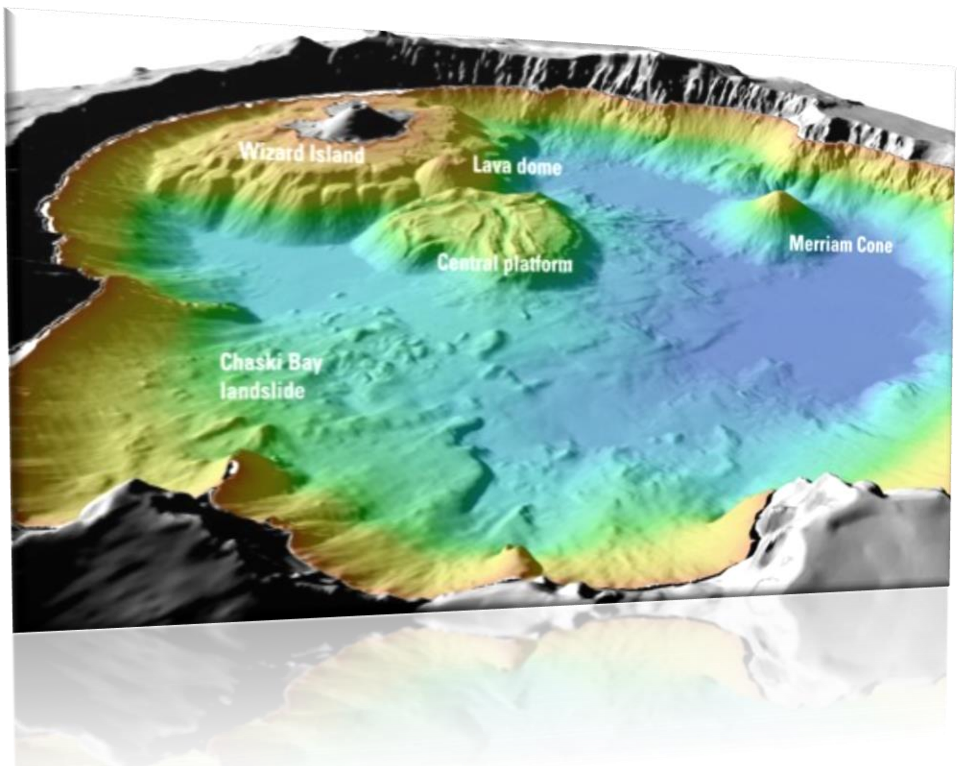
Crater lake in Oregon occupies a circular caldera **8 km in diameter** that was formed after a great tephra eruption about 6600 years ago by a volcano posthumously called **Mount Mazama**.


Eruptions of Ash and Pumice


Steam Explosions


Today
Garfield Peak
Wizard
Island
Llao Rock


Caldera Collapse


Wizard Island
Lava dome
Merriam Cone
Central platform
Chaski Bay
landslide

Volcan Irazu, Costa Rica

Fissure eruptions

Some volcanic eruptions occur when lava reaches the surface via elongated fissures. These events are called **fissure eruptions**.

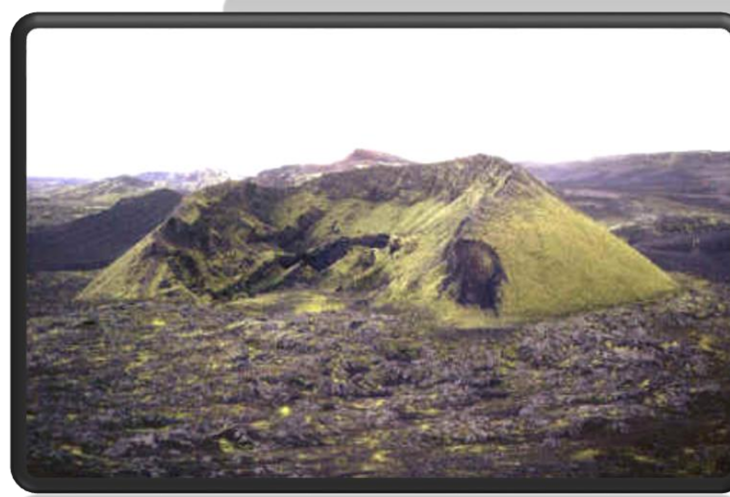
Such eruptions, which can be very dramatic, are characteristically associated with **basaltic magma**.

Successive lavas that emerge as fissure eruptions on land tend to spread widely and may create flat lava plains called **basalt plateaus**.

In **1783** a **fissure eruption** at **Laki** in **Iceland** occurred along a fracture **32 km** long.

Lava flowed **64 km** outward from one side of the fracture and nearly **48 km** outward from the other side. Altogether the flow covered an area of **588 km^2**. The volume of the lava extruded was **12 km^3**, the largest lava flow in historic times and also one of the most deadly.

The flow destroyed *homes* and *food supplies*, *killed livestock*, and *covered fields*. In the ensuing *famine*, *9336 people died*.



Volcanic Hazards

Since **A.D. 1800** there have been **18 volcanic eruptions** in which a **thousand or more people died**. Yet millions of people live in areas where there are active volcanoes.

Like other natural phenomena, volcanic hazards have many effects that include:

- Lava Flows
- Violent Eruptions and Pyroclastic Activity
- Poisonous Gas Emissions
- Volcanic Mudflows
- Flooding
- Tsunamis
- Volcanic tremors and Earthquakes
- Atmospheric Effects
- Famine and Disease

Lava Flows

Most types of volcanoes produce at least some lava, but extensive **lava flows** are most characteristic of the **quieter types of volcanoes** such as those found in **Hawaii**.

Because lava flows are closely **controlled by topography**, it is often possible to **predict** the general **direction** and **course** of a flow.

Some lavas can travel downhill at remarkably **high velocities**.

Basaltic lava, for example, can travel as fast as **64 km/h** down a steep slope.

Such fluidity is rare, however, and the rates of flow are more commonly measured in **meters per hour** or even **meters per day**.

Therefore, lava flows are usually **slow enough that people are not endangered**.

This means that in dealing with the hazardous effects of lava flows the main focus is on **preventing property damage**, **not on saving lives**.

One of over 100 houses destroyed by the lava flow in Kalapana, Hawaii, in 1990.

Lava flows are one of the few aspects of volcanism that can be **controlled** by human intervention.

In **1935**, **bombing** was tried, *with limited success*, during an eruption of **Mauna Loa** in order to spare the **city of Hilo** from excessive damage.

The goal of bombing is to ***block*** or ***divert*** the advancing lava flow, either by

altering the topography ahead of the flow

or

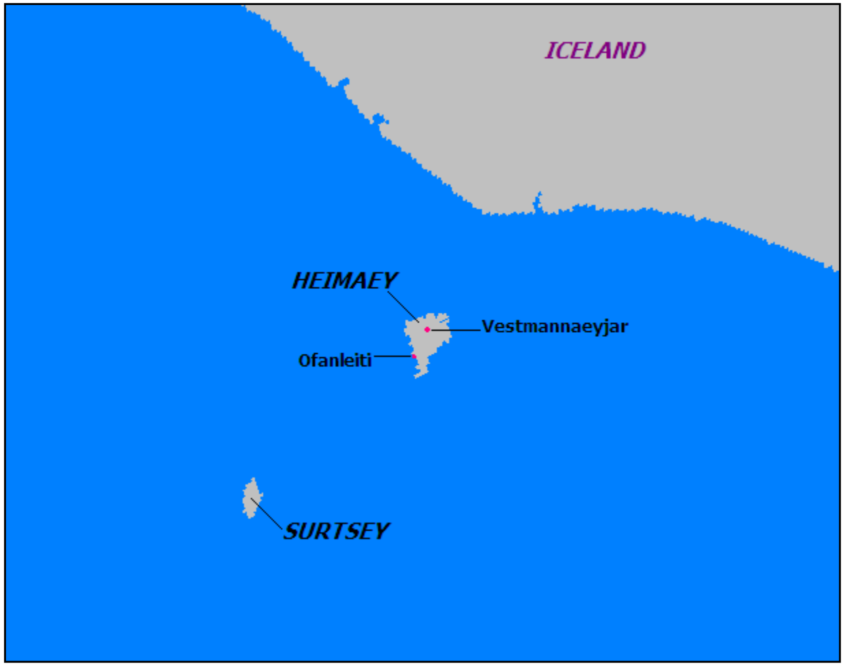
by creating a barrier by blocking the channel or causing a lava tube to collapse.

The **construction of artificial barriers** is based on the same principle, that is, ***creating a blockage*** and ***diverting the flow*** from its natural course.

Walls and bulldozed rock barriers constructed for this purpose have been tested – again *with limited success* – in **Hawaii**, **Iceland**, and **Japan**.

Hydraulic chilling involves *spraying water on an advancing lava flow so that the front of the flow solidifies*.

During a **1973** eruption of **Heimaey Island**, off the cost of **Iceland**, fire boats sprayed seawater on advancing lava flows. This action is credited with having saved the harbor of the fishing village of **Vestmannaeyjar**.



Violent Eruptions and Pyroclastic Activity

Unlike slowly moving lava flows, **hot, rapidly moving pyroclastic flows** and **laterally directed blasts** may overwhelm people before they can run away.

Pyroclastic flows sweep down the flanks of Mayon volcano, Philippines, in 1984.

The most destructive pyroclastic flow this century (in terms of loss of life) occurred on the **Caribbean island of Martinique in 1902**. In that eruption an **avalanche of hot ash** rushed down the flanks of **Mont Pelee** at a speed of more than **160 km/h**, overwhelming the city of **St. Pierre** and instantly killing **29,000 people**.

Pyroclastic debris sometimes contains blocks the **size of cars**.

In the **1968** eruption of **Arenal Volcano** in **Costa Rica**, large falling blocks crashed through the roofs of houses **3 km** away.

However, much of the damage from **pyroclastic eruptions** is caused by the **widespread fall of ash**. For example, in **A.D. 79** many citizens in the nearby towns of **Pompeii** and **Herculaneaum** were killed in the eruption of **Mount Vesuvius**. Most of the victims apparently were either buried and suffocated by falling ash or crushed by buildings that collapsed under the weight of the ash.

Poisonous Gas Emissions

Many volcanoes emit **gases** more or less continuously.

Although **water vapor** is the main gas emitted by volcanoes, other kinds of gases are often present, many of them potentially **harmful to people, animals, or vegetation**.

Some are **toxic**, such as **carbon monoxide (CO)**.

Some are **acidic**, such as **hydrochloric acid (HCl)**, and **hydrofluoric acid (HF)**.

In other cases, the emitted gases mix with water vapor to form **acidic solutions**, such as **sulfuric acid (H_2SO_4)**.

Perhaps the best known examples of the destructive capabilities of volcanic gases occurred in **Cameroon** in **West Africa**. **Lake Monoun** is part of a series of summit crater lakes in small, young basaltic volcanoes in northwestern Cameroon.

In **August 1984**, a release of CO_2 gas from **Lake Monoun** caused the deaths of **37 people**.

Volcanic Mudflows (Lahars)

A volcanic mudflow is technically referred to as a **lahar**.

Rain can loosen tephra piled on a steep volcanic slope and start a deadly lahar.

Lahars are common features of volcanic eruptions and can have devastating consequences.

Lahar from a March 1982 eruption of Mount St. Helens

In **1985**, a small eruption of the **volcano Nevado del Ruiz in Colombia** melted part of the icecap on the mountain's summit. Mudflows were formed when the volcanic ash mixed with the meltwater. The massive lahars moved swiftly down river valleys on the flanks of the volcano, killing at least **23,000 people** and causing more than **US$212 million in property damage**.

Because they follow topography, lahars are **relatively predictable**.

Sometimes they can be **diverted by barriers or tunnels**, and they are subject to the same types of control techniques as are lava flows.

Flooding

It is common for volcanic eruptions to be accompanied or preceded by **flooding**, which may in turn cause mudflows.

In some cases flooding may be **caused by** the **rupture of a summit crater lake**.

Flooding can also result **when rivers are blocked by lava flows or lahars**.

Some river courses in the vicinity of **Mount Pinatubo** were permanently altered after the **1991 eruption**, primarily by lahars that filled and blocked major drainage channels and diverted the rivers.

Before and after the eruption: a river valley filled in by pyroclastic flow deposits

Tsunamis

Violent undersea eruption can cause giant sea waves called **tsunamis**.

Tsunamis set off by the eruption of **Krakatau** in **1883** killed more than **36,000 dwellers** on the coast of **Java** and other **Indonesian islands**.

Volcanic tremors and Earthquakes

Eruptions are commonly **preceded** by **local earthquakes**.

They may be **caused by the cracking and splitting open of fissures as the magma chamber inflates**.

At both **Mount St. Helens (1980)** and **Mount Pinatubo (1991)**, hundreds of small earthquakes were recorded daily before the main eruption sequence, providing information that was used in predicting the onset of the eruption.

The seismic activity may last only a **few days** or **weeks** or may continue for **months** or even **years**.

The seismic prelude to the **79 A.D. eruption of Mount Vesuvius** lasted **16 years**.

Volcanic tremor or **harmonic tremor** consists of a more or less **continuous, low frequency, rhythmic ground motion**.

It may be associated with **actual movement of the magma** (e.g., boiling, convection, or drag of the magma against the chamber walls).

Volcanic activity is associated with **tectonic seismicity** because the distribution of both volcanoes and earthquakes is controlled by the locations of **active plate boundaries**.

It has been suggested – though not confirmed – that large earthquakes may contribute to the onset of major volcanic eruptions.

Atmospheric Effects

Climatic effects result primarily from the **ejection of ash and extremely fine particles and droplets called aerosols high into the stratosphere** during major eruptions.

Some eruption columns reach such great heights that **high-level winds transport fine debris and sulfur-rich gas around the world**.

By **blocking incoming solar energy**, such atmospheric pollution can **lower average temperatures** at the land surface and cause spectacular sunsets as the **sun's rays are refracted by the airborne particles and aerosols**.

The **1991 eruption of Mount Pinatubo** blasted more than **8 km^3** of fine pyroclastic material and sulfur-rich gas high into the atmosphere, causing significant **global cooling** for as long as **two years**.

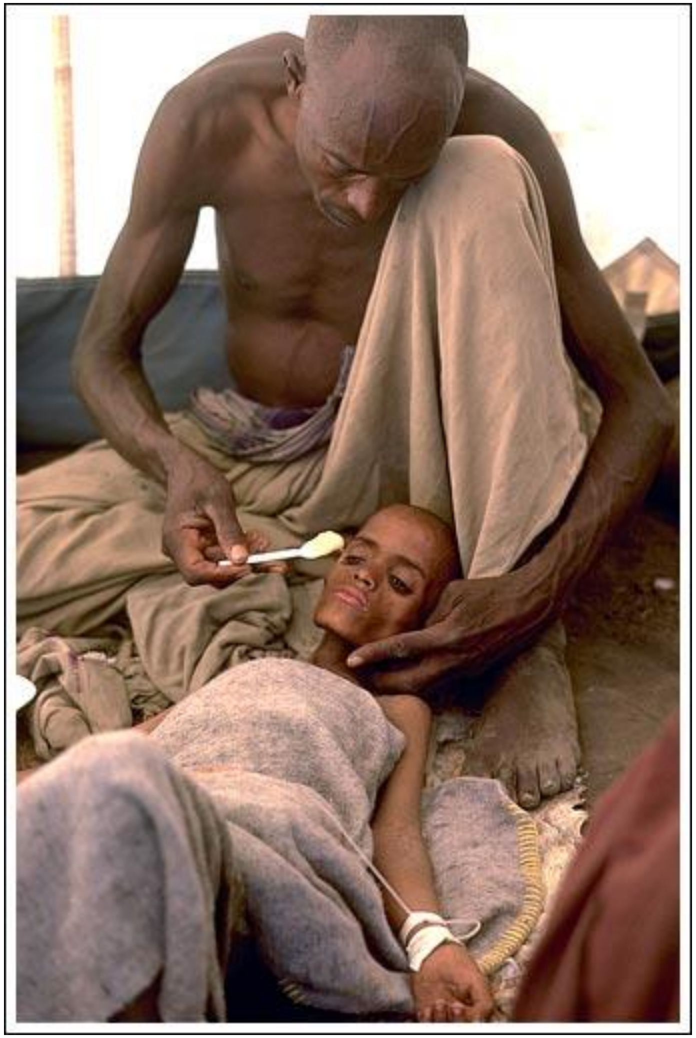
In **1815**, **three days of total darkness** followed the major pyroclastic eruption of **Tambora in Indonesia**; the darkness extended as much as **500 km** from the volcano. The following year was called "**the year without a summer**;" average global temperatures fell more than **1ºC** below normal

Volcanic material ejected into the atmosphere can also cause **toxic** or **acidic fallout**.

Salty and acidic precipitation can damage crops, contaminate soil, and corrode materials.

Famine and Disease

Periodic ash falls can contribute significantly to **soil fertility**. However, a major tephra eruption may wreak such havoc on agricultural land and livestock that **famine** results.



The **effects can be exacerbated** by

long-term climatic changes and by

the **dislocation of people** and

interruption of basic services

associated with other aspects of the eruption.

Most of the deaths that resulted from the **1991 eruption of Mount Pinatubo** were caused not by the effects of the eruption itself but by **disease**, **lack of water and sanitation**, and **related problems** in **temporary camps for the homeless**.

Beneficial Aspects of Volcanism

Volcanoes have actually done much more good than harm to human beings:

1. The **origin and evolution of the atmosphere and oceans** were (and still are) directly dependent on the outgassing of volatile materials through volcanoes.

2. Volcanoes have **created many thousands of square kilometers of new land**.

3. Areas near volcanoes are characterized by **very fertile soils and high agricultural productivity**. (periodic ash falls, especially when they are rich in potassium, phosphorus, and other elements, are effective natural fertilizers)

4. Volcanism is linked with the **formation of mineral deposits**.

5. **Using water warmed by hot rocks**, people can heat or cool their houses, generate electricity, and swim in geothermally heated pools.

Predicting Volcanic Eruptions

Active volcanoes are those that have erupted recently, or at least within recorded history. Every year about 50 to 60 volcanoes erupt.

Extinct volcanoes are those that have not erupted within recorded history. They are deeply eroded and show no signs of future activity.

Dormant volcanoes are those that have not erupted in recent memory and show no signs of current activity, but they are not deeply eroded. They are in between the two extreme categories: active and extinct volcanoes. They can become active with unnerving ease.

Mount St. Helens had been dormant for 123 years before its 1980 eruption.
Mount Pinatubo had been dormant for more than 400 years before its 1991 eruption.
Mount Vesuvius was widely considered extinct before its eruption in A.D. 79.

To some extent, **volcanic hazards CAN be anticipated** if experts are able to gather data before, during, and after eruptions.

With sufficient information, the experts can advise civil authorities on when to implement *hazard warning* and when to *move endangered populations* to areas of lower risk.

In the context of volcanism:

Prediction (**short term**) offers a fairly specific date for an expected event

Forecast (**long term**) is a more general statement of likelihood

Long-Term Forecasting of Volcanic Eruptions

It is based primarily on:

1 Identification of a **volcano’s tectonic setting** as **active**, **dormant**, or **extinct**.

2 Studying the **volcano's past behavior**:

1. To ascertain the historic style of eruption. This is important in predicting the type of activity to be expected and the area that might be affected by an eruption.
2. To determine the volcano’s eruption interval.

For example, in **1975** D. R. Crandell and colleagues wrote that Mount St. Helens “**will erupt again, perhaps before the end of this century**.” the volcano erupted 5 years later. **This is a good example of a successful long-term forecast.**

Short-Term Prediction of Volcanic Eruptions

Short-term prediction of volcanic eruptions and the issuance of warnings are based primarily on:

Monitoring of volcanic activity – this has two main goals:

1. To allow scientists to **track the distribution and movement of magma** in the volcanic “plumbing” system.
2. To permit the **detection of physical anomalies and the identification of precursor phenomena** – that is, events or processes that signal the onset or progression of activity within the volcano.

Monitoring the movement of magma

There are some techniques whereby volcanologists can actually attempt to **monitor the distribution and movement of a magma body** within a volcano. **Changes in the magma body may indicate that an eruption is imminent.**

Several techniques are used in such studies:

- **Seismic studies**
- **Change in magnetic field**
- **Change in electrical resistivity**
- **Magma chamber modeling**

Physical anomalies and precursor phenomena

Physical anomalies are recognized as precursors or warning signs pointing to the onset of a major event.
A **physical anomaly** is **any physical occurrence that is out of the ordinary and is linked in some way to activity within the volcano**.

Following are some of the most common anomalies that typically precede volcanic eruptions:

- **Ground deformation**
- **Changes in the temperature of crater lakes, well water, or hot springs**
- **Change in heat output at the surface**
- **Change in the composition of gases**
- **Local seismic activity**