Volcanoes

Leo Li

February 2023

Table of Contents

1 Introduction

Volcanism is the eruption of lava onto the surface of the earth, resulting in the formation of extrusive igneous rocks. Volcanism occurs in various geologic settings, producing a wide variety of different structures and deposits. The understanding of volcanoes and their associated geologic processes are critical to our understanding of Earth's geology.

2 Volcanic structure and formation

Volcanoes form when magma rises through and ruptures the crust. The composition of the magma that is erupted largely determines the resulting morphology of the volcano.

- **Magma chamber** A volcano is essentially composed of a *magma chamber* and a vent from which lava is extruded. A *conduit* connects the vent to the magma chamber.
- **Vocanic neck** Rock solidified within the conduit of a volcano which is later exposed is called a volcanic neck. The flanks surrounding the conduit are often composed of pyroclastic material and/or lava flows, depending on the form of volcano.
- **Eruption column** When volcanoes erupt, they eject gas, ash, and other molten or glassy materials into the atmosphere in an *eruption column*. These columns will often rise through the troposphere in updrafts produced by the hot material. The prevailing wind can blow the eruptive column in a certain direction, after which it will fall, producing *pyroclastic deposits*.

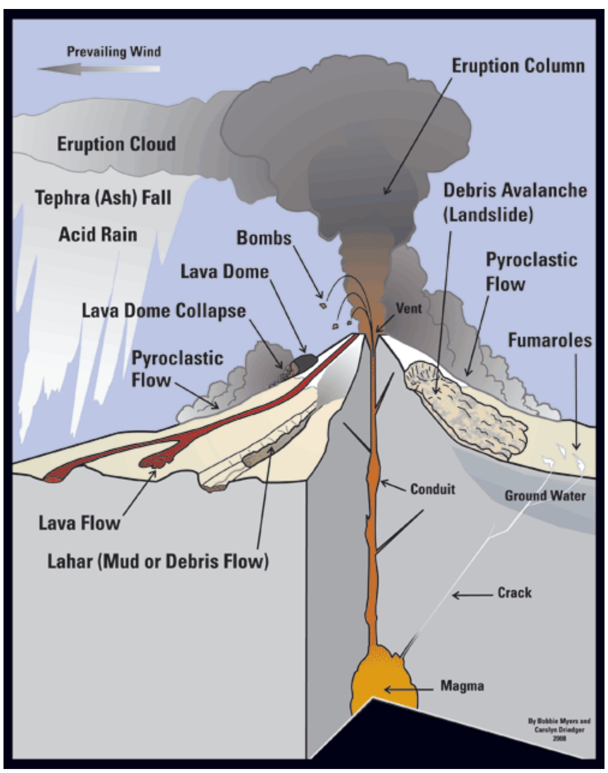

Fig. 1: Diagram of volcanic structures

2.1 Magma viscosity

The viscosity of magma (and the resulting magma) determines the structure of the volcano formed. The viscosity of a melt is principally determined by two factors: silica content and temperature.

- **Silica content** The viscosity of magmas increase with increasing silica content. Silica (SiO_4) in the solid state forms a network solid (which we know as quartz). When molten, this network of silica tetrahedra loses its overall structure. However, it polymerizes the melt, with non-continuous chains of silica tetrahedra present, inhibiting flow. Therefore, increased silica content in a melt produces more viscous magma.

- **Ion size** Other ions present in the melt (such as iron, magnesium or aluminum) modify the polymerization of the melt. In general, larger ions (notably magnesium and iron, which are abundant in mafic melts) de-polymerize the silica in a melt, lowering the overall viscosity. Contrarily, silicon, aluminum and other smaller ions aid in the polymerization of a melt, increasing its viscosity.
  - **Mafic vs. Felsic** As you may notice, this trend in viscosity aligns with the traditional classifications of igneous rocks: felsic magmas (65-75% silica and low in larger Mg and Fe ions) form viscous mgmas, while increasingly mafic magmas (lower silica concentrations and higher large-ion Mg, Fe concentrations) produce thinner magmas.

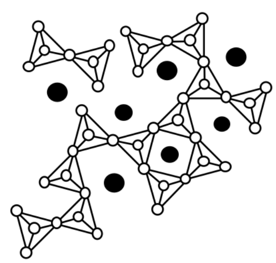

Fig. 2: Diagram of silicate melt structure. Note the tetrahedra and surrounding cations.

- **Temperature** The temperature of magma is another property that affects viscosity. Generally, the viscosity of a melt decreases with increasing temperature: bonds between components of a magma are broken as temperature increases (decreasing polymerization), leading to a less viscous liquid. Likewise, viscosity increases as the melt freezes to form a solid.

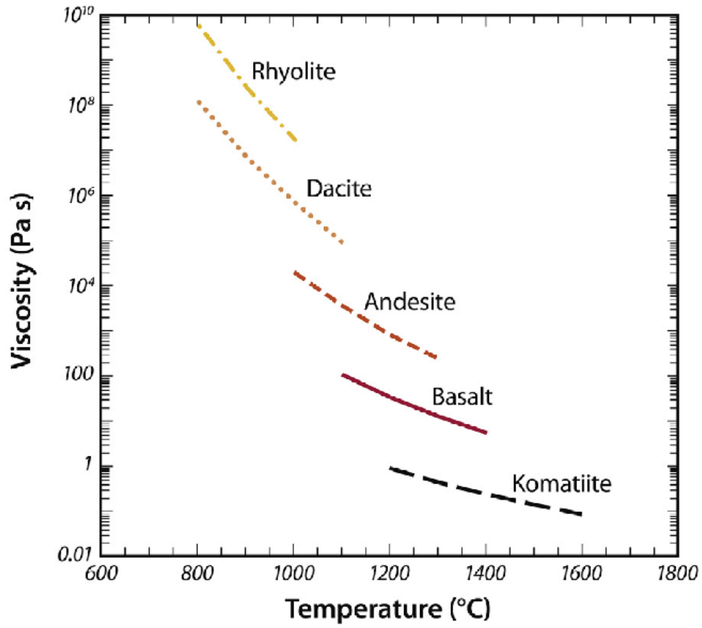

Fig. 3: Graph of magma viscosity with temperature. Note the decreasing trend in viscosity with increasing temperature.

- **Volatile content:** The concentration of volatiles in magmas also contributes significantly to the viscosity of the melt. The most abundant of these volatiles are H_2O and CO_2.
  - **H_2O** Water reacts with SiO_4 in the mamga, reducing polymerization, which decreases viscosity. For this reason, water is more soluble in silica-rich felsic magmas than in more mafic ones. As a result of this reaction, the introduction of water into a magma lowers its viscosity. Note that water is usually introduced into magmas at subduction zones, where water in oceanic lithosphere heats as it subducts, evaporates, and enters the mantle as volatile H_2O.
  - **CO_2** The role of carbon dioxide is more complex. CO_2 is most soluble in mafic magmas, and plays a similar role to water. However, overall, the solubility of carbon dioxide in magmas is lower than that of water. Additionally, recall that the addition of volatiles to a magma lowers its melting point (this is the mechanism behind flux melting).

2.2 Volcano Morphologies

The morphology of volcanoes are dependent on the lavas that they extrude. There are four basic types of volcanoes to begin: shield volcanoes, which form from basaltic mamgas, composite volcanoes, which form from andesitic lavas, cinder cones, which form from andesitic to basaltic lavas, and lava domes.

2.2.1 Shield Volcanoes

Shield volcanoes form from low-viscosity basaltic magmas. Shield volcanoes are principally found along hotspots (such as Mauna Loa in the Hawaiian island chain), where basaltic lavas are produced. Shield volcanoes form as basaltic lava is extruded *effusively* (meaning eruption is not explosive, but rather lava flows out of vents). Because basaltic magmas have a relatively low viscoity, the lava flows are able to travel quite far from the vent before fully solidifying; typically, basaltic lava flows are around one meter thick, and can exceed 20 kilometers in length. Shield volcanoes are formed from overlapping lava flows. As a result, they typically have very gently sloping sides (less than 10º), and can grow to become very wide. Unlike other volcanoes, which typically have one main vent from which lava exits, shield volcanoes often erupt along fissures, producing a "curtain" of lava.

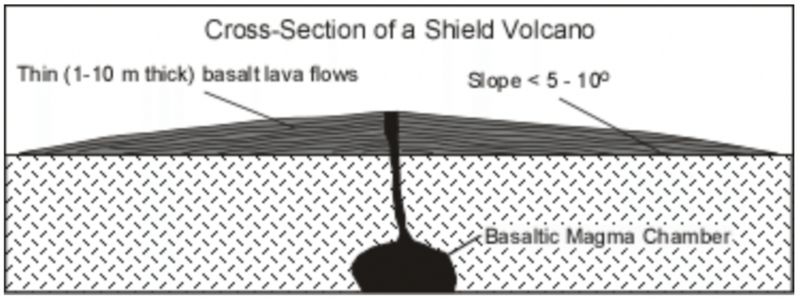

Fig. 5: Profile of a shield volcano. Source: Tulane EENS

Fig. 6: Mauna Loa, a shield volcano part of the Hawaiian-Emperor Seamount chain. Note the gently sloping sides characteristic of shield volcanoes.

2.2.2 Composite Volcanoes

Composite volcanoes (also known as stratovolcanoes) form from medium-viscosity andesitic magmas. Composite volcanoes, as the name suggests, are composed of a composite of andesitic lava flows and ejected pyroclastic material.

- **Explosive eruptions** Due to the higher viscosity of andesitic magma, eruptions from composite volcanoes are generally explosive rather than effusive. As you may recall from chemistry class, the solubility of gasses in fluids decreases with decreasing pressure. Likewise, as magmas rise through the crust, dissolved CO_2 and other volatiles in the magma exsolve, producing a separate gaseous phase in the magma chamber. Over time, pressure builds up as more magma enters the chamber and more gas is exsolved, eventually producing an explosive eruption.

- **Types of debris** Lava ejected from the volcano during this process cools, producing various forms of pyroclastic debris including bombs (large chunks of partially-molten material), blocks (large chunks of solidified material), ash (rapidly cooled fragments of lava), and other forms of glassy material.

- **Properties of the flow** Andesitic lava flows are also formed. However, these will only travel a limited distance from the vent before solidifying. As a result, a composite volcano will often have a steeper profile at higher altitudes, with gently sloping flanks due to the presence of lava flows closer to the vent.

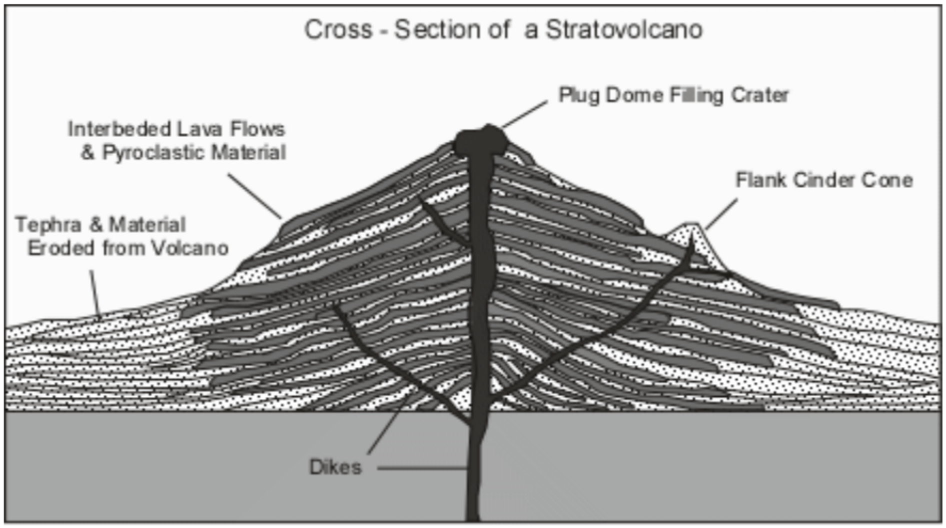

Fig. 7: Profile of a stratovolcao. Source: Tulane EENS 3050

2.2.3 Cinder Cones

Cinder cones, also known as tephra cones, are volcanoes formed from tephra ejected during strombolian eruptions, which are characterized by explosive eruptions of andesitic to basaltic volcanoes. They are usually small, with steep flanks, and can essentially be described as piles of tephra surrounding a central vent. In contrast, composite and shield volcanoes have a structure that is at least partially composed of cooled and solidified lava flows. As a result, the slopes of cinder cone volcanoes are controlled by the angle of repose (the steepest angle of which a type of granular material can be piled without slumping) of the tephra from which they are composed.

Cinder cones often occur in groups, and are associated with intraplate volcanism. Their development begins with the eruption of andesitic to basaltic magma from an initial vent. The explosive eruption of this magma produces pyroclastic material, often in the form of scoria and other glassy fragments, which settle around the vent. Following successive eruptions, the pile of tephra surrounding the vent grows, producing the flanks of the volcano. Eventually, the volcano becomes degassed, and is no longer capable of erupting explosively. Lava then flows from the base of the volcano, as the degassed lava is denser than the surrounding tephra. The lava flows will often flow from the base of the volcano rather than from the 'vent', as the unconsolidated flanks of the volcano are unable to bear the pressure of extruded lava. Cinder cones often occur along the flanks of other shields, calderas or composite volcanoes.

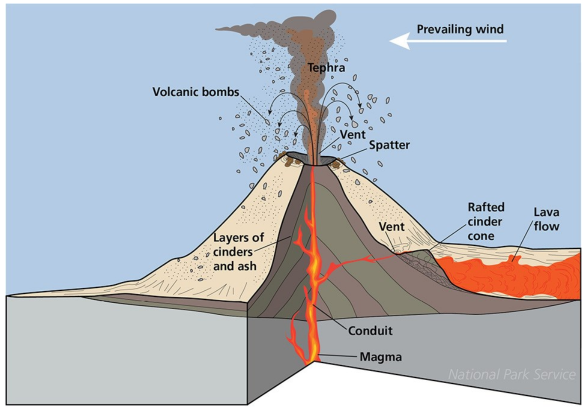

Fig. 8: Diagram of cinder cone (source: National Park Service)

2.3 Volcanic Features

A number of landforms are produced during volcanic eruptions. These include lava flows, lava domes, calderas, pyroclastic flows, intrusions of various forms (dikes, sills, etc.) and spatter cones.

- **Lava flows** Lava extruded from volcanic vents can often flow along the flanks of a volcano, producing a lava flow. Lava flows travel at different rates depending on the viscosity of the lava, with rhyolitic lavas flowing at only a couple meters per hour, while basaltic lava flows can reach speeds of 10 kilometers per hour (komatiitic lavas, which no longer erupt, would likely have flowed considerably faster, with a viscosity similar to that of liquid water).

  Lava flows possess a range of textures, dependent on their composition. Basaltic lavas in particular form two different lava flow types: Pahoehoe (rope-like) flows, and A'a flows (rough). The differing appearances of these flows are a result of flow rates, with the surface of the lava flow cooling more quickly than the interior, forming a "skin".

  - **Pahoehoe** In Pahoehoe flows, this skin is breached by underlying lava, but is allowed to form again rapidly. This results in the ropy appearance of the flow.
  - **A'a** In A'a flows, the flow rate exceeds that which allows the skin to form, and a splintery layer of fragments forms on the surface of the flow.
  - **Pillow lava** When basaltic lavas erupt underwater, the expansion of the "skin" surrounding the interior of the lava lengthens and inflates, forming lobes known as pillows.

  Lava flows of more felsic compositions form thicker and less voluminous flows extending only a small distance from the vent.

Fig. 9: Image of an A'a lava flow. Cooled Pahoehoe lava can be see beneath the advancing edge of the flow.

- **Lava Domes** Rhyolitic lavas in particular are known for producing a range of features resulting from their very high viscosity. These include lava domes, coulées, and spines. Lava domes are mounds produced by the extrusion of viscous lava. Lava domes grow as viscous lava piles above (exogenic) or is injected into (endogenic) existing rock. As the dome expands, rock at the surface flakes off, forming breccias along the rims of the dome.

  Domes can also experience explosive eruptions when they partially collapse allowing magma to rapidly depressurize, forming pyroclastic flows.

  Lava domes are also associated with other features, most prominently cryptodomes and lava spires. Cryptodomes are dome shaped structures produced by the injection of viscious magma at a shallow depth beneath the surface. Lava spires are vertical chunks of rock forced upwards from a vent, often from an existing lava dome.

- **Pyroclastic Flows** are fast-flowing masses of hot gas and volcanic material that are producied by explosive eruptions. They form when the eruption column of an explosive eruption falls, producing a mixture which then streams down the flanks of a volcano. When convection currents holding up the erupted material subside, the column collapses. Pyroclastic flows can travel at speeds up to 700 kilometers per hour, making them some of the most dangerous volcanic events for humans.

- **Calderas** When particularly large volumes of lava are erutped in a relatively short period of time, the magma chamber beneath a volcano can be partially to fully emptied. The collapse of the overlying strata into the emptied lava chamber forms a depression called a caldera.

  Calderas can encompass areas up to hundreds of square kilometers, and are thus associated with some of the largest known volcanic events. Many of these (such as the eruptions of Lake Toba, Yellowstone, and La Garita volcanoes to name a few prominent examples) are associated with global cooling events, with the volume of material ejected enough to temporarily lower the albedo of the earth.

  When magma intrudes into a caldera, the center of the caldera may be uplifted, forming a *resurgent dome.*

3 Pyroclastic Deposits

The lava and gases ejected during an explosive eruption cool rapidly to form various pyroclastic materials.These are classified based on their size, and pyroclastic rocks are classified based on their composition of these types of particles.

Classification of Pyroclasts		
Average Particle Size	Unconsolidated Tephra	Rock
<64 mm	Bombs or Blocks	Agglomerate
2-64 mm	Lapilli	Lapilli Tuff
<2 mm	Ash	Ash Tuff

The ash, lava and other materials ejected from a volcano during explosive eruptions form rocks composed of these fragments. An explosive eruption ejects a column of debris into the atmosphere, mostly consisting of ash and hot gases. These columns are able to rise by heating surrounding air to produce a buoyant column. Once this column cools however, the pyroclasts fall, and are deposited in layers surrounding the volcano. This unconsolidated tephra is lithified thorugh various processes to produce *tuff*. These processes include diagenesis after burial, welding at high temperatures, fumarolic alteration, or hydrothermal alteration.

- **Diagenesis** The process by which sediment - in this case, tephra - is lithified via compaction of pore spaces and cementation by precipitated material at depth due to great pressure and temperature.
- **Welding** Welding occurs when tuff is deposited at sufficiently high temperatures to partially melt and weld together.
- **Fumarolic alteration** Gases emitted by fumaroles can alter surrounding material, including tephra, which can produce tuff
- **Hydrothermal alteration** Groundwater heated by volcanic activity can react with tephra and assist in diagenesis and lithification, helping to form tuff.

Successive eruption of the same volcano will often produce layers of tuff in the surrounding strata, with some calderas producing tuff layers hundreds of meters in thickness. Tuffs that are welded together are termed *ignimbrites*, and are formed from pryoclastic flows.

Example 2.1 (USESO Open Round 2021) A volcano currently extrudes rhyolitic magmas but used to extrude basaltic magmas. Which of these is likely true about the volcano's history (*)?
(A) The silica content of the magma increased over time
(B) The solidification temperature of the magma increased over time
(C) The explosivity of the volcano decreased over time
(D) The viscosity of the magma from the volcano decreased over time
(E) The magma may have assimilated felsic continental crust

Solution: The specified volcano currently extrudes rhyolitic magmas, but once extruded basaltic magma. You can immediately recognize that the magma involved has changed from a mafic magma to a felsic one. We know that the silica content in rhyolitic magma is higher than that of basaltic magma; thus A is correct. As we also understand that the melting point of magma increases with decreasing silica content, we know that the melting point of the given magma must be decreasing as it becomes more felsic. We can thus conclude that B is false. As follows, C must also be false, as the explosivity of volcanic eruptions is greater with rhyolitic lavas than with basaltic lavas (the latter erupting *effusively* rather than explosively). Additionally, as rhyolitic lavas are more viscous, there is a greater likelihood of pressure buildup from exsolved gases, causing a more explosive eruption. Choice D is also false, as we know the viscosity of the volcano has increased since rhyolitic lavas are more viscious. For choice E, recalling the mechanisms of magmatic differentiation, we know that the assimilation of felsic continental crust by a mafic magma can produce a more felsic magma, and thus choice E is also correct.