2. Volcanism

2.1. Volcanoes and plate tectonics

Volcanism is the eruption of magma at the surface of a planet. Rocks produced by volcanic processes are called volcanic rocks. The most prominent feature of volcanism is the ***volcano***, an accumulation of volcanic material (e.g. molten rock, rock fragments, and gas) ejected from a central chimney or ***vent***.

First let's have a look at the distribution of volcanoes around the world and their relationship with plate tectonics (Fig. 15).

Figure 15: Global distribution of volcanoes and tectonic plates. Note that this map does not show underwater volcanoes.

The map above tells us that there is a close link between the distribution of volcanoes and plate tectonics. The great majority of volcanoes are located along plate boundaries. Most volcanoes displayed on the map are related to subduction zones. But volcanoes are also found along divergent boundaries (see the East African Rift in Fig. 15). Since the map above does not show volcanoes located below sea surface, those related to mid-ocean ridges are not displayed. However, one should keep in mind that underwater volcanoes may account for as much as 80% of Earth's volcanoes!

Volcanism occurs wherever magma reaches Earth's surface. This happens along tectonic plate boundaries: mid-ocean ridges, continental rifts and subduction zones[*]. But there is a third geologic setting related to volcanism that is not located along a plate boundary: ***hot spots***. Examples of hot spots are Hawaii (see red dots in the middle of the Pacific Plate in Fig. 15, see also Fig. 16), Yellowstone (continental hot spot in western USA), and Iceland (which happens to be also on the Mid-Atlantic Ridge). The mechanism of formation of these hot spots is not very well understood. A commonly accepted hypothesis suggests that the source of hot spots comes from deep within the mantle, perhaps even from the mantle-core boundary, and that a hot spot forms when a narrow jet of mantle rock called ***mantle plume*** reaches the surface.

Figure 16: Relief map showing Hawaii and the Emperor Seamount Chain (left) and sketch of a seamount chain related to the presence of a hot spot beneath a moving oceanic plate (right). As the plate moves toward the subduction zone, a succession of volcanoes is formed above the fixed hot spot. Volcanoes are carried away by the plate (much like a conveyor belt) and progressively sink as they (and the plate underneath) cool down and contract. At the same time, ocean waves and currents erode and carry away some of the volcanic material.

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[*] Not in regions of continental collision (e.g. Himalayas) because the magma solidifies before reaching the surface.

Knowing how the temperature of Earth's interior evolves with increasing depth (**geothermal gradient**) is crucial to understand why volcanic activity occurs in a particular geologic setting. The geothermal gradient in the Earth's crust is on average 30°C/km. Its value greatly depends on the tectonic setting. For example, it increases sharply beneath mid-ocean ridges where the crust is thin and magma is formed near the surface. When the geothermal gradient intersects the rock solidus[**], the rock begins to melt and a magma is produced (Fig. 17, see figure caption for further explanations).

Figure 17: Cross section of the oceanic crust and mantle showing three geologic settings associated with volcanism: mid-ocean ridge, hot spot, and subduction zone. The red curve delineates the geothermal gradient (temperature vs. depth) and the green curve delineates the solidus of mantle rock. Note that the melting temperature (solidus) decreases with decreasing depth/pressure. The first graph to the left shows the geotherm of a portion of the oceanic crust that is not related to volcanic activity ("normal" situation). The geotherm and the solidus do not intersect and rock does not melt. In the three geologic settings where volcanic activity occurs, the geotherm and the solidus intersect and rock begins to melt once temperature reaches the solidus. Source: modified from Wikipedia (author: Woodloper).

2.2. The volcanic "plumbing" system

Magma usually originates in the asthenosphere by the processes described in figure 17. The magma, less dense (hotter) than surrounding rocks, makes its way up through the lithospheric mantle and crust by moving along fractures and by melting surrounding rocks. Once magma reaches the surface, it is called **lava**. A volcano is made of successive layers of lava and/or **pyroclasts** (see section 5.6.). The path taken by the magma from its source to the surface delineates different geologic structures described in the figure below (Fig. 18).

2.3. Interactions between volcanoes and other geosystems

Volcanoes interact with other geosystems (e.g. atmosphere, hydrosphere; Fig. 19). As we will see later, volcanic gases (mainly water vapor, but also CO_2, SO_2, and lesser N_2, H_2, CO, S, and Cl) released in the atmosphere may influence the climate. Volcanic activity also influences the biosphere. Catastrophic volcanic eruptions have been a plausible cause of mass extinctions in the geological past. Very large volcanic eruptions may cause short-term global cooling due to volcanic aerosols[*] remaining in the upper atmosphere and blocking the sunlight, and may be responsible for acid rains and long-term global warming due to massive release of water vapor and CO_2 in the atmosphere. Volcanic activity is also closely related to the circulation of groundwater heated in the vicinity of a magma (**hydrothermal circulation**), and therefore has an impact on the hydrosphere too. Hydrothermal water returns to the surface as **hot springs**. Hot springs are sometimes

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[**] The solidus of a rock is its melting temperature. Below the solidus the rock is completely solid. Melting begins when the temperature reaches the rock solidus.

[*] Tiny solid particles and liquid droplets (e.g. sulfuric acid and water)

characterized by violent, intermittent eruptions of hot water called **geysers**.

Figure 18: Cross section of a portion of the lithosphere through which magma is rising toward the surface. Magma typically accumulates in the crust in large **magma chambers** (1). Pieces of surrounding rocks can be incorporated in the magma and change its chemical composition (2). The magma starts to crystallize as it cools, which changes the composition of the remaining melt (3). Some of the magma leaves the chamber through fractures and forms large sheets, either parallel to rock layers —**sill**— (4) or intersecting rock layers —**dyke**— (5). A volcano is composed of a **central vent** (6) which may branch off and form a **side vent** (7). Lava is ejected from the vents and form **lava flows** (8). Other materials which are ejected from vents are **pyroclasts** (ash, volcanic bombs) and gases (9).

Figure 19: Interactions between volcanoes and other geosystems: atmosphere, biosphere and hydrosphere (see text for explanations).

2.4. Types of lavas and volcanic explosivity

Magmas/lavas may have different chemical compositions. Obviously, the composition of the rock from which the magma is initially derived (**parent rock**) is important in determining the composition of the resulting melt. Temperature is also crucial in controlling magma composition because different minerals begin to melt at different temperatures (Fig. 20).

Magmas produced at mid-ocean ridges and oceanic hot spots are derived from the partial melting of asthenospheric mantle rock. They are enriched in Fe and Mg. Their composition is referred to as **mafic** (from **ma**gnesium and **f**erric, Fig. 20). If such magma cools down slowly within the oceanic crust, the resulting intrusive igneous rock is called a **gabbro**. On the other hand, if it reaches the surface and cools down quickly, the resulting extrusive igneous rock is called **basalt**. Gabbro and basalt have similar compositions but differ by their texture. The former is coarse-grained whereas the latter is fine-grained. Gabbro and basalt are the two most common rocks of the oceanic crust. Basaltic magma has a very low content of silica and is very hot. The **viscosity** of magma is proportional to its silica content[*] and inversely proportional to its temperature. Therefore the viscosity of basaltic magma is relatively low, i.e. relatively fluid (Fig. 20). Hawaii is an oceanic hot spot and its volcanoes are characterized by fast-flowing, low-viscosity lavas and non-explosive eruptions. Magma viscosity determines whether a volcanic eruption is potentially more or less explosive. Highly viscous magmas tend to remain stuck in the volcanic vent and act like a cork.

Another important factor determining the nature of volcanic eruptions is the concentration of **volatile compounds** (e.g. HO_2, CO_2) present in the magma. A volatile-rich, highly viscous magma is much more likely to give rise to an explosive eruption. A magma nearing the surface

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[*] Silica molecules (SiO_2) tend to form chains which greatly increase the viscosity of the magma.

behaves like a soda drink when you unscrew the bottle cap. The volatiles contained in the magma form gas bubbles which expand due to the pressure drop. Decreasing the amount of volatiles dissolved in the magma make it also more viscous. A volatile-rich, highly viscous magma is likely to give rise to an explosive eruption due to the pressure that progressively builds up in the chimney and is suddenly released in the form of a violent explosion.

Magma may gain components by melting the surrounding lithospheric rocks during its ascension toward Earth's surface (***crustal contamination***). If a basaltic magma initially derived from the partial melting of asthenospheric mantle penetrates the continental crust, it can melt the surrounding rocks and absorb elements from continental crustal rocks. Typical igneous rocks of the continental crust are ***granite*** and its extrusive equivalent, ***rhyolite***. Their composition is referred to as ***felsic*** (from **fel**dspar and **si**lica). Their color is lighter than mafic igneous rocks because felsic minerals are lighter in color than mafic minerals (Fig. 20). Mafic and felsic rocks are the two end-members of a continuum of rock/magma compositions. A basaltic magma traveling inside the continental crust can therefore become relatively more felsic as it melts surrounding rocks. Felsic lavas are highly viscous because there are not as hot as mafic lavas and contains a lot more silica (Fig. 20). Related volcanic activity will therefore be more explosive. Magmas with felsic or intermediate compositions may be produced in the following geologic settings: continental hot spots (e.g. Yellowstone), continental rifts (e.g. East African Rift), and subduction zones (e.g. Japan). In continental hot spots and continental rifts, the magma initially derives from asthenospheric mantle rock but becomes more felsic as it penetrates the continental crust and melts the surrounding rocks. In subduction zones, the initial melt is derived from asthenospheric mantle rock, oceanic crust and sedimentary rocks of various compositions (more or less silica-rich). In the case of an ocean-continent subduction, the magma can potentially become more felsic as it penetrates the continental crust. Note that in all these geologic settings (continental hot spots, continental rifts, and subduction zones) basaltic (mafic) volcanism can also take place.

In subduction zones (continent-ocean, ocean-ocean), the magma is often enriched in volatiles such as water (filling the space between sediment grains or in hydrated minerals, e.g. clay minerals) and CO_2 (from marine carbonate sediments). If the magma is also rich in silica, then the risk of explosive eruption is high. On the contrary, the magma produced at oceanic hot spots is characterized by a low volatile content, a high temperature, and a basaltic composition (low silica content), and therefore the risk of violent explosion is low.

We already mentioned (see caption of Fig. 18) that crystallization in a magma chamber influences the chemical composition of the residual melt. The process by which magma composition changes during crystallization is called ***Crystal fractionation***. The order in which minerals crystallize in a cooling magma has been determined experimentally. The idealized succession of minerals formed when magma cools is referred to as the Bowen series (see related slide). As

magma crystallizes, the residual melt becomes progressively more felsic. Therefore the nature of volcanism (i.e. more or less felsic, more or less explosive) also depends on the timing of extraction of the residual magma[*].

Mixing of different magmas is another way to change magma composition (***magma mixing***) and influence magma composition, hence the nature of volcanism.

From the text above, you can easily see why it is so important to understand the process of magma formation. Magma composition has a huge influence on the type of volcanic eruption it triggers and the nature of the risk it involves for human populations.

Figure 20: Classification model of igneous rocks. Igneous rocks are classified according to their mineralogical and chemical compositions, here expressed by the proportion of selected minerals (expressed as a % of rock volume) as a function of the silica content (expressed as a % of rock weight). The upper part of the figure shows images of rock samples. Note the difference of color between felsic (lighter) and mafic (darker) rocks. Source: modified from Understanding Earth 6th edition (rock images: Imperial College Rock Library, except granodiorite: US National Park Service website, and peridotite: Wikipedia).

2.5. Types of eruptions and volcanoes

Two categories of eruptions can be distinguished: ***central eruptions*** and ***fissure eruptions***. The former are associated with volcanoes in which lava and other volcanic material are ejected from a central vent. The latter are eruptions during which lava erupts from fissures, cracks in the Earth's crust.

The type of lava influences the type of volcano. For example, ***shield volcanoes*** like Hawaii are formed by basaltic lavas related to an oceanic hot spot (Fig. 21A). In this setting low-viscosity lava easily flows out of the vent and spreads over an extensive area to form a large volcano with low-angle slopes. In contrast, ***volcanic domes*** are formed by highly viscous rhyolitic lavas which tend to remain in the vent and produce a dome-shaped cap on top of the volcano (Fig. 21B). Volcanoes composed primarily of pyroclastic layers (ashes and other larger fragments of volcanic rocks) are called ***cinder-cone volcanoes*** (Fig. 21C). These volcanoes are typically related to basaltic volcanism because a large fountain of magma (low-viscosity magma) is needed to deposit abundant fine-grained pyroclasts which form a cone. Successions of lava flows and pyroclastic layers are characteristic of ***stratovolcanoes*** (Fig. 21D). When the roof of a magma chamber that has been partially emptied collapses, it forms a large depression called a ***caldera*** (Fig. 21E). Another geologic structure related to central eruptions is called a ***diatreme*** (Fig. 21F). Diatremes are only known from the geologic record. No active diatreme system exists today. They

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[*] Note that magma viscosity is also influenced by the crystals it contains. A magma that has begun to crystallize before reaching the surface and yields a high crystal content is more viscous than magma with a low crystal content.

consist of broad vents filled with fragments of rocks and solidified magma, and result from large explosive eruptions of material initially found at great depths in the mantle. Diamonds originating from the mantle may be found in some diatremes (e.g. the Kimberley diamond mine in Australia).

Fissure eruptions (Fig. 21G) are mainly associated to rifting along divergent boundaries (e.g. Iceland). Large amounts of basaltic lava can be produced during these eruptions (***flood basalts***). Gigantic flood basalts are found in the geologic record and are evidence of past volcanic eruptions whose intensities were much greater than those of modern eruptions (e.g. Columbia River Basalts in USA, Deccan Plateau in India). It is probable that these large eruptions have had a huge impact on the biosphere and may even have caused mass extinctions (e.g. end-Permian mass extinction related to Siberian Flood Basalts or Siberian Traps). Large amounts of volcanic ashes may also accumulate during fissure eruptions and form thick layers of ***ash-flow deposits***, another prominent feature of fissure eruptions.

Figure 21: Types of eruptions and volcanoes, the magma compositions to which they are related, and typical examples of volcanic edifices. Examples cited are those of active volcanic systems except the Kimberley diatreme (approx. 80 million years old). Source: modified from Understanding Earth 6th edition.

2.6. Volcanic rocks

Volcanic rocks comprise two types of rocks: ***extrusive igneous rocks*** (EIRs) and ***pyroclastic deposits*** (accumulations of ***pyroclasts***). EIRs form by rapid cooling of magma/lava near or at Earth's surface. Pyroclastic deposits are pieces of EIR of various sizes, shapes, and textures ejected during volcanic eruptions.

The texture of EIRs depends on the cooling rate of magma/lava. Slow cooling produces larger crystals. A common texture seen in EIR is characterized by larger crystals "floating" in a matrix made of tiny crystals (***porphyritic texture***, Fig. 22A). This texture is formed when a magma starts cooling slowly in the crust －forming large crystals－ and the remaining melt cools faster as the magma approaches Earth's surface －forming tiny crystals－. A uniformly fine-grained texture indicates a uniformly rapid cooling very near or at Earth's surface (Fig. 22B). Cooling may be so rapid that crystals have no time to form. In this case, the resulting rock is an amorphous (non-crystalline) ***volcanic glass*** (***obsidian***, Fig. 22C).
Fast-cooling EIRs often display a vesicular texture (spherical cavities in the rock, Fig. 22E). This texture results from the formation of gas bubbles in the magma when the pressure drops during volcanic eruptions and gas is released and expands (think about what happens when you open a bottle of soda). ***Pumice*** is an extremely vesicular volcanic glass typically formed during violent explosive volcanic eruptions (Fig. 22E). The density of pumice is so low that it can float on water.

Pyroclasts are produced either by rock fragmentation during volcanic explosions or by the solidification of pieces of lava ejected in the air. They are classified according to their size. The finest pyroclasts are *volcanic ashes* (<2 mm, Fig. 23A). When they accumulate and become solid, the resulting rock is called a *volcanic tuff* (Fig. 23B). The accumulation of larger, angular rock fragments is called a *volcanic breccia* (Fig. 23C). Pieces of lava ejected in the air that are 2-64 mm in diameter are called *lapilli*. Pyroclasts larger than 64 mm are called *volcanic bombs* (Fig. 23D). They typically have the shape of a rugby ball and can reach several meters across! Another volcanic hazard is the *pyroclastic flow*. A pyroclastic flow is a mixture of hot ashes and gases moving down the slope of a volcano at very high speed (Fig. 24).

Figure 22: Examples of extrusive igneous rocks: (A) porphyritic andesite with large, light-colored crystals "floating" in a dark-colored matrix made of tiny crystals (scale bar = 2 cm, source: Imperial College Rock Library), (B) basalt composed uniformly of tiny crystals invisible to the naked eye (scale bar = 2 cm, source: Imperial College Rock Library), (C) obsidian −note the shiny, glassy surface of the sample−(source: USGS), (D) vesicular basalt (source: Geological Survey of Ireland), and (E) pumice −usually light in color−(scale bar = 1 cm, source: Ersoy et al., 2010).

Figure 23: Examples of pyroclasts and pyroclastic deposits: (A) volcanic ashes and SEM image of one single ash particle (scale bar = 30 μm, source: USGS), (B) outcrop of volcanic tuff (source: USGS), (C) volcanic breccia composed of fragments of diverse volcanic rocks (source: Colorado Geological Survey), (D) small volcanic bombs (scale bar = 2 cm, source: USGS).

2.7. Hazards vs. benefits

The danger of volcanic eruptions comes less from lava flows −you see them coming from far away− or volcanic bombs −unlikely to hit you unless you are very unlucky or very close to the crater− than from *pyroclastic flows*, *lahars* and *lanslides* (Fig. 24). *Pyroclastic flows* (defined in the previous paragraph) are rapid and sudden events which can quickly engulf inhabited valleys in an extremely hot cloud of dust and gas. *Lahars* are torrential mud flows made of a mixture of pyroclasts and water flowing down the slopes of volcanoes. They can form in various situations: lava melting glacier ice, pyroclastic flow melting snow or mixing with a river, or rain falling on volcanic ashes. Another deadly volcanic hazard is *landslide*. The flanks of a volcano can become unstable during an eruption and a portion may collapse and slide downhill. A large landslide occurring underwater or a large chunk of volcano sliding into the sea or into a lake can trigger a *tsunami*, which is another possible cause of fatalities related to volcanic eruptions.

Figure 24: Illustration of volcanic hazards. Photographs: lahar (left) and pyroclastic flow (right). Source: USGS.

Unlike earthquakes, it is sometimes possible to tell whether a volcano is likely to erupt soon. Examples of indicators of an upcoming eruption are seismic activity (changes in the intensity and frequency of earthquakes), ground deformation (swelling of the volcano), and gas emissions (gas released due to pressure drop within a magma approaching the surface). In ideal cases, these signals allow to predict eruptions several days before they actually occur (although eruptions can occur without obvious detectable precursory signs!).

Volcanic activity has also qualities that are advantageous for human populations. Nutrient-rich **volcanic soils** are fertile and good for agriculture (Fig. 25A). Therefore many people's lives depend on volcanoes. Volcanic rocks, gases and mineral deposits related to volcanic activity may be of great economic value. Volcanic rocks may be used as building stones. **Minerals and chemicals** produced by volcanoes can be used by the industry. For example, perlite (a kind of volcanic glass) can be used for insulating buildings or filtering beer; boric acid can be used as antiseptic and insecticide; sulfur can be used as a component of fertilizers, cellophane, bleaching agent... Another important resource related to volcanic activity is **geothermal energy**. The heat from geothermal fields can be harvested to warm buildings and to produce steam that can be used to generate electricity (Fig. 25B). The production of electricity from geothermal energy is particularly relevant today given the necessity to reduce our dependence on fossil fuels and nuclear energy.

Figure 25: Illustrations of the relationship between volcanoes and human populations. (A) Satellite view of the Sakurajima near Kagoshima city －note the green flanks of the volcano with cultivated fields at the foot and a densely populated area nearby－(source: Google Earth), and (B) geothermal power plant (background) with hot springs (foreground) in Iceland (source: Wikipedia).