The laws governing the activity of volcanoes

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Where on Earth are there volcanoes? Why and how do volcanoes erupt? Why are they capable of erupting in very different ways? To answer these questions, magmas must be tracked from their source tens of kilometres down to the surface. It all starts in the Earth's mantle, beneath the crust, whose movements are responsible for the formation of magma. Because it is lighter than the surrounding rocks, magma is pulled out of its source and rises to the surface. It often accumulates in a reservoir. There it cools, crystallizes, changes its composition and physical properties, to the point of increasing its concentration of volatile elements. A volcanic reservoir is not stable and eventually releases the magma it contains. When the magma is pushed to the surface, it degasses. Depending on the amount of gas released, an eruption can take the form of a liquid flow or a gas jet carrying fragments of magma at high speed. Much progress has been made in volcano physics, but many uncertainties still limit the experts' predictions.

1. How a volcano is built

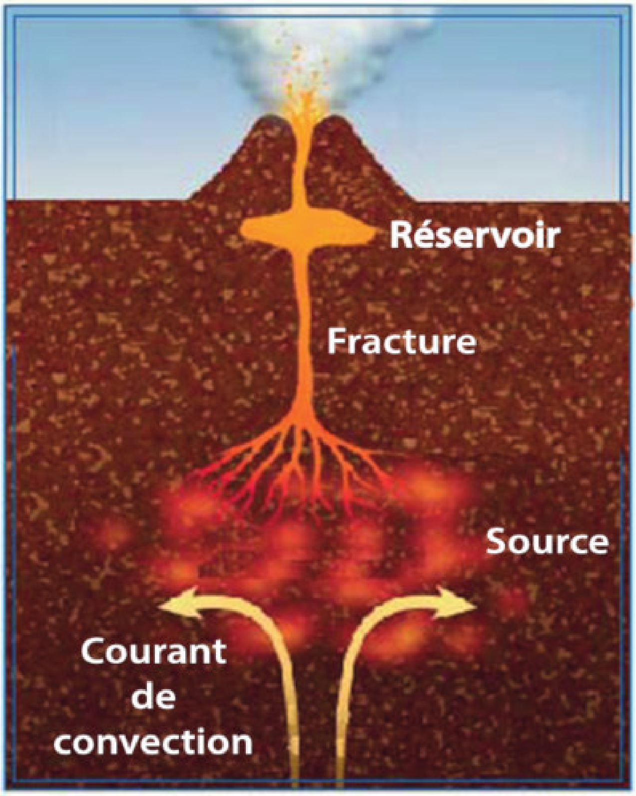

Figure 1: Diagram showing the different parts of a volcanic system. The deep source of magma is mostly related to large-scale movements in the earth's mantle (an updraft is represented here). The magma rises to the surface by fracturing the surrounding rocks. Near the surface, it often accumulates in a reservoir. [Source: Author's figure]

A volcano is built from a source of **magma** [1], which in most cases is located more than forty kilometers deep in the **Earth's mantle** [2]. Magma is formed by the fusion of rocks in the mantle and then travels to the surface. A gigantic plumbing system is established to bring it to the volcano (Figure 1).

Magma rises to the surface because it is **lighter** than the surrounding rocks. When it encounters formations that are less dense or particularly resistant to deformation, it stops and accumulates in a **reservoir**. While in the reservoir, this magma cools and partially **crystallizes**, leaving minerals and **residual** magma whose composition changes as crystallization progresses. This mechanism is responsible for the wide variety of magmas and **eruptive regimes** on Earth. A reservoir is not stable and eventually fractures, allowing the magma to resume its ascent to the surface. It is in this last phase that the regime of an eruption is established. The last part of the volcanic system is **the edifice** itself, which can rise to several kilometres in altitude and which can undergo far-reaching changes.

Volcanoes can remain active for hundreds of thousands of years and can rise several kilometres in altitude. The age of **Etna** in Sicily, for example, is estimated at half a million years. The largest volcano on Earth is **Mauna Kea** on the island of Hawaii, which remained active for nearly a million years and is now extinct. Its summit rises almost ten kilometres above the seabed.

2. The sources of volcanoes

Outside its core, the Earth is essentially solid and produces magma only in a few specific places. As it cools, its **mantle** is driven by large **convection movements** [3] with speeds ranging from a few centimetres to a few tens of centimetres per year. These movements take two different forms: **large cells** associated with **plate movements** [4], which are responsible for the expansion of the ocean floor and continental drift, and localized, approximately cylindrical upward currents called **plumes** or **hot spots** [5].

Mantle rocks are assemblages of minerals and are not pure bodies. **Melting** does not take place at a given temperature and takes place over a temperature range from the **solidus** [6], which marks the appearance of a liquid, to the **liquidus** [7], which sees the last solid disappear. On Earth, it can occur in two very different ways.

2.1. Decompression melting

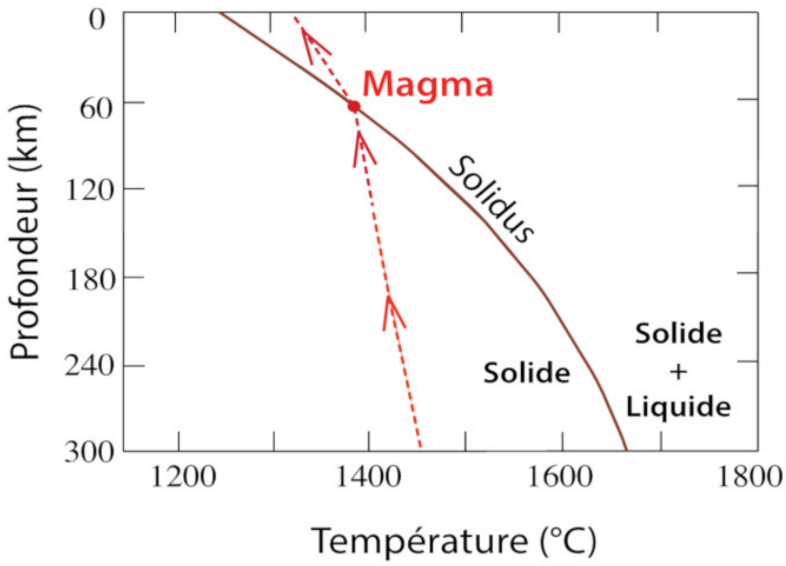

Figure 2. The solidus curve of the mantle rocks, which marks the beginning of melting. The red dashed curve shows the temperature variation for a rock with an upward movement. At great depth, the mantle is at high temperatures but below solidus: it is solid. As they rise to the surface, the mantle rocks cross the solidus boundary and partially melt. [Source: Author's figure]

This is the most important melting mechanism and it is counter-intuitive because it acts as the **temperature of the rocks decreases**. The mantle solidus temperature increases with pressure at a rate of more than 5°C per kilometre. In the present state of our planet, the mantle is entirely solid at great depths but at a fairly high temperature. As its rocks rise to the surface, their **pressure decreases** and they expand. Assuming adiabatic conditions, the work of the pressure forces is compensated for by a decrease in their sensible energy, and thus by a decrease in their temperature, at a low rate of about 0.5°C per kilometre. In an ascending current, the temperature eventually reaches the **solidus curve**, which triggers melting (Figure 2).

This mechanism is responsible for **two types of volcanoes** (Figure 3). The first are associated with the upward currents of convection cells, which are materialized at the surface by **ridges** [8] running across the ocean floor. These volcanoes are little known because they are located more than two kilometers under the sea, but they are responsible for the largest amount of **lava** [9] produced on Earth. Volcanoes of the second type are the largest, such as those in Hawaii and Reunion Island, and are due to **mantle plumes** (also called hot spots).

2.2. Fusion by hydration

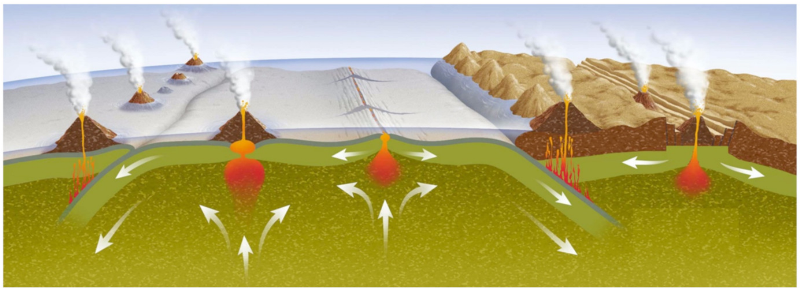

Figure 3. The relationship between volcanoes and the internal movements of the planet. Four types of volcanoes are shown. The most abundant are associated with convection currents in the Earth's mantle, either ascending or descending. On the right side of the figure, volcanoes are shown that originate in areas of extension. [Source: Author's figure]

Even in small quantities, **water lowers** the solidus **temperature**. Rocks that have stayed at the surface have been hydrated on contact with the hydrosphere. They are dragged into the cold downdrafts of the **subduction zones** [10] and dehydrate at depth. The water thus released penetrates the surrounding mantle and melts it, much like the salt used on roads in winter to clear them of ice. Associated volcanoes (Figure 3) are famous, such as Mount Pelee in Martinique and Mount Fuji in Japan, and build island arcs, as in Japan and the West Indies.

2.3. The distribution of volcanoes on Earth

Other mechanisms are at work on Earth, for example within a **thickened continental crust** or in an **extension zone**, but are not responsible for large amounts of magma on a global scale. In any case, the ultimate cause of volcanism lies in the internal movements of the Earth's mantle that develop over thousands of kilometres (Figure 3). Magma is produced as it rises and falls. Volcanoes are **markers of global activity** and can be considered permanent on a human scale.

3. The rise of magmas

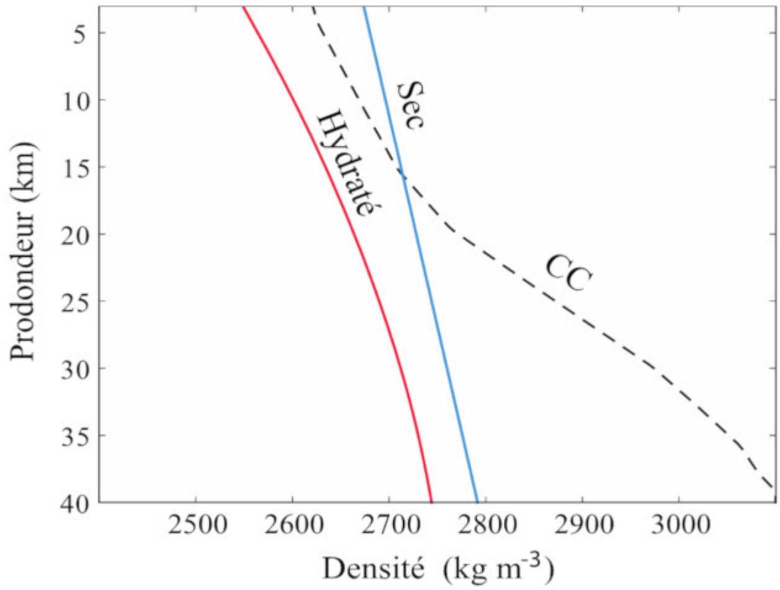

Figure 4. Variation of density as a function of depth. The dotted line (CC) corresponds to rocks of the continental crust. The other two curves show the densities of basaltic magma that is either "dry", i.e. contains no water in solution, or hydrated with a concentration of 0.8 percent water by weight. These two magmas are lighter than the crust at a depth of more than 15 kilometres. [Source: Author's figure]

Under terrestrial conditions, the fusion of rocks does not go to completion and the magma is originally an interstitial liquid within a solid matrix. The magma is lighter than its matrix and is propelled upwards by **Archimedes' thrust** [11] (Figure 4). In order for it to be extracted from its source, it must not be dispersed in small pockets isolated from each other, which is only achieved if it exists in sufficient quantities. This is why we do not see magmas on the Earth's surface corresponding to very low partial melting rates. The most abundant magmas on earth, the **basalts** [12] of **the oceanic ridges**, correspond to a melting rate of about 20-25%. The extraction itself is done through the deformation of the solid matrix that must close behind the magma. This deformation is very slow and large flows of magma can only be obtained by collecting the liquid produced in a large volume.

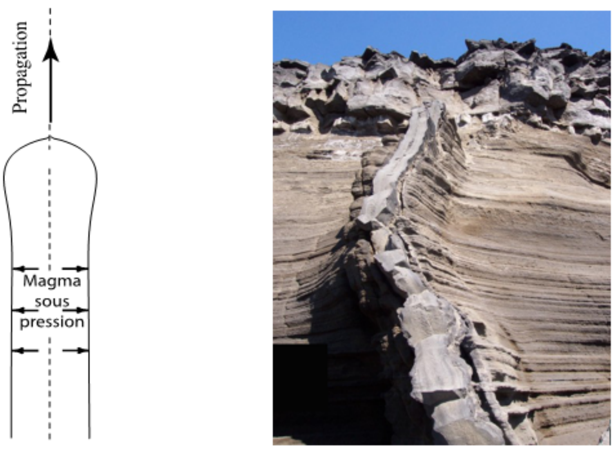

Figure 5. Left: propagation of magma by hydraulic fracturing. Pressurized magma opens a fracture in the rocks and rises under the effect of Archimedes' thrust. Right: A dyke crossing the strata of a cliff in Iceland [Source: Author's figure and personal collection]

Closer to the surface, the rocks of the crust do not deform easily. The driving force is still **Archimedes' force** (Figure 4) but the mechanism of magma ascent is no longer the same. A rock has a given threshold of mechanical strength and fractures when the magma pressure exceeds a certain value. The magma propagates in a narrow **crack** called a **dyke** [13] in geology (Figure 5). This **hydraulic fracturing** phenomenon is accompanied by small earthquakes and can be detected from the surface. When the source dries up, the magma slows down and eventually freezes. A crack filled with solidified magma remains (Figure 5).

4. Volcanic reservoirs and their magmas

Magmas are complex liquids made of many **oxides**, of which the oxides of **Silicon** (SiO_2), **Iron** (FeO and Fe_2O_3) and **Aluminium** (Al_2O_3) are the most abundant. A magma can be produced by the partial melting of a rock or by partial crystallization of a more "primitive" magma. Its chemical composition dictates its **physical properties** and therefore the eruptive conditions.

4.1. The formation of volcanic reservoirs

"Primitive" magma can rise as long as it is lighter than the rocks it encounters and as long as it is able to fracture them. Near the surface (Figure 4), rocks are often less dense than this magma, either because they are of sedimentary origin or because they are fractured. When the magma reaches them, the Archimedean force changes sign and opposes the ascent. Elsewhere, rocks denser than the magma and particularly resistant to deformation can prevent the magma from passing. In both cases, a **reservoir** forms below the surface.

A reservoir plays a fundamental role. Fed by a deep source with a low flow rate, it serves as a magma accumulator and allows very large volumes to erupt quickly. In addition, it acts as a **chemical reactor** where the magma changes composition.

4.2. The manufacture of "advanced" magmas

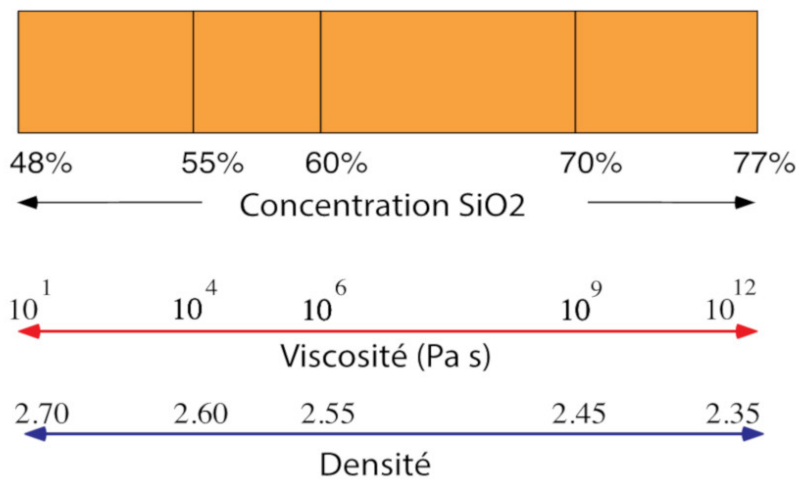

Figure 6. A "magmatic series" and associated physical properties. The magmas shown, called basalt, andesite, dacite and rhyolite, are produced by the partial crystallization of a basaltic magma. They are the successive residual liquids that form as crystallization progresses in a reservoir. [Source: Author's figure]

Within a reservoir, the magma loses its heat on contact with the colder surrounding rocks and solidifies. As with melting, solidification does not occur en bloc and is spread over a temperature range. The magma gradually crystallizes and leaves a **residual liquid** with a changing composition. The successive magmas are part of what is called a **magmatic series**. Figure 6 illustrates the different liquids that are produced when a basalt crystallizes. A volcano can eject basalt at its beginning and then gradually eject all the other magmas in the series, which are often referred to as "evolved".

A magma reservoir is capable of generating **eruptions in a closed system**, but can also be replenished by primitive magma. It can undergo complex changes in chemical composition depending on the sequence of re-injection and eruption. Residual magma may tend towards evolved compositions and then return to more primitive compositions.

4.3. Viscosity of magmas

A basalt is a hundred times more viscous than cooking oil, which is itself a hundred times more viscous than water. A remarkable fact is the enormous **variation in the viscosity** of magmas, shown in Figure 6 for those that are dry, i.e. without water. Between a **basalt** and a **rhyolite** [14], the **viscosity** increases by more than ten orders of magnitude! An extremely viscous magma such as rhyolite flows very slowly and has a fundamentally different behavior from that of a basalt. Thus, **the same volcano can produce very different eruptions when the composition of the magma changes**.

4.4. Volatile species and volcanic gases

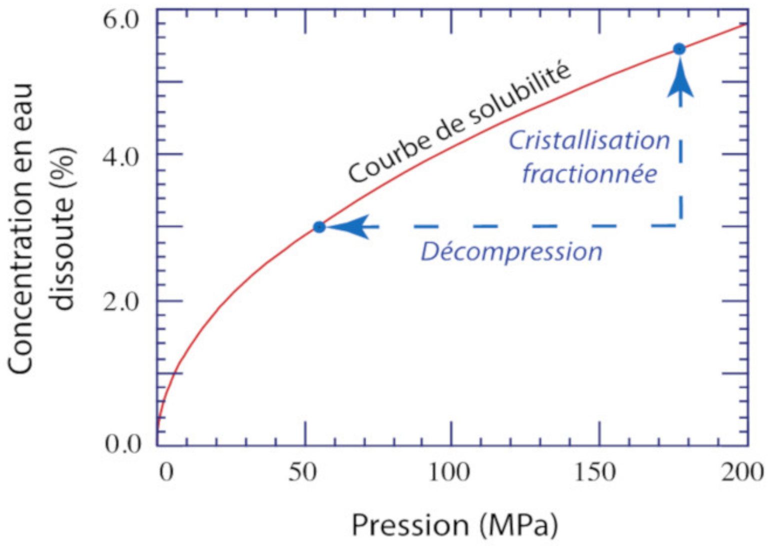

Figure 7. Water solubility curve in rhyolitic magma containing 3% water, a rather low value. All this water is in solution at pressures above 50 MPa (500 bars), which corresponds to a depth of about 2 km. Above the solubility threshold, the magma is saturated and some of the water appears as gas. Magma can reach saturation in two different ways, by decompression during ascent or by fractional crystallization in a reservoir. [Source: Author's figure]

The last ingredients needed to understand the behaviour of flares are **volatile species** such as water and carbon and sulphur dioxides. They are present in small quantities in the mantle rocks and concentrate in the magma during melting. At high pressures at depth, they are soluble in the magma (Figure 7). At magmatic and surface temperatures, they are in a **gaseous state**. Among them, water is the most abundant. Its concentration is typically a few percent by weight. Despite these small amounts, **water has a major effect** on the behaviour of the magma in a volcanic vent, as we will see later. It also affects the viscosity of the magma, which drops by a factor of ten for every 1% addition.

4.5. The rupture of the reservoir

For a **blowout** to occur, the reservoir must release the magma it contains, which can be due to two phenomena. The first is **the injection of mag** ma from the source, which is constantly active. The reservoir swells until its walls can no longer withstand the stress. The second phenomenon is **crystallization**. Volatile elements that are in solution in the primitive magma cannot be taken up by the crystals with very few exceptions. As a result, they become enriched in the residual liquid as crystallization progresses. When their concentration finally reaches the solubility threshold, the magma is saturated and a gaseous phase appears. From that moment on, the reservoir contains a mixture of magma and **gas bubbles**, whose density is much lower than that of the original magma. At constant mass, the decrease in density causes the volume to increase and thus the reservoir to swell.

In both cases, the **inflation of the tank signals that a blowout** is in the making. It results in a ground lift at the surface, the amplitude of which is usually several centimetres. Such deformation is easily measurable with today's tools.

5. The main eruptive regimes

5.1. Two main categories of eruption

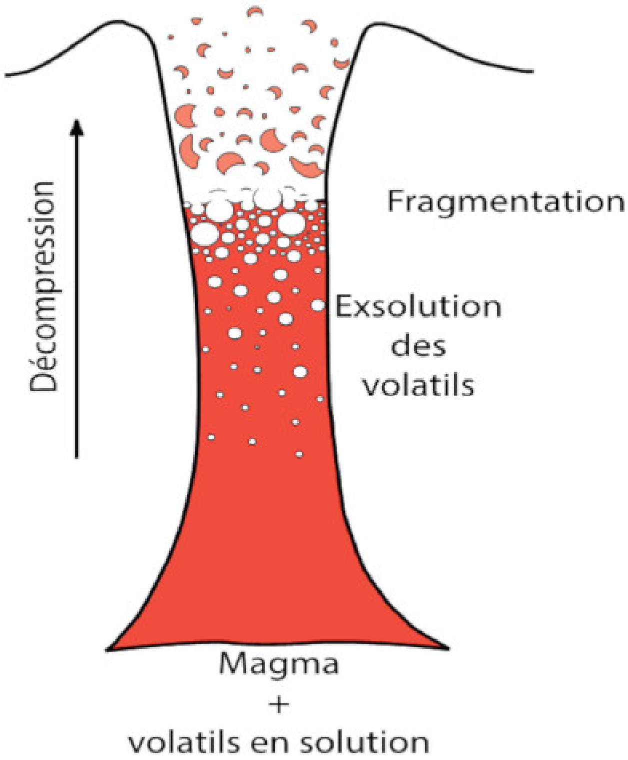

Figure 8. Decompression sequence in a volcanic conduit. The magma becomes progressively charged with gas bubbles due to the exsolution of volatile species and the expansion of the gas. The suspension of magma and gas bubbles becomes unstable and the magma is pulverized into fragments that are carried by a gas jet. [Source: Author's figure]

Two main categories of eruption can be distinguished according to the amount of **gas** present in the magma at the exit of the volcanic conduit. When this quantity is low, the gas is dispersed in **bubbles** within the magma. The mixture of gas and magma behaves like a fluid and the eruption takes the form of a **liquid flow**. When the amount of gas is high, the magma is **pulverized** and it is the magma that is dispersed within the gas. Figure 8 illustrates the **decompression sequence** in a flaring duct in this case. As the magma rises, solubility decreases as the pressure drops (Figure 7) and an increasing amount of volatile species collects in a gas phase. The volcanic mixture of magma and gas first takes the form of a suspension of bubbles in liquid and then goes through a stage of **magmatic** "**foaming"**, which is not stable. The bubbles burst and the flow takes the form of a jet of gas carrying fragments of magma. This regime is referred to as "**explosive**".

5.2. Two "explosive" regimes

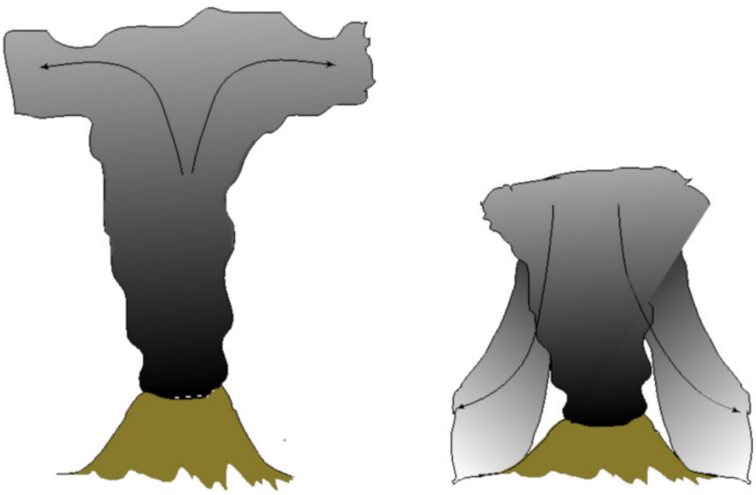

Figure 9. The two main explosive regimes. Left: a Plinian column rises at high altitude to a level where the rarefied atmosphere is less dense than the volcanic mixture. The mixture propagates laterally, allowing its fragments to sediment. Right: a pyroclastic flow is due to the collapse of an eruptive column that remained denser than air. [Source: Author's figure]

Plinian eruptions (Figure 9) are the most spectacular. At the exit of the eruptive mouth, a powerful **jet** of volcanic gas carries **fragments of lava** at a speed generally between 100 and 300 m/s (this is the speed of sound in the mixture) (Figure 10). An **eruptive column** rises in the atmosphere to an altitude that can exceed thirty kilometres. When it meets the very rarefied air in the upper atmosphere, the volcanic mixture eventually spreads laterally. It is then animated by an essentially horizontal movement and lets the fragments of magma fall as rain over very large surfaces. We find the **deposits** of the "Minoan" eruption of the island of Santorini in the Aegean Sea, which took place in 1600 B.C. approximately, over several hundred thousand square kilometres. Plinian eruptions often turn into pyroclastic flows, a much more catastrophic regime described below, and it would be more accurate to speak of the Plinian phase of an eruption. The typical duration of a Plinian phase is a few tens of hours.

Figure 10. The column from the May 1980 eruption of Mount St Helens, Washington State, USA. A mixture of gas and magma fragments exits the volcanic conduit at high velocity. [Source: United States Geological Survey, Public Domain]

In the case of **pyroclastic flows** [14] (Figure 9), the mixture of gas and magma is similar to that of a Plinian eruption at the outlet of the eruptive mouth but the regime changes in the atmosphere. The flow rates and quantities of magma emitted are almost the same, but the eruptive column rises only a few kilometers from the ground. The volcanic mixture **falls back near the outlet point** and is channelled into a powerful narrow flow instead of being distributed over a large area at high altitude (Figure 11). The effects are devastating. Pyroclastic flow deposits are much thicker than their Plinian analogues and show complicated stratifications, indicative of the chaotic and violent conditions of their emplacement.

The famous eruption of **Vesuvius** in 79, which destroyed the Roman cities of Pompei and Herculaneum, shows that untimely changes in eruptive regimes can occur. The volcano started in a Plinian regime, which is unpleasant and destructive in the long term but not fatal for the people. It **changed regime abruptly** and began to emit violent and deadly pyroclastic flows.

Video 1: Example of an atmospheric column of gas and ash that develops during an explosive eruption. [Source: Ashraf Bouiafri]

5.3. The role of turbulence

Figure 11. A pyroclastic flow descending the slopes of Sinabung volcano in Indonesia. This flow is not due to the collapse of an atmospheric column, but to the explosion of a thick lava flow loaded with gas bubbles. [Source: Jean-Guillaume Feignon, distributed via imaggeo.egu.eu]

The devastating eruptions just described do not require much gas. In fact, it all depends on how you measure the **amount of gas**. If we count by weight, terrestrial magmas rarely contain more than 5% volatile species. However, since the gas phase has a very low density, it dominates the mixture when measured by volume. For example, for only 1% of the total weight, water vapour already occupies about 95% of the volume.

An important consequence of the **low amount of volatiles** in the magmas is that the mixture escaping from a volcano is denser than the atmosphere in any state. Without an increase in the amount of gas, this mixture cannot rise to high altitude. Under these conditions, how can Plinian eruptions be produced?

Video 2: Example of pyroclastic flow at Sinabung volcano in Indonesia [Source: Marc -Volcano - Szeglat]

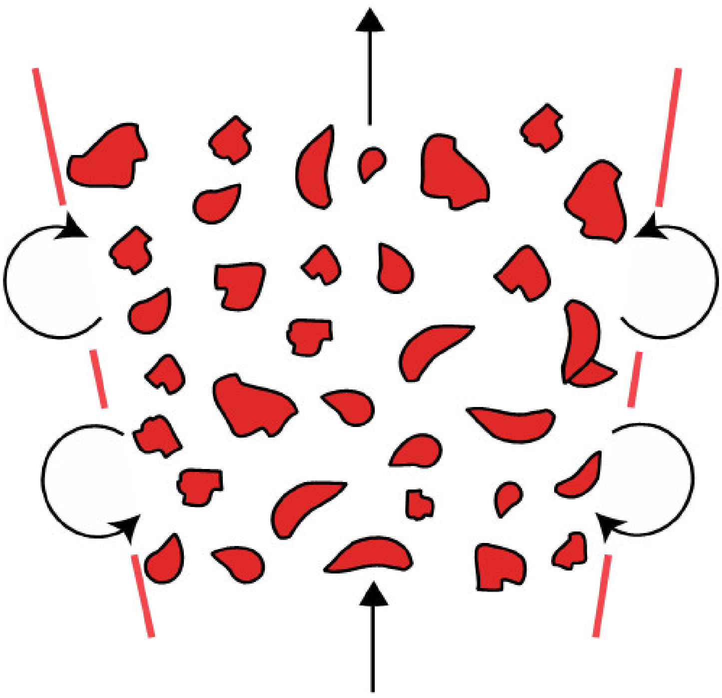

Figure 12. Diagram explaining how an atmospheric flaring column can become lighter than the surrounding air. Turbulence creates vortices that bring air back into the column. As the column rises, the amount of air increases and the density decreases. Source: Author's figure]

The origin of the two explosive regimes is to be found in the behaviour of the eruptive column as it rises in the atmosphere (Figure 10). The flow is fast and in a **turbulent regime**, such that vortices incorporate air into the column (Figure 12). The mixture becomes progressively lighter. As long as it is **heavier than air**, it slows down under the action of its weight. If its rate of ascent falls to zero, it falls back to the ground near the outlet. This is the regime of **pyroclastic flows** (Figure 9). If the amount of air ingested by the column is large, the volcanic mixture eventually becomes **lighter than air**. In this case, it is propelled upwards by Archimedes' thrust. This is the **Plinian regime** (Figure 9). An eruptive column that produces pyroclastic flows rarely exceeds a few kilometers in altitude, whereas those of the Plinian regime can exceed 20 kilometers.

5.4. Lava flow eruptions

Lava flows are of several types depending on the viscosity of the lava and the slope of the volcano. Basaltic eruptions can form vast lava fields over extremely large distances, even on horizontal ground. Lava flows on the Columbia Plateau in western North America have travelled several hundred kilometres. More viscous lavas, such as dacites and rhyolites (Figure 6), do not spread much and form thick flows over the eruptive conduit. These are called "**lava domes**". In 1980, the lava dome at Mount St. Helens, Washington State, USA, reached a thickness of 300 meters.

Video 3: Example of a lava flow eruption and growth of a lava dome on the Chiveloutch volcano in Russia. [Source: Newsfalre]

5.5. Some other rash regimes

Basaltic volcanoes have two particular explosive eruptive regimes of lower intensity. In a **lava fountain**, the flow in the conduit takes the form of a central gas jet that pulls up a film of liquid lining the edges. At the outlet, the result is a spectacular wall of lava that can rise several hundred metres high. Fountains of lava are common at Etna in Sicily and at the Kilauea volcano in Hawaii. **Strombolian explosions** are an extreme case with a very low lava flow. These are mostly gaseous eruptions, caused by the **explosion of large pockets of volcanic gas**. The eruptive conduit is saturated with lava and can remain open for several years. As the name suggests, these eruptions are common on the island of Stromboli off the coast of Naples.

The "**fiery clouds**", made famous by the catastrophic eruption of Mount Pelee in 1902, are pyroclastic flows (Figure 11). They are formed by the **explosion of a lava dome**, and are characterized by a mixture of pieces of the solidified shell of the dome and fragments of liquid magma from the core of the dome. They are shorter and have smaller volumes than those resulting from the collapse of an atmospheric column. It was flows of this type that destroyed the city of Saint-Pierre de Martinique during the eruption of Mount Pelée in 1902.

Phreatic eruptions, as opposed to previous **eruptions**, do not eject magma, but only fragments of the volcanic edifice and its bedrock. The magma plays an indirect role in these eruptions by heating and vaporizing the water contained in the surrounding rocks. These eruptions can throw **huge boulders** and often precede a magmatic eruption itself.

6. The volcanic edifice

Some volcanoes can reach heights of up to ten kilometres: this is the case for volcanoes in Hawaii, for example, where the land area represents only a small proportion of the total.

In the continents or island arcs at the edge of the oceans, the buildings are more modest but can still rise to several kilometres in altitude.

Such important buildings **change the eruption conditions**. First of all, the magmas have to travel an additional distance to reach the exit point. The density of the magma once again plays a vital role. The higher it is, the harder it is to climb to the summit. In some cases it is no longer possible and the eruption takes place **on the sides of the volcano**. A second effect is that the edifice induces a compressive stress field in the superficial parts of the volcanic base. These stresses can become strong enough to **divert the dykes**, which stop their vertical progression and inject themselves laterally. Beyond a certain distance from the edifice, the magma returns to an undisturbed environment and resumes its ascent, forming satellite cones.

A volcanic edifice is **fragile**. Under the effect of deformation due to the magma that penetrates it, it can be destabilized and collapse. The magma within it decompresses and expands abruptly, creating a destructive **surge**. This is what happened at the beginning of the 1980 eruption of Mount St Helens in Washington State, USA.

7. Knowledge and uncertainty assessment

The physics of volcanoes has developed considerably over the last forty years. The **main mechanisms** involved can be considered to have been identified and understood, but there are still major gaps in our knowledge. The damage caused by an eruption depends primarily on the **total volume** that is ejected and its **duration**, and these are still variables that can only be measured after the fact. Neither the dimensions of the magma reservoirs nor the composition of the magma(s) they contain are precisely known. The eruptions often undergo **regime changes**, alternating for example between Plinian phases and pyroclastic flows and ending with the emission of lava flows. Taken individually, these regimes are understood, but the **complete eruptive sequence** is not. All these questions seem to be out of reach at the present time and can probably only be answered by the development of **fine imaging methods** to follow the course of an eruption at its source, in and out of the magma reservoir.

8. Messages to remember

Magmas are **produced continuously** on Earth and do not stay deep for long.

Volcanoes are located in a few specific places, linked to the **internal activity of** the planet.

The magmas rise to the surface on their own, under the effect of **Archimedes' thrust**.

Magmas of very different compositions and physical properties are produced by **partial crystallization** in reservoirs.

The regime of an eruption depends on the **physical properties** of the magma and its **water** content.

At high gas concentrations, the eruption takes the form of a **turbulent atmospheric column** carrying pulverized magma.

Notes and References

Cover image. January 2006 eruption of Augustine Volcano, Alaska [Source: Credit: United States Geological Survey, public domain http://www.avo.alaska.edu/image_full.php?id=5927].

[1] A magma is a liquid produced by the fusion of a rock.

[2] The Earth's mantle is the layer that occupies the largest volume in the Earth, between the base of the crust and the earth's core at a depth of almost 2900 kilometres.

[3] The phenomenon of convection describes the movements that occur spontaneously in a fluid when its density varies spatially, for example when it is cooled from above.

[4] Plates are the large rigid surface units that move across the surface of the Earth.

[5] Plumes, or hot spots, are localized updrafts of approximately circular cross-section that are generated by a small source.

[6] The solidus is the temperature at which a solid starts to melt.

[7] Liquidus is the temperature at which a solid is completely melted.

[8] Ocean ridges are underwater mountain ranges in the middle of the oceans. They are the mark of the ascending parts of the convection cells in the mantle.

[9] Lava is the name given to the liquid that escapes from a volcano. It is made of magma containing varying amounts of gas bubbles and crystals.

[10] Subduction zones are the places where the plates sink into the Earth's interior. They mark the downdrafts of the convection cells of the Earth's mantle.

[11] Archimedes' thrust is the force that is exerted on a volume that is lighter than the fluid that surrounds it.

[12] The word basalt refers to the magmas that are formed by partial fusion of the rocks of the earth's mantle when the fusion rate does not exceed 30%.

[13] A dyke is a crack that is opened by pressurized magma.

[14] Rhyolite is the magma that forms at the end of the basalt crystallization sequence.

[15] The adjective pyroclastic refers to "pyroclasts", which are fragments of magma (the word comes from "pyro" which means on fire and "clast" which means rock fragment).

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