

THE IN A HURRY SERIES

# Volcanoes

## *in a Hurry*

How the Earth blows its top

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# The Whole Thing in One Page

The volcano in your head is probably a mountain with a hole in the top, a reservoir of red liquid underneath, and an eruption waiting for pressure to become unbearable. It is a useful logo and a bad model.

A volcano is a changing system of melt, gas, rock, water and connected pathways. Rock below it melts only partly, and often because conditions change rather than because the rock becomes hotter. Pressure falls as hot mantle rises beneath spreading plates or hotspots. Water from a descending plate lowers the melting threshold above a subduction zone. Hot magma can also melt colder crust by transferring heat. The melt that results is less dense than much surrounding rock, but buoyancy does not give it an open lift to the surface. It must collect, fracture, stall, react, crystallise and find connected weakness.

Many volcanic systems are therefore less like a buried vat than a tall, untidy region of crystals, melt, gas and rock extending through the crust. Magma changes inside it. Crystals remove some elements and concentrate others in the remaining liquid. Fresh batches interact with older material. Gases stay dissolved under pressure, then form bubbles as magma rises. Those bubbles can expand and accelerate the mixture. They can also escape through permeable magma, fractures or an open vent. Whether pressure is retained or released matters as much as how much gas was present.

The opening to the surface helps decide what the public sees. Fluid basalt may pour from a fissure and travel in channels or tubes. Sticky magma may heap into a dome that later collapses. Rapidly expanding gas may tear magma into ash and pumice, drive a high eruption column, or send a hot current along the ground. External water can add steam-driven fragmentation. A flank can fail, releasing pressure sideways. A storage region can drain until the roof collapses and leaves a caldera. The same volcano can perform several of these acts in one eruption, and other systems never build a central mountain at all.

That is why the greatest danger is not always the red part. Lava is usually

visible and comparatively slow. Pyroclastic density currents, lahars, ash, gases, landslides and volcano-generated tsunamis can travel farther, arrive faster or continue longer. Tambora altered weather far beyond Indonesia in 1815 because sulfur reached the upper atmosphere. Galunggung stopped all four engines of a passenger jet in 1982 without touching it with lava. Pinatubo in 1991 showed that earthquakes, swelling ground, gas chemistry, geological mapping and institutional judgement can create a useful forecast, while also showing that rain can turn fresh deposits into years of mudflows.

No instrument sees the whole system. Volcanologists combine imperfect signals and compare them with the volcano's past. Unrest may lead to eruption, stall underground or change character. Forecasts are conditional windows, not appointments.

Volcanism also builds. It raises islands, makes oceanic crust, renews landscapes, concentrates minerals, supplies geothermal heat and leaves material that weathering can turn into productive soil. The gift and the threat come from the same movement of matter.

Then the loop closes. An eruption may drain regions, fill others, open fractures, seal conduits, remove slopes or rearrange valleys. The event is produced by the system and then edits it. A volcano's history is part of its mechanism.

That is the book.

## Why You Should Care

On 24 June 1982, a British Airways Boeing 747 flew into volcanic ash from Galunggung while cruising at 37,000 feet. All four engines lost power. For sixteen minutes the aircraft descended without them, reaching about 12,000 feet before the crew restarted three engines and made an emergency landing in Jakarta. The ash cloud had turned a long-haul passenger jet into a glider without placing lava anywhere near it.

Fine fragments of rock and glass had risen into an international airway, travelled with the wind and entered machines designed to cross continents.

The encounter helped prompt aviation authorities to build international procedures for detecting and avoiding volcanic ash. It gives the first reason to care: volcanoes punish the wrong mental model. The cone is local. The system is not. By estimated average annual volume, roughly three-quarters of magma reaching Earth's surface is emplaced along mid-ocean ridges, beyond ordinary human sight.

Their reach works at every scale. A fissure can open through a neighbourhood while the summit kilometres away collapses. A landslide can remove one side of a mountain and release pressure sideways. Rain can remobilise ash long after the eruption has ended. A column can place sulfur where atmospheric circulation distributes its effects between hemispheres. Material entering the sea can move water into a tsunami. To understand a volcano, you have to follow matter after it leaves the vent and pressure before it gets there.

The second reason is that volcanoes make the inaccessible planet observable. Nobody can lower a camera through tens of kilometres of crust and watch magma assemble. Eruptions bring up samples. Earthquakes reveal cracking rock. Changes in gravity, gas, temperature and surface shape betray movement below. A volcano is therefore both an event and an experiment, except the apparatus is a mountain-sized region of crust and the experiment refuses to repeat itself under controlled conditions.

The third is that volcanic landscapes are places where people live, farm, travel and build. They do so for good reasons. Weathered ash can support productive soils. Geothermal systems offer heat and power where the geology and engineering permit it. Volcanism creates islands, lays down new ground and concentrates useful minerals. Naples faces Vesuvius because a volcano does not erase the advantages of a bay, a climate, roads, family and history. Risk is not ignorance with a postcode. It is often the price of remaining somewhere valuable.

Then there is time. Human memory calls a volcano quiet after a few generations. Rock has a longer filing system. Pinatubo had no remembered historical eruption when it woke in 1991, yet its deposits recorded earlier

large events. Yellowstone is commonly described as overdue because three ancient caldera-forming eruptions are treated like entries on a timetable. The arithmetic is tidy and the geology is not. Volcanoes do not save pressure for a scheduled appointment.

That gap between human time and geological time makes forecasting both possible and difficult. Past deposits constrain what a system has done. Instruments show what it is doing now. Neither supplies the exact next act. A useful forecast may identify rising probability, likely locations and plausible hazards while remaining unable to name the hour, volume or ending. Decisions still have to be made inside that uncertainty.

Read this subject properly and a smoking summit stops being the main question. You begin asking where the melt came from, how it changed, whether gas can escape, what pathway is opening, what could fail, which valleys collect flow, where the wind is going and what evidence would change the forecast. The spectacle remains. It becomes legible, and the ground beneath an apparently ordinary landscape begins to look like evidence rather than scenery.

## The Core Ideas

### **A Volcano Is a System, Not a Mountain**

A perfect volcanic cone is the shape produced when repeated eruptions build material around a fairly persistent vent. It is one possible result, not the definition. Iceland has long fissures that pour lava without constructing one commanding summit. The East African Rift contains fields of small cones and craters spread across broad ground. Large explosive eruptions may leave a caldera, a depression formed mainly when rock above a withdrawing magma body loses support and collapses. About three-quarters of the average annual magma volume reaching Earth's surface is estimated to be emplaced along mid-ocean ridges. That is a volume estimate, not a census of observed eruptions, and it exposes the bias built into a mountain-centred subject.

The useful boundary is functional. A volcanic system includes the region where melt forms, the paths by which it rises, the places where it accumulates and changes, the gas and hydrothermal fluids that move through surrounding rock, the fractures that connect those regions, and the vents or fissures through which material escapes. The mountain, where one exists, is the deposit left by part of that traffic.

This corrects the familiar underground diagram, but it must not become a replacement cartoon. A neat liquid chamber beneath a central pipe can exist for a time as a local feature. Many well-studied arc and continental volcanoes instead show a taller, less orderly arrangement in which crystal-rich mush contains melt-rich lenses, films and pockets. Magma can enter from below, stall at several depths, move sideways, cool into rock or feed more than one vent. Yet ridges, basaltic shields, volcanic fields and hydrothermal explosions need not share that architecture. A model earns its place by clarifying a system, not by making every system look alike.

West Mata and Kīlauea show why the wider unit matters. In 2009, cameras more than a kilometre deep watched West Mata in the Pacific erupt, with broken rock in the plume and glowing pillow lava flowing down the slope. On land, Kīlauea's summit caldera and long rift zones belong to one changing system. In 2018 magma left the summit region, moved down the East Rift Zone, opened fissures in the lower flank and erupted tens of kilometres away. Withdrawal accompanied repeated collapse at the top. Calling the lower fissures one volcano and the summit another would have hidden the connection between them.

The system also extends beyond molten rock. Groundwater heated by magma can circulate, alter rock and drive steam explosions. Acidic fluids may weaken a flank. Old lava flows and ash deposits control drainage, which controls later lahars. An eruption can therefore emerge from an interaction between magma, gas, water, rock strength and inherited landscape rather than from pressure in one container.

Landform names remain useful. Shield volcano, stratovolcano, lava dome, cinder cone and caldera describe recurring shapes and hint at past

behaviour. Trouble begins when shape becomes personality. A stratovolcano can produce lava, ash, flank collapse, lahars and long quiet intervals. A basaltic shield can erupt explosively when water enters the system or gas is trapped. In a monogenetic field, a new eruption may open a new vent instead of returning to an established cone. A caldera can host later cones, lakes and hydrothermal explosions.

The first question should be larger than what kind of mountain is this. Ask where melt or heat is supplied, where material has changed, which pathway is opening, how water and gas are involved, and what could leave. The answer is the volcano.

## **Solid Rock Melts When the Conditions Change**

The mantle is hot enough to deform over geological time, yet most of it is solid. This surprises people because red lava encourages the picture of a molten layer beneath a thin crust. Its temperature generally stays below the pressure-dependent melting boundary. Deep rock can be far hotter than a kitchen oven and remain crystalline because the melting threshold rises under the weight above it. Magma forms when a portion of rock crosses its melting boundary, and there are several ways to make that happen.

The first is decompression. Hot mantle rising beneath a mid-ocean ridge, continental rift or some intraplate settings experiences falling pressure faster than it loses heat. Its path crosses the solidus, the boundary at which melting begins. Only part of the rock melts. The liquid takes some chemical components more readily than others, so a small melt is not a miniature sample of its source. It can be compositionally distinct from the crystals left behind.

The second is the addition of volatiles, especially water. At a subduction zone, an oceanic plate descends carrying hydrated minerals, altered crust and sediment. As pressure and temperature increase, water-rich fluids are released into the hot mantle above. Water lowers the melting threshold of that mantle wedge. The slab is therefore not best imagined as melting wholesale into a line of volcanoes. Its fluids help neighbouring mantle melt,

while sediment and crustal components can contribute to the chemistry in more complicated ways.

The third is heat transfer. Basaltic magma entering continental crust can warm surrounding rock enough to produce partial melts with different compositions. Magma generated by one process can therefore help generate more magma at another level. Crustal thickness, composition and temperature influence what emerges, which is one reason volcanoes above broadly similar plate boundaries do not behave identically.

These mechanisms explain much of the global pattern. Ridges and rifts favour decompression melting. Volcanic arcs mark many subduction zones. The Pacific Ring of Fire is shorthand for many separate plate boundaries and volcanic arcs around the ocean margin, not one connected volcanic machine. Hotspot chains record long-lived supply beneath moving plates, although the detailed origins of mantle plumes and intraplate volcanism vary by setting. The map is strong evidence for plate tectonics, but it is not a vending machine in which each boundary produces one standard magma.

Once melt exists, it still has to move. Lower density can provide buoyancy, but surrounding rock may be too strong, the melt fraction too small or the permeability too poor for rapid separation. Tiny melt fractions can percolate along grain boundaries. Larger accumulations may overpressure their surroundings and open a dyke, a blade-like fracture filled with magma. A dyke can rise, move sideways, branch or freeze. Much magma produced within Earth never erupts. It crystallises underground and becomes intrusive rock.

Source conditions leave a chemical inheritance. Basalt commonly begins as mantle-derived melt. More silica-rich magmas may evolve from basaltic parents, incorporate crustal material or include crustal melts. Yet source does not dictate the final eruption. The magma can spend years, centuries or longer being altered by cooling, crystallisation, mixing and degassing. Two batches formed in similar mantle may reach the surface with different temperatures, crystal loads and gas histories.

The lesson is more useful than the school diagram. Volcanoes do not erupt because a universal molten interior occasionally leaks. They begin when a local combination of pressure, temperature and composition produces partial melt, and when some of that melt finds a route through mostly solid Earth.

## **Magma Acquires a History Before It Erupts**

Magma is a mixture, not a pure liquid. It may contain melt, crystals and gas bubbles in proportions that change during ascent and storage. Its chemistry records where it came from and what happened on the way. That history matters because viscosity, gas solubility, crystallisation and temperature help determine whether the mixture flows, stalls, foams, fragments or plugs its own exit.

Basaltic melts are usually hotter and less polymerised than rhyolitic melts. Silica in a melt forms linked structures with oxygen; as that network becomes more developed, the liquid commonly resists flow more strongly. Temperature also matters because cooling increases viscosity. Crystals add another source of resistance, especially when abundant enough to interact. A cool, crystal-rich basalt can move less freely than its label suggests, while a hot, gas-poor rhyolite need not produce a colossal explosion. Composition is a strong influence, not a verdict.

Cooling begins a chemical sorting process. Minerals crystallise in an order set by pressure, temperature, water content and composition. If early crystals separate from the remaining melt, they remove particular elements and leave the liquid enriched in others. This fractional crystallisation can shift magma towards more silica-rich compositions. The new liquid may be smaller in volume but more viscous and able to hold substantial dissolved water at depth.

The surrounding crust joins the negotiation. Magma can heat, fracture and partly melt wall rock. It may assimilate some of that material, though melting and incorporating crust requires energy and is never free. Fresh magma may recharge an older storage region, adding heat, mass and gas. Two

magmas can mix incompletely, leaving streaks, enclaves, zoned crystals and chemical gradients. Such evidence can show that a system changed shortly before eruption without proving that mixing alone pulled the trigger.

The old chamber model treated storage as waiting. The newer picture is busier. A crystal mush can persist over a large vertical range, with melt being extracted, injected, transferred and frozen. A shallow melt-rich body may assemble when heat and new magma mobilise part of that system. Some volcanoes are fed frequently; others spend long periods with small, cooling intrusions that never reach the surface. A long repose interval does not measure the level in a hidden tank.

Crystals are among the best witnesses. A crystal can grow in layers as its environment changes. Its core may record one pressure and composition, its rim another. Diffusion begins to blur sharp chemical boundaries at rates that can be modelled, giving estimates for the interval between a disturbance and eruption. Different minerals preserve different signals and clocks. The result is rarely a single stopwatch reading, but it can distinguish changes that occurred over years from those in the final days or hours.

Magma also changes by losing gas. Carbon dioxide commonly begins to exsolve at greater depth than water because their solubilities behave differently. Gas may rise through the system, alter melt and escape at the surface while most magma remains below. Conversely, crystallisation can concentrate dissolved volatiles in the residual melt until bubbles form even without large upward movement. This process can increase pressure in a confined region.

By the time magma erupts, its name is shorthand for a biography. Basalt, andesite, dacite and rhyolite classify composition, but eruption behaviour depends on the route taken through pressure, temperature, crystals, gas and time. The rock collected after an eruption is not merely debris. It is the cooled record of decisions made by physics before anyone could observe them directly.

## Gas Pressure Depends on Escape

A bottle of sparkling water looks still before it is opened because pressure keeps carbon dioxide dissolved. Reduce the pressure and bubbles appear. Magma carries a more varied load of dissolved volatiles, chiefly water, carbon dioxide and sulfur species. The comparison helps with exsolution and then runs out, because magma can be many orders of magnitude more viscous than water, crystals obstruct the mixture, bubbles interact with one another, and the container is fracturing rock.

At depth, high pressure allows substantial volatile material to remain dissolved in melt. As magma rises, the pressure falls. Bubbles nucleate, grow and reduce the bulk density of the mixture. Their expansion can accelerate ascent and help propel magma and fragments through the vent. Above it, expanding gas drives the initial jet; if that mixture entrains and heats enough air, buoyant convection can sustain a high column. Gas supplies energy, but not through one identical mechanism in every eruption.

Gas content alone does not separate quiet lava from explosive ash. A central question is whether gas escapes relative to the rate at which magma rises and pressure falls. In fluid magma, bubbles may rise, join and burst. Connected bubbles can create permeable pathways through which gas leaks ahead of the melt. An open vent can release pressure through persistent puffing or lava-lake activity. The same system may alternate between gas-rich explosions and quieter effusion as the conduit geometry changes.

Viscous magma makes separation harder. Bubbles may remain trapped and stretch with the moving melt. Crystallisation can squeeze gas into the remaining liquid and make the mixture more resistant at the same time. If gas expansion outpaces escape, the foam can reach a point at which magma fragments into ash, pumice and larger clasts carried by the gas. Fragmentation is a transition in a moving multiphase material, not a bomb detonating inside a hollow peak.

The rate of ascent matters. Slow ascent gives gas more time to leak through

permeable magma or surrounding fractures, though cooling and crystallisation can create a plug. Rapid ascent can preserve overpressure and drive violent fragmentation. Yet slow dome growth can remain dangerous because the dome stores hot, unstable material on a steep slope. Collapse may release pyroclastic density currents without a new deep explosion.

External water adds another route to fragmentation. Groundwater, a crater lake, ice, seawater or wet sediment can flash to steam when mixed efficiently with hot magma or rock. Rapid heat transfer and repeated cracking can produce fine ash in phreatomagmatic eruptions. A phreatic explosion may occur when pressurised steam breaks rock even if fresh magma does not reach the surface. Water does not guarantee a larger eruption; contact area, confinement, mixing and supply decide whether it quenches, fragments or barely interferes.

Gas is also evidence. Sulfur dioxide output can indicate shallow degassing magma. Carbon dioxide may escape from greater depth. Changes in ratios can show that storage, ascent or scrubbing by water has altered, but no reading has one interpretation. Rain, wind, hydrothermal chemistry and blocked pathways can change what reaches an instrument. Gas monitoring is strongest when earthquakes, deformation and thermal observations tell a compatible story.

And gas is a hazard in its own right. Sulfur dioxide irritates lungs and forms acidic pollution. Carbon dioxide can collect in low ground because it is denser than air. Fluorine deposited on ash can contaminate grazing land. A volcano need not throw a single glowing rock to make the atmosphere near it unsafe. The volatile material that helped move the magma can travel separately from it.

## **The Route Selects Among Possibilities**

Magma does not rise through a permanent pipe drilled from mantle to crater. It forces open fractures, enters old weaknesses and responds to the stress field around it. A dyke is usually a thin sheet compared with its length and height. It can propagate because pressure at its tip breaks rock, then stop when it loses pressure, reaches a tougher layer or enters a stress regime that turns it sideways. The final vent may open kilometres from the place where unrest was first detected.

The route changes the pressure history. A long, narrow conduit creates friction and encourages crystallisation at its cooler margins. A widened or newly fractured path can raise discharge. A blocked upper conduit can retain gas; a permeable plug can leak it. Branches divide supply. A lava lake or open vent may buffer pressure until collapse, sealing or fresh input changes the connection. These are engineering consequences in a structure that builds and damages itself while operating.

Topography and rock strength can intervene before magma reaches the surface. Mount St Helens in 1980 developed a growing bulge on its north flank as magma intruded into the volcano. On 18 May an earthquake accompanied the collapse of that flank in an immense landslide. Removing the overlying mass caused rapid decompression of the shallow magmatic and hydrothermal system. The first devastating blast travelled laterally into the space the landslide had opened. A vertical-cone model would have pointed attention in the wrong direction.

Caldera formation is another route problem. During a large eruption or sustained withdrawal, magma can leave a shallow storage region faster than it is replenished. The roof fractures along faults and subsides, sometimes in stages, while eruption continues around or within the collapsing block. The depression is therefore mainly a structural collapse feature, though explosions and erosion modify it. Later magma may use the ring faults, build new domes or erupt far inside the older caldera.

Kīlauea in 2018 supplied a different version. After changes at the long-lived

Pu'u O'o vent, magma migrated down the East Rift Zone. Earthquakes traced the movement. Fissures opened through the lower district, first producing variable lava and then high-rate effusion as a more direct connection developed. At the summit, withdrawal led to repeated collapse events that enlarged the caldera. The eruption on the flank and the destruction at the summit were two responses to one redistribution of magma.

Routes can also meet water. A vent beneath a glacier may melt water faster than it drains, producing floods. A fissure beneath shallow seawater may fragment magma and build a ring of tuff. If eruption establishes a dry island or insulated conduit, behaviour can become less explosive even while magma supply continues. One eruption can thus move from water-driven ash to lava as the exit changes its own surroundings.

This is why named styles are temporary descriptions. Hawaiian, Strombolian, Vulcanian, Plinian and other terms capture recurring combinations of discharge, gas release, fragmentation and plume behaviour. They do not assign a permanent temperament to a volcano. Vesuvius has produced lava and explosive eruptions. Etna can feed lava flows, fountains and ash columns. A single event may begin with steam explosions, proceed through sustained column formation, collapse into ground-hugging currents and end with dome growth.

The route is often the missing variable when two eruptions from related magma look unlike each other. Source and composition set possibilities. Storage changes the material. Gas, external water and rock strength alter the pressure and failure conditions. The connected path then selects among those possibilities by controlling how quickly material moves, where it emerges and whether the system vents, fragments or fails sideways. It matters because it works with the other controls, not because it replaces them.

## **The Hazard Is Whatever Finds a Way Out**

Lava dominates photographs because it glows, moves visibly and draws a clean line between before and after. It can ignite buildings, cut roads, bury land and reach the sea. Fluid flows may advance slowly enough for people to leave, then accelerate in channels or on steep ground. Thick blocky flows can move less gracefully and remain hot for long periods. Lava is a serious hazard. It is a poor summary of the ways volcanoes cause harm.

Pyroclastic density currents are hot mixtures of particles and gas that move along the ground under gravity. They may form when an eruption column becomes too dense to remain buoyant, when a lava dome collapses, or when material boils over a vent. Dense parts are channelled by valleys; dilute surges can cross ridges and spread more widely. Their speed, heat and load make survival close to the source unlikely. The AD 79 eruption of Vesuvius buried Pompeii under falling pumice before later currents reached the city, while Herculaneum experienced a different sequence because position and topography altered what arrived.

Ash takes the opposite route. Particles smaller than two millimetres can rise high, travel with wind and settle across regions. This is pulverised rock, mineral and volcanic glass, commonly sharp and abrasive. Wet ash loads roofs and machinery. Fine ash enters ventilation, contaminates water, damages crops, reduces visibility and disrupts electricity and transport. At Galunggung in 1982, ash entered the engines of a Boeing 747 at cruising altitude and stalled all four. Distance from the crater had not removed the aircraft from the volcanic system's reach.

Lahars follow water and gravity. Rain, melting snow or ice, crater-lake release and other water sources can mobilise loose ash and blocks into a dense slurry. A flow can entrain more sediment and grow as it travels down a river valley. It may occur during an eruption or months and years later, when a storm crosses fresh deposits. Pinatubo's 1991 eruption ended before its lahar crisis did. Seasonal rain repeatedly shifted volcanic sediment across inhabited lowlands.

A volcano may fail as a mountain. Intrusion, earthquakes, steep construction and hydrothermal alteration can weaken a flank. The resulting landslide can bury valleys, uncover pressurised magma, transform into a debris avalanche or enter water and generate waves. Krakatau's 1883 eruption produced devastating tsunamis around the Sunda Strait through a complex marine sequence. Numerical reconstruction identifies rapid entry of large pyroclastic flows into the sea as the most plausible source of the largest waves, while allowing that collapse and explosions also occurred. At island volcanoes and coastal systems, displaced water may carry the hazard beyond any line reached by ash or lava.

Gases have their own geography. Sulfur dioxide and acidic aerosols move with air and weather. Carbon dioxide can accumulate in depressions and poorly ventilated places. Fluorine on ash can poison livestock after the sky has cleared. The same eruption may therefore create different danger zones for breathing, roofs, aircraft, rivers and coastlines.

Magnitude does not settle impact. A modest explosive eruption above ice can generate far-reaching lahars. A larger event in a remote setting may kill nobody. A low VEI fissure eruption can cover extensive ground and release major gas pollution. The Volcanic Explosivity Index says something useful about explosive size; it does not combine route, population, wind, rainfall, topography, warning and duration into one answer.

The physical reading is straightforward. Follow each material. Heavy hot currents follow slopes. Mud follows drainage. Ash follows wind and altitude. Gas follows circulation and density. Landslides follow weakness. Tsunamis follow displaced water and coastlines. The vent begins the map. It does not finish it.

## **Every Eruption Rebuilds What Comes Next**

A volcano grows by losing material. Lava solidifies into new ground. Ash and blocks settle around vents. Pyroclastic currents fill valleys. Domes rise, fracture and collapse. At the same time, explosions excavate craters, landslides remove flanks and calderas lower entire summit regions. Construction and destruction are one process viewed at different moments.

Those changes feed back into later behaviour. A lava flow can block a river and create a lake. Loose ash supplies future lahars. A filled valley sends the next current elsewhere. A new cone changes the slopes around a vent. Hydrothermal fluids circulate through fresh fractures and gradually turn strong rock into weak clay-rich material. A conduit that remains hot and open may favour repeated discharge; one that cools and crystallises can seal, redirect gas or force the next intrusion to find another path.

Kīlauea's 2018 collapse made this loop visible at human speed. Magma withdrawal from beneath the summit accompanied repeated subsidence, producing a much larger caldera. The pressure, geometry and water access of the summit system after that sequence were not the same as before it. Any later summit activity would begin inside a structure made by the preceding eruption. The event did not reset the volcano to zero. It created a new starting condition.

Large calderas make the same point over longer periods. Collapse establishes ring faults and fractured zones that can guide later intrusions, hydrothermal circulation and eruptions. Lakes may occupy the depression. New domes and cones rise inside it. A landscape that looks like the remains of one ancient explosion may be an active collection of younger systems using the inherited architecture.

The chemical system remembers as well. Recharge may mix with residual magma. Crystals survive from earlier stages and are recycled. Degassed magma may remain in a conduit while gas-rich material rises beneath it. An eruption can draw preferentially from one depth and leave another part untouched. The next batch therefore enters a system containing thermal,

chemical and mechanical leftovers.

This path dependence defeats recurrence arithmetic. A volcano's past is indispensable because deposits reveal possible styles, directions and scales. It is not a metronome. Three intervals between ancient eruptions do not create a due date, and an average repose time does not restore the same magma, stress, conduit or landscape. Yellowstone is not overdue. Its history constrains possibilities while its present behaviour must be measured directly.

Volcanism also rebuilds the wider planet. It creates oceanic crust and islands, supplies gases and heat, and leaves rocks that weather into soil. Eruptive and hydrothermal systems concentrate metals. Geothermal circulation can be used for energy. These gains are uneven and often delayed. Fresh lava begins as bare, unweathered ground before colonisation and soil formation. Geothermal fields can be corrosive and difficult to manage. Fertile land near a volcano does not cancel the hazard that helped make it.

The atmosphere carries another legacy. Large explosive eruptions can inject sulfur dioxide high enough for sulfate aerosol to spread and reflect sunlight, cooling parts of the climate system for a limited period. Ash itself usually settles too quickly to provide the main global effect. Tambora in 1815 and Pinatubo in 1991 differed greatly in scale, setting and consequence, but both show that what leaves a vent can change conditions far beyond the deposit map.

A volcanic system is therefore historical in a strict physical sense. Its present state contains old intrusions, emptied regions, sealed cracks, altered slopes and redistributed sediment. Monitoring reads change against that inherited baseline. Forecasting improves when the history is reconstructed, yet every new event modifies the object being forecast. The volcano makes the eruption. The eruption remakes the volcano.

# How It Actually Works

## A landscape before unrest

On 20 February 1943, farmer Dionisio Pulido watched an eruptive vent open in his maize field in western Mexico. By the next day the new cone of Parícutin stood about thirty metres high; by the fifth it exceeded 150 metres. The eruption continued until 1952. No pre-existing cone had awakened. Magma had opened a new outlet within the Michoacán-Guanajuato volcanic field, now mapped as containing more than 1,400 vents. The cone was the record of the eruption, not its precondition.

A volcanic landscape spends most of its time doing nothing that looks volcanic. Rivers cut old deposits. Forest grows over lava. In some systems, fumaroles release steam or small earthquakes occur beneath terrain that has not erupted within living memory. The apparent quiet contains several possible states. The deep supply may have stopped. Melt may be intruding and freezing. A hydrothermal system may circulate above residual heat. A crystal-rich region may contain enough melt to move if new magma or gas arrives.

Volcanologists begin with a baseline rather than a dramatic signal. Seismometers record ordinary earthquake rates and types. Satellite radar and ground instruments measure slow deformation. Gas teams sample vents, springs and plume chemistry. Thermal cameras and satellites watch heat. Geologists map deposits to reconstruct where lava, ash, pyroclastic currents and lahars went before. Without that history, a new tremor is a noise without context.

The mapping begins far from any instrument. A road cutting may expose alternating lava, soil and ash. A river wall may hold a thick, poorly sorted lahar deposit above an older forest surface. Charcoal can be dated, minerals analysed and layers traced across valleys. In a monogenetic field, scattered old vents show that future magma need not return to a known cone. The word dormant describes a judgement about present likelihood, not sleep that can be timed from the outside.

The first operational question is whether the system has changed. The second is whether the change is moving towards the surface. The third is what kind of event the evidence permits. Those questions rarely receive their answers at the same time.

## **The first signals**

Magma entering or moving through rock changes stress. Brittle rock breaks, producing volcano-tectonic earthquakes. Fluids moving through cracks can generate longer, more resonant signals. Continuous tremor may accompany sustained movement of magma or gas, but similar labels can contain several physical sources. The useful information lies in location, depth, migration, frequency content and how the pattern evolves.

The ground may swell as pressure increases or subside as magma withdraws. Modern geodesy can resolve small movements using continuous satellite positioning, tiltmeters and radar measurements from orbit. Shape matters. Broad uplift may suggest a deeper source; sharp local deformation may indicate a shallow intrusion. Yet one mathematical source fitted to surface motion is not a photograph of a chamber. Different underground geometries can produce similar deformation.

Gas may change before lava appears. Carbon dioxide can separate at greater depth and travel ahead of shallower sulfur-rich gas. Rising sulfur dioxide can indicate magma approaching levels from which it can degas openly. Ratios may shift as new magma arrives, a conduit seals or groundwater scrubs part of the plume. Rain and wind alter measurements. A falling gas signal may mean supply is declining, or that the route has become blocked.

Heat, spring chemistry, crater-lake temperature and water level add further clues. None is a countdown clock. Intrusions commonly stall. Earthquake swarms end. Ground that rose can deflate without eruption. The task is to identify convergence: several independent observations changing in a sequence that a physical model can explain.

This is also why alert levels are not direct translations of one instrument. A

swarm at a frequently active volcano may be ordinary, while the same pattern beneath a long-quiet system can be novel. Deep earthquakes can mark new supply without imminent eruption. Shallow tremor, rapid inflation and rising gas together may justify a stronger forecast, but even that combination leaves several endings open. Scientists update the interpretation as new data arrive, asking which scenarios have gained or lost support. An alert is therefore a compressed judgement about evidence and consequences, not a machine's verdict.

Networks have limits. A well-monitored volcano can be compared with years of baseline data. Elsewhere, the first seismometers may be installed after unrest begins, and cloud, terrain or conflict may interrupt observations. The physics does not change, but the confidence available to decision-makers does.

## **A crack becomes a route**

An intrusion begins to propagate when magma pressure overcomes the least compressive stress and the resistance of surrounding rock. A dyke may be only metres thick yet extend for kilometres. Earthquakes can mark breaking at the advancing tip, while deformation shows the sheet widening behind it. If the tip approaches the surface, cracks may open, gas may escape and steam explosions may begin before lava arrives.

The route competes with cooling and pressure loss. Magma crystallises against cold walls. Gas escapes into fractures. Branches divide the flow. A dyke may turn sideways along a weak layer or follow a rift zone where the stress field favours opening. This is why evacuation around one summit can miss a vent that opens on a distant flank.

At the surface, the first material need not represent the fresh magma driving the episode. Old, cooler magma may be pushed out first. Later lava can become hotter or chemically different as a more direct connection develops. Samples taken through time can therefore reveal the plumbing becoming organised while the eruption is under way.

Approaching magma also changes groundwater. Wells may warm or

change chemistry, springs may shift, and steam can pressurise sealed fractures. If a steam explosion opens the surface, it may eject old rock before any juvenile magma appears. The first crater can therefore announce that heat and pressure reached shallow levels without proving that an open magmatic conduit exists. Once lava erupts, the vent may remain a short-lived crack, migrate along a fissure or focus into one outlet as cooling seals the rest.

The opening phase often looks disorderly because the route is being made in real time. Fountains pulse as gas slugs arrive. Walls collapse into the vent. Fragments weld, cool and build ramparts that channel later lava. The exit begins shaping the flow almost as soon as it forms.

## **Kīlauea, 2018**

At the end of April 2018, the floor of Pu'u O'o, a long-lived vent on Kīlauea's East Rift Zone, collapsed. Earthquakes then migrated down-rift. Cracks opened through roads and gardens in the lower district. On 3 May the first fissure erupted in Leilani Estates, far from Kīlauea's summit. The early outbreaks were brief and chemically variable, consistent with magma that had been stored within the rift being displaced and remobilised.

The magnitude 6.9 flank earthquake occurred on 4 May. Fissure opening continued through the lower rift. Later in May hotter magma from farther up-rift reached the lower zone and discharge increased sharply. Lava fountains fed channels that carried fluid basalt towards the sea. Some flows advanced through developed land; others reused low ground created by earlier flows. The eruption eventually covered a broad area, but the map was drawn by fissure position, supply rate, slope and channel formation rather than by distance from a central crater.

At the summit, the lava lake fell as magma left the upper system. Rock above the withdrawing reservoir began to fail. Collapse occurred in repeated events, each accompanied by earthquakes and abrupt pressure changes, enlarging the summit depression. Together, migrating earthquakes, ground deformation, lava chemistry, discharge measurements and summit

subsidence described the redistribution as it unfolded.

The chemistry sharpened the sequence. Early lava included material that had resided within the lower rift. Later products became more magnesian and hotter as magma associated with the established upper system arrived. The change helped explain why discharge intensified after the first fissures had already opened. Petrology was not a retrospective ornament. Rapid sample analysis supplied evidence about which part of the system was feeding the active vents.

The timing of collapse events and changes in the lower eruption showed measurable coupling through the wider system. This was not a rigid piston connected by one pipe. Drainage and structural failure communicated through the wider reservoir and rift while different parts responded on different timescales.

The main lower-rift eruption and summit-collapse sequence waned after roughly three months, but the volcano that remained had a changed summit, altered rift pathways and kilometres of new lava. The next episode would begin from that state, not from the Kīlauea shown on the previous year's map.

## **Mount St Helens, 1980**

Mount St Helens reawakened in March 1980 with earthquakes and steam explosions. A crater opened near the summit. Magma intruded into the north flank, which began to bulge outward. The deformation was direct evidence that the mountain itself was becoming part of the pressure system. Scientists recognised the possibility of a landslide, but the scale and consequence of the coupled failure remained difficult to forecast.

At 8:32 on the morning of 18 May, a magnitude 5.1 earthquake accompanied the collapse of the north flank. The landslide was not a side effect after the eruption. It removed the load confining shallow magma and hot groundwater. Rapid decompression produced an expanding lateral blast that overtook part of the moving debris and spread northwards. Forest was flattened across a fan that a summit-centred circular hazard model would

not have described.

A vertical eruption column then rose, ash travelled across the United States, pyroclastic currents moved over the devastated northern side, and melting snow and ice contributed to lahars in river valleys. One failure sequence produced a debris avalanche, lateral blast, vertical column, ash fall, hot ground currents and mudflows.

The deposit preserved their order. Landslide material lay beneath blast and pyroclastic deposits in key places. Photographs, seismic records and eyewitness observations constrained the timing. Mount St Helens became a demonstration that route geometry can change in seconds when the enclosing mountain fails.

The weeks before the event had supplied an unusually visible warning. Survey measurements and photographs tracked the north flank moving outward as a cryptodome, an intrusion that deformed the mountain without erupting as lava. The bulge focused concern on slope instability, but no instrument could specify the exact moment at which the flank would lose support. This distinction matters. A process can be recognised and monitored while its threshold remains uncertain.

The landslide also changed the scale faster than the magmatic supply changed. Material that had been confined at pressure found an abrupt low-pressure boundary. The blast expanded through the newly opened north side before a mature vertical column was established. The decisive transition came from removal of rock, which is why an eruption cannot be understood by magma chemistry alone.

## **When the column stands or falls**

Above an explosive vent, gas and fragmented magma leave as a high-speed jet. It entrains surrounding air, which heats and expands. If the mixture becomes less dense than the atmosphere around it, convection carries a column upwards. At altitude it spreads laterally into an umbrella cloud, and wind sorts ash by size, density and shape as it falls.

A column can fluctuate as discharge and wind change. If too much dense material enters for entrainment to keep the mixture buoyant, part or all of it collapses. The falling mixture accelerates downslope as a pyroclastic density current. Large particles concentrate near the base while turbulent ash and gas may rise above it. Valleys guide much of the dense flow, but energetic dilute portions can escape confinement.

Column height is therefore informative but incomplete. A tall plume may spread ash widely. A lower collapsing column can be more lethal near the volcano. The same eruption can switch between the two. Observers who see the top of a plume from a distance may miss the ground current leaving its base.

Particle behaviour continues after fragmentation. Coarse blocks fall close to the vent. Pumice can be carried farther because gas bubbles make it light for its size. Fine ash may remain aloft, clump into aggregates in moist clouds, acquire electrical charge and produce lightning. Aggregation makes some fine material fall sooner than a grain-by-grain model predicts. Wind shear can carry different levels of the plume in different directions, so one ash cloud does not have one simple downwind edge.

The column also interacts with the atmosphere it enters. Stable layers can spread an umbrella cloud. Strong crosswinds bend weak plumes and increase mixing. Tropical thunderstorms and typhoons add water, redistribute ash and alter roof loading. Eruption rate matters, but weather helps decide where the products go.

## **Pinatubo, 1991**

Pinatubo entered written history as a forecasting problem. The volcano in the Philippines had no remembered historical eruption, and its upper slopes were home to Aeta communities. In April 1991 steam explosions opened vents on the north flank. Earthquake activity increased. Philippine volcanologists, joined by a USGS team, installed instruments under severe time pressure while geological fieldwork searched river cuts and slopes for evidence of earlier eruptions.

The deposits changed the scale of the question. Thick pyroclastic material showed that Pinatubo had produced large explosive eruptions before. Seismicity migrated, sulfur dioxide emissions rose and ground deformation indicated intrusion. Scientists issued evolving scenarios rather than one certain prediction. As evidence strengthened, hazard zones and warnings were revised. The forecasts mattered because they were tied to action by Philippine authorities, military commands and communities rather than left as measurements in a report.

One episode showed why interpretation outranks a rising line on a graph. Sulfur dioxide emissions increased and then fell before the climactic eruption. A naive reading could treat the decline as improvement. It was ambiguous: supply might have weakened, water might have scrubbed the plume, or the path carrying gas to the surface might have changed. Continued earthquakes and deformation kept dangerous scenarios alive. No single signal was permitted to cancel the rest of the evidence.

Petrological work later showed interaction between different magmas before eruption. That evidence improved the reconstruction of how the system became mobilised, but it did not turn the observed mixing into a universal trigger. The forecast had to be made before the full rock record existed.

Magma reached the surface in early June. A lava dome appeared, and explosive activity escalated. On 15 June the climactic eruption drove a vast column into the atmosphere while Typhoon Yunya crossed the region. Wet ash became heavier on roofs. Pyroclastic currents spread around the volcano. Withdrawal of magma accompanied summit collapse and formation of a caldera.

The scientific success was substantial and bounded. Monitoring and geological interpretation gave enough lead time for large evacuations, reducing exposure near the volcano. The team did not predict every transition or eliminate danger. The typhoon compounded ash loading, and many buildings failed. Instruments close to the volcano were damaged or lost. A forecast can be useful without describing the event in full.

Pinatubo also refused to end on 15 June. Monsoon rain remobilised loose deposits into lahars that repeatedly travelled down surrounding valleys. Channels filled, shifted and rose. Sediment buried land and threatened settlements for years. The eruption column had lasted hours; the altered drainage system became a long-running volcanic process.

## **The long aftermath**

The end of visible eruption is a change of phase, not a clean stop. Lava cools from the outside while its interior remains hot. Domes crack and shed blocks. Gas output declines unevenly. Rain begins moving ash before vegetation has stabilised it. Rivers cut into new deposits and carry sediment downstream. Crater lakes form where heat, water supply and drainage allow them.

Scientists map the new surface, measure deposit thickness and volume, collect samples and compare them through time. These observations revise the model used during the crisis. A vent thought to be fed from one depth may contain crystals recording several storage levels. A mapped pyroclastic current may have crossed a ridge considered protective. The next hazard map should contain those corrections.

The system below cools, crystallises and readjusts to changed pressure. Fresh magma may arrive before the previous batch has frozen. An open route may support continued degassing or small eruptions. Alternatively, the conduit seals and unrest shifts elsewhere. There is no universal point at which one eruption ends and preparation for the next begins. The distinction is imposed for reporting; the volcano continues changing.

Human labels can lag the physical transition. Authorities may lower an alert after seismicity and gas decline, yet keep lahar warnings through wet seasons. A dome-building episode may pause for months before extrusion resumes. Fumaroles can persist for centuries above cooling intrusions. Conversely, a volcano can return to background after an intrusion that never erupted. Each outcome becomes part of the baseline against which future unrest is judged.

The archive continues to move as well. Wind strips ash from one slope and redeposits it on another. Rivers destroy some layers and expose others. Soil and vegetation hide the sharp boundary between eruptive periods. The neat event reconstructed in a diagram is a scientific ordering of deposits that nature has already begun to edit.

## **How we know**

Volcanology combines evidence with different blind spots. Instruments record earthquakes, deformation, gas, heat, sound, gravity and hydrology during unrest, but they sample the surface response to hidden processes. Erupted lava, ash and crystals preserve chemistry, pressure and timing, but only for material that escaped. Deposits reveal older events, though erosion, burial, vegetation, remobilisation and poor historical records remove or distort them. Satellite observations broaden coverage while losing some local detail, and the deep ocean remains under-observed.

Laboratory experiments and numerical models test how multiphase magma, fractures, plumes and currents behave under controlled assumptions. They constrain mechanisms rather than reproduce a whole volcano. Confidence is strongest when independent methods with different failure modes converge: migrating earthquakes match deformation, gas changes fit petrology, and predicted deposits appear where mapping later finds them. Forecasts remain conditional because several underground arrangements can produce similar signals and because the system changes while it is being measured.

## **What People Get Wrong**

**“A volcano is a hollow mountain full of liquid rock”**

The image survives because it is easy to draw. A triangular cone, a round chamber, one pipe and arrows pointing upwards fit on a school page. Lava emerging from a crater appears to confirm it.

Real systems can contain shallow melt-rich regions and focused conduits, but the whole is commonly taller, less liquid and less permanent. Magma may occupy interconnected lenses within crystal-rich mush, enter at several depths, travel sideways in dykes, freeze as intrusions or release gas through separate fractures. A vent can open far from the summit. Calderas, fissure systems and submarine ridges make poor cones without becoming less volcanic. Even geophysical images are interpretations of density, conductivity or wave speed, not photographs of a red cavern.

The correction matters because the simple diagram predicts danger in the wrong place. Kilauea's 2018 lava erupted along its lower rift while the summit collapsed. Mount St Helens released its most destructive blast through a failed flank. A mountain-centred model encourages a circular map around the top. A system model asks where pressure, weakness, groundwater and connected routes extend, which is closer to both the monitoring problem and the ground people occupy.

## **“Hotter magma makes a more explosive eruption”**

Heat looks like stored violence, so the hottest lava seems the likeliest to explode. The usual tendency runs partly the other way. Hot basalt is often fluid enough to let gas separate and to flow from a vent, while cooler silica-rich magma commonly resists bubble escape and can fragment explosively.

That tendency is not a rule. Explosivity depends on volatile content, ascent rate, crystal load, permeability, confinement, conduit geometry and interaction with external water. Basalt can produce powerful explosions when gas is trapped or water mixes efficiently with magma. Rhyolite can extrude as a slow dome after much of its gas escapes. Cooling can increase viscosity and crystallisation, while recharge can add heat and gas at once. Eruption style may change during one event as the gas supply and conduit evolve.

Temperature is therefore one variable in a moving mixture. Treating it as an explosion gauge hides the process that matters: whether expanding gas can

leave without tearing the magma apart. The practical question is not which magma is hottest, but how composition, crystals, pressure and route control gas escape during ascent.

## **“Lava is the main volcanic killer”**

Lava earns the starring role because it is bright, cinematic and easy to identify. It can destroy homes and infrastructure, and fast channelised flows or lava entering occupied areas leave little room for complacency. Yet people can often see a lava flow and move away before it arrives.

Many lethal volcanic events use different material. Pyroclastic density currents move hot particles and gas along the ground. Lahars carry water and debris down valleys, sometimes long after the eruption. Ash can collapse roofs, damage lungs and disable machinery across large regions. Flank collapse and caldera activity can generate tsunamis. Carbon dioxide can pool in low places, while sulfur gases harm health and crops. Some of these products outrun sight, sound or a person trying to escape on foot.

Historical fatality databases are dominated by a limited number of catastrophes and are incomplete, so they should not be turned into a universal ranking. The durable correction is physical. Hazard follows the route available to each product. Watching the red flow while ignoring the river, wind, unstable slope or collapsing column can leave the faster danger outside the frame.

## **“The VEI tells you how dangerous an eruption is”**

The Volcanic Explosivity Index is useful because it compresses uneven information about explosive eruptions into a broadly logarithmic scale. Erupted tephra volume carries the greatest weight, with plume height and descriptive evidence helping where records are poor. The result makes rough comparison possible across historical and prehistoric events.

It does not measure total energy, lava volume, sulfur yield, tsunami potential, exposure or the ability of people to leave. A VEI 3 eruption can be deadly if a pyroclastic current reaches a town. A low-index fissure eruption

can cover extensive land and release sustained gas. A larger eruption in a remote region may kill nobody. Two events with similar tephra volume can have different climate effects because sulfur content and injection height differ. Reconstructed volumes also depend on erosion, deposit density and how far the search extends.

The index became persuasive because one number appears to answer a question that has several dimensions. Use it for explosive magnitude and then put it down. Danger requires product, path, timing and place. VEI is a label on one part of the event, not a score for the whole outcome.

## **“Scientists can predict eruptions like eclipses”**

An eclipse follows orbital mechanics in a system measured with extraordinary precision. A volcano is a changing, partly hidden system whose geometry, material properties and boundary conditions are inferred from surface signals. The word predict encourages a false standard: exact time, place, size and style.

Volcanologists can often do something more useful. They detect departures from baseline, map past deposits, identify likely vent areas, estimate conditional probabilities and describe scenarios. At Pinatubo in 1991, converging earthquakes, deformation, gas, geological evidence and expert judgement supported warnings and evacuation before the climactic eruption. Elsewhere, unrest has persisted for months or years and ended without magma reaching the surface. Steam explosions can occur with little clear magmatic warning. False alarms and missed transitions are therefore properties of the problem, though weak monitoring and poor interpretation can worsen them.

Forecast quality varies with the volcano and the network observing it. Success means narrowing uncertainty enough to guide a decision, not announcing certainty. A forecast should state what evidence supports it, what period it covers, which outcomes remain plausible and what would change the assessment. Clockwork is unavailable. Conditional foresight is not failure.

## **“Yellowstone is overdue”**

Yellowstone has produced three immense caldera-forming eruptions over roughly the past two million years. “Supervolcano” is a popular label for a volcanic centre that has produced a VEI 8 eruption, not a separate shape or a permanent eruption style. The label draws attention to scale and then encourages the false picture of one giant chamber repeatedly reaching a fixed threshold. Subtract the dates, average the intervals and a due date appears. This treats geological events as a bus service delayed by bad arithmetic.

An average interval does not identify a periodic mechanism. There are too few giant events to establish a clock, their intervals are unequal, and the system after each collapse was physically different. Magma supply, crustal storage, stress and hydrothermal circulation evolve. Yellowstone has also produced many smaller lava flows and hydrothermal explosions. Those are more representative of its later history than a compulsory repeat of the largest outcome. Hydrothermal explosions can be locally severe without announcing a new caldera cycle.

Past deposits matter because they show what has occurred and help constrain scale and location. Present monitoring matters because it shows whether the current system is departing from baseline. Neither supports the claim that pressure accumulates until an average date arrives. Yellowstone may erupt again, and its hydrothermal hazards are real. “Overdue” adds confidence without evidence and directs attention towards the least likely familiar spectacle.

## **“Volcanoes emit more carbon dioxide than humans”**

Volcanoes are part of the long carbon cycle. Magma and diffuse volcanic systems release carbon dioxide from land and sea, during eruptions and between them. Over geological time that transfer has helped shape the atmosphere. The claim becomes false when deep time is used to dismiss the present annual comparison.

USGS synthesises published estimates for volcanic carbon dioxide, including diffuse land and submarine sources, at roughly 0.13 to 0.44 gigatonnes a year. The Global Carbon Budget's preliminary estimate for fossil-fuel and cement emissions in 2025 is 38.1 gigatonnes. The volcanic range is not a measurement for that single calendar year, but both figures describe annual mass flows. Even the top of the volcanic range is about two orders of magnitude below the human fossil-fuel and cement flow. A spectacular eruption does not reverse the comparison.

Large explosive events may cool climate for a few years because sulfur dioxide forms reflective sulfate aerosol in the stratosphere. Their carbon dioxide contribution remains small beside sustained fossil-fuel emissions. Ash may darken the sky locally, but ash injected into the stratosphere usually falls out within days to weeks and is not the principal agent of multi-year global cooling.

The myth is attractive because natural sources sound too large for human activity to dominate. It confuses stock, flow and timescale. Volcanic carbon belongs to a long-term geochemical cycle. Human activity adds a far faster extra flow from geological stores. Volcanoes help explain how carbon enters the atmosphere over deep time. They do not explain the modern rise instead of us.

## Use It

### **Read source, storage, route and exit**

When a volcano appears in the news, divide the story into four questions. What is supplying melt or gas? Where has material accumulated or changed? Which route is opening? What is leaving the system?

The distinction prevents one observation from doing too much work. Deep earthquakes may indicate new magma entering the crust without saying where it will stop. Inflation may fit pressure in a storage region without proving eruption. A migrating swarm can mark a dyke advancing sideways. Rising sulfur dioxide suggests shallow degassing, while lava chemistry may

show that older material was expelled before fresher magma arrived.

Then look at the exit. An open fissure, blocked conduit, lava dome, crater lake and unstable flank create different pressure histories from related magma. The model works backwards as well. If an eruption changes from ash-rich explosions to sustained lava, ask whether the route widened, water access declined or gas escaped more freely. This replaces volcanic personality with a mechanical sequence that evidence can test.

## **Separate unrest, eruption and impact**

Three different questions are often compressed into one headline: is the system changing, will material reach the surface, and what will happen to people or infrastructure? Keep them apart.

Unrest includes departures from baseline such as earthquake swarms, deformation, gas changes and heating. It may end without eruption. Eruption means material or energy has escaped through a vent, but that category spans a small steam explosion, a lava flow, a sustained ash column and caldera collapse. Impact begins when those products meet aircraft, buildings, water supplies, roads, crops or occupied land. Its scale depends on paths and exposure as well as eruption magnitude.

This separation makes apparently conflicting reports easier to read. Scientists can be confident that unrest is magmatic while uncertain whether it will erupt. They can be confident that an eruption has begun while uncertain whether discharge will increase. A large eruption can produce limited loss of life after effective evacuation, while a smaller one can be catastrophic in a confined valley. Uncertainty at one step does not erase knowledge at the others.

## **Translate labels back into mechanisms**

Volcanology needs shorthand. Shield, stratovolcano, Plinian, phreatic, VEI 5 and alert level orange all compress information. None should be treated as a complete explanation.

For a landform, ask what kinds of deposits built it and where vents have

migrated. For an eruption-style word, ask about fragmentation, discharge, gas escape, water and column stability. For VEI, ask which estimate of tephra volume or plume height supports the classification and what the number omits. For an alert level, read the observatory's definition because colour systems and thresholds differ between countries.

This habit exposes false comparisons. A high VEI does not automatically mean high sulfur injection. A shield volcano does not guarantee harmless effusion. A phreatic eruption does not require fresh magma at the surface. A named style can change within hours. Labels are handles for communication; mechanisms tell you what could happen next. When the label and the observations appear to disagree, prefer the observations and find out how the term is being used.

## **Follow valleys, wind and water**

First separate the jobs being done by water. Water released from a descending plate can lower the melting threshold of the mantle above it. Water dissolved in magma can exsolve as pressure falls. External water can fragment hot magma or rock. Hydrothermal circulation can weaken a flank. Rain or meltwater can remobilise loose deposits into lahars. One familiar substance is doing five different jobs.

A circular distance from the summit is rarely enough. Each volcanic product obeys a route.

Lava follows slope but can be channelled by its own levees, enter tubes or cross old topography by filling low ground. Pyroclastic density currents are strongly influenced by gravity and valleys, though energetic surges can cross ridges. Lahars use drainage networks and can grow by entraining sediment. Ash distribution depends on particle size, plume height and winds at several atmospheric levels. Gas can be carried downwind or collect locally in depressions. Landslides and tsunamis require their own maps.

So read a hazard map by product rather than colour alone. Find river channels, saddles, steep flanks, coastlines and likely ash sectors. Notice that the safest direction for one hazard may be wrong for another. High

ground can protect against a lahar and expose a person to ash or gas. A valley distant from the vent can remain dangerous after the summit looks quiet. The practical geography begins at the source and then follows the material's physics.

## **Treat forecasts as decision windows**

A useful volcanic forecast should contain a period, an outcome and a degree of confidence. "An eruption is possible" is incomplete unless the reader knows whether that means the next day, month or decade, and what observations could raise or lower concern.

Look for scenarios rather than one event. A report might distinguish continued unrest, a small steam explosion, dome growth and a larger magmatic eruption. Each has different evidence and consequences. The forecast can then support staged decisions: restrict a crater, move equipment, prepare transport, evacuate a valley or wait for another signal. The action threshold need not require scientific certainty because the cost of waiting and the cost of acting are different questions.

Revisions are evidence of updating, not proof that the earlier forecast was dishonest. New data can close one scenario and open another. The important test is whether the reasoning is visible: what changed, which interpretation gained support, and which observations would falsify it? Confidence should follow convergence among independent signals, not the volume of one graph or the authority of one speaker.

## **Look for the long tail**

An eruption's dramatic phase attracts the camera and often occupies the smallest fraction of its consequences. Ask what remains mobile after the plume fades.

Loose ash can be lifted again by wind, washed into reservoirs or turned into lahars by seasonal rain. Thick lava can stay hot and unstable. A dome may collapse after pauses. River beds rise as sediment arrives. Infrastructure fails through abrasion, corrosion and repeated cleaning rather than one

impact. Sulfate aerosol from a large eruption can influence climate for a few years, while carbon dioxide from ordinary volcanic activity belongs to a far slower cycle.

The geological tail is longer. Weathering turns lava and ash into soil. New coastlines erode. Hydrothermal circulation alters rock and may prepare a future landslide. Calderas fill with water or later vents. A declaration that the eruption has ended is operationally necessary, but it does not mean the system or landscape has stopped responding. When comparing events, include aftermath and recurrence of secondary hazards rather than ranking only the first day's spectacle.

## **The limits**

These lenses are not a local safety guide. The same term can cover different conditions, and a general reader cannot reconstruct a live volcano from public graphs. Follow the responsible observatory and emergency authority for exclusions, aviation notices and evacuation instructions. A technically informed amateur still lacks the full data, field access and institutional context.

Monitoring is uneven. Some volcanoes have dense networks and decades of baseline observations. Many have sparse instruments, difficult access or communities exposed to more hazards than local institutions can measure. Silence may mean background behaviour, failed equipment or no sensor at all. Global databases are also biased towards land, recent history and eruptions that left recognisable deposits.

The central model has limits too. Source, storage, route and exit organise the subject, but boundaries blur. Gas can move without magma. Several storage regions may interact. External water can dominate the first explosions. Structural collapse can overtake the magmatic sequence. Models simplify hidden geometry because no observer sees the complete system. Use them to ask better questions, not to manufacture certainty.

## The one thing to keep

Keep the moving system.

The cone is what accumulated. The volcano is the changing connection among partial melt, stored magma, gas, water, fractured rock, the surface and the atmosphere. An eruption is one interval in that movement, not the moment when an otherwise inert object switches on.

That idea corrects several errors at once. It explains why a summit can subside while a flank erupts, why a new vent can appear in a broad field, why lava and ash from related magma travel differently, why a valley remains exposed after the crater quietens, and why an ancient collapse can guide later activity. It also explains what monitoring is trying to detect. Earthquakes, deformation, gas, heat and changing water are indirect signs that material, pressure or pathways have changed.

No single diagram covers every ridge, shield, caldera, cone and steam-driven crater. The discipline comes from asking the same physical questions without demanding the same answer: what is present, what changed, what is confined, what can move, and where can it go?

Once that becomes habitual, quiet ground no longer looks inert. The mountain stops being the explanation. It becomes the latest piece of evidence.

## Terms

**Magma.** Molten or partly molten material below the surface, usually containing liquid, crystals and dissolved or exsolved gas. Its mixture and history matter more than the cartoon image of pure liquid rock.

**Lava.** Magma that has reached the surface. The change of name marks location, not a sudden chemical transformation, although cooling, crystallisation and gas loss continue rapidly after emergence.

**Vent.** An opening through which volcanic material escapes. A vent may be a summit crater, a flank opening, part of a fissure or a short-lived outlet that

seals during the same eruption.

**Crater.** A bowl-shaped depression around a vent, commonly excavated by explosion or collapse and rimmed or modified by ejecta. It is usually much smaller than a caldera and may sit inside one.

**Caldera.** A large volcanic depression formed mainly when the roof above a withdrawing shallow magma body collapses. Later lakes, domes, cones and hydrothermal systems can occupy the inherited structure.

**Conduit.** A focused passage carrying magma and gas towards a vent. Its width, roughness, bends, crystals, fractures and plugs influence pressure loss, degassing, discharge and whether an eruption remains stable.

**Dyke.** A sheet of magma that cuts across existing rock, often opening as a fracture under pressure. Dykes can rise, migrate sideways, branch, stall or feed fissures far from a summit.

**Monogenetic field.** A region of scattered vents, each commonly formed during one eruptive episode. Later magma may open fresh ground rather than reuse an old cone, requiring field-scale mapping.

**Magma reservoir.** A subsurface region containing magma that can be stored, transferred or mobilised. It need not be a permanent liquid chamber and may include several melt-rich lenses within a larger system.

**Crystal mush.** A framework of abundant crystals containing interstitial melt and gas. Mush can persist through much of the crust, release melt, receive recharge or be partly remobilised before eruption.

**Volatile.** A chemical component, especially water, carbon dioxide or sulfur species, that can dissolve in magma at pressure and form a gas as conditions change. Volatiles drive and diagnose eruptions.

**Viscosity.** Resistance to flow. In magma it depends strongly on composition, temperature, crystals and bubbles. High viscosity can hinder gas escape, but no viscosity value by itself determines eruption style.

**Permeability.** The ability of connected pores, bubbles or fractures to

transmit fluid or gas. Permeable magma can vent pressure; sealing or collapse of pathways can retain gas and change behaviour.

**Decompression melting.** Partial melting caused when hot rock rises and pressure falls faster than temperature. It is important beneath mid-ocean ridges, continental rifts and several intraplate volcanic settings.

**Flux melting.** Partial melting promoted when volatiles lower a rock's melting temperature. Water released from a subducting plate helps generate melt in the mantle wedge above it.

**Hotspot.** A long-lived volcanic region within or near a plate, commonly linked to anomalously hot upwelling mantle. A chain can form as a plate moves, though hotspot structures and origins vary.

**Subduction zone.** A boundary where one plate descends beneath another. Fluids released from the descending slab promote melting above, feeding volcanic arcs with diverse magma compositions and hazards.

**Rift.** A region where the crust is being pulled apart. Extension encourages faulting, dyke intrusion and decompression melting, producing fissure eruptions, volcanic fields and, if sustained, new plate boundaries.

**Basalt.** A dark, relatively silica-poor volcanic rock commonly derived from mantle melt. Basaltic magma is often hot and fluid, yet trapped gas or external water can still produce explosive activity.

**Andesite.** An intermediate volcanic rock common in many arcs. The term describes composition, not a fixed eruption style; andesitic magma may feed lava flows, domes, ash columns and pyroclastic currents.

**Rhyolite.** A silica-rich volcanic rock, usually formed through extensive magma evolution, crustal melting or both. Rhyolitic melt is commonly viscous, but gas history and ascent decide whether it explodes or extrudes.

**Tephra.** Fragmental material thrown from a vent, from fine ash to lapilli and large blocks or bombs. The term describes erupted fragments without specifying composition, transport distance or eruption mechanism.

**Volcanic ash.** Tephra smaller than two millimetres, made of rock, mineral and glass fragments. It is abrasive, can travel far in plumes and may disrupt roofs, engines, water and electricity.

**Pyroclastic density current.** A ground-hugging mixture of hot particles and gas driven by gravity. It can form from column collapse, dome collapse or direct vent discharge and may outrun evacuation close by.

**Lahar.** A flowing mixture of water and volcanic debris. Lahars follow valleys, entrain sediment and may occur during an eruption or years later when rain remobilises unstable deposits.

**Phreatic eruption.** A steam-driven explosion that fragments existing rock when groundwater or hydrothermal fluid becomes pressurised. Fresh magma need not reach the surface, which can limit clear magmatic warning.

**Phreatomagmatic eruption.** Explosive fragmentation caused by interaction between magma and external water. Efficiency depends on contact, mixing, confinement and water supply, so water does not guarantee one outcome.

**Effusive eruption.** An eruption dominated by lava reaching the surface without sustained explosive fragmentation. Effusion can still destroy extensive ground, produce gas pollution and build unstable domes or steep flow fronts.

**Plinian eruption.** A sustained explosive eruption feeding a high convecting column of gas and tephra. Named after Pliny's account of Vesuvius, it can produce widespread ash and column-collapse currents.

**Volcanic Explosivity Index.** A broadly logarithmic scale for estimating explosive magnitude, weighted mainly by tephra volume and supported by plume and descriptive evidence. It is not a complete danger, energy or climate scale.

# Go Deeper

## The inviting overview

Tamsin Mather, *Adventures in Volcanoland: What Volcanoes Tell Us About the World and Ourselves* (Abacus, 2024). Mather is an Oxford volcanologist who moves between field science, planetary history and human encounters with volcanoes. The book is broad without becoming a catalogue and is the easiest next step from this one. Its strength is scale: gases measured at a crater connect to the atmosphere, climate and the evolution of Earth. It is more reflective than a technical primer, so use it for curiosity, places and the larger meaning of the science rather than as a reference manual for every mechanism.

## The eyewitness source

Pliny the Younger, *The Letters of the Younger Pliny*, translated and introduced by Betty Radice (Penguin Classics, 1969; later reprints). Read letters 6.16 and 6.20, Pliny's accounts of the AD 79 eruption of Vesuvius and the death of his uncle, Pliny the Elder. They are short, observant and foundational to the language of explosive eruptions. They are also one witness writing years later from a limited position. Read them beside modern deposit studies rather than as a complete event report. The value lies in watching perception struggle to describe a phenomenon for which ordinary experience supplied no scale.

## Eruptions in history

Clive Oppenheimer, *Eruptions That Shook the World* (Cambridge University Press, 2011). This is the book for the bridge between volcanology and human history. Oppenheimer follows large eruptions through ice cores, chronicles, archaeology, climate evidence and political consequence, while testing claims that are often repeated too confidently. Tambora, unidentified climate-forcing eruptions and deep-time events receive room unavailable here. Some chapters are denser than the opening suggests, and causal chains from eruption to social change remain hard to prove. That difficulty is part of the recommendation: the book shows how to separate a volcanic signal from the history later attached to it.

## The specialist reference

Haraldur Sigurdsson, Bruce Houghton, Stephen R. McNutt, Hazel Rymer and John Stix, eds., *The Encyclopedia of Volcanoes*, second edition (Academic Press, 2015). This is not a cover-to-cover next read. It is the authoritative desk reference for following one question into professional depth: melt generation, magma chambers, eruption columns, ash, lahars, gases, monitoring, climate or planetary volcanism. Chapters are written by specialists and vary in difficulty, terminology and date sensitivity. Begin with the topic that most altered your mental model, then use its bibliography to reach primary research. The scale is the warning and the benefit: nearly every clean sentence in a short book opens into a field of its own.

## Notes and Sources

Scientific descriptions, institutional guidance and bibliographic details were checked on 4 September 2026. Volcanic systems vary sharply, so general mechanisms in the text are framed as tendencies and interacting controls rather than universal rules. Historic eruption volumes, plume heights, dates and fatality totals are reconstructed from records of uneven quality; the body avoids exact figures where the number would add false precision rather than understanding.

## The Whole Thing in One Page and Why You Should Care

**The system model.** The replacement of a permanent shallow liquid tank with vertically extensive, changing systems of mush, melt-rich lenses, intrusions and gas is based chiefly on Cashman, Sparks and Blundy's 2017 review and the broader physical synthesis by Cashman and Sparks in 2013. The model does not deny shallow melt-rich bodies, and the body now states directly that ridges, shields, volcanic fields and hydrothermal systems need not share one architecture.

**Galunggung and British Airways Flight 9.** WMO records that on 24 June 1982 a British Airways Boeing 747 lost power on all four engines at 37,000 feet after ingesting ash from Galunggung. It descended without power for sixteen minutes to about 12,000 feet, where three engines restarted, and made an emergency landing in Jakarta. Decorative details not established by that account were removed. WMO links the Galunggung encounters to the international procedures that developed into the International Airways Volcano Watch.

**Constructive effects.** Island and crust formation, weathered volcanic soils, geothermal systems and mineral concentration are standard consequences described across *The Encyclopedia of Volcanoes*. These are conditional benefits. Fresh deposits are not immediately fertile, and resource potential does not guarantee safe or economic development.

## Notes on the Core Ideas

**A volcano as a system.** Cashman, Sparks and Blundy review evidence for transcrustal magmatic systems in which much stored material is crystal-rich and shallow melt-rich regions may assemble rapidly. Edmonds and colleagues provide a compatible overview of reservoir architecture and dynamics. Neal and colleagues document the 2018 Kīlauea sequence linking down-rift magma movement, lower East Rift Zone fissures and summit collapse. NOAA's Pacific Marine Environmental Laboratory estimates that 75 per cent of the average annual magma volume reaching Earth's surface is emplaced along mid-ocean ridges. The wording preserves that denominator rather than converting it into a count of eruptions. NOAA Ocean Exploration documents the 2009 West Mata observation used as the submarine anchor. The text uses West Mata and Kīlauea to demonstrate connection without reducing all volcanism to one geometry.

**How rock melts.** Decompression melting, volatile-assisted melting above subduction zones and heat transfer into crust are established petrological mechanisms synthesised in the second edition of *The Encyclopedia of Volcanoes*. The text states that fluids released from the descending slab promote melting in the mantle wedge rather than saying the slab melts wholesale. Partial melt differs chemically from its source because elements partition unevenly between melt and residual crystals. The Pacific Ring of Fire is used as geographical shorthand for numerous circum-Pacific boundaries and arcs, not as one connected magmatic system.

**Magma evolution.** The accounts of fractional crystallisation, crustal interaction, recharge, mixing, crystal mush and melt mobilisation draw on Cashman and Sparks, Cashman, Sparks and Blundy, Edmonds and colleagues, and the reservoir synthesis by Sparks and colleagues. Crystals can preserve changing pressure, temperature and composition; diffusion chronometry can estimate timescales, but values depend on mineral, model and thermal history. The body therefore describes ranges of timing rather than giving one supposedly universal pre-eruption clock.

**Gas and fragmentation.** Water, carbon dioxide and sulfur species

dominate volcanic volatile discussions, with solubility changing with pressure and composition. The account of exsolution, bubble growth, permeability, gas escape and fragmentation follows Cashman and Sparks and standard chapters in *The Encyclopedia of Volcanoes*. USGS gas guidance supports the distinctions among gas species, depths of separation and health effects. External water can fragment magma or drive steam explosions, but efficiency depends on contact and confinement; the text rejects the claim that water always intensifies an eruption.

**Routes, conduits and structural failure.** Dyke propagation, conduit flow and changing vent geometry are treated from the physical reviews. Mount St Helens is supported by USGS Professional Paper 1250, the principal multi-author scientific account of the 1980 eruption. Its north-flank landslide removed confining pressure and was followed by the lateral blast. Caldera language follows standard volcanology: roof subsidence after withdrawal is central, while explosions and erosion may modify the depression.

**Hazards.** Definitions and mechanisms for ash, pyroclastic density currents, lahars, volcanic landslides and gases were checked against current USGS Volcanic Hazards Program material. Ash is defined by grain size, below two millimetres, and consists of rock, mineral and glass fragments. Pyroclastic density currents can result from column collapse, dome collapse or direct vent discharge. Lahars may grow by entrainment and recur after an eruption. The historical analysis by Auker and colleagues supports the claim that a small number of events dominate recorded totals. Brown and colleagues updated the database through 2017 and showed that the dominant fatal mechanism changes strongly with distance, with pyroclastic density currents prominent at intermediate distances and lahars, tsunamis and tephra prominent farther away. Both records are incomplete and shaped by preservation and reporting, so no universal hazard ranking or global fatality forecast is inferred from them.

**Krakatau and tsunamis.** Simkin and Fiske provide the historical and geological synthesis. Maeno and Imamura tested caldera collapse, phreatomagmatic explosion and pyroclastic-flow entry against historical

coastal observations and the Batavia tide-gauge record. Their numerical results identify rapid pyroclastic-flow entry into the sea as the most plausible source of the largest 1883 tsunami, while allowing that all three processes may have occurred and combined. The body retains that distinction and does not generalise it to every volcanic tsunami.

**Volcanic climate effects.** USGS climate summaries distinguish rapidly settling ash from sulfur dioxide that forms sulfate aerosol in the stratosphere. Oppenheimer's 2003 reconstruction of Tambora supports its exceptional historic magnitude and major sulfur-driven climate effects. Exact sulfur and mortality estimates vary by method and source, so the manuscript uses the event to explain mechanism rather than repeat a single dramatic number.

## Notes on the operating sequence

**Baselines and monitoring.** The treatment of seismicity, deformation, gas, heat, hydrology and deposit mapping follows the National Academies' 2017 consensus report, Sparks's review of eruption forecasting and current USGS monitoring guidance. A geophysical source model is an inference from surface data rather than a direct image. Unrest may end without eruption, and individual signals can have several physical explanations. The Smithsonian Global Volcanism Program records Dionisio Pulido observing the vent form in his field on 20 February 1943, the cone reaching about thirty metres the next day and more than 150 metres on the fifth, activity continuing until 1952, and the wider field containing more than 1,400 vents across about 200 by 250 kilometres.

**Kīlauea in 2018.** Neal and colleagues record collapse at Pu'u O'o on 30 April, opening of lower East Rift Zone fissures on 3 May, the magnitude 6.9 earthquake on 4 May, later arrival of hotter magma, high-rate lava effusion and repeated summit collapse. The paper describes the eruption as Kīlauea's largest lower East Rift Zone eruption and caldera collapse for at least two centuries. The manuscript preserves the observed sequence without assigning one causal function to the magnitude 6.9 earthquake. Exact volume and area figures are omitted because they are unnecessary to

the model.

**Mount St Helens in 1980.** USGS Professional Paper 1250 supports the March onset of unrest, deformation of the north flank, the magnitude 5.1 earthquake and landslide at 8:32 on 18 May, rapid decompression, lateral blast, eruption column, pyroclastic currents and lahars. The claim that the landslide was mechanistically integral, rather than a later by-product, is central to the scientific reconstruction.

**Eruption columns.** Gas thrust, air entrainment, buoyant convection, umbrella spreading, particle fallout, aggregation and column collapse are standard plume processes described in *The Encyclopedia of Volcanoes* and Cashman and Sparks. Column height can indicate discharge but does not alone determine near-source danger. Wet aggregation and wind shear complicate simple downwind fallout models.

**Pinatubo in 1991.** The sequence from April steam explosions through expanding seismic, gas and deformation evidence, early June dome growth and the 15 June climactic eruption is based on *Fire and Mud*, edited by Newhall and Punongbayan. The volume documents collaboration between PHIVOLCS and USGS, geological recognition of older large deposits, evolving warnings, Typhoon Yunya, caldera formation and the years of lahars that followed. The drop in measured sulfur dioxide before the climax is retained only as an ambiguous single signal; the book lists several possible transport or supply explanations rather than presenting conduit sealing as the established cause.

**Evidence limits.** Deposits preserve only material that survived erosion, burial and remobilisation. Instruments record indirect surface responses. Laboratory and numerical models isolate mechanisms under assumptions. The National Academies report and the major reviews support the manuscript's rule that confidence rises when methods with different blind spots converge.

## Notes on What People Get Wrong

**The chamber image.** Seismic tomography and other geophysical imaging measure properties such as wave speed, density or electrical behaviour. Their coloured cross-sections are modelled interpretations, not photographs of molten caverns. The transcrustal system literature supports the narrowed correction.

**Temperature and explosivity.** Basaltic magma is commonly hotter and less viscous than rhyolitic magma, but volatile content, permeability, ascent rate, crystals, external water and conduit state alter behaviour. The text therefore avoids a compositional ladder in which basalt is safe and rhyolite is explosive by definition.

**Lava and fatality.** Auker and colleagues provide the earlier statistical analysis, Brown and colleagues the updated distance and victim classification, and USGS hazard pages the physical mechanisms. The manuscript does not claim that one hazard always kills most people because the answer depends on period, location, event selection and reporting.

**VEI.** Newhall and Self created the Volcanic Explosivity Index in 1982 as a practical estimate of explosive magnitude using several kinds of evidence, with erupted tephra volume central. It was designed for uneven historical records. It does not include population exposure, route-specific hazards, lava volume, sulfur yield or a complete measure of energy.

**Forecasting.** Sparks and the National Academies define eruption forecasting probabilistically. Pinatubo is a strong documented success, but its performance depended on observable unrest, field geology, instrumentation, expertise, communication and action. The text does not generalise that setting to every volcano.

**Yellowstone.** Current USGS Yellowstone Volcano Observatory explanations reject the overdue claim. USGS defines 'supervolcano' through a past VEI 8 eruption rather than as a separate landform or fixed style. The three major caldera-forming eruptions occurred at unequal intervals and do

not establish periodicity. Yellowstone's later history includes smaller lava flows and hydrothermal explosions, and the most likely future volcanic event is not assumed to be another caldera-forming eruption.

**Carbon dioxide.** USGS synthesises volcanic emissions, including diffuse land and submarine sources, at about 0.13-0.44 gigatonnes of carbon dioxide per year. The *Global Carbon Budget 2025*, published in 2026, gives a preliminary 2025 fossil-and-cement estimate of 38.1 gigatonnes. The volcanic range is not a calendar-year inventory, so the text identifies the different observation basis while comparing compatible annual mass flows. The climate distinction between carbon dioxide, rapidly settling ash and stratospheric sulfate aerosol is maintained.

## Use It and Terms

The practical lenses derive from the physical chain of source, storage, pathway, product and aftermath. They do not replace local warnings or emergency instructions. Alert systems differ by country, and public colour labels must be read through the issuing observatory's definitions. The terms follow usage in *The Encyclopedia of Volcanoes*, USGS hazard guidance and the principal reviews. "Reservoir" is retained because it remains standard, but its definition explicitly rejects the assumption of a permanent wholly liquid tank.

## Notes on Go Deeper

Mather's *Adventures in Volcanoland* was first published by Abacus in the United Kingdom in 2024. Radice's complete English translation of Pliny's letters appeared in Penguin in 1969 and remains in print in later editions; letters 6.16 and 6.20 contain the Vesuvius accounts. Oppenheimer's *Eruptions That Shook the World* was published in print by Cambridge University Press in 2011. The second edition of *The Encyclopedia of Volcanoes*, edited by Sigurdsson, Houghton, McNutt, Rymer and Stix, was published by Academic Press in 2015.

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