

COURSE

How Volcanoes Work

10 Chapters

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HOW VOLCANOES WORK

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How Volcanoes Work 🏆

Chapter 1 · Inside the Earth

Stand on Arthur's Seat in Edinburgh and you are standing on the worn-down remains of a volcano. It last erupted a very long time ago (roughly 340 million years, *check*), long before there were any people, or even dinosaurs, to be alarmed by it. The city around it is built on lava, ash and the rock that cooled inside the old vent. Volcanoes are not strange exceptions to how a planet behaves: they are the planet letting off heat. So the first chapter does not start with eruptions at all. It starts underground, with three questions: what is the Earth made of, where does its heat come from, and how does solid rock end up as liquid?

> **WHAT WAS RUN**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. You only need Python 3 and its standard library. The numbers are round, textbook-style values, good for building intuition and not for a geophysics paper. Where a figure is approximate or not checked against a source it is marked *(check)*.

The Layers of the Earth

The Earth is not a uniform ball of rock. It is layered like a peach with a thin skin, a very thick flesh and a stone at the centre, except that this peach has a liquid layer and a solid centre. The layers are known from earthquake waves: waves speed up, slow down, bend and vanish as they cross boundaries between different materials, and that is how we "see" things nobody can drill to. (The deepest borehole ever made goes about 12 km down, which is less than 0.2% of the way to the centre.)

LAYER	DEPTH (APPROX.)	STATE	WHAT IT IS MADE OF
Crust	0 to 5-10 km under oceans, 30-50 km under continents	solid rock	basalt (oceans), granite-like rock (continents)
Mantle	to about 2890 km	solid rock that flows very slowly	iron- and magnesium-rich silicate rock (peridotite)
Outer core	2890 to about 5150 km	liquid metal	mostly iron and nickel

LAYER	DEPTH (APPROX.)	STATE	WHAT IT IS MADE OF
Inner core	5150 km to the centre (6371 km)	solid metal	iron and nickel, held solid by pressure

Notice that the only layer that is liquid is the outer core, and no volcano ever draws from it. Volcanoes are fed from the top of the mantle and the crust, a layer only a few hundred kilometres thick. Here is how big each layer is, using Python to work out its share of the radius and of the volume:

```
R = 6371                                  # radius of the Earth in km
layers = [("crust", 35), ("mantle", 2890 - 35),
          ("outer core", 5150 - 2890), ("inner core", 6371 - 5150)]

inner = R
for name, t in layers:
    outer = inner
    inner = outer - t
    vol = (outer**3 - inner**3) / R**3 * 100      # volume of a shell, as a % of the who
    print(f"{name:11s} {t:5d} km  {t / R * 100:5.1f}% of radius  {vol:5.1f}% of volume")
# crust          35 km    0.5% of radius    1.6% of volume
# mantle       2855 km   44.8% of radius   82.0% of volume
# outer core   2260 km   35.5% of radius   15.6% of volume
# inner core   1221 km   19.2% of radius    0.7% of volume
```

The crust is about half a percent of the radius and under two percent of the volume: proportionally thinner than the skin of an apple. The mantle is by far the biggest piece, over 80% of the planet by volume. (The 35 km crust is a typical continental figure. Ocean crust is thinner, so the true average is lower.) Almost everything volcanic happens in that thin skin and the part of the mantle just beneath it.

Lithosphere and asthenosphere: the mechanical layers

Geologists also split the outer Earth by *how it behaves* and not what it is made of. The **lithosphere** is the crust plus the very top of the mantle: cold, stiff and brittle, broken into the tectonic plates. Below it the **asthenosphere** is hotter mantle that is still solid but soft enough to creep, like very stiff toffee over millions of years. Plates ride on it. This division matters for

volcanoes because most magma is made in or just under the lithosphere, and the plates decide where it can get out (Chapter 2 of this course, and Geology & Plate Tectonics Fundamentals 1 for the full plate story).

Where Does the Heat Come From?

A planet 4.5 billion years old should have cooled down. It has not, and the reason is that the Earth has three heat sources:

SOURCE	WHAT IT IS	NOTE
Leftover formation heat	energy from the Earth's violent assembly out of colliding rock, and from iron sinking to form the core	the "primordial" heat, still escaping
Radioactive decay	uranium, thorium and potassium-40 atoms in the rocks slowly decay and release heat	a major continuing source; most of it sits in the crust and mantle (check the exact share)
Core crystallisation	as the liquid outer core slowly freezes onto the inner core, it gives out latent heat	a smaller but steady supply from the centre

The total heat flowing out through the surface is tiny per square metre, only about 0.09 watts (check), less than a thousandth of the heat the Sun delivers to the same patch of ground. You never feel it. But over the whole planet it adds up to roughly 40 trillion watts (check), and that is the engine behind plate tectonics, mantle flow and volcanoes. A volcano is simply a place where a lot of that heat reaches the surface in a hurry.

Temperature and Pressure Going Down

Two things rise as you go deeper: **temperature** and **pressure**. Pressure is the easy one: it is just the weight of the rock above, so `pressure = density × g × depth`. A gigapascal (GPa) is a billion pascals, about ten thousand times atmospheric pressure.

```
G = 9.81

def pressure_gpa(depth_km, density=3000):
```

```
    return density * G * depth_km * 1000 / 1e9      # kg/m3 * m/s2 * m = pascals; /1e9 = G

for d in (10, 35, 100, 410):
    print(d, round(pressure_gpa(d), 2))
# 10 0.29
# 35 1.03
# 100 2.94
# 410 12.07
```

At the base of a 35 km crust the pressure is about 1 GPa, ten thousand times what we live under at the surface. (Density really increases with depth, so these round figures drift; they are fine for a first picture.)

Temperature is trickier. Near the surface it climbs at roughly 25 °C for every kilometre, the **geothermal gradient** (it varies a lot from place to place). If that straight line continued unchanged, rock at 100 km would be at about 2500 °C and the centre would be hotter than anything known. It does not continue. Below the stiff lithosphere, heat is carried by rock slowly flowing upward, and the temperature climbs far more gently: roughly 1300 to 1400 °C at the top of the asthenosphere and perhaps 4000 °C or more at the core boundary (check). You will test this in Exercise 3.

Why Does Rock Melt?

Here is the puzzle that surprises most people: **the mantle is almost entirely solid, even though it is hotter than the melting point of rock at the surface.** The reason is pressure. Squeezing a material makes it harder for its atoms to spread out into the looser arrangement of a liquid, so the melting temperature rises with depth. Rock that would be liquid at 1300 °C on the surface stays solid at 1300 °C a hundred kilometres down.

That leads to the three ways to make magma, and only one of them is "just make it hotter":

WAY TO MELT	WHAT CHANGES	WHERE IT HAPPENS
Decompression melting	hot mantle rises, pressure drops, the melting point drops below the rock's temperature	mid-ocean ridges, rifts, many hotspots (the most common source of magma on Earth)

WAY TO MELT	WHAT CHANGES	WHERE IT HAPPENS
Flux melting	water and other volatiles from sinking plates lower the melting point	subduction zones, such as the Andes and Japan
Heat-transfer melting	hot magma rising into the crust melts the surrounding rock	continental crust over a magma supply, e.g. the source of some silica-rich magmas

Decompression melting is the heart of this chapter, and a small model shows it. Say dry mantle rock starts to melt (its **solidus**) at about 1100 °C at the surface and the temperature rises by about 130 °C for every GPa of pressure (rough values, *check*). Take mantle at 1350 °C that rises without losing much heat. At what depth does it begin to melt?

```
G = 9.81

def solidus(p_gpa):
    return 1100 + 130 * p_gpa              # melting temperature at pressure p

mantle_t = 1350
p = (mantle_t - 1100) / 130            # pressure where solidus = mantle temperature
depth = p * 1e9 / (3300 * G) / 1000   # pressure -> depth in km
print(round(p, 2), round(depth, 1))
# 1.92 59.4

for d in (100, 80, 60, 40, 20, 0):
    p = 3300 * G * d * 1000 / 1e9
    s = solidus(p)
    print(d, round(s), "melting" if mantle_t > s else "solid")
# 100 1521 solid
# 80 1437 solid
# 60 1353 solid
# 40 1268 melting
# 20 1184 melting
# 0 1100 melting
```

Melting starts at roughly 60 km, where the pressure has fallen to about 1.9 GPa. The rock has not been heated: it has only been *released*. Below 60 km it is solid; above that it begins to melt, and the higher it rises the more it melts. In reality only a few percent of the rock melts, a trace of

liquid soaked between solid crystals, like water in a sponge. That liquid is lighter than the rock around it, so it seeps upward and collects.

HOT SPOTS AND MELT VOLUME

A hotter plume of mantle crosses the solidus *deeper*, so it has a taller column in which to melt, and it makes more magma. That is one reason hotspot volcanoes such as Hawaii and Iceland are so productive. Exercise 2 puts numbers on it.

Magma or Lava?

The words are not interchangeable, and getting them right is the quickest way to sound like you know what you are talking about:

TERM	MEANING	CONTAINS
Magma	molten rock **underground**	liquid melt, dissolved gas, and often crystals and bits of solid rock
Lava	molten rock that has **reached the surface** (and the rock it forms when it cools)	most of the dissolved gas has escaped
Tephra	fragments of rock blown out of a volcano: ash, lapilli, bombs	it is magma that has been torn apart by escaping gas (Chapter 4)

The difference is more than vocabulary. Magma carries dissolved gas, held in the liquid by pressure like the fizz in a sealed drinks bottle. When magma nears the surface and the pressure drops, the gas wants out. How that gas escapes, gently or violently, decides whether you get a calm lava flow or an explosion. That is the subject of Chapter 4, and the reason this course keeps returning to pressure.

Common mistakes

Thinking the mantle is liquid (it is solid rock that flows over millions of years; only the outer core is liquid); thinking volcanoes tap the core (they do not: magma forms in the top of the mantle and the crust); thinking magma needs a higher temperature than the surroundings (decompression melting needs lower *pressure*, not more heat); and using "lava" for molten rock that is still underground.

Where This Leads

You now have the starting kit: a thin, brittle crust floating on a huge, slowly flowing mantle, a steady heat supply, a melting point that rises with pressure, and three ways of making magma. Arthur's Seat is what is left when one of those magma supplies reached the surface and then went quiet. Chapter 2 asks the obvious next question: why are volcanoes found where they are, in long lines around the Pacific, in the middle of oceans and along the African rift, and not scattered at random? The answer is the plates.

EXERCISE 1

Write `pressure_gpa(depth_km)` using a density of 3300 kg/m^3 (typical upper mantle rock) and print the pressure at 10, 50, 100, 200 and 400 km. Then rearrange the formula to work out the depth at which the pressure reaches exactly 1 GPa. About how many kilometres of rock add one gigapascal?

View solution

EXERCISE 2

Using the model from the chapter (solidus = 1100 + 130 × P, in °C with P in GPa; density 3300 kg/m^3), write a function that returns the depth where melting starts for a given mantle temperature. Compare ordinary mantle at 1350 °C with a hot plume at 1500 °C. How much deeper does the plume start to melt, and how many times taller is its melt column? Predict the answer before you run it.

View solution

EXERCISE 3

Take the near-surface geotherm T = 15 + 25 × depth (°C, km). Print the temperature it predicts at the Moho (35 km), find the depth where it would reach 1350 °C, and print what it predicts at 100, 400 and 2890 km. Which of those answers is obviously impossible, and what does that tell you about how heat really moves through the deep Earth?

View solution

QUICK REFERENCE

- **Layers:** crust, mantle (solid, flowing slowly), outer core (liquid), inner core (solid)
- **Mechanical layers:** lithosphere (stiff, plates) over asthenosphere (soft, creeping)
- **Heat sources:** leftover formation heat, radioactive decay, core crystallisation
- **Pressure:** density × g × depth; about 1 GPa at 30 to 35 km
- **Melting:** the melting point rises with pressure, so most magma is made by *reducing* pressure (decompression), by adding water (flux) or by heating from hot magma
- **Magma** is underground; **lava** has reached the surface; **tephra** is blown-out fragments

COMING NEXT

How Volcanoes Work 2 shows where volcanoes live: the plate boundaries, hotspots and rifts, and the Ring of Fire around the Pacific.

How Volcanoes Work

Chapter 2 · Where Volcanoes Live

Put a pin in a map for every volcano that has erupted in the last ten thousand years and the pins do not scatter evenly. They form long chains: a great horseshoe around the Pacific, a line down the middle of the Atlantic, a crack through East Africa, and a few lonely dots in the middle of oceans. How Volcanoes Work 1 explained how rock melts. This chapter explains *where* the conditions for melting are found, and the answer is almost always the same: at the edges of tectonic plates, plus a handful of special places that are not.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Only Python 3 and its standard library are needed. Speeds, distances and counts are round textbook-style values for intuition. Anything not checked against a source is marked *(check)*.

Plates in Motion

The lithosphere (the stiff outer shell from Chapter 1) is broken into about a dozen large plates and several smaller ones. They ride slowly on the soft asthenosphere below. "Slowly" is the key word: a plate moves at roughly the speed a fingernail grows, a few centimetres a year. Over geological time that is enormous, because a million years is a very long time. A handy conversion is `1 cm per year = 10 km per million years`.

```
for name, s in [("Mid-Atlantic Ridge (total)", 2.5), ("East Pacific Rise (total, fast)",
                ("Pacific plate over Hawaii", 8), ("Nazca plate moving east", 7)]:
    print(f"{name:32s} {s:5.1f} cm/yr = {s*10:5.0f} km per million years")
# Mid-Atlantic Ridge (total)         2.5 cm/yr =    25 km per million years
# East Pacific Rise (total, fast)   15.0 cm/yr =   150 km per million years
# Pacific plate over Hawaii          8.0 cm/yr =    80 km per million years
# Nazca plate moving east            7.0 cm/yr =    70 km per million years
```

(These are approximate present-day speeds, *check* before quoting them.) At 8 cm a year the Pacific plate covers 80 km in a million years and 8000 km in a hundred million. For the full story of how plates were discovered and how they move, see Geology & Plate Tectonics Fundamentals 1. Here we need only the three things plates can do at an edge.

BOUNDARY	MOTION	VOLCANIC?	MAGMA COMES FROM
Divergent	plates pull apart	yes, very much	decompression melting as mantle rises to fill the gap
Convergent	plates push together; one dives under the other	yes, explosively	flux melting above the sinking plate
Transform	plates slide past each other	almost never	none: nothing is made hot or released

Divergent Boundaries: Ridges and Rifts

Where two plates move apart, the hot mantle beneath rises into the gap. As it rises the pressure falls, and Chapter 1's decompression melting switches on. The magma that forms fills the gap and freezes as new crust. This is happening along the **mid-ocean ridges**, a chain of undersea mountains some 60,000 km long (check), the longest volcanic system on Earth. Most of the planet's volcanic output is made there, quietly and mostly unseen below the waves. Iceland is the exception that proves the rule: it sits on the Mid-Atlantic Ridge but is so well supplied with magma (it is also a hotspot, see below) that the ridge rises above sea level, and you can walk between two plates in the rift valley at Thingvellir.

The same process on land is a **continental rift**. The East African Rift is a place where a continent is slowly being pulled in two, with a string of volcanoes along it such as Nyiragongo and Erta Ale. If the rift keeps widening for tens of millions of years, the sea will flood in and a new ocean will form, exactly as the Atlantic did.

Convergent Boundaries: Subduction Zones

Where two plates meet, the denser one sinks beneath the other in a process called **subduction**. This usually means an oceanic plate (cold, old and dense) diving under another plate. The sinking slab carries water locked in its rocks and sediments. As it sinks, heat and pressure squeeze that water out into the hot mantle wedge above it. As Chapter 1 showed, water lowers

the melting point, so the mantle melts (flux melting). The new magma is rich in gas and silica, which makes it sticky and explosive (Chapter 3 explains why).

The volcanoes do not appear at the trench where the slab starts to sink. They appear further inland, in a line called the **volcanic arc**, above the point where the slab is roughly 100 km deep (check; it varies between 70 and 150 km). How far inland depends on the angle the slab dives at, its **dip**. Simple trigonometry gives the answer:

```
import math

def arc_distance(depth_km, dip_deg):
    return depth_km / math.tan(math.radians(dip_deg))   # horizontal distance from the t

for dip in (20, 30, 45, 60):
    print(dip, round(arc_distance(100, dip)))
# 20 275
# 30 173
# 45 100
# 60 58
```

A shallow dive puts the arc far from the trench (275 km at 20 degrees) while a steep dive brings it close (58 km at 60 degrees). Real arcs sit roughly 100 to 200 km from the trench (check), which fits slab dips around 30 to 45 degrees.

Subduction zones come in two flavours. In an **island arc** (the Aleutians, the chain that includes Krakatoa's Indonesian neighbourhood) one oceanic plate dives under another oceanic plate. In a **continental arc** (the Andes, the Cascades with Mount St Helens, Mexico's Popocatepetl) an oceanic plate dives under a continent. In both cases the same flux-melting recipe applies.

> Common mistake
> Thinking the trench itself is volcanic. The trench is the deep scar where the slab bends downward, and it is almost always empty of volcanoes. The volcanoes sit in an arc well inland, above the part of the slab that is releasing water.

The Ring of Fire

Now the famous map makes sense. The **Ring of Fire** is a horseshoe about 40,000 km long (check) that follows the edge of the Pacific plate and its neighbours. Almost all of it is subduction zones: the Andes, Central America, Mexico, the Cascades, Alaska, the Aleutians, Kamchatka, Japan, the Philippines, Indonesia, New Zealand. Roughly three quarters of the world's active volcanoes and most of its largest earthquakes are on it (check the exact shares). The Ring is not one thing but a long string of separate subduction zones that join up because the Pacific is mostly surrounded by plates that meet it at sinking edges. A quick count over some well-known volcanoes shows the pattern:

```
from collections import Counter

volcanoes = [("Mount St Helens", "subduction"), ("Fuji", "subduction"), ("Pinatubo", "su
             ("Krakatoa", "subduction"), ("Popocatepetl", "subduction"), ("Kilauea", "ho
             ("Mauna Loa", "hotspot"), ("Yellowstone", "hotspot"), ("Erta Ale", "rift"),
             ("Nyiragongo", "rift")]

c = Counter(s for _, s in volcanoes)
for k, v in c.most_common():
    print(f"{k:11s} {v} ({v/len(volcanoes)*100:.0f}%)")
# subduction  5 (50%)
# hotspot     3 (30%)
# rift        2 (20%)
```

That is a hand-picked list of famous names, so it says nothing about the true global split, but it shows the three families of setting.

Hotspots: Volcanoes Away From Edges

A few volcanoes sit in the middle of plates, far from any boundary: Hawaii, Yellowstone, and (in a sense) Iceland. The usual explanation is a **hotspot**: a long-lived, unusually hot upwelling of mantle, often drawn as a rising **plume**, that stays put while the plate drifts across it. Chapter 1 showed that hotter mantle melts over a taller column and makes more magma, so a hotspot can build a huge volcano. As the plate moves on, the volcano is carried away from its supply, goes extinct, and a new one forms over the hotspot. The result is a **chain** of volcanoes that gets older along its length, like holes burnt in a moving sheet of paper. In Hawaii the oldest islands in the

main chain are in the north-west, around 5 million years old at Kauai, and the youngest are in the south-east, with the Big Island still active (check the ages). From the distance and the age, the plate's speed falls out:

```
dist, age = 520, 5.0                  # km from Kauai to the hotspot, million years (che
speed = dist * 1e5 / (age * 1e6)   # km to cm, divided by years
print(round(speed, 1), "cm/yr")
# 10.4 cm/yr

for d in (100, 300, 500):
    print(d, round(d * 1e5 / (speed * 1e6), 1))
# 100 1.0
# 300 2.9
# 500 4.8
```

About 10 cm a year, in the right range for the Pacific plate (a little more than the 8 cm quoted above, because the round figures are only rough). This is the pattern used to read plate motion from old volcanoes. Scientists still argue about the details: some hotspots seem to drift slowly, and whether every hotspot is fed by a deep plume from the core-mantle boundary is debated (check the current state of that debate). Hawaii is the textbook case.

Scotland and the volcano that is not on a boundary

Arthur's Seat is not on a plate edge either, and nothing like a hotspot sits under Edinburgh today. In the Carboniferous, roughly 340 million years ago (check), Scotland sat near the equator, on the edge of a continent being stretched. The volcanoes around Edinburgh and the Midland Valley formed in that stretching, a rift-like setting. The plates have since carried Scotland north to its present position, and the volcanoes are long dead. A volcano's setting tells you about the plate tectonics *of its own time*, not necessarily of today. Chapter 9 returns to Scotland's volcanic past.

Putting It Together

SETTING	HOW MAGMA FORMS	TYPICAL MAGMA	EXAMPLES
Mid-ocean ridge	decompression melting	runny basalt	Iceland, the Mid-Atlantic Ridge
Continental rift	decompression melting	varied, often basalt	East African Rift
Subduction zone	flux melting	sticky, gas-rich, explosive	Andes, Japan, Cascades
Hotspot	decompression of a hotter plume	basalt, sometimes silica-rich under continents	Hawaii, Yellowstone
Transform	none	none	San Andreas Fault (no volcanoes on it)

The "typical magma" column is a preview. The same melting mechanisms give very different eruptions depending on what the magma is like, and that is the next chapter's subject: How Volcanoes Work 3 looks at silica, viscosity and why a Hawaiian lava flow and a Mount St Helens blast are such different events.

EXERCISE 1

Write `km_per_myr(cm_per_yr)` and use it for the Mid-Atlantic Ridge (2.5 cm/yr), the Pacific over Hawaii (8) and the East Pacific Rise (15). Then work out how many million years each plate would take to cross 1000 km. As a sanity check, a fingernail grows about 3.5 cm a year (check): how many times faster is that than the Mid-Atlantic Ridge spreads?

View solution

EXERCISE 2

An island chain gets older by 5 million years over 520 km. Work out the speed of the plate in km per million years and in cm per year, then predict the age of volcanic rock found 100, 300 and 500 km from the active hotspot. Before you run it, guess whether the 300 km island is nearer 2, 3 or 4 million years old.

View solution

EXERCISE 3

Using `arc_distance(depth_km, dip_deg)`, print the arc-to-trench distance for slab dips of 20, 30, 45 and 60 degrees at a slab depth of 100 km. Then work backwards: if a real arc sits 150 km from the trench above a slab 100 km deep, what is the dip? Hint: use `math.atan`. Which gives a narrower arc, a shallow or a steep slab?

View solution

QUICK REFERENCE

- **Plate speed:** a few cm per year; 1 cm/yr = 10 km per million years
- **Divergent (ridges, rifts):** decompression melting; mostly basalt; most volcanism on Earth, mostly underwater
- **Convergent (subduction):** flux melting above the sinking slab; arc about 100 km above the slab depth; sticky, explosive magma
- **Transform:** plates slide past each other; almost no volcanoes
- **Ring of Fire:** a horseshoe of subduction zones around the Pacific; most of the world's active volcanoes
- **Hotspot:** a fixed hot upwelling; the plate drifts over it and leaves a chain that gets older along its length

COMING NEXT

How Volcanoes Work 3 looks at magma and its chemistry: silica, viscosity and dissolved gas, and the range from basalt to rhyolite.

How Volcanoes Work

Chapter 3 · Magma and Its Chemistry

How Volcanoes Work 2 showed where magma forms. The same Earth can produce a Hawaiian lava flow that a person can calmly walk away from and a Mount St Helens blast that flattened a forest, and the difference is mostly down to what the magma is made of. Two ingredients decide almost everything: how much **silica** it contains, and how much **gas** is dissolved in it.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Only Python 3 and its standard library are needed. Viscosities, solubility constants and rock boundaries are round textbook-style values for intuition, not data for real hazard work. Anything not checked against a source is marked *(check)*.

What Magma Is Made Of

Magma is mostly melted silicate rock: silicon and oxygen (silica, SiO_2) together with aluminium, iron, magnesium, calcium, sodium and potassium, plus dissolved gases and sometimes crystals. Geologists name a magma by its silica content, measured in weight percent. Direct melting of mantle rock gives low-silica magma; the more the magma later evolves in the crust, the more silica-rich it becomes, and silica-rich magma is the stuff of explosive volcanoes.

TYPE	SILICA (WT%)	TEMPERATURE	TYPICAL SETTING	COLOUR OF ROCK
Basalt	about 45 to 52	1100 to 1250 C (check)	ridges, Hawaii, Iceland	dark
Andesite	about 52 to 63	about 900 to 1000 C (check)	subduction arcs: Andes, Japan	medium grey
Dacite	about 63 to 69	about 800 to 900 C (check)	arcs, Mount St Helens (check)	light grey
Rhyolite	over 69	about 700 to 850 C (check)	continental hotspots and arcs: Yellowstone	pale, pink or white

The boundaries are conventions, not natural walls, so a function that sorts a measurement into a type is just a ladder of comparisons:

```
def rock_type(sio2):
    if sio2 < 45: return "ultramafic"
    if sio2 < 52: return "basalt"
    if sio2 < 63: return "andesite"
    if sio2 < 69: return "dacite"
    return "rhyolite"

for s in (47, 50, 58, 66, 73, 40):
    print(s, rock_type(s))
# 47 basalt
# 50 basalt
# 58 andesite
# 66 dacite
# 73 rhyolite
# 40 ultramafic
```

This ties straight back to Chapter 2. Decompression melting of the mantle at ridges and hotspots gives basalt. Flux melting at subduction zones, followed by the magma stewing in the crust and picking up more silica, gives andesite and rhyolite. Where a volcano sits therefore predicts what it erupts.

Viscosity: How Sticky Is It?

Viscosity is resistance to flow, measured in pascal seconds (Pa s). Silica matters because silicon and oxygen atoms link into chains and sheets in the melt, and these networks make the liquid stiff: more silica means more linking, so higher viscosity. Cooler magma is also stickier, and crystals and bubbles make it stickier still. The span is huge:

```
visc = {"water": 1e-3, "honey": 10, "basalt": 1e2, "andesite": 1e6, "rhyolite": 1e10}
for name, v in visc.items():
    print(f"{name:9s} {v:9.0e} Pa s   {v/visc['basalt']:9.1e} x basalt")
# water         1e-03 Pa s     1.0e-05 x basalt
# honey         1e+01 Pa s     1.0e-01 x basalt
```

```
# basalt        1e+02 Pa s     1.0e+00 x basalt
# andesite      1e+06 Pa s     1.0e+04 x basalt
# rhyolite      1e+10 Pa s     1.0e+08 x basalt
```

These are order-of-magnitude values (check; real figures range over several powers of ten with temperature and water content). Even so, the message is clear. Basalt is somewhat thicker than honey and flows in rivers. Rhyolite is a hundred million times thicker than basalt: it hardly flows at all and tends to pile up in a dome. A person can outpace a basalt flow on foot but could not watch a rhyolite flow move.

> Common mistake
> Treating "lava is hot, so it is all runny". Temperature matters, but silica matters far more. A cooler rhyolite is vastly stickier than a hotter basalt.

Dissolved Gas

Magma holds dissolved gas, mostly **water vapour** (typically a few percent by weight in arc magmas, check), then carbon dioxide and sulfur dioxide. Gas dissolves in melt much as carbon dioxide dissolves in a sealed bottle of fizzy drink: pressure keeps it in solution. Open the bottle and the pressure drops, so the gas comes out as bubbles. Magma rising towards the surface does the same, a process called **exsolution**. For water, a rough rule is that solubility rises with the square root of the pressure:

```
import math
K = 0.4          # wt% water per sqrt(MPa), rough value (check)
RHO, G = 2500, 9.8

def pressure_mpa(depth_km):
    return RHO * G * depth_km * 1000 / 1e6

def solubility(p_mpa):
    return K * math.sqrt(p_mpa)

for depth in (8, 4, 1, 0.1, 0):
    p = max(pressure_mpa(depth), 0.1)
    print(f"{depth:4} km  {p:6.1f} MPa  holds {solubility(p):4.2f} wt%")
```

```
#    8 km   196.0 MPa  holds 5.60 wt%
#    4 km    98.0 MPa  holds 3.96 wt%
#    1 km    24.5 MPa  holds 1.98 wt%
#  0.1 km     2.5 MPa  holds 0.63 wt%
#    0 km     0.1 MPa  holds 0.13 wt%
```

So a magma that carries 4 wt% water holds all of it at a depth of around 4 km or more, but starts to unload as it climbs, and at the surface it can hold almost none. The gas that comes out is the fuel for the next chapter.

Why Gas and Viscosity Together Decide the Eruption

Bubbles form in every magma that rises. What changes is what happens to them. In runny basalt the bubbles rise, merge and escape easily: the gas leaves quietly and the lava flows, sometimes in fountains. In sticky rhyolite the bubbles cannot get out. They grow, crowd each other and stay trapped, so the pressure builds until the magma is blown to pieces. Add the fact that arc magmas tend to carry more water, and the Chapter 2 pattern follows: subduction zones are explosive, ridges and hotspots are mostly gentle.

	BASALT	ANDESITE / DACITE	RHYOLITE
Silica	low	medium	high
Viscosity	low	high	very high
Dissolved water	low	medium	often high
Gas escape	easy	harder	very hard
Typical behaviour	lava flows, fountains	domes, explosions	big explosions, domes

Arthur's Seat again

The Edinburgh volcanoes from Chapter 2 were largely basaltic (check, with some related rock types), which fits the stretching setting: lava flows and ash, not Yellowstone-style catastrophes. The chemistry in the rocks is a record of the magma that made them.

EXERCISE 1

Write `rock_type(sio2)` using the boundaries 45, 52, 63 and 69, and run it on the silica values 47, 50, 58, 66, 73 and 40. Which of them would you expect to be the most explosive, and why?

View solution

EXERCISE 2

Write `pressure_mpa(depth_km)` (rock density 2500 kg per cubic metre) and `solubility(p_mpa)` using K = 0.4. For a magma holding 4 wt% water in total, print how much is dissolved and how much has exsolved at 200, 100, 50, 25, 10 and 1 MPa. At roughly which pressure do bubbles first appear?

View solution

EXERCISE 3

Use the ideal gas law, `V = nRT / P` with R = 8.314, to find how much water vapour 1 m^3 of magma at 900 C releases when 0, 2, 2.74 and 3.6 wt% has exsolved at 100, 25, 10 and 1 MPa (water is 0.018 kg per mole). Roughly how many times its own volume is the gas near the surface? Why does that matter for sticky magma?

View solution

QUICK REFERENCE

- **Silica:** basalt about 45 to 52, andesite 52 to 63, dacite 63 to 69, rhyolite over 69 wt%
- **Viscosity:** more silica and lower temperature mean stickier; basalt about 10^2 Pa s, rhyolite about 10^{10} (check)
- **Gas:** mostly water vapour; dissolved under pressure, exsolves as magma rises
- **Solubility rule:** water held is roughly K times the square root of pressure
- **Runny magma:** gas escapes, lava flows. **Sticky magma:** gas is trapped, explosions

COMING NEXT

How Volcanoes Work 4 looks at why volcanoes erupt: gas pressure, bubble growth, magma chambers and what triggers an eruption.

How Volcanoes Work

Chapter 4 · Why Volcanoes Erupt

How Volcanoes Work 3 ended with gas coming out of rising magma. This chapter asks the question that matters most: what actually makes a volcano erupt? The short answer is that an eruption happens when the pressure inside the magma system beats the strength of the rock holding it in, or when the magma has so much gas that it tears itself apart on the way up. Both ideas are simple enough to model in a few lines of Python.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Only Python 3 and its standard library are needed. Rock strengths, stiffness values and densities are round values for intuition, not data for real hazard work. Anything not checked against a source is marked *(check)*.

Bubbles Grow as Magma Rises

Exsolved gas behaves roughly like an ideal gas: at a fixed temperature, pressure times volume stays constant (Boyle's law). A bubble that forms deep down, under 100 MPa, has to expand enormously as the pressure around it falls:

```
P0 = 100.0   # MPa, where the bubble starts
for p in (100, 50, 25, 10, 1, 0.1):
    print(f"{p:6} MPa  bubble is {P0/p:6.0f} x its volume at 100 MPa")
#    100 MPa  bubble is      1 x its volume at 100 MPa
#     50 MPa  bubble is      2 x its volume at 100 MPa
#     25 MPa  bubble is      4 x its volume at 100 MPa
#     10 MPa  bubble is     10 x its volume at 100 MPa
#      1 MPa  bubble is    100 x its volume at 100 MPa
#    0.1 MPa  bubble is   1000 x its volume at 100 MPa
```

Notice where the growth happens. Pressure falls by half from 100 to 50 MPa and the bubble only doubles, but the final drop from 1 MPa to atmospheric pressure makes it ten times bigger

again. Most of the expansion happens in the last few hundred metres, so the magma is a thick liquid for most of its journey and becomes a foam only close to the top. This is why eruptions can seem to accelerate suddenly. (The sum above ignores extra gas that keeps leaving the melt and joining the bubbles, so the real growth is even larger.)

Two Ways Out: Flow or Fragmentation

What happens next depends on the Chapter 3 result. If the magma is runny, the expanding bubbles move through it and escape, and the magma is only mildly frothed: it spills out as lava. If it is sticky, the bubbles cannot get away. The magma becomes a foam of more and more gas with thinner and thinner walls of melt between the bubbles, until the walls break. At that point the gas is no longer inside the liquid: the liquid is inside the gas, a spray of fragments carried upwards at speed. This is **fragmentation**, and the fragments are volcanic ash and pumice. It is the line between a gentle eruption and an explosive one.

	BEFORE FRAGMENTATION	AFTER FRAGMENTATION
What is continuous	the melt	the gas
What is in bits	the bubbles	the magma (ash, pumice)
Result	lava flow or dome	explosive column

> Common mistake
> Picturing an explosive eruption as "magma bursting out of a tube full of liquid". It is a foam turning into a gas-driven spray. The gas does the work, not the liquid.

The Magma Chamber

Magma rarely rises straight from the mantle to the surface. It collects in **magma reservoirs** in the crust, often a few kilometres down. Modern studies suggest these are less like a big underground lake and more like a spongy "mush" of crystals with pockets of melt in between (check), but the word chamber is still used because it makes the physics easy to picture. A chamber sits under pressure from the rock around it, roughly the weight of the rock above, called the **lithostatic pressure**. An eruption needs the magma to get *extra* pressure on top of

this, which geologists call **overpressure**, enough to crack the roof and push a path (a dyke) upwards.

What Triggers an Eruption

A chamber can sit quietly for centuries. Something has to change. The usual triggers are:

- **Recharge:** new, hotter magma arrives from below and squeezes the chamber, raising the pressure.
- **Gas build-up:** as a chamber cools, crystals grow and the remaining melt is pushed towards saturation, so it releases more bubbles (sometimes called second boiling). More gas means more pressure.
- **Buoyancy:** magma is lighter than the rock around it, so a tall enough column pushes upwards on its roof.
- **External events:** large earthquakes, collapses of part of the volcano, or removal of ice or water load might nudge a system that is already close to the edge (check how often).

Here is a toy model of recharge. Each year a bit more magma is injected into a 10 km^3 chamber, and each cubic kilometre pushes the pressure up by an amount set by the stiffness of the system. When the overpressure reaches the strength of the roof (about 10 MPa, a round figure, check), the roof cracks and the model erupts:

```
STRENGTH = 10.0   # MPa, tensile strength of the roof (check)
K = 8000.0        # MPa per unit fractional volume change (rough, check)
chamber = 10.0    # km3
over = 0.0
for yr in range(1, 11):
    inject = 0.0005 * yr      # supply grows with time, km3 per year
    over += K * inject / chamber
    state = "ERUPT" if over >= STRENGTH else "ok"
    print(f"year {yr:2d}: injected {inject:.4f} km3, overpressure {over:5.2f} MPa {state}")
    if over >= STRENGTH: break
# year  1: injected 0.0005 km3, overpressure  0.40 MPa ok
# year  2: injected 0.0010 km3, overpressure  1.20 MPa ok
# year  3: injected 0.0015 km3, overpressure  2.40 MPa ok
# year  4: injected 0.0020 km3, overpressure  4.00 MPa ok
# year  5: injected 0.0025 km3, overpressure  6.00 MPa ok
# year  6: injected 0.0030 km3, overpressure  8.40 MPa ok
```

```
# year  7: injected 0.0035 km3, overpressure 11.20 MPa ERUPT
```

The pattern is the point: nothing seems to happen for years, the pressure creeps up, and then a threshold is crossed. Real volcanoes are messier, since magma can leak out, rock can flow slowly instead of cracking, and a chamber can wait for a long time near the threshold. Still, this is why the rise in pressure matters more for forecasting than any single dramatic event, which Chapter 8 returns to.

Buoyancy alone

Magma is less dense than the rock around it (here 2400 against 2700 kg per cubic metre, round values). A connected column of height `h` therefore pushes on its roof with a pressure of (rock density minus magma density) times g times h:

```
rho_magma, rho_rock = 2400, 2700
G = 9.8
for h in (100, 1000, 5000):
    dp = (rho_rock - rho_magma) * G * h / 1e6
    print(f"column {h:5d} m: buoyant overpressure {dp:5.2f} MPa")
# column   100 m: buoyant overpressure  0.29 MPa
# column  1000 m: buoyant overpressure  2.94 MPa
# column  5000 m: buoyant overpressure 14.70 MPa
```

A column a few kilometres tall is needed before buoyancy alone matches the roof strength, so in practice it adds to gas pressure and recharge rather than acting alone.

Arthur's Seat again

The Edinburgh volcanoes were active roughly 340 million years ago (check). Nothing about them was different in kind from the model above: magma collected, pressure built, and the crust, stretched as in Chapter 2, gave way in a series of eruptions. Their basaltic magma (check) was runny enough to let most of its gas escape, so lava flows and ash beds rather than a huge explosion record what happened.

EXERCISE 1

Using Boyle's law, print the volume of a bubble (starting at 1 unit under 100 MPa) at 100, 50, 25, 10, 5, 1 and 0.1 MPa, together with its radius (volume to the power one third). By what factor does the radius grow? Where in the rise does most of the growth happen?

View solution

EXERCISE 2

Write `years_to_eruption(strength, inject_per_year)` for the recharge model with a constant supply (K = 8000, chamber 10 km^3). Compare roof strengths of 10 and 20 MPa with supply rates of 0.001 and 0.002 km^3 per year. What does a stronger roof change about the wait, and about the eruption that follows?

View solution

EXERCISE 3

Compute the buoyant overpressure for columns of 100, 500, 1000, 3000 and 5000 m, then work out the column height needed to reach a 10 MPa roof strength. Is buoyancy likely to be the only trigger?

View solution

QUICK REFERENCE

- **Bubble growth:** pressure times volume is constant, so most expansion happens in the last few hundred metres
- **Fragmentation:** a foam of bubbles breaks; gas becomes continuous and magma becomes ash and pumice
- **Overpressure:** pressure above the surrounding rock's; an eruption needs it to exceed the roof strength (about 10 MPa, check)
- **Triggers:** recharge, gas build-up, buoyancy, sometimes external events
- **Buoyancy:** (rock density minus magma density) times g times column height

COMING NEXT

How Volcanoes Work 5 looks at the types of volcano: shield, stratovolcano, cinder cone, caldera and fissure.

How Volcanoes Work

Chapter 5 · Types of Volcano

How Volcanoes Work 4 explained why a volcano erupts. This chapter asks why volcanoes do not all look the same. A volcano is a heap built from its own eruptions, so its shape is a record of what it erupts and how: runny lava builds a broad, gentle dome, sticky magma and ash build a steep cone, and a very big eruption can empty the ground beneath the volcano and leave a hole. The chemistry from How Volcanoes Work 3 and the gas behaviour from How Volcanoes Work 4 explain nearly every shape.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Only Python 3 and its standard library are needed. Slopes, heights and sizes are round values for intuition, not surveyed data. Anything not checked against a source is marked *(check)*.

Five Shapes, Five Stories

TYPE	TYPICAL SLOPE	BUILT FROM	USUAL MAGMA
Shield	a few degrees	thousands of thin lava flows	basalt, runny
Stratovolcano	20 to 35 degrees (check)	alternating lava, ash and rubble	andesite to dacite, sticky
Cinder cone	about 30 to 35 degrees	loose fragments thrown out and landing around the vent	usually basalt, gas-rich
Caldera	a hole, not a cone	collapse after a large eruption	often rhyolite, sometimes basalt
Fissure	almost flat	lava from a long crack	basalt, runny

Shield Volcanoes: Wide and Low

Runny basalt travels a long way before it stiffens, so each flow spreads thinly and the volcano grows outwards as much as upwards. The result looks like a warrior's shield laid on the ground. The Hawaiian volcanoes are the classic example, and Mauna Loa is one of the largest volcanoes on Earth by volume even though its slopes are gentle enough to walk up without noticing (check). Iceland also has many shields. A shield's gas escapes easily (Chapter 4's "flow" route), so eruptions tend to be effusive, with fountains and rivers of lava rather than explosions.

Stratovolcanoes: Steep and Layered

Sticky magma cannot spread, and gas cannot escape cleanly, so these volcanoes alternate between lava flows and explosive layers of ash and rubble. The word **strato** refers to the layers. They are the postcard volcanoes: Fuji, Vesuvius, Mount St Helens, Pinatubo. Because the cone is built partly from loose fragments and weak, altered rock, it can be unstable, and a flank may collapse. They produce the most dangerous eruptions at the everyday scale, which Chapter 7 covers.

Cinder Cones: Piles of Fragments

A cinder cone forms when gas-rich magma fountains at a single vent and the fragments (cinders, or scoria) fall back around it. Loose material can only be piled up to its **angle of repose**, the steepest slope at which it stays put, about 30 to 35 degrees for cinders (check). That is why cinder cones are so regular, as if drawn with a ruler. They are small, often a few hundred metres high, and they form quickly, sometimes in a single eruption lasting months or years. Paricutin in Mexico started in a farmer's field in 1943 and grew to over 300 m in its first year (check).

Turning Shape Into Numbers

Because each type is close to a cone with a characteristic slope, a very small amount of trigonometry turns slope and base width into height. For a cone with base radius `r` and slope angle `a`, the height is `r` times the tangent of `a`:

```
  import math
```

```
types = [("shield", 3, 50), ("stratovolcano", 25, 8), ("cinder cone", 33, 0.5)]
for name, slope, r in types:
    h = r * math.tan(math.radians(slope))
    print(f"{name:14s} slope {slope:2d} deg, base radius {r:4.1f} km -> height {h:5.2f} k
# shield         slope  3 deg, base radius 50.0 km -> height  2.62 km
# stratovolcano  slope 25 deg, base radius  8.0 km -> height  3.73 km
# cinder cone    slope 33 deg, base radius  0.5 km -> height  0.32 km
```

A shield with a base 100 km across is only 2.6 km high, which is why you cannot see its shape from the ground, while a stratovolcano 16 km across is more than 3 km high and dominates the skyline. The same idea works for volume: a cone has a volume of one third of its base area times its height. Giving every type a 1 km radius makes the contrast clear:

```
import math
def cone_volume(r_km, angle_deg):
    h = r_km * math.tan(math.radians(angle_deg))
    return math.pi * r_km**2 * h / 3
for name, a in (("shield", 3), ("stratovolcano", 25), ("cinder cone", 33)):
    print(f"{name:14s} {a:2d} deg: 1 km radius cone holds {cone_volume(1, a):.3f} km3")
# shield          3 deg: 1 km radius cone holds 0.055 km3
# stratovolcano  25 deg: 1 km radius cone holds 0.488 km3
# cinder cone    33 deg: 1 km radius cone holds 0.680 km3
```

A steep cone packs about a dozen times more material into the same footprint than a shield. A shield's enormous size therefore comes from its width, not its steepness: to get a big volume you need a very big base.

Calderas: When the Roof Falls In

A caldera is not built up but let down. In a very large eruption the chamber empties faster than the rock above it can hold itself up, and the roof sinks into the space left behind, like a piston dropping into a cylinder. The result is a roughly circular basin many times wider than any vent. Crater Lake in Oregon and the Yellowstone caldera are famous examples, and the 2018 collapse

at Kilauea's summit showed the same process on a smaller scale (check). Basaltic calderas can also form, but the biggest ones come from explosive eruptions of sticky, silica-rich magma.

A rough "piston" model says the volume erupted is about the volume of the hole, the area of the circle times the depth of collapse:

```
import math
def caldera_diameter(volume_km3, depth_km):
    return 2 * math.sqrt(volume_km3 / (math.pi * depth_km))
for v in (1, 10, 100, 1000):
    print(f"{v:5d} km3 erupted, 1 km collapse: caldera about {caldera_diameter(v, 1.0):5
#     1 km3 erupted, 1 km collapse: caldera about   1.1 km wide
#    10 km3 erupted, 1 km collapse: caldera about   3.6 km wide
#   100 km3 erupted, 1 km collapse: caldera about  11.3 km wide
#  1000 km3 erupted, 1 km collapse: caldera about  35.7 km wide
```

> Common mistake
> Calling a caldera "a big crater". A crater is a bowl at the top of a cone made by explosion or erosion at the vent. A caldera is a collapse structure, usually a kilometre or more across, and the volume of the hole is linked to the volume of magma that left.

Fissures: Volcanoes Without a Cone

When magma finds a long crack, as along a spreading rift, it can erupt along its whole length instead of from one vent. A fissure eruption often begins as a curtain of lava fountains that later narrows to a few vents. Iceland's Laki fissure in 1783 and Holuhraun in 2014 are examples, and the 1783 eruption is remembered for its gas more than its lava (check), which Chapter 9 will return to. Fissures build lava plains, not mountains, and the largest flood basalts in Earth's history were erupted this way.

Arthur's Seat again

Edinburgh shows several of these types in one city. Arthur's Seat is the eroded remains of a volcano whose vent was cut by glaciers, and the lava layers of Salisbury Crags and the plug of Castle Rock belong to the same volcanic landscape (check details). Rock records show that the

area was a volcanic field rather than a single mountain. The tell-tale difference with a young volcano is that erosion has stripped away the cone and revealed its plumbing, which is why geologists can study it so closely.

EXERCISE 1

Write `height(base_radius_km, slope_deg)` and print the height of shield volcanoes with slopes of 2, 3 and 5 degrees and base radii of 20, 50 and 100 km. What happens to the height when the base radius doubles, and why is a shield hard to recognise from the ground?

View solution

EXERCISE 2

Rearrange the cone volume formula to find the radius of a cone of given volume and slope. For 0.1 km^3 of material, print the radius and height (in metres) at 33, 25 and 3 degrees. How does slope change the shape for the same volume?

View solution

EXERCISE 3

Using the piston model, print the caldera width for 50 km^3 erupted with collapse depths of 0.5, 1 and 2 km. Then work out the volume needed for a 20 km wide caldera with 1 km of collapse. Does that fit a normal eruption?

View solution

QUICK REFERENCE

- **Shield:** runny basalt, a few degrees of slope, huge but low
- **Stratovolcano:** sticky magma, layers of lava and ash, steep and often dangerous
- **Cinder cone:** fragments piled at the angle of repose, about 30 to 35 degrees, small and quick
- **Caldera:** a collapse basin left after a large eruption; hole volume is about the magma erupted
- **Fissure:** eruption along a crack, building plains rather than cones

- **Cone height:** base radius times tan(slope); cone volume: one third of base area times height

COMING NEXT

How Volcanoes Work 6 looks at eruption styles: effusive and explosive, from Hawaiian to Plinian, and the VEI scale.

How Volcanoes Work

Chapter 6 · Eruption Styles

How Volcanoes Work 5 showed that a volcano's shape records what it erupts. This chapter looks at how it erupts. Two ingredients decide almost everything: how sticky the magma is (How Volcanoes Work 3) and how easily its gas escapes (How Volcanoes Work 4). Runny, gas-poor magma leaks out as lava. Sticky, gas-rich magma tears itself apart. Between those extremes sit a set of named styles, and a single scale, the Volcanic Explosivity Index, puts a number on how big an explosive eruption was.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Only Python 3 is needed. Volumes are rounded tephra figures for intuition, not surveyed data. Anything not checked against a source is marked *(check)*.

Effusive or Explosive

An **effusive** eruption pours out lava that flows across the ground. An **explosive** eruption fragments magma into ash and rock and blasts it into the air. The difference is the gas story from Chapter 4: if bubbles can drift out as the magma rises, it flows; if they are trapped and expand violently, it explodes. Many eruptions are both at once, or switch from one to the other, so treat the two words as the ends of a scale.

STYLE	MAGMA	WHAT IT LOOKS LIKE	EXAMPLE
Hawaiian	runny basalt, gas escapes easily	lava fountains and long flows, mostly gentle	Kilauea
Strombolian	basalt, gas collects in bubbles	regular bursts flinging glowing fragments	Stromboli
Vulcanian	stickier andesite, a plug of cooled magma	short, sharp explosions that break the plug	Sakurajima (check)
Plinian	sticky, gas-rich dacite to rhyolite	a tall, steady column of ash that can reach the stratosphere	Vesuvius AD 79, Pinatubo 1991

Reading the Four Styles

Hawaiian eruptions are the friendliest. The magma is so runny that gas slips out almost freely, producing fountains tens to hundreds of metres high and rivers of lava that usually travel slowly enough to walk away from. They build the shield volcanoes of Chapter 5.

Strombolian eruptions are named after Stromboli, off Italy, which has been erupting almost constantly for a very long time (check). Big gas bubbles rise through the basalt and burst at the surface, throwing glowing clots of lava out every few minutes. This builds the cinder cones of Chapter 5.

Vulcanian eruptions are named after Vulcano, another Italian island. The magma is sticky enough that the top of the conduit cools into a plug. Pressure builds beneath it until it blows, sending a dark cloud of ash and blocks a few kilometres up. Then the vent reseals and the cycle repeats, sometimes within hours.

Plinian eruptions are the biggest everyday-scale explosions, named after Pliny the Younger, who described the AD 79 eruption of Vesuvius. Gas-rich, sticky magma is torn into fine fragments and driven upwards in a column that climbs until the cloud is no longer lighter than the air around it, then spreads sideways in an umbrella. Columns can reach tens of kilometres, into the stratosphere (check). When the column cannot hold itself up it can collapse and send flows of hot ash down the slopes, which Chapter 7 covers as one of the worst hazards.

> Common mistake
> Thinking that a volcano has one fixed style. Style belongs to an eruption, not to a mountain. Vesuvius has had mild and enormous eruptions, and a single eruption such as Pinatubo's began with small explosions before the great Plinian climax. Also, sticky magma does not always explode: if it loses its gas slowly it can ooze out as a thick dome instead.

Putting a Number on Size: the VEI

Describing an eruption as "big" is not much use for comparison, so volcanologists use the **Volcanic Explosivity Index (VEI)**, a scale from 0 to 8 based mainly on the volume of erupted fragments (tephra), with the height of the ash column as a supporting clue (check). Each step is roughly ten times the volume of the one before, the same logarithmic idea as the earthquake scales. Approximate lower limits for the volume of tephra:

VEI	VOLUME (AT LEAST)	ROUGH DESCRIPTION	FAMILIAR EXAMPLE (CHECK)
0	below 10^4 m^3	non-explosive	Hawaiian lava flows
1	10^4 m^3	gentle	Stromboli
2	10^6 m^3	explosive	frequent, many a year
3	10^7 m^3	severe	fairly common
4	10^8 m^3	cataclysmic	Eyjafjallajokull 2010
5	10^9 m^3	paroxysmal	Mount St Helens 1980, Vesuvius AD 79
6	10^{10} m^3	colossal	Pinatubo 1991, Krakatoa 1883
7	10^{11} m^3	super-colossal	Tambora 1815
8	10^{12} m^3	mega-colossal	Yellowstone's largest eruptions

That table is easy to turn into a function. Walk up the list of limits and count how many are exceeded:

```
def vei(volume_m3):
    limits = [1e4, 1e6, 1e7, 1e8, 1e9, 1e10, 1e11, 1e12]
    n = 0
    for i, lim in enumerate(limits):
        if volume_m3 >= lim:
            n = i + 1
    return n

events = [("Kilauea summit fountain", 5e5), ("Eyjafjallajokull 2010", 2.7e8),
          ("Mount St Helens 1980", 1e9), ("Pinatubo 1991", 1e10), ("Tambora 1815", 1.5e1
for name, v in events:
    print(f"{name:26s} {v:9.1e} m3 -> VEI {vei(v)}")
# Kilauea summit fountain    5.0e+05 m3 -> VEI 1
# Eyjafjallajokull 2010      2.7e+08 m3 -> VEI 4
# Mount St Helens 1980       1.0e+09 m3 -> VEI 5
# Pinatubo 1991              1.0e+10 m3 -> VEI 6
# Tambora 1815               1.5e+11 m3 -> VEI 7
```

What a Logarithmic Scale Means

Because each VEI step is about ten times the volume, the gaps are enormous. A VEI 7 holds at least 10,000 times the material of a VEI 3. This also explains the frequency pattern: small eruptions happen all the time, large ones are rare, and the very largest happen over spans of tens of thousands of years or more (check). The scale has limits worth knowing: it measures explosive output, so a huge, slow, effusive eruption can rate low even though it moves a great deal of rock, and it says nothing about harm. A modest VEI 4 near a city can do more damage than a VEI 6 in the middle of an ocean.

```
import math
# How many minimum-size VEI 3 eruptions fit in the smallest VEI 6 and VEI 7?
for big, limit in ((6, 1e10), (7, 1e11)):
    print(f"VEI {big}: {limit / 1e7:,.0f} times the minimum VEI 3 (10 million m3)")
print(f"Steps from VEI 3 to VEI 7: {int(math.log10(1e11 / 1e7))} powers of ten")
# VEI 6: 1,000 times the minimum VEI 3 (10 million m3)
# VEI 7: 10,000 times the minimum VEI 3 (10 million m3)
# Steps from VEI 3 to VEI 7: 4 powers of ten
```

Arthur's Seat again

The Edinburgh volcano of about 340 million years ago (check) belonged to a period of mostly basaltic activity, so its eruptions were probably of the Hawaiian and Strombolian kind, with lava flows and fragments building a volcanic field rather than a tall Plinian column. We cannot assign a VEI to it, because erosion has removed most of the loose ash that the scale depends on. The VEI is easiest to apply to recent eruptions whose deposits survive.

EXERCISE 1

Write `vei_km3(volume_km3)` that converts cubic kilometres to cubic metres and reuses the VEI function. Print the VEI of a 0.0005 km^3 eruption, 0.27 km^3, 10 km^3 and 150 km^3. Where does the unit conversion come from?

View solution

EXERCISE 2

Store the VEI lower limits in a dictionary and print how many times larger the VEI 6 and VEI 7 thresholds are than VEI 3, then the ratio between each pair of neighbouring VEI levels. Which step breaks the "ten times" pattern?

View solution

EXERCISE 3

Write a toy `style(silica_pct, gas)` that returns Hawaiian, Strombolian, Vulcanian or Plinian from the silica percentage and a gas level of low, medium or high. Print six cases. Why can this only be a memory aid and not a forecast?

View solution

QUICK REFERENCE

- **Effusive vs explosive:** lava flows when gas escapes, a blast when it cannot
- **Hawaiian:** runny basalt, fountains and flows, builds shields
- **Strombolian:** regular bursts of glowing fragments, builds cinder cones
- **Vulcanian:** short, sharp explosions that break a plug in the vent
- **Plinian:** a tall, sustained ash column from sticky, gas-rich magma
- **VEI:** 0 to 8, based on erupted volume; each step is about ten times the last (the 1 to 2 step is a hundred)
- **Limits:** the VEI measures explosive size, not harm or effusive output

COMING NEXT

How Volcanoes Work 7 turns to hazards: ash, pyroclastic flows, lahars, gases and tsunamis, with Pompeii and Krakatoa as the case studies.

How Volcanoes Work

Chapter 7 · Hazards

How Volcanoes Work 6 sorted eruptions by style and size. This chapter asks what they do to people and places. The honest answer is that lava, the thing in the pictures, is rarely the main killer. It is usually slow enough to walk away from. The deadly hazards are the ones that move fast, travel far, or arrive without a visible warning: pyroclastic flows, lahars, ash, gas and tsunamis.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Speeds, densities and distances are rounded, order-of-magnitude figures for intuition, not survey data. Anything not checked against a source is marked *(check)*.

Ranking the Hazards

HAZARD	WHAT IT IS	HOW FAR IT REACHES	WARNING TIME
Lava flow	molten rock moving over the ground	usually a few km (check)	hours to days
Ashfall	fine fragments carried by wind	tens to hundreds of km	minutes to hours
Pyroclastic flow	hot cloud of gas and ash racing downhill	often 5 to 30 km (check)	almost none
Lahar	volcanic mudflow of ash, water and debris	can exceed 100 km along valleys (check)	minutes to hours
Gas	carbon dioxide, sulfur dioxide and others	from the crater to a whole valley	none unless monitored
Tsunami	wave from a collapse or an explosion at sea	across a whole sea or ocean	minutes near the source

Ashfall

Volcanic ash is not soft like wood ash. It is tiny shards of glass and rock, abrasive, heavy when wet, and mildly conductive. It is the hazard that reaches the most people, because the wind carries it far beyond the cone. A few millimetres closes roads, contaminates water, clogs air filters and grounds aircraft, because glass can melt inside a jet engine and coat its parts. Tens of centimetres can collapse roofs, especially when rain soaks the ash, since wet ash is roughly half as heavy again as dry ash (check). The 2010 eruption of Eyjafjallajokull was only a VEI 4 (How Volcanoes Work 6), yet its ash closed much of European airspace for days, which shows once more that the VEI measures size, not impact.

Pyroclastic Flows and Surges

A **pyroclastic flow** is an avalanche of hot gas, ash and rock fragments that runs along the ground, driven by gravity. A **surge** is a thinner, more dilute version that can leap over obstacles. They form when a Plinian column collapses (How Volcanoes Work 6), when a lava dome collapses, or when an explosion blasts sideways. Temperatures run to hundreds of degrees Celsius and speeds to well over 100 km/h (check). Nothing outruns one on foot, and the heat and ash kill by burns and by suffocation. The French phrase *nuee ardente*, "glowing cloud", is the older name for the same thing.

Case study: Pompeii, AD 79

The Vesuvius eruption of AD 79 is the classic example, and we have an eyewitness, Pliny the Younger, who watched from across the bay. For many hours the eruption was a tall Plinian column that rained pumice on Pompeii, a town roughly ten kilometres from the vent (check). Many people left during that phase. The column then collapsed and sent pyroclastic surges through the surrounding towns, killing those who had stayed within minutes. Here is why distance gave no real protection once the flows began:

```
def minutes(distance_km, speed_kmh):
    return distance_km / speed_kmh * 60

distance = 10      # km, Vesuvius to Pompeii, roughly (check)
for who, speed in (("walking", 5), ("running", 12), ("pyroclastic surge", 100)):
    print(f"{who:18s} {minutes(distance, speed):6.1f} min")
# walking            120.0 min
# running             50.0 min
```

```
  # pyroclastic surge     6.0 min
```

Pompeii is also remarkable for what it preserved. Ash buried the town quickly, so buildings, objects and the shapes of bodies in the hardened ash survive to be studied. The same eruption that destroyed the town gave us a snapshot of Roman life.

Lahars

A **lahar** (an Indonesian word) is a flowing mixture of volcanic debris and water, with the consistency of wet concrete. The water can come from melted snow and ice, a crater lake, or heavy rain falling on loose ash. Lahars follow river valleys, can travel at tens of kilometres an hour, and can happen days, months or even years after an eruption while the ash is still loose. The 1985 eruption of Nevado del Ruiz in Colombia melted part of its ice cap, and lahars buried the town of Armero, killing more than 20,000 people (check). It remains a grim lesson in why forecasting has to be followed by communication and evacuation (How Volcanoes Work 8).

Gas

Gas (How Volcanoes Work 4) can kill without an eruption. Carbon dioxide is heavier than air and pools in low ground, such as valleys and craters, where people and animals can suffocate without noticing. Sulfur dioxide irritates the lungs and eyes and, in large amounts, makes rain acidic. Volcanic fog, called *vog* in Hawaii, affects health and crops far from the vent. A famous example is Lake Nyos in Cameroon, where in 1986 a cloud of carbon dioxide released from the lake killed well over a thousand people in nearby villages (check).

Tsunamis and Case Study: Krakatoa, 1883

Volcanoes make tsunamis in three ways: part of the cone collapses into the sea, a pyroclastic flow enters the water, or an explosion displaces the water. Krakatoa, between Java and Sumatra, erupted in August 1883 at about VEI 6 (How Volcanoes Work 6). Its final explosions were heard thousands of kilometres away (check), and the tsunamis that followed killed tens of thousands of people along nearby coasts (check). Most of the deaths in that eruption were from the waves,

not from the ash. A tsunami moves at a speed set by water depth: at the pace of a jet in the deep ocean, and more slowly in shallow water.

```
import math
# Shallow-water wave speed: v = sqrt(g * depth)
for depth in (20, 100, 2000):
    v = math.sqrt(9.81 * depth) * 3.6
    print(f"depth {depth:5d} m -> {v:5.0f} km/h")
# depth    20 m ->    50 km/h
# depth   100 m ->   113 km/h
# depth  2000 m ->   504 km/h
```

Common mistake

Thinking that the danger ends when the eruption does, or that the hazard is the lava. Lahars follow rain for years, gas pools in low ground, and a tsunami can hit a coast that never saw the eruption. A related trap is believing that distance alone means safety: the right question is how fast each hazard travels and which way the valleys, wind and sea lead.

Arthur's Seat again

Edinburgh's old volcano (How Volcanoes Work 5) was a basaltic field, so its main hazards would have been lava and fragments close to the vents, with ashfall downwind, rather than large pyroclastic flows. If a volcano like that erupted today in a city of half a million people, the problem would be less the scale of the eruption than the number of people, roads and buildings close to the vent. Exposure, not just the size of the eruption, decides the risk.

EXERCISE 1

Write `tsunami_speed_kmh(depth_m)` using `sqrt(g * depth)`. Print the speed for depths of 50, 200, 1000 and 4000 m, then the time for a wave to cross 150 km of sea 40 m deep. Why does the wave slow down and grow taller near the coast?

View solution

EXERCISE 2

Write `ash_load_kpa(thickness_mm, density)` and compare dry ash (1000 kg/m^3) with wet ash (1500 kg/m^3) at 10, 50, 100, 200 and 300 mm against an assumed roof limit of 2 kPa. At what depth does wet ash become dangerous, and why should roofs be cleared?

View solution

EXERCISE 3

Store typical speeds for a pyroclastic flow, a lahar and wind-borne ash in a dictionary and print the arrival time in minutes at 5, 10 and 30 km. Which hazard leaves the least time, and what does that mean for evacuation planning?

View solution

QUICK REFERENCE

- **Lava:** destroys property but is usually slow enough to escape
- **Ashfall:** reaches the most people; closes airspace, collapses roofs when wet
- **Pyroclastic flow:** hot, fast, ground-hugging, almost no warning; the deadliest type at close range
- **Lahar:** volcanic mudflow along valleys, possible long after the eruption
- **Gas:** carbon dioxide pools in low ground; sulfur dioxide harms lungs and crops
- **Tsunami:** speed is sqrt(g x depth); collapse, flows or explosions can generate it
- **Pompeii:** a Plinian phase gave time to leave; the column collapse did not
- **Krakatoa:** most deaths came from the waves, not the ash

COMING NEXT

How Volcanoes Work 8 turns to monitoring and forecasting: seismicity, ground deformation, gas and satellites, with past successes and failures.

How Volcanoes Work

Chapter 8 · Monitoring

How Volcanoes Work 7 showed that the deadliest hazards often arrive with little warning. This chapter is about buying that warning. Volcanologists cannot see inside a volcano, so they watch the signs that magma on the move leaves at the surface: small earthquakes, a swelling cone, changing gas, rising heat. No single signal is reliable, but together they can turn a surprise into a planned evacuation.

WHAT WAS RUN

Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. All data are invented for practice, not real measurements. Anything not checked against a source is marked *(check)*.

The Main Signals

SIGNAL	WHAT IS MEASURED	WHAT IT CAN MEAN	INSTRUMENT
Seismicity	number, size and depth of earthquakes	rock breaking, or fluid moving, as magma pushes up	seismometers
Deformation	swelling, tilting or stretching of the ground	magma filling a chamber, as in How Volcanoes Work 4	GPS, tiltmeters, radar satellites
Gas	amount and mix of sulfur dioxide and carbon dioxide	fresh magma rising and releasing gas	spectrometers, gas sensors, drones
Heat	temperature of the ground and crater	hot material nearer the surface	thermal satellites, infrared cameras
Other	water chemistry, gravity, magnetic field, sound	changes below ground	sensors and surveys

Seismicity

Earthquakes are the workhorse of monitoring. A volcano normally has a background rate of small quakes. When magma or fluids start to move, the rate rises, the quakes may become shallower, and some arrive in **swarms**, many small events in a short time. A volcano can also produce a continuous shaking called **volcanic tremor**, linked to fluid moving underground (check). The simplest question is: is today unusual compared with this volcano's own normal?

```
import statistics

quakes = [3, 5, 4, 6, 3, 5, 4, 48, 95, 160]   # quakes per day (invented)
base = statistics.mean(quakes[:7])         # first week = background
print(f"background {base:.1f}")
for day, q in enumerate(quakes, 1):
    if q > 3 * base:
        print(f"day {day:2d}: {q:4d}  {q / base:5.1f}x  SWARM")
# background 4.3
# day  8:   48   11.2x  SWARM
# day  9:   95   22.2x  SWARM
# day 10:  160   37.3x  SWARM
```

Ground Deformation

When magma collects in a chamber, the ground above it can rise by centimetres, like a slowly inflating balloon, and then deflate after an eruption. Instruments measure this in three ways. **GPS** stations record their own position to millimetres. **Tiltmeters** measure the changing slope of the ground. **InSAR**, radar from satellites, compares images taken on different days and maps the change over a whole volcano without anyone going near it. Sometimes the signal is the rate rather than the total: a swelling that speeds up deserves more attention than a steady one.

```
uplift_mm = [0, 2, 4, 6, 9, 14, 22]       # GPS height each week (invented)
rates = [b - a for a, b in zip(uplift_mm, uplift_mm[1:])]
print("weekly uplift:", rates)
# weekly uplift: [2, 2, 2, 3, 5, 8]
```

The total is only 22 mm, but the weekly rate has quadrupled, which is the real news.

Gas and Heat

Fresh magma releases gas as it rises (How Volcanoes Work 4). Carbon dioxide leaves the magma early and deep, while sulfur dioxide comes out closer to the surface, so a rising ratio of sulfur dioxide to carbon dioxide can hint that magma is climbing (check). Gas is measured by instruments at the crater, by sensors on aircraft and drones, and by satellites that detect sulfur dioxide clouds. Thermal cameras and satellites watch for a warming crater or the glow of new lava.

Satellites

Satellites matter because many volcanoes are remote, dangerous or in countries without a large monitoring budget. They provide radar deformation maps, thermal images, ash and sulfur dioxide plumes, and regular photographs. They do not replace instruments on the ground, but they widen the net to volcanoes that have no instruments at all.

Forecasting: What It Can and Cannot Do

A forecast is not a prophecy. Scientists use monitoring data to decide how likely an eruption is, and sometimes how big, using a mix of statistics, past behaviour of the same volcano and physical models. Many agencies communicate with **alert levels**, a ladder from normal through advisory and watch to warning, each tied to actions. The best-understood case is a volcano that has erupted before and is well instrumented, because its past behaviour tells scientists what a build-up looks like.

Successes and failures

- **Pinatubo, 1991 (success).** Scientists in the Philippines, helped by American colleagues, read the warning signs and told authorities to evacuate tens of thousands of people before the huge climactic eruption (check). It is usually cited as the best example of forecasting saving lives.
- **Mount St. Helens, 1980 (partial).** The volcano was watched closely and areas were closed, but the lateral blast spread farther than expected, and some people died outside the zone (check). It showed that knowing an eruption is coming does not mean knowing exactly what it will do.

- **Nevado del Ruiz, 1985 (failure of communication).** The hazard was recognised and hazard maps existed, but warnings were not turned into an evacuation in time. More than 20,000 people died in the lahars (check).
- **Eyjafjallajokull, 2010 (a different problem).** The eruption was monitored, yet the difficult question was ash in the air, and aviation authorities had to decide on thresholds quickly (How Volcanoes Work 7).

The lesson of these cases is the same: forecasting is a chain, from data to scientists to authorities to the public. The chain fails at its weakest link, and the weakest link is rarely the instrument.

> Common mistake
> Treating one signal as a countdown. A swarm can fade, swelling can stall for years, and an eruption can follow weak signs. Quiet volcanoes with long gaps between eruptions are the hardest to read, because nobody knows what their normal looks like. Another trap is to assume every false alarm is a failure: a few evacuations that turn out unnecessary are the cost of the times when they are not.

Arthur's Seat again

Edinburgh's volcano (How Volcanoes Work 5) is extinct, so it is not monitored the way a living volcano is. The comparison is still useful. If a new vent opened in central Scotland, the first warning would probably be a swarm of small earthquakes, and the lack of any local record of what normal looks like would make interpretation harder, a good reason to keep a baseline for any region where the risk is not zero (check).

EXERCISE 1

Write `alert_level(count, background)` that returns "normal", "advisory", "watch" or "warning" using the ratio of the daily quake count to the background rate (thresholds 2, 5 and 15). Apply it to seven days of counts and print the ratio and level. Why compare with the volcano's own background rather than use one fixed number for all volcanoes?

View solution

EXERCISE 2

Given daily sulfur dioxide and carbon dioxide emissions as two lists, compute the SO_2/CO_2 ratio each day and flag any day when it is more than double the first day's ratio. What other explanations could there be for a changed gas reading besides rising magma?

View solution

EXERCISE 3

Some forecasts use the inverse-rate method: if 1/rate of a signal falls along a straight line, the line reaches zero at a predicted time. Fit a line to 1/rate for six days of invented, accelerating quake rates (least squares by hand) and find when it reaches zero. Why should the answer be treated as a range of dates, not one moment?

View solution

QUICK REFERENCE

- **Seismicity:** compare the rate with the volcano's own background; look for swarms and tremor
- **Deformation:** GPS, tiltmeters and InSAR show swelling; the rate matters as much as the total
- **Gas:** a rising SO_2/CO_2 ratio can mean magma is rising
- **Satellites:** radar, thermal and gas views of remote volcanoes
- **Alert levels:** normal, advisory, watch, warning, each tied to actions
- **Pinatubo:** forecasting worked; **Nevado del Ruiz:** the warning did not become action
- **Forecast:** a probability, not a countdown

COMING NEXT

How Volcanoes Work 9 looks at volcanoes and climate: Tambora, Pinatubo, supereruptions, Iceland and Scotland's volcanic past.

How Volcanoes Work

Chapter 9 · Climate

How Volcanoes Work 8 was about warning people before an eruption. This chapter zooms out to what a big eruption does to the whole planet. Ash falls out within days, but gas can stay in the upper atmosphere for years, and that is how a volcano in one country can change the weather on another continent. The chapter ends with the longer view, including the volcanoes that once shaped Scotland.

> **WHAT WAS RUN**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. The numbers are simplified or invented for practice. Anything not checked against a source is marked *(check)*.

Why a Volcano Can Cool the Planet

Volcanoes release carbon dioxide, a warming gas, but in a single eruption the amount is small compared with human emissions (check). The short-term effect is the opposite. A big explosive eruption throws sulfur dioxide into the **stratosphere**, the layer above the weather (How Volcanoes Work 6). There it turns into tiny droplets of sulfuric acid, called **sulfate aerosols**, which spread around the globe and reflect some sunlight back to space. Less sunlight reaches the surface, so the planet cools for a year or two. Ash matters much less, because the particles are heavy and fall out quickly.

MATERIAL	WHERE IT GOES	HOW LONG IT LASTS	CLIMATE EFFECT
Ash	falls out near the volcano	days to weeks	little
Sulfur dioxide	reaches the stratosphere, forms aerosols	one to three years (check)	cooling
Carbon dioxide	mixes into the whole atmosphere	very long	slight warming, small per eruption

Height is the key. A large eruption in the tropics can push gas into the stratosphere, where air circulation spreads it to both hemispheres. A similar eruption near the poles tends to spread less

widely (check). Sulfur that stays low in the weather layer is rained out within days or weeks.

Pinatubo, 1991: The Measured Case

Mount Pinatubo in the Philippines (How Volcanoes Work 8) is the best-measured example, because satellites and modern instruments were watching. It put about 20 million tonnes of sulfur dioxide into the stratosphere and the global average temperature dropped by roughly half a degree Celsius over the following year or so, before recovering (check). Because it was recent and well observed, Pinatubo is the benchmark that scientists use to test climate models.

```
import math

peak = 0.5          # peak cooling in degrees C (Pinatubo-like, check)
tau = 1.0           # e-folding time in years (invented)
for year in range(0, 6):
    print(f"year {year}: {peak * math.exp(-year / tau):.2f} C")
# year 0: 0.50 C
# year 1: 0.18 C
# year 2: 0.07 C
# year 3: 0.02 C
# year 4: 0.01 C
# year 5: 0.00 C
```

The snippet uses exponential decay: each year a fixed fraction of the aerosol veil is gone. It is a model of the shape of the recovery, not a prediction, and real data are noisier.

Tambora, 1815: The Year Without a Summer

Tambora, in what is now Indonesia, erupted in April 1815 in the largest eruption of the last few centuries, about VEI 7 (How Volcanoes Work 6, check). The sulfur it injected cooled the Northern Hemisphere. In 1816 Europe and North America had a cold, wet summer with failed harvests, food shortages and rising prices, which is why 1816 is called the **Year Without a Summer** (check). Tambora is a reminder that the climate effect of a volcano is a human story too: the main victims of a cold year are farmers and the people who depend on their crops.

ERUPTION	YEAR	SULFUR DIOXIDE (APPROX.)	EFFECT
Pinatubo	1991	about 20 million tonnes (check)	global cooling of about 0.5 °C
Krakatoa	1883	comparable to Pinatubo (check)	noticeable cooling and vivid sunsets
Tambora	1815	several times Pinatubo (check)	the Year Without a Summer

Supereruptions

A **supereruption** is the top of the scale: roughly VEI 8, more than a thousand cubic kilometres of erupted material (How Volcanoes Work 6, check). Famous sites include Yellowstone in the United States, Toba in Indonesia and Taupo in New Zealand. They are rare, on the order of one every tens of thousands of years (check), and their effects would be global: a deep, multi-year cooling and widespread ashfall that would disrupt agriculture on a large scale. Rare is not the same as due. These volcanoes show no sign of an eruption soon, and scientists track them closely (How Volcanoes Work 8).

> Common mistake
> Reading "once every 17,000 years" as a schedule, and then deciding one is overdue. Random events do not keep time: gaps vary a lot, and a long wait does not raise the odds of the next one. Exercise 1 puts numbers on this.

Iceland: Eruptions That Reach Europe

Iceland sits on a hotspot and a rift at once (How Volcanoes Work 2), so it erupts often. Its eruptions matter to the UK for two reasons. One is air travel, as seen with Eyjafjallajokull in 2010 (How Volcanoes Work 7). The other is gas and cold. The 1783 to 1784 Laki fissure eruption released huge amounts of gas, caused a hazy fog over Europe, and is linked to poor harvests and a very hot then very cold sequence of weather, with many deaths in Britain (check). Laki was effusive rather than explosive (How Volcanoes Work 5), which shows that a gentle eruption that lasts months can still carry gas far.

Scotland's Volcanic Past

Scotland has no active volcano today, but it has a long volcanic history, written in its rocks. Arthur's Seat in Edinburgh (How Volcanoes Work 5, How Volcanoes Work 8) is the remnant of a volcano that was active about 340 million years ago, when Scotland lay much nearer the equator (check). Much later, around 60 million years ago, volcanoes in the west, in places such as Skye, Mull and the Giant's Causeway region across the water, were active as the North Atlantic began to open (check). Both periods sit in a geological story that moves on a different clock from human history. Plate tectonics (How Volcanoes Work 2) carried Scotland north over hundreds of millions of years and the volcanoes went quiet as the ground left the places where magma was being made.

VOLCANOES AND LONG-TERM CLIMATE

Over millions of years volcanoes are part of the carbon cycle, releasing carbon dioxide that rock weathering slowly removes (check). Some of the largest past mass extinctions are linked to huge lava outpourings that lasted many thousands of years (check). That is a very different thing from a single eruption cooling the planet for a year or two.

EXERCISE 1

Write `chance(years, return_time)` returning the probability of at least one event in a span, assuming random timing: `1 - exp(-years / return_time)`. Print the chance of a supereruption over 100, 1,000 and 10,000 years for return times of 17,000 and 50,000 years (invented range). Why does a long wait since the last one not make the next one due?

View solution

EXERCISE 2

Write `cooling(so2_mt, year)` that scales a 0.5 °C peak by the amount of sulfur dioxide (20 million tonnes gives 0.5 °C) and decays it with a one-year time constant. Print years 0 to 3 for a Pinatubo-like (20) and a Tambora-like (60) eruption. Name two reasons real cooling would differ from this simple model.

View solution

EXERCISE 3

Put Arthur's Seat (340 million years ago), the western Scottish volcanoes (60 million) and Tambora (211 years) on a one-day clock where Earth is 4,540 million years old (check). Print how many seconds before midnight each one is. What does the result say about how much of the volcanic record humans have measured?

View solution

QUICK REFERENCE

- **Cooling comes from sulfur,** not ash: sulfate aerosols in the stratosphere reflect sunlight
- **Pinatubo 1991:** about 0.5 °C of global cooling, the benchmark case
- **Tambora 1815:** the Year Without a Summer, 1816
- **Supereruptions:** VEI 8, rare, global effects; rare does not mean due
- **Iceland:** frequent eruptions, and Laki showed gas can travel far
- **Scotland:** volcanoes about 340 and 60 million years ago, none active now

COMING NEXT

How Volcanoes Work 10 is the capstone: assess a hypothetical volcano, draw a hazard map, build simple Python models and pull the whole course together.

How Volcanoes Work

Chapter 10 · Capstone: Read a Volcano

How Volcanoes Work 9 zoomed out to the climate and to deep time. This last chapter brings everything together. You will play the part of a volcano scientist handed a brand new, **hypothetical** volcano, "Mount Ardent", and asked three questions: what kind of eruption can it produce, who is in danger, and how much warning could we get? Every number below is invented for practice.

> **WHAT WAS RUN**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output shown in the comments is what Python printed. Mount Ardent, its villages and all thresholds are made up. Anything not checked against a source is marked *(check)*.

Step 1: Read the Magma

Start with the chemistry (How Volcanoes Work 3). Silica makes magma sticky, and sticky magma that holds gas is the recipe for explosions (How Volcanoes Work 4). Suppose Ardent's past lavas and ash deposits are about 58% silica with plenty of dissolved gas. A tiny function can turn that reasoning into a first guess at the eruption style (How Volcanoes Work 6).

```
def style(silica, gas):
    if silica < 52:
        return "effusive (runny basalt)" if gas == "low" else "fire-fountaining"
    if silica < 63:
        return "mixed: lava flows and explosions"
    return "explosive (sticky, gas-rich)"

for silica, gas in ((48, "low"), (58, "high"), (72, "high")):
    print(f"silica {silica}%, gas {gas}: {style(silica, gas)}")
# silica 48%, gas low: effusive (runny basalt)
# silica 58%, gas high: mixed: lava flows and explosions
# silica 72%, gas high: explosive (sticky, gas-rich)
```

Ardent at 58% silica falls in the middle: a stratovolcano (How Volcanoes Work 5) that could produce lava flows and also serious explosions. The cut-off values are rough rules of thumb (check). A real assessment would also look at the plate setting (How Volcanoes Work 2): Ardent sits above a subduction zone, which is where this kind of magma usually forms (check).

Step 2: Estimate the Size

Next, how big could it get? The geological record around the volcano shows deposits from several past eruptions. Each step on the VEI scale is roughly ten times more erupted material (How Volcanoes Work 6). The function below converts a volume into an approximate VEI. It is simplified, because the real scale also uses plume height and other measures (check).

```
def vei(volume_km3):
    """Rough VEI from erupted volume (each step is about 10x, simplified)."""
    thresholds = [0.00001, 0.001, 0.01, 0.1, 1, 10, 100, 1000]
    return sum(volume_km3 >= t for t in thresholds)

for volume in (0.001, 0.05, 1.5, 30):
    print(f"{volume:7.3f} km3 -> VEI {vei(volume)}")
#   0.001 km3 -> VEI 2
#   0.050 km3 -> VEI 3
#   1.500 km3 -> VEI 5
#  30.000 km3 -> VEI 6
```

Suppose Ardent's record shows many small and medium eruptions, a few around 1 cubic kilometre, and one big event of about 30. The sensible planning choice is a **likely** scenario (VEI 3 to 4, which happens often), and a **worst credible** scenario (VEI 5 to 6, which is rare). Planners prepare for both and do not pretend the worst case is impossible.

> Common mistake
> Planning only for the biggest eruption on record, or only for the most likely one. The first overspends and gets ignored, the second leaves people unprepared for the rare big event. Good hazard planning uses both a likely and a worst credible scenario.

Step 3: Draw the Hazard Map

A hazard map divides the land into zones by how dangerous it is (How Volcanoes Work 7). Real maps use the terrain, because lahars follow valleys (How Volcanoes Work 7), and the wind, because ash falls downwind. For this exercise we use the simplest possible map: rings of distance. Red is within 5 km, orange within 15 km, yellow within 30 km, and anything further is green. Each grid cell is 5 km wide.

```
import math

size = 11
vx, vy = 5, 5              # the volcano sits in the middle cell
cell = 5                   # km per cell
for y in range(size):
    row = ""
    for x in range(size):
        d = math.hypot(x - vx, y - vy) * cell
        if x == vx and y == vy:
            row += "^ "
        else:
            row += ("R " if d <= 5 else "O " if d <= 15 else "Y " if d <= 30 else ". ")
    print(row)
# . . Y Y Y Y Y Y Y . .
# . Y Y Y Y Y Y Y Y Y .
# Y Y Y Y Y O Y Y Y Y Y
# Y Y Y O O O O O Y Y Y
# Y Y Y O O R O O Y Y Y
# Y Y O O R ^ R O O Y Y
# Y Y Y O O R O O Y Y Y
# Y Y Y O O O O O Y Y Y
# Y Y Y Y Y O Y Y Y Y Y
# . Y Y Y Y Y Y Y Y Y .
# . . Y Y Y Y Y Y Y . .
```

The map is a circle because the model ignores wind and valleys. It shows the main idea (the closer, the worse) and also its main weakness: a real map is rarely a neat circle, and a village 20 km away down a river valley can be in more danger than one 10 km away behind a ridge.

Step 4: Who Is Exposed?

A hazard only becomes a **risk** when people are in its way. Four villages sit around Ardent. We give each hazard zone an invented "exposure weight" (the share of people likely to be affected) and add up the totals. Exercise 1 asks you to build this table.

VILLAGE	DISTANCE	POPULATION	ZONE
Aldwick	4 km	1,200	red
Brae	12 km	5,000	orange
Corrie	28 km	20,000	yellow
Dunmore	45 km	80,000	green

The biggest town, Dunmore, is in the safest zone, and the smallest village, Aldwick, is in the most dangerous one. Risk is hazard multiplied by exposure, so the plan has to cover both. For example, Aldwick needs an early evacuation route, while Corrie, with many people at modest risk, needs plans for ash and for supplies.

Step 5: Warning Time and Monitoring

Finally, how much warning could we get, and from what? How Volcanoes Work 8 described the signals: earthquakes, ground swelling and gas (How Volcanoes Work 8). A simple observatory could combine them into an alert level, which is what Exercise 3 does. The honest limit, repeated from How Volcanoes Work 8, is that unrest can settle without an eruption, so alert levels are judgements, not predictions.

Warning time also depends on the hazard. Ash falls slowly and can be waited out indoors (How Volcanoes Work 7). A lahar travelling down a valley at 40 km/h would take only minutes to reach the nearest village (invented speed; real speeds vary a lot, check). That is why the evacuation decision has to be made on the alert level, before the eruption, not when the lahar is seen. Exercise 2 puts numbers on this.

The Whole Course in One Table

You now have the full chain, from the planet's interior to the bus stop. Here is the course in one table.

QUESTION	SHORT ANSWER	CHAPTER
Why is there magma?	Heat and falling pressure or added water make rock melt	How Volcanoes Work 1
Where do volcanoes form?	Plate boundaries, hotspots and rifts	How Volcanoes Work 2
What sets the behaviour?	Silica, viscosity and dissolved gas	How Volcanoes Work 3
Why does it erupt?	Gas pressure and bubble growth, plus a trigger	How Volcanoes Work 4
What shapes are there?	Shield, stratovolcano, cinder cone, caldera, fissure	How Volcanoes Work 5
How do they erupt?	Effusive to explosive, measured on the VEI	How Volcanoes Work 6
What can hurt people?	Ash, pyroclastic flows, lahars, gas, tsunamis	How Volcanoes Work 7
Can we see it coming?	Often, with several signals together; never certain	How Volcanoes Work 8
What about the climate?	Stratospheric sulfur cools the planet for a year or two	How Volcanoes Work 9

WHERE EDINBURGH FITS

Arthur's Seat is the local reminder that volcanoes are part of the Earth's long story, and not only a distant hazard (How Volcanoes Work 9). The next time you walk up it, you are standing on the roots of a volcano that went quiet about 340 million years ago (check).

EXERCISE 1

Write `zone(distance_km)` using the ring rules above and a weights dictionary (red 1.0, orange 0.4, yellow 0.1, green 0.0, invented). For the four villages, print each village's zone and exposed population (population times weight), then the total. Which village has the highest risk to its people, and which has the biggest population? Why are they different?

View solution

EXERCISE 2

Write `ash_mm(distance_km)` where ash is 50 mm thick at 10 km and halves every further 10 km, and `lahar_minutes(distance_km)` for a lahar at 40 km/h. Print ash at 10, 20, 30 and 50 km, and lahar arrival at 5, 15 and 30 km. What does the lahar result mean for when an evacuation has to be ordered? Name one thing the ash model ignores.

View solution

EXERCISE 3

Write `alert(quakes_per_day, uplift_mm, so2_tonnes_per_day)` that scores each signal 0, 1 or 2 (invented thresholds: quakes 20 and 100, uplift 10 and 50 mm, gas 200 and 1,000 tonnes), adds the scores and maps the total to normal, advisory, watch or warning. Test it on a quiet, a restless and a critical volcano. Why combine several signals instead of using one?

View solution

QUICK REFERENCE

- **Assessment order:** magma chemistry, likely and worst credible size, hazard zones, exposed people, monitoring and warning time
- **Risk** is hazard times exposure: the biggest town is not always the most at risk
- **Plan for two scenarios:** a likely one and a worst credible one
- **Lahars** leave minutes of warning, so evacuate on the alert level
- **Alert levels** combine seismic, ground and gas signals, and remain judgements
- **Every model here is simplified:** real maps use terrain and wind, real thresholds come from data

COURSE COMPLETE

That is the end of the course. You can now follow a volcano from the heat inside the Earth, through the chemistry and the gas, to the eruption, the hazards, the monitoring and the climate. If you read a news

story about an eruption, try asking the five questions of this chapter: what magma, how big, who is exposed, what is being measured, and what would change the plan.