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Clive Oppenheimer
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Fire and brimstone: how volcanoes work

'Some volcanos are in a state of incessant eruption; some, on the contrary, remain for centuries in a condition of total outward inertness, and return again to the same state of apparent extinction after a single vivid eruption of short duration; while others exhibit an infinite variety of phases intermediate between the extreme of vivacity and sluggishness.'

G. P. Scrope, *Volcanos* (1862) [1]

The Earth is cooling down! This has nothing to do with contemporary global warming of the atmosphere and surface. I refer instead to the Earth's interior – the source of the molten rocks erupted by volcanoes throughout the planet's 4.567 billion year history. Aeons before the continents drifted to anything like their familiar positions, and as early as 3.34 billion years ago, parts of the Earth were already colonised by primitive bacterial life forms. At this time, volcanoes erupted lavas with a much higher content of an abundant green mineral called olivine than found in most modern volcanic rocks. This testifies to much higher eruption temperatures for the ancient lavas compared with present-day eruptions from Mt Etna or the Hawaiian volcanoes. In turn, it reveals that the Earth's largest internal shell, the olivine-rich mantle, which comprises about 84% of the Earth's volume, used to be considerably hotter, too (anywhere between 100 and 500 °C depending on whom you believe). While the Earth changes irreversibly through time, it also exhibits behavioural cycles acted out on vastly different timescales, such as the amalgamation and break-up of supercontinents; the clockwork advance and retreat of ice ages steered by oscillations in the Earth's axis of rotation and orbit around the Sun; the seasons; and the tides.

A glance at a global map of active volcanoes, earthquake epicentres and plate boundaries (Figure 1.1) provides compelling evidence

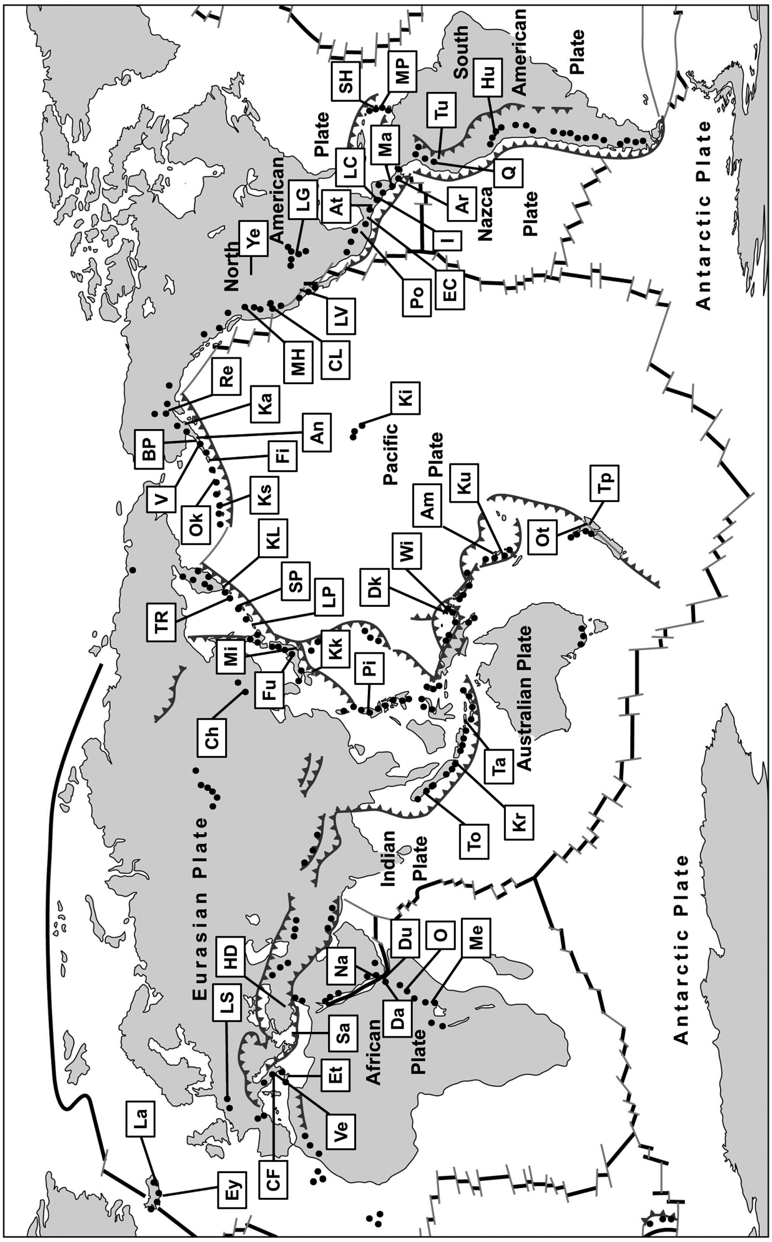
North American Plate
South American Plate
Nazca Plate
Pacific Plate
Eurasian Plate
Indian Plate
Australian Plate
African Plate
Antarctic Plate
Antarctic Plate
SH
MP
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Figure 1.1

for the coupling of tectonic and eruptive processes. Most volcanoes lie on the oceanic ridges formed as tectonic plates separate from each other. The volcanoes here exist in perpetual darkness except for their own magmatic glow. They erupt unobserved except by bizarre life forms that thrive on volcanic nutrients, and, just occasionally, by cameras on deep-diving research submarines. Nevertheless, collectively, they erupt far more lava than all the land volcanoes. This ocean-ridge volcanism also provides a particularly good example of how external pressure can influence the characteristics of eruptions. The overlying 2.5 kilometres of water exerts a crushing pressure 250 times the air pressure at sea level. This inhibits anything like the kind of explosive volcanism observed at the Earth's surface.

As newly formed oceanic plate trundles away from the volcanically active ridge, it cools and increases in density. Around much of the Pacific, the plate sinks back into the Earth's interior at a 'subduction zone', associated with some of the most dangerous volcanoes of the 'Ring of Fire'. Yet other volcanoes are located in the middle of nowhere, far from any plate boundaries. Hawai`i, right in the centre of the Pacific plate is, perhaps, the best known example but there are other 'hotspot' volcanoes both in the oceans and on the continents. Finally, volcanoes also congregate along the axis and flanks of great tears in the continents like the East African Rift Valley. To understand these various occurrences we need first to plumb the depths of the Earth to consider

Caption for Figure 1.1 Map summarising tectonic plates, bounded by spreading ridges (black segments), transform faults (light grey lines) and subduction zones (toothed lines), and distribution of volcanoes (dots). For clarity's sake, only a few the 1300 or so volcanoes known to have erupted in the last 11,500 years are shown but most of those discussed in the text are labelled as follows: Am (Ambrym), An (Aniakchak), Ar (Arenal), At (Atitlán), BP (Black Peak), CF (Campi Flegrei), Ch (Changbaishan), CL (Crater Lake / Mazama), Da (Dabbahu), Dk (Dakataua), Du (Dubbi), EC (El Chichón), Et (Etna), Ey (Eyjafjallajökull), Fi (Fisher Caldera), Fu (Fuji), HD (Hasan Dağı), Hu (Huaynaputina), I (Ilopango), Ka (Katmai), Ki (Kīlauea), Kk (Kikai), KL (Kurile Lake), Kr (Krakatau), Ks (Kasatochi), Ku (Kuwae), La (Laki), LC (Loma Caldera), LG (La Garita), LP (Lvinaya Past), LS (Laacher See), LV (Long Valley Caldera), Ma (Masaya), Me (Menengai), MH (Mt St Helens), Mi (Miyake-jima), MP (Mont Pelée), Na (Nabro), O (O'a), Ok (Okmok), Ot (Okataina), Pi (Pinatubo), Po (Popocatépetl), Q (Quilotoa), Re (Redoubt), Sa (Santorini), SH (Soufrière Hills volcano), SP (Sarychev Peak), Ta (Tambora), To (Toba), Tp (Taupo), TR (Tao-Rusyr Caldera), Tu (Tungurahua), V (Veniaminof), Ve (Vesuvius), Wi (Witori), Ye (Yellowstone).

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where all this lava comes from in the first place. Before proceeding, let us agree on one element of the often intimidating nomenclature of igneous petrology: magma is molten rock below the surface; lava is what comes out of a volcano.

1.1 ORIGINS OF VOLCANOES: THE MANTLE

Virtually all volcanism on Earth begins in the 'mantle', the largest of the shells that constitute the planet (Figure 1.2). It lies between the

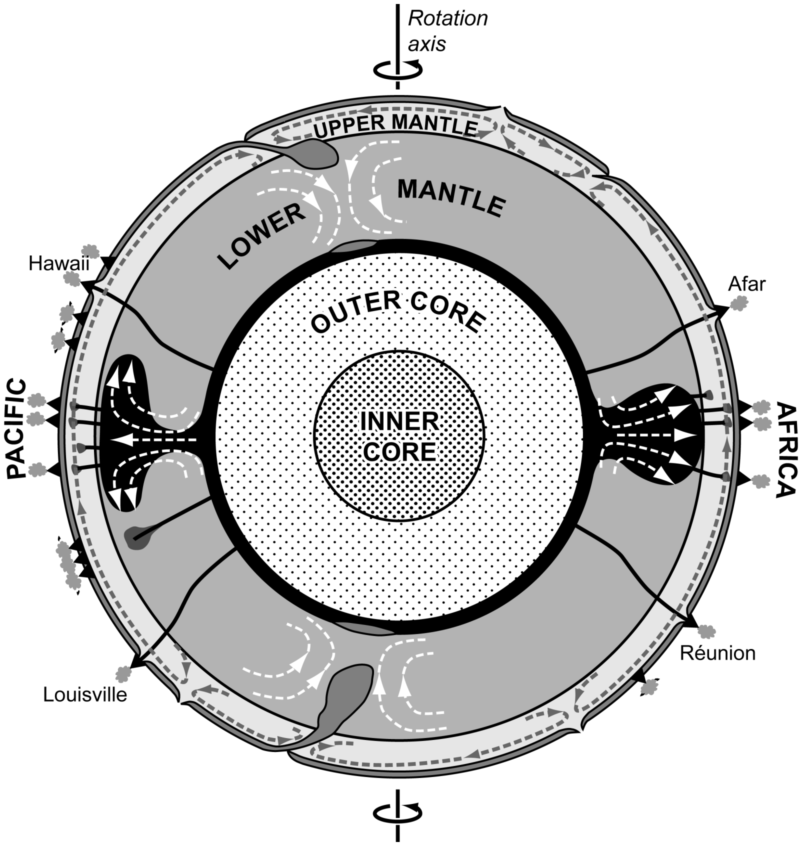

Figure 1.2 The Earth cut through its centre, illustrating 'primary' upwelling plumes thought to originate in the lowermost part of the mantle. Also shown are the plume tails beneath Hawai`i and Louisville (part of a seamount chain in the Pacific Ocean), Afar (northeast Africa) and Réunion (Indian Ocean), and subduction zones where the Earth's tectonic plates are recycled in the mantle. Modified from reference 2 with permission from Elsevier.

silica-rich crust (on which we live), and the dense, iron-rich core. The mantle is composed largely of a rock called peridotite which, in turn, is comprised of a number of crystalline minerals. Along with olivine are other silicate minerals including two kinds of pyroxene, garnet and plagioclase feldspar, and small quantities of metal oxides. A handful of elements – oxygen, silicon, magnesium, iron, aluminium and calcium – compose over 99% of the mass of peridotite. Although the mantle is solid – and we can be certain of this because it transmits certain kinds of earthquake waves that could not pass through a liquid – it is hot enough that it can flow by a slow process, called creep, in which crystals slip past each other, and atoms and ions diffuse from one place to another. (Ice is a more familiar example of a solid that can flow when it is thick enough, as attested to by glaciers and ice sheets.)

A combination of heat and gravity causes the mantle to flow. The Earth is hot inside – this is obviously the case since the lavas pouring out of volcanoes can reach temperatures well over 1100 °C; anyone who has approached within a few metres of a lava flow will be familiar with their searing radiance. Less prosaic is the question of where the heat comes from. Some of it, amazingly, dates back to the formation and infancy of the Earth. This primordial heat came from several sources including the kinetic energy of meteorite hails, chemical reactions, and the decay of some very ephemeral but fiercely radioactive elements. In addition, crystallisation of the Earth's core and radioactive decay of lingering isotopes of uranium, potassium and thorium continue to release heat into the Earth's interior.

Meanwhile, deep space is exceptionally cold. In fact, the electromagnetic radiation filling the cosmos indicates a background temperature of –270.43 °C (close to the absolute limit of –273.15 °C). The Earth is thus way out of thermal equilibrium with space, and consequently loses heat to it. Although the large size of the Earth renders this a slow process, hence the longevity of the primordial heat, the heat is transferred by convection out of the Earth to its surface. Like a pot of soup on the stove, the mantle is heated from the core beneath it while being cooled from above by heat radiation into space. Like most substances, the hotter the mantle, the lower its density; thus, under the action of gravity, hotter regions of mantle rise, while colder regions sink. This circulation of the solid mantle is essential to the melting that gives rise to magmas, and without it there would be no volcanoes on Earth.

If it still seems odd to think of the solid mantle flowing, there is a wonderful illustration of its fluid nature to be observed today in regions

Table 1.1 *Key properties of magmas and some comparative materials.*

Material	Silica content (% by mass)	Typical temperature (°C)	Viscosity (pascal seconds)
Water	–	20	$\sim 10^{-3}$
Ice	–	<0	$\sim 10^{12}$
Honey	–	20	~10
Peanut butter*	–	20	~200
The mantle**	~45	>1300	7×10^{18}
Basaltic magma	45–52	1100	10^2–10^3
Intermediate magma	52–63	1000	10^3–10^5
Silicic magma	>63	800	10^5–10^{10}

* Smooth not crunchy.
** The solid but convecting upper mantle known as the asthenosphere.

of Scandinavia, Siberia and North America that were covered in thick ice during the last ice age, which peaked 18,000 years ago. The weight of up to three kilometres thickness of ice was enough to push the Earth's crust down into the mantle, which then flowed away from the zones of greatest ice accumulation. It was the slow process of solid mantle creep that allowed this fluid behaviour. When the ice disappeared, the mantle crept back and the land surface started rising, and this continues today. By dating past shorelines using radiocarbon techniques (Section 4.1.3) it is possible to determine the pace of uplift, which continues at peak rates of around one centimetre per year). This rate of 'glacial rebound' yields an estimate of the mantle's viscosity (a measure of how well a material will flow when a force is applied to it; Table 1.1). It is 35 quadrillion times stickier than peanut butter!

Volcanoes exist because the mantle melts. But what causes melting? Two key processes are involved: one occurring at oceanic ridges and hotspots, the other at subduction zones. Interestingly, neither process is associated with heating. The first is the depressurisation that occurs as mantle convection currents rise to within 300 kilometres or so of the surface. Before exploring 'decompression melting' further, we need to recall that peridotite, like many rocks, is composed of several minerals. The different minerals have different melting temperatures; in fact, individual minerals themselves display a range of melting point according to their chemistry – olivine, for example, comes in a compositional spectrum between iron-rich and magnesium-rich varieties, which melt at different temperatures. Melting points are not only sensitive to chemical composition, they are also strongly dependent on pressure. With falling pressure, melting point drops.

As hot, solid mantle rises up in a convection current, and decompresses due to the reduced weight of rock above it, it can begin to melt. Crucially, the ascending mantle current is not so hot that all of it melts by this process. Instead, it is just those mineral constituents with the lowest melting points that melt; the high-melting-point minerals remain solid. Typically, somewhere between 1 and 20% of the peridotite melts, and hence the process is known as 'partial melting'. It is extremely important in the Earth since, over the course of geological time, it has changed the mantle's composition (by preferentially extracting certain magma-loving elements), and led to the growth of the crust and continents. The minerals pyroxene and plagioclase feldspar have lower melting temperatures than olivine, so a typical decompression event yields a liquid whose content best approximates a mixture of pyroxene, plagioclase feldspar and a little olivine. This melt is typically referred to as 'basaltic' and contains around 45% silica (SiO_2) by mass. The great pressure squeezes the basalt 'melt' from the crystals remaining in the mantle, a process a bit like depressing the plunger in some coffee makers. The melt percolates upwards forming pools of magma, which continue to rise owing to their lower density than their surrounds. Basalt contains all the ingredients needed to generate new oceanic crust at mid-ocean ridges.

Decompression melting is also responsible for the hotspot volcanoes, which are distinguished from oceanic ridges by their association with localised and especially hot upwelling zones known as mantle plumes [2] (Figure 1.2; Chapter 6). Their higher temperature sometimes results in a larger degree of partial melting. Volcanoes appear where mantle plumes blowtorch through the plates – this is how the Hawaiian Islands and the trail of seamounts to their north formed over the last 70 million years. Mantle plumes today account for something like 5–10% of the heat and magma extracted from the Earth's mantle. When mantle plumes impinge on continents they can initiate the kind of rifting for which East Africa is justly famous (Section 7.1). If sustained, the stretching of the continent can end up with the formation of a new ocean basin. One spectacular location where this occurs today is in the Danakil Depression of Ethiopia (Figure 1.3). Iceland is also generally considered to be the result of

Figure 1.3 Aerial photograph of the Da'Ure eruption site in Ethiopia close to Dabbahu volcano. This must rank as one of the world's smallest explosive eruptions! It was triggered by the passage of a 60-kilometre-long dike of basaltic magma, which destabilised a silicic magma body relatively close to the surface. This view shows part of the fissure, a small lava dome, and the blanket of fine ash produced by the explosive activity.

hotspot volcanism, and mantle plumes have been responsible for the greatest outpourings of lava known in the geological record, sometimes called 'large igneous provinces' (Section 6.2).

The creation of new oceanic crust at ridges and its consumption at subduction zones represents the Earth's main means of cooling its infernal depths (hotspot volcanoes also contribute). The total length of ridges worldwide is around 50,000 kilometres. Taking an average spreading rate of five centimetres per year (comparable to the growth rate of human hair and fingernails) indicates that around 2.5 square kilometres of new ocean floor are born every year.

While the association between volcanism and rising currents of hot mantle seems logical, the reason why volcanoes develop at subduction zones, where old, cold oceanic plate plummets back into the mantle, is less intuitive. The answer is the second key process that causes the mantle to melt: hydration. To understand this, we need to begin at the oceanic rift. One of the most remarkable features of active oceanic ridges are the chimneys, known as black smokers, which belch hot fluids charged with minerals rich in sulphur. This brew of chemical nutrients feeds bacteria that, in turn, nourish an entire ecosystem of bizarre creatures thriving in the stygian waters. The discharges result from the percolation and circulation of seawater deep into the brand-new oceanic crust. The seawater reacts with the hot volcanic rocks, extracting sulphur but at the same time hydrating minerals such as olivine. The crystals end up accommodating a quantity of water molecules. The result is to transform basalt into a slippery green rock called serpentinite. As the oceanic plate trundles sideways from the volcanic ridge on its journey to a subduction zone, it carries this incarcerated seawater with it. Meanwhile, the seabed also accumulates water-rich clays and other waterlogged sediments. Much of this water is ultimately drawn down into the subduction zone.

The sinking oceanic plate carrying its complement of seawater experiences ever greater pressures the deeper it penetrates the Earth's interior. Once it reaches a depth of around 100 kilometres, the clay minerals, along with the olivine and pyroxene crystals that had trapped seawater when the crust was created at the ridge, now find themselves under phenomenal pressure, and their regular frameworks can no longer contain the water. It is expelled, along with seawater trapped in pores between minerals, and the resulting fluid percolates into the overlying mantle.

The addition of water to the mantle dramatically depresses its melting point, causing partial melting. If this seems unusual consider an analogous process. In parts of the world that experience cold winters, the authorities grit icy roads with salt. This addition lowers the freezing point of water by a few degrees, which is enough to turn ice into water, so long as it is not too cold (it is even possible to use this principle to make ice cream). In the case of a subduction zone, the melts and water-rich fluids that are produced migrate upwards. Unlike oceanic ridges, subduction zones may source magmas that rise into thick overlying continental crust (as in the Andes). This typically provides much greater opportunity for chemical and physical evolution of the initial magma composition than is the case for oceanic volcanoes, and results in an amazing variety of magma types and volcanic activity.

1.2 MAGMA

Magma is a fascinating and remarkably complex substance. It represents the building material of volcanoes. The challenges of

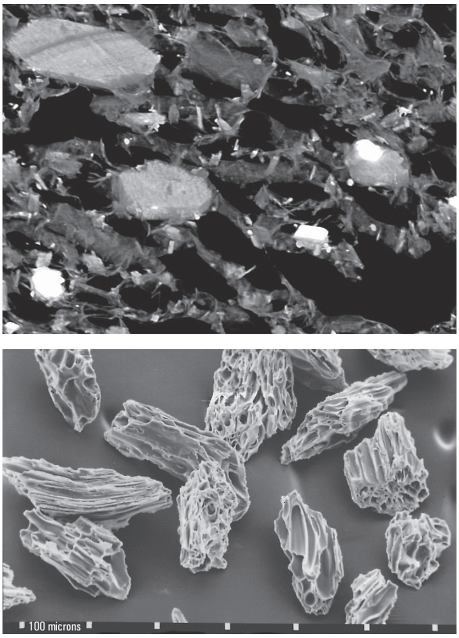

Figure 1.4 Images of ash and pumice: (top) an X-ray image of a sample of pumice (just half a millimetre across) that was erupted by Soufrière Hills volcano on Montserrat in 1997. The larger crystals within the lozenge-shaped sample are of the mineral amphibole and the minute, needle-like crystals are plagioclase feldspar. The black regions are bubbles; the remainder is glass (melt cooled too rapidly to crystallise). Image courtesy of Alain Burgisser. (Bottom) Scanning electron microscope image (0.6 millimetres across) of ash from a very large eruption 600,000 years ago of Brokeoff volcano, California. Note the shapes of gas-bubble holes (vesicles) – some have been stretched out into tubes by the explosivity of the eruption. Credit: A. M. Sarna-Wojcicki, US Geological Survey.

understanding its properties stem partly from the extraordinarily complex physical behaviour of molten rock with changing temperature, and the additional complications that arise from its constitution by all three phases of matter: solid, liquid and gas (Figure 1.4). The solid component is in the form of crystals of one or more minerals (such as olivine, feldspar, pyroxene and quartz). These are generally suspended in a silicate melt, which is dominated by loose arrangements of silicon and oxygen atoms and a brew of other elements including aluminium, sodium, potassium, calcium, magnesium and iron. In addition, the melt contains ‘volatile’ components, such as water, carbon dioxide, sulphur, and lesser amounts of halogens (chlorine, fluorine, bromine