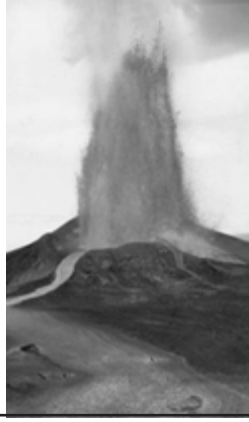
FUNDAMENTALS OF PHYSICAL VOLCANOLOGY

Fundamentals of Physical Volcanology



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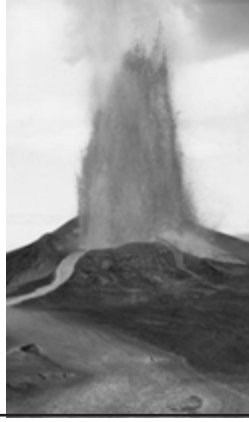

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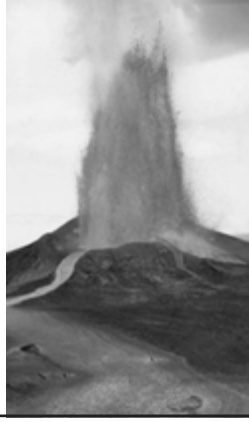
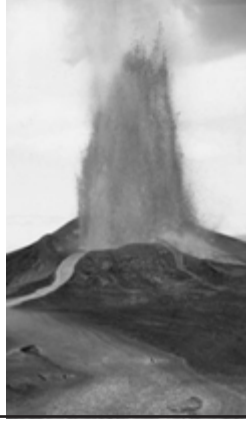
Preface



Our knowledge of the physics of how volcanoes work has expanded enormously over the past 40 years, as have our methods of studying volcanic processes. In the late 1960s, George Walker conducted experiments into the fall-out of volcanic particles from eruption clouds by using stopwatches to time the fall of pieces of tephra dropped down a stairwell at Imperial College, London. Now, technology exists which uses RADAR interferometry from satellites to monitor tiny changes in the shape of volcanoes, and broadband seismometers can detect the "heartbeat" (and "indigestion") of volcanoes as magma moves around deep inside them. Sometimes, however, as we gain increasingly in-depth knowledge of a subject, it becomes all too easy to focus on the minute details and hard to see the fundamental principles underlying all the complex behaviours that we observe. In this book we have attempted to step back from the details, and to view volcanoes as systems governed by some basic physical principles. Our approach is to consider the physical processes that control the formation, movement and eruption of magma, starting in the source region and following the magma upwards. Our intention is to show that, for all the apparent complexity of volcanoes, a little basic physics can go a long way in explaining how they work, and that often eruptions that may at first sight look remarkably different from one another are, in fact, physically much the same.

Acknowledgments



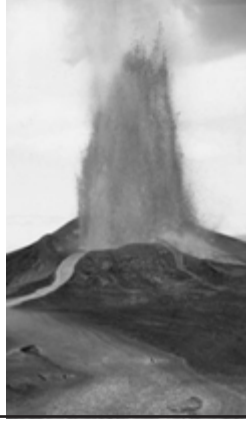
EAP: This book developed out of an undergraduate course that I taught for a number of years at the University of Leeds. That course benefited from and evolved due to the feedback of the students who took it, and I thank them all for their enthusiasm. A number of colleagues at Leeds – Joe Cann, Sue Bowler, Jane Francis, Mike Leeder and Pete Baker – offered their time and thoughts to that course and I thank them very much for their input and support. My knowledge of Strombolian activity was greatly improved by a trip to Stromboli with staff and students at Leeds, and I thank Jurgen Neuberg, Graham Stuart and Roger Clark for taking me along with them. Much of the writing of the book took place while I was working at the State University of New York at Buffalo, and I thank Marcus Bursik, Tracy Gregg and Mike Sheridan for discussions and ideas shared during that time. Nigel Burrows offered invaluable help converting my many old slides to digital format. This book would never have been finished without the treatment I received from the Chronic Fatigue Syndrome Service at Ysbyty Eryri, Caernarfon: a huge thank you to Dr Helen Lyon Jones, Marian Townsend, Anne the nutritionist and Dr Paul Nickson for their dedication and encouragement. Many thanks to my mother for the constant nagging to get this book finished, and for the belief that it could be done. To my son, James, a big thank you for putting up with my hours at the computer. Most of all to David, who always reminded me of the importance of punctuation and who enthusiastically applied red ink to the many drafts of this book, my innumerable thanks for providing the support, emotional and financial, needed to make the completion of this book possible.

LW: When my co-author suggested that we collaborate on this book I was very happy to agree, as I have devoted most of my time since 1968 to understanding the physics of volcanic processes. During that year, while I was working on a pre-Apollo study of the mechanical structure of the surface of the Moon, we began to get spacecraft images showing very long lava flows in the lunar *mare* areas, and in an effort to learn more about lava eruptions I visited the eminent British volcanologist George Walker, then at Imperial College London, to ask what was known about the physics of eruptions. George patiently, and with some amusement, explained to me just how little was known about this subject at that time, and by the end of my visit my career path was decided. My interest in the Moon remained, and broadened as spacecraft visited other solar system objects. Indeed, the study of how planetary environments control the boundary conditions (e.g., acceleration due to gravity, atmospheric pressure) under which volcanoes operate has been a major source of ideas. An equally important source of inspiration for me has been my interaction with the more than 30 graduate students who have worked with me on volcanic topics over the last 35 years. I must also thank my immediate colleagues at Lancaster, Harry Pinkerton, Steve Lane, Jennie Gilbert and Ray MacDonald, for their unfailing willingness to enlighten a mere physicist on the finer points of geology and geochemistry, and I am indebted to the numerous other scientists with

whom collaboration has been so stimulating over the years, especially Stephen Sparks, James Head, Peter Mouginis-Mark and, of course, my co-author Elisabeth Parfitt. Thanks for logistic help in locating and manipulating images go to Peter Neivert at Brown University and Ian Edmondson at Lancaster University. Last, but very much not least, thanks to my wife Dorothy for her unfailing tolerance and support.

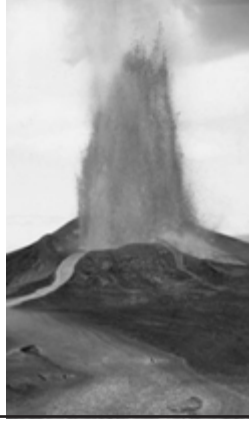
Both: We wish to thank John Guest, Michael Branney and Tracy Gregg for their helpful comments on parts of this book; as ever, errors and omissions remain our responsibility.

Dedication



In memory of George Walker, who was an inspiration to us both.

Glossary



'a'a A type of lava having a very rough surface texture.

absolute temperature The thermodynamic temperature of a substance, measured on a scale where zero corresponds to the molecules forming the substance having no motion. The unit of absolute temperature is the Kelvin (K); the Kelvin has the same size as the degree Celsius (°C) and 0K corresponds to –273.15°C.

accidentally breached An accidentally breached lava flow is one in which an overflow or breakout from the main channel occurs when the channel is blocked by material breaking off its walls.

accretionary lapilli Small (between 4 and 32 mm in diameter) rounded particles formed by the accretion of large numbers of smaller particles in a volcanic eruption plume. The small particles may be held together by water, ice, or electrostatic forces.

acidity spikes Localized high concentrations of sulfuric acid found at certain depths in ice cores drilled in polar regions. These correspond to the deposition of snow soon after volcanic eruptions which released large amounts of sulfate aerosols into the atmosphere.

active continental margin The edge of a continental land mass at which one of the plate-tectonic processes of subduction or faulting is taking place.

aerosols Small droplets of water in the atmosphere in which volatile species, especially sulfur dioxide, are dissolved.

air drag The force exerted on a particle moving through the atmosphere as a result of the friction between the surface of the particle and the air.

andesite A rock type of intermediate silica content, commonly associated with subduction zones.

arachnoids Tectonic structures up to many hundreds of kilometers in diameter, with complex central parts and radiating fracture systems, seen in the crust of Venus. The name suggests that they look like spiders.

ash cluster A collection of ash particles loosely held together by moisture, ice, or electrostatic forces.

ash pellet A collection of ash particles strongly held together by moisture, ice, or electrostatic forces.

basalt A rock type with a low silica content, commonly associated with ocean floor spreading.

basaltic andesite A rock type of low to intermediate silica content.

base surge A cloud of hot gas and entrained particles flowing out close to the ground from the site of a volcanic (or nuclear) explosion.

billion Used in this book in its American context to mean the number 10^9, i.e., one thousand million.

Bingham plastic A liquid that has not only a viscous resistance to deformation and flow, but also a finite strength that must be overcome by any applied force before any flow takes place.

block lava A type of viscous lava in which the surface fractures into large blocks.

block-and-ash flow deposit A mixture of coarse and fine pyroclasts. deposited from a pyroclastic density current.

bulk modulus The property of a material expressing the way the density changes with pressure.

buoyancy The phenomenon whereby a low-density body surrounded by a higher-density fluid in a gravitational field experiences an upward force.

caldera A steep-walled depression, commonly found at the summit of a volcano, formed when a large volume of magma is removed quickly from an underlying magma reservoir and the overlying rocks slide down along faults to fill the vacated space.

canali Long (many hundreds of kilometers), narrow (a few kilometers wide) channels seen on the surface of Venus.

carbonatite A rare type of magma consisting mainly of liquid carbonates rather than liquid silicates, produced in the mantle beneath some continental areas.

channelized lava flow A lava flow in which liquid lava moves in a central region bordered on either side by a bank (called a levée) of stationary lava.

choked flow The flow of a fluid under conditions such that the speed of the fluid is equal to the speed of sound within the fluid. This is the maximum speed that can be reached by the fluid unless special conditions apply.

coalescence The joining together of two separate gas bubbles within a liquid (or of two droplets of liquid in a gas).

cock's tail plume The distinctive "feather-edged" jet of ash and steam formed in an explosion when a large amount of water gains access to a vent.

co-ignimbrite ash fall deposit A fine-grained deposit of pyroclasts settling out on the ground from a co-ignimbrite cloud.

co-ignimbrite cloud An eruption cloud of gas and small pyroclasts formed as gas rising through an ignimbrite carries small particles upward with it as it escapes.

column collapse The condition in which an eruption column fails to be positively buoyant in the atmosphere, so that a lower fountain of gas and entrained particles forms over the vent instead.

compound lava flow field A region containing many lava flow units, most of which have formed by new flows breaking out from the margins of earlier-emplaced flows.

conservation of momentum The physical law that asserts that the momentum of a system (the product of mass and velocity) cannot be destroyed, only redistributed among the components of the system.

continental arc An arcuate chain of volcanoes at the margin of a continent.

convective region Part of the interior of a fluid or plastic solid within which convection (relative movement of different parts of the fluid due to density differences) is taking place.

convergent margin A location where the edges of two tectonic plates are being driven into collision.

cooling unit One or more layers of pyroclastic particles (or lava) emplaced so soon after one another that they cool as though they had been emplaced at the same time.

cooling-limited Description of a lava flow that ceases to move because the front of the flow has cooled to the point of effectively being a solid.

corona (plural: **coronae**) One of a number of large (many hundreds of kilometers) roughly circular regions on Venus where tectonic forces have fractured and folded the surface rocks.

cryovolcanism A volcanic process in which liquid water rather than liquid rock is the moving fluid.

dacite A type of magma with intermediate to high silica content.

dark halo deposit A roughly circular region on the Moon where dark pyroclasts are deposited around an explosive vent.

de Lavalle nozzle Part of a volcanic conduit or dike where the shape changes from converging upward to diverging upward, thus allowing magma flowing through the conduit to accelerate from subsonic to supersonic speeds.

decompression The expansion of a material, especially a gas, when the pressure acting on it decreases.

decompression melting The process whereby solid rock begins to melt when the pressure acting on it decreases even if the temperature does not change.

diapir A body of plastic material that rises buoyantly as a coherent mass within a larger body of plastic material.

diffusion The process whereby the atoms or molecules of a volatile compound migrate by moving between the atoms or molecules of a host material.

dike A fracture filled with volcanic material cutting through earlier-emplaced host rocks.

dilatant Description of a type of nonNewtonian fluid in which the viscosity increases as the applied stress increases.

divergent margin A boundary between two tectonic plates, almost always on the ocean floor, at which new crustal material is being supplied by volcanic eruptions or intrusions as the plates move apart.

dome A deposit of (commonly viscous) lava where the width and maximum thickness are of the same order because the lava has not spread far from the vent.

dusty gas A gas containing solid particles so small that frictional drag forces effectively force the particles to travel at the same speed as the gas.

ejecta Any material thrown out from a vent (rather than flowing away from it) during volcanic activity.

elastic Description of any material that changes its shape when a stress is applied to it but recovers its original shape when the stress is removed.

energy equation An equation describing the law that says that the total energy of a system cannot be destroyed, only redistributed among its parts.

entrainment The process whereby the flow of one material through or past another surrounding material causes some of the surrounding material to be mixed into the flowing material.

equivalent diameter A geometric property of a flowing fluid in a channel equal to four times the cross-sectional area at right angles to the direction of flow divided by the length of the perimeter in contact with the floor and walls.

exit velocity The speed at which volcanic materials emerge through a surface vent.

expansion wave A moving zone within a fluid across which the pressure decreases significantly.

explosive Description applied to any process that takes place suddenly, or that involves a very large pressure change.

exsolution level The depth at which gas dissolved in a rising magma first starts to come out of solution and form gas bubbles in response to the decreasing pressure.

exsolve Release a gas from solution in a liquid. The opposite of dissolve.

fiamme Pumice clasts in the interior of an ignimbrite deposit that have become stretched sideways while still hot as the deposit is compressed by the weight of overlying material.

filter-pressing The process whereby magma is squeezed out of its partly molten source rocks when stress causes compaction of the unmelted material.

fissure A fracture in rock, more particularly an elongate surface vent from which magma is erupted.

flood basalt eruption A rare kind of basaltic eruption in which a very large volume (thousands of cubic kilometers) of basalt is erupted in a geologically short space of time.

flow unit A lava flow which is the product of a single eruptive event from a single vent.

focus The location beneath the surface where an earthquake takes place.

fractional crystallization The formation of crystals in a cooling liquid. One or more types of crystal may form at any one time, but each forms over its own characteristic temperature range.

fragment A piece of material broken from a larger piece of material.

fragmentation The process of breaking a material into smaller pieces. The material may be a solid or a liquid.

fragmentation level The depth below the surface at which shearing stresses tear a magma containing gas bubbles apart into clots of liquid carried along by the gas released from the bubbles broken by the tearing process.

friction A force that opposes the motion of any two materials in contact and sliding past one another.

frost ring A layer inside the trunk of a tree, forming parallel to the bark and marking a time when the growth of the tree was inhibited by unusually cold weather.

fumaroles Places where volatile compounds being released from the interior of a volcanic

deposit reach the surface and settle to form deposits on the ground as they cool.

Gas Laws The laws describing the way the pressure, temperature, density, and internal energy of gases are related.

gas-thrust region The lowest part of an eruption column, where the inertia of the erupted materials, which has been determined by the expansion of volcanic gases beneath the surface, is the main control on their motion.

giant dike swarm A group of dikes radiating for great distances (at least many hundreds of kilometers) away from some region where a very large magma reservoir has existed at some time.

graben A trench-like depression formed in an area of extensional forces. The crust is forced apart and breaks along two parallel normal faults dipping toward one another, with the ground between the faults moving downward.

grading The variation of the average grain size of a deposit with vertical position within it. In normal grading the mean size increases downward, whereas in reverse (or inverse) grading it increases upward in the deposit.

granular flow The flow of a body of material consisting of discrete solid clasts in which only the interaction between clasts controls the motion – any gas or liquid between the clasts has no important effects.

Hawaiian Description applied to eruptions like those common in Hawai'I, where basaltic lava is erupted, commonly explosively.

heat pipes Regions where heat is transported upward through the crust mainly by the frequent passage of magma through the surrounding rocks.

heterogeneous nucleation The process of the formation of gas bubbles in a liquid supersaturated in a dissolved volatile compound when the bubbles nucleate on crystals in the liquid or irregularities in the boundary between the liquid and its solid surroundings.

hindered settling The settling of solid particles in a fluid where the particles are so close together that they either collide with one another or interfere with the smooth flow of the fluid around them.

homogeneous nucleation The process of the formation of gas bubbles in a liquid supersaturated in a dissolved volatile compound when the bubbles have no solid surfaces on which to nucleate and so appear at random within the liquid.

hot spot Place where there is an unusually large upward flow of heat from the mantle toward the surface. Generally a location of significant volcanic activity.

hyaloclastite A type of fragmental and chemically altered rock produced when erupting lava interacts strongly, generally explosively, with surface water.

hyaloclastite ridge A ridge composed of fragmental and chemically altered rock produced when a fissure eruption occurs in shallow water, most commonly beneath a glacier.

hydromagmatic Description of any eruption process in which magma or lava interacts with external water.

hydrothermal Description of any process involving the circulation of water at shallow depths in the crust as a result of heat supplied by intruded magma.

ignimbrite A large body of rock formed from the deposition of pyroclasts that have traveled from a vent as a pyroclastic density current.

ignimbrite-forming A type of explosive eruption that produces large volumes of pyroclasts emplaced as pyroclastic density currents.

inertial region An alternative description (see "gas-thrust region") of the lowest part of an eruption column where the inertia of the erupted material dominates the motion.

inflation The word has two uses in volcanology: (i) the enlargement of a magma chamber as new magma is added to it from the mantle; (ii) the process whereby a lava flow gets thicker after it has been emplaced as a result of additional magma being forced into its interior.

intraplate Any process that occurs within, i.e., well away from the boundaries of, a tectonic plate.

inversely graded Description of a deposit of pyroclasts in which the average grain size increases upward in the deposit.

island arc An arcuate group of volcanic islands formed above a subduction zone at the edge of a tectonic plate.

isopach A contour line on the map of a volcanic deposit joining places where the thickness of the deposit is the same.

isopleth A contour line on the map of a volcanic deposit joining places where the grain size of the deposit is the same.

jökulhlaup The Icelandic word for a "glacier-burst," the sudden release of a very large volume of water that has accumulated under a glacier as a result of melting caused by an eruption there.

juvenile In volcanology, the word implies material that has come directly from the deep interior of the planet.

kimberlite A rare type of mafic rock resulting from the eruption or intrusion of magma coming from unusually great depth in the mantle. Economically important because some kimberlites bring with them diamonds from the mantle.

kinetic energy The type of energy associated with the movement of material.

komatiite A type of ultramafic magma forming low-viscosity lava flows, common in early Earth history.

laccolith An intrusion of magma that has a relatively large vertical extent compared with its horizontal width.

Large Igneous Province A region where large volumes of basaltic lava have been erupted – essentially a more general term for a region in which a flood-basalt eruption has happened.

lava breakout A place where lava breaks out from the edge of an existing lava flow deposit.

lava dome A relatively thick and short lava flow deposit.

lava flow An individual deposit of a discrete phase of an effusive eruption.

lava flow field A group of lava flow deposits emplaced in successive phases of a prolonged eruption.

lava fountain A jet of hot pyroclasts ejected from an explosive volcanic vent, rising to a significant height, and then falling back to the surface. Also called a fire fountain.

lava tube The interior of a lava flow where the surface layers of the flow have ceased to move and thus form an insulating roof reducing heat loss from lava still flowing beneath.

levée The stationary edge of a lava flow.

level of neutral buoyancy See "neutral buoyancy level."

linear rille A type of graben found on the Moon.

liquidus The temperature at which a magma is completely molten.

lithic clast A fragment of rock broken from the rocks through which a volcanic event has taken place and incorporated into the erupted volcanic materials.

lithosphere The outer part of a planet where the rocks behave as brittle solids, consisting of the crust and the upper part of the mantle.

lithostatic load The pressure at a given depth below the surface due to the weight of the overlying layers of rock.

littoral cone A cone-shaped accumulation of pyroclasts on land close to the ocean, built up by explosions when lava enters the water.

maar A crater formed by an explosive interaction between magma approaching the surface and surface or near-surface water.

magma Molten or partly molten rock beneath the surface of a planet.

magma ocean A layer of molten rock on the surface of a planet, formed when the outer layers of the planet accumulate so fast that heat from the impact of each added asteroid cannot be radiated away completely before the next impact happens.

magma reservoir A long-lived body of magma beneath the surface that forms when new magma from the mantle is added faster than the existing magma body can cool.

magmon A localized concentration of magma in the pore space of host rocks. The rocks deform to allow the magma concentration to pass through, so that it moves like a wave through the host rocks.

mantle plume A part of the mantle where buoyancy causes the mantle rocks to rise toward the surface. Commonly the site of pressure-release melting.

maria (singular: **mare**) The latin name for the dark areas on the Moon, consisting of floods of basaltic lava filling very large impact craters.

mass extinction A biological event in which large numbers of species die out in a geologically relatively short space of time.

mass flux The mass of magma passing though a volcanic system every second.

meteoric Generally, description of any phenomenon associated with the atmosphere. In volcanology, applied to near-surface water that has collected as a result of rain or snow.

mid-ocean ridge The ridge formed along a constructive tectonic plate margin by the accumulation of lavas erupted onto the ocean floor.

mush column A zone within the crust where magma passes through so often that the host rocks are partly molten.

negatively buoyant Description of material that is denser than the material surrounding it, so that it will tend to sink through its surroundings.

neutral buoyancy level Any location above or below ground where volcanic materials have the same density as their surroundings.

Newtonian Description of a fluid with the property that any change in applied stress produces a directly proportional change in rate of deformation.

nonNewtonian Description of a fluid in which the rate of deformation is not directly proportional to a change in the applied stress.

normally graded Description of a pyroclastic deposit in which the grain size increases downward in the deposit.

nova (plural: **novae**) A type of tectonic structure on Venus in which fractures radiate out from a central zone.

nuclear winter A prolonged period of cooling when heat reaching the surface from the Sun is greatly reduced by dust in the atmosphere thrown up from the explosion of a large number of nuclear weapons.

nuée ardente French for "burning cloud," one of the possible names for a pyroclastic surge.

ophiolite A body of rock consisting of the subsurface part of an old spreading center now uplifted and exposed at the Earth's surface by tectonic forces.

p waves Primary waves, compressive waves spreading out from an earthquake focus into the surrounding rocks. These waves travel faster than any other type of seismic waves.

pahoehoe A type of lava where the surface is smoothly folded into a series of ripples called ropes.

pahoehoe toe A small lava flow unit consisting entirely of pahoehoe lava extending for a short distance from a larger flow unit.

partial melting The process in which part of a mass of rock melts, the liquid still containing the mineral grains that have not yet melted.

perched lava pond A lava flow that has spread out sideways so that it has a similar width to its length. The shape is sometimes controlled by pre-existing topography but can be self-generated by a suitable combination of eruption rate and very shallow ground slope.

peridotite A type of rock rich in olivine, found in the Earth's mantle.

petrology The general term for the study of all aspects of rocks.

phoenix cloud Alternative term for a co-ignimbrite cloud.

phreatomagmatic Description of an eruption involving interaction between magma and surface, near-surface or ground water.

phreato-Plinian Description of a sustained explosive eruption in which magma interacts with surface or ground water, generally resulting in more fragmentation of the magma than in a Plinian eruption.

pillow A lava flow lobe that is approximately as wide as it is thick, produced by a low lava extrusion rate under water.

pillow lava A lava flow consisting of a pile of pillows.

plastic Description of a fluid that is capable of deforming smoothly in response to an applied stress.

plastic viscosity The property of a non-Newtonian fluid expressing the ratio between a change in applied stress and a corresponding change in rate of deformation.

plate One of a series of sections of the Earth's lithosphere behaving as a rigid solid.

plate tectonics The term applied to our current understanding of the structure of the Earth's

lithosphere, with rigid plates sliding as discrete structures on top of the plastic mantle and interacting at their edges.

Plinian Description of a sustained explosive discharge of volcanic gas and pyroclasts forming a large eruption cloud in the atmosphere.

Poisson's ratio An elastic property of a solid, specifically the ratio of transverse to longitudinal strain (i.e., fractional deformation) when a tensional force is applied.

potential energy Generally, a form of energy associated with the position of an object in a force field. In volcanology this is the planetary gravitational field.

pressure-balanced Description of a volcanic fluid emerging from a vent in such a way that the pressure within the fluid is equal to the atmospheric pressure at the level of the vent.

pressure-release melting An alternative term for decompression melting.

pumice A piece of volcanic rock containing vesicles.

pyroclastic density current A mixture of gas and suspended or entrained solids released in a sustained explosive eruption and forming a dense fluid that moves along the ground at high speed.

pyroclast General term for any fragment of volcanic material produced in an explosive eruption.

pyroclastic fountain A mixture of gas and pyroclasts erupted explosively though a vent, traveling upward, and then falling back to the surface.

pyroclastic surge A relatively short-lived form of pyroclastic density current.

regolith A fragmental layer on the surface of a planet. If a biological component is present, as on Earth, the regolith is called soil.

residence time The time that particles or aerosols spend in the atmosphere before settling to the ground. More generally the time taken for any particles suspended in a fluid to settle out.

rheology The study of the way fluids deform in response to applied stresses.

rhyolite A rock type with a high silica content.

Ring of Fire The regions around the rim of the Pacific Ocean dominated by volcanic activity.

rootless lava flow A lava flow formed by the accumulation and coalescence of hot pyroclasts falling from a lava fountain.

rootless vent The site of a volcanic explosion that is not directly underlain by a volcanic vent, for example a place where an explosion occurs in a lava flow advancing over waterlogged ground.

s waves Secondary waves, shear waves spreading out from an earthquake focus into the surrounding rocks. These waves can propagate in solids but not in liquids.

saltate To bounce over the ground, as when particles are almost suspended in a strong wind.

saturated Description of a fluid containing the maximum amount of volatiles allowed by the current pressure and temperature.

sedimentation The settling of particles from a fluid to form a layer at the base of the fluid.

seismic gap A subsurface region within which no sources of seismic waves occur because the region is occupied by magma.

seismic velocity The speed of a seismic wave, a sound wave in rock generated by an earthquake.

shear modulus The elastic property of a solid expressing the fractional amount by which it deforms in response to a shearing stress.

sheet flow A lava flow that is very wide compared with its thickness.

sill A sheet-like body of magma, often approximately horizontal, intruded at some depth below the surface along the interface between two preexisting rock layers.

sinuous rille A meandering type of channel found on the Moon and Mars where hot turbulent lava has eroded the surface over which it has flowed.

slug A body of gas rising through a volcanic dike or conduit where the vertical extent of the gas is much greater than the width of the dike or conduit.

solidus The temperature below which a magma is completely solid.

soliton A solitary wave, i.e., a wave that travels without changing its size or shape.

solubility law The law specifying how much of a given volatile compound can be dissolved in a magma at a given pressure and temperature.

spatter rampart A ridge parallel to a fissure vent consisting of pyroclasts ejected from the fissure.

spreading center A boundary between two tectonic plates at which new crust is being created by volcanic eruptions and intrusions and the plates are moving apart.

stoping The process whereby blocks of country rock become detached from the roof or walls of a magma reservoir and fall into the magma.

strain rate The rate at which a solid or liquid changes its length, expressed as a fraction of its original length, as a result of an applied stress.

stratosphere The second layer of the Earth's atmosphere, lying above the troposphere.

Strombolian A style of explosive volcanic activity characterized by the intermittent arrival, at the surface of the magma in a vent, of giant gas bubbles that burst, throwing out the disrupted liquid skin of the bubble.

subaerial Description of any process taking place in an atmosphere.

subduction The process whereby some tectonic plates are forced down into the Earth's interior beneath other plates.

subPlinian Description of a class of sustained explosive volcanic activity producing relatively small eruption plumes in the atmosphere.

supersaturated Description of a fluid containing more of a dissolved volatile compound than it should be capable of dissolving under its current pressure and temperature conditions. This is an unstable state leading to bubble formation by exsolving gas.

surface tension A molecular attraction force acting parallel to any interface between two fluids and tending to reduce the area of contact.

tensile strength The strength of a material when subject to a tensional force.

tephra General term for relatively fine grained fragmented volcanic rock.

tephra jet Alternative name for a cock's tail plume.

terminal velocity The steady speed reached by an object falling through a fluid in a gravitational field when the upward drag force exerted on it by the fluid is just equal to the downward gravitational force.

tessera (plural: **tesserae**) A type of terrain on Venus characterized by extensive faulting in more than one direction.

thixotropic Description of a type of non-Newtonian fluid in which the viscosity decreases as the applied stress increases.

tholeiitic Description of a common type of basalt, rich in the minerals plagioclase and pyroxene, formed at mid-ocean ridges.

toothpaste lava A type of lava with a very rough surface texture consisting of many sharp spines roughly arranged in rows.

tractional Description of a process that involves a frictional force from an overlying fluid dragging a particle sideways.

triple junction A tectonically complex region where the boundaries between three tectonic plates meet.

tropopause The boundary between the troposphere and the overlying stratosphere, lying at a latitude- and season-dependent height of ~10–15 km.

troposphere The lowest part of the Earth's atmosphere.

ultraPlinian An unusually energetic form of Plinian explosive eruption.

umbrella region The uppermost part of a volcanic eruption cloud where vertical motion ceases and gas and pyroclasts spread sideways in the atmosphere.

undersaturated Description of a fluid containing less of a dissolved volatile than it is capable of dissolving under its current pressure and temperature conditions.

vein A relatively small and narrow fracture in a rock containing material that is different from the host rock. Commonly used in volcanology to describe a small off-shoot from a dike.

vesicles The holes in volcanic rocks showing where gas bubbles were present as magma rose to the surface.

viscosity The property of a fluid describing its resistance to deforming and flowing when a stress is applied to it.

volatile Generally, the description of any chemical compound with a low boiling point. Used in volcanology to refer to the gases commonly dissolved in magma at depth in the planet.

Volcanic Explosivity Index A single number between 0 and 8 giving a combined measure of the magnitude and intensity of a volcanic eruption.

volcanic tremor Relatively long-lived and steady seismic activity associated with the flow of magma through a volcanic dike or conduit.

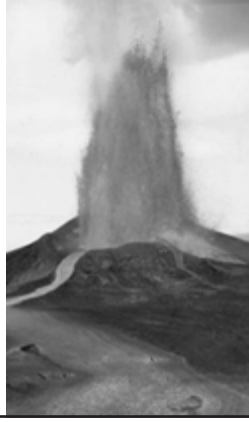
volume-limited Description of a lava flow that ceases to advance because the supply of magma from the vent has ceased.

welding The development of mechanical strength between hot pyroclasts in close contact causing them to stick together.

xenolith A fragment of rock accidentally incorporated into rising magma and brought up from the interior of the planet.

yield strength The stress level that must be exceeded before a non-Newtonian fluid will begin to deform and flow.

1 Volcanic systems



1.1 Introduction

A volcanic eruption is an amazing event to watch: dangerous and frightening but also fascinating and awe-inspiring. While most people will never experience an eruption first-hand, accounts of volcanic eruptions in the media, television documentaries and Hollywood films all mean that even those living far from an active volcano have some idea of what volcanic eruptions are like.

Volcanic eruptions vary tremendously in style and in the deposits they produce, from lava fountaining eruptions in Hawai'I (Fig. 1.1), through moderately explosive eruptions, such as the 1980 eruption of Mount St Helens (Fig. 1.2) which devastated the area immediately around the volcano and deposited ash as much as 1500 km downwind from the volcano, to huge explosive eruptions which have occurred in the geological past, such as the eruption 600,000 years ago at Yellowstone which covered half of the United States with ash. They vary in scale from tiny eruptions producing a few cubic meters of lava to eruptions which can produce up to ~2500 km^3 of ash or lava (enough to cover the whole of Great Britain with a layer more than 10 m thick, enough to bury all but the tallest buildings!). They vary in duration from a few seconds to years or decades. They vary tremendously in frequency – an observer at Stromboli volcano (in the Aeolian Islands, north of Sicily) usually has only to wait a matter of minutes to see an eruption, whereas an observer at Yellowstone National Park could wait 100,000 years or more to see a volcanic eruption!

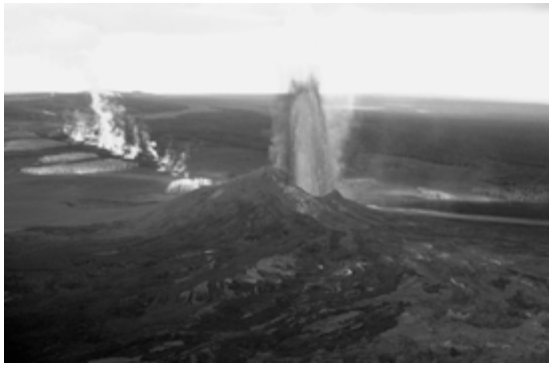


Fig. 1.1 An approximately 300 m high lava fountain eruption from the Pu'u 'O'o vent on the East Rift Zone of Kilauea volcano, Hawai'I. (Photograph by Pete Mouginis-Mark, University of Hawai'I.)

Why does a volcanic eruption occur where it does and when it does, and what controls what the eruption is like? Physical volcanology is the branch of geology which seeks to answer these questions by applying basic physical principles to find out how volcanoes work. The study of volcanoes in this way over the last 30 years or so has shown that, despite the apparent complexity of individual volcanic eruptions, the basic physical processes which govern them are often surprisingly simple, and furthermore the processes can be very similar in eruptions which superficially appear very different from each other. In this book we seek to describe these physical processes and to underline their similarities in eruptions which are apparently so different in character.

Fig. 1.2 Eruption cloud from the sustained phase of the May 18, 1980 eruption of Mount St Helens volcano, Washington State, USA. The lower part of the cloud is almost vertical but near the top the cloud and the small particles falling from it are being carried away downwind. (Photograph taken by Robert Krimmel, courtesy of U.S. Geological Survey/Cascades Volcano Observatory.)

1.2 Styles of volcanic eruptions

Direct observations of volcanic eruptions, recorded on film, in photographs, and in written eye-witness accounts, combined with geological observations of older volcanic deposits, show that the styles, scales, and products of volcanic eruptions vary tremendously from volcano to volcano. In this section we will look at these different styles of volcanic activity, but we will start by drawing a basic distinction between effusive and explosive eruptions.

Volcanic eruptions can be divided into two main classes: effusive and explosive. An **effusive** eruption is one in which molten rock called **magma**, rising from the deep interior of the Earth, flows out of a vent as a coherent liquid called **lava**. Both while they are still molten and after they cool, the bodies of rock formed on the surface in this way are called **lava flows**. An **explosive** eruption is one in which the magmatic material is torn apart as it is erupted into pieces called **pyroclasts**. These can range from hot clots of still-molten liquid to much cooler, irregularly shaped fragments of solid rock. Explosive activity happens when the magmatic liquid rising from great depth is torn apart by the expansion of gas bubbles formed by the release of volatile compounds dissolved in the liquid. The term effusive eruption is often used, incorrectly, to denote any eruption in which lava flows are produced. Hawaiian eruptions, in particular, are often referred to as effusive because they produce lava flows. However, in fact very many of these eruptions are explosive, and the lava flows they produce are formed indirectly, by coalescence of lava clots accumulating near the vent, rather than by the direct oozing of the magma from the vent.

We now present a broad overview of the range of styles of volcanic activity that occur on Earth. All but the first style – effusive – are explosive in character.

1.2.1 Effusive eruptions

An effusive eruption is an eruption in which lava flows away from a vent as a coherent liquid. For

Fig. 1.3 An approximately 160 m high, 400 m wide lava dome slowly growing in the vent of the May 18, 1980 eruption of Mount St Helens volcano, Washington State, USA. (Photograph taken on August 22, 1981 by Lyn Topinka, courtesy of U.S. Geological Survey/Cascades Volcano Observatory.)

Fig. 1.4 Part of a dense, sheet-like lava flow erupted on the ocean floor, where the high pressure suppresses gas release, minimizing explosive activity and the formation of gas bubbles in lavas. (Image courtesy of Monterey Bay Aquarium Research Institute, © 2001 MBARI.)

instance, after major explosive eruptions have finished their explosive phase it is common for viscous lava to ooze from the eruptive vent to form a lava dome (Fig. 1.3). In deep submarine eruptions, where the pressure of the overlying water is great enough to suppress the release of gas from the erupting magma, the dominant mode of eruption is effusion (Fig. 1.4). In other cases lava may effuse from a vent because the lava has previously lost the gas which was initially dissolved in it. This happens, for instance, at Stromboli, where repeated small explosions every few tens of minutes allow the escape of most of the gas from a substantial volume of magma stored at shallow depth. That magma is then erupted every few years as lava flows.

1.2.2 Hawaiian-style eruptions

The **Hawaiian** eruption style is named after the predominant style of activity observed at the currently active volcanoes of the Hawaiian Island chain. The term **Hawaiian** can be applied, though, to any eruption exhibiting this same style regardless of where in the world it occurs. Hawaiian eruptions are characterized by their lava fountains (Fig. 1.1). These are composed of hot, incandescent clots of magma (often up to 1–2 m in diameter) which are ejected from the vent at speeds of ~100 m s^{-1} and typically rise to heights of only a few tens to hundreds of meters above the vent before falling back to the ground. The majority of the clots of magma fall close to the vent and are still very hot upon landing (~1135°C), hot enough that the clots coalesce on the ground forming fluid lava flows which may travel several kilometers or even tens of kilometers from the vent (Fig. 1.5). Some of the clots and smaller clasts landing close to the vent are cooled enough during flight and after landing that they are too cool to form lava flows but instead weld together forming a spatter cone or spatter rampart around the vent (Fig. 1.6). A small amount of the erupted material is sufficiently fine grained

Fig. 1.5 Lava fountain forming lava flows at the Pu'u 'O'o vent on the East Rift Zone of Kilauea volcano, Hawai'I. Hot clots of magma falling within the cone have formed a lava pond that is overflowing from the lowest point on the rim of the cinder cone to form a lava flow. On the right side of the cone, clots are coalescing as they land to form a rootless lava flow. (Photograph taken on June 30, 1984 by J.D. Griggs, courtesy of Hawaiian Volcano Observatory.)

Fig. 1.6 Spatter ramparts along either side of a fissure vent on the East Rift Zone of Kilauea volcano, Hawai'I. Figure is standing at the location of the fissure itself. (Photograph by Lionel Wilson.)

that it is carried downwind from the vent forming a **tephra** blanket (Fig. 1.7). Hawaiian eruptions are sustained eruptions which can last for hours or days – in some cases for years. The magmas involved in Hawaiian eruptions are usually hot magmas called **basalts**. The combination of their chemical composition (especially the relatively low silica content) and high temperature gives these magmas a relatively

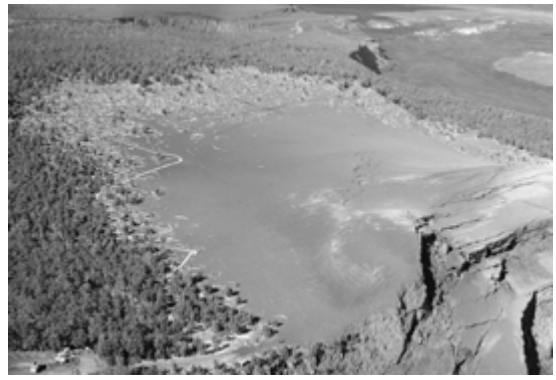


Fig. 1.7 Tephra blanket from the Pu'u Puai vent near the summit caldera of Kilauea volcano, Hawai'I. The blanket extends into the forest from the edge of the cinder cone at the bottom right of the image. (Photograph by Pete Mouginis-Mark, University of Hawai'I.)

low **viscosity**. Lavas erupted at Kilauea volcano in Hawai'I, for example, commonly emerge with temperatures of ~1140–1150°C and viscosities of 50–100 Pa s. Basaltic magmas come directly from zones of melting in the mantle with very little interaction with other rock types on their way to the surface.

1.2.3 Flood basalt eruptions

Another type of basaltic lava-forming eruption is the **flood basalt eruption**. Humans have yet to witness a flood basalt eruption because the most recent one occurred ~20 million years ago, but their deposits have been mapped out in many parts of the world (Fig. 1.8). These are eruptions which generate enormous volumes of basaltic lava. They occur in sequences, so that the volume of an entire flood basalt province can be as great as 10^6 km^3. Individual lava flows in such a province can be more than 600 km long and 100 m thick with volumes as great as 2000 km^3. There is considerable debate about the exact character of these eruptions but they appear to be similar to Hawaiian eruptions, though with individual events producing far larger volumes of lava and with the lava being erupted far more rapidly.

The closest equivalent to a flood basalt eruption yet observed by humans is the Laki or "Skaftár Fires"