VOLCANOLOGY: VOLCANIC ACTIVITIES, CHEMISTRY AND EFFECTS ON ENVIRONMENT

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Summary

Volcanic eruptions are one of the World's largest sources of hazards. This chapter reviews the main concepts of modern volcanological research, which is aimed at understanding how volcanoes work and how to mitigate the risk. The article starts by describing what volcanoes are, and how they are shaped by volcanic eruptions. The main mechanisms for magma formation and migration are then reviewed, following magma from the mantle up to the surface, where it erupts, with different behaviours depending on its chemical/physical properties, and its eventual contact with large quantities of water. The rise of magma towards the surface generates a series of phenomena, involving, for instance, seismicity and ground deformations. Observations of these phenomena are used to recognize pre-eruptive patterns and ultimately to forecast eruptions. The chapter continues by describing the main kinds of hazard associated with volcanic eruptions and the best techniques for forecasting them.

1. Introduction

Volcanology is a general term for the study of volcanoes. Actually, the science of volcanoes involves several different disciplines, namely stratigraphy, sedimentology, structural geology, mineralogy and petrology, geochemistry of rocks and fluids, seismology, geodesy, thermodynamics, tectonics, statistics etc. In addition, volcano-monitoring devices involve disciplines such as engineering, solid state physics, remote sensing, opto-electronics, gas-chromatography and spectroscopy, etc.

This means that volcanology is an intrinsically complex research field, based on several concepts coming from different disciplines, generally lacking simple physical descriptions and possibly involving non-deterministic processes. Volcanology is then, for many aspects, a pioneering science in a state of rapid evolution.

Basically, volcanoes behave like thermal machines, converting thermal energy into mechanical work (eruptions). The higher the efficiency of thermal energy-work conversion, the higher the explosivity of the volcano—a parameter which is closely related to the hazard. The complete spectrum of volcanic eruptions ranges from the very low efficiency of effusive eruptions from mid-ocean ridges and Hawaiian shields to the very high explosivity of Plinian and Phreato-magmatic eruptions, passing through intermediate explosivity levels going from Strombolian- to Vulcanian-like eruptions. There are at least 1500 recognised active volcanoes around the World, and a further 10 000 or so are also potentially active. On average each year, about 50 volcanoes erupt. About 500 million people live under direct volcanic threat. About 75% of the largest eruptions occur from volcanoes erupting for the first time in recorded history, making forecast difficult. More than 95% of active volcanoes are not adequately monitored. At several volcanic areas, high urbanization nearby makes the associated risk very high. Volcanic hazard from large eruptions involve not only the impact of erupted products and the direct economic impact, but also the global impact on climate and secondary impacts such as famine. In the future, the continuous growth of population, urbanization and industrialization will generally increase the volcanic risk.

Highly explosive volcanic eruptions are anyway among the most wasting disasters in nature, able to completely eliminate life in areas of several hundred thousand square kilometres. At one end of the eruption spectrum there are the large caldera-forming eruptions, which, together with the Plinian ones, have also strongly affected human history and the course of civilisation itself.

2. Volcanic Edifices

Eruptive activity, involving explosions and/or magma effusion, continuously builds and destroys new volcanic edifices, called volcanoes. Their shape strongly depends on the eruption style. Volcanoes formed in a single eruption are called monogenetic volcanoes, while they are called polygenetic volcanoes if eruptions tend to occur over a long time at that vent. Typical polygenetic volcanoes are characterised by high topography, formed by magma accumulated during many eruptions from the same vent. If the vent has roughly equivalent sizes in all directions, volcanoes take the typical shape, with a high level of radial symmetry, and with a crater roughly located at the highest point, in correspondence with the main magma emission vent. If, on the other hand, the vent is a fracture very elongated in one direction, the shape of the volcanic edifice is characterised by high topography sections repeated over a long range, like the ocean ridges and rift zones. The slope of topography on a volcano depends on the eruption mechanism: effusive activity involving large quantities of very fluid magma produce edifices with a large basal area, small slopes and generally high elevation, called 'shields'; these are well represented by the Hawaiian volcanoes. In contrast, explosive activity mainly involving pyroclastic products produces volcanoes with a small basis and high slopes, with shapes at the highest levels markedly varying from one eruption to another, due to the continuous destruction and rebuilding typical of explosive activity. Volcanoes characterised by mixed effusive-explosive activity are called strato-volcanoes, or composite volcanoes. They can be found either in association with subduction zones or at the interior of lithosphere plates. Some of best-known volcanoes belong to this category, including classical Italian volcanoes like Etna, Stromboli, Vulcano, and Vesuvius. Composite volcanoes are formed by alternating layers of effusive (lavas) and explosive (pyroclastic) products. Most activity occurs from the central crater, but several eruptions may come from lateral fractures. Volcanic fields are often formed by monogenetic volcanoes, formed by a single eruption. They are typically a product of explosive activity, and take different names depending on their shapes, strictly linked to their genetic mechanisms. They are called cinder cones or scoria cones when they are mainly constituted by cinder or scoria; the ratio between height and base diameter typically ranges between 1/5 and 1/15, and lava flows are sometimes present.

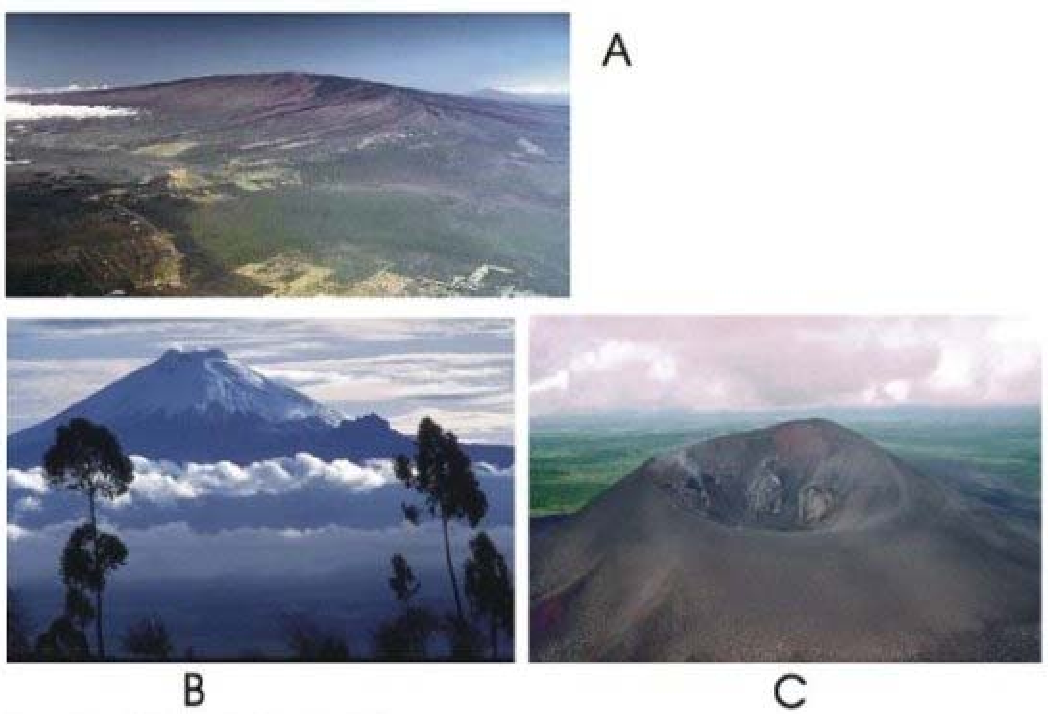
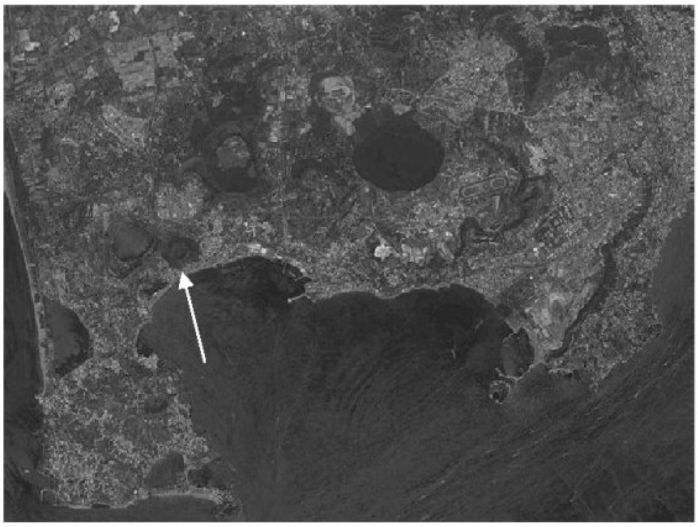


Figure1. Examples of different volcanic edifices:

A) Mauna Loa **shield volcano** at Hawaii (U.S.A.). Rising gradually to more than 4 km above sea level, Mauna Loa is the largest volcano on our planet. Its long submarine flanks descend to the sea floor an additional 5 km, and the sea floor in turn is depressed by Mauna Loa's great mass another 8 km. This makes the volcano's summit about 17 km above its base. Photograph by J.D. Griggs.

B) Cotopaxi, Ecuador, a **stratovolcano** with a summit elevation of 5911 m. It has erupted 50 times since 1738, the last one in 1904. Note the highly symmetric shape, almost perfectly conical. Picture by Kristen Risnes.

C) Cerro Negro, Nicaragua, the most recent basaltic **cinder cone** to form in the western hemisphere. The most recent eruption was in May-August 1995.



D) Satellite photo of the Campi Flegrei **caldera** (Italy), characterised by very high urbanisation, including part of the city of Naples (easternmost part of the image) and the town of Pozzuoli (at the center). Note the presence of numerous volcanic craters, in this roughly circular depression, part of which is located beneath sea level. Also note some of typical collapse structures at the borders of the depression, evidenced in the photo as high scarps. Volcanic cones and craters here are monogenetic, i.e. formed by a single eruption. The arrow indicates the Monte Nuovo cone, formed by the last eruption that occurred in 1538.

Monogenetic volcanoes formed as a consequence of magma-water interaction are: tuff rings, tuff cones and maars. Tuff rings are characterised by height/base ratios in the range 1/10 to 1/30, and are probably generated by the interaction of magma with the water table. Tuff cones have height/base ratios of the order of 1/10 and probably form from the interaction of magma and sea water (or magma and lake water). Maars are characterised by typical depressions, formed as a consequence of explosions due to magma-water contact at very shallow depth; the water table generally fills the depressions, thus becoming lakes, with the products of the explosion located just around the lake forming low relief. Slow extrusion of very viscous magma can furthermore produce lava domes, which are often formed at the end of explosive eruptions, when degassed magma from the bottom of the chamber tends to refill parts of the volcanic edifice destroyed by the explosive phase. Besides the single volcanoes, in nature volcanic fields exist; these are areas with high concentrations of volcanoes. Some of these volcanic fields occupy areas characterised by annular depressions, called calderas. Calderas form when explosive eruptions cause the collapse of the surface rocks. The most likely mechanism for caldera formation is the rapid drainage of large quantities of magma from shallow depths, causing the collapse of the suddenly uncompensated area. Caldera collapse can involve large areas, of several hundreds of square kilometres, but it also frequently occurs at the top of composite volcanoes. Caldera depressions are subsequently refilled by products from new volcanic centers formed inside. The collapse area is delimited by ring fracture systems, which represent the limits along which the collapse has occurred. These fractures are called ring dykes when outward-dipping, and cone sheets when inward-dipping, which is the most common situation. Examples of different volcanic edifices can be seen in Figure 1.

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Biographical Sketch

Giuseppe De Natale, graduated in Physics from the Federico II University in Naples (Italy) in 1983, and started his research activity at Osservatorio Vesuviano soon after. In 1993 he earned a PhD in Geophysics at Universitè Pierre et Marie Curie. In 1989 he became a Researcher at Osservatorio Vesuviano (Naples, Italy), and in 1994 Associate Geophysicist. He is currently Research Director at the Osservatorio Vesuviano-INGV. From 1993 to 1999, he was in charge of several seismic networks of Osservatorio Vesuviano. From 1996 to 2000 he was a Member of the Board of Directors of Osservatorio Vesuviano and of the Italian National Geophysical Council. From 1997 to 2001 he was a Member of the Scientific Council of the National Group for Solid Earth Geophysics. From 2001, he was Chief of the Volcano

Physics Department at the Naples section of the INGV (National Institute for Geophysics and Volcanology).Giuseppe De Natale was also Professor of Solid Earth Geophysics at University of Basilicata (Potenza) and University La Sapienza (Rome), from 1997 to 2002. His research activity spans several fields of Geophysics, from seismology to seismotectonics, to various aspects of the physics of volcanoes. He has been the author of about 130 scientific papers, about 90 published in first class International Journals. He also served as Editor for several special issues of International Journals devoted to seismology and volcano physics, and was convenor of several international meetings. His recent research activity led to new interpretations of volcano-tectonic seismicity, and new models for caldera unrests based on coupled mechanical-thermal-fluid-dynamic effects. He is also active in the development of new monitoring systems for volcanic and tectonic areas, both for geophysics and geochemistry. He participated, as Group or Project Leader, to several Research Projects funded by the European Union, Italian Group of Volcanology, Italian Civic Protection, etc. Recently, he was involved in an International UN Committee to build a surveillance system at Nyiragongo volcano (Democratic Republic of Congo).