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Understanding the Geological History of Volcanoes: An Essential Prerequisite to Their Monitoring

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1.1. Introduction

How necessary is it to know the past behavior of a volcano in order to monitor it? This chapter will attempt to shed some light on this question. It will present approaches to understanding the eruptive history of a volcano, both in the near and distant past, in order to establish scenarios for future eruptions and a monitoring strategy. Our objective will be to show how improving the knowledge of eruption history, eruption types and timescales is fundamental to improve the prediction and management of eruptions in the short and long term.

For any Earth scientist, it is trite to say that geological time differs from human time. However, this must often be recalled, as we, *Homo sapiens*, have a strong tendency to prefer simple reasoning and to trust a selective perception of the facts supporting our preconceived ideas. In geology, and thus in volcanology, a century that represents the whole of a human lifetime

Hazards and Monitoring of Volcanic Activity 1,
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has little meaning for the complex processes that govern the Earth's evolution, and a long-term process can suddenly change in a catastrophic way. The geological history of volcanoes should help us grasp this.

Today, the monitoring of an active volcano is carried out by the simultaneous use of a set of geophysical and geochemical methods, most often using ground or airborne measurement devices, various samplings and analyses. The deployment of these sensor networks, the acquisition of these data or the realization of these samples must be carried out according to a pre-established strategy based on the knowledge we have of the eruptive past of the volcano, its structure, the assessment of what could be its future activity and, of course, the financial and human resources involved.

Multidisciplinary approaches to tracing magma and fluid transfer from source to surface are now systematic for many volcanoes, whether using natural samples, experiments or the integrated use of geochemical, geophysical and numerical methods. The need for permanent and efficient observation facilities, whether or not they constitute a volcanological observatory (see Chapter 4), has been widely demonstrated. The time is no longer for one-off observations or exploratory missions but for long-term monitoring of volcanoes, both instrumentally and geologically. The implementation of monitoring networks, their spatial configuration, the choice of methods and the choice of parameters to be monitored as a priority are part of a strategy based on the knowledge of the lithology, the structure, and the history of the volcano. Understanding what are, and have been, the processes modifying magmas and their properties – accumulation, storage, transfer, differentiation, crystallization and degassing, as well as the rates and timescales of these processes – is essential to understand the driving forces modulating volcanic activity. A detailed knowledge of the frequency of intrusive and eruptive episodes, their duration and their succession in time according to their nature, is essential to understand the magmatic evolution of a volcano and for a comprehensive assessment of hazards and risks.

The roots of volcanology lie in two letters from Pliny the Younger to the Roman historian Tacitus, describing in detail the eruption of Vesuvius in 79 CE. These observations are now part of world geological history, laying the foundation for the archetype of so-called "Plinian" eruptions. The "modern era" of volcanology probably began with the establishment of the first volcanological observatories at the end of the 19th century in Italy, Japan and then in Hawaii at the beginning of the 20th century (see Chapter 4). The Hawaiian Volcano Observatory (HVO), from its establishment in 1912 by

Thomas A. Jaggar, has of course carried out systematic and continuous monitoring of seismic and ground deformation activity preceding, accompanying and following eruptions, and also a wide variety of other geological, geophysical and geochemical observations and investigations that have greatly improved the understanding of eruptive mechanisms, their causes and their diversity. This understanding, in turn, has been essential to the improvement and diversification of volcano monitoring techniques now routinely used by other volcanological observatories. Geological knowledge and monitoring are intimately linked as are observation, instrumentation, experimentation and modeling. Current developments in new geochemical and petrological approaches, as well as ongoing advances in analytical and imaging techniques, are making it possible to finely document the elemental and isotopic compositions of liquids and minerals, fluid and melt inclusions, as well as textures, with an ever-better precision and spatial resolution. This greatly improves our knowledge of the past magma supply of a volcano and, consequently, of its eruptive past.

The knowledge of the geological history of a volcano is an essential prerequisite for any monitoring of its activity, in order to predict volcanic eruptions or other events. This knowledge is essential for the characterization of hazards (types of eruptions, frequency, cyclicity, changes in eruptive regime and cascade effects) and therefore for the reflection on future eruptive scenarios and the assessment of volcanic risk. It is also essential for the strategic approach to the implementation of volcano monitoring (methods, dimensioning of networks, etc.) and for volcanic risk management.

1.1.1. *Historical volcanology at the crossroads of various disciplines: the example of the Samalas eruption in 1257*

One of the most powerful eruptions in history occurred near the end of the Middle Ages, profoundly affecting the global climate. Its origin, for a long time unknown, was the subject of multiple researches and hypotheses. The source of this “mysterious” eruption was then revealed by the analysis of a set of evidence resulting from a multidisciplinary approach (Lavigne et al. 2013).

The ice core record (see section 1.7.2) showed that one of the largest eruptions recorded in the last 7,000 years was in 1257–1258 (Oppenheimer 2003).

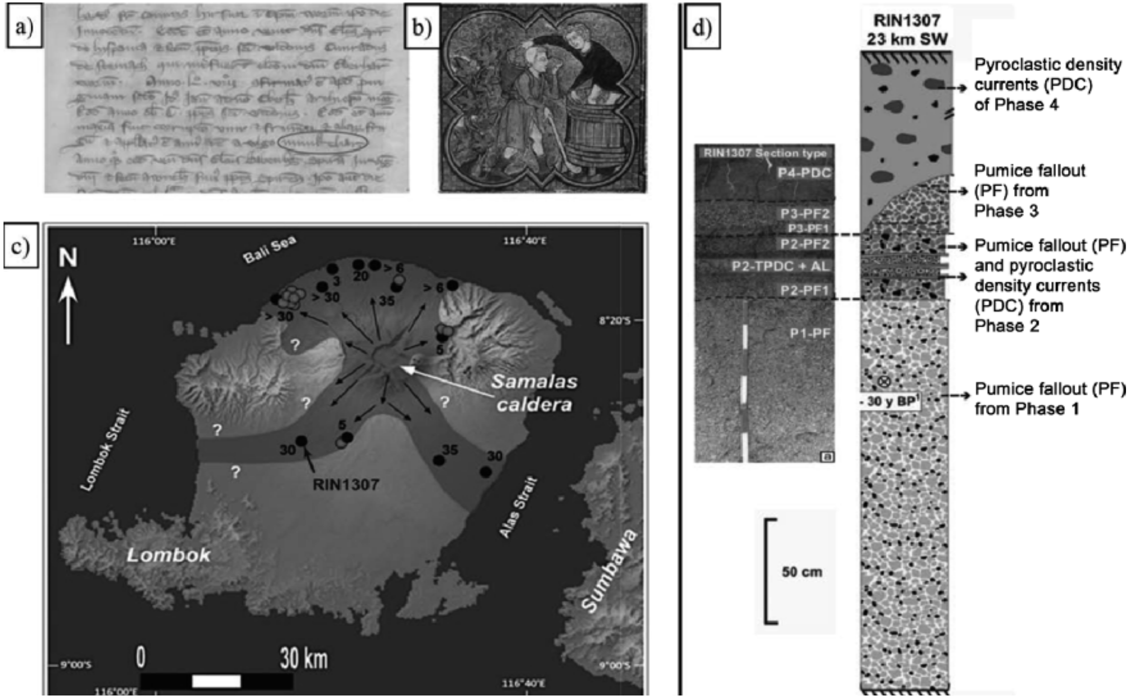


Figure 1.1. *The eruption of the Samalas volcano in Indonesia, in the year 1257, had a major impact on the global climate. The source of this eruption, which remained unknown for a long time, has been found through the interpretation of various types of geological and climatic data and ancient texts. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.1.– *a) and b) Medieval manuscript excerpt and illustration describing the climatic impact observed in 1258 following the eruption of Samalas volcano, and illustration describing the dust veil and climatic disturbances in 1258 (from Guillet et al. 2017). c) Map of Lombok Island (Indonesia) and distribution of pyroclastic flows (purple) attributed to the 1257 eruption around Samalas volcano (from Lavigne et al. 2013) (top right). d) Photograph of deposits from the 1257 eruption and stratigraphic log for the RIN 1307 reference section located 23 km SW of the volcano (from Vidal et al. 2015). See reference articles for details.*

Sulfate concentrations recorded from Greenland and Antarctic ice cores indicate that the eruption generated the largest injection of sulfate aerosols into the stratosphere during our era, far exceeding that of the 1815 Tambora eruption and causing climate disruption (see Chapter 2 for explanation of climate disruption) (Sigl et al. 2015; Vidal et al. 2016; Guillet et al. 2017). The task of identifying the volcano that caused this major eruption took nearly 30 years. The enigma was solved in a convincing way by crossing stratigraphic data (distribution maps of deposits), geomorphological data (3D reconstruction of the ancient collapsed volcano), physical volcanology (volume and flow of the eruption, height of the eruptive column), geochemistry (comparison of the composition of glassy particles collected in the volcano ash with those found in the polar ice and associated with the peak of concentration of sulfate aerosols), ^{14}C dating and the exploitation of a medieval chronicle in ancient Javanese (Babad Lombok). This work identified Samalas, located in the Rinjani volcanic complex on the island of Lombok, Indonesia, as the source of the mysterious eruption (Lavigne et al. 2013). An eruptive column reaching the altitude of 43 km is thought to be responsible for dispersing 33–40 km^3 (DRE – dense rock equivalent) of ash in four eruptive phases including Plinian pumice fallouts and pyroclastic flows, in both hemispheres of the globe, impacting the climate both locally and globally (see Figure 1.1) (Vidal et al. 2015).

This reconstruction of a historical eruption, and its connection to one of the largest Indonesian craters, was made possible by combining different pieces of information that constitute the keys to the reconstruction of the past history of volcanoes: the interpretation of deposits left near or in the region of the volcano that caused their emission, the petrological characterization of these deposits and their comparison with known sources, the use of distant archives, in this case polar ice cores, the recording of past events by dendrochronology, the modeling of climatic data, the use of historical archives and image analysis. The above example, applied to a specific eruption, describes the more global approach that must be taken when reconstructing the geological history of a volcanic edifice as a whole in order to characterize potential future hazards and risks.

1.1.2. *Hazard characterization, geological analysis and future eruptive scenarios*

Knowledge of the geological history of volcanoes forms the basis of current methodology for volcanic hazard assessment. The geological characterization of past eruptions of a volcano, the interpretation of its geological archives and their translation into hazard maps or even volcanic risk maps (see Chapter 3), and their processing by probabilistic approaches are part of the long-term assessment of the activity of a volcano. It is intended to plan strategies, procedures and measurements for monitoring active or potentially active volcanoes, just not to assess the day-to-day status of the volcano (Crandell et al. 1984). These issues enable the necessary dialog between scientists and civil protection authorities and provide essential information to the populations living near volcanoes. The risk assessment is based on the documented history of the volcano under study.

However, understanding the geological history of volcanoes is not completely absent from the day-to-day risk assessment, in addition to the continuous observations and measurements carried out by the geophysical and geochemical monitoring networks. This knowledge of the volcano's past behavior must be considered in the assessment of the daily state of the volcano and its day-to-day evolution, as well as the sequences of eruptive events for similar volcanoes, which can provide information on a range of potential behaviors (Jousset et al. 2012). These insights define the "experience" of the observatory, which still represents the basis for assessing the state of a volcanic system today, even if the development of so-called "expert" computer systems tends to grow.

1.1.3. *Mount St. Helens, May 18, 1980*

The eruption of Mount St. Helens volcano that began on May 18, 1980, made a profound impact on the scientific community working in volcanology. It allowed the first observation and characterization of a previously unknown type of explosive eruption, and it demonstrated that several types of dangerous phenomena can be combined in a very short period of time during a single eruption. Within a few hours, this eruption produced a flank collapse, a direct lateral blast, avalanches and debris flows, pyroclastic flows and large tephra falls. Above all, it was the first highly explosive eruption to benefit from prior knowledge of the volcano’s history and from enhanced instrumental monitoring.

The work of Crandell and Mullineaux (1978) is a wonderful illustration of the contribution of research on volcanoes to volcanic risk assessment. Two years before the eruption, Dwight Crandell and Donal Mullineaux published a report in the Geological Survey Bulletin, presenting the results of several years of geological studies of past eruptions of Mount St. Helens (Crandell and Mullineaux 1978). In this work, the nature of past eruptive events, their frequency and the threats they could pose to people and property in case of a future eruption are outlined. This study is part of a larger investigation of the volcanoes of the Cascade Range in the western United States of America, initiated in 1967 by the USGS. It appeared as early as 1975 (Crandell et al. 1975) that Mount St. Helens is the youngest and most active of the Cascade volcanoes. Based on the interpretation of eruption sequences over the last 4,500 years, Crandell and Mullineaux (1978) predicted an eruption of Mount St. Helens “within the next hundred years, and perhaps even before the end of the century”. Their prediction proved to be correct, but that is probably not the most important thing. The major contribution of their study lies in the description given of the phenomena associated with a future eruption, and their representation in a volcanic hazard map. Their assessment of volcanic hazards, deduced from the study of deposits left by past eruptions, was an essential contribution to the management of the 1980 eruption and the minimization of the risks associated with this eruption. Based on the 1978 volcanic hazard mapping proposed by Crandell and Mullineaux, an evacuation zone was established by the authorities, saving many lives during the sudden explosion of May 18, 1980.

The first signs of activity at Mount St. Helens appeared on March 16, 1980, with shallow seismic activity located beneath the volcano (Lipman and Mullineaux 1981). In the following days, this seismic activity proved unusual and a monitoring network was installed. On the basis of the volcanic hazard mapping proposed in 1978 by Crandell and Mullineaux (1978), access to the volcano and to potentially exposed areas was limited. A few hundred inhabitants were evacuated. On March 27, the first phreatic explosions were observed at the summit, as well as the opening of numerous fractures associated with the formation of a crater and the initiation of a bulge on the upper part of the northern flank of the volcano (see Figure 1.2).

An intensive program of geophysical monitoring of these events was then set up by USGS researchers and technical staff. The analysis of volcanic risks was further developed on the basis of Crandell and Mullineaux's work. Until mid-May, the high rate of seismicity, the spectacular deformation of the northern flank of Mount St. Helens and the intermittent phreatic eruptions led them to consider the possibility of a major eruption in the near future. These conditions also justified maintaining the restricted area established at the end of March. The catastrophic explosion of May 18 at 8:32 a.m. began without any further warning. Fifty-seven people were killed, mainly by asphyxiation or burns, including scientists and photographers working on the edge of the exclusion zone.

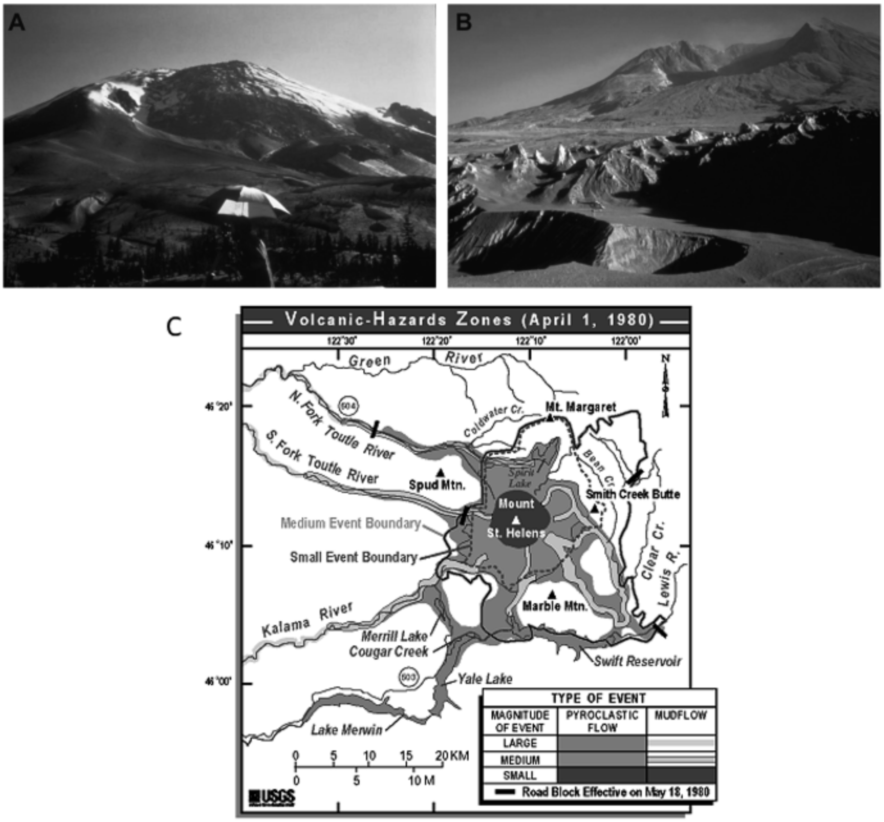


Figure 1.2. *The 1980 eruption of Mount St. Helens in the United States is a key example of how knowledge of the geological history of a volcano can be used to monitor it. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

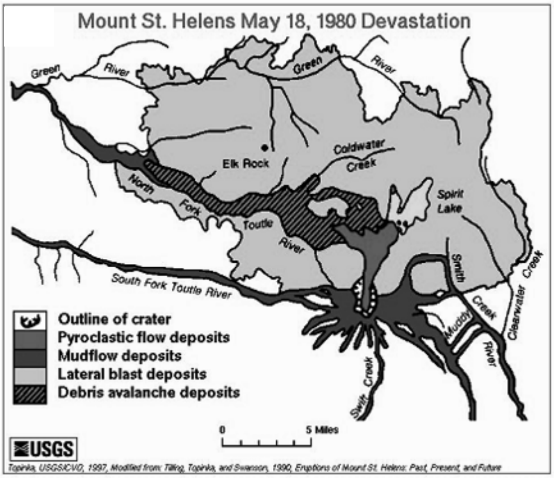
COMMENT ON FIGURE 1.2.– *a) Bulging of the north flank of Mount St. Helens before the eruption, April 27, 1980 (Cascades Volcano Observatory Photo Archives). b) Mount St. Helens after the May 18, 1980 eruption (September 10, 1980). The volcano has lost about 400 m of its height (USGS Volcano Hazards Program). c) Volcanic hazard zonation for a possible eruption of Mount St. Helens, based on the map proposed by Crandell and Mullineaux (1978), revised to April 1, 1980.*

1.1.4. *Lessons learned from the eruption of Mount St. Helens*

The validity and usefulness of the volcanic hazard assessment and zoning maps, which had been published 2 years earlier, were thus fully demonstrated, albeit with a few important differences. The hazard assessment was based on eruptive events of the past 4,500 years. It assumed that future events from the volcano would be similar in type and intensity to those of that period. The prodigious collapse of the northern flank of the volcano and the resulting debris avalanche and lateral blast had not occurred during the period studied and, even if such events had occurred in the late Pleistocene, they were not known, and therefore not anticipated, in the risk assessment published in 1978. Such a slide of the northern flank of the volcano had, however, been envisaged in the month before the eruption, because of the continuous and significant deformation measured on this flank, but the extent of the debris avalanche and the magnitude of the directed blast were underestimated, affecting a much larger area than originally anticipated (see Figure 1.3).

Among the lessons learned after this eruption, we note the complementarity, as demonstrated here, between geological data and instrumental monitoring data, for the prediction of events and the evaluation of the possible course of the eruption. It will also be noted that, even if one cannot rely exclusively on knowledge of past history, it must be considered as a starting point for a probabilistic approach, for which it is essential to take into consideration possible analogs elsewhere in the world (Lipman and Mullineaux 1981).

Regardless of the volcano, destructive events may exceed those of the past. However, should the largest known eruption of any similar volcano in the world be taken as a reference for establishing a monitoring strategy? Since the 1980 eruption of Mount St. Helens, other work on the recent geologic history of this volcano has complemented Crandell and Mullineaux's study. For example, Pallister et al. (1992) reassessed the eruptive activity during the last 500 years, highlighting variability in magma composition and discussing possible links between the different phases of activity (five major explosive eruptions, including the one in May 1980, and other more moderate ones) and deep inputs of new magma. How does magma chemistry, a major parameter determining the eruptive regime, evolve from one eruption to the next? The knowledge of the functioning of the magma system of the volcano, whatever it is, is a key parameter of the monitoring. At Mount St. Helens, the absence of deep geophysical precursors and the lack of evidence of deep magma reinjection led to the conclusion that the May 1980 eruption resulted from the partial crystallization of a surface reservoir in which the magma had remained for a few centuries to millennia, and thus from the effect of the so-called "second boiling" (supersaturation in CO_2 and H_2O induced by this partial crystallization). The magma reservoir(s) of a volcano is/are formed in a place (rheological and/or density contrast) where the accumulation of magmas, formed by a slow and continuous process at greater depth, is possible. The episodic release of these magmas toward the surface to feed an eruption is a complex process that we cannot fully predict, but it allows, for a single volcanic edifice, to feed emissions that vary in terms of volume and eruptive regime. These variations in eruptive regimes are particularly difficult to predict. We know that they result from changes in the physicochemical properties of magmas, or from external parameters such as the presence of water, the geometry of eruptive conduits or the morphology of the edifice (Cassidy et al. 2018).



Topinka, USGS/CVO, 1997, Modified from: Tilling, Topinka, and Swanson, 1990, Eruptions of Mount St. Helens: Past, Present, and Future

Figure 1.3. *Mapping of deposits from the 1980 eruption at Mount St. Helens (note the difference in scale with map 1.2C) (Topinka, USGS/CVO 1997 adopted from Tilling et al. 1990). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

a) b)

Figure 1.4. *Two contrasting eruptive styles at Kilauea in Hawaii. a) The lava lake at Halema'uma'u crater in 1893. The lava lake is contained by levees formed by small overflows or weak projections, originating from the lava lake itself (https://www.usgs.gov/media/images/k-lauea-visit-was-a-prelude-revolution; photo Brother Bertram). b) The phreatic eruption of Halema'uma'u on May 18, 1924 (https://www.usgs.gov/media/images/explosive-eruption-column-halema-uma-u-1115-am-may-18-1924; photo Kenichi Maehara)*

1.1.5. *The diversity of eruptive regimes*

If the eruption of Vesuvius in 79 CE has a special place in the history of volcanology, it obviously does not alone account for the reality of the eruptive activity of this volcano. Although it is essential to take into account major paroxysms in order to assess the volcanic risk and to prepare the measures to be implemented for the protection of the population, the forecasting of volcanic activity by the Vesuvius Observatory must take into account all the possible events, including the more common phases of activity, and therefore consider the diversity of eruptive regimes.

The eruption of Mount St. Helens has shown how difficult it is to anticipate changes in the eruptive regime of a volcano. From a purely phreatic eruption, which does not present any significant danger, the eruption can rapidly evolve toward a catastrophic outcome with a major magmatic paroxysm. This suddenness has been demonstrated by many examples beyond Mount St. Helens, for example, Soufrière Hills on Montserrat in 1995 (Kokelaar 2002; Sparks et al. 2002; Voight et al. 2002). This implies a good knowledge of past eruptions, their succession, and also of the diversity of magmas and eruptive regimes within a single eruption.

The variability of eruptive regimes largely results from the diversity of magmas and the conditions of their transfer to the surface. Magmas undergo profound changes in their physical properties due to variations in pressure and temperature conditions during their evolution in the magma reservoir, during their ascent to the surface and during the eruption itself (Sparks 2003). Degassing, cooling and crystallization during magma ascent induce a drastic change in their physical properties, especially viscosity. Degassing conditions strongly determine the regime under which magma rises and will erupt to the surface (Moretti et al. 2018). Active magma systems interact strongly with their environment, inducing deformation and rupture of the bedrock and disturbances of subsurface aqueous systems. These various processes and interactions that have direct physical and phenomenological effects during eruption must be identified from petrological and geochemical studies of previous eruptions. They serve as a basis for modeling to improve the understanding of the physics of the processes involved. Given the uncertainties and complexity of nonlinear systems such as volcanoes, it is still very difficult to make accurate predictions (Sparks 2003). For eruptions, predictions and hazards must be expressed in probabilistic terms and take into account uncertainties. This has important consequences in the management of volcanic crises, which must integrate the human parameter, whose importance is great.

This implies that the scientists in charge of crisis management must have an appropriate dialog with the authorities and the public and must be prepared for a probabilistic approach.

What scenarios are or should be considered? This question inevitably arises when a volcano enters a period of instability. For volcanological observatories or scientists in charge of monitoring, it is then essential to be able to base their reflections and monitoring strategies on a strong geological knowledge allowing for anticipation of a possible scenario for the coming eruption. The 1976 La Soufrière crisis in Guadeloupe clearly demonstrated the scientific and communication biases induced by this lack of knowledge. The scientists did not have a sufficient geological framework to interpret the signals. An analysis of this crisis has been made a posteriori, in the light of our knowledge and with current tools, in particular those of Bayesian statistical analysis. This analysis shows that if, at the climax of the crisis, the probability of a magmatic intrusion was high, the prediction of the outcome of the eruption remained uncertain (Hincks et al. 2014; Komorowski et al. 2018).

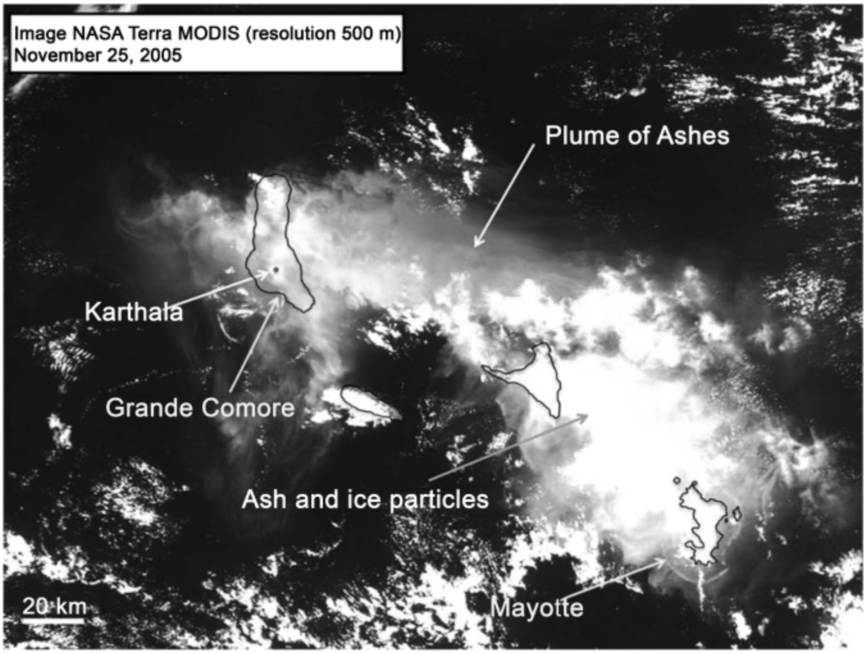


Figure 1.5. *NASA Terra MODIS image of the ash plume from the violent strombolian eruption at Karthala volcano, Grande Comore, on November 25, 2005. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.5.– *The Comoros archipelago (in the Indian Ocean) is composed of the islands of Mayotte, Anjouan, Moheli and Grande Comore. Their outline is shown in black. The red dot marks the position of the Karthala crater, origin of the eruption. The 2005 eruption marks a significant change in the eruptive regime of this volcano, which usually has mostly effusive eruptions. The ash plume extended for about 280 km and reached an altitude of ~12 km (Bulletin of the Global Volcanism Network, vol. 30, no. 11 - November 2005).*

Variability in eruptive regimes is not limited to volcanoes with relatively low eruption frequency. Volcanoes with frequent activity, such as Etna (Behncke et al. 2008; Calvari et al. 2018; La Spina et al. 2019), or even quasi-continuous activity such as Stromboli (Calabrò et al. 2020) or basaltic shield volcanoes such as Kilauea in Hawaii or Piton de la Fournaise on Reunion Island, also experience multiple eruptive regimes, often during a single eruption. For the latter, lava lake activity, powerful lava fountains, violent strombolian explosions or phreatic or phreatomagmatic activity may alternate, whereas these volcanoes are often considered essentially effusive (see Figure 1.4). Deposits of phreatic and phreatomagmatic explosions such as Keanakāko'i ash at Kilauea (Swanson et al. 2012, 2014) or Cendres de Bellecombe (Bellecombe Tephra sequence) at Piton de la Fournaise (Bachèlery 1981; Ort et al. 2016) are probably the best examples of this eruptive variability, as are the violent, phreatomagmatic strombolian eruptions of Karthala in 2005 in Grande Comore (Bachèlery et al. 2016) (see Figure 1.5).

1.2. Relative and absolute dating and the importance of timescales: chronology of eruptions

The aim here is not to describe the dating methods but to recall their importance in determining the main periods of building of the volcano as well as in understanding the succession in time of recent eruptive episodes, and to show what are the possible methods based on a few selected examples.

The time factor is a key element in the behavior of a volcano. As we have already stated, a volcano irregularly ejects magmas formed by slow and deep processes acting continuously. This transition from a continuous process to an episodic and irregular process is determined by the transit of magmas through the mantle, the crust and the volcanic edifice, and thus by their storage and physico-chemical evolution within one or more magma reservoirs. Time plays a major role in these processes, hence the importance of understanding the past activity of a volcano. In an eruptive sequence, it is essential to be able to determine the frequency of eruptions. This frequency makes it possible to assess how quickly the batch of magma that can feed the next eruption can be reconstituted, its degree of chemical evolution, and therefore the rate of recurrence of the different types of eruptions. These data allow us to reconstruct past eruptive cycles, to know their duration and the sequence of events within the same cycle. From this knowledge, we can determine the state of the volcano and what we can expect from its activity in the near future. This is essential data for volcano monitoring.

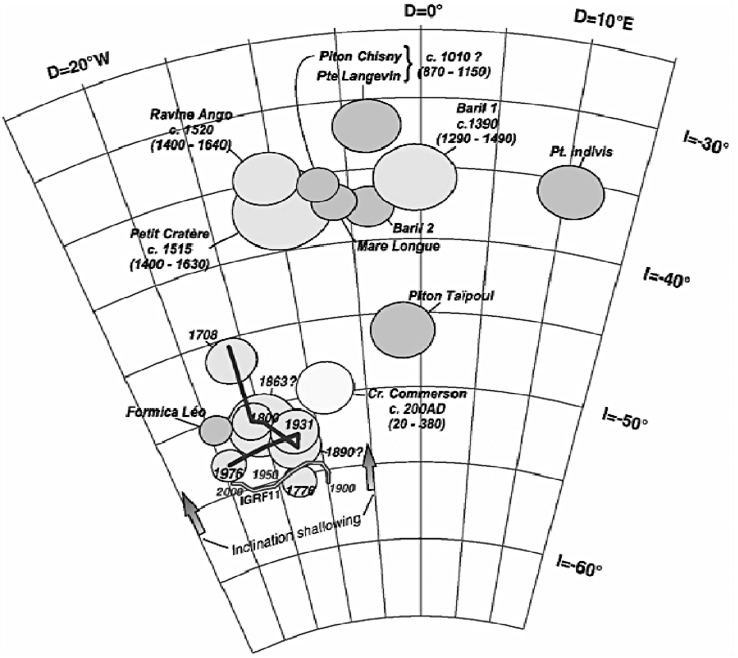


Figure 1.6. *Archeomagnetic directions obtained for recent lava flows from the Piton de la Fournaise volcano (on Reunion). The secular variation of Earth's magnetic field is used here to date recent lava flows*[1] *(according to Tanguy et al. 2011). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

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[1] Dating by archeomagnetism: volcanic rocks record the ambient magnetic field during their cooling. The secular variation of Earth's magnetic field is used to date recent lava flows (see

Reconstructing this history implies having a set of data that allow us to assess the time within an eruptive sequence. This requires an effort of systematic dating of events, either by absolute dating methods that allow us to accurately locate the events in time, or by relative dating that allows us to locate the events between them without absolute reference. Several methods allow the absolute dating of volcanic rocks, their choice depending on the age range targeted and the nature of the material to be dated.

There is a wide range of radiometric methods for dating the rock itself or the minerals or glass within a tephra. The most frequently used are the $^{40}Ar/^{39}Ar$, K-Ar and Rb-Sr isotopic methods, the methods using the isotopes of the decay chain of Uranium and Thorium, the exposure to cosmogenic nuclides and the fission traces. The ^{14}C method is most frequently used for “young” ages (<50 ka), but it requires finding fragments of carbonized wood from trees burned by lava flows (Rubin 1987), or shell or coral fragments, especially for tephra sampled in marine environments (Köng et al. 2016).

The relative dating of events can be tackled with the help of the stratigraphy of pyroclastic and epiclastic flows or deposits, the biostratigraphy, the stable isotopes ($\delta^{18}O$), the geographical or geomorphological relationships between two events, the archeomagnetism and paleomagnetism (see Figure 1.6), the geomorphology of volcanic cones or lava flow surfaces, or even, in favorable conditions, from the vegetation cover (see Box 1.1). Other methods are more rarely used in volcanology, such as thermoluminescence, hydration crust development, ice cores, varves, dendrochronology or lichenometry.

Figure 1.6). The brown line connects historically dated flows (95% confidence circles in yellow). The beige circles represent lava flows that are historically undated or whose proposed date is questionable. The light yellow circle represents the tephra emitted by the Commerson crater (dated by ^{14}C). The secular variation on Reunion appears significantly different from that observed in Europe. In particular, the low amplitude of the directional variations observed over the last 250 years (inclination (I) within the limits of –50° and –55°, declination (D) from –13° to – 9°) makes any dating archeomagnetic difficult for this period. In contrast, a larger directional variation exists for the period 1750–1000 CE. This approach makes it possible to determine the date of recent flows but not precisely.

The colonization of new lava flows emitted by volcanoes in the intertropical zone is the focus of much attention, both in the emerged domain (Ah-Peng et al. 2007; Albert et al. 2020) and in the marine domain (Zubia et al. 2018). On land, rapid plant growth in these warm and humid contexts allows for rapid invasion of new flows by lichens, mosses and shrubs. This is used for dating purposes for recent lava flows with unknown ages. Dating methods such as lichenometry or dendrochronology can be used considering that, in these biologically favorable contexts, the development of vegetation on the flows (see Figure 1.7) depends mainly on the age of emplacement of the lava flow (Atkinson 1971).

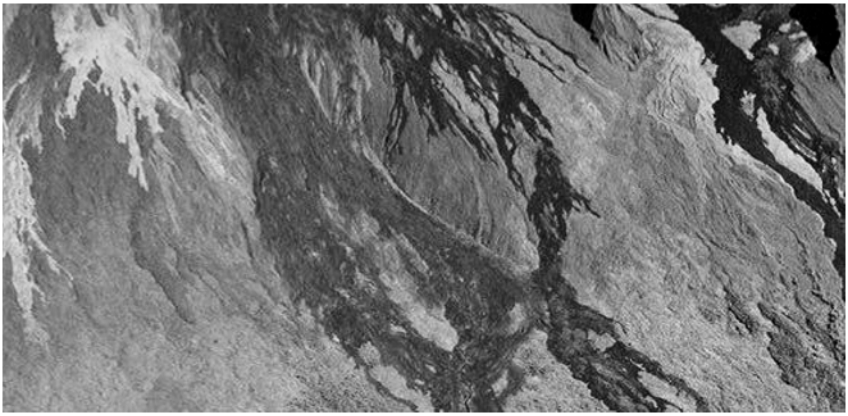

Figure 1.7. *Differences in vegetation coverage of recent flows on the eastern flank of Piton de la Fournaise. The most recent flows are largely devoid of vegetation and appear dark; the oldest (a few hundred years) are entirely covered*

These approaches have been developed on Reunion Island where Piton de la Fournaise is frequently active with several eruptions per year (Lénat and Bachèlery 1988; Peltier et al. 2009a). Although the frequency of eruptions is well known for the last decades, mainly since the establishment of a volcanological observatory in 1980, this is not the case for the historical eruptions that took place between the 18th and mid-20th centuries. The “biological” dating is therefore one of the tools used to enrich the knowledge of the eruptive history of this volcano. For example, Albert et al. (2020) use the strong correlation between the maximum diameter at the base of *Agarista salicifolia* and the age of lava flows. This relationship, established from flows of known age (historical observation or ^{14}C dating), can be used to estimate the age of recent undated flows (see Figure 1.8).

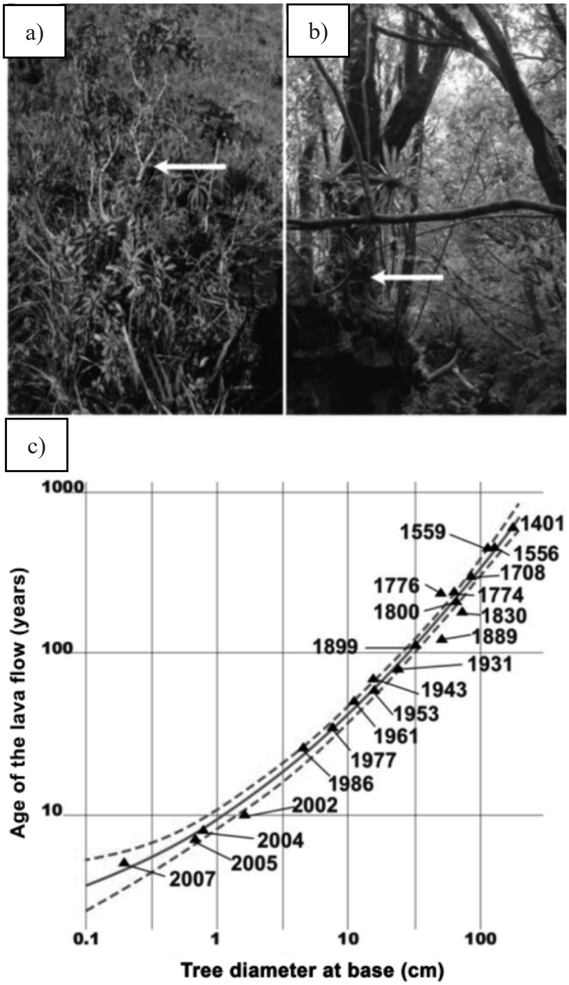

Figure 1.8. *The different growth stages of Agarista salicifolia (marked by white arrows) are used to date recent flows from the Piton de la Fournaise volcano*

COMMENT ON FIGURE 1.8.– *a) A young agarista installed on a 1986 lava flow. b) Agarista installed on a 1708 lava flow. c) Calibration curve for dating volcanic activity based on the relationship between lava flow age and maximum diameter at the base of Agarista salicifolia (according to Albert et al. 2020).*

Box 1.1. *Dating of recent lava flows at Piton de la Fournaise on Reunion Island*

1.3. Frequency of eruptions, eruptive cycles and future eruption scenarios

The eruptions in one volcano can sometimes have very different characteristics. The chemical composition of the magma and its evolution over time are, of course, key parameters, but they are not the only ones. The morphological and structural evolutions of the edifice also determine the functioning of the volcano. Therefore, if we want to evaluate what the eruptive activity of a volcano could be, it is not possible to refer only to the most recent period. Santorini, in the Aegean Sea, or Italy's Vesuvius are good examples.

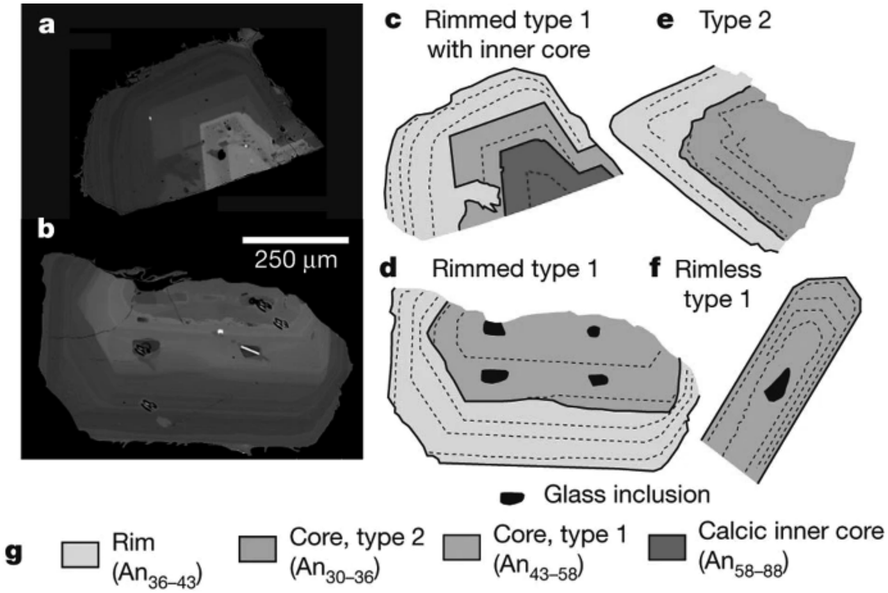

Figure 1.9. *Crystals in lavas and pyroclastics are archives of the evolution of magmas within volcanoes, as shown here by the compositions of plagioclase crystals in the pumice from the Minoan eruption in Santorini. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.9.– *Chemical variations measured on zoned plagioclase crystals from the Minoan eruption at Santorini (~1600 BCE) have shown that, despite 18,000 years separating the Minoan eruption to the* *previous major eruption, most Minoan magma crystals record the recharging of the magma reservoir by large volumes of silicic (and some mafic) magma less than 100 years before the eruption and that mixing between the different magmas took place a few months before the eruption was initiated. These are essential pieces of data for monitoring Santorini-type volcanoes (according to Druitt et al. 2012).*

The reconstruction of long time series of eruptions allows to evaluate the regularity over time of the behavior of these volcanoes, and in particular the existence of cycles including different types of eruptions and eruptive regimes. It also allows us to assess the length of rest periods and thus the return times of some eruptions or even the conditions for magma reservoir recharge and eruption initiation (Druitt et al. 2012) (see Figure 1.9).

The work of reconstructing the history of a volcano requires a lithological and stratigraphic analysis of the emitted products, as well as the most comprehensive dating of the events, to determine the timing of the eruptions. It is essential to be able to determine the frequency of eruptions in the past and the time interval between major eruptions of explosive volcanoes, often Plinian eruptions. In Santorini, a dozen major Plinian eruptions have occurred over the last 360,000 years, with a recurrence period of about 30,000 years. The rhythmicity of these events suggests that an eruption such as the one Santorini experienced around 1600 BCE, which likely destroyed the Minoan civilization, is unlikely in the coming centuries (Druitt et al. 1989; Jenkins et al. 2015; Barberi and Carapezza 2019). The most intense volcanic event that is considered likely to occur today is a sub-Plinian eruption (Vougioukalakis et al. 2017).

Vesuvius is one of the three historically active volcanoes of Campania, one of the central provinces of Italy. Its volcanic activity shows a great variability of eruptive regime, from Plinian paroxysms such as the eruption of 79 CE to much more modest lava effusions. The last period of activity from 1631 to 1944 (see Figure 1.10) allows us to characterize these lower energy eruptions. Vesuvius has not erupted since 1944. Throughout its eruptive history, this volcano has often experienced long periods of rest lasting several centuries or tens of centuries. The longer the period of rest before the eruption, the more violent the “reawakening”. The assessment of the future activity of Vesuvius should not be only based on the recent period but should integrate several cycles of activity.

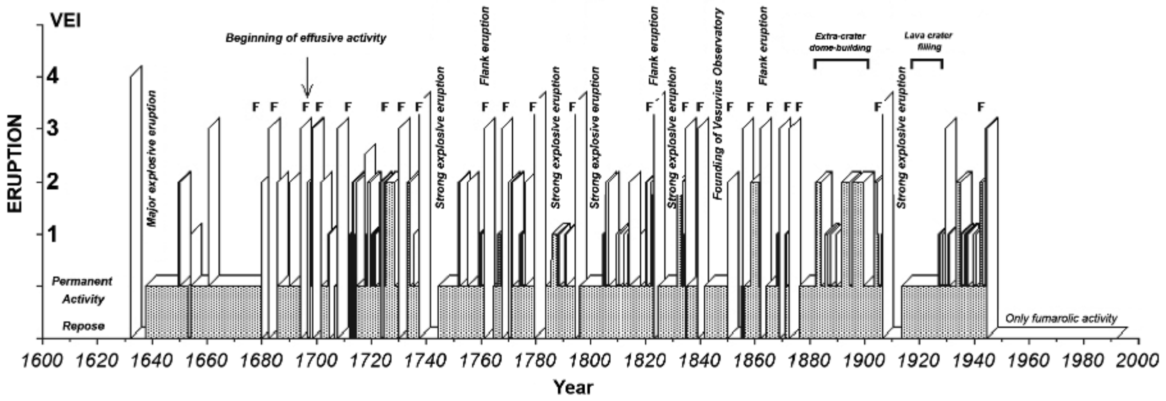

Figure 1.10. *The eruptive activity of Vesuvius between 1631 and 1944. The horizontal bars indicate periods of permanent activity. The height of the vertical bars indicates the Volcanic Explosivity Index (VEI*[2]*) value of the eruptions; "F" indicates the main violent strombolian eruptions (based on Scandone and Giacomelli 2013)*

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[2] VEI or Volcanic Explosivity Index is an index proposed by Newhall and Self (1982). A semi-quantitative scale compares the size of eruptions, with a scale of 0–8 taking into account both the magnitude of the eruption with the volume and its intensity with the height of the plume.

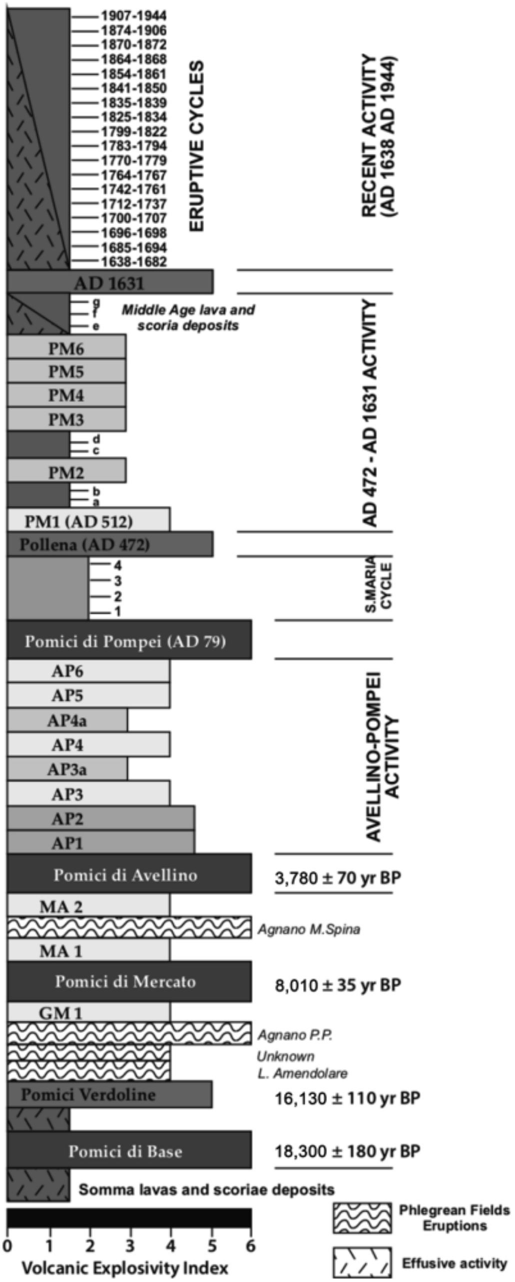

Figure 1.11. *Chronostratigraphy of the eruptions of Vesuvius in the last 18,000 years (according to Cioni et al. 2003)*

The eruption of March 1944 began with an essentially effusive activity, before a paroxysmal phase during which the eruptive column could reach nearly 10 km in altitude. It ended a period of 300 years of intense eruptive activity that had begun immediately after the sub-Plinian eruption of 1631. During this period from 1631 to 1944 (see Figure 1.10), Vesuvius was in near constant activity, with alternating effusive eruptions, and weak to violent strombolian explosions (Scandone et al. 2008; Scandone and Giacomelli 2013).

The reconstruction of the geological history of Vesuvius during the last 18,000 years (Cioni et al. 2003) (see Figure 1.11) shows a succession of large Plinian eruptions (VEI > 5), of which the eruption of 79 CE is the last. Several sub-Plinian eruptions (VEI 4–5) have marked the inter-Plinian periods, the two most recent occurring in 472 and 1631 (Arrighi et al. 2001). Alternating with these major eruptions, several smaller explosive (VEI ≈ 3) and effusive eruptions occurred. Although it is likely that not all low-magnitude eruptions have been recorded, this historical record provides an accurate picture for the activity of the Somma-Vesuvius complex over the past 20,000 years.

Figure 1.12. *Fresco in a villa in Pompeii showing Vesuvius before the eruption of 79 CE (the oldest representation of Vesuvius)*

Plinian eruptions of the type of 79 CE are rare events, spaced in time by thousands of years. The major risk at Vesuvius in the coming years is probably not related to an eruption of this type. A sub-Plinian eruption such as those of 1631 and 472 are therefore used as a reference by the Osservatorio Vesuviano and the Italian civil protection to draw up a possible eruption scenario. The statistical processing of these data indicates, for Vesuvius, that the most likely event (probability >70%) is an event of lower energy (VEI = 3). However, a sub-Plinian explosive eruption like the one in 1631, with VEI = 4 (27% probability) is considered as the reference scenario (Marzocchi et al. 2004; Gurioli et al. 2010).

1.4. Historical activity through texts, iconography and archeology

The reconstruction of the eruptive history of a volcano is based on different complementary studies. In addition to the study of deposits left by eruptions, the study of historical documents (texts, paintings, sketches, photos, etc.), when they are available, makes an important contribution to the reconstruction of the history of a volcano. It often provides a wealth of information to characterize the activity of the volcano in the near past. With the exception of the volcanoes of the Mediterranean area for which the historical period covers several millennia, the period covered is often short, a few hundred years at most. The information provided by the historical documents depends not only on this duration, on the existence of usable documents, but also on the type of activity of a given volcano. If we compare the historical periods of Piton de la Fournaise on Reunion Island and La Soufrière on Guadeloupe, two islands for which the "historical period" is more or less the same (i.e. since 1635–1640), the large number of eruptions and morphological changes described for Piton de la Fournaise provides significant information on the evolution of its eruptive and tectonic activity, whereas for La Soufrière, the historical documents only provide information on phreatic events, which represent a minor type of manifestation for this volcano.

Numerous texts, paintings, sketches and drawings describe past eruptions of Italian volcanoes, beginning with Pliny the Younger's famous description of the paroxysmal phase of the Vesuvius eruption in his two letters to the historian Tacitus. Pliny's description of a sustained eruptive event of long duration (19 hours) provides the temporal framework used by Sigurdsson et al. (1982, 1985) to place the various successive pyroclastic units in time.

Differently, the morphology of Vesuvius before the eruption of 79 CE is detailed by Strabon (58 BCE–21 CE), a Greek geographer and historian, who describes a Vesuvius whose slopes are occupied by dwellings and farmland, while the flat and desolate summit reveals its volcanic nature (see Figure 1.12). The activity of Vesuvius, like that of Etna (see Figure 1.13) or Stromboli, is widely described, regardless of the time period considered (Barberi et al. 1993; Scandone et al. 1993; Branca and Del Carlo 2004; Branca and Abate 2019).

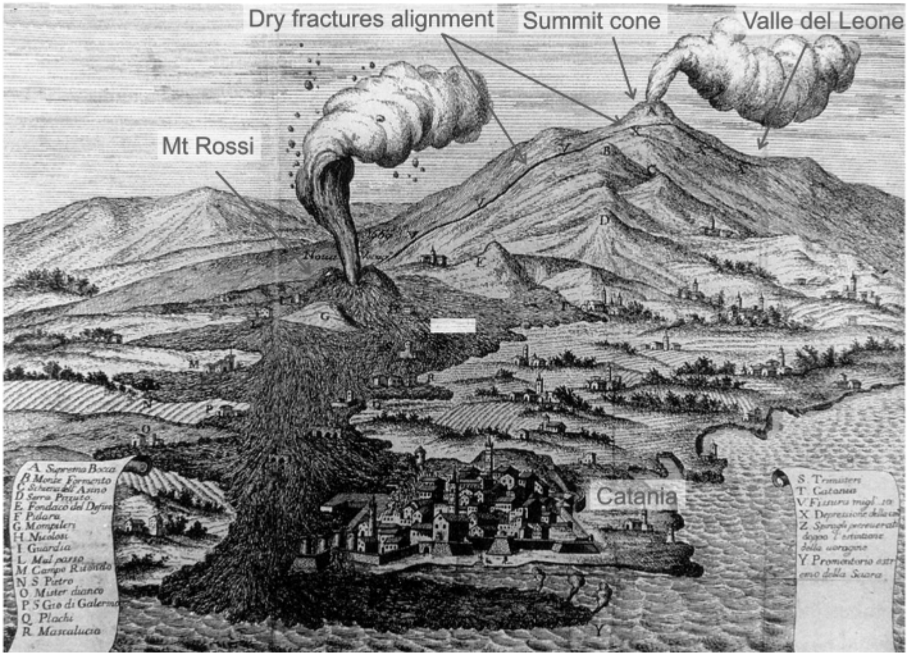

Figure 1.13. *Lava flow of Etna, coming from Mt. Rossi, entering the city of Catania in 1669. Copper engraving (1792) by Alfonso Borelli (1670) (from Branca and Abate 2019)*

Historical chronicles can sometimes replace or be extended by oral tradition (Cashman and Giordano 2008 and references therein), such as in Kilauea where Hawaiian oral tradition complements written historical chronicles dating back only to 1794 (Swanson 2008), or for countries where a rich oral tradition holds greater sway than the written word such as in the Comoros (Allibert 2015) or Indonesia (Troll et al. 2015).

1.5. The work of the pioneers

The descriptions left by geologists, volcanologists, geographers or scientists of the 18th and 19th centuries deserve an attentive reading. They relate, often with great precision, facts, events or landscapes today inaccessible to observation. We will highlight here three prominent figures who have each marked the history of volcanology: Professor Alfred Lacroix, the naturalist Jean-Baptiste Bory de Saint-Vincent and the ambassador William Hamilton. The work of another prominent figure, Thomas Jaggar, founder of the Hawaiian Volcano Observatory, will be discussed in Chapter 4.

1.5.1. *Alfred Lacroix*

Alfred Lacroix's descriptions (see Figure 1.14) of the eruptions of Mount Pelée in Martinique in 1902–1903, or those of Piton de la Fournaise on Reunion Island, are essential writings for understanding the eruptive history of these volcanoes. In May 1902, after the volcanic eruption in Martinique that killed 28,000 people, the Academy of Sciences and the Ministry of Colonies decided to send a mission to the West Indies to study the circumstances of the disaster. It arrived on June 23 and was led by Alfred Lacroix. Following a new deadly eruption on August 30, Lacroix, who had just returned to Paris, made a new trip to Martinique and stayed there until March 1903. At a time when volcanology was still in its infancy, Lacroix made essential observations for the understanding of volcanoes by describing eruptive manifestations that were unknown until then, such as the devastating pyroclastic flows, as well as the growth and destruction of the domes and spines that marked this eruption.

In 1911, he studied the Piton de la Fournaise on Reunion Island, a volcano of a different type from those of the West Indies. He drew up an inventory of the eruptions, which remains today the only source of knowledge for many eruptions of the 19th century and the beginning of the 20th century. He also described the evolution of the Dolomieu crater at Piton de la Fournaise between 1911 and 1938 (see Box 1.2), a period during which a major collapse took place, comparable in many ways to the one that, 70 years later, in 2007, was the object of much scientific attention (Michon et al. 2007, 2011; Peltier et al. 2009b; Staudacher et al. 2009). Lacroix worked hard for the creation of volcanological observatories that he had endowed with substantial resources. It is therefore partly thanks to him that France has one of the most efficient networks for volcanic risk mitigation.

A professor at the National Museum of Natural History in Paris, he wrote, among others, *Minéralogie de la France et de ses Colonies*, as well as *Minéralogie de Madagascar*, in which he described numerous mineral species, but in volcanology his major contributions are *La Montagne Pelée et ses éruptions*, published in 1904, and *Le Volcan actif de l'île de La Réunion et ses produits*, published in 1936[3].

Figure 1.14. *Alfred Lacroix (1863–1948), renowned mineralogist and geologist*

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[3] See http://roches.mnhn.fr/bio/lacroixbio.htm.

1.5.2. *Jean-Baptiste Bory de Saint-Vincent*

Jean-Baptiste G.M. Bory de Saint-Vincent (1778–1846) was a great traveler who visited the volcanic islands, taking advantage of the great expeditions around the world that marked the 17th century. Bory de Saint-Vincent (see Figure 1.15) was a naturalist and therefore, at that time, a polyvalent: botanist, geographer and volcanologist. He described in great detail the Piton de la Fournaise, of which he made the first ascent of the summit on October 25, 1801. His descriptions of its summit area allow us to become aware of the activity of this volcano in the 18th century. Marked by the existence of a lava lake at the summit crater and the formation of a vast lava field, probably during long-lasting eruptions (Lénat et al. 2001), this type of activity differs significantly from the one we know today for this volcano (see Box 1.2).

He opened the way to scientific research on the Piton de la Fournaise. His work *Voyage dans les quatre principales îles des mers d'Afrique*, published in 1804, contains numerous observations of the central zone of that volcano, and also of the littoral zone with its numerous recent flows, today buried under vegetation or by other more recent flows.

Figure 1.15. *Bory de Saint-Vincent (1778–1846)*

The collapse, over 300 m deep, of the summit caldera of Dolomieu at Piton de la Fournaise in April 2007, has revealed formations that were previously inaccessible to observation. This natural section, revealing the recent history of Piton de la Fournaise, has aroused great interest and led to a re-evaluation of the history of the volcano's summit over the past three centuries.

The approach combines a lithostratigraphic interpretation of these new outcrops and the crater periphery, made possible by the acquisition of high-resolution photographs, with a detailed examination of historical (post-1640) documents in which the morphology or eruptive activity of the summit zone is described (Peltier et al. 2012; Michon et al. 2013).

This comparison of iconographic documents and geological observations (Figures 1.17–1.19) has allowed us to make a new contribution to the knowledge of the history of the building of the terminal cone of Piton de la Fournaise. The changes in the eruptive dynamics of the volcano are described, with the construction of an ancient cone during which phases of explosive activity dominated, followed by a more effusive period, itself subdivided into two periods. Links with the successive collapses of the summit crater (or caldera) can also be established. The current phase of activity following the collapse of 2007 can thus be evaluated by considering this past functioning.

These studies show, in particular, that the activity of Piton de la Fournaise has recently evolved. During the 18th and 19th centuries, the eruptive activity was characterized by several sustained, long-lasting, effusive eruptions, associated with frequent phreatic explosions and ending with phreatomagmatic explosions. On the other hand, the 20th century and now the 21st century correspond to periods mainly marked by periodic effusive activity, coexisting with minor phreatic explosions during summit collapses resulting from lateral eruptions.

The current central cone of Piton de la Fournaise was probably built quite rapidly, during a phase of sustained effusive activity (Lénat et al. 2001), essentially centered on the western summit crater (Bory) and following a period of intense explosive activity. Since the end of the 19th century, the growth of the central cone is less, and the activity has moved eastward (Dolomieu), where frequent caldera or pit-crater collapses and phases of refilling of these craters follow each other.

Box 1.2. *The history of the morphological evolution of the Dolomieu crater – Piton de la Fournaise, Reunion Island*

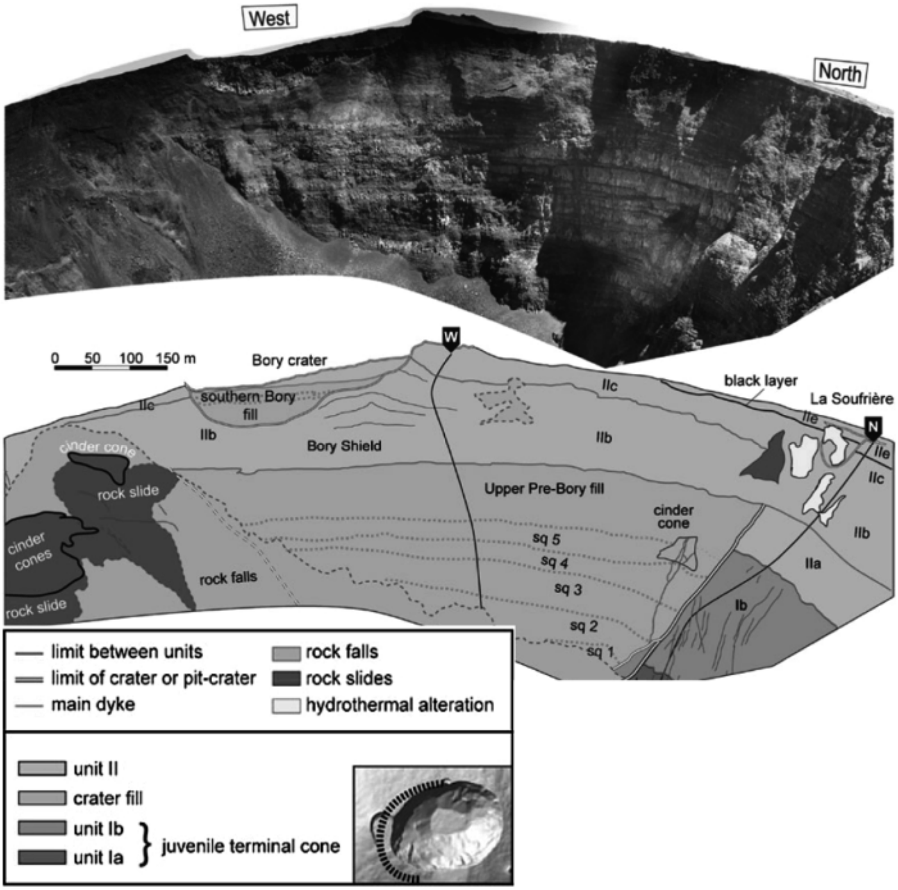
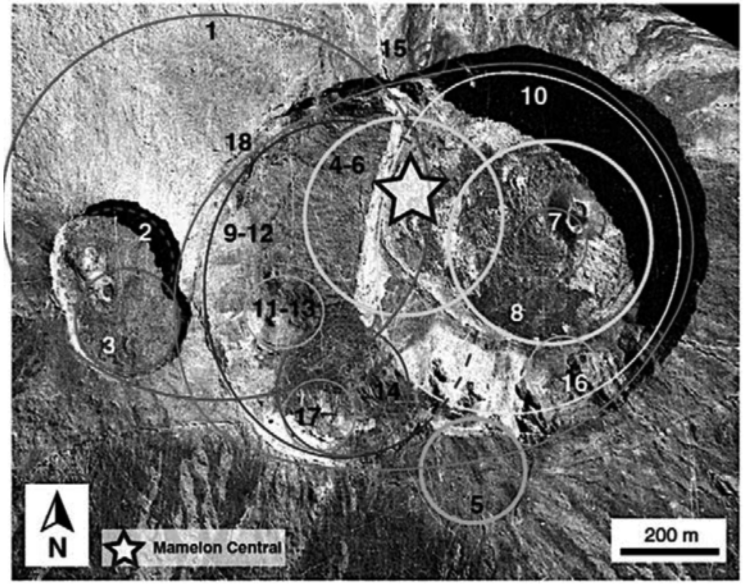


Figure 1.16. *Panorama and interpretation of the formations in the western wall of the Dolomieu crater. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.16.– *Mosaic of photographs taken in September 2009. Units in green correspond to emissions from the Bory and Dolomieu craters. The blue units represent the refilling of an older crater, revealed by the 2007 collapse (from Peltier et al. 2012).*



ID number		Date	Name
1	——	<1708	"Cratère Ouest"; Pre-Bory pit crater$_b$
2	- - -	1708/51	Bory crater$_c$
3	——	?	
4	——	1759	"Crater of 1766"$_d$
5	——	1791	"Bouche nouvelle"$_{d\,:\,1791-1801}$; Dolomieu crater$_{c\,:\,1801-1878}$; Petit Plateau pit crater$_b$
6	——	1812	
7	——	1821/44	"Brûlant crater"$_{e\,:\,1851-1860}$
8	——	1860	"Brûlant crater"$_{e\,:\,1860-1878}$; Dolomieu crater$_{f\,:\,1878-1931}$
9	——	1874	Enclos Velain$_{g\,:\,1911-1980}$; Dolomieu crater$_{h\,:\,1980-2007}$
10	——	1931/35	"Brûlant crater"$_{h\,:\,1931-1980}$; Dolomieu crater$_{h\,:\,1980-2007}$
11	——	1933	---
12	——	1934/35	---
13	——	1953	---
14	——	1961	---
15	——	1964	Soufrière pit crater$_h$
16	——	1986	---
17	——	2002	---
18	——	2007	Dolomieu caldera$_g$

a : Lénat et Bachèlery (1990) ; b : Michon *et al.* (2009) ; c : Bory de Saint-Vincent (1804) ; d : Lacroix (1936) ; e : Maillard (1853) ; f : Velain (1878) ; g: Lacroix (1912) ; h: Bachèlery (1981) ; i : Michon *et al.* (2007)

Figure 1.17. *Delineation of the successive collapses at the summit of Piton de la Fournaise, identified from historical documents and scientific literature. The overlapping of the different collapses is clearly visible. The area collapsed in April 2007 (orange line) includes all the collapses of the last 300 years (from Michon et al. 2013). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

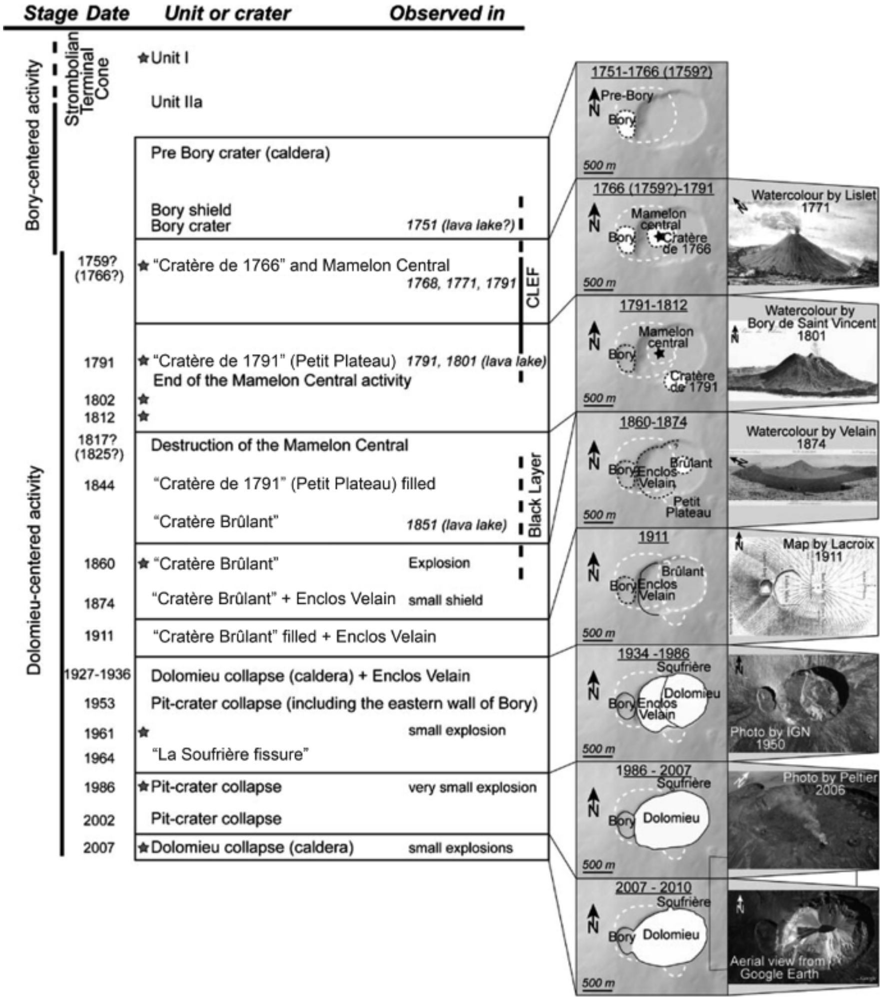


Figure 1.18. *Summary of the historical activity of the Piton de la Fournaise, compared with the morphological evolution of the summit of the Piton de la Fournaise deduced from available iconographic documents. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.18.– *The red stars represent the most explosive phases. Distinct periods define the major changes. White dotted lines and white areas define filled or active craters for each period (from Peltier et al. 2012). Reproduced watercolors and drawings are from Bory de Saint-Vincent (1804), Vélain (1878) and Lacroix (1936, 1938).*

1.5.3. *William Hamilton*

Nothing predestined William Hamilton (1731–1803) (see Figure 1.19), a Scottish aristocrat and British ambassador to the Kingdom of Naples, to become one of the world-renowned volcanologists of his time. From 1765 to 1779, he witnessed several eruptions of Vesuvius and faithfully described their progress. He reported on these observations through regular publications in the *Philosophical Transaction of the Royal Society of London*, the first of which in 1768 (Hamilton 1768) marked his entry into the scientific world.

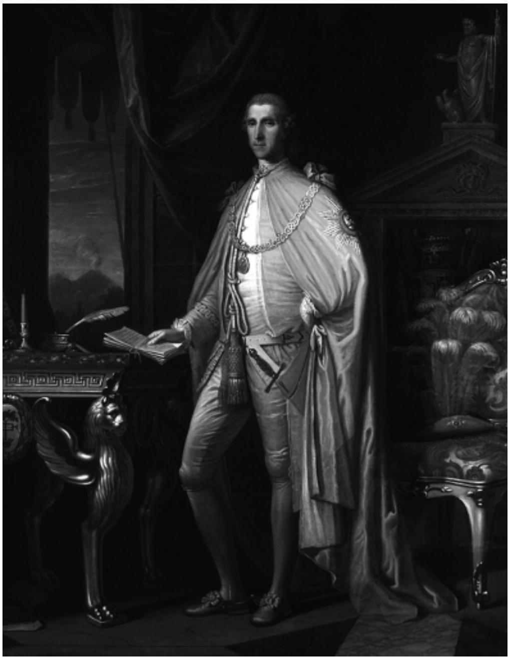


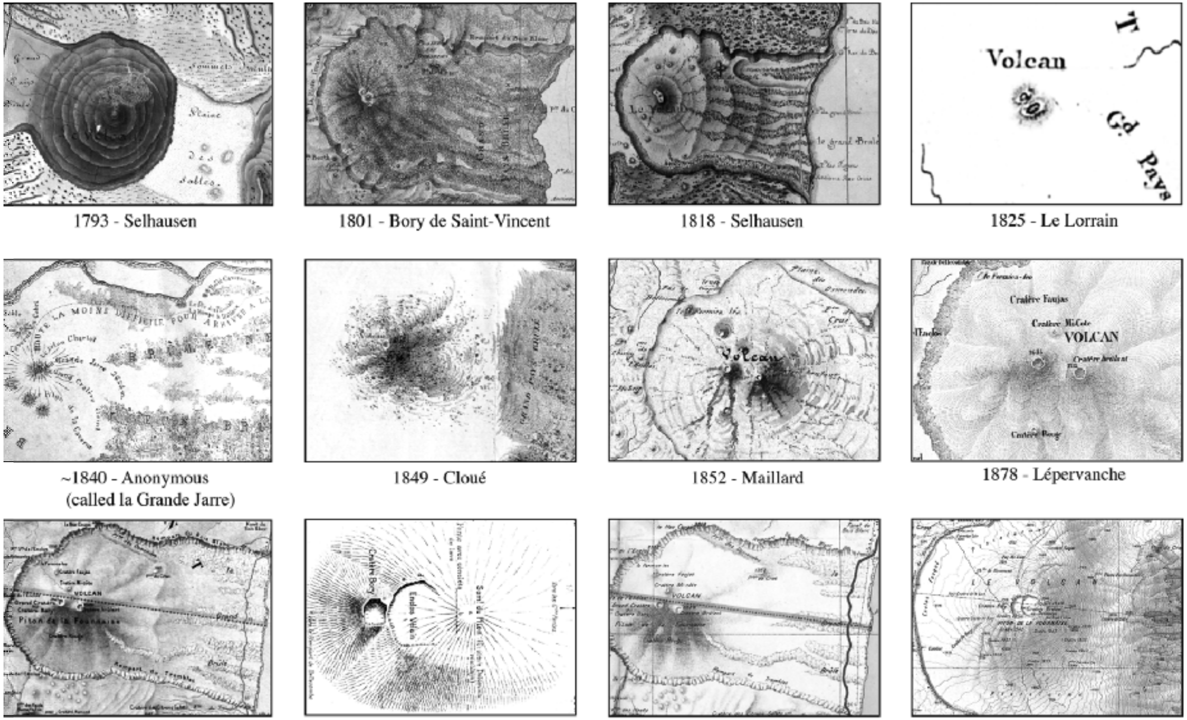
Figure 1.19. *Sir William Hamilton by David Allan*

In 1776, he published his contributions in a book entitled *Campi Phlegraei*, accompanied by numerous illustrations in gouache by Pietro Fabris. This work of great scientific interest allows us to visualize the morphological evolution of Vesuvius and its crater and to follow the sequence of eruptions of this volcano, which today we describe as violent strombolian to effusive. This work was completed with a supplement in 1779 relating the exceptional eruption of that same year (see Figure 1.20).

Figure 1.20. *The eruption of Vesuvius on the morning of August 9, 1779. An impressive eruptive column rises above the crater. Reproduction of a gouache by Pierre Fabris in Pausilippe*

1.6. The contribution of old maps

The use of old maps also provides a lot of information on the transformations that volcanoes have undergone over time. Their accuracy increases, of course, as the means of cartography improve. The imprecision of the oldest documents sometimes requires a lot of precaution before they can be used. Old maps provide information about how people of the time perceived their space and the importance they gave to places. In this respect, volcanoes often take an important place because they are a strong element of the landscape and of the life of the inhabitants. The maps constitute milestones in the chronology of events structuring a landscape, marking the main changes in geography, and also depending on the evolution of techniques of perception and representation of space (see Figure 1.21). On Reunion Island, this evolution is particularly noticeable. Iconographic and cartographic representations of Piton de la Fournaise evolve over time, moving from a cartography of discovery of then-unknown spaces, struggling to precisely circumscribe the location and morphology of the volcano, to a cartography constructing a conceptual image of the volcano, refined as mapping techniques advance (Germanaz 2005, 2016).



1793 - Selhausen

1801 - Bory de Saint-Vincent

1818 - Selhausen

1825 - Le Lorrain

~1840 - Anonymous (called la Grande Jarre)

1849 - Cloué

1852 - Maillard

1878 - Lépervanche

1906 - Ulysse Robert

1911 - Lacroix

1935 - Geographical Service of Madagascar

1957 - IGN

Figure 1.21. *Evolution and cartographic representation of Piton de la Fournaise on old maps of Reunion Island (1793–1957). This period clearly shows the growth of the Dolomieu crater (formerly “Cratère Brûlant”) at the expense of the Bory crater (document Germanaz 2016). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

From being purely descriptive of the landform, the 18th century planimetric maps quickly evolved toward the first geological maps representing the most striking flows of the time, whether at Etna (Branca and Abate 2019) or on Reunion Island (see Figure 1.22) and the Comoros (Bory de Saint-Vincent 1804; Lacroix 1936, 1938). They are an important tool in volcanic risk management (Leone and Lesales 2006).

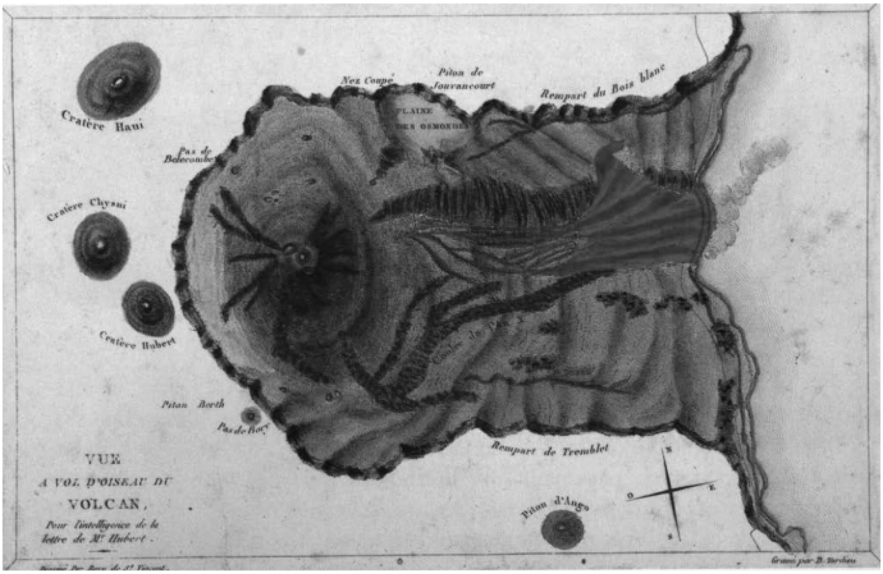


Figure 1.22. *Cartographic representation of the eruption of the year X (1801–1802) at Piton de la Fournaise (Bory de Saint-Vincent 1804). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

1.7. Volcanic archeology

The behavior of populations in the face of natural disasters (the combination of their knowledge of hazards, their perception of risk, the past experiences and the way situations make sense, and their compliance with instructions) is a determining aspect in terms of risk. Volcanoes are no exception to this logic, and there is a growing body of work in the humanities and social sciences on these issues (Morin et al. 2016; Fearnley et al. 2018; Avvisati et al. 2019). Questions regarding the behavior of populations faced with eruptions can also be addressed from past eruptions, in what can be called volcanological archeology. The examples are numerous. We refer to the work of Cashman and Giordano (2008) for a compilation as well as the special issue of the journal *Quaternary International* (Sevink et al. 2019 and references cited).

In recent years, the Huaynaputina eruption of February-March 1600 in southern Peru (VEI 6) has been the focus of a major archeological project. This eruption was one of the largest historical Plinian eruptions and the most voluminous eruptive event in the history of South America, causing a global cooling of 1.1° and the burial of numerous Inca villages (more than 12 already identified), in an area 75 km east of Arequipa. The Plinian phase produced about 15 km^3 of pumice fallout over an area covering more than 400,000 km^2, according to field data and the interpretation of Spanish chronicles (Thouret et al. 2002; Prival et al. 2020). Archeologists have been able to uncover evidence that the area was inhabited at the time of the eruption, based on fragments of ceramic pots and vessels found within the fallout. Here, volcanologists are working with archeologists to uncover these lost villages. Various geophysical techniques such as geo-radar, electromagnetic methods and thermal imagery allowed to identify the Inca infrastructures buried under the pyroclasts.

The research undertaken in Pompeii, in the ruins of the city destroyed by the eruption of Vesuvius in 79 CE, now has a completely different scope since it allows us to link the different phases of the eruption, deduced from the study of the deposits and historical documents, to the situation and possible attitude of the victims buried under the pumice fallout.

Were the inhabitants of Pompeii in 79 CE unlucky? Yes, certainly. We have seen (see section 1.4.2) the low frequency of Plinian eruptions, such as that of 79 CE. Moreover, the geological archives left by past eruptions of Vesuvius have shown that the fallout from explosive eruptions, since the Plinian eruption of Avellino about 3,700 years ago, has spread mainly east and northeast (Andronico and Cioni 2002; Sulpizio et al. 2010), with the prevailing winds in the region being mainly westerly. The deposits left by the first phase of the 79 CE eruption show an unusual extent to the southeast and south, thus directly concerning the city of Pompeii. The 79 CE eruption had two main phases: first, a Plinian eruptive column that caused widespread tephra fallout; then, a column collapse phase that generated pyroclastic density currents (Sigurdsson et al. 1985). Although both phases caused casualties, the eruption was not continuous, which could have caused the inhabitants still present in Pompeii during the first phase to leave their homes (Scarpati et al. 2020). Nearly half of the victims were in the streets and on the roads during the second phase of the eruption (Luongo et al.

2003a, 2003b). Important excavation work has been undertaken in ancient Pompeii, allowing, among other things, to propose an alternative for the exact day of the eruption of 79 CE (October 24 instead of August 24). This work also showed that a significant proportion (≃38%) of the victims died in their homes, during the first phase of the eruption, due to the collapse of the flat roofs of their houses under the weight of the pyroclastic deposits accumulated in large quantities due to that peculiar wind regime (Luongo et al. 2003b). This observation led the authorities in charge of civil protection to modify the so-called “red zone” delimited in case of a major eruption.

1.8. Eruptive dynamics, types of eruptions, structural evolution: the use of volcanic “archives” through geological field interpretation

The reconstruction of the history of volcanoes over long periods of time implies, of course, a geological analysis of the products emitted by past eruptions. This usually begins with the interpretation of the geological sequences and the characterization of the processes that led to their formation. Magmatic or igneous rocks are present in a wide variety of lithological facies. They are not only the result of a simple cooling and crystallization process but also the product of flow, fragmentation, sedimentation and reworking phenomena that often reflect complex eruptive regimes. Field geology requires its own learning, especially for volcanic rocks that often constitute geological units of small extent, with multiple facies changes, sometimes within the same unit. Contrary to what is often assumed, it is often more difficult to correctly interpret a sequence of pyroclastic fallout and flow that can be partially reworked (see Figure 1.23) than to mathematically solve a physical problem. This implies observation and interpretation skills that must be based on a learning and knowledge that, unfortunately, is often far too absent in our university teaching.

The field work must allow the characterization of the geological formation in situ, in its context and with respect to its environment. This is a fundamental prerequisite for any laboratory analysis carried out on the samples collected. This fieldwork will also allow us to establish the relationships between the units and their relative chronology. This is obviously an essential aspect of the reconstruction of the eruptive history of a volcano. “If the knowledge of the field geology is poor, all studies based on collected samples and field measurements will also be poor. Conversely, a good understanding of the field geology provides the basis for good geologic interpretation” (Jerram and Petford 2012).

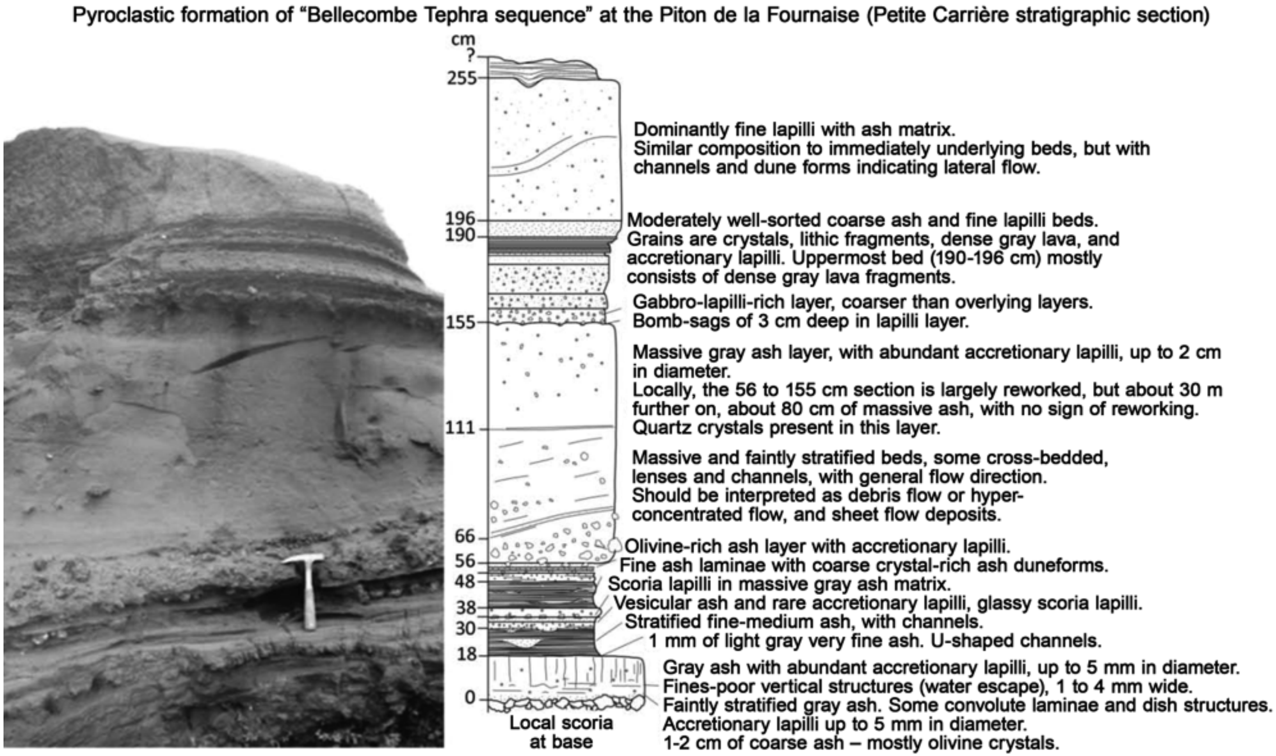


Figure 1.23. *a) Photo of deposits and b) stratigraphic column of one of the main outcrops of the “Bellecombe Tephra sequence” at the Piton de la Fournaise in on Reunion Island*

COMMENT ON FIGURE 1.23.– *This deposit is mainly the result of phreatomagmatic explosions that produced breccias, pyroclastic flows, and ash and lapilli fallout. The upper part of the Bellecombe Tephra sequence contains numerous hydrothermally altered fragments indicating the involvement of a mature, deep-seated hydrothermal system (photo: P. Bachèlery, after Ort et al. 2016).*

Volcanic rocks, derived from magmas emitted on Earth's surface, are directly the result of eruptions. These rocks are therefore the essential keys to decipher the eruptive history, even if intrusive or plutonic rocks, emplaced at various depths, are also part of this history. The study of the deposits on land is often extended by the study of these same deposits at sea, in order to obtain the most accurate knowledge of the whole geological record.

The work carried out on La Soufrière on Guadeloupe shows how much knowledge of the activity of this volcano has progressed since the phreatic eruption of 1976. Studies of deposits on land (Boudon et al. 1988) and at sea (Deplus et al. 2001; Boudon et al. 2007) have characterized the volcanic and tectonic activity of the volcano over the last 9,000 years, highlighting the exceptional recurrence of catastrophic flank landslides, all related to magmatic activity (Komorowski et al. 2005; Boudon et al. 2007; Komorowski et al. 2008). Today, a detailed chronology of the eruptive history of the Grande Découverte-La Soufrière complex on Guadeloupe exists even for the last 50,000 years (Legendre 2012; ANR CASAVA Final Report) (see Figure 1.24).

The chronostratigraphic data, in particular the characterization of turbulent and dilute pyroclastic flow deposits, allow to characterize not only the frequency and the magnitude of the magmatic activity, but also the chain of events (dome growth, explosive phases, flank destabilization and directed explosions). This shows that most eruptions consist of multiple phases with time-varying eruptive regimes, following an eruptive scenario that could be analogous to that of the 1980 Mount St. Helens eruption (Lipman and Mullineaux 1981) or the Soufrière Hill eruption on Montserrat (Sparks and Young 2002; Voight et al. 2002).

Examples of geological reconstructions of volcano activity are numerous in the literature. In a different context from that of the West Indies, one can cite the evidence of alternating Strombolian and violent Strombolian dynamisms at Antuco volcano in Chile (Romero et al. 2020) or the evidence of pyroclastic flows at Stromboli (Lucchi et al. 2019). This work of "reading" the volcanic archives allows us to recognize the different "modes of expression" of the volcano, the types of eruptions it has experienced in the past, the structural and dynamic characteristics and the temporal relationships between these different types of eruptions.

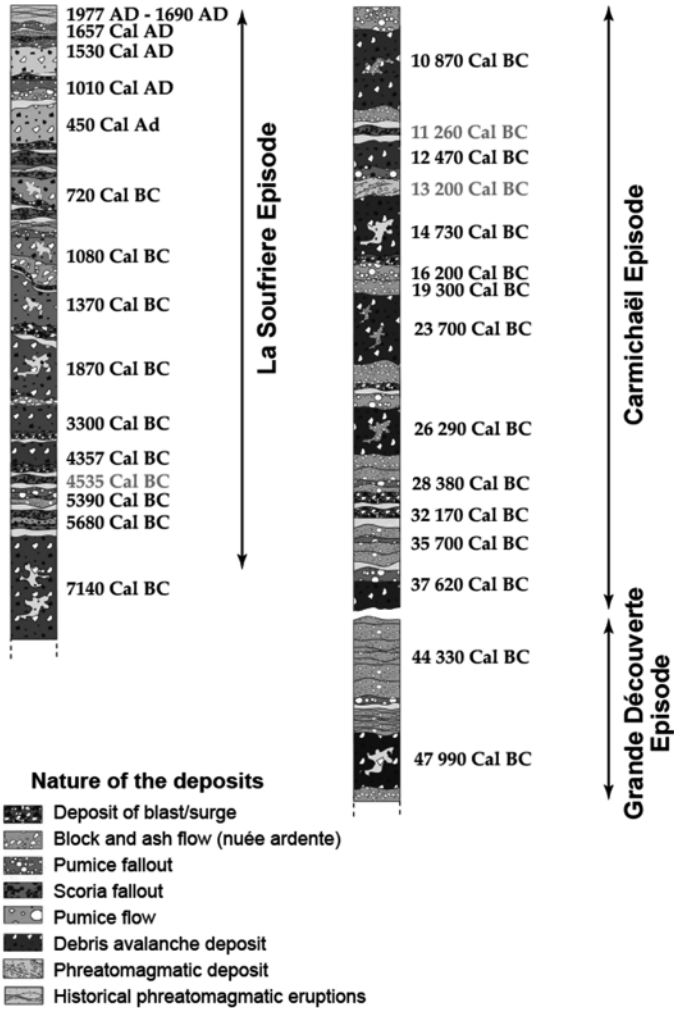


Figure 1.24. *Synthetic log of the eruptive stratigraphy of the Grande Découverte-La Soufrière complex over the past 50,000 years. Shown in green are the three explosive events of the Madeleine-Trois-Rivières complex (Legendre 2012). Extract from the final report of the ANR CASAVA[4] project. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

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[4] https://sites.google.com/site/casavaanr/.

On a basaltic volcano like Piton de la Fournaise, the operational monitoring strategy is going to be adapted according to the different types of eruptions the volcano has experienced in the past. Although explosive paroxysms are known (Bachèlery 1981; Morandi et al. 2016) (see also Figure 1.23), the reconstruction of the eruptive history of Piton de la Fournaise shows that the most common eruption type for this volcano in the current period is the emission of lava flows from lateral fissures, opening on the flanks, and emitting small amounts of pyroclastic material (Bachèlery 1981; Lénat and Bachèlery 1988; Villeneuve and Bachèlery 2006; Peltier et al. 2009a; Staudacher et al. 2016) (see Figure 1.25).

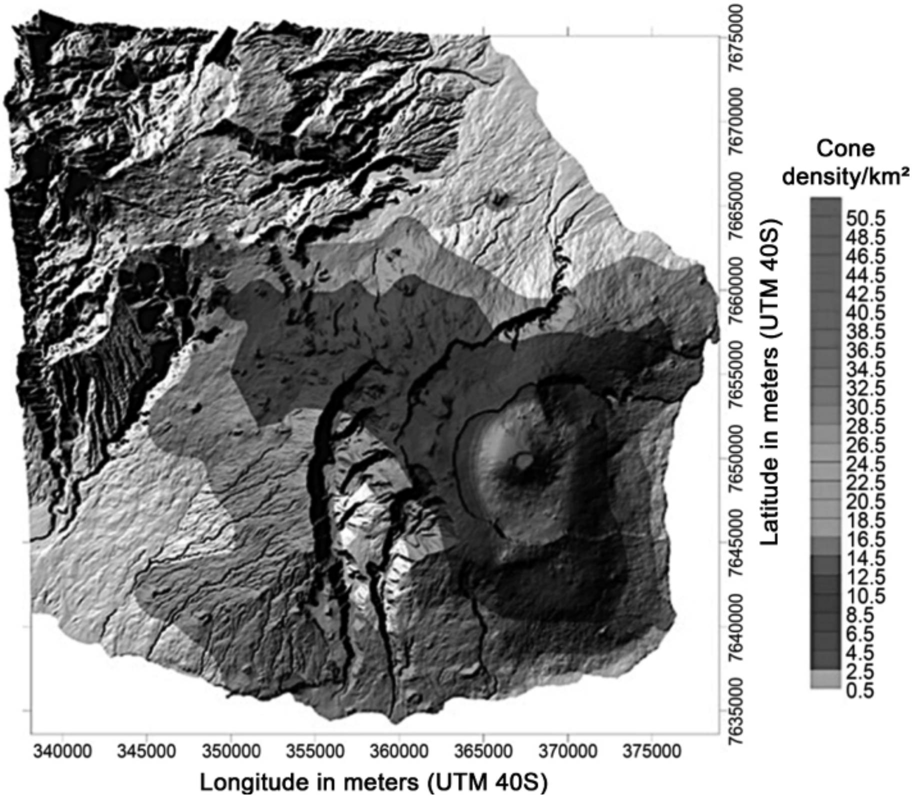

Figure 1.25. *Spatial distribution of historic and prehistoric eruptive cones and fissures on the Piton de la Fournaise volcano (extract from Villeneuve and Bachèlery 2006). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

1.9. Structural framework and evolution

The structural evolution of a volcanic edifice during the Holocene is, of course, part of its recent geological history. Two types of tectonic events are particularly important in the monitoring of currently active volcanoes, because their frequency is such that they may occur with a non-zero probability in the near future: flank landslides, which concern many volcanoes, and summit collapses forming a caldera or a pit-crater.

The importance of flank destabilizations has been highlighted at many eruptive sites regardless of their nature, based on consideration of the geology of the formations on land (Martí 2019) and also from work at sea (Le Friant et al. 2015). These events are now fully integrated into monitoring strategies.

In the case of destabilization resulting in a sector collapse, such as that experienced by Mount St. Helens in 1980, the rocks involved in the collapse form a characteristic deposit called “debris avalanche deposit”. This deposit can be recognized by a bulge in the terrestrial or submarine morphology, and by its brecciated aspect, where brecciated blocks (block facies) coexist within a brecciated matrix (matrix facies) (Ui et al. 2000; Carey and Schneider 2011; Perinotto et al. 2015). In the case of destabilization resulting from the intrusion of a viscous magma, they may be followed by a directed lateral explosion (blast). In general, these flank collapses deeply mark the volcanic morphology, leaving a characteristic horseshoe-shaped amphitheater and a large deposit that can be channeled into the valleys or spread widely in a fan at the foot of the edifice. These gravity flows, when affecting island volcanoes, are likely to generate large tsunamis (Paris et al. 2017; Pistolesi et al. 2020).

Flank collapses with debris avalanche deposits, better understood since the 1980 eruption of Mount St. Helens, are considered in potential eruptive scenarios. They have been recognized for many volcanoes in both continental and oceanic domains (Gorshkov 1959; Moore et al. 1989; Holcomb and Searle 1991; Normark et al. 1993; Carracedo et al. 1999; Day et al. 1999; Van Wyk De Vries et al. 2001; Masson et al. 2002, 2008; Mitchell 2003; Oehler et al. 2008; van Wyk de Vries and Davies 2015; Paris et al. 2018), sometimes reoccurring, whether for stratovolcanoes with differentiated magmas or for basaltic shield volcanoes. Work carried out on La Soufrière on Guadeloupe has revealed nine collapses of varying magnitude in less than 10,000 years, the last of which was in 1530

(Komorowski et al. 2008). At Mount Pelée, at least two such events are also known (Vincent et al. 1989; Boudon et al. 2013). On Reunion Island, giant flank landslides also mark the geological history of the island (Lénat et al. 1989; Oehler et al. 2008; Le Friant et al. 2011).

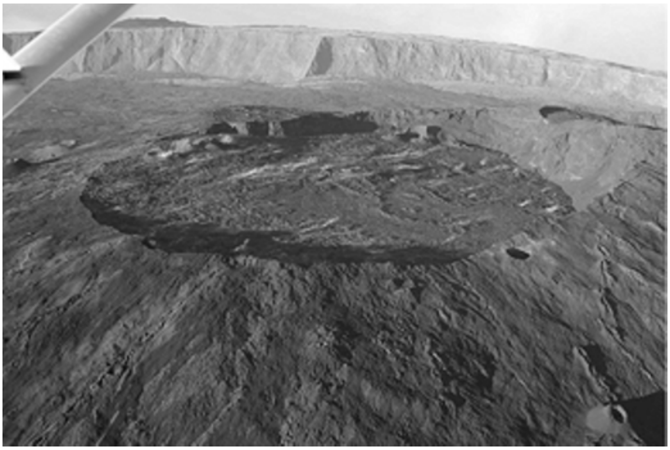

Figure 1.26. *The summit crater Dolomieu at Piton de la Fournaise (Reunion Island) on April 5, before the caldera collapse of April 6, 2007. The collapse, more than 300 m deep, took place mainly in less than 24 hours (photo: Lucette Ferlico)*

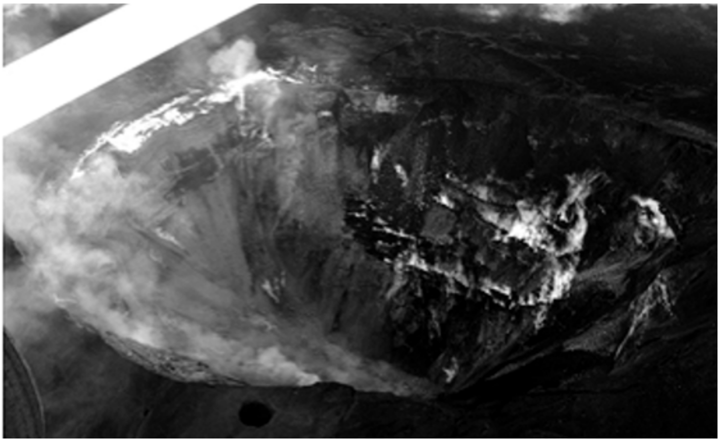

Figure 1.27. *The summit crater Dolomieu at Piton de la Fournaise on April 7. The collapse, more than 300 m deep, took place mainly in less than 24 hours (photo: Lucette Ferlico)*

While collapses affecting the summit of basaltic volcanoes and forming a so-called pit-crater are relatively common, five caldera collapses were also observed and monitored by monitoring networks during the late 20th and early 21st centuries: Fernandina, Galapagos, 1968 (Simkin and Howard 1970); Myakejima, Japan, 2000 (Geshi et al. 2002); Piton de la Fournaise, Reunion Island, 2007 (Michon et al. 2007, 2009; Peltier et al. 2009b; Staudacher et al. 2009); Bárdarbunga, Iceland, 2014 (Sigmundsson et al. 2014; Gudmundsson et al. 2016; Riel et al. 2016; Sigmundsson 2019); and Kilauea, Hawaii, 2018 (Anderson et al. 2019; Neal et al. 2019). They serve as a reference to describe and anticipate this type of major change in the morphology and structure of a volcano. Calderas are large depressions, more or less circular or elliptical, formed during the collapse of the top of the volcano following large eruptions or lateral intrusions that affect a main magma chamber located a few kilometers deep (MacDonald 1965). The collapse of the Dolomieu caldera at Piton de la Fournaise in 2007 (see Figures 1.26 and 1.27) occurred along a circular fault system and is clearly attributed to the emptying and incremental collapse of the roof of a magma chamber located at shallow depth (Michon et al. 2007, 2011; Massin et al. 2011). These events, although infrequent, must be considered in monitoring strategies. At Piton de la Fournaise, at least two collapses of the Dolomieu caldera have occurred in the last 100 years (see Box 1.2).

1.10. The use of distant archives

1.10.1. *The record of large eruptions in marine and lake sediments*

Tephrochronology, often used in the near field to determine the history of volcanoes, can also be addressed for medium- to long-distance areas. Marine (Bazin et al. 2019) and lake sediments (Lane et al. 2011, 2013), or speleothems (Bazin et al. 2019), are excellent archives for tephra and can provide a detailed record of Quaternary explosive volcanism.

Volcanic sequences described on land may be incomplete due to erosion, or made inaccessible because they are covered by younger products, or simply difficult to interpret due to dense vegetation cover, especially in the intertropical zone. Distant deposits left by explosive eruptions (tephra) in cores taken from marine or lacustrine sediments (see Figure 1.28) are then of great use to reconstruct more completely the records of explosive eruptions of nearby volcanoes, allowing access to the petrology of these events or to date them (Paterne et al. 1988, 1990; Narcisi 1996; Fretzdorff et al. 2000; Hamann et al. 2010; Sulpizio et al. 2010; Gudmundsdóttir et al. 2011; Cassidy et al. 2014; Çağatay et al. 2015; Albert et al. 2017; Leicher et al. 2019). For example, a tephra layer related to the eruption of Pavin Lake (4,720 ± 170 BCE), from a few millimeters to a few centimeters thick, is found in many peatlands and lacustrine deposits in the Massif Central (Juvigné and Miallier 2016).

Figure 1.28. *Sampling and exploitation of deep-sea sediment cores on board an oceanographic vessel*

COMMENT ON FIGURE 1.28.– *The sediment cores contain pelagic or hemi-pelagic sediments rich in foraminifera, allowing a chronology to be obtained thanks to* ^{14}C *and* $\delta^{18}O$*, gravity deposits from turbidity currents, and tephra layers from the sedimentation of eruptive plumes (photos: P. Bachèlery).*

These tephra layers are made up of the accumulation of glassy or small-size pumice fragments. The fallout from the volcanic plumes, transported by the wind and then by the marine currents for the deposits at sea, can thus constitute a thin deposit on vast surfaces. Their identification is not always easy. Problems such as bioturbation, dispersal by currents and marine erosion can disrupt the preservation of marine tephra or thin volcaniclastic layers (Gudmundsdóttir et al. 2011; Cassidy et al. 2014). Collected near volcanoes or volcanic islands, more distant tephra deposits thus provide a "history" of nearby explosive eruptions, complementing the knowledge of eruptive history determined from the study of deposits conducted in the proximal domain. Many works have demonstrated the importance of these approaches and their contribution to volcanic hazard forecasting (Watkins et al. 1978; Gehrels et al. 2006; Bertrand et al. 2008; Sulpizio et al. 2008; Insinga et al. 2014).

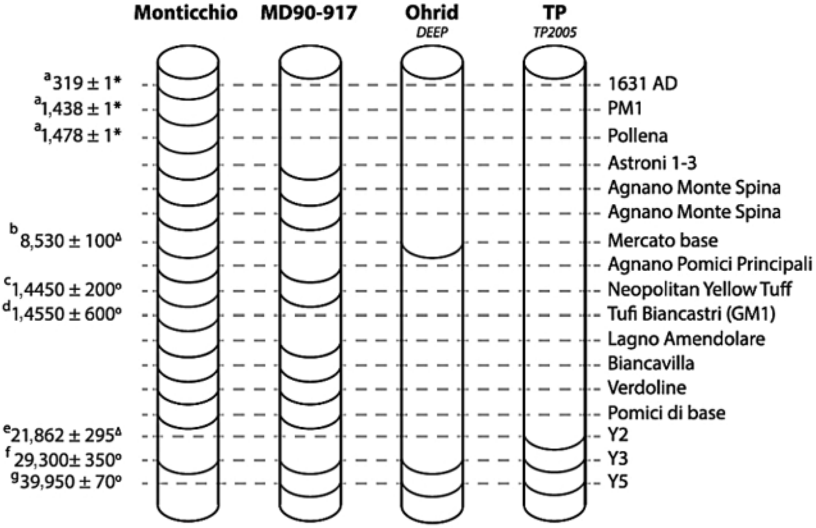

Figure 1.29. *Well-dated tephra levels identified in some terrestrial and marine sediment cores from the Mediterranean area (lake sediments: Monticchio Maar, Italy, Ohrid, Greece, and Tenaghi Philippon (TP), Turkey; marine sediments: MD90-917, southern Adriatic Sea). For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.29.– *Tephra in red are dated using* $^{40}Ar/^{39}Ar$ *or* ^{14}C *methods (from Bazin et al. (2019) – see references included).*

Another use of marine and lacustrine tephra is the correlation of (distal) deposits from very large (Plinian) eruptions and relatively infrequent explosive eruptions (Pyle et al. 2006; Bazin et al. 2019). These deposits, present over large areas, provide regional isochronous markers that can be cross-correlated over large areas. They are widely used in paleoclimate studies (Lowe 2011). While sedimentary archives, whether marine or lacustrine, can be used in many contexts, it is probably in the Mediterranean area that the greatest number of studies is available. A chronology based on major events is now established with good accuracy, from independent sources mixing data from lake sediments (varves) and data from marine sediments (Insinga et al. 2014; Bazin et al. 2019) (Figure 1.29). Tephra layers with a wide distribution are used as a reference for further work. If the Y-5 tephra is the most widespread layer in the deep-water sediments of the eastern Mediterranean (Keller et al. 1978; Pyle et al. 2006), there are several other reference layers for which the relationship with an eruption on land is more or less well-established (Zanchetta et al. 2011; Albert et al. 2015, 2017). In the Ionian, Tyrrhenian and Adriatic seas, these tephra layers serve as a basis for locating in time the main tectonic and gravity events, some of which are of direct interest to current or recent volcano activity.

In the marine realm, because volcanic environments are often tectonically active, volcaniclastic tephra deposits (of pyroclastic origin) are often associated with other types of volcaniclastic deposits, particularly on the continental slopes and flanks of volcanic islands and on the surrounding abyssal plain. These are epiclastic sediments, resulting from the degradation of lava flows and other geological units constituting the submarine or subaerial flanks of volcanoes (Manville et al. 2009; Carey and Schneider 2011; Cassidy et al. 2014). They result from the fragmentation of pre-existing rocks and can have a wide range of thicknesses and textures, depending on their origin (Carey and Schneider 2011). Volcaniclastic deposits thus originate from the transport of volcanic clasts as a result of landslides, collapses and mass flows, floods or from the entry of pyroclastic flows into the sea (Le Friant et al. 2009). They can form density currents whose deposits (turbidites) are characteristic (Bouma 1962; Piper and Normark 2009). Their diversity is inherent to the diversity of fragmentation, transport and deposition processes from which they result. For volcanic islands, they provide information about the gravity and eruptive processes that have affected the island over several hundred thousand years (Garcia and Hull 1994; Trofimovs et al. 2008; Babonneau et al. 2016; Hunt and Jarvis 2017). In sediment cores, these deposits can be interbedded with tephra fallout offering the opportunity to reconstruct the volcanic and tectonic history of a volcano or volcanic area (Schneider et al. 2001; Gudmundsdóttir et al. 2011; Köng et al. 2016; Hunt and Jarvis 2017) (see Figures 1.30 and 1.31).

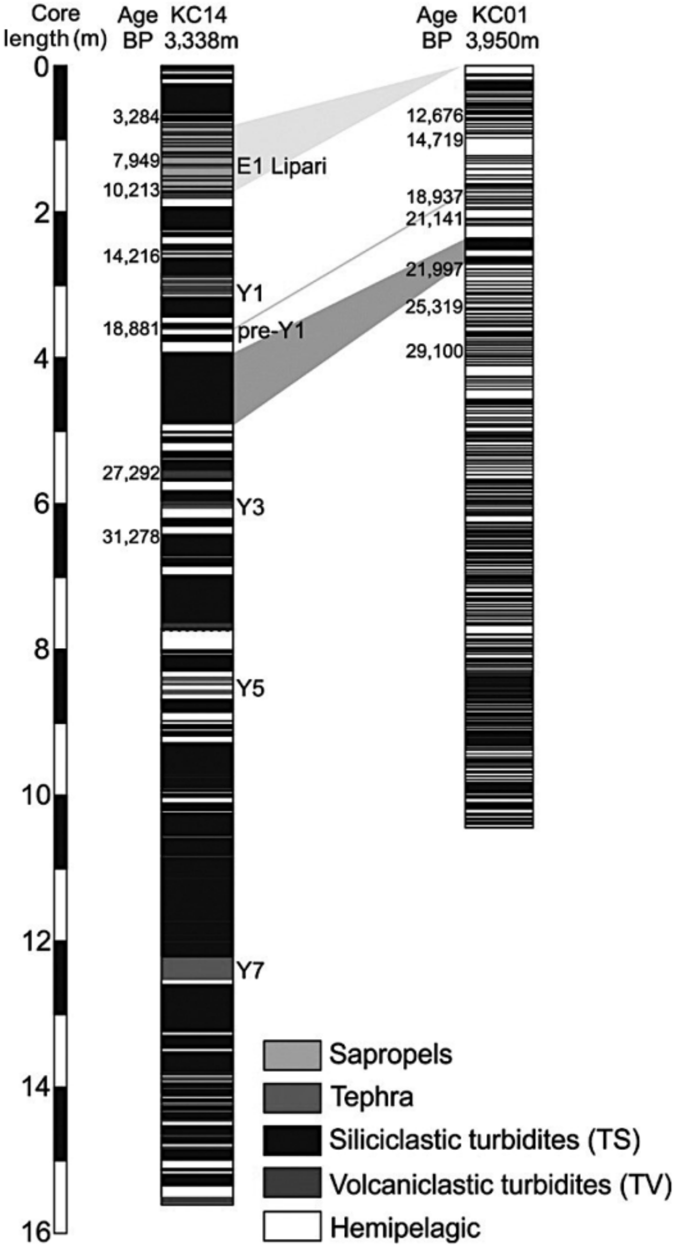

Figure 1.30. *Logs of two sediment cores taken from the Ionian Sea, down the slopes of Sicily and Calabria. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.30.– *Major gravity events in the area, particularly volcaniclastic turbidites from Etna, are identified in the chronology established using tephra layers and sapropels (organic-rich sediments). From Köng et al. (2016).*

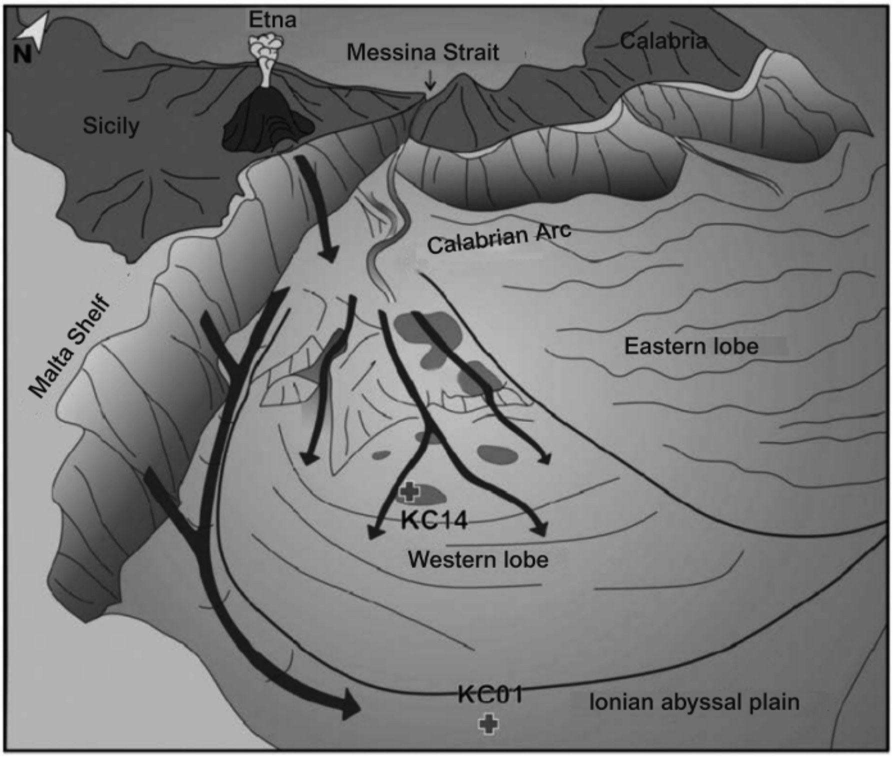

Figure 1.31. *Reconstruction of the main underwater gravity flows on the Calabrian arc (from Köng et al. (2016))*

1.10.2. *The recording of large eruptions in ice cores*

The use of polar ice cores as an archive to determine Earth's past climate is well known (Palais et al. 1987; NGICP 2004; Jouzel et al. 2007).

Ice cores, taken from the polar ice caps (Antarctica and Greenland), or from high altitude glaciers, are archives of the past climate, and also of the major internal and external events that have affected our planet or, for the recent period, of the human-induced industrial upheavals. Tephrochronology in ice cores is, for instance, a method used to study Icelandic volcanoes (Moles et al. 2019). Year after year, the accumulation of snowfall on Icelandic glaciers and ice caps traps ambient air, pollens and other particles in successive layers allowing their dating and the constitution of this frozen chronological archive. The oldest continuous ice cores can be dated back 123,000 years in Greenland and 800,000 years in Antarctica. The nature of the particles trapped in these cores varies according to the area from which they were taken.

Tephra ejected by eruptions powerful enough to send fragments and aerosols around the world are preserved in the cores, allowing them to be dated (Oppenheimer 2003; Davies et al. 2010; Narcisi et al. 2010). Thus, records of eruptions such as those of Vesuvius in 79 CE, Huaynaputina in 1600, Tambora in 1815, Krakatau in 1883 or El Chichon in 1982 have been identified in ice cores (see Figure 1.32) (Zielinski et al. 1997). The discovery of glassy particles associated with a particularly high volcanic sulfate aerosol record, found in Greenland and Antarctic ice cores, is also at the origin of the discovery of the Samalas eruption in 1257 (see section 1.1.1). The profound climatic changes from 43 and 42 BCE, which were among the coldest years in the Northern Hemisphere in recent millennia and marked the beginning of one of the coldest decades, are attributed to an eruption of Okmok volcano in Alaska (McConnell et al. 2020). These authors suggest that the climatic effects of this eruption may have induced the fall of the Roman Republic and led to the rise of the Roman Empire. In addition to identifying past eruptions, the work done on the cores can also provide complementary data on current major eruptions, as for the 1991 Pinatubo eruption with the estimate of the sulfur dioxide (SO_2) flux from ice core measurements (Cole-Dai et al. 1997). These approaches provide an opportunity to quantify the role of volcanism in ongoing climate change and to contribute to the study of the long-term relationship between eruptions, particularly very large eruptions, and climate variability.

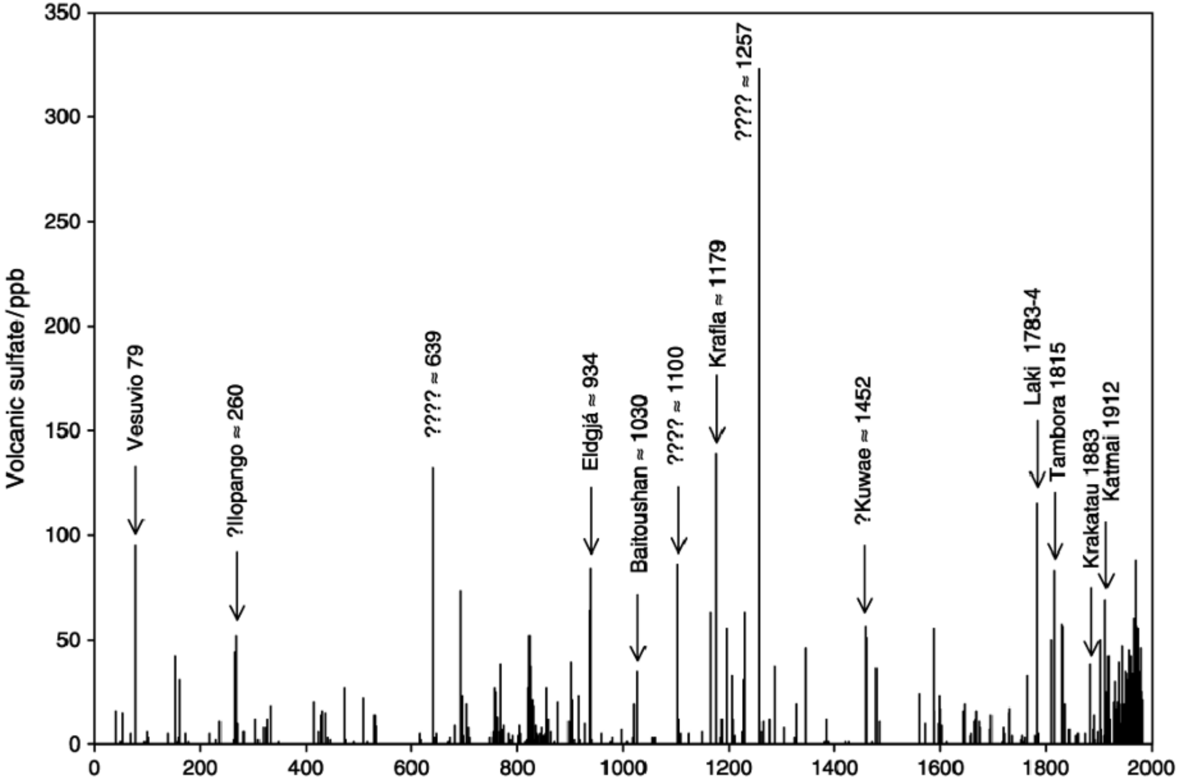

Figure 1.32. *Volcanic sulfate record in the GISP2 core (Greenland) for the first 20 centuries of our era*

COMMENT ON FIGURE 1.32.– *While many eruptions can be traced, several anomalies, including that of 1257, were not yet assigned to a specific volcano (see section 1.1.1) (after Oppenheimer 2003, origin of data and methods are presented in the publication).*

1.11. From the knowledge of a volcano's past to the identification of an operational monitoring strategy and the assessment of volcanic risks

We have thus seen various aspects of the construction of the geological history of volcanoes. By definition, this is a largely multidisciplinary task, as the approaches are so varied. This work must serve several key objectives of volcano monitoring:

– to bring a basic knowledge on the magmatic sources, types of magmas, their possible evolution and residence times, determining parameters to evaluate the rheological properties of magmas, their richness in gas;

– to establish the structural framework of the eruptions, the modalities of the magmatic injection, the existence of destabilization of the volcano flanks in the past, in connection or not with the eruptions;

– to evaluate the variability of eruptive regimes and the diversity of eruption styles, to establish a spatial and temporal mapping of hazards;

– to appreciate chronological variability and timescales.

All this knowledge allows us to establish strategies for geophysical and geochemical monitoring of a volcano, to establish scenarios for future eruptions, necessary for the constitution of risk management plans by the authorities and to make a diagnosis of the state of the volcano before and during an eruption.

When in 1977, following the eruption that partially destroyed the town of Piton Sainte-Rose, the decision was made to establish a volcanological observatory on Reunion Island (see Figure 1.33) to carry out operational monitoring of Piton de la Fournaise, geological knowledge of this volcano was limited. The chronology of the eruptions was partially known, in particular thanks to the work of Lacroix (1936, 1938) and to various reports published during the 1960s and 1970s. However, the diversity of eruptions, their spatial distribution, the sequence of events and their dynamic and petrological characteristics, necessary for the reflection that led to the setting up of the first observation networks, were the subject of work initiated to clarify the history of this volcano. From this work, and from the experience acquired by volcanologists at Kilauea in Hawaii, a volcano with similarities to Piton de la Fournaise, the first components of the observation and measurement strategy for monitoring were forged (Kornprobst et al. 1979; Bachèlery 1981; Chevallier et al. 1981; Chevallier and Bachèlery 1981; Bachèlery et al. 1982; Lénat and Aubert 1982; Bachèlery and Montaggioni 1983; Lénat and Bachèlery 1988). Thus, the conditions of lateral migration of magma toward short rift-zones with a fan-like morphology, the feeding of these eruptions by small magmatic reservoirs located at shallow depths under the summit of the volcano and the existence of recurrent explosive phases in the history of the volcano could be determined, offering the first pieces of a volcanic risk assessment (Villeneuve and Bachèlery 2006).

Figure 1.33. *The Piton de la Fournaise volcano observatory in the 1980s (photo: Jean-François Lénat)*

Today, probabilistic volcanic hazard assessment is becoming increasingly important (Marzocchi et al. 2004; Hincks et al. 2014; Connor et al. 2015). Based on the knowledge of the geological history of a volcano, it enables us to establish a probability of occurrence of the different types of eruptions, thus allowing a more quantitative anticipation of eruptions and facilitating the dialog with national or regional authorities in charge of civil security. Probabilistic risk maps for the various types of hazards identified for a volcano are now an important communication tool for raising awareness of volcanic risk (see Chapter 3).

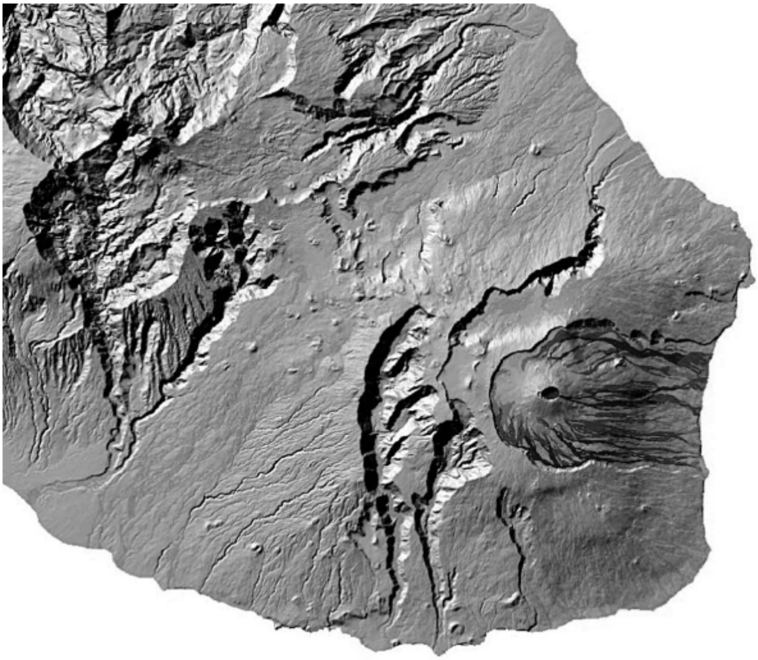

Figure 1.34. *Vulnerability map, derived from numerical simulations showing the probability of an eruptive fissure opening and the path of the associated flows, according to the type, location and frequency of past eruptions. For a color version of this figure, see www.iste.co.uk/lenat/hazards.zip*

COMMENT ON FIGURE 1.34.– *This type of document assesses the vulnerability of an area to lava flow invasion (from red: very high to green: low) (from Nave et al. 2016 modified).*

We began this chapter by emphasizing the importance of hazard mapping derived from the work of Crandell and Mullineaux (1978) at Mount St.

Helens, and inferred from their work on the eruptive history of that volcano. Such an approach remains more relevant than ever, with real improvements in our knowledge, in the quality of available data, in survey and imagery techniques offering high spatial and temporal resolution, in our understanding of the physics of volcanic processes, and in the computer processing of data. Simulations and models, which consider a wide range of factors, criteria and indicators to assess the probability of a particular eruptive scenario occurring, have developed in a few decades and are becoming increasingly important, also for operational monitoring purposes (see Figure 1.34). In parallel, the evolution of statistical models allows for better identification of uncertainties inherent to volcanic hazards, and a better consideration of diverse data sets, including subjective data through expert elicitation, in decision trees of volcanic events through Bayesian statistical methods (Neri et al. 2008; Hincks et al. 2014). The goal is to provide quantitative, probabilistic estimates of the occurrence and magnitude of potential volcanic events.

1.12. Conclusion

The geological history of a volcano is the knowledge base on which hazard identification and monitoring of a volcano's activity is founded. Any forecasting requires a good knowledge of the eruptive past of the volcano in order to be able to make a valid assessment of future eruptive behavior or the course of an ongoing eruption.

The acquisition of this knowledge implies approaching the history of the volcano at different temporal scales, using various types of archives. The historical activity (a few tens to hundreds of years) can be determined by the analysis of ancient works, narratives, descriptions, illustrations and archeological sites, and by the analysis of deposits left by the most recent eruptions, or of the vegetation covering them. Longer timescales (a few hundred to tens of thousands of years) are accessible from older sequences of deposits and geological structures resulting from the volcano's activity, and also by the study of more distant archives such as the record of eruptions in marine and lacustrine sediments, or by ice. Finally, the understanding of the structural and petrological context, and of the regional setting, complements this knowledge with data whose evolution is slower.

The work necessary to acquire this knowledge base must constitute the core of research on volcanoes, in addition to the geophysical and geochemical approaches implemented by volcanological observatories and research laboratories. Forecasting volcanic eruptions requires a good knowledge of the eruptive patterns specific to each volcano. This implies that each volcano be the subject of geological and volcanological studies, at the heart of which must be the determination of past eruptive dynamisms and regimes and the chronology of eruptions, in addition to geophysical, geochemical and magma monitoring (Agrinier et al. 2019).

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