Advances in Volcanology

Valerio Acocella

Volcano-Tectonic Processes

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...and the Earth becomes my throne!
(James Hetfield, 1991)

Dedicated to
Francesca, Flavia and Elena

Foreword

When Prof. Valerio Acocella asked me to write a Foreword for his book on Volcano-Tectonics (VT), I replied "… errr, OK, but I am not a volcano-tectonicist". Professor Acocella retorted that he wanted a non-VT specialist to write the Foreword as it may more-convincingly endorse the reception of the book into the general sphere of volcanology. Being a general, academic, physical volcanologist (apart from a 10-year stint on the geologic aspects of burial of high-level nuclear waste for the US Nuclear Regulatory Commission), who has spent his career on explosive eruptions and their products (except for a currently 20+-year love affair with the lava flows in large igneous provinces), this was a fair point, so I acquiesced.

The book before you by Valerio Acocella is the first of its kind. It is not that VT is new, but it has not been defined and laid out before as Valerio does here, and its importance may have been underplayed, but it should not be after this treatise. Some the world's greatest geologists have been, at times, VT specialists. I am reminded of Arthur Holmes, a believer in Alfred Wegener's continental drift hypothesis, who, in the 1930s–1940s, almost nailed what we now accept as plate tectonics and its relationship to magmatism and volcanism. Also Rein van Bemmelen in the 1940s–1950s, who, while mapping Indonesia with its overwhelmingly volcanic nature for the Dutch Government, got very close to a plate tectonic hypothesis for the controls on volcanism. But it is not just in the relationship between volcanism and tectonic plates that some of the leading twentieth-century geologists touched upon VT. In the area of applied geological science, geologists such as Jim Healy in New Zealand, while working almost solely on developing the geothermal prospects for that county in the 1950s–1960s, became intimately involved with the relationships of the Taupo Volcanic Zone fault structures, its calderas and ignimbrites, and the prospective geothermal fields, some of which came online as power-plants in his lifetime.

Despite beginnings in the early 1900s, with the instigation of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) under the umbrella of the International Union of Geodesy and Geophysics (IUGG), *volcanology* was slow to develop and was only becoming a distinct discipline by the mid-1970s. It was definitely not a major discipline in my undergraduate days in the UK (1965–1970), but it had its stars ushering the science from different countries at different times, and with various approaches and purposes, for example, Sigurdur Thorarinsson in Iceland, Jim Cole and Colin Vucetich in New Zealand, Shigeo Aramaki and

Isamu Murai in Japan, Hans-Ulrich Schmincke in Germany, Franco Barberi in Italy, Bob Smith in the USA and George Walker in the UK (and, later, New Zealand and Hawai′i). In parallel, the development of a more modern approach to VT slowly gathered momentum and prominence. Notable here is David Pollard, using an approach via rock mechanics, who began publishing on the emplacement of intrusions such as laccoliths (1973). Pollard's work with his student Paul Segall on non-volcanological applications began appearing in the 1980s, but Segall's work developed into volcanic applications in the 1990s. Another early proponent of VT was Kazuaki Nakamura, who in the 1970s promoted the use of volcanoes as indicators of tectonic stress.

Mainly in the 1990s and this century, others who helped to develop the field of VT include Agust Gudmundsson, representing Iceland, Germany and the UK. Agust, initially moving along a similar path to Pollard and Segall, merging rock mechanics principles and field studies, led to improved understanding of matters such as emplacement of intrusions and calderas. Also, Cynthia Ebinger (USA) contributed much to defining the regional relationships between magmatism and tectonics. Daniel Dzurisin (USA) made important studies on volcano geodesy, mainly on Yellowstone and the Cascadian and Aleutian volcanoes. The development of GPS was important to VT as, together with InSAR, it boosted studies of volcano deformation over the last two decades. And now, Valerio is bringing all this together as a mature text on this well-developed sub-discipline of geosciences, where the main branches of volcanology and structural geology meet.

This book and its topics contribute to the development of modern volcanology, not only in terms of understanding volcanoes (there is a mini course on volcanology at the beginning), but also in explaining the role of VT in defining volcanic hazards and forecasting eruptions. Chapters 1 and 2 are introductory and provide the fundamentals. Chapters from 3 to 9 focus on the rise of magma towards the surface, describing the main volcano-tectonic processes associated with magma rise. Chapters from 10 to 13 provide regional and stylistic perspectives. Details of the contents can be found in the Preface.

Convincing the broader volcanological community about the importance not only of this book, but also of volcano-tectonics in general, is a purpose of this Foreword. A goal is to engender within the volcanological community a broader realization of volcano-tectonics. I admire tremendously those colleagues who can finish writing books—so, Valerio, congratulations! I hope that this hard-won fruit of your labour brings your readers much useful information and brings you a well-deserved round of appreciation.

Dear, generous readers, I promote to you a book on a new field which is beautifully illustrated, thoroughly researched and wide-ranging. It is a first, and I hope it will spur on many other similar studies and texts in the future.

Berkeley, CA, USA
January 2021

Steve Self

Preface

Among the various university courses I took for my geoscience degree, volcanology and structural geology motivated me by far the most. Volcanoes and deformed rocks are indeed the most impressive expressions of the activity of our planet, a real manifestation of power and energy. As a student, this often came into my mind, imagining a faulted volcano pouring out blood-red lava! What can be more dramatic than faults ripping a volcano apart? It is like destroying a source of destruction.

With this intriguing image, it became natural to dive into what at that time was whispered as “volcano-tectonics”. Indeed, in the early 1990s volcano-tectonics was still a rather ambiguous term, with some professors claiming that volcano-tectonics resulted from volcano stratigraphy and others mystically invoking the term anytime they could not explain a process occurring at a volcano. At that time, volcano-tectonic studies were rare, even within the international community, although I somehow realized that there was so much to study and understand on the topic. So, once I decided that research in volcano-tectonics would be my future (but without getting stuck with volcano stratigraphy), it was straightforward to look for opportunities after my university degree. In this delicate step, I was lucky enough to have the support of a couple of open-minded mentors, Renato Funiciello and Antonio Lazzarotto, who granted me total support and freedom in studying volcano-tectonic and tectono-magmatic problems during and after my Ph.D., providing me with the opportunity to express myself in this mystical topic.

Today, after two and a half decades, research in volcanology has grown to an extent that was unconceivable in the 1990s. Boosted by an impressive technological support, volcanology currently relies on continuous inputs from several disciplines within the geoscience field, as well as from independent disciplines in different fields of science, including mathematics, physics, chemistry, engineering, statistics and informatics. The result of this integration is the firm establishment of several modern research branches making up current volcanology. Among these is, indeed, volcano-tectonics, which has grown from its infancy of the late ‘80s-early ‘90s to a mature and leading topic, relying on many different techniques and tools. Today any form of confusion has definitely disappeared, and it would be appropriate to say that volcano-tectonics considers any stress-deformation process, occurring at any scale, related to the accumulation, transfer and eruption of shallow magma. These stress-deformation processes may be magma-induced or, conversely, encourage or control the accumulation, transfer and eruption of magma. In any case, focused on the conditions promoting magma accumulation, transfer and eruption, volcano-tectonics plays a fundamental role also in understanding pre-eruptive processes, providing the theoretical ground to eruption forecasting.

Therefore, (a) the impressive growth and identity acquired by this branch of volcanology, (b) which is also essential to understanding pre-eruptive processes and forecasting eruptions, (c) thus deserving to be better appreciated within the wider volcanological community, (d) especially given the lack of an accessible reference text summarizing the main achievements, are the four main motivations which, a few years ago, encouraged me to write a monograph on volcano-tectonics.

Indeed, while today there are so many academic texts on volcanoes dealing with general or particular aspects of their activity, especially eruptions, there are extremely few texts, and all released very recently (after I began preparing this monograph), which have started to consider specific aspects of volcano-tectonic processes. Distinctive from these texts, the present monograph claims to provide the first comprehensive and practical overview on volcano-tectonic processes, occurring at the local (volcano) and regional (plate boundary) scale.

Under these premises, this monograph aims at summarizing, with an integrated approach, the current (as of mid-2020) state of the art on volcano-tectonics, including its importance for volcanic hazards, as well as to provide a complementary reference for anyone interested in volcanoes and volcanic activity. *Volcano-Tectonic Processes* is in fact conceived as an accessible monograph, which may be appreciated by academics of any degree level, from upper-level undergraduate students with a general knowledge in volcanology to Ph.Ds, post-docs, researchers, lecturers and professors interested in volcanic, magmatic, structural and tectonic processes. I expect *Volcano-Tectonic Processes* to be especially appreciated by students and young researchers working on volcano-tectonic problems and experienced volcanologists wishing to throw off any residual mysticism on the topic. Although the ideal audience is supposed to have a background in geoscience (including volcanologists, structural geologists, geologists and geophysicists), this monograph may be of interest also for anyone fascinated by volcanoes and with some elementary knowledge in geoscience.

Volcano-Tectonic Processes is organized into three main parts.

Chapters 1 and 2 provide the fundamental introductory knowledge, defining many terms commonly used in the successive chapters and giving the reader the opportunity to approach volcano-tectonics with an appropriate, accessible and shared background. In both chapters, only the essential information, that is most useful for volcano-tectonics, is given, with the recommendation to rely on more specific and comprehensive textbooks for any detail.

Chapter 1 introduces the main notions about volcanoes and volcanic activity, at the same time highlighting how all the distinctive aspects of volcanoes directly or indirectly derive from their tectonic setting, a feature which is considered in detail in the third part of the book. After the overview on volcanoes and their activity, this chapter introduces and places volcano-tectonics into context.

Chapter 2 introduces the main concepts regarding deformation of the Earth's crust, merging knowledge from rock mechanics, rheology, structural geology, tectonics and geodynamics. This is a summary of the "tectonics" side of volcano-tectonics, and many volcanologists may not be very familiar with its content.

Chapters from 3 to 9 make up the second and main part, describing volcano-tectonics processes at the local (volcano) scale. These chapters follow magma in an ideal path rising through the crust, accumulating and developing magma chambers, whose activity may affect the structure and shape of the volcanic edifices, generating vertical collapses (calderas) or lateral collapses (flank collapses). Calderas and flank collapses may in turn affect the shallower transfer and eruption of magma. Therefore, knowledge of all these volcano-tectonic processes and their related signals, as revealed by monitoring systems, may allow understanding the state of active volcanoes and ultimately forecasting eruptions.

Following this ideal path, Chap. 3 discusses the rise of magma in the crust, moving from classic theories on diapirism to more modern perspectives on dikes. The latter include the fundamental factors contributing to dike propagation or arrest, which ultimately control the ascent of magma towards the surface and the possibility of an eruption.

Chapter 4 focuses on the arrest, emplacement and accumulation of the magma rising in the shallow crust, considering the development of various types of intrusions, as sills, laccoliths, bysmaliths and lopoliths, as well as larger plutons. Emphasis is then given to the formation and development of magma chambers, as deriving from the growth of the aforementioned intrusions. The nucleation of dikes from magma chambers is also considered.

Striking surface evidence of the dynamics of large and long-lived magma chambers is provided by calderas. With this regard, Chap. 5 focuses on the long- and short-term surface effects of magma withdrawal and magma accumulation within a chamber, including caldera collapse and resurgent uplift. The processes affecting shallow magma transfer and eruption at calderas are also considered.

Another major process affecting the shape of a volcanic edifice is flank collapse, a dramatic consequence of flank instability. Both flank instability and collapse are the focus of Chap. 6. Flank instability and collapse are commonly associated with eruptions, seismicity and, in coastal areas, tsunamis, playing a pivotal role in multi-hazard assessments at many active volcanoes.

Calderas and flank collapses may severely alter the shape of a volcanic edifice, so that the shallow propagation path of the magma nucleated from an underlying chamber may be affected by these topographic variations. With this regard, Chap. 7 examines the stress variations imposed by topography and other conditions associated with the shallower transfer and eruption of magma, providing the ground for a functional approach to eruption forecasting.

As magma approaches the surface, monitoring data become essential to detect shallow magma accumulation or transfer and to finally forecast eruptions. To this aim, Chap. 8 reviews the geodetic, geophysical and geochemical monitoring approaches applicable to volcano-tectonics, including the popular mathematical source models involving geodetic data. These monitoring approaches, interpreted in the frame of the previously discussed volcano-tectonic processes, allow capturing and understanding any anomalous state of the volcano, or unrest, possibly leading to an impending eruption.

Chapter 9 exploits knowledge from all the previous chapters to define hazard at volcanoes, in order to mitigate volcanic risk. The chapter first considers unrest processes at volcanoes, focusing on how the distinctive contribution of volcano-tectonics may help interpret unrest signals towards forecasting eruptions, which is the ultimate challenge for volcanology. Then, the state of the art on the delicate problem of eruption forecasting is presented.

Finally, Chaps. 10 to 13 make up the third part of the book, considering the regional tectonic framework of volcanoes, building on the message introduced in Chap. 1, that all the distinctive aspects of volcanoes directly or indirectly derive from their tectonic setting. Therefore, this part of the book changes scale, relating volcanoes and volcanic activity to the tectonic setting, which is probably the least explored topic of volcano-tectonics. Here, after a theoretical introduction (Chap. 10), key regional examples are illustrated for an in-depth understanding, highlighting general and distinctive behaviour, and offering a holistic view of tectono-magmatic processes affecting our planet.

In particular, the introductory Chap. 10 considers the distribution and general features of volcanoes in the plate tectonics frame. This chapter reviews major volcano-tectonic processes along divergent and convergent plate boundaries and hot spots, also including polygenic and monogenic volcanism. The surprisingly active role of magma in shaping plate boundaries and intraplate settings is highlighted.

Chapter 11 describes the development of divergent plate boundaries, with a progression from continental to transitional and finally oceanic domains, as currently observed in different key rift zones. A final discussion summarizes and highlights the main tectono-magmatic behaviours of rift zones, providing a general working hypothesis for their activity.

Chapter 12 focuses on representative convergent plate boundaries, which are the most hazardous areas on Earth, in terms of volcanic activity, seismicity and tsunamis. These boundaries may experience orthogonal and oblique convergence, generating volcanic arcs with extremely variable structure and activity. A final discussion summarizes and highlights the main tectono-magmatic behaviours of the arc volcanoes, including their relationships with mega-earthquakes.

Last, Chap. 13 describes the main features of hot spot volcanoes, considering examples from representative oceanic and, subordinately, continental hot spots. A final discussion summarizes and highlights similarities and differences in the tectono-magmatic behaviour of hot spot volcanoes, also providing an original working hypothesis to explain the recurrent features.

These chapters have been written with the aim of maintaining an accessible level for non-experts while trying to offer an original and comprehensive overview on volcano-tectonic processes. To achieve this, each chapter is introduced at the beginning, placing its content into context, and summarized at the end, providing an overview of the main notions. In between the introduction and the summary, an integrated approach, merging available knowledge mainly from geological, geophysical, modelling, monitoring and petrological data, has been followed, avoiding any limitation deriving from relying only on a specific method. Indeed, far from being technical, this monograph tries to summarize the general processes suggested by all types of available data, in order to be of interest to the broadest audience.

While writing the book, I soon realized that, because of the editorial "space problem" (this term pops up in several chapters), I had to make a summary of many important notions, also omitting many points. In the end, I realize that the several hundred of pages of this monograph are simply the tip of an iceberg. Nevertheless, this tip is fundamental to finding the coordinates whereby to access and place into context the related notions making up rest of the iceberg. With this aim, I referred to numerous key-studies in the references for further deepening (apology for any study I may have omitted, but the selection was among more than 10,000 papers and books). In this, I have attempted to maintain a balance between the importance of giving comprehensive and useful references to the reader and, at the same time, keeping the reading of the text as smooth as possible, without too many interruptions due to the citations. As a result, the references have been sometimes grouped together at the end of a topic. This implies that, in these cases, a specific reference may not necessarily refer to the sentence(s) immediately preceding it, but even to a previous one. This also implies that the reference supporting a given argument should, in some cases, be identified among a few other references. A quick glance at the topic of these citations in the reference list at the end of each chapter allows prompt identification of the appropriate reference for the specific sentence.

In addition, to facilitate reading of the text, key terms or definitions have been usually highlighted in bold when introduced for the first time and equations and mathematical derivations have been kept at a minimum, with the possibility to refer to the original study in case details are needed. Likewise, each chapter ends with a list of the main symbols used in the text, although this does not include any additional symbol appearing only in a specific figure, which is explained in the related caption.

Writing this monograph has been more challenging and time-consuming than expected, although it has allowed me to appreciate the impressive number of studies on volcano-tectonics and to deepen several topics outside my limited personal experience. This effort comes at what I believe is a mature stage in my career, where many scientific curiosities have been finally satisfied, although new exciting ones come into sight at the horizon. But it also comes at an extremely delicate period for the academia of Italy, with a lack of opportunities, initiatives and resources that has been ongoing for nearly a decade, worsened by a general incapacity or refusal from colleagues and institutions to rely on meritocracy. This makes the future of research in the Italian academia highly uncertain, the only certainty being that the country is losing competitiveness.

Thus, it is with a heavy heart and the legacy of this monograph that I plunge myself into the uncertain future.

Rome, Italy
September 2020

Valerio Acocella

Acknowledgements

Before the “ordinary” acknowledgment of colleagues, friends, collaborators and family, I must start from afar, with a quite eccentric note.

This monograph is in many ways a result of 25 years of hard and committed work, in which I made field campaigns in five continents, run thousands of models, read many thousands of papers, wrote a respectable (not thousands, though) amount of papers and projects, presented and convened at countless meetings, reviewed and edited hundreds of manuscripts, thought many courses, and much more… Yes, this is the usual academic life, some may say. I am not sure if it is, but surely I enjoyed doing all this in the fast lane. Odd as it may seem for an academic, as speed requires energy, I must thank James Hetfield, Lars Ulrich, Kirk Hammett, Cliff Burton, Jason Newsted and Rob Trujillo, aka Metallica, for having provided the required fuel for so many years. Without their pace, I would have certainly accomplished much less.

Now, on a different note, the “ordinary” acknowledgments.

While this book has been typed by a single Author, I consider it as the result of the direct and indirect collaboration, participation, attention, support, discussions, suggestions and comments of many colleagues and friends over 25 years.

First of all, I must thank my mentor Renato Funiciello for having given me the opportunity, mainly during my master thesis and post-doc, to dive into volcano-tectonics, always enthusiastically supportive in those early formative years. Antonio Lazzarotto then gave me the unique possibility to start my career with a Ph.D. on tectono-magmatic problems at the University of Siena, showing a similar supportive enthusiasm.

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Many colleagues and friends helped me in reviewing early or late versions of the chapters of this book, providing constructive criticism, ideas and suggestions. In particular, Adelina Geyer, Agust Gudmundsson, Anthony Hildenbrand, Luca Ferrari, Mike Poland, Thomas Sisson, Andres Tassara, and Benjamin vanWyk deVries provided helpful reviews on an earlier version of some chapters. In addition, Falk Amelung, Bill Chadwick, Shan de Silva, Francesca Funiciello, Derek Keir, Chris Kilburn, Luis Lara, Peter Lipman, Thierry Menand, Chris Newhall, Mike Poland, Eleonora Rivalta, Joel Ruch, Laura Sandri, Steve Self, John Stix and Alessandro Tibaldi provided prompt, enthusiastic and invaluable support in reviewing the late version of one or more chapters. Professor Steve Self also kindly provided the Foreword to this monograph. Finally, Falk Amelung, Roger Buck, Michael Heap, Thierry Menand, Sigurjon Jonsson and Marlene Villeneuve provided additional helpful discussions on specific topics. Needless to say, while many ideas and suggestions in this book are borrowed from them, the errors are all mine!

I am also thankful to colleagues who enthusiastically assisted in (a) finding and providing bibliographic material and in (b) providing appropriate figures and images.

Among the former, I must thank for their patience Marco Neri and Matteo Trolese, who used very different but equally effective approaches, and the personnel at the Roma Tre BAST Library (Enza Gasbarro, Marta Izzi, Marco Muscolino).

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Here I would also take the opportunity to thank in advance any reader who will send his/her comments to me so that improvements can be made for a next edition.

Finally, on a more personal note, I would like to remember those with whom I shared my personal life while in the academia.

First, Serena Majetta provided so much support, dedication enthusiasm and love in those carefree early days that, without her, things may have been different today: an angel in paradise.

Then, Roberta and, in particular, my parents Nicola and Anna, who supported me long before I ever started to think about volcanoes. Needless to say, without them, and their constant love, there would have been no book on Volcano-Tectonic Processes, and much, much more.

Lastly, my deepest thoughts go to those who stayed next to me for so many years and, inevitably, also experienced most of the burden imposed by writing this book: my own family. Flavia and Elena had to bear the load of an absent minded and grave father for many months. Francesca had to cope with a frantic and, at the same time, dull husband for even longer… Yes, at moments we all felt like “All work and no joy make Valerio a dull boy”. Luckily for us, this book was not written in wintertime at the Overlook Hotel, so I can now focus again on our amusing journey together.

Contents

About the Author

Valerio Acocella professor of Volcano-Tectonics and Volcanic Risk at the University of Roma Tre, Rome, Italy, has been studying volcanoes worldwide for more than two decades, publishing approximately 150 scientific papers. He has coordinated large research projects on Etna and Campi Flegrei, as well as the IAVCEI Commission on Calderas. He has been serving as editor for several scientific journals and organizing sessions at many scientific meetings.

Volcanoes and Volcanic Activity

1

1.1 Introduction

Volcanoes are an astonishing manifestation of the activity of planets and their satellites, as observed in active and/or fossil examples on Earth, Mars, Venus, Mercury, the Moon and the Jovian satellite Io. On Earth, volcanoes are one of the most impressive evidence of the same imbalance in energy that is also driving plate tectonics. Active volcanoes have terrified and at the same time fascinated populations and civilizations for thousands of years. This instinctive attitude towards volcanoes has been gradually replaced, in the last centuries, by a more rational curiosity and scientific approach, heralding the birth of volcanology, although only in the last decades volcanology has grown to the point of understanding general processes. Nevertheless, this increased knowledge has been only partially paralleled by an improved capacity to forecast eruptions and mitigate the environmental impacts of volcanic activity, which remain the ultimate and exciting challenges for modern volcanology.

Any synthesis of the general knowledge gained on volcanoes would deserve a voluminous monograph, and for an overview several appropriate texts may be examined (e.g., Schmincke 2004; Lockwood and Hazlett 2010; Sigurdsson et al. 2015). Here this introductory chapter builds up on these texts to summarize the fundamental concepts on volcanoes and their activity, also pairing Chap. 2, which summarizes the basic notions on crustal deformation. Both introductory chapters provide the essential background to the remaining eleven chapters focusing on the stress-deformation processes associated with the rise, emplacement and eruption of shallow magma (i.e., in the upper crust), at the local and regional scale, which concern volcano-tectonics.

Under these premises, the main aims of this chapter are to introduce the:

- distribution, composition and types of volcanoes, as deriving from the plate tectonics frame;
- main types of volcanic activity;
- concepts of volcanic hazard and risk;
- volcano-tectonic processes, that are the focus of this book.

1.2 The Volcano Factory

Volcanoes are found exhibiting very different types of activity on several planets and satellites: in this book the focus is on the volcanoes on Earth. Herein a **volcano** is a vent that develops when **magma**, that is a high-temperature (generally >650 °C) mixture containing melt, crystals

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and gases, erupts on the Earth's surface, in subaerial, subglacial or subaqueous environments. The repeated eruption of magma and accumulation of volcanic deposits from one or more vents in the same location over time develops a **volcanic edifice**. This commonly has a quasi-conical shape and is from tens to thousands of metres high and several tens of metres to several tens of kilometres wide. The edifice may be characterized by a summit depression, or **crater**, up to a few hundred of metres wide and deep, from which the magma is erupted. Occasionally, magma may also be erupted from the slopes or flanks of the edifice, or even outside, through **peripheral vents** (Fig. 1.1; e.g., Schmincke 2004, and references therein).

When reaching the surface, erupted magma feeds volcanic activity, rapidly solidifying and forming **volcanic** rocks. However, most magma remains trapped at depth in the crust and solidifies more slowly, forming **plutonic** or **intrusive** rocks: taken together, volcanic and plutonic rocks constitute **magmatic** (or igneous) rocks. Therefore, while it is tempting to relate a volcano to the topographic construction built by the erupted magma, it should be understood that the volcanic edifice is just the surface part of a larger system developed at depth. Indeed, a volcano should be considered, in the broadest sense, as the surface expression of a deeper and complex network of magma, which may eventually erupt. This network defines the **plumbing system** of the volcano, which consists of magma penetrated within the surrounding or country rocks, forming shallow **intrusions** with different shapes (Burchardt 2018, and references therein). The physical conditions of these intrusions vary significantly. For example, their thermal state may range from molten (between ~700 and ~1200 °C, depending upon magma composition) to solid (that is, completely crystallized, at the country rock temperature at that depth), passing through an intermediate mushy state, where melt and crystals coexist. The geometry of the magmatic intrusions forming the plumbing system is also extremely variable, although some basic shapes may be recognized, as described below.

The shallowest portion of the plumbing system, just below the volcanic edifice, may include a subcylindrical and vertically elongated central **magmatic conduit**, which feeds the eruptions

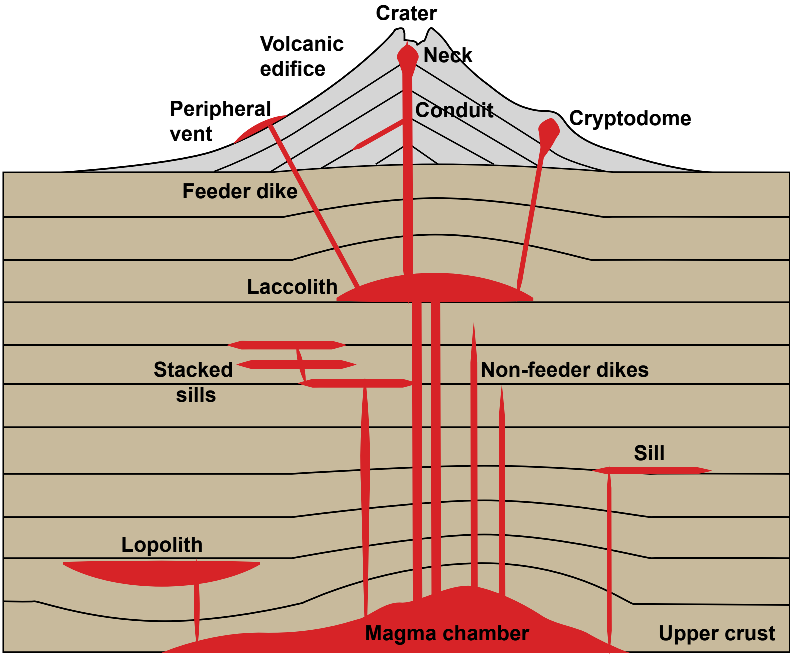

Fig. 1.1 Scheme of a volcano, consisting of the volcanic edifice, the central conduit and the shallow plumbing system, made up of different types of intrusions. Not to scale

connecting the vent(s) to a zone of deeper magma supply. The upper part of the magmatic conduit may include **necks** (vertically-elongated feeders below the vent, made up of solidified magma) or **cryptodomes** (very shallow and viscous magma stagnating and solidifying without reaching the surface). The plumbing system below the upper magmatic conduit mainly consists of intrusions with planar shape, or **magma-filled fractures**, with thickness much smaller than the lateral extent (Fig. 1.1; Burchardt 2018, and references therein). Magma-filled fractures discordant with the country rock layers are named **dikes**. These, described in Chaps. 3 and 7, are responsible for the rise of magma and, ultimately, for feeding eruptions (feeder dikes). Magma-filled fractures concordant with the country rock layers are named **sills**. Slls may thicken as a consequence of the increase in pressure of the intruded magma, eventually forming **laccoliths**, where the upper surface of the intrusion is domed, or **lopoliths,** where the lower surface of the intrusion is domed. Sills, laccoliths and lopoliths, as described in Chap. 4, are thus concordant magmatic intrusions characterized by different conditions of storage, or **emplacement**, of magma in the crust. These intrusions allow accumulating large quantities of magma (up to thousands of km^3) at shallow depth (usually a few km), promoting the development of **magma chambers** and **magma reservoirs**. These two terms are often used synonymously, although the former should refer to the melt-dominated region, and the latter to the mush-dominated (melt and crystals) region, characterized by cooling and solidification (see Chap. 4; e.g., Sparks et al. 2019, and references therein). At deeper levels magmatic intrusions include plutons and batholiths. A **pluton** is an isolated, solidified and massive intrusion of magma, with an average volume of 10^2–10^3 km^3; some plutons may represent solidified magma chambers of extinct volcanoes. A **batholith** is a larger intrusion, with an average volume of $\sim 10^4$ km^3, deriving from the assemblage of several plutons at a few tens of kilometres of depth.

Magmatic **gases** accompany the rise, emplacement and eruption of magma. Gases may be dissolved (in solution) within the magma, or exsolved (distinct) from the magma, depending on their pressure, temperature and composition, as well as on the magma composition (Fischer and Chiodini 2015, and references therein). These gases mainly consist of water vapour (H_2O), carbon dioxide (CO_2) and, subordinately, of sulphur dioxide (SO_2), hydrogen sulphide (H_2S), carbon monoxide (CO), hydrogen chloride (HCl) and hydrogen fluoride (HF). Magmatic gases released from a magma reservoir or chamber may contaminate, heat and pressurize the meteoric fluids in shallow or deep aquifers, thus forming a **hydrothermal system**. Many volcanoes show a hydrothermal system above the magma chamber, whose presence requires three components: fluids (meteoric and magmatic), permeability through rocks (fractures) so that fluids can circulate, and heat source (magma).

Magma, with its cargo of dissolved and exsolved gases, provides the energy within the volcano factory: magma transported in bursts to the surface is the most remarkable and readily observable evidence of the larger energy stored within the Earth. The energy associated with magma drives a wide range of processes: among these, the rise of magma towards the surface is largely a consequence of its heat, which makes magma lighter than the country rock, gaining the buoyancy pressure to rise.

1.3 Distribution of Volcanoes and Origin of Magmas

The distribution of volcanoes on the Earth's surface is determined by the availability and, ultimately, the generation of magma. These conditions depend on the tectonic setting, as described in the frame of the plate tectonics theory. Plate tectonics not only explains the location of volcanoes, but it also justifies the variable chemical composition of the erupted magmas. This compositional variability is in turn associated with different physical properties and finally responsible for the development of different types of volcanic edifices and eruptive styles. This section provides an introduction to the plate tectonic processes responsible for magma generation, to explain in the subsequent sections the resulting main compositional and physical variations of magmas, the different types of volcanic edifices and eruptive styles. The concepts described in this section are then discussed in more detail in Chap. 2 (concerning crustal deformation) and Chaps. 10–13 (concerning the regional context of volcanism).

The Earth consists of several shells with different physical and chemical properties (Fig. 1.2a; e.g., van der Pluijm and Marshak 2004, and references therein). The **crust** is the Earth’s thinnest and outermost shell, made up of magmatic, metamorphic and sedimentary rocks. The crust can be divided into oceanic and continental: the former is found below oceans and is thinner (thinning to ~5 km) and denser (average density of ~2900 kg/m^3); the latter is found on continents, and is thicker (up to ~80 km) and lighter (average density of ~2700 kg/m^3). The boundary between the crust and the underlying layer, the mantle, is geophysically defined by the marked increase in the velocities of the seismic waves (from approximately 7 to over 8 km/s) and is called the Mohorovicic Discontinuity (or **Moho**). The **mantle** is ~2870 km thick and is predominantly solid, although in geologic time it behaves like a viscous fluid. It has average density of ~4600 kg/m^3 and its upper part mainly consist of Fe- and Mg-rich silicates, forming a rock called peridotite. Then, at ~2900 km of depth the Earth’s core begins, with a radius of nearly 3500 km and average density of ~10,600 kg/m^3. The core is thought to consist mainly of nickel and iron; its outer portion is liquid, whereas the inner is solid.

Using a more dynamic subdivision of the Earth’s outer portion, the crust and the uppermost mantle together form the **lithosphere**. This can reach a thickness of 150–200 km below continents and may be defined as the mechanically coupled, relatively cool (<1280 °C) and rigid outer portion of the planet (Fig. 1.2a; e.g., Stuwe 2007, and references therein). This behaviour is opposed to that of the underlying hotter (>1280 °C) and less viscous **asthenosphere**, which is the portion of upper mantle characterized by variable amount of partial melt (from ~2 to ~10%) and with variable thickness, reaching in some places ~300 km of depth. This partially molten zone is commonly explained by the depth increase in temperature approaching the melting point of the peridotite. The increase in temperature with depth derives mainly from the radiogenic heat produced by the radioactive decay of the isotopes in the Earth’s interior, as well as from the primordial heat left over with its formation. Because the Earth is much hotter in its core than the outer mantle or the crust, heat migrates along thermal gradients to the Earth's surface and then radiates into space: this results in the release of heat, or **heat flow**. The mean heat flow of the Earth is estimated as of ~92 mW/m^2, although in volcanic areas magma and hot fluids may produce heat flows up to a few W/m^2 and, locally, over 100 W/m^2, as for example in parts of Yellowstone caldera (Wyoming, USA; e.g., Lucazeau 2019, and references therein). The rate of increase in temperature with regard to the depth within the Earth is expressed by the **geothermal gradient**. This gradient decreases with depth: for example, the mean geothermal gradient within a depth of 5 km in a continental crust is 25–30 °C/km, to become ~15 °C/km at a depth of 40 km; in volcanic areas the geothermal gradient may be higher than 200 °C/km, as for example in the Kenya Rift (Lagat 2003).

According to the theory of plate tectonics, the Earth’s lithosphere consists of seven major plates and several minor plates which slowly move (on average with velocity of cm/yr) with regard to each other, following deeper circulation in the Earth’s mantle. An assumption of plate tectonics is that the lithospheric plates are essentially rigid, implying that the deformation resulting from their relative motion focuses along the plate boundaries. As a result, the distribution of seismicity and the largest earthquakes also focus along the plate boundaries (Fig. 1.2b; e.g., Le Pichon 1968). Depending upon the predominant relative motion between neighbouring plates, three types of plate boundaries, each

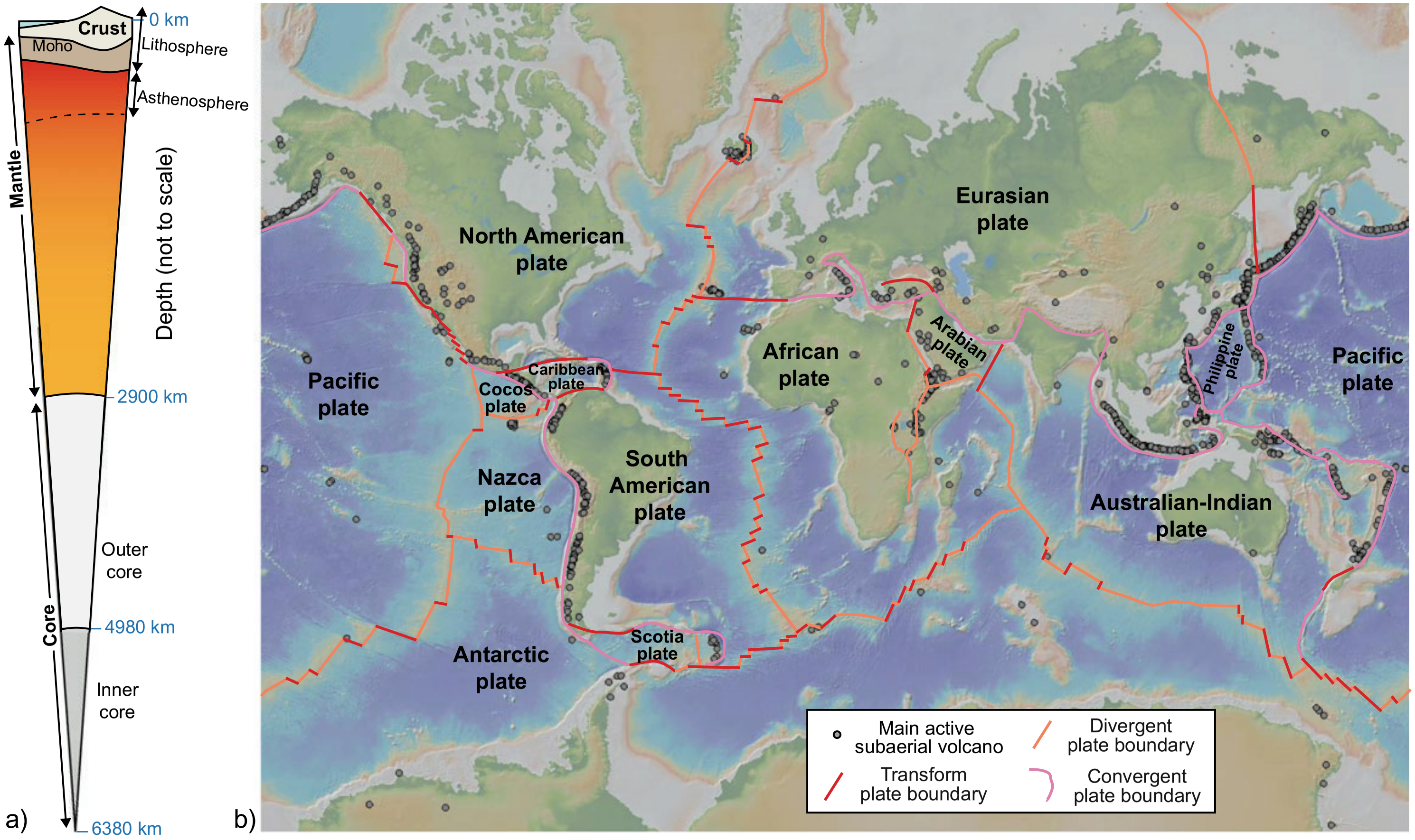

Fig. 1.2 **a** Subdivision of the internal portion of the Earth into several shells. **b** The distribution of active volcanoes on the surface of the Earth closely mimics the boundaries of the main lithospheric plates, which may be characterized by divergent, convergent or transform motions