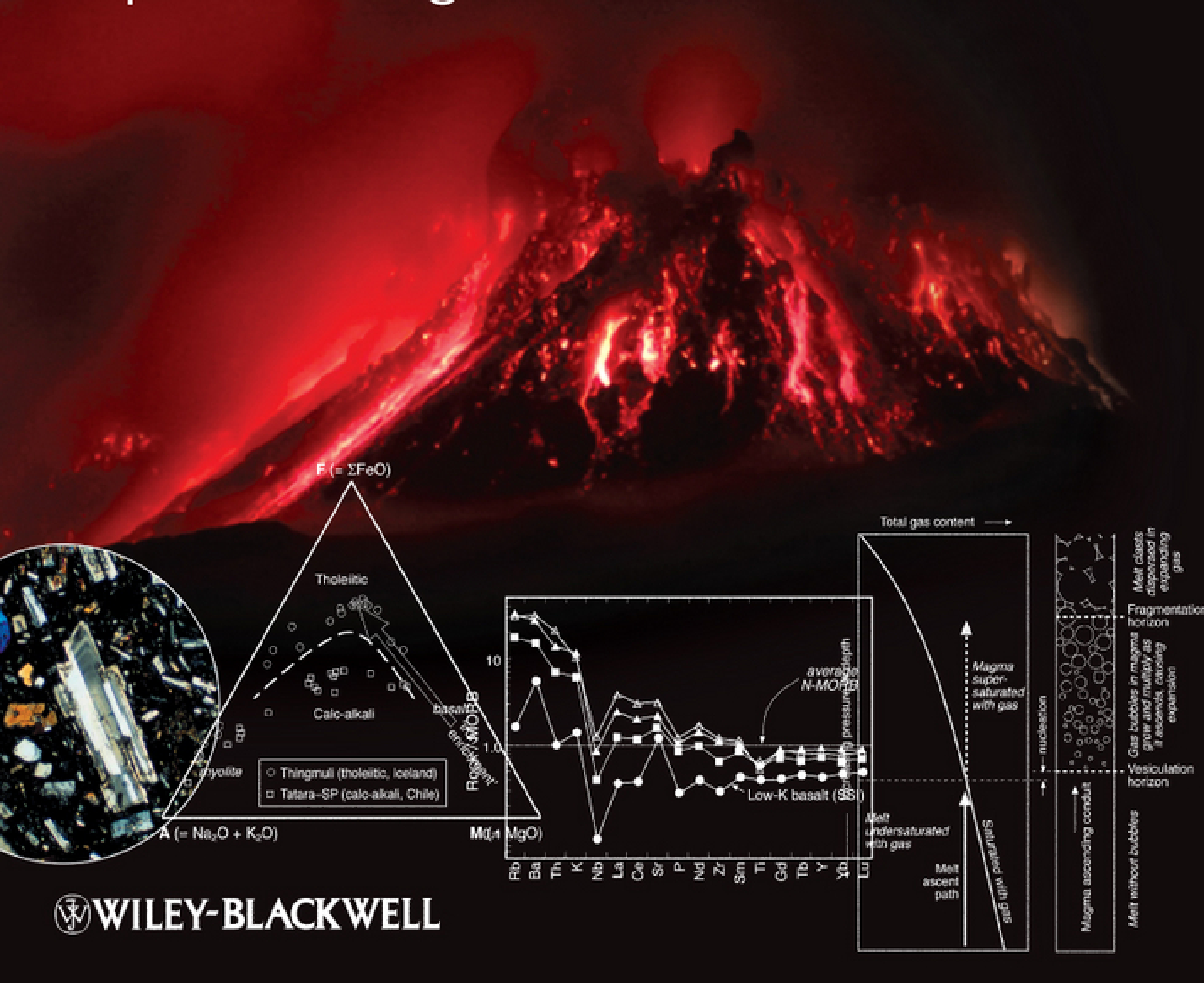
ROBIN GILL

IGNEOUS ROCKS AND PROCESSES

a practical guide



WILEY-BLACKWELL

Contents

Companion website for this book: wiley.com/go/gill/igneous

Index

Igneous Rocks and Processes

A Practical Guide

Robin Gill

Department of Earth Sciences
Royal Holloway
University of London

WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

Blackwell Publishing was acquired by John Wiley & Sons in February 2007. Blackwell's publishing program has been merged with Wiley's global Scientific, Technical and Medical business to form Wiley-Blackwell.

Registered office: John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

111 River Street, Hoboken, NJ 07030–5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell

Library of Congress Cataloguing-in-Publication Data

Gill, Robin, 1944–

Igneous rocks and processes: a practical guide/Robin Gill.

p. cm.

Includes bibliographical references and index.

ISBN 978-1-4443-3065-6 (hardcover: alk. paper) – ISBN 978-0-632-06377-2

(pbk.: alk. paper)

1. Rocks, Igneous. 2. Magmatism. I. Title.

QE461.G495 2010

552′.1-dc22

2009031380

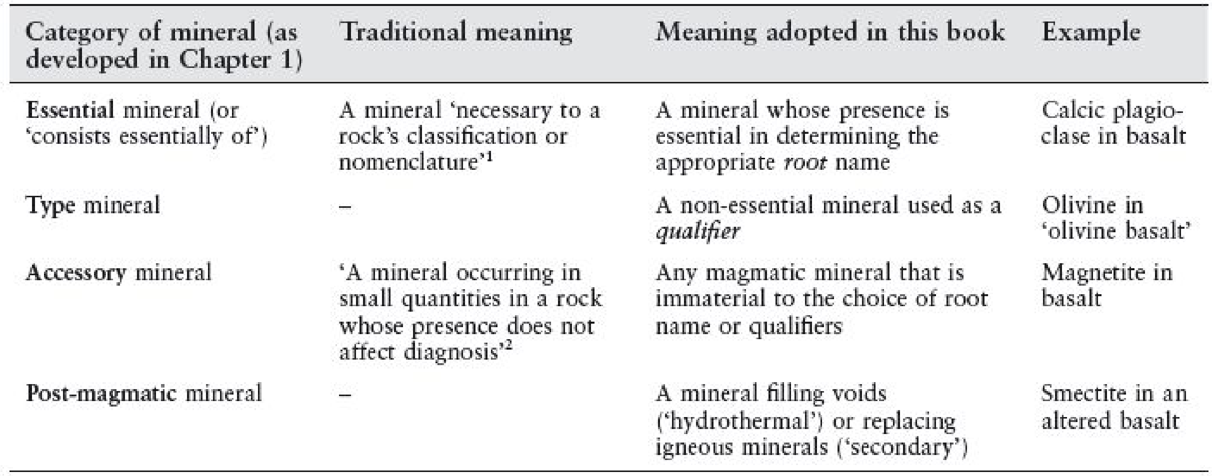
To Mary

Preface

This book has grown from my experiences teaching a second-year igneous petrology course at Royal Holloway, University of London. At this intermediate level, one 's primary goal is to help students to develop appropriate descriptive and interpretive techniques. An emphasis on skills dictates a different order of priorities to those that one would embrace in writing a book on petrogenesis. Faced with an intermediate rock of unknown provenance, a student should be encouraged to describe objectively the rock that they see, and to infer what they can from this information, rather than bend their analysis to fit a pre-conceived name, origin or tectonic association. The term 'andesite' should emerge from the student's examination, on the basis of the mineralogy they observe or the chemical data they are presented with, not because they happen to know that the rock comes from Japan (useful hint though that might be). Therefore, as I see it, the book that students need at this stage is one that can help them translate a set of observations (e.g. 'a rock consisting of abundant plagioclase and hornblende phenocrysts set in a finegrained groundmass, mainly consisting of intermediate plagioclase + augite + opaques') into an informative, appropriate name ('plagioclase-hornblende-phyric andesite' – see Chapter 6). Intermediate students also need guidance in interpreting textures and geochemical data intelligently for themselves, in order to draw informed conclusions about magmatic processes. To support this practical student-led emphasis, most chapters in the book are devoted to major rock families (basalts, gabbroic rocks, granitic rocks, etc.); geotectonic environments are of course discussed, but they do not determine the structure of the book as they might in a text emphasizing magma genesis.

Once the nuts and bolts of igneous nomenclature have been introduced in Chapter 1, the order of chapters reflects a logical journey from the simplest, most abundant, least fractionated products of mantle melting (basalts, Chapter 2) and their plutonic equivalents (Chapters 4 and 5), through to more evolved magma types in Chapters 6 and 8. The final chapter examines the alkali rocks, whose diversity and mineralogical complexity challenge even the most dedicated student! Chapters 3 and 7 digress, at the points in the book where this is most pertinent, to examine experimental petrology (an invaluable laboratory window on magma evolution) and concepts of physical volcanology.

As to igneous nomenclature, I have aimed at what I hope is a judicious blend of traditional petrographic practice and current International Union of Geological Sciences (IUGS) convention (Le Maitre, 2002). The minerals observed in a rock are discussed here under four conceptual headings: *essential* minerals, *type* minerals, *accessory* minerals and *post-magmatic* minerals. 'Essential' and 'accessory' are familiar terms from traditional usage but assume slightly different meanings in this book, as the table shows:



Category of mineral (as developed in Chapter 1)	Traditional meaning	Meaning adopted in this book	Example
Essential mineral (or 'consists essentially of')	A mineral 'necessary to a rock's classification or nomenclature'[1]	A mineral whose presence is essential in determining the appropriate *root* name	Calcic plagioclase in basalt
Type mineral	–	A non-essential mineral used as a *qualifier*	Olivine in 'olivine basalt'
Accessory mineral	'A mineral occurring in small quantities in a rock whose presence does not affect diagnosis'[2]	Any magmatic mineral that is immaterial to the choice of root name or qualifiers	Magnetite in basalt
Post-magmatic mineral	–	A mineral filling voids ('hydrothermal') or replacing igneous minerals ('secondary')	Smectite in an altered basalt

[1] AGI Glossary of Geology, 2nd edition 1960.

[2] Holmes (1928).

The term 'type mineral' merely makes explicit a concept that we understand implicitly whenever we speak of 'olivine basalt' . It goes without saying that the same mineral may assume essential status in one rock type (nepheline in nephelinite), act as a type mineral in another (nepheline in alkali gabbro) or be present as an accessory in a third, according to abundance and context. The notion of ‘post-magmatic mineral’ is introduced to emphasize that a real igneous rock may in its current state contain minerals that never coexisted with the melt from which it originally formed.

In writing rock definitions, I have stuck to one cardinal principle: the definition of a rock type should be founded on purely descriptive criteria, free of genetic connotations. Accordingly the adjective ‘volcanic’ has been omitted from the definition of basalt and ‘plutonic’ from that of gabbro. Though this diverges from IUGS canon (Le Maitre, 2002, p 60 [1]) I believe the logic is unassailable: a fine-grained sample from the chilled margin of a gabbroic intrusion, if found unlabelled in a drawer, would objectively be called a basalt, whereas the coarse-grained basic part of a thick komatiite lava would logically be called a gabbro (following, for example, Arndt et al., 1977). In other words, it should not be necessary to know where a rock comes from, or where it formed, in order to assign the appropriate name. To speak of a ‘fine-grained gabbro’ (MacKenzie et al., 1982, p12) is a logical contortion that ought to be queried by any intelligent student. The principles adopted here happen to be similar to the nomenclature adopted by the British Geological Survey (Gillespie and Styles, 1999).[2]

The ‘practical’ in the book’s title highlights my aim to support students’ own work in the petrology teaching lab or in research projects. Being a pragmatist, I have included outline optical data to allow simple mineral identification without recourse to a separate mineralogy text,[3] which (experience suggests) many students are reluctant to buy today; this summary optical information is given in

Appendix A and in boxes at appropriate points in the body of the book. Appendix B covers various petrographic calculations, including a simplified CIPW norm scheme as an aid to understanding concepts like silica undersaturation. Appendix C summarizes the symbols and units used throughout the book. Figures and tables appearing in explanatory boxes are identified by numbers having *three* parts; so 'Fig. 1.3.1' identifies the first (or only) figure of Box 1.3 (which is of course the third box in Chapter 1). 'Fig. B3' refers the reader to Figure 3 in Appendix B . A general glossary is also provided to enhance the book's usefulness; terms defined in it are highlighted in **bold** where first mentioned in a chapter or section, or where cross-referenced in the glossary itself.

[1] Elsewhere, however (p3), the IUGS defines volcanic rock as 'an igneous rock with an **aphanitic** texture, i.e. a relatively fine-grained (<1 mm) rock …'. Rather than adopt this ambiguous usage, the term 'volcanic' is reserved in this book for its traditional genetic meaning, describing an igneous rock crystallized from magma that erupted at (or very close to) the surface.

[2] See www.bgs.ac.uk/bgsrcs/.

[3] The optical principles summarized in Appendix A are intended merely as a reminder, not as an introductory course.

Acknowledgements

The following organizations are thanked for permission to reproduce figures (the numbers in parentheses) or other material specified: American Geophysical Union (Figs. 5.3.1a,b,c; 6.4; 6.24; 9.13), American Journal of Science (Fig. 9.7b), Blackwell Science (Figs. 6.16; 8.23; 9.7c), British Geological Survey (Fig. 4.3e), Caribbean Helicopters (Fig. 6.3b), Elsevier (Figs. 2.13; 4.9; 4.14a; 5.4; 5.12; 5.13; 5.6.1; 6.17; 6.26a; 6.4.1; 8.7; 8.16; 8.18; 9.3; 9.14; 9.15; 9.18; Plate 2.10), Geological Society of America (Figs. 4.14b; 5.8a; 5.3.2; 6.7; 6.21b,c; 6.26b), Geological Society of Australia (Fig. 4.6.2), Geological Society of London (Figs. 4.4; 9.6; 9.8; 9.11; 9.16; 9.6.1 and a text extract from Guest et al., 2003), Geological Survey of Denmark and Greenland (GEUS) (Figs. 2.2d; 4.3; 4.6; 4.6.1; 8.3a; 8.8; 8.10a-c; 8.13b), Geologists' Association (Figs. 7.6; 8.5b), Getty Images (Fig. 7.9a), Integrated Ocean Drilling Program (Fig. 2.9a), Leicester Literary and Philosophical Society (Fig. 2.14), Mineralogical Association of Canada (Fig. 9.23), Mineralogical Society of America (Fig. 6.6), Montserrat Volcano Observatory (Fig. 7.4a and the front cover image), The Open University (Figs. 6.13; 6.21), Oxford University Press (Figs. 3.12; 4.4.1; 5.3; 5.8b; 5.11; 5.5.2; 6.18; 8.15; 8.19; 8.4.1; 9.7a; 9.20; 9.22), Penguin Books (text passage from Radice, 1963), Springer Business Media (Figs. 4.13; 5.9; 6.5; 7.17b; 9.4.1), Wiley Interscience (Fig. 2.5) and U.S. National Academy of Sciences (Fig. 5.4.1). The U.S. Geological Survey is warmly acknowledged as the source of many public-domain images used in this book (see captions); if only some other geological surveys were as generous.

The following people are warmly thanked for providing illustrations or giving permission to reproduce figures: J. Bedard (Fig. 4.3d); Smithsonian Institution of Washington DC (Figs. 6.3a & d); J. Blundy (Fig. 7.17b); A. Bussell (Fig. 8.10d); J.P. Davison (Fig. 2.5); C.H. Donaldson (Fig. 5.9); C.H.

Emeleus (Fig. 4.3e); R. Greeley (Fig. 6.3e); D. Millward (Fig. 7.4b); I. Modinou (Fig. 2.2a); J.S. Myers (Fig. 4.6.3).

I thank the following colleagues for kindly providing samples or images for the following colour plates: D. Alderton (Plate 8.5)' F. Belton (9.18; 9.19), J.B. Dawson (9.10), C.M.H. Edwards (6.1; 6.2), J.G. Fitton (2.1), C.A. Goodrich (2.10), I.S. McCallum (4.9; 5.1; 5.2), E. McPherson (5.8; 5.9), M.A. Menzies (5.5), R.H. Mitchell (9.1; 9.2), I. Modinou (2.6), G. Stripp (4.11), R.N. Taylor (6.4; 6.5), C. Tiltman (7.2), B.G.J. Upton (9.9), P. Wallace (6.11), J. Walton (9.5), A. Zaitsev (9.4). Figure 2.9(c) was kindly provided by Integrated Ocean Drilling Program. I am most grateful to Eric Tomme and Jonathan Stone for providing Montserrat photographs. Other images are from my own collection or that of the Department of Earth Sciences, Royal Holloway, University of London. I am particularly grateful to Aubrey Lambert of Carl Zeiss (Germany) for giving me permission to reproduce the Michel-Levy chart.

Grazie mille to Giulia Kistruck for kindly translating a passage in Chapter 7 from Italian. Kevin D ' Souza, Neil Holloway, Frank Lehane and Mark Longbottom are thanked for their skilled technical support over many years. I am grateful to Ian Francis and Kelvin Matthews of Wiley-Blackwell for their unstinting support.

Above all, I am very grateful to Dave Alderton, Grant Cawthorn, Godfrey Fitton,[1] John Gamble, Ray Macdonald, Colin Macpherson, Nick Petford and Anatoly Zaitsev for critically reviewing sections of the book, and to Richard Arculus and Jon Blundy for their many constructive comments on the complete manuscript. These perceptive contributions have added materially to the book's substance and accuracy. Its shortcomings of course remain my responsibility alone.

[1] who also improved algebraic rigour in Box 3.2.

Chapter 1

An introduction to magmas and magmatic rocks

WHY STUDY MAGMATIC ROCKS?

The purpose of this book is to stimulate the reader's interest in magmatic rocks and processes, to develop key skills of describing, classifying and naming such rocks, and to show how much we can learn about igneous processes from careful, informed interpretation of rock textures, mineralogy and geochemistry. The book is aimed primarily at the intermediate-level student of geology who already has a basic knowledge of igneous rocks, but anyone starting from scratch should find that the opening chapter and relevant boxes – together with the Glossary – provide the minimum introduction they require. The emphasis throughout the book will be on practical investigation, mainly by means of the polarizing microscope; basic mineral-identification data have therefore been included to provide – between one set of covers – all that the student needs during a typical igneous practical class.

The logical place to begin any 'ig. pet.' course is to ask what purpose the petrologist, geologist or volcanologist hopes to accomplish in studying igneous rocks. Why do we do it? What kinds of things do we hope to learn? What answers are we trying to find? Such questions should always engage the mind of a petrologist who embarks on a petrographic or geochemical study; petrological science has moved on a long way from the early days when merely describing an igneous rock was an end in itself. In real life, a petrologist may study a suite of igneous rocks with one or more objectives in mind, including:

- understanding eruptive *processes*;
- assessing from previously erupted products the *hazard* presented by a volcano to surrounding communities;
- investigating *magma evolution* in a sub-volcanic magma chamber;
- documenting the *structure* and *formation* of oceanic or continental crust;
- inferring past *tectonic environments* (e.g. mid-ocean ridge, island arc) from the compositions of ancient igneous rocks;
- understanding the formation of economic *mineral deposits* associated with igneous rocks.
- establishing the *absolute age* of a succession of sedimentary and volcanic rocks (igneous rocks being easier to date isotopically than sedimentary rocks);
- identifying the *source* from which a magma has originated, and under what *conditions* melting occurred (i.e. investigating 'magma genesis');
- identifying from erupted magmatic rocks the character and distribution of *geochemical domains* in the underlying mantle, and their evolution in time.

In every such investigation, there is likely to be a role for carefully describing the igneous rocks involved, but the ultimate goal is usually to learn about magmatic processes, or the conditions under which those processes operate. That goal – of studying igneous rocks to learn about process – will come up again and again in this book, because understanding what goes on in magmatic systems is the modern petrologist's principal aim in life. Igneous rocks can tell us not only about processes taking place on the Earth's surface at the present time, but also:

- about processes that have taken place earlier in Earth history, and

- about processes that operate in parts of the Earth that are not directly accessible to us, for example in a magma chamber that originally lay 5 km below an active volcano (but whose contents – or erupted products – are now exposed at the surface).

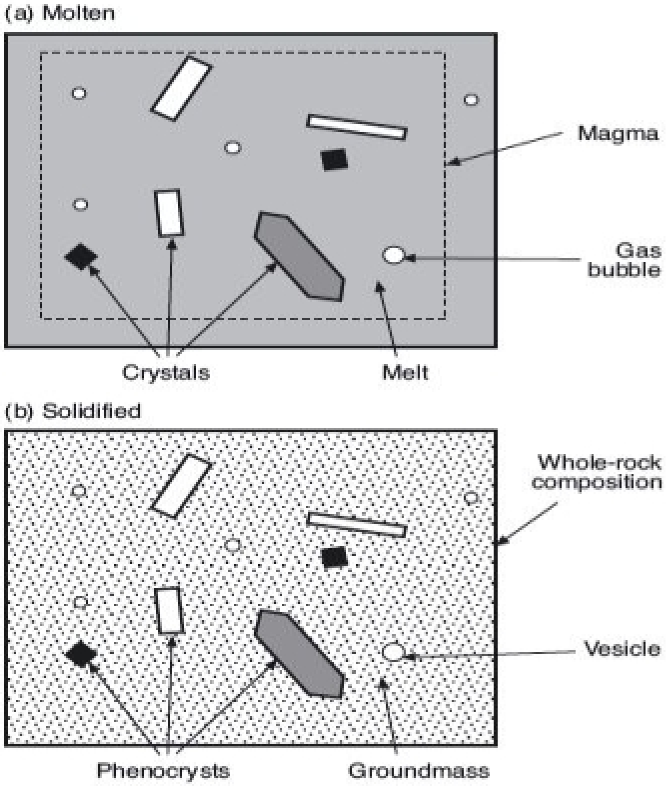
Today, anyone working with igneous rocks has to apply a range of skills, including the analysis of field relationships, hand-specimen identification in the field, the description and interpretation of thin sections, the allocation of informative rock names, the quantitative interpretation of rock and mineral analyses (often including trace elements and isotope ratios), and the interpretation of experimental equilibria and phase diagrams. This book provides a basic introduction to all but the first of these practical and interpretive skills. The book is not intended to take the place of advanced texts dealing with theories of igneous petrogenesis.

The remainder of this chapter is devoted to introducing the basic vocabulary that will be needed for a clear explanation of igneous rocks.

WHAT IS ‘MAGMA’?

Igneous rocks are those that form from molten products of the Earth’s interior. Petrologists use two words for molten rock. **Magma**[1] is the more general term that embraces mixtures of melt and any crystals that may be suspended in it. A good example would be flowing lava which contains **crystals** suspended in the melt (Fig. 1.1): the term magma refers to the entire assemblage, embracing both solid and liquid states of matter present in the lava. **Melt**, on the other hand, refers to the molten state on its own, excluding any solid material which might be suspended in or associated with it. The difference becomes clearer if one considers how one would chemically analyse the distinct chemical compositions of the magma and melt, once the lava flow had solidified (Fig. 1.1). The *magma* composition could be estimated by crushing up a sample of the solidified lava, including both phenocrysts and groundmass (ensuring they are present in representative proportions). Analysing the *melt* composition, however, would require the groundmass or glassy matrix – the solidified equivalent of the melt between the phenocrysts – to be physically separated out and analysed on its own.

Fig. 1.1 Terminology used to designate the different constituents of (a) a molten lava and (b) the same lava in the solid state.



In fact, ‘magma’ may be used in a still broader sense. An ascending magma body, as it approaches the surface, commonly contains gas bubbles as well as phenocrysts, bubbles formed by gas that has escaped from the melt due to the fall in pressure that accompanies ascent (see Box 1.4). The term ‘magma’ is generally understood to embrace melt, crystals *and* any gas bubbles present (Fig. 1.1). Once erupted on the surface, on the other hand, and having lost some of its gas content to the atmosphere, the molten material is more appropriately called ‘lava’. Determining a representative chemical analysis of the original magma composition, including the gaseous component, would however be difficult: as the melt solidified and contracted on cooling, the gaseous contents of the vesicles would escape to the atmosphere (and they would in any case be lost during crushing of the rock prior to analysis). Determining the concentrations of these **volatile** magma constituents – from the solid rock that the magma eventually becomes – therefore requires a different analytical approach that will be discussed later.

Magmas are originally formed by melting deep within the Earth (Chapter 2). The initial melting event most commonly takes place in the mantle, though passage of hot magma into or through the continental crust may cause additional melting to occur there as well, adding to the chemical and petrological complexity of continental magmatic rocks. In oceanic and continental areas, mantle-derived magmas are liable to undergo cooling and partial crystallization in storage reservoirs (magma chambers) within the crust (Chapter 3), and such processes widen considerably the diversity of magma compositions that eventually erupt at the surface.

THE DIVERSITY OF NATURAL MAGMA COMPOSITIONS

What do we mean by magma (or rock) composition?

The overall composition of an igneous rock can be expressed in two alternative ways:

- as a quantitative geochemical analysis, giving the percentage by mass of each of the main *chemical* constituents (Box 1.1);
- as a list of the *minerals* present in the rock as seen under a microscope, perhaps including an estimate – qualitative or quantitative – of their relative proportions.

Though correlated, these two forms of analysis are not entirely equivalent in the information they convey. As a quantitative statement of chemical composition that can be plotted on graphs (e.g. Fig. 1.2) and used in calculations, a geochemical analysis provides the more exact information. The **bulk analysis** (also known as a **whole-rock analysis**) of a volcanic rock approximates closely – except for volatile components – to the composition of the magma from which it formed, considered at a stage before it had begun to crystallize. Careful analysis of geochemical data can reveal a lot about the *source* of the melt and the *conditions* (pressure, depth, extent of melting) under which the melt originally formed.

In some circumstances, however, other forms of rock analysis are of more practical use. Geochemical analyses, requiring elaborate laboratory facilities, are not usually available at the field stage of an investigation, when a geologist will normally find mineralogical and textural observations on hand-specimens a more practical way of characterizing, and discriminating between, the different rock types present in the area. Moreover, the occurrence in thin section of certain key indicator minerals – such as quartz, olivine, nepheline, aegirine–augite – provides immediate, key clues about the melt’s chemical composition without resorting to the expense of geochemical analysis. The mineralogy of an igneous rock also provides information on *post-magmatic processes* (weathering, hydrothermal

alteration) that may have made its chemical composition unrepresentative of magma composition (Box 1.4).

The study of a rock's mineralogical composition and texture – using a polarizing microscope to examine a thin section – is the science called *petrography*. A petrographic analysis of an igneous rock can range from a simple list of minerals seen (noting the textural relationships between them) to a full quantitative analysis of their relative volumes measured in a thin section. Qualitative petrographic examination is the normal prelude to geochemical analysis: it allows one to screen a suite of samples to eliminate unrepresentative or unsuitable specimens, and thereby avoid the expense of unnecessary chemical analyses. But a petrographic examination tells us a lot more about the rock than just its suitability for geochemical analysis: careful study of the rock's texture provides much information about the *eruption and crystallization history* of the magma.

It follows that a geochemical analysis and a petrographic (mineral-based) analysis give us complementary information about an igneous rock, and neither alone provides a complete understanding of the rock's origin and history.

Box 1.1 Chemical analyses of rocks and minerals

Most igneous rocks and minerals, and the magmas from which they form, fall into the class of chemical compounds called **silicates** – consisting of metals combined with silicon and oxygen.

The simplest way to visualize the chemical composition of complex silicate materials is as a mixture of oxides: silicon dioxide (SiO_2 – also known as 'silica') is usually the most abundant oxide in igneous rocks and minerals, and the oxides of titanium (TiO_2), aluminium (Al_2O3), iron (Fe, both ferric Fe_2O_3 and ferrous FeO), manganese (MnO), magnesium (MgO), calcium (CaO), sodium (Na_2O), potassium (K_2O) and phosphorus (P_2O_5) are usually present in significant amounts as well. A typical silicate analysis, giving the *percentage by mass* of each of these oxides (traditionally referred to – inappropriately – as a ‘weight percent’ analysis), is shown in the table below. * The advantage of reporting an analysis in terms of *oxide* percentages is that it neatly introduces the right amount of oxygen into the analysis without the need to analyse it directly. The elements listed, whose oxides are normally found at levels greater than 0.1% by mass, are collectively referred to as the **major elements**.

Table 1.1.1 Analysis of a typical basalt.

SiO_2	48.3
TiO_2	2.591
$Al_2 O_3$	13.03
$Fe_2 O_3$ (ferric)	6.84
FeO (ferrous)	7.72
MnO	0.23
MgO	5.46
CaO	10.91
Na_2O	2.34
K_2O	0.51
P_2O_5	0.26
H_2O^+	1.41
CO_2	0.49
Total	100.1

Note that iron may be shown in the analysis as both ferric (trivalent) and ferrous (divalent) forms; the reason for doing so is that Fe^{3+} and Fe^{2+} ions behave differently in melts and mineral crystals, as explained in Box 2.6. Nonetheless, most modern analyses show only the total amount of iron oxide, expressed either as ‘ΣFeO’ or as ‘ΣFe_2O_3’ – the sigma symbol (Σ) denoting the summation; formulae for such calculations are given in Box 2.6.

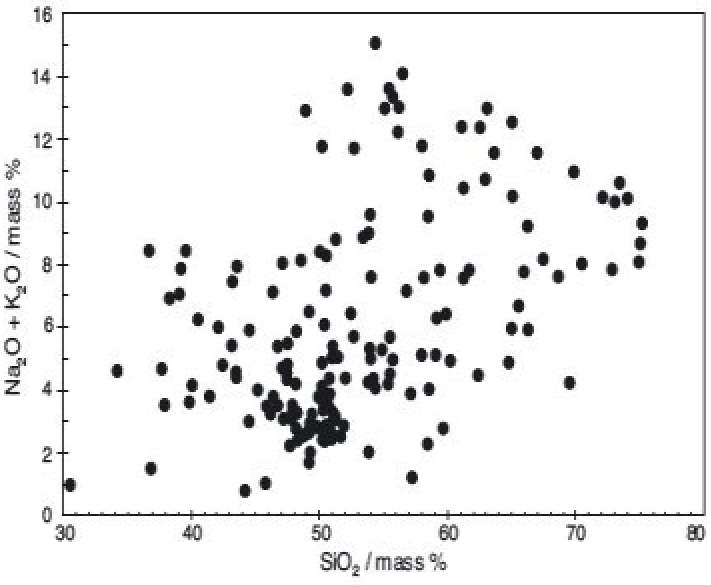
The last two items in the analysis (Table 1.1.1) record the mass percentages of the two main **volatile** constituents of the rock (see Box 1.3). The analysis ends with a total percentage for all of the oxides determined, a cross-check which, in a good analysis, will normally lie between 99.5% and 100.5%.

Numerous other chemical elements are present in magmas, rocks and minerals at concentrations below 0.1%. These less abundant constituents are known as **trace elements**, and their concentrations are expressed in parts per million by mass (‘ppm’ = µg g^{-1} = microgrammes of *element* per gramme of sample) or, in the case of the least abundant trace elements, in parts per billion (ppb = ng g^{-1} = nanogrammes of element per gramme of sample). In spite of their low concentrations, trace elements provide important information about magma sources and conditions of formation.

Most rock analyses are prepared today either by inductively coupled plasma–atomic emission spectrometry (‘ICP-AES’) or by X-ray fluorescence spectrometry (‘XRFS’); both are capable of determining major elements and selected trace elements in igneous rocks. Details of these and other methods – beyond the scope of this book – may be found in Gill (1997), which also describes the sample preparation required prior to analysis.

[*] Analyses of some non-silicate minerals (oxide, carbonate, phosphate and sulphate minerals) may be presented in the same way; SiO_2 will be a subordinate component in such cases.

Fig. 1.2 Plot of total alkalis ($Na_2O + K_2O$) against SiO_2 (both in mass %) for a representative range of terrestrial volcanic rock analyses (representing igneous melt compositions). Data from Wilson (1989) with selected additions from Carmichael et al (1974) and Cox et al (1979). All data have been recalculated volatile-free (see Box. 1.3), except in the case of those analyses from Wilson (1989) for which no volatile data are given, which are assumed to have been volatile-corrected.



How widely do natural magma compositions vary?

Figure 1.2 shows a large number of geochemical analyses of volcanic rocks from various geotectonic environments plotted in a **variation diagram**. The vertical dimension in this diagram depicts the sum of the Na_2O and K_2O contents (each, and their sum, expressed in mass percent [mass %; see footnote[2]], i.e. grams of oxide per 100 g of rock) for each sample. The horizontal dimension shows the corresponding SiO_2 content (also in mass %), and each data point in the graph – that is, each pair of Na_2O+K_2O and SiO_2 co-ordinates – represents an individual rock analysis. In such diagrams, the rock analysis is taken to represent the original magma’s composition. This particular plot is known as a ‘total-alkalis *versus* silica’ (or ‘TAS’) diagram and it is widely used for the geochemical classification of volcanic rocks (see Fig. 1.4).

The main purpose of showing this diagram here is to illustrate how widely natural silicate magmas can vary in their composition: SiO_2 contents range from 31% to 76%, and total alkali contents vary from 1% up to 15%. (This range is solely for silicate magmas: if natural **carbonatite** magmas were considered as well, the compositional range would become still greater.) This wide range of composition can be attributed primarily to four contributions that play a part in magma genesis:

- source composition and mineralogy (e.g. whether crust or mantle);
- depth of melting;
- extent (%) of melting;
- shallow magma-chamber fractionation processes, such as **fractional crystallization**.

The effects of these factors will be discussed in later sections of the book. The important conclusion to be drawn here is that natural volcanic rock (and magma) compositions lie scattered across a wide range of total alkaliSiO_2 space, with no obvious internal breaks to divide up them into natural sub-groups. In other words, Nature creates within the Earth a *continuum* of potential magma compositions, and any categories or subdivisions we choose to erect (e.g. for the purpose of attaching names) are essentially arbitrary and man-made.

PARAMETERS USED TO CLASSIFY IGNEOUS ROCKS

Unless igneous petrologists are to communicate entirely in numbers, they need a consistent nomenclature that allows this wide compositional spectrum to be sub-divided into smaller fields, to which specific rock names can be applied, just as a state is divided for administrative purposes into named counties and districts.

Modern igneous nomenclature rests on three types of observation, each of which may influence the name given to a rock:

- *qualitative* petrographic observations (e.g. the presence or absence of quartz);
- *quantitative* petrographic data (e.g. the
- percentage of quartz in the rock);
- *chemical* composition (e.g. position in a TAS diagram – Fig. 1.4).

These can be illustrated further by considering three elementary ways in which we categorize igneous rocks.

Classification by qualitative criteria – grain size

Figure 1.3 a shows how igneous rocks are divided into coarse -, medium-and fine-grained categories, based on a qualitative (or semiquantitative) estimate of the average grainsize of the *groundmass* of the rock (N.B. *not* on the size of any phenocrysts present). This estimate may be based on hand-specimen observation or, more reliably, on thin section examination. According to the grain-size category in which it falls (fine, medium or coarse), a rock of basaltic mineralogy, for example, would be called a basalt, a dolerite (UK) or diabase (US),[3] or a gabbro.

Another example of a qualitative observation used in rock classification is the presence of quartz or nepheline in the rock, indicating whether it is **silica-oversaturated** or **silica-ndersaturated**.

Classification by mineral proportions colour index

Familiar adjectives like ‘ultramafic’ and ‘leucocratic’ refer to the relative proportions of dark and light minerals in an igneous rock, where ‘dark’ and ‘light’ relate to the appearance of the minerals in hand-specimen, as indicated