

Igneous Rocks and Processes

A Practical Guide

Robin Gill

*Department of Earth Sciences
Royal Holloway
University of London*

 **WILEY-BLACKWELL**

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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 fine-grained 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 <i>root</i> name	Calcic plagioclase in basalt
Type mineral	–	A non-essential mineral used as a <i>qualifier</i>	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 60¹) 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/bgsrscs/.

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

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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 petrol-

ogist 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

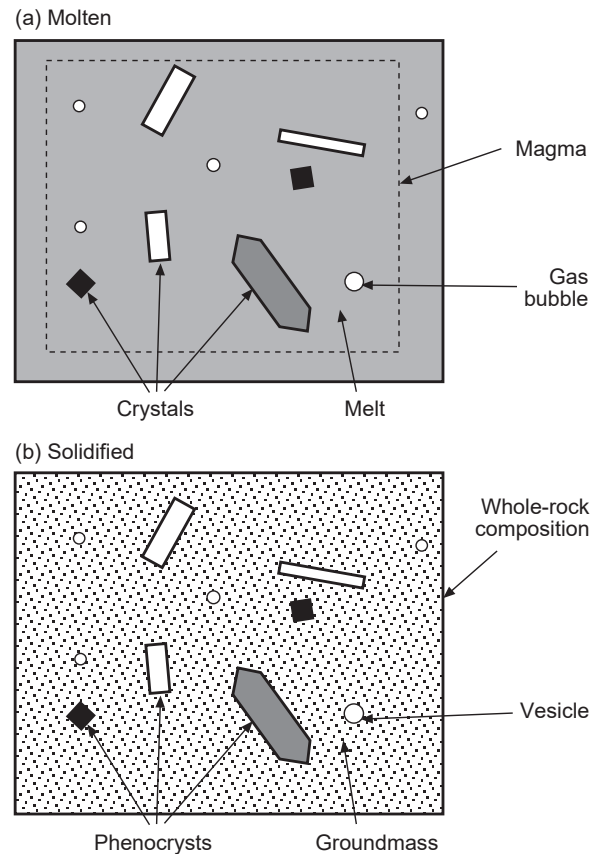


Fig. 1.1 Terminology used to designate the different constituents of (a) a molten lava and (b) the same lava in the solid state.

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.

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

¹ Terms printed in **bold** are defined (and in some cases their etymology is explained) in the Glossary.

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

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_2O_3), 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_2O_3	13.03
Fe_2O_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	<u>0.49</u>
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 ‘ $\Sigma\text{Fe}_2\text{O}_3$ ’ – 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’ = $\mu\text{g g}^{-1}$ = 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.

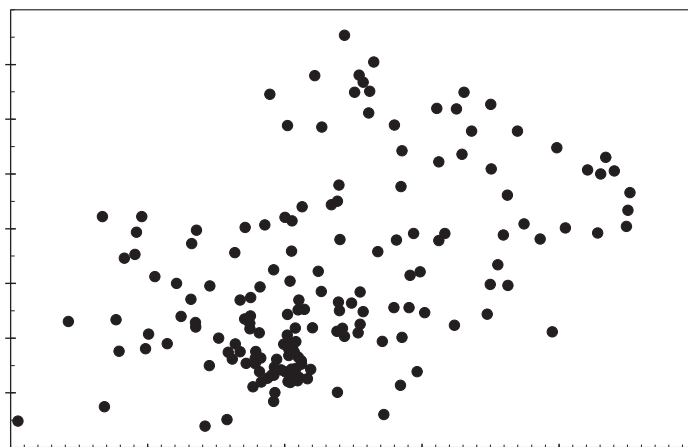


Fig. 1.2 Plot of total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) against SiO_2 (both in mass %) for a representative range of terrestrial volcanic rock analyses (representing igneous melt compositions). Data from Wilson (1989) with selected additions from Carmichael et al (1974) and Cox et 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.

us complementary information about an igneous rock, and neither alone provides a complete understanding of the rock's origin and history.

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 per cent [mass %; see footnote²], i.e. grams of oxide per 100g 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 $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and SiO_2 coordinates – 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 alkali- SiO_2 space, with no obvious internal breaks

² In this book, the term 'mass percent' is used in preference to the traditional but less appropriate term 'weight percent'.

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 1.3a shows how igneous rocks are divided into coarse-, medium- and fine-grained categories, based on a qualitative (or semi-quantitative) estimate of the average grain-size 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.

³ The IUGS *Subcommission on the systematics of igneous rocks* (Le Maitre, 2002) recommends the use of microgabbro in place of dolerite or diabase.

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-undersaturated**.

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 on the left of Fig. 1.3b. Dark minerals are known alternatively as **mafic** or **ferromagnesian** minerals; light minerals are also known as **felsic** minerals. The percentage of dark minerals is known as the **colour index** of the rock.

Quantitative measurements of mineral proportions in a thin section rely on a technique known as *point counting*. This entails mounting the thin section of interest in a special device attached to the microscope stage, which allows the slide to be advanced by regular small increments in both *x* and *y* directions by pressing relevant buttons. Starting near to one corner of the slide, the operator identifies the mineral under the cross-wires at each point as the thin section is stepped systematically across the stage, recording the number of ‘hits’ for each mineral present. Having acquired several hundred data points covering a significant area of the thin section, the percentage of each mineral is easily calculated. As the percentages calculated are proportional to the aggregate area of each minerals on the slide surface, such methods determine relative mineral proportions *by volume*, not by mass. As most dark minerals are significantly denser than the light minerals, this fact introduces a bias that must be borne in mind if mineral proportions determined in this way are compared with geochemical analyses (which are expressed in percentages *by mass*).

Strictly interpreted, all of the descriptors shown in Fig. 1.3b should be based on *quantitative* mineral proportions determined in this way, which is a time-consuming exercise. For most day-to-day purposes, however, the terms may be applied on the basis of a quick ‘eyeball’ estimate of dark and light mineral proportions.

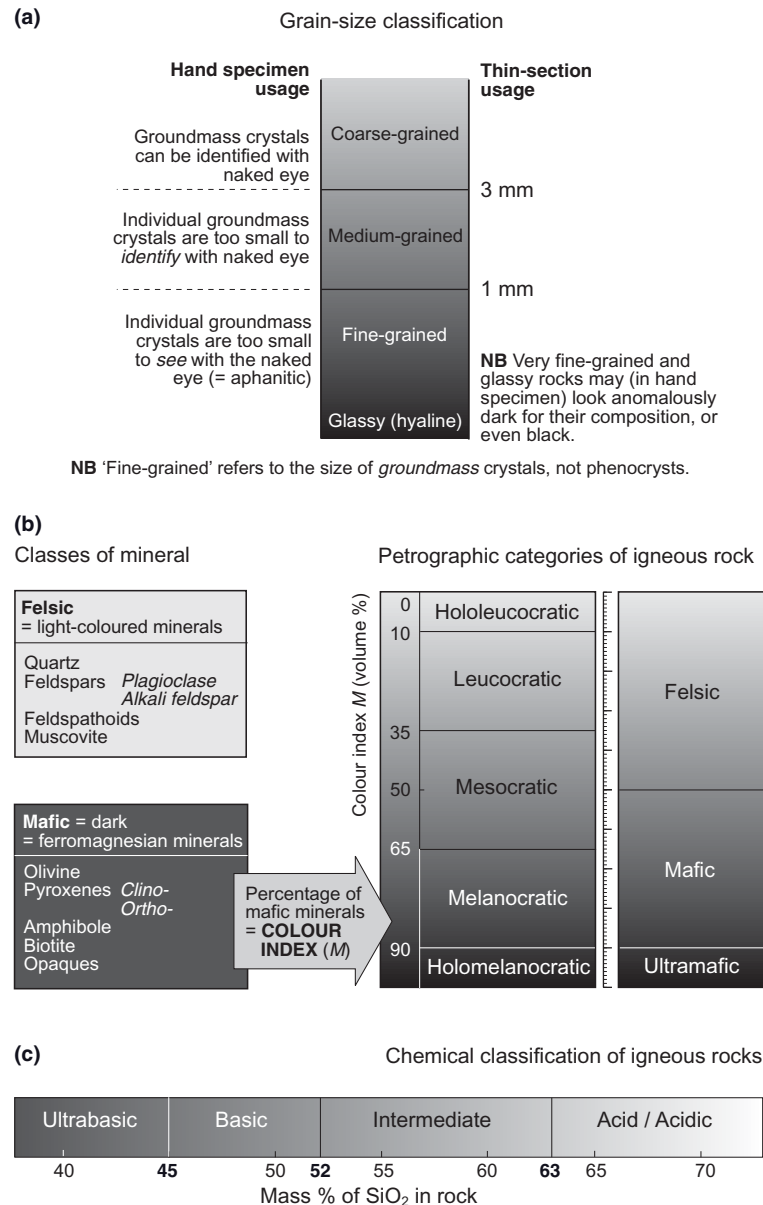


Fig. 1.3 Three simple ways in which igneous rocks may be categorized: (a) by grain size of the groundmass. The boundary between medium-grained and coarse-grained has been placed at 3 mm in conformity with Le Maitre (2002); other conventions (e.g. Cox et al., 1988) have used 5 mm; (b) by volume proportions of light (felsic) and dark (mafic) minerals observed under the microscope; (c) by silica content (requiring a chemical analysis). The boundary between intermediate and acid in (c) has been placed at 63% SiO₂ in conformity with Le Maitre (2002); previous conventions placed it at 65%. An analysis used to determine whether a sample is ultrabasic, basic, intermediate or acid should first be recalculated to a volatile-free basis (see Box 1.3).

It may help the reader to know the origins of words like **melanocratic** and **leucocratic**: they derive from the Greek roots *melano-* (meaning 'dark' as in *melanoma* and *melancholy*), *leuco-* (meaning 'light-coloured' as in

leucocyte – the medical term for a white blood cell), and *-cratic* (meaning 'ruled by', as in *democratic* and *autocratic*). The term **mesocratic** – though self-contradictory (since a rock cannot be dominated by something

between dark and light minerals!) – is the label applied to rocks having colour indices in the range 35–65.

Classification by chemical composition – acidic versus basic

The first classification of igneous rocks that most students encounter is the one that divides rocks into *ultrabasic*, *basic*, *intermediate* and *acid* categories. This classification is based on the SiO₂ content of the rock, as shown in Fig. 1.3c (based on values adopted by the International Union of Geological Sciences [IUGS]). The SiO₂ content, the first parameter in the geochemical analysis shown in Box 1.1, cannot be known until the sample has undergone laboratory analysis, and herein lies the main disadvantage of this classification: it cannot be used to describe rocks as they are being collected in the field or examined under the microscope.

It is important to draw a clear distinction between the silica content of a rock (which usually lies between 40% and 75%) and the quartz content (rarely more than 30%, and often zero): silica (SiO₂) is a chemical *component* present in all silicate minerals, whereas quartz (which has the same composition, SiO₂) is a *mineral* with a particular composition and crystal structure. Quartz represents surplus SiO₂, i.e. that left over after all the other silicate minerals have captured their share of the available silica in the melt.

The term ‘silicic’, a less precisely defined term widely used in North America, is broadly synonymous with ‘acid’.

DEVisING A BASIC PETROGRAPHIC NOMENCLATURE FOR IGNEOUS ROCKS

The initial emphasis in this book will be on rock nomenclature based on qualitative petrographic observations, as these are most relevant to undergraduate practical classes and field work.

Most igneous rock names consist of a **root name** (such as *basalt*, *andesite*, *trachyte*) prefaced by one or more **qualifiers** that highlight any distinctive textural or compositional features that the rock in question may possess (e.g. *olivine* basalt, *plagioclase-phyric* andesite, *aphanitic* trachyte).

What is a basalt?

A well known dictionary of petrology defines ‘basalt’ as follows:

According to modern usage, basalt is a volcanic rock composed essentially of labradorite, pyroxene and iron ore, with or without interstitial glass or chlorite.⁴

This definition, though recognizably referring to basalt, has a number of shortcomings that are worth highlighting in the interests of clarity:

- 1 As commonly understood, ‘volcanic’ is a *genetic* term (implying eruption on the Earth’s surface) that may, in a few cases, be difficult to prove in the field. Though most basalts are indeed products of surface eruptions, petrologists prefer to base rock nomenclature on *descriptive* criteria relating to the individual sample, independent of field interpretation. In other words, it should be possible to give an appropriate name to an unlabelled rock sample pulled out of a drawer, without knowing the kind of body from which it was actually collected. The key descriptive characteristic that discriminates basalt from dolerite and gabbro is that it is the *fine-grained* member of this family. A fine-grained basic rock forming the chilled contact of a dyke (a hypabyssal rock), or even that of a major intrusion (a plutonic rock), qualifies as a basalt just as much as a basic lava flow. The centre of a thick basic lava flow may, on the other hand, be medium-grained (qualifying as dolerite) or in extreme cases even coarse-grained, in spite of its undoubtedly volcanic origin.
- 2 ‘Pyroxene’ is not specific enough: the pyroxene characteristic of basalt (and dolerite and gabbro) is high-Ca pyroxene, usually the variety known as augite (Box 2.1). Basalts *may* contain low-Ca pyroxene – enstatite – as well, but never without high-Ca pyroxene. A precise definition of basalt should therefore specify *augite* (or high-Ca pyroxene) as the essential pyroxene.

⁴ Tomkeieff et al (1983).

- 3 'Labradorite' (An_{50} – An_{70} – see Box 1.2), on the other hand, is too restrictive. In some terrestrial basalts and gabbros, plagioclase cores fall within the more calcic range of bytownite (An_{70} – An_{90}), and lunar basalts even contain anorthite (An_{90} – An_{100}). Recognizing this wider range of plagioclase compositions in natural basalts, it is advisable simply to stipulate 'calcic plagioclase' (meaning any plagioclase whose anorthite content exceeds 50%) as the essential plagioclase in a basalt.
- 4 'With or without interstitial glass ...' is redundant in a concise definition.
- 5 Chlorite is a hydrous sheet silicate mineral that never crystallizes directly from magma and is never found in fresh igneous rocks. Where it does occur in igneous rocks, it is invariably as a **secondary** product of the **hydrothermal alteration** of igneous minerals such as pyroxene, or as a constituent of hydrothermal veins. As the product of late-stage hydrothermal or low-grade metamorphic (i.e. post-magmatic) processes, affecting some basalts but not others, it has no place in the definition of an igneous rock.

A more accurate and succinct petrographic definition of 'basalt' is as follows:

Basalt is a fine-grained igneous rock consisting of the essential minerals calcic plagioclase and augite.

How does one determine under the microscope whether a plagioclase is calcic or sodic? A simple technique is described in Box 4.1, but the practical details need not concern the reader at this stage.

'Essential', 'type', 'accessory' and 'post-magmatic' minerals

The above definition of a basalt rests on the presence of two key minerals: high-Ca pyroxene and calcic plagioclase. Any fine-grained igneous rock containing these two minerals qualifies to be known by the **root name** 'basalt'. However, petrologists routinely divide basalts into sub-groups according to other minerals they may contain. For instance, the occurrence of olivine in a basalt, in addition to augite and calcic plagioclase, places a basalt in the important sub-group called 'olivine basalt'. Not all minerals present in a rock are used in this way, however. For the purpose of giving rocks simple, informative names, it is helpful to consider the minerals a rock contains under four conceptual headings:

1 *Essential minerals*: those minerals whose presence in the rock determines the root name given to it. For example, the dominance of calcic plagioclase and augite in a *coarse-grained* rock leads unavoidably to the root name 'gabbro'. The absence of either of these essential minerals would invalidate the name: had olivine been present in place of augite, for example, the rock would be called a troctolite (Chapter 4).

2 *Type minerals*: minerals whose presence does not affect the root name, but does allow a rock type to be sub-divided by the use of **qualifiers**. For example, an *olivine gabbro* contains olivine in addition to calcic plagioclase and augite. The minerals selected to serve as type minerals usually tell us something about the composition of the rock: the presence of olivine, for example, indicates that a gabbro is somewhat SiO_2 -deficient; the presence of aegirine in a syenite indicates that it is **peralkaline**.

3 *Accessory minerals*: minerals present in a rock (often in minor amounts) that tell us little about its key chemical characteristics and therefore have little to contribute to rock nomenclature. Examples are chromite, magnetite, apatite and ilmenite.

4 *Post-magmatic minerals*: minerals that formed *after* complete crystallization of the magma:

- **hydrothermal** minerals filling veins and other voids (e.g. zeolite)
- **secondary** minerals, replacing original minerals (e.g. epidote).

As post-magmatic minerals are formed in late hydrothermal rather than igneous processes, they play no role in igneous nomenclature but, because their formation may have been accompanied by significant chemical changes, their presence should always be noted.

Box 1.2 Expressing the composition of a solid solution mineral

Olivine and plagioclase are two among many minerals that consist of **solid solutions**: any natural olivine, for example, is a mixture – on the molecular scale – of two compounds, Mg_2SiO_4 (forsterite, often abbreviated to Fo) and Fe_2SiO_4 (fayalite, abbreviation Fa).

Table 1.2.1 below shows a simplified olivine analysis, expressed in mass percentages of SiO_2 , FeO and MgO (Box 1.1). A more concise way of stating the composition of a solid-solution mineral is as percentages of its **end-member** molecules, in this case Mg_2SiO_4 and Fe_2SiO_4 . To see how this is done, it is helpful first to rewrite each formula in its alternative form, namely $(\text{MgO})_2(\text{SiO}_2)$ and

Table 1.2.1 Calculating end-members for a simplified olivine analysis.

	Simplified olivine analysis, mass %*	Oxide RMM	Moles available per 100g of sample†	Moles allocated to $2\text{FeO} \cdot \text{SiO}_2^\ddagger$	Moles allocated to $2\text{MgO} \cdot \text{SiO}_2$	Total moles allocated	Residuals
SiO_2	39.58	60.09	0.6588	0.1157	0.5414	0.6571	0.0017 [§]
FeO	16.63	71.85	0.2315	0.2315		0.2315	0.0000
MgO	43.66	40.32	1.0828		1.0828	1.0828	0.0000
Total	99.87		1.9731				
		Moles of X_2SiO_4 :		0.1157	0.5414	0.6571	
		Molar % Fa and Fo [#] :		17.61%	82.39%	100.00	

* ‘Oxide mass %’ can be visualized as *grammes of each oxide per 100 g of sample*.

† Each number in column 1 divided by the corresponding RMM in column 2 gives *moles per 100 g of sample*.

‡ If n moles of FeO are available, they combine with $0.5n$ moles of SiO_2 to form $0.5n$ moles of fayalite.

§ The small excess of SiO_2 (amounting to 1 part in 400 of available SiO_2) may reflect analytical error or the fact that small amounts of CaO and MnO present in the original analysis have been neglected in the simplified version shown above.

[#] = $100 \times 0.1157 / 0.6571$, etc.

It should be emphasized that a mineral that has essential status in one rock may serve as a type mineral in another, and as an accessory mineral in a third.

Examples of the essential minerals that define the common volcanic rock types are given in Table 1.1, together with the main type minerals upon which qualifiers may be based. This table is a simplification of the quantitative nomenclature spelled out in Le Maitre (2002). It is more common today, if a major element analysis is available, to derive a fine-grained rock’s root name from its chemical composition plotted in Fig. 1.4, rather than from petrographic criteria. Since Fig. 1.4 has been based on a large compilation of petrographically well characterized volcanic rocks (Le Maitre, 2002), there is generally a good correlation between petrographic and chemical nomenclature.

A reader trying to memorize root names and their definitions can easily reduce each

definition in Table 1.1 to a simple code. For example, nephelinite could be represented as ‘cpx+ne’. The coarse-grained equivalent (e.g. ijolite, Table 9.3) could be specified by writing the same code in capitals.

Devising a full petrographic name

This hierarchy of minerals forms the basis for giving petrographic names to all igneous rocks. It provides for informative names such as *olivine gabbro*, *hornblende andesite* and *muscovite biotite microgranite*; in each of these compound names, a **root name** is prefaced by one or more **qualifiers**. The most important qualifiers indicate the type minerals present (which often provide clues about magma composition). A petrographic rock name has the general form:

(type mineral 3) (type mineral 2) (type mineral 1) ... root name

(FeO)₂(SiO₂). Doing so makes clear that *one* molecule of forsterite (Mg₂SiO₄), for example, is made by combining *two* molecules of MgO with *one* molecule of SiO₂. Such calculations become easier when the original analysis is expressed in numbers that reflect how many *molecules* (or moles) of each end-member are present, rather than how many *grammes*.

This transformation is accomplished by dividing each oxide percentage (mass % = *g of oxide per 100 g of olivine*) in column 1 by the relevant relative molecular mass ('RMM' in column 2). The result, in column 3, shows the number of *moles of each oxide per 100 g of olivine*. The 0.2315 moles of FeO can then be combined with $0.2315 \div 2 = 0.1157$ moles of SiO₂ to produce 0.1157 moles of (FeO)₂SiO₂ (see table). Likewise 1.0828 moles of MgO can be combined with $1.0828 \div 2 = 0.5414$ moles of SiO₂ to produce 0.5414 moles of (MgO)₂SiO₂. Dividing each of these numbers by their sum (0.6571) and multiplying by 100 gives the *molar percentage* of each **end-member** in this sample of olivine. The result shown in the Table can be written in the short-hand form Fo₈₂, the most concise way of expressing any olivine's composition.

Similar calculations allow plagioclase compositions to be expressed in terms of the molar percentage of the anorthite molecule (e.g. An₅₆ for a plagioclase with 56 mole % of An and 44% Ab). The following names are widely used for specific ranges of composition:

anorthite	An ₁₀₀ –An ₉₀ (also refers to the pure end-member CaAl ₂ Si ₂ O ₈)
bytownite	An ₉₀ –An ₇₀
labradorite	An ₇₀ –An ₅₀
andesine	An ₅₀ –An ₃₀
oligoclase	An ₃₀ –An ₁₀
albite	An ₁₀ –An ₀ (also refers to the pure end-member NaAlSi ₃ O ₈).

Solid solution in pyroxenes is more complex, so representing the composition of a pyroxene requires *three* compositional end-members: Mg₂Si₂O₆, Fe₂Si₂O₆ and Ca₂Si₂O₆ (as explained in Box 2.1). The presence of small amounts of Al₂O₃ and TiO₂ in most natural pyroxenes complicates matters a little, but for present purposes this can be ignored. Garnet compositions are still more complex and require *six* end-members (Box 5.2). Such 'formula calculations' are explained in more detail in Gill (1996, Chapter 8).

Note the convention (see Le Maitre, 2002) that, if several type minerals are listed in a rock name, the most abundant of them is listed last (i.e. closest to the root name). So a granite containing more biotite than muscovite would be called a *muscovite biotite granite*, not a biotite muscovite granite. The logic behind this convention is that muscovite serves here as a minor qualifier, indicating what kind of *biotite granite* we are dealing with.

The decision as to which minerals should be highlighted as type minerals is a matter of petrological judgement; experience, together with Table 1.1, will suggest which minerals have compositional significance in each case. One rule applies in all circumstances: no mineral that has the status of an essential mineral in a particular rock (one indispensable in determining the root name) can also

feature as a type mineral. It would be a tautology to speak of an *augite basalt*, for instance, since the presence of augite is required by the root name basalt anyway, and needs no further emphasis.

Nonetheless, in dealing with an andesite, where the mafic mineral may be augite, low-Ca pyroxene, hornblende *and/or* biotite (Table 1.1), it *would* be appropriate to specify augite as a type mineral: whereas hornblende and biotite are characteristic of more **evolved**, lower-T, hydrous examples of andesite magma, the name *augite andesite* signifies that we are dealing with a relatively **primitive**, high-T or anhydrous andesite magma.

Appending type minerals to a rock name gives useful qualitative information (beyond what is available from the root name alone) about the chemical composition of the magma from which a rock crystallized, as will become

Table 1.1 Root names and essential minerals for the petrographic identification of the principal fine-grained igneous rocks. Where percentages are specified, these are estimates of volume % that may be based on qualitative visual assessment of a thin section. A number of minerals mentioned below may be unfamiliar at this stage (e.g. **feldspathoid**); they are introduced in later chapters. LCP, low-Ca pyroxene, including enstatite and pigeonite (see Box 2.1); plag, plagioclase; calcic plag, An_{50–100}; sodic plag, An_{0–50}; foid, **feldspathoid**.

Root name	Essential minerals required	Possible type minerals
basalt	augite + calcic plag	olivine, LCP (→ tholeiitic basalt ¹), minor nepheline (+ olivine → alkali basalt ¹)
basanite	augite + calcic plag + foid (>10%) + olivine (>10%)	nepheline, leucite or analcite (according to the dominant foid)
tephrite	augite + calcic plag + foid (>10%) (olivine < 10%)	nepheline, leucite or analcite (according to the dominant foid)
nephelinite	augite + nepheline	olivine, melilite
leucitite	augite + leucite	olivine, melilite
trachybasalt	Calcic plag + augite + alkali feldspar <i>or</i> foid	
andesite	sodic plag ² + a mafic mineral (pyroxene <i>or</i> hornblende <i>or</i> biotite)	pyroxene, hornblende or biotite (according to the dominant mafic mineral present)
latite	sodic plag + alkali feldspar	quartz (<20%)
trachyte	alkali feldspar ³ ± sodic plag	quartz (<20%), foid (<10%), aegirine-augite, biotite
phonolite	alkali feldspar ³ ± sodic plag + foid (>10%)	aegirine, riebeckite, biotite; It is also normal to specify the dominant foid if not nepheline, e.g. 'leucite phonolite'
dacite	sodic plag ⁴ + alkali feldspar + quartz (>20%)	hornblende, biotite
rhyolite ⁵	alkali feldspar ³ ± sodic plag + quartz (>20%)	biotite, aegirine

¹These types of basalt are usually distinguished according to chemical (rather than mineralogical) criteria. The concepts are explained in Chapter 2 (Box 2.4).

²Plagioclase phenocrysts, abundant in most andesites, are commonly zoned with calcic cores; the *mean* feldspar composition is however An <50.

³Alkali feldspar exceeds plagioclase

⁴Plagioclase exceeds alkali feldspar.

⁵Rhyolites commonly have a glassy groundmass.

apparent in later chapters. Type minerals provide one way for the petrologist to discriminate between otherwise similar rock types. The same is true of various other kinds of qualifier that may prove useful in specific circumstances, telling us about eruptive processes and crystallization history:

- It may be relevant to highlight textural features in a rock name if, for instance, differences in texture serve to discriminate between two sub-groups: similarities in eruption conditions or crystallization history may be shared by representatives of one batch of magma, but differ from those experienced by a second batch.
- Textural qualifiers such as **vesicular**,

porphyritic (though see below), **seriate**, **spherulitic**, **welded**, **ophitic** and **poikilitic** provide key information about small-scale magma processes or conditions of crystallization.

- The identity of the phenocrysts present in a rock may be spelled out by prefacing the rock name with, say, *olivine-phyric* (if phenocrysts consist of olivine alone) or *olivine-augite-phyric* (if olivine *and* augite phenocrysts are present). An andesite containing plagioclase phenocrysts and hornblende in the groundmass would be referred to as a *plagioclase-phyric hornblende andesite*. Notice here that, although the mere presence of plagioclase is spelt out by the root name *andesite*, the fact that plagioclase occurs *as phenocrysts*

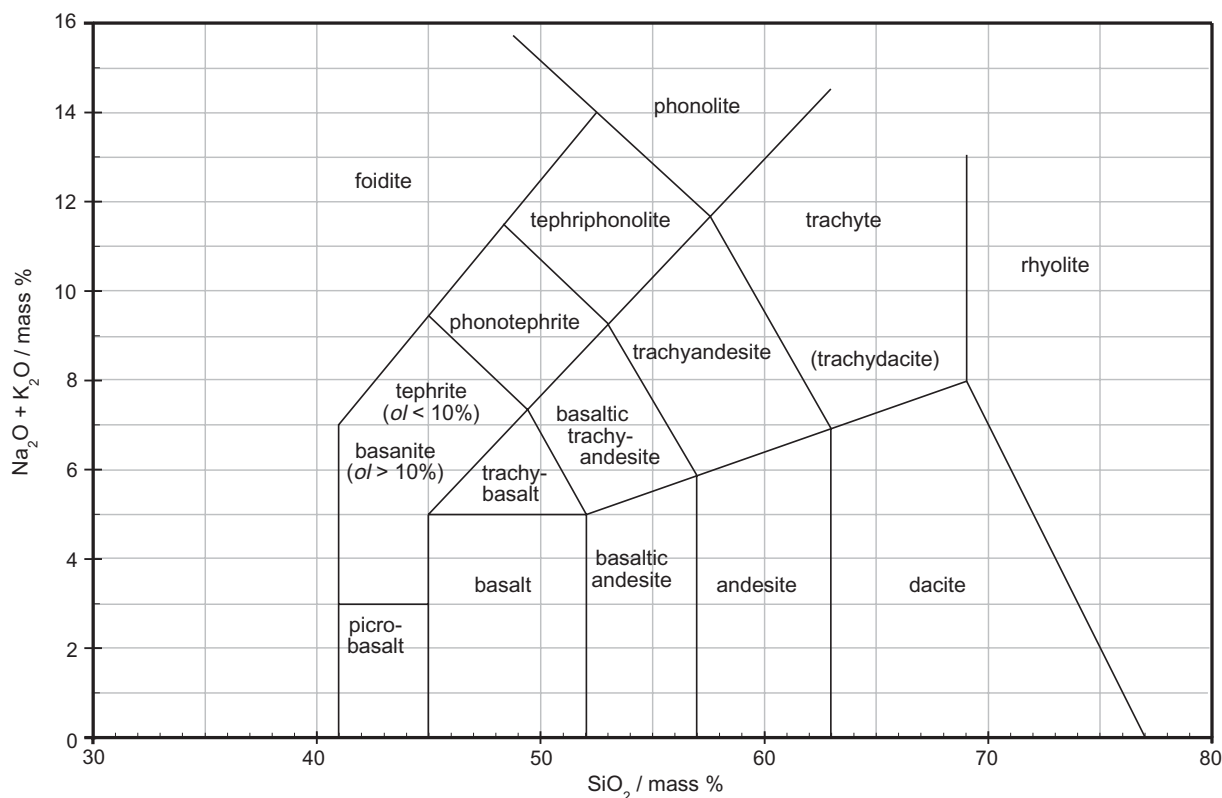


Fig. 1.4 TAS grid showing the fields for common rock types designated by the *IUGS Subcommittee on the Systematics of Igneous Rocks* (Le Maitre, 2002). * All analyses require correction for volatile content (Box 1.3) prior to plotting in this diagram.

* The symbol 'ol' refers to **normative** olivine content (explained in Box 2.4). Rock compositions falling in the trachyte field may be given the name trachydacite if quartz amounts to more than 20% of the **normative** felsic minerals as a whole (quartz + feldspars). Such details need not concern the reader of Chapter 1.

needs emphasizing by means of the prefix 'plagioclase-phyric'.

- As Fig. 1.1 shows, the identity of the phenocrysts in a volcanic rock tells us which minerals had begun to crystallize prior to eruption (e.g. in a sub-volcanic magma chamber).
- Petrologists also use a variety of chemical qualifiers (e.g. low-K, high-K, peralkaline, peraluminous) to refine particular rock names. Such chemical parameters will be described in the following section.

CHEMICAL SUBDIVISION OF IGNEOUS ROCKS AND MAGMAS

There are certain circumstances in which petrographic nomenclature based on the polarizing microscope cannot work on its

own. One example is where a rock contains a significant amount of glass. Most submarine basalts, for instance, consist of small amounts of olivine and plagioclase crystals (augite crystals are rarely seen) set in a glassy matrix. Volcanic glass represents melt that, for a variety of reasons (e.g. rapid chilling), has had insufficient time to crystallize. Consequently, a portion of the chemical components that *would* (under different conditions) have crystallized into recognizable mineral crystals – upon which a petrographic name could have been based – is held back in a glass phase whose composition cannot be determined under the microscope. For such a rock, or one whose groundmass crystals are too fine-grained to identify under the microscope, the rock name must be allocated on the basis of a geochemical analysis.

Not surprisingly, the mineralogical composition of a rock – on which petrographic rock nomenclature is based – correlates strongly with its chemical composition. One can therefore map the divisions between the petrographic rock types discussed above (and shown in Table 1.1) on to appropriate major element variation diagrams, and use these as an alternative basis for allocating rock names. Figure 1.4 shows a TAS diagram upon which a grid of fields and boundaries has been constructed, according to the recommendations of the *International Union of Geological Sciences* (Le Maitre, 2002). The boundaries are drawn empirically so that they fit as closely as possible the distribution on this diagram of a large suite of petrographically identified rock samples (see Le Maitre, 1976). In plotting analyses on this diagram, it is important

to ensure that they have been recalculated in volatile-free form to eliminate as far as possible any distorting effects due to alteration or weathering (Box 1.3).

Two reservations need to be made clear. The first is that the correlation between mineralogy and chemical composition is not perfect, and therefore a rock name devised from Fig. 1.4 for a crystalline rock may in a few cases differ from its petrographic name. For this reason a rock name should be based on petrographic criteria where this is possible. The other reservation is that the alkali metals Na and K are among the most **mobile** elements in post-magmatic hydrothermal processes, and therefore their concentrations may change in such alteration processes (Box 1.4). This limits the reliability of Fig. 1.4 when applied to altered volcanic rocks, even when

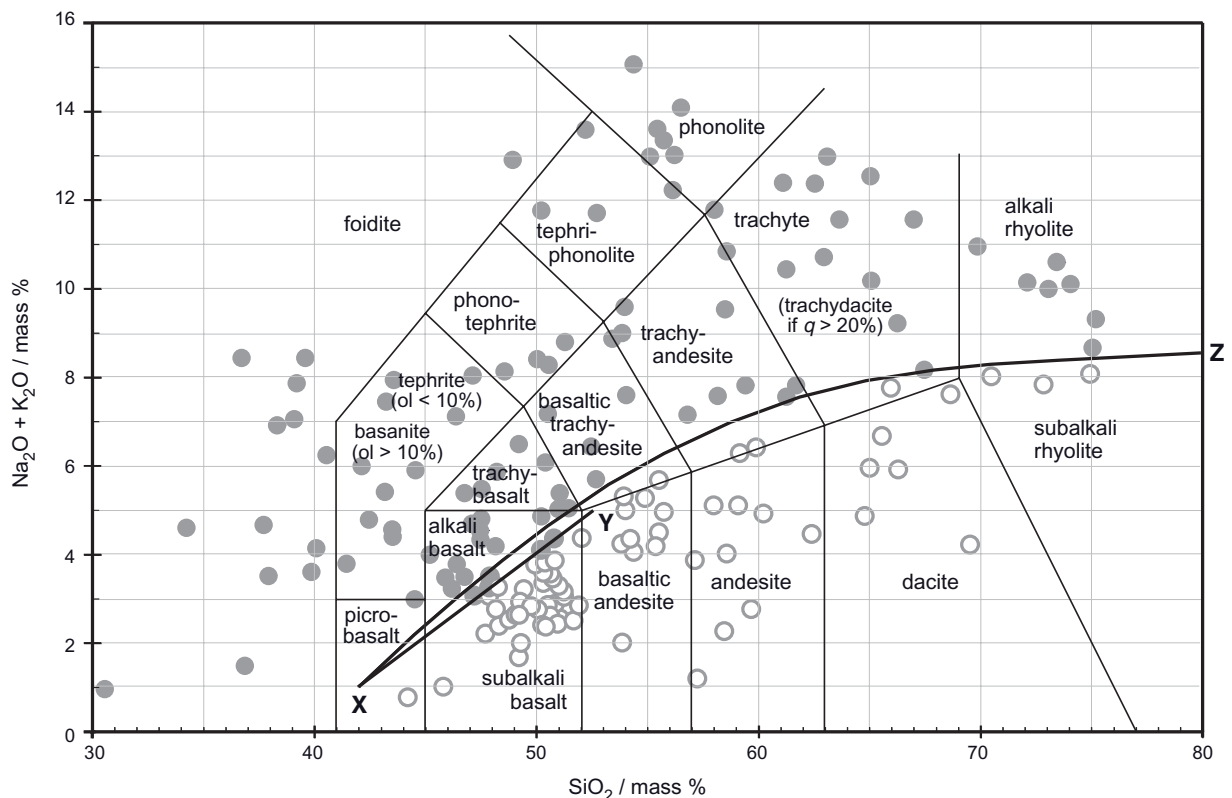


Fig. 1.5 TAS plot showing the division between **subalkali** and **alkali** series of volcanic rocks: the line X-Y shows the dividing line of Macdonald and Katsura (1964) for Hawaiian basalts, and the curve X-Z shows the dividing line of Miyashiro (1978) for a wider range of volcanic rocks. Basalts lying close to these boundaries are often called **transitional** basalts. The Fig. also shows the compilation of volcanic rocks depicted in Fig. 1.2: open symbols represent analyses of subalkali affinity, filled ones those of alkali affinity. Analyses require correction for volatile content (Box 1.3) prior to plotting in this diagram.

analyses have been recalculated volatile-free (Box 1.3).

This chemical approach is not used for naming coarse-grained rocks: there is no need to do so, as the essential and type minerals are usually present in large enough crystals to

be readily identified under the microscope, or even in hand-specimen (Table 8.1). One should note that the mechanical sorting and selective accumulation of different types of crystals that may occur during slow crystallization (leading to the formation of **cumulate**

Box 1.3 Why recalculate volcanic rock analyses to eliminate volatiles?

Though igneous melts contain significant amounts of primary H_2O , CO_2 , SO_2 and other dissolved gases at depth, these volatile constituents are effectively lost into the atmospheric-pressure surface environment on eruption. The contents of H_2O and other volatiles we measure in natural volcanic rocks are mostly due to the presence of hydrous minerals resulting from incipient hydrothermal alteration or weathering: they reflect post-magmatic changes in the mineralogy of the rock rather than original magma chemistry.

For the reasons discussed in Box 1.4, every effort should be made in the field to collect only the freshest material available for geochemical investigations, but in a representative collection of volcanic rocks some samples will unavoidably be more altered than others. In an analysis totalling 100%, the introduction of secondary volatiles depresses the concentrations of other constituents (Fig. 1.3.1), and it follows that some apparent differences between individual samples may arise simply from differences in the degree of alteration. Therefore, although a major element analysis should always include an estimate of total volatile content (e.g. a 'loss-on-ignition' determination) as a means of monitoring alteration, it is normal practice to recalculate analyses into a volatile-free form before plotting geochemical data for volcanic rocks. This is done by multiplying each element or oxide concentration by the factor:

$$\frac{\text{analysis total \%}}{\text{analysis total \%} - \text{volatiles \%}}$$

The reasoning behind this calculation is outlined in Fig. 1.3.1.

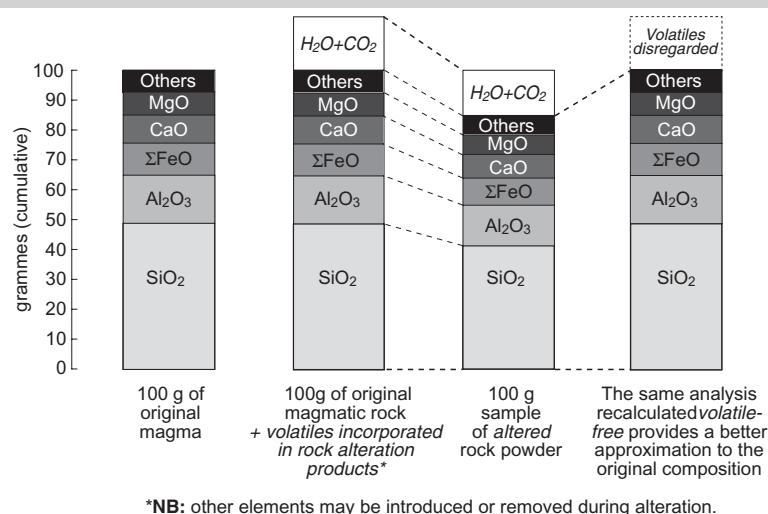


Fig. 1.3.1 Why rock analyses are re-calculated volatile-free before plotting.

rocks as discussed in Box 1.4) means that the chemical composition of a plutonic rock depends on the proportions of minerals that happen to have accumulated within it, and may be only indirectly related to the composition of the magma from which they crystallized.

Geochemical qualifiers

Figure 1.4 shows how a volcanic rock's geochemical composition can be used to allocate a root name (where a petrographic name would be difficult to determine). Rock geochemistry also provides a number of qualifiers that allow us to subdivide those rock types that embrace magmas from a number of sources. Basalts have for many years been

divided into **alkali** and **subalkali** sub-groups. Various criteria have been devised for doing this; the simplest are shown in Fig. 1.5. The line XY shows the boundary drawn by Macdonald and Katsura (1964) to divide the sub-alkali basalts that form the bulk of Hawai'i (including shield volcanoes such as Kilauea) from the alkali basalts that have erupted at later stages of volcano development. To show how this can be applied, the analyses represented in Fig. 1.2 have been reproduced here, with the basalts symbolized in a manner reflecting whether they are alkali or subalkali basalts in the Macdonald and Katsura classification.

Petrologists have recognized for a long time that subalkali basalts tend to fractionate (evolve) towards low-alkali evolved melts

Box 1.4 Does an igneous rock analysis represent a magma composition?

In the quest to discover the origins of magmas and the conditions under which they form, extensive use is made of major element, trace element and isotopic analyses of *volcanic* rocks. The key assumption in doing so is that such analyses accurately represent the chemical compositions of the magmas from which the volcanic rocks crystallized. How widely can this assumption be justified, and what factors limit its application?

Degassing and volatile release

Magma confined at depth in the Earth contains gases dissolved in the melt. As load pressure is relieved during ascent toward the surface, this gas content will progressively come out of solution to form separate bubbles of gas (often apparent as **vesicles** in erupted lavas), which may escape from the magma into the atmosphere (Fig. 2.7). Such 'degassing' is common in all magmas held in shallow magma chambers or erupted on the surface. It follows that the volatile content measured in a fresh volcanic rock sample will generally be less than the true content originally dissolved in the melt at depth.

How can we determine the true pre-eruption 'magmatic' volatile contents of erupted volcanic rocks? One approach is to analyse the volatile content of minute *glass inclusions* (generally referred to loosely – even though no longer molten – as '**melt inclusions**' because they represent trapped melt) within individual phenocrysts, as illustrated in Plate 6.11. The tensile strength of the surrounding crystal effectively 'armours' the melt inclusion against rupture and gas escape as the host magma ascends towards the surface; micro-analysis of the 'trapped' volatile content of these glass inclusions provides the best available measure of that of the undegassed melt (see for example Hammer, 2006).

Hydrothermal alteration and low-grade metamorphism

Anhydrous minerals formed at melt temperatures such as olivine and plagioclase, if exposed to hydrous fluids at lower temperatures during cooling (for example, when fluids circulate through a thick volcanic succession), are prone to react and recrystallize into hydrous **secondary** minerals such as **smectite**, serpentine, chlorite and epidote. The analysis of a volcanic rock that has undergone such alteration or low-grade metamorphic reactions will therefore show elevated contents of H₂O and other volatile species, introduced by these post-magmatic reactions, that bear no relation to the

such as dacite and rhyolite, whereas alkali basalts fractionate toward more alkali-rich evolved melts such as trachyte or phonolite. It is therefore appropriate not only to divide *basalts* into alkali and subalkali classes, but to apply the same distinction to their respective families of residual melts as well. The curve XZ represents the dividing line introduced by Miyashiro (1978) for this purpose, and the more evolved melt compositions shown in Fig. 1.5 have also been symbolized according to which side of this line they lie on.

The broad division of Fig. 1.5 into alkali and subalkali fields, more or less according to Miyashiro's line, is not just an artefact of nomenclature but reflects a profound petrological distinction, as explained in Chapter 9. It is therefore no accident that the

curve XZ lies close to the IUGS dividing lines between basaltic trachyandesite and basaltic andesite, between trachyandesite and andesite, and between trachyte and dacite. The curve also serves to divide the large field of rhyolite into subalkali and alkali varieties, which are characteristic of different tectonic environments.

A related diagram that is widely used to subdivide subduction-related volcanic rocks is shown in Fig. 1.6. In many island arcs, the potassium content of volcanic rocks increases in a systematic manner with distance of the eruption site from the trench or, more accurately, with the depth of the subduction zone below the point of eruption. Nomenclature is needed that reflects these variations, and therefore subduction-related basalts,

original volatile content of the magma. Allowance can be made for this secondary volatile content (see Box 1.3) but it is much harder to correct for any changes in the contents of relatively soluble non-volatile elements such as Na_2O , K_2O and CaO that may also have accompanied these reactions. For this reason geochemical work needs to be based on unaltered samples that show negligible amounts of such post-magmatic minerals under the microscope.

Crystal accumulation

In deep-seated magma chambers where the cooling rate is slow, crystals may sink or float in the melt according to their density and crystal size, and may then form deposits in which one mineral (or more than one) is selectively concentrated at particular horizons. Alternatively, one type of crystal may nucleate more efficiently on the chamber floor and walls than other minerals and thereby become selectively concentrated there. The possibility of such selective accumulation processes, operating on various scales, means that the composition of a plutonic rock hand-specimen will not accurately record the melt composition from which it crystallized. Moreover, accumulations of early crystals will generally have higher Mg/Fe (in the case of ferromagnesian minerals) or higher Ca/Na (in plagioclase) than the melt from which they separated (see Fig. 3.4).

Though crystal accumulation processes exhibit their most dramatic effects in large layered intrusions (Chapter 4), they are also known to occur in minor intrusions and even in thick lava flows (Chapter 2). Whereas in volcanic rocks the minerals that form can be seen as dictated by magma chemistry, in plutonic rocks where crystal sorting may have occurred the converse applies: the whole-rock chemical composition is in part a consequence of the minerals present and the proportions in which they happen to be combined.

Xenocrysts and xenoliths

Many igneous rocks contain foreign material in the form of **xenoliths** (Plate 5.3), torn from conduit walls during magma ascent, or present in a disaggregated state as individual *xenocrysts*. A bulk chemical analysis of the host rock will not faithfully represent the composition of the host magma if such exotic matter has not been carefully picked out during sample preparation. Even when obvious foreign bodies have been removed, the analysis may be distorted by chemical exchange between magma and xenoliths, especially in the case of slowly cooled plutonic host rocks.

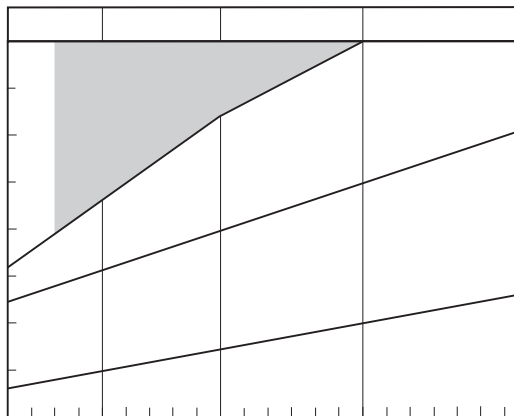


Fig. 1.6 K_2O versus SiO_2 diagram showing the boundaries used to subdivide subduction-related volcanic rocks. Analyses require correction for volatile content (Box 1.3) prior to plotting in this diagram. Boundaries shown are those defined by Le Maitre (2002), except for the one separating the shoshonite association which is from Peccerillo and Taylor (1976).

andesites and dacites are commonly allocated to low-K, medium-K or high-K magma series as defined in Fig. 1.6. Such divisions are not however applied to within-plate or constructive-margin volcanic rocks.

There are other examples of using geochemical qualifiers to refine rock nomenclature that will be discussed in later chapters (see for example Figs. 6.8b,c, 8.14, 8.19, 9.8.1 and 9.24).

REVIEW

Learning to study igneous rocks has much in common with learning a new language; success in both pursuits involves three essentials:

- vocabulary – learning a host of new words, both *nouns* (rock names) and *adjectives* (textural, mineralogical and geochemical qualifiers);
- grammar – learning the rules, conventions and structure (e.g. Le Maitre, 2002) upon which precise description relies;
- lots of practice, through which the learner gradually gains confidence and fluency (see exercises below).

This first chapter has introduced the basic syntax upon which the petrographic ‘language’ of igneous rock nomenclature is based. We have noted that the range of natural magma compositions represented by analyses of volcanic rocks from various settings is essentially a continuum. When straight lines are drawn on a diagram like Fig. 1.4 to define the domain of each rock name, we need to remember that – like fences on a prairie – their position is arbitrary, being determined by convenience and convention and not by any fundamental breaks in magma composition. Just as fences may be moved (and as words change their meaning with time), so petrological boundaries may shift as the details of nomenclature are refined in the light of new research. As an example, the boundaries shown in Fig. 1.6 have slightly different positions according to which paper you look at. This simply emphasizes the arbitrary nature of the boundaries in Fig. 1.4 rather than diminishing their validity.

On the other hand, the broad division of basalts and their diverse fractionation products in Fig. 1.5. into alkali and subalkali domains represents a fundamental petrological boundary that dictates the course of melt evolution, as discussed in detail in Chapter 9.

Adjectives like ‘fine-grained’, ‘melanocratic’ and ‘ultrabasic’ draw on a variety of qualitative and quantitative observations about a rock.

To clarify the underlying principles of igneous nomenclature, the minerals present in an igneous rock are segregated (in this book) into four conceptual categories: essential minerals (determining the rock’s root name as in Table 1.1), type minerals, accessory minerals and post-magmatic minerals. This formulation is merely one way of codifying, or putting into explicit terms, an approach that all petrologists implicitly use in devising rock-names for igneous rocks.

EXERCISES

- 1.1 A thin section of an igneous rock contains phenocrysts ranging in size from 2–6 mm, and a groundmass consisting of crystals less than 0.05 mm in size. Should this rock be described as fine-, medium- or coarse-grained?