Developments in Petrology 7

IGNEOUS PETROLOGY

CHARLES J. HUGHES

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PREFACE

For many years there has been a noticeable lack of senior undergraduate texts in igneous petrology that might bridge a gap between, on the one hand, several excellent introductory petrography-orientated texts and, on the other hand, more advanced texts heavily predicated on a thermodynamic and/or chemical approach to the subject. Furthermore, in the last decade and a half, say since the appearance of the prescient synthesis of Arthur Holmes' *Principles of Physical Geology*, second edition, in 1965, we have witnessed a profound re-orientation of igneous petrology in relation to global tectonics. A giant step has been taken in clothing R.A. Daly's historic comment,

> "A final philosophy of earth history must be largely founded upon the unshakable facts known about igneous rocks"

with evidence and conclusions from both young and old igneous rocks. Ophiolites, Proterozoic igneous rocks, and a few other conspicuous growth areas apart, we now seem to be entering a relatively quiet period of amassing and interpreting a considerable amount of increasingly sophisticated analytical data about igneous rocks, coupled however with a slackening in the rate of new major advances in synthesis and understanding. Thus at this particular time it seems appropriate to attempt to integrate the structure of recent conceptual advances with the firm foundation provided by classical petrology.

The approach in this book is hence predicated initially on field and other direct observations and on an historical background. This approach leads naturally from observational facts about extrusive and intrusive rocks and a classical mineralogical classification, via differentiation processes married to experimental work, to the evolution of ideas on igneous rock series and the recent explosion of the relationship of these to plate tectonics and inferred mantle processes, and to an indication of some current problematical areas. Students do seem to benefit from an appreciation of the historical path of discovery and evolution of ideas about igneous rocks in order to make intelligible the present body of knowledge and thrust of contemporary research.

I have assumed that a reader of this book will have had some elementary training in the physical sciences and some first courses in geology including introductory petrology, and ideally has access to a good thin-section collection of igneous rock suites and the opportunity to read up or attend parallel courses in relevant aspects of geochemistry and isotope geology.

This approach is well illustrated by the choice of references — a perennial and important problem in texts. Many classic and benchmark papers are included, together with a large number of up-to-date review articles and books, and a selection of more specific papers that the writer personally has found interesting and informative, particularly those which may express contrary or modifying opinions to contemporary conventional wisdom. In so far as this book may fail to achieve a compromise between the desirable attributes of readability, brevity, and information source, the reader may be provoked into reading some of these references. As Gilbert Highet in his *The Art of Teaching* so appositely recommends, there is no comparison between the benefit to be derived from looking up work in the original and that from tamely accepting someone else's commentary.

My advice therefore to readers of this book is to use it as I will — with marginal notes and additions, queries, expressions of dissent, etc., as not only is any book imperfect but also our subject is continually evolving. Any suggestions and rectifications will be gratefully received and acknowledged.

I should like to take this opportunity to record a great debt to teachers and comrades over the years. Foremost among these is my former teacher and supervisor, Professor L.R. Wager. Fashions may change in igneous petrology as in other things, but a man's stature does not. Lawrence Wager, mountaineer and field geologist, perceptive petrographer and innovative thinker, possessed the true scientific knack of being able to apply himself assiduously to important problems capable of a solution at the time. A major part of his legacy to igneous petrology is a now dispersed group of igneous petrologists that received their training under him at Oxford and in the Hebrides and Greenland, and elsewhere. I also recall with great pleasure the camaraderie of geologists over the years in Zambia, Zimbabwe, Union of South Africa, Ghana, Egypt, Morocco, Spain, France, Federal Republic of Germany, Switzerland, Scandinavia, Eire, United Kingdom, U.S.A., Canada, Iceland, India, Nepal, Malaysia, Australia, New Zealand and Japan, and especially the stimulus afforded by undergraduate and graduate students and colleagues at Memorial University of Newfoundland over the last fourteen years.

Among colleagues at MUN I should especially like to thank in the context of this work Glenys Woodland for the major part of the typing with able assistance from Lillian Murphy, Cynthia Neary and Betty Andrews; Clifford Wood, Gary McManus and colleagues for drafting services and advice; and Jeanne Mills, Adele Poynter and George Einarson for help with references. I owe a particular debt to my friend and colleague, Dr. John G. Malpas, for his pains in cheerfully reading the text and making numerous suggestions for improvement despite other heavy claims on his time.

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St. John's, Newfoundland
January 1981

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GLOSSARY

Units used in this book and their conversions to SI units:

Concentration	ppb	(parts per billion)		
	ppm	(parts per million)		
	vol.%	(per cent by volume)		
	wt.%	(per cent by weight)		
Energy	cal.	(calorie)	4.184 J	(joule)
Length	Å	(ångström)	10^{-10} m	(meter)
	fathom	(nautical fathom)	1.8288 m	
Mass	t	(metric ton, tonne)	10^{6} g	(gram)
Pressure	atm.	(atmosphere)	$1.013 \cdot 10^{5}$ Pa	(pascal)
	bar		10^{5} Pa	
Temperature	°C	(degree Celsius)	K	(kelvin)
Time	day		86,400 s	(second)
	a	(year)	$3.16 \cdot 10^{7}$ s	
Viscosity	P	(poise)	10^{-5} N m^{-2} s^{-1}	

S.I. unit prefixes:

μ (micro)	10^{-6}	k (kilo)	10^{3}
m (milli)	10^{-3}	M (mega)	10^{6}
c (centi)	10^{-2}	G (giga)	10^{9}

Abbreviations, acronyms, and symbols used in text:

AFM variation diagram	alkalis: iron oxide: magnesia
An	proportion by weight of anorthite, the higher-temperature component, in the solid-solution series anorthite—albite; for example, An_{81} signifies a composition of 81 wt.% anorthite
BABI	basaltic achondrite best initial
CFSE	crystal field stabilization energy
CI	crystallization index
C.I.	colour index
CMAS system	$CaO—MgO—Al_2O_3—SiO_2$
DI	differentiation index
DLVL	depleted low-velocity layer
E	explosion index

En	proportion by weight of enstatite in the solid-solution series enstatite—ferrosilite (see note above on An)
FAMOUS	French American Mid-Ocean Undersea Study
FI	fractionation index

Abbreviations, acronyms, and symbols used in text (continued):

FMA variation diagram	*see AFM* variation diagram
Fo	proportion by weight of forsterite in the solid-solution series forsterite—fayalite (see note above on An)
h	vertical distance in kilometres to Benioff seismic zone
HREE	heavy rare-earth elements
IAT	island-arc tholeiite
K_{55}-value	wt.% K_2O in a series at a silica content of 55 wt.%
LIL	large-ion lithospheric
LKT	low-potassium tholeiite
LREE	light rare-earth elements
LVL	low-velocity layer
M-value	100Mg/(Mg + total Fe)
Mg ratio	$100Mg/(Mg + Fe^{2+})$
MORB	mid-ocean ridge basalt
OIT	oceanic-island tholeiite
PHMP	primordial hot mantle plume
Q	dimensionless quantity expressing seismic measure of anelasticity within the mantle
REE	rare-earth elements
SBZ	supra-Benioff seismic zone
SI	solidification index
$(^{87}Sr/^{86}Sr)^0$	initial $^{87}Sr/^{86}Sr$ ratio

See also general index for references to further explanation and usage in context of the above.

Frequently used abbreviations of normative mineral molecules for CIPW classification:

ab = albite	fo = forsterite	ne = nepheline
ac = acmite	fs = ferrosilite	ns = sodium metasilicate
an = anorthite	hm = hematite	ol = olivine
C = corundum	hy = hypersthene	or = orthoclase
di = diopside	il = ilmenite	Q = quartz
en = enstatite	lc = leucite	wo = wollastonite
fa = fayalite	mt = magnetite	

Chemical symbols and elements:

Ac	actinium	B	boron	Cd	cadmium
Ag	silver	Ba	barium	Ce	cerium
Al	aluminium	Be	beryllium	Cl	chlorine
Ar	argon	Bi	bismuth	Co	cobalt
As	arsenic	Br	bromine	Cr	chromium
At	astatine	C	carbon	Cs	caesium
Au	gold	Ca	calcium	Cu	copper

Chemical symbols and elements (continued):

Dy	dysprosium	Mo	molybdenum	Sb	antimony
Er	erbium	N	nitrogen	Sc	scandium
Eu	europium	Na	sodium	Se	selenium
F	fluorine	Nb	niobium	Si	silicon
Fe	iron	Nd	neodymium	Sm	samarium
Fr	francium	Ne	neon	Sn	tin
Ga	gallium	Ni	nickel	Sr	strontium
Gd	gadolinium	O	oxygen	Ta	tantalum
Ge	germanium	Os	osmium	Tb	terbium
H	hydrogen	P	phosphorus	Tc	technetium
He	helium	Pa	protactinium	Te	tellurium
Hf	hafnium	Pb	lead	Th	thorium
Hg	mercury	Pd	palladium	Ti	titanium
Ho	holmium	Pm	promethium	Tl	thallium
I	iodine	Po	polonium	Tm	thulium
In	indium	Pr	praseodymium	U	uranium
Ir	iridium	Pt	platinum	V	vanadium
K	potassium	Ra	radium	W	tungsten
Kr	krypton	Rb	rubidium	Xe	xenon
La	lanthanum	Re	rhenium	Y	yttrium
Li	lithium	Rh	rhodium	Yb	ytterbium
Lu	lutetium	Rn	radon	Zn	zinc
Mg	magnesium	Ru	ruthenium	Zr	zirconium
Mn	manganese	S	sulphur		

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Chapter 1

MINERALOGY OF IGNEOUS ROCKS

1.1. INTRODUCTION

Igneous rocks, apart from those few which are wholly or partly glassy, are composed of minerals and a knowledge of these minerals therefore is one logical starting point for study. Indeed the microscopic determination in thin sections of the content, abundance, and textural relations of component minerals remains, as it was for classical petrographers, the most widely used tool in the investigation of igneous rocks.

A **mineral** is a naturally-formed chemical compound having a definite chemical composition and crystalline structure reflecting an ordered arrangement of constituent atoms. The words "definite chemical composition" need qualification: a certain amount of **crystalline solution** (alternatively referred to as **solid solution** or **diadochy**) is possibly whereby atoms, essentially of similar sizes, may substitute to a varying extent for each other within certain crystal lattices. This may at first sight appear to the student to be an unwelcome complication. The possibilities, however, for diadochy between major elements are few in number, and the resultant mineral compositions vary in a systematic manner that can reveal a great deal about magma compositions, temperatures of crystallization, fractional crystallization processes and the like (see Chapter 6), and thus prove to be a most useful tool in our understanding of the genesis of igneous rocks. The characteristic crystalline structures of the different minerals (with some degree of variation resulting from this crystalline solution) are reflected in differing optical properties which readily facilitate identification in thin section.

The actual number of distinct mineral species found in any one igneous rock is small, commonly no more than about half a dozen. This in part reflects the small number of chemical elements that are at all abundant in igneous rock compositions, the possibility of substitution between some of these elements within crystal lattices, and the possibility of further substitution such that most remaining elements present in small concentrations in a magma accommodate themselves in the crystal lattices of the common minerals as dispersed elements rather than form distinct mineral species. This observed small number of minerals in any igneous rock also reflects more fundamentally the operation of the phase rule and some close approach to equilibrium conditions of crystallization, thus explaining the systematic way in which magmas of similar compositions have crystallized to give similar proportions of the same small set of minerals.

In addition to this restraint, the range of magma compositions has well-defined limits, and the *total* number of mineral species found in all but rare and compositionally exceptional igneous rocks such as carbonatite is thus also very limited. The olivines, pyroxenes, amphiboles, micas, feldspars, feldspathoids and quartz, plus a few oxide species in fact make up ~99% of the overall content of igneous rocks. The feldspars alone comprise ~50%, and pyroxenes and quartz a further 25%, of igneous rocks in general (although not necessarily, of course, of each individual igneous rock).

1.2. CHEMICAL CONSIDERATIONS

1.2.1. The chemical elements

Just as igneous rocks are composed of minerals, so minerals are composed of chemical elements. The periodic table of elements will be familiar to most readers of this book; it is reproduced here (Table 1.1) for reference purposes, and includes the atomic numbers and atomic weights of the first 92 elements including all 90 known to exist naturally on Earth*. The horizontal rows are the seven periods corresponding to the number of electron shells surrounding an atomic nucleus. The major vertical columns contain groups of elements that are related by a similar number and configuration of electrons in an outer shell of up to eight electrons, and hence have comparable chemical properties — properties that commonly show progressive shifts within a group related to the differing atomic weights of its members. Well-recognized groups among the commoner elements include the alkali elements (Li, Na, K, Rb, Cs), the alkaline earth elements (Ca, Sr, Ba), the halogens (F, Cl, Br, I), and the inert or noble gases (He, Ne, Ar, Kr, Xe).

Note that a systematic progression when tabulated in order of increasing atomic number is interrupted in periods *4* to *7* by sets of elements occurring immediately after group IIA. Following the simple Bohr model of the atom, with progressively higher atomic numbers increasing by integral steps, electrons have to be added one by one to the envelope of electron shells to balance the increase in the number of protons in the nucleus. These electrons are added to the outer shell (the one whose electron configuration has a decisive influence on chemical properties) in atoms up to calcium, atomic number *20*. After calcium and succeeding group-IIA elements, however, a certain number of electrons are added progressively to inner electron shells,

*Technetium, atomic number *43*, has no stable nuclides and does not occur naturally on Earth; its presence in certain stars has, however, been inferred from examination of their spectra indicating that thermonuclear synthesis was proceeding there at or just before the time that their light now reaching us was emitted. Promethium, atomic number *61*, similarly has not been detected on Earth.

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