Early Precambrian Basic Magmatism

EARLY PRECAMBRIAN BASIC MAGMATISM

edited by

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Preface

Basic magmatic rocks make up approximately three-quarters of the crust of the present day Earth. Because we can observe and study the volcanic products of present day tectonic regimes comprehensively, we can shed light on ancient tectono-magmatic provinces, and thereby deduce the petrogenesis and evolution of the oldest basic rocks. This is the primary objective of this book.

The book was conceived in order to provide a comprehensive review of the basic rocks produced during the first half of the Precambrian, i.e. the Archaean and early Proterozoic, to about 1.8 Ga years ago. Two major questions are addressed. First, what basic magmas were generated during the early Precambrian: were these magmas globally uniform, and to what extent were prevailing tectonic controls and compositions analogous to those of the present day? Clearly, this can be answered only by bringing together fundamental information about all relevant basic magmatic events. Second, is there any systematic temporal variation in the nature of basic suites, and what implications might such variations have on our interpretations of early Earth history? Are there important differences between early Archaean, late Archaean, Proterozoic and modern basic magmatic suites? The book uses two approaches to address these questions. Early chapters examine the fundamental characteristics of these basic rocks, whilst later chapters assess regional distribution and development by providing an overview of each major early Precambrian craton.

There is considerable evidence for the rapid growth of continental crust towards the end of the Archaean (*c.* 2.5 Ga). This was a diachronous event and associated basic magmatic activity also responded, but at different rates and in different ways throughout the world. For this reason we decided to include the early Proterozoic under our umbrella term 'early Precambrian'.

Despite summarising the wealth of data and the intensity of geological research on early Precambrian basic rocks, this book probably raises as many new questions as have been answered. Nonetheless, we hope that it represents a comprehensive account which will provide further stimulus for future work into the occurrence, character, origin and development of all types of early Precambrian basic rocks, and that ultimately this will lead to a better understanding of early Earth history.

This book is a contribution to IGCP projects 217 (Proterozoic geochemistry), 257 (Precambrian mafic dyke swarms) and 280 (The oldest rocks on Earth).

RPH
DJH

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Symbols and Abbreviations

Rock types

BIF	banded iron-formation
CAB	calc-alkali basalt
IAT	island are tholeiite
HMB	high-Mg basalt
MORB	mid-ocean ridge basalt (N-MORB: normal; E-MORB: enriched; T-MORB: transitional)
OIB	ocean island basalt
SHMB	siliceous high-Mg basalt
STPK	spinifex-textured peridotitic komatiite
VAB	volcanic arc basalt

Minerals

Ab	albite
An	anorthite
En	enstatite
Fs	ferrosilite
Fo	forsterite
Mt	magnetite
Ol	olivine
Pl	plagioclase
Px	pyroxene
X_{Cr}^{spinel}	ionic Cr/(Cr + Al) of spinel
X_{Mg}^{px}	ionic Mg/(Mg + Fe) of pyroxene

Geochemistry

Ga	thousand million years (10^9 years)
Ma	million years (10^6 years)
AFM	Alkali–Fe–Mg wt% oxide proportions
CHUR	chondritic uniform reservoir
ε_{Nd}	Nd epsilon parameter: $10^4 \times [(Nd_i/Nd^t_{CHUR}) - 1]$, where Nd^t_{CHUR} is the $^{143}Nd/^{144}Nd$ ratio of CHUR at the time of formation of the rock
$Fe_2O_3^*$, FeO^*	all Fe expressed as Fe_2O_3, FeO
fO_2	oxygen fugacity
GPa	giga pascal (10 kbars)
HFSE	high field strength elements (Nb, Ti, P, Zr)
LILE	large ion lithophile elements (K, Rb, Sr, Ba, LREE)
La_N	La value normalised to La in average chondrite
$K_{D(PGE)}^{sulphide}$	distribution coefficient (PGE in sulphide phase)
KREEP	K-, REE-, and P-rich lunar rocks
mg′	Mg number, Mg/(Mg + Fe)
Nd_i	initial $^{143}Nd/^{144}Nd$ ratio
NME	normalised multi-element plot (spider diagram)
P	pressure (GPa)
PGE	platinum group elements (Ru, Rh, Pd, Re, Os, Ir, Pt)
ppm	parts per million
REE	rare-earth elements (H: heavy; L: light; M: middle)
REE_N	chondrite-normalised REE values
Sr_i	initial $^{87}Sr/^{86}Sr$ ratio
T	temperature (°C)
T_p	potential temperature

1 Introduction: basic magmatism and crustal evolution

R.P. HALL and D.J. HUGHES

The bulk of the crust of the Earth comprises, and probably always has comprised, igneous rocks which are basic or basic derivative in character, and a vast amount of scientific effort has gone into understanding their petrogenesis over the past fifty years. Why, then, distinguish the basic magmatism of the early Precambrian for particular attention? In a sense the reasons are obvious and simple. At that time, the Earth was a hotter body than now, more capable of producing higher temperature magmas. The brittle plate tectonics which control modern magma genesis were possibly not so prevalent, and entirely different processes may have operated. The present differentiation between oceanic and continental crust and their attendant lithospheres was probably less well defined. All of these factors influenced and contributed to differences in the composition, style and volume of basic magmatism in the early Precambrian compared with what we see today. Understanding the mechanisms and details of the various processes must bring a clearer insight into the evolution of the mantle and thus to the processes which produce basic magmas – both old and modern. It also contributes to our knowledge of how and when continental crust differentiated and developed its modern characteristics, and to how and why much of the metallogenesis of the early Earth took place.

The text has two distinct parts: Chapters 2 to 8 present a thematic view of various aspects of early basic magmatism, whereas the remaining nine chapters are regional syntheses, cataloguing the distribution and petrological characteristics of basic magmatism in the major Precambrian cratons of the world (Figure 1.1). The second part of the review is not balanced or fully comprehensive – but nor is the available information. For example, perhaps one of the most glaring omissions is the lack of reference to the Aldan Shield of eastern Siberia (Kazansky and Moralev, 1981; Bibikova, 1984). In some chapters, where the particular emphasis is on the Archaean alone rather than including the early Proterozoic, again this generally reflects the balance of available information.

What is the significance of 'Early Precambrian' rather than, say, 'Archaean' in the title? This simply reflects a pragmatic approach to what the geological record presents. For a variety of good reasons, early Precambrian stratigraphers can happily place the Archaean–Proterozoic boundary at or about 2.5 Ga (depending on the craton). However, discussions on the temporal geochemical changes in basalts (rather than komatiites, which are almost exclusively Archaean) would be pointlessly restricted by choosing 2.5 Ga as a limit (Condie, Chapter 3). Similarly, taking this specific age as an upper limit would make discussions about major layered intrusions rather difficult as, for example, the Bushveld Complex (2.05 Ga) would have to be excluded, although this complex is clearly related to processes which became significant in the late Archaean

Figure 1.1 Sketch map showing the distribution of the major early Precambrian shields of the world (cross-hatching: Archaean; stipple: early Proterozoic). Map compiled from Condie (1982) and authors of Chapters 9 to 17.

(Hatton and Von Gruenewaldt, Chapter 4; Roberts *et al.*, Chapter 8). There is much evidence to suggest that the Archaean–Proterozoic transition (as an interval of time, rather than the 2.5 Ga boundary) was a period of profound magmatic and tectonic change, marked by a rapid increase in the rate of continental crustal growth, by the inception of modern plate-tectonic processes and by a clear change in the character of basic magmatism. The production of silica-poor ultramafic komatiites stopped and the newly thickened and extended continental crust was intruded by large volumes of more silicic noritic magmas which, when mixed with contemporaneous tholeiitic magmas, formed the major layered intrusive complexes that characterise this period of time. So we are flexible; 'Early Precambrian' has no particular limit although it broadly corresponds to the Archaean and early Proterozoic (> 1.75 Ga).

1.1 Early thermal and magmatic history of the Earth

Arndt (1987) commented on the interpretation of the geochemistry of komatiites, pointing out the problems in unravelling the effects of contamination and the consequent difficulties in determining the nature of source compositions. He used the apposite phrase 'through a dirty window' to describe our view of the Earth's early mantle as revealed by the geological record. In reality the situation is worse than that. The windows are indeed dirty, but they also only look out on part of the view. There are many aspects of the early history of the Earth of which we have virtually no view at all. For example, from the time of condensation or aggregation from the solar nebula to about 4.3 Ga we have no record whatsoever. Indeed, we know vastly more about the magmatic history of the Moon than we do of the Earth between 4.6 and 3.8 Ga, which was the period of highest terrestrial planetary heat production, when the effects of decay of the highly energetic short-lived nuclides ^{244}Pu and, more particularly, ^{26}Al (Figure 1.2), combined with gravitational heating.

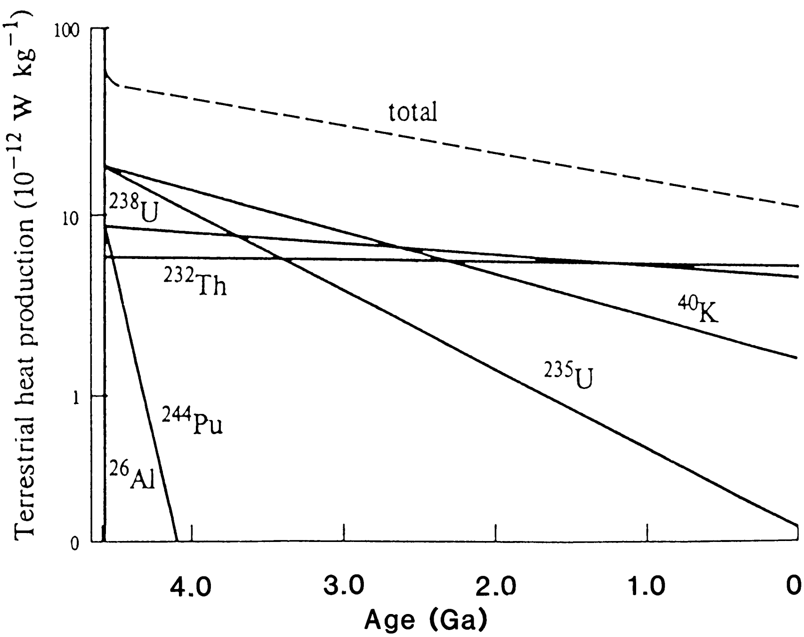

Figure 1.2 Heat production from the significant radioactive nuclides available at the Earth's formation. K, Th and U values extrapolated from present crust and mantle abundances. Al and Pu values estimated from nucleosynthesis theory using stable isotopes in the Allende meteorite (after O'Nions *et al.*, 1978).

Simon (Chapter 7) shows that the Moon provides us with a very clear example of how basic magmatism might have evolved under these conditions. Intense early heating led to the formation of a lunar magma ocean at around 4.6 Ga, the fractionation and solidification of which produced the bedrocks of the lunar highlands. Bombardment by residual nebula debris produced impact melts and highland regolith material between 4.6 and 3.8 Ga and, finally, the mare basalts formed by partial melting of heterogeneous cumulates of the former magma ocean. However, although this is an example of how basic magmatism developed in a terrestrial planet, it is very unlikely to be an appropriate model for the Earth's early history because of the intrinsic geochemical differences between the two planets.

Bickle (Chapter 6) points out that the evidence against substantial early Precambrian mantle degassing, combined with the lack of large-scale fractionation of many trace elements in the mantle, mitigates strongly against there ever having been a major terrestrial mantle melting event, a magma ocean (cf. Nisbett and Walker, 1982). However, the geological record suggests that at least part of the upper mantle may have undergone significant melting during the first 100 Ma of the Earth's history. Similarly, the total heat supply and the nature of the Moon's accretion and fractionation did not allow it to continue as a dynamic system after about 3 Ga, whereas the Earth was by this time clearly producing a wide range of basic magmas from the largely unfractionated silicate mantle which had efficiently separated from the core. In contrast, the last major event on the Moon was very different, producing mare basalts by partial melting of a highly fractionated source. The one aspect that must have been common to both planets was intense early meteoritic bombardment and cratering. But this event had largely finished by 3.8 Ga and any record of it has been lost on the Earth, save for the evidence of the occasional late major impact, of which the Sudbury event (1.85 Ga) was possibly one (Hall and Hughes, Chapter 5).

1.2 Early Precambrian oceans and greenstone belts

Cattell and Taylor (Chapter 2) rightly emphasise the predominance and importance of komatiites and related rocks in the Archaean record. As both they and Bickle (Chapter 6) point out, the early Archaean (pre-3.0 Ga) equivalents of ocean basins must have been dominated by ultramafic lavas which would have led to a rapid overturn in (at least) upper mantle material and must have been the major source of terrestrial heat loss. However, we now see almost none of these ancient oceanic rocks. Perhaps the only candidates are the 3.4–3.1 Ga Malene supracrustal rocks in southern West Greenland (Hall *et al.*, Chapter 11) where komatiitic and tholeiitic metavolcanics occur with abundant slices and sheared fragments of harzburgite. However, these rocks are isoclinally folded together with slightly younger acid gneisses and are generally at amphibolite facies. There are no komatiitic ophiolites, no unequivocal sections through the Earth's early oceanic crust – but perhaps we could hardly expect that.

Of course, what we do find is that the early Precambrian komatiites, komatiitic basalts and tholeiites occur mainly in so-called greenstone belts. There is considerable discussion in the following chapters (and much more elsewhere: see Condie, Chapter 3 and Smith, Chapter 16, Table 16.4) about the nature and significance of greenstone belts. Were they entirely ensialic? Were they equivalent to back-arc basins with incipient oceanic crust? Was true subduction involved? The extent to which greenstone belts represent contracted minor oceans is the subject of much controversy, and Smith (Chapter 16) comments on recent suggestions that the Barberton greenstone belt in the Kaapvaal Craton of South Africa might be an ophiolite. Without doubt there are greenstone belts and greenstone belts, but all too often fragmentary preservation and metamorphic overprinting obscures their significance. There is certainly hope in the better preserved examples and, for example, Thurston (Chapter 10) shows that in the Archaean Superior Province in Canada it is possible to recognise four distinct lithological associations within the different greenstone belt assemblages: shallow platform sequences, oceanic sequences, arc volcanism and pull-apart basins. However, one of the major problems which still remains in interpreting virtually every greenstone belt is the nature of their original base. Recent geophysical evidence suggests that greenstone belts may extend at most down to 6 km (Smith, Chapter 16). Critical basal contacts are all too often obscured, sheared or are simply tectonic. Perhaps the only unequivocal example of a greenstone belt in unconformable contact with underlying gneissic basement is the 2.6 Ga Belingwe (now Mberengwa) greenstone belt in Zimbabwe (Smith, Chapter 16). However, it seems clear from geochemical evidence that association with continental crustal rocks of some sort is a prerequisite for most greenstone sequences. It is interesting to note that the oldest preserved rocks of all, those at Isua in West Greenland (3.8 Ga; Moorbath and Taylor, 1981), comprise a sediment-dominated supracrustal sequence and, indeed, one which has no komatiites among its volcanics (Gill *et al.*, 1981). The 4.3–4.1 Ga zircons from the Yilgarn Block in Western Australia (Froude *et al.*, 1983) were presumably derived from acid differentiates of some sort. Thus, although the nature and size of the early Archaean 'continent' at Isua is totally unknown and, as Moorbath (1983) points out, 'four zircons do not make a continent', evolved continental crustal material was clearly being produced at or about 4.0 Ga and was available to support the earliest greenstone belts.

The oldest greenstone belts (> 3.0 Ga) are only well preserved in the 3.55 Ga Warrawoona Group in the Pilbara Block in Western Australia (Purvis, Chapter 14) and in the 3.46 Ga Barberton greenstone belt (Smith, Chapter 16). In these, a familiar stratigraphic sequence is found in which basal komatiites are followed by tholeiitic basalts, their derivatives and various sediments. In other cratons, the oldest belts are fragmented at best. Remnants of komatiite–tholeiite sequences occur in the 3.6–3.3 Ga Minnesota River gneiss terrane in the USA (Snyder *et al.*, Chapter 9), in a variety of > 3.0 Ga sequences in the Zimbabwe and Gabon Cratons in Africa (Smith, Chapter 16), in the Yilgarn Block in Australia (Purvis, Chapter 14) and possibly in the 3.4–3.0 Ga Sargur Group of the Dharwar Craton in India (Weaver, Chapter 15) and the > 3.5 Ga Imataca Complex in the Venezuelan part of the Amazonian Craton in South America (Wirth *et al.*, Chapter 17). Elsewhere, such as in the 3.5 Ga Qianxi Group in Hebei Province of eastern China (Jahn, Chapter 13) and in the > 3.2 Ga portions of the Singhbhum and Aravalli Cratons in India (Weaver, Chapter 15), amphibolite enclaves in gneisses are all that can be recognised. The early geological record is hardly a comprehensive one on which to base modelling for the > 3.0 Ga Earth.

After 3.0 Ga the geological record expands dramatically. Virtually every early Precambrian craton has extensive greenstone belt terranes of between 3.0 and 1.8 Ga, often with very well preserved stratigraphies. Many Archaean ones, such as the 2.7 Ga Abitibi Belt in the Superior Province of Canada, are dominated by komatiites in their lower portions (Thurston, Chapter 10), whereas early Proterozoic ones, such as the 2.1 Ga Jatulian succession in northern Norway (Brewer and Pharaoh, Chapter 12), are predominantly tholeiitic. To a large extent this variation is time dependent. There was a marked decline in the rate of komatiite production with the approach of the Archaean–Proterozoic boundary and after 2.5 Ga komatiitic rocks are very rare in most greenstone belts. However, they are not totally absent. For example, both the 2.1 Ga Rio Itapicuru greenstone belt in the São Francisco Craton and the 2.1 Ga Inini belt in the Amazonian Craton of South America contain komatiitic rocks (Wirth *et al.*, Chapter 17).

The nature of the associated derivative rocks in the stratigraphically higher parts of greenstone belts also appears to have changed with time. Older sequences tend to have evolved members with 'arc-like' characteristics, whereas younger ones tend to have more obviously calc-alkaline members (Condie, Chapter 3). There is a general progression towards the bimodal basalt–rhyolite association which characterises so many Proterozoic greenstone belts (Pharaoh *et al.*, 1987). However, this is neither a simple progression nor a universal rule. There are many instances of Archaean greenstone belts with extensive, highly evolved components. For example, many of the Dharwar greenstone belts in India have metavolcanic sequences ranging from basalt through andesite to rhyolite, with only a rare komatiitic component (Weaver, Chapter 15).

The rather enigmatic term 'greenstone belt' sometimes becomes less than appropriate for some of the more well-preserved sequences of basic volcanic rocks, particularly in the late Archaean and early Proterozoic. For example, the basalts and komatiites of the Hamersley Basin in Western Australia (Purvis, Chapter 14) and the Ventersdorp

Supergroup in South Africa (Smith, Chapter 16) were clearly erupted onto fully stabilised crust and are the equivalents of within-plate flood basalts. Elsewhere in the early Proterozoic, basaltic rocks occur in the earliest complete and unequivocal examples of modern plate-tectonic style orogenic belts. Of these, the 2.0–1.8 Ga Wopmay Orogen on the western side of the Archaean Slave Province in Canada is perhaps the best known (Hoffman, 1980), although there are many others, for example those in the 2.0–1.75 Ga Svecofennian of Scandinavia (Brewer and Pharaoh, Chapter 12).

Many of these changes are reflected much more subtly in the geochemistry of the basic rocks and Cattell and Taylor (Chapter 2) and Condie (Chapter 3) in particular discuss the nature of temporal geochemical variation in the basic rocks of the early Precambrian. In general, komatiites fall into two groups: those which are Al-depleted and those which are Al-undepleted. 3.0–2.5 Ga komatiites (Munro-type) tend to be Al-undepleted but are LREE-depleted. However, although > 3.0 Ga komatiites tend to be Al-depleted, the temporal pattern falls down rapidly. Of the two well-preserved early Archaean examples, those from Barberton are not LREE-depleted whereas those of similar age from Pilbara are strongly depleted. However, it is emphasised that this might well point to the paucity of statistically meaningful information for the > 3.0 Ga Earth rather than to the lack of real temporal change.

A range of siliceous high-magnesium basalts (SHMB) which often show LREE enrichment and negative ε_{Nd} begin to appear as flows and minor intrusions in late Archaean greenstone belts. The best documented of these occur in the Yilgarn Block in Western Australia (Cattell and Taylor, Chapter 2, and Purvis, Chapter 14). Cattell and Taylor do not distinguish these rocks from komatiitic basalts and they favour a simple model for their origin in which komatiitic magma is contaminated by continental crustal material. With Purvis, they point to the evidence provided by the presence of 3.5 Ga zircons, presumed to represent an old sialic crustal contaminant, in the 2.7 Ga flows at Kambalda in the Yilgarn Block. However, Purvis discusses the difficulties in applying the crustal contamination model universally and suggests the possibility of a contaminated lithospheric source in some cases.

Tholeiitic basalts are widespread in every early Precambrian volcanic environment. However, Condie (Chapter 3) points out that what we see in the record is very unlikely to represent statistically what was erupted, because of inevitable preservational bias. In particular, early Precambrian basalts with oceanic (MORB) and within-plate basalt characteristics are rare. Most early Precambrian basalts have a subduction-zone component. Those from the Archaean tend to have island arc affinities whereas those from the Proterozoic tend to be similar to modern calc-alkaline suites. If the geological record is at all statistically reliable, this geochemical variation presumably reflects the nature of the greenstone belts in which most of these basalts occur and the increasing maturity of the continental crust with which they are associated.

1.3 Continental crust and the major basic intrusions

The rate of growth of continental crust has been the subject of much speculation. Some authors have preferred an early, rapid growth model, with continental crust broadly achieving its present extent prior to the earliest geological record, whereas others prefer a slower model, with close to the present crustal extent not being reached until the Archaean–Proterozoic transition (Figure 1.3). Much of this is speculation indeed.