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Alkaline Igneous Rocks

EDITED BY

J. G. FITTON & B. G. J. UPTON

Grant Institute of Geology
University of Edinburgh
Edinburgh EH9 3JW

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Contents

Preface

The papers contained in this volume were presented at a symposium held in Edinburgh in September 1984, which marked the passage of ten years since the publication of *The Alkaline Rocks* edited by Henning Sørensen. In organizing the symposium and compiling this volume we aimed to review recent developments in the petrology and geochemistry of alkaline igneous rocks. We have, for example, paid particular attention to work on lamprophyres and carbonatites which are rock associations of current interest not covered in Sørensen's book. Reviews of recent work on some of the classic alkaline provinces, such as East Africa, southern Greenland and the Kola Peninsula, are included together with reviews of less well-known areas. Other papers discuss the impact of experimental, geochemical and isotopic studies on our understanding of the generation and evolution of alkaline magmas.

We are indebted to the contributors for their collaboration in producing this volume and it is with sadness that we note the death, on 14 February 1986, of Brian Baker, whose pioneering field studies formed the basis for much of our knowledge of the tectonic and volcanic evolution of the East African Rift. An obituary and appreciation of his work is published in the *Journal of Volcanology and Geothermal Research* (**28**, v–vii). We are grateful to The Geological Society and The Royal Society of Edinburgh for their generous assistance with the symposium costs, to Lucian Begg and Dodie James for their help with organizing the symposium and producing this volume, and to our colleagues for the care and enthusiasm with which they reviewed the manuscripts. The efforts of Edward Wates and his staff at Blackwell Scientific Publications are also gratefully acknowledged. To all these we offer our sincere thanks.

J.G.F.
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magmatism, oceanic and continental intraplate magmatism without clear tectonic control, and alkaline magmatism related to subduction processes. In practice, however, this classification is not always easy to apply.

Continental rift valleys provide, volumetrically, the most important occurrences of alkaline igneous rocks although continental rifting is not always accompanied by magmatism. The best known example (arguably the type example) is the East African Rift which, in the course of its long history, has yielded almost the entire spectrum of alkaline magmas. Three papers in this volume are devoted to various aspects of magmatism in the East African Rift. **Baker** reviews its magmatic associations with respect to tectonic development and discusses the origin of the magmas, particularly in relation to the problems presented by the strongly bimodal distribution of basic and salic lava compositions. He concludes that the salic magmas evolved from basic parental magmas by processes of crystal fractionation (cf. **Bailey**). **Macdonald** focusses attention on the peralkaline silicic central volcanoes of Kenya and also favours an origin by crystal fractionation for most of the evolved magmas. There is little evidence for contamination of the evolving magmas with ancient continental crust except in the case of the Naivasha comendites. It is not always possible to demonstrate a genetic link between basic and evolved magmas in the East African Rift, however. The Chilwa alkaline province in Malawi, at the southern end of the rift, is an essentially intrusive province in which salic rocks predominate. The scarcity of basic rocks in this part of the rift has led **Woolley & Jones** to suggest that the evolved magmas were produced directly by melting of metasomatised mantle and lower crust.

Insight into the processes occurring at depth beneath rift valleys may be gained by studying ancient and deeply eroded examples. The Proterozoic Gardar province in South-West Greenland is probably the best studied of these and is reviewed by **Upton & Emeleus**. One of the most striking features of the province is the presence of giant dykes, up to 800 metres wide. These are dominantly basic but in places show *in situ* differentiation into more salic rocks. Salic magma generated in the wider portions of these dykes migrated upwards and may ultimately have accumulated to produce central complexes in which basic magma was subordinate or absent (e.g. the Ilímaussaq intrusion, **Larsen & Sørensen**). The giant dykes, therefore, play a crucial role in understanding the relationship between basic and salic magmas in this and possibly other rift systems.

The separation of continents to form ocean basins must always be preceded by a phase of continental rifting, leaving volcanic and intrusive complexes stranded along passive continental margins. The vigorous magmatism which accompanies continental separation is generally tholeiitic in character as, for example, in the Karoo and Deccan flood basalt provinces. Alkaline magmas, however, may be emplaced along the trailing continental margin during the waning phase of magmatism, long after the spreading centre is established off-shore. The Tertiary volcanic rocks exposed along the east coast of Greenland (described by **Nielsen**) provide an excellent example of such an alkaline province.

A second major occurrence of alkaline igneous rocks is provided by intraplate magmatic provinces whose activity and siting are not subject to any obvious tectonic control. In the ocean basins such magmatism manifests itself as ocean islands which are sometimes aligned in chains with ages increasing away from the active centres, as in the Hawaiian islands. In these cases it is possible to relate the magmatism to convective plumes within the asthenosphere. The Hawaiian islands (reviewed by **Clague**) show clearly defined magmatic cycles starting with alkaline magmas (represented by Loihi seamount), passing through a voluminous tholeiitic shield-building stage and returning to alkaline magmatism during the waning phases of individual volcanic centres. These cycles seem to result from movement of the oceanic plate over a rising plume of partially molten asthenosphere in which the degree of melting increases towards the centre. They may be typical of ocean islands in general and are broadly analogous to similar cycles seen in flood basalt provinces preserved on passive continental margins.

Continental intraplate magmatism may also show age progressions as in the Niger–Nigeria province (**Bowden** *et al.*). These progressions are, however, very rare and not so clearly defined as in ocean island chains, probably because the continental lithosphere is thicker and less easily penetrated than oceanic lithosphere. The Monteregian Hills and White Mountain provinces of eastern North America (**Eby**), for example, show no obvious progression but their seaward extension, the New England seamounts, show a regular decrease in age eastwards. Reviews of other continental intraplate alkaline provinces are given by **Fletcher & Beddoe-Stevens** (Velasco province, Bolivia) and **Kogarko** (Kola Peninsula). The Cameroon line in West Africa (**Fitton**) includes both continental and oceanic alkaline volcanic centres. None of these examples shows any clear progression of ages. Some continental provinces undergo repeated alkaline magmatism in one place over long periods. For example, the Kola Peninsula (**Kogarko**) was the site of alkaline magmatism in the mid Proterozoic and again in the Devonian. Such examples could be the result of coincidence but are more likely the result of the repeated exploitation of zones of weakness in the lithosphere.

Destructive plate boundaries provide the third tectonic setting in which alkaline igneous rocks may occur. During the life of a subduction zone the characteristic calc-alkaline magmas tend to become more potassic with time and may give way to volcanic rocks of the shoshonitic association, some members of which may contain leucite. A discussion of subduction zone processes is beyond the scope of this volume and the reader is referred to the reviews of Gill (1981) and Ewart (1982). There are, however, two circumstances under which subduction processes can lead to the generation of more 'normal' alkaline magmas.

Once the descending slab has become dehydrated at depth it loses its capacity to stimulate the generation of calc-alkaline magmas but it can still cause melting in the overlying asthenosphere. This can lead to the production of alkaline magmas from the mantle above the deepest parts of subduction zones. One such example of alkaline magmas erupted under a compressive regime is provided by the Trans-Pecos province of west Texas (**Barker**). The alkaline rocks in this area grade south-westwards into the calc-alkaline rocks of the Sierra Madre Occidental in Mexico and **Barker** relates both suites to subduction of the Farallon Plate.

After the cessation of subduction, relaxation of the former compressive regime often results in extension and the generation of alkaline magmas. The resulting switch from subduction-related calc-alkaline to extensional alkaline magmatism appears to be a common phenomenon. It occurred, for example, in the western U.S.A. about 17 Ma ago and in parts of Africa and Arabia at the end of the Pan-African metamorphic episode during the late Precambrian. An example from the Pan–African belt in Mali is discussed by **Liegeois & Black**.

The origin of alkaline magmas has attracted a great deal of interest among igneous petrologists over the last ten years or so. This interest has been stimulated by two important and characteristic features of alkaline rocks. Firstly, they contain high concentrations of LILE and yet isotopic evidence suggests that their parental magmas had a mantle source which had been depleted in these elements for a long time. Thus alkaline igneous rocks may provide useful information about enrichment and/or melting processes in the mantle. Secondly, many mafic alkaline volcanic rocks contain xenoliths inferred to have originated within the mantle (**Menzies**). These are often enriched in LILE when compared with concentrations expected of chondritic mantle material and sometimes contain amphiboles and micas of metasomatic origin (**Bailey**). Such clear evidence for the existence of metasomatically enriched mantle, coupled with the problem of extracting LILE-rich magmas from LILE-poor mantle, has led to hypotheses involving mantle metasomatism as a precursor to alkaline magmatism. These hypotheses, reviewed by **Bailey**, have gained popularity over the past fifteen years and are invoked by several contributors to this volume. Mantle metasomatism neatly explains many of the features of alkaline magmatism. For example, the frequent association of alkaline magmatism with areas of large-scale regional uplift is consistent with the relatively low density of metasomatized mantle.

An essential feature of all models involving a metasomatized mantle source for alkaline magmas is that this source must lie in the lithosphere. This is the only part of the mantle where enriched material can remain in one place for long periods without being swept away by convection. The lithospheric mantle beneath the continents is likely to be chemically and isotopically different from that beneath the oceans. Continental lithospheric mantle is old and will have had as complex a metamorphic and magmatic history as the overlying crust. Oceanic lithosphere, on the other hand, is relatively young and probably depleted in LILE. These differences should be reflected in the compositions of continental and oceanic alkaline rocks. However, alkali basalts erupted in continental and oceanic settings are generally identical both chemically (**Fitton**) and isotopically (**Menzies**). Since enriched mantle xenoliths are only commonly found in continental regions it follows that the enriched lithospheric mantle represented by these xenoliths is not the source of most continental and oceanic alkaline magmas. An asthenospheric source is therefore implied. This is not to say that enriched continental lithospheric mantle is never involved in the generation of alkaline magmas. There is good evidence (e.g. **Edgar**) that pockets of ancient enriched mantle beneath cratonic regions provide the source for LILE-rich mafic and ultramafic alkaline rocks such as micaceous kimberlite (**Dawson**), and lamproite and other potassic igneous rocks (**Bergman**). It is significant that these rock types are exclusively continental. More extensive melting may involve the continental lithosphere mantle in the production of less exotic rock types such as flood tholeiite and mildly alkaline basalt. **Upton & Emeleus**, for example, argue for a lithospheric mantle source for the Gardar alkaline magmas.

If most alkaline magmas have an ultimate source in the asthenosphere then they must share this source with unequivocally asthenosphere-derived rocks such as mid-ocean ridge basalt (MORB). The consistent isotopic differences between MORB and alkali basalts (and indeed all intraplate basalts) requires that the asthenosphere be heterogeneous. This heterogeneity may result from the entrainment of lower mantle material in deep mantle plumes as suggested for the Hawaiian island chain (**Clague**). The entire convecting upper mantle may also be heterogeneous on a small scale and alkaline magmas may be generated by the selective melting of LILE-enriched streaks while more extensive melting produces MORB (**Fitton**). Geochemical studies on ocean island basalts from the South Atlantic

(**Weaver** *et al.*) suggest that one component of these enriched streaks is provided by subducted ocean-floor sediment.

Derivation of LILE-rich magmas from an asthenospheric source depleted in these elements requires either very small degress of partial melting or extensive crystal fractionation. There can be no doubt that many alkaline rocks are the products of extensive low pressure crystal fractionation but this cannot be true of those alkaline rocks which host mantle xenoliths. Even the most magnesian alkaline rocks, which must represent near-primary magmas, are rich in LILE. Small-degree partial melting ($<1\%$) is therefore required to produce such magmas. McKenzie (1985) has recently shown that the extraction of melt fractions as small as 0.2% is not only physically possible but inevitable where the melt viscosity is low, as it probably is in the case of alkaline magmas. Experimental studies on alkaline rocks and synthetic analogues (reviewed by **Edgar**) provide useful constraints on the feasibility of fractional crystallization and partial melting models and on the temperatures and pressures involved.

Many lines of evidence suggest that volatile components form a significant part of alkaline magmas. The development of extensive zones of metasomatised country rock (fenite) around alkaline plutons, the abundance of chlorine and fluorine in some alkaline igneous rocks, and the frequently explosive eruption of alkaline magma all point to high concentrations of volatiles. These volatile components play an important role in the evolution of alkaline magmas and yet relatively little is known about them. Constraints on their composition have been provided by fluid inclusion studies (**Harris & Sheppard**) and by thermodynamic considerations (**Kogarko**).

The effects of volatile components on the evolution of alkaline magmas can be seen clearly in both intrusive and extrusive rocks. **Larsen & Sørensen**, for example, discuss the crystallization history of the Ilímaussaq intrusion in South-West Greenland and show how the upward migration of low-density, low-viscosity volatile-rich magma delayed crystallization under the roof of the intrusion. Silicic alkaline pyroclastic deposits around central volcanoes in Kenya often show striking variations in the abundance of some incompatible elements within a single vertical section, implying compositional zonation in the magma chamber before eruption. **Macdonald** shows that these variations are too large to be accounted for by crystal fractionation alone and suggests that some elements have been transported to the magma chamber roof zones as complex ions in a volatile phase.

Carbonatites provide perhaps the best illustration of all of the influence of volatile components on the origin and evolution of alkaline rocks. There is now a consensus that their parental magmas originate by the separation of an immiscible carbonate liquid phase from a CO_2-saturated nephelinite or phonolite magma. There is, however, some disagreement over the nature and subsequent evolution of this parental carbonate magma. **Le Bas** argues that the parental magma is rich in alkalis and similar in composition to the natrocarbonatite lavas erupted from Oldoinyo Lengai. This magma evolves at low pressure towards the more common calcite carbonatite (sövite) by loss of alkalis to the surrounding country rocks which are metasomatized (fenitized) as a result. **Twyman & Gittins** offer an alternative scheme in which sövite magmas are parental and natrocarbonatite magmas are derived from them by crystal fractionation.

Most petrologists now believe that evolved alkaline magmas are produced by the fractional crystallization of basic magma. The more highly undersaturated parental magmas represented by basanite and nephelinite will produce undersaturated derivatives such as phonolite and foyaite. Mildly alkaline and transitional basalt magma is likely to produce trachyte and, with extreme fractionation, alkali rhyolite. The production of peralkaline acid rocks by crystal fractionation alone is likely to be an inefficient process. The operation of this process, however, is clearly demonstrated by their association with transitional basalt on some ocean islands, such as Ascension (**Harris & Sheppard**). Peralkaline acid rocks only occur in abundance in continental environments, however, and here there is often good evidence that crustal contamination has accompanied crystal fractionation. Well-documented examples of the operation of crustal contamination in the evolution of alkaline magmas are presented by several of the contributors to this volume. **Downes**, for example, shows that the assimilation of lower crustal granulite has affected the evolution of alkaline magmas in the French Massif Central and uses isotope data to estimate the extent of this contamination. Other examples are presented by **Bowden** *et al.* (Niger–Nigeria granite ring complexes), **Eby** (Monteregian Hills and White Mountain provinces, North America), **Fitton** (Cameroon line, West Africa) and **Fletcher & Beddoe-Stevens** (Velasco province, Bolivia). Other authors propose the derivation of evolved alkaline magmas directly from metasomatized mantle or lower crust (**Bailey**; **Woolley & Jones**).

Our understanding of the origin and evolution of alkaline magmas has come a long way since the publication of Sørensen's book in 1974, largely through the acquisition of a far larger geochemical and isotopic data base. The contributions to this volume review the current state of this understanding. Emphasis has shifted from crustal to mantle processes with the recognition of mantle metasomatism and its possible role as a precursor to alkaline magmatism. More recently, though, there has been a swing towards the opposite view, that mantle metasomatism is *caused by* alkaline magmatism. Theoretical and experimental studies on the migration and segregation of small-degree melts seem destined to accelerate this swing. Despite these advances, however, many mysteries remain unsolved and alkaline rocks will still provide a fruitful field of research for many years to come, yielding further insights into the nature of mantle processes and the evolution of magmas.

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J. G. FITTON & B. G. J. UPTON, Grant Institute of Geology, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, U.K.