Carbonatite–Nephelinite Volcanism

An African Case History

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Extrusive carbonatite agglomerate on Sukuru Island in the foreground, with the dome of the Homa Mountain carbonatite complex in the background viewed across Homa Bay

To
Albertus Magnus
patron of earth scientists

It is hard enough for us
to work out what is on earth,
laborious to know what lies within our reach;
who then can discover
what is in the heavens?

Wisdom, 9, 16.

Preface

There are at least three approaches which may be taken in writing about the geology of an igneous rock association. One is to survey the geology of all the examples and integrate the results. A second is to study in detail the structural and petrological relations of a suite of well-developed examples within a limited area, and to deduce the principles involved. A third is to examine the subject via analytical and experimental mineralogy and petrology. It is appropriate at this point to acknowledge the stimulation received from A. Harker's old (1909) but inspiring book 'The Natural History of Igneous Rocks'.

For the carbonatite–nephelinite rock association, the first approach has been partially covered in the last decade by the publication of several books. H. Sørensen's book 'The Alkaline Rocks' (1974) considered many aspects of the petrology of the saturated and undersaturated igneous rocks, but purposely omitted detailed accounts of carbonatitic, melilite-bearing and alkaline ultramafic complexes. P. J. Wyllie's book 'Ultramafic and Related Rocks' (1967) had covered some of these missing aspects, and carbonatites had received extensive coverage in two further books. One, edited by O. F. Tuttle and J. Gittins (1966), is a collection of essays each probing deeply into different fields of carbonatite research plus a comprehensive catalogue of the carbonatite complexes known at that time. The other, by E. Wm. Heinrich (1966) is a monograph covering the whole geology of carbonatites. But, as Pecora said 'the problem of the origin of carbonatites cannot be divorced from that of the origin of alkalic igneous rocks' (1956, p. 1539).

Of the three approaches listed above, the second is that taken in this book, whilst the third still awaits comprehensive treatment although some notable contributions towards it are contained in Parts IV and V of Sørensen's book and in the many publications of Wyllie and his co-workers.

The kimberlite–carbonatite association is not examined in detail here, this field having received consideration in two recent works: 'Lesotho Kimberlites' by P. H. Nixon (1973b), and M. G. Bardet's two-volume work 'Géologie du diamant' (1973, 1974), which consider mainly African aspects. More comprehensive is the volume reporting the recent conference held at Cape Town concerning kimberlites which is published as 'Physics and Chemistry of the Earth' Volume 9 (1975). There are also the numerous articles written by J. B. Dawson on the subject. Although the kimberlite–carbonatite association is not described here, a relationship between that association and the ijolite–carbonatite association is recognized, and some aspects of this relationship are discussed in this book. The very slight 'fenitization' associated with kimberlitic carbonatites is different from normal fenitization, and perhaps should not be so termed. The petrological link between the nephelinitic carbonatite complexes (e.g. Fen, Magnet Cove and those in western Kenya) and kimberlitic carbonatite occurrences is via the alnoitic and meimechitic rocks, and all gradations appear to exist. But the carbonatites at the two ends of this spectrum appear to be quite distinct. I believe that the former differentiate from a Na–K–Ca carbonatitic magma whilst the latter do not.

Sørensen's 'The Alkaline Rocks' (1974) accentuates the very wide variation in the mineralogy, petrology and structural geology of the alkaline igneous rocks, and he rightly ends the book with the statement (p. 535) that 'there is now general agreement that no single parent magma is responsible for the formation of alkaline rocks, since alkaline rocks occur in many petrological associations'. In the present book, which utilizes the foundations set in the books mentioned above, I have attempted to scrutinize the petrological evidence of a carefully chosen area. The area includes a strongly alkaline igneous rock assemblage within which (a) only one comagmatic association is present, (b) numerous volcanic and sub-volcanic examples of the products of this magma are available for study, and (c) worldwide analogies can be recognized. The chosen area is western Kenya. It is at the centre of the Tertiary and Quaternary petrographic province which encompasses the east Ugandan alkaline complexes (well-known from the works of K. A. Davies and B. C. King) and the alkaline volcanic complexes of northern Tanzania including the active carbonatite volcano of Oldoinyo Lengai (published works by J. B. Dawson). It is quite distinct from the contemporaneous Kenya(Gregory) Rift Valley Province.

The Kenyan portion of the area chosen, together with that part of the Ugandan region south of Moroto and the western part of the Tanzanian region, is entirely free of basalts—an area of 75 000 km^2 (30 000 square miles). And there has been no basaltic volcanism since the late Proterozoic. The basic volcanic rocks of the area are nephelinites and their derivatives, coexisting with carbonatites. The west Kenyan area, particularly around Homa Bay where numerous alkaline igneous complexes occur, is thus an ideal situation for the study of carbonatite–nephelinite volcanism (in much the same way that Tilley considered the Hawaiian Islands to be an ideal natural laboratory for studying the differentiation of basalts).

The aim of this book is to establish the field relations and petrological processes involved in the evolution of carbonatitic and nephelinitic magmas in a type area, to show that such magmatism can develop independently of basalt magmas, and to suggest that carbonatite–nephelinite volcanism is a normal product of partial melting deep in the upper mantle which can happen beneath any continent in the world. A future step will be to discover whether or not some evolutionary path connects the olivine-poor nephelinites, which characterize the carbonatitic association, with the olivine-rich nephelinites which occur associated with basaltic provinces. Another problem for future consideration is the applicability of the model here erected for the evolution of carbonatites and associates in a non-orogenic stable platform region to occurrences in other structural settings.

The book is in three parts. The first introduces the scope of the subject, reviews the alkaline magmatic associations of the world, gives the geological background to the area chosen for study and defines a nomenclature for the alkaline rocks. The second part (Chapters 4 to 21) considers in detail the petrology of the western, central and eastern regions of the west Kenyan province, and the final part gives the conclusions reached concerning the evolution of the area, the magmatic and metasomatic processes involved (22 'rules' are deduced) and the petrogenesis of carbonatitic and nephelinitic igneous rocks.

The field relations, structure and petrology of the complexes are emphasized as they form the prime data on which any petrogenesis must be founded. One general rule that emerges is that there is a four-stage sequence in the emplacement of carbonatite complexes, beginning with the magmatic intrusion of sövitic carbonatite, followed by minor intrusions of alvikitic carbonatites and then ferruginous and dark-coloured carbonatites (ferrocarbonatites), and finally a low temperature stage marked by veins of calcitic carbonatite with associated fluorite, baryte and quartz mineralizations.

The detailed geochemistry of the complexes is not included in this book. Many hundreds of analyses ('wet', XRF and 'probe') of major and minor constituents have been made of the rocks and minerals of the region and some are given in Appendix 2. Many of them have been used in helping to solve problems presented in the book but the full discussion of the geochemistry must await publication elsewhere. Barber (1974) discusses the geochemical sequences within the carbonatites, and Rankin (1973, 1975) the fluid inclusions within apatites from carbonatites and ijolites.

Within the province lies Rusinga Island, famed for its Miocene volcanic gravels in which *Proconsul* was found, and further east around Homa Mountain are Pleistocene gravels with the remains of early man. In both regions, the key to the chronology lies in the interpretation of the volcanic episodes, and the waxing and waning of the lakes in the area. Chapters 7 and 20 give details of the sedimentary history supported by K–Ar dates and the variable lake levels.

The book is a result of teamwork, and the authorships of chapters listed on the 'Contents' page indicate those involved in collecting and evaluating the data and in assisting me to write the chapters. I am most grateful for their ready cooperation, but the full responsibility for any errors rests with me.

M. J. Le Bas

Leicester
April, 1976

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Contents

Chapter 1

Carbonatite–nephelinite igneous provinces

The carbonatite–nephelinite–ijolite igneous provinces of the world are defined, and compared with kimberlitic occurrences. The olivine-rich and olivine-poor nephelinite associations are distinguished.

Contents

1. Introduction

The classic igneous intrusions of Fen (Brögger, 1921; Saether, 1957) and Alnö (Eckermann, 1948) in Scandinavia, of Magnet Cove, Arkansas (Erickson and Blade, 1963), of Iron Hill, Powderhorn, Colorado (Larsen, 1942; Nash, 1972) and of Chilwa, Malawi (Garson and Smith, 1958) are typical examples of carbonatite–ijolite magmatic igneous complexes, but they do not have preserved for inspection the full range of volcanic and subvolcanic rocks. Likewise, the famous Caledonian mafic alkaline igneous complexes of the Kola Peninsula in northwestern USSR (Kukharenko *et al.*, 1965) are deficient in the extrusive facies. These deficiencies merely reflect the change with depth consequent on the vertical differentiation of rock-types that can be observed by contrasting different complexes. Thus the older, and therefore usually more deeply eroded, complexes reveal the more mafic developments, as pointed out by Heinrich (1966).

The principal rock-types developed in the carbonatite–nephelinite magmatic association are carbonatites, nephelinites, ijolites, pyroxenites, and fenites. It can be said that the development of fenites is the hallmark of this association. Kimberlitic rocks do occur but are rare, the nature of the petrographic association is different and many are not true kimberlites (Mitchell, 1970); carbonatitic and alnoitic rocks are present, but nepheline-bearing rocks are very infrequent and typical fenites are absent. There are, however, instances of the petrographic halfway-stage between these two associations, such as the Maimecha group of complexes in northern Siberia, which demonstrate that there is nearly smooth petrological gradation from the carbonatite–kimberlite association to the carbonatite–ijolite–nephelinite association. The occurrence of nephelinite provides a common factor between the carbonatite–nephelinite volcanic association and the basalt–nephelinite association such as that of the Kenya Rift valley where the basalts are alkaline, not tholeiitic (Williams, 1972). The nephelinites of the two associations have been distinguished by Wood (1968 and in Bailey, 1974b). He shows that the nephelinites in association with basalts are olivine-rich, but those in association with carbonatite complexes contain few olivine phenocrysts. The latter correspond to the melanephelinites which are characteristically rich in augite phenocrysts but lacking in olivine except in cumulate rocks. Rock (1976a) similarly made a distinction, but based on the presence or absence of plagioclase between (a) alkaline gabbroic complexes with which are associated syenites, nepheline–syenites and peralkaline acid rocks and (b) carbonatitic complexes with associated ijolites, nepheline–syenites and pyroxenites.

A problem lies in the fact that plutonic ijolites and the associated nephelinite lavas have differing bulk chemical compositions (Bailey, 1974b). This is not surprising when it is seen (Chapter 3) that ijolites most frequently have about 55% nepheline and 45% mafics, whilst the accompanying lavas (usually olivine-poor nephelinites) have approximately 35% nepheline and 60% mafic minerals. If an average melanephelinite is taken, and 25% augite plus 5% magnetite are subtracted from it, then a chemical composition quite close to that of ijolite is obtained (see Appendix 2). Likewise, nephelinitic compositions can be achieved by adding cumulative pyroxenite to ijolite. Therefore ijolite and nephelinite can be regarded as chemically equivalent, as by Carmichael *et al.* (1974, p. 504), and the term ‘nephelinitic magmatism’ may be used to designate the subvolcanic and plutonic activity of ijolites, as well as nephelinite volcanism.

Some of the 30% mafic material subtracted above is represented by phenocrystal augite, but not all of it, and there is a real difference in the phase relations of the minimum melting point compositions of associated ijolite and nephelinite, as recognized by King (1965). The explanation appears to lie in the differing pressure conditions of plutonic ijolite and volcanic nephelinite. The mineralogical components diopside and nepheline contribute the major part of the mineralogy of ijolite and nephelinite, and it is known from the experimental work of Kushiro (1974), Nolan (1966), Edgar (1964) and Edgar and Parker (1974), that the position of the minimum melting point is pressure-sensitive. Higher pressures tend to reduce the size of the nepheline liquidus field.

Enough has been said to indicate that carbonatite and ijolite are interpreted as an interdependent natural igneous pair, and it is the purpose of this book to investigate the relationships and processes controlling the pair. Until now, most investigations have been somewhat eclipsed by the unusual petrology of the carbonatitic component of the pair, with the nepheline-rich component taking second place. Books have been written about carbonatites, and about ijolites and nephelinites, but none has dealt satisfactorily with the relationship between them. The recent textbook by Carmichael, Turner and Verhoogen does begin to redress the balance (1974, in Chapters 10 and 13), but it does not make the fundamental distinction, mentioned above, between the olivine-rich and olivine-poor nephelinites, nor does it point out that the occurrence of peridotitic xenoliths of possible mantle origin is largely confined to the olivine-rich variety. In Kenya and Uganda, not a single lherzolite and only a few pyroxenite xenoliths are known from the carbonatite–nephelinite complexes, and this has certainly not been for lack of searching.

Igneous complexes displaying carbonatitic and nephelinitic rocks are present in all the continental masses of the world, and the distribution of the principal ones is outlined in the following sections. In the oceans, the typical carbonatite association as described in this book is absent, but carbonatites associated with alkali basalts and rare nephelinites are known on Fuerteventura in the Canary Islands, and in the

Cape Verde Islands (Fuster *et al.*, 1968; De Assunçao *et al.*, 1968; Allegre *et al.*, 1971; Klerkx *et al.*, 1974). Recent investigation by the author suggests that the Canary and Cape Verde carbonatites are associated with nepheline–syenites and titan-augite-bearing gabbroic rocks, and that there are few true ijolites. Kimberlitic rocks are likewise rare in the oceanic areas, but one example, which is non-diamontiferous and has associated alnoite and ankaratrite, is that described by Allen and Deans (1965) from Malaita in the Solomon Islands.

2. The Americas

(a) Canada and Greenland

The Canadian carbonatite–ijolite complexes are considered to occur in four groups of age ranges 1750–1550, 1100–850, 600–300 and 125–90 m.y., approximately, Hudsonian, Grenville, Palaeozoic and Cretaceous, respectively (Doig, 1970).

The geology of the two older groups is not well known. They are badly exposed, and in many cases were detected only by geophysical measurements, followed by drilling to prove them. Most of them lie along the Kapuskasing High which is an anomalous gravity and magnetic linear feature extending from Lake Superior to James Bay in eastern Ontario. The oldest group includes the carbonatite–pyroxenite complexes of Argor, Goldray (or James Bay North and South respectively), Cargill and Spanish River just off the High near Lake Huron (Gittins *et al.*, 1967; Gittins *et al.*, 1975; Robertson and Watkinson, 1974).

Two of the Grenville age complexes, of Clay-Howells and Firesand, also lie on the Kapuskasing High and include carbonatites. Several more of this age group lie just to the west and east of the High. On the west is the carbonatite–ijolite–fenite complex of Prairie Lake, and eastward is the carbonatite–fenite–syenite complex of Nemegosenda, and the carbonatite–ijolite–fenite complexes of Lackner Lake and Seabrook. Also in this age group is the Big Beaverhouse carbonatite–fenite complex some 500 km west of James Bay, and in the vicinity are many more undated carbonatitic complexes. Further possible associates of this age group are the syn-orogenic nepheline-rich rocks of the Haliburton-Bancroft area of eastern Ontario (Appleyard, 1974).

Just north of Ottawa in the Mt Laurier area is another group of Grenville age carbonatitic nepheline-bearing rocks (Doig and Barton, 1968), and further north at Bachelor Lake (50°N, 76°W of Greenwich) is the carbonatitic kimberlite diatreme dated at 1100 m.y. (Watson, 1967). Even further north (56°N, 69°W) is the Castignon Lake complex of kimberlitic and carbonatitic breccias and diatremes which cut folded Aphebian sediments (1550 m.y.) of the Labrador trough. No ijolites or nephelinites occur, but there are meimechites and volcanic tuffs preserved. Dimroth (1970) describes the Castignon lake complex as differing from the normal carbonatite complexes of Scandinavia and East Africa, and more like some South African and Siberian examples.

The proterozoic (1300–1100 m.y.) province of Gardar in south Greenland is well described by Upton (in Sørensen, 1974, pp. 221–238). The principal complexes are: Kungnat, Gronnedal-Ika, Nunarssuit, Tugtutoq, Narssaq, Ilimaussaq, Igaliko and Narssarssuaq. The province lacks ijolite and is principally syenitic with some alkali gabbros and granites, a few carbonatites and fenites, and rare alnoitic rocks. Plagioclase fractionation is an important process in the genesis of these rocks (Stephenson, 1976). Unlike many of the Canadian alkaline complexes, those of Gardar are beautifully exposed and their geology is well known.

Apart from some isolated carbonatite–ijolite–fenite occurrences in British Columbia, such as at Ice River (Campbell, 1961), the Palaeozoic (mainly Lower) group of complexes is considered by Doig (1970) to be related to the St Lawrence Rift system. Within the western extension of this Rift system near Lake Nipissing are the carbonatite–fenite–syenite complexes of Calander Bay, Manitou Is., Burrit Is. and Iron Is. In the area around Ottawa and Montreal, on the edge of the Rift system, there is a cluster of alkaline and syenitic complexes (Eastview, Buckingham, Chatham, Rigaud) but there are no well developed nepheline-bearing or carbonatitic rocks. Further east along the St Lawrence Rift system, carbonatites and syenites do occur at Chicoutimi and in the Mutton Bay area of Quebec which yield dates between 560 and 580 m.y. (Doig and Barton, 1968).

At Cape Aillik on the Labrador coast opposite the Ivigtut area, there are Palaeozoic carbonatites associated with alnoitic rocks in a dyke complex. Further and similar lamprophyric kimberlitic and carbonatitic rocks are present at Umanak, half way up the west coast of Greenland (~72°N), and by Sondre Isortoq fiord near the Arctic circle (Goff, 1973). Another example of lamprophyric carbonatite activity is at Ford's Bight near Cape Aillik, but this one is Mesozoic (King and McMillan, 1975), as is probably that in the vicinity of Frederikshab just south of the 62° line of latitude (Andrews and Emeleus, 1971).

The St Lawrence Rift system also includes the well developed carbonatite–ijolite–gabbro–alnoite series of Cretaceous intrusions, collectively known as the Monteregian province. They are described by Currie (1970) and others in a symposium volume on the Monteregian Hills edited by G. Perrault (1970), and by Philpotts (in Sørensen, 1974, pp. 293–310). The province is remarkable for its wide variety of rocks from alkaline basaltic to kimberlitic, and in this may indicate a widely heterogeneous parentage for the province. The Oka complex has been particularly closely studied (Eby, 1975).

Tertiary nephelinitic and possibly carbonatitic rocks have recently been reported by Brooks and Rucklidge (1974) within Kangerdlugssuaq on the east coast of Greenland near Skaergaard. Ijolites and sodic pyroxenites occur in the Gardiner and other intrusions there, and uncompahgrite is additionally present at Gardiner (Gittins, personal communication). They are now under investigation. The alkaline rocks may represent an early phase of the North Atlantic basaltic province (Greenland–Hebrides) which incorporates both alkaline and tholeiitic evolutionary trends, and may be compared with the Karroo cycle postulated by Cox (1972).

(*b*) *United States*

As indicated by Heinrich (1966) and Sørensen (1974), carbonatitic and ijolitic complexes are not so frequently developed in the USA as they are further north. The Proterozoic (1400 ± 50 m.y.) carbonatite of Mountain Pass, California, is accompanied by syenites but there are no nepheline-rich rocks.

The Gem Park, the McClure Mt–Iron Mt, and the Democrat Gulch complexes of the Arkansas River area of Colorado are late Proterozoic (about 700 m.y.), and include pyroxenites, gabbros, syenites, lamprophyres and carbonatites.

There are only few occurrences of Palaeozoic carbonatitic complexes in the USA. The funnel-shaped intrusion of Iron Hill, Powderhorn, in Colorado (Temple and Grogan, 1965; Nash, 1972) is of Cambrian age (580–520 m.y.), contains the full range of plutonic rocks in the carbonatite–ijolite suite including fenite and pyroxenite, and is the type locality of uncompahgrite. Another is the cluster of 70 late Devonian explosion breccia pipes of St Genevieve in Missouri (Zartman *et al.*, 1967) which contain alnoitic and carbonatitic material, and another is the kimberlitic diatreme at Hicks Dome in Kentucky, dated at 260 m.y.

During the Upper Cretaceous period, carbonatitic magmatism was particularly well developed. The famous occurrence at Magnet Cove (dated ~95 m.y.) in the Ouachita Mountains of Arkansas includes volcanic and subvolcanic rocks. There are phonolites, trachytes, carbonatites, syenites, ijolites and pyroxenites; also some diamontiferous kimberlite pipes nearby in Pike Co., southwestern Arkansas. Fenites are not described (Erickson and Blade, 1963) but the foliated micro-syenites around the ijolites described as banded trachyte might be a product of fenitization. Further pyroxenites, ijolites and carbonatites, of post-Carboniferous age, are present in the circular complex at Potash Sulphur Springs ten kilometres west of Magnet Cove, nepheline–syenites at Little Rock, and carbonatitic kimberlite pipes were emplaced in the late-Cretaceous in eastern Kansas (Brookins, 1969).

Also in the Upper Cretaceous, volcanic rocks of the Balcones province were extruded in Texas along part of the Ouachita structural belt near Uvalde. There are abundant olivine–nephelinites, some melilite-bearing, also some phonolites, basalts and basanites. The basaltic and olivine–nephelinitic magmas are considered (Spencer, 1969) to be primary magmas which arose independently, in the same manner that Varne (1968) has deduced to be the case at Moroto in Uganda.

At much the same time as this alkaline magmatism took place in southern United States, another alkaline igneous province was active in Montana and adjoining parts of Idaho and Wyoming. In the Bearpaw and Highwood mountain area of central Montana, syenitic, carbonatitic and kimberlitic diatremes are exposed (Pecora, 1962; Hearn, 1968), but typical fenites and ijolites are not present. Further west in Montana, near Libby (Boettcher, 1967), and in Ravalli and Lemhi Counties in Idaho, there are Cretaceous pyroxenite, syenite and carbonatite sheets. The complexes appear to be integrated with the potassic rocks of the shoshonite association (Joplin, 1968) which extends along the eastern edge of the Rocky Mountain cordillera.

The kimberlites in and around the Hopi and Navajo districts of northeastern Arizona (Watson, 1967) comprise about 300 diatremes and maar-type volcanoes of late Tertiary age. Some carbonate-bearing rocks accompany them, and some lamprophyres, but no nephelinitic rocks.

(*c*) *South America*

In Brazil, where most of the individual complexes occur, two principal provinces are recognized (Amaral *et al.*, 1967). Melcher and Almeida (1972) give evidence for further possible provinces. The earlier province, in and around the southern parts of Sao Paulo state is Upper Jurassic to Lower Cretaceous, 150–120 m.y., and the other is late Cretaceous to early Tertiary (85–50 m.y.) and extends northwest from Rio de Janeiro across the Minas Gerais, an area famous for its kimberlitic derivatives. The earlier province, includes Jacupiranga, Ipanema, Registro, Serrote and Itapirapua complexes which are each largely composed of pyroxenites, carbonatites, fenites, ijolites and syenites and, except for Itapirapua, are well known for their titaniferous magnetite deposits. This province coincides in age with the Parana Basin basaltic volcanism but, for the most part, just precedes the onset of basaltic volcanism which marked the opening of the South Atlantic (Siedner and Mitchell, 1976). The later alkaline province, includes Araxa, Salitre, Tapira, Coromandel (Patos) and Catalao, which are mostly composed of carbonatites (with extensive niobium and barium mineralizations) some pyroxenites and syenites. The geology of the associated kimberlitic deposits is not well known (Bardet, 1973, Pt. 1, p. 124). At Pocos de Caldas, about 200 km north of Sao Paulo city, is a large syenitic complex which includes phonolitic and nephelinitic extrusive rocks, but no carbonatites. It is dated between 63 and 80 m.y. and, together with Itatiaia syenitic complex and others further to the west, may constitute a southerly extension of the later Brazilian alkaline province.

(*d*) *Synopsis*

The distribution in time and space of American examples shows that magmatic provinces can be recognized though they are poorly defined and in some cases are mixed with the magmatic products of other tectonic regimes. The latter subject has been discussed by Barker (1969, 1970) and Bass (1970).

Over the 1750–1550 m.y. period in Canada, ultramafic and carbonatitic complexes were formed, with an isolated carbonatitic occurrence a little later in California. During the late Proterozoic of Canada (Grenville) and in the Gardar Province of Greenland, ijolitic and carbonatitic magmatism occurred in abundance with only few alnoitic and kimberlitic developments. None is recognized further south.