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Igneous silicate rocks associated with carbonatites: their diversity, relative abundances and implications for carbonatite genesis

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ABSTRACT. — Data on the diversity and relative abundance of igneous rock types associated with carbonatite have been compiled for 377 occurrences, which represents 82% of the ~450 carbonatite occurrences known to the author. Extrusive carbonatite is found at 40 localities and for the purposes of analysis these are treated separately. The extrusive carbonatite association is characterised by the high proportion of occurrences that contain mantle debris (xenoliths and/or xenocrysts) and the occurrence of melilite-bearing rocks in nearly half of them. 22% of intrusive carbonatite localities have no associated igneous silicate rocks while a diverse range of rock types are associated with the rest. These rocks are listed, quantified and described and lead to the conclusion that six series of rocks can be distinguished as being associated with carbonatites. These are: 1. melilitite-nephelinite-phonolite-trachyte (melilitolite), 2. nephelinite-phonolite trachyte (ijolite), 3. basanite-trachyte (alkali gabbro), 4. phonolite-trachyte (foid syenite), 5. trachyte (syenite), and 6. kimberlite. A high proportion of occurrences with representatives of series 1 to 3 also contain ultramafic rocks, which may be cumulates. The presence of mantle debris in some carbonatite occurrences and the absence of associated silicate rocks from others are taken as evidence of derivation of these carbonatites directly from the mantle. The remaining carbonatites are considered to have been generated by differentiation (separation) from magmas represented by the associated silicate rocks that are the result of partial melting in a metasomatised lithosphere. This model indicates that carbonatites can be generated in a number of ways, and the close association with a broad spectrum of silicate liquids implies that there is probably some variation in carbonatite liquid compositions.

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RIASSUNTO. — I dati sulla diversità e la relativa abbondanza dei tipi di rocce ignee associate con carbonatiti sono stati compilati per 377 occorrenze, che rappresentano l'82% delle 450 occorrenze conosciute dall'autore. Carbonatiti estrusive sono state trovate in 40 località e per lo scopo di quest'analisi sono state trattate separatamente. L'associazione di carbonatiti estrusive è caratterizzata da un'alta proporzione di occorrenze contenenti frammenti di mantello (xenoliti e/o xenocristalli) e quasi la metà, sono associate alla presenza di rocce contenenti melilite. Il 22% delle località con carbonatiti intrusive non hanno asssociate rocce ignee silicatiche, mentre un vasta gamma di tipi di rocce sono associate con le rimanenti occorrenze. Queste rocce sono catalogate, quantificate, descritte e portano alla conclusione che sei serie di rocce possono essere distinte in associazione con le carbonatiti. Queste sono: 1. melilitite-nefelinite-fonolite-trachite (melilitolite), 2. nefelinite-fonolite-trachite (ijolite), 3. basanite-trachite (alcali gabbro), 4. fonolite-trachite (sienite), 5. trachite (sienite), 6. kimberlite. Un alta proporzione di occorrenze con rocce rappresentative delle serie da 1 a 3, contengono inoltre associate rocce ultrafemiche, che possono essere cumulati. La presenza di materiali di mantello in alcune carbonatiti e l'assenza di rocce silicatiche associate, è considerata evidenza della loro derivazione diretta dal mantello. Le rimanenti carbonatiti sono considerate essere generate da differenziazione (separazione) da magmi rappresentati dalle rocce

silicatiche associate, che si generano dalla fusione parziale di litosfera metasomatizzata. Questo modello indica che le carbonatiti possono essere generate in diversi modi e che la loro associazione ravvicinata con un ampio spettro di liquidi silicatici implica che ci sia probabilmente un certo grado di variazione nella composizione dei liquidi carbonatitici.

KEY WORDS: *carbonatite, igneous silicate rocks, diversity, abundance, petrogenesis.*

INTRODUCTION

It is generally known that, in the broadest sense, carbonatites are often spatially associated with alkaline igneous rocks such as ijolites and nepheline syenites, and this intimate association can be taken to indicate that they are broadly consanguineous. However, there is a surprisingly wide spectrum of igneous silicate rocks that are found in carbonatite complexes and the aim of this paper is to attempt to quantify their relative abundance. By 'abundance' is not meant the relative volumes of the silicate rocks, although if it was possible to obtain such information it would be of great interest, but instead to explore their diversity and to attempt to quantify the major rock types. I am presently aware of some 450 carbonatite occurrences worldwide, although earlier this was only some 330 (Woolley, 1989), and for 82% of these I have sufficient data to attempt to categorise them according to the associated silicate rocks. Although this approach may appear rather simplistic it does, I believe, throw up interesting relationships and generates a number of carbonatite-silicate rock associations all of which need to be considered in any all-embracing carbonatite petrogenesis. Other 'field' features that will be very briefly considered, and which show significant correlations with different carbonatite-silicate rock associations, include intrusive versus extrusive, simple diatremes versus intrusive complexes and minor versus major volcanic edifices.

DATA SOURCES

A summary of the areas covered by the data sources is given in Table 1. The major sources are books describing the alkaline rocks of North and South America (Woolley, 1987), the former U.S.S.R. (Kogarko *et al*., 1995), which includes Russia, Ukraine and Kazakhstan, and Africa (Woolley, 2001). The data for Finland, Norway and Sweden are taken from the author's ongoing unpublished work and some information for occurrences including extrusive carbonatite are from the unpublished thesis of Abigail Church (1995). Descriptions of 377 localities were used, of which 40 include extrusive carbonatite. Thus the findings are based on 82% of the occurrences of which I am aware and it is thought unlikely that when the remaining 18% of carbonatite occurrences are taken into consideration there will be any significant changes to the results presented in this paper.

ORGANISATION OF THE DATA SET

The occurrences were initially divided into two groups, depending on whether or not extrusive carbonatite is present (Table 1). As will be described later, there are some differences in the nature and proportions of the

TABLE 1

Carbonatite data used in this survey

Total number of carbonatite occurrences = 453		
Of which those with extrusive carbonatite = 40		
Location of occurrences used in survey		
	Intrusive	**Extrusive**
North and South America	109	5
Africa	148	24
Russia, Ukraine, Kazakhstan	68	1
Finland, Norway, Sweden	12	0
Rest of extrusive occurrences	-	10
	337	**40**
Percentage used of those known	**82%**	**100%**

TABLE 2

Igneous silicate rocks associated with extrusive carbonatites

Extrusive silicate rocks		Intrusive silicate rocks	
Melilitite	15	Melilitolite	7
Nephelinite	17	Ijolite/melteigite	5
Phonolite/tephrite	12	Phon/ting/neph sy	11
Trachyte	1	Syenite	1
Basalt	1	Essexite	1
Meimechite	1	Lamprophyre	2
Analcimitite	1	Pyroxenite	4
None	13	None	19

Note: 18 occurrences include melilite-bearing rocks = 47%

silicate rocks associated with extrusive carbonatite which are considered significant. For each occurrence the presence, or absence, of the rocks listed in Table 2 for the extrusive carbonatite association and Table 4 for the occurrences including intrusive carbonatite only were entered on a spreadsheet.

OCCURRENCES WHICH INCLUDE EXTRUSIVE CARBONATITE

Data for 40 occurrences of extrusive carbonatite have been compiled and have been scanned in terms of the nature of the associated igneous silicate rocks, the presence or absence of mantle materials, and their overall structure.

Associated igneous silicate rocks

Both extrusive and intrusive silicate igneous rocks are found associated with extrusive carbonatites and their nature is indicated in Table 2, the first five rock types in the table representing coarse- and fine-grained equivalents. The last four rock types do not apparently have such equivalents, but this is not significant given the small number of occurrences. Localities with no associated silicate rocks are numerous, comprising nearly half for the intrusive ones, but this could simply reflect lack of outcrop in comparatively young occurrences. What is probably the most significant fact is that nearly half of all extrusive carbonatites were erupted from centres with associated melilite-bearing rocks. This is a major difference from the intrusive centres, as discussed below.

Structures

The first column of Table 3 shows a simple structural division of the extrusive carbonatite occurrences into volcanoes and diatremes. For five occurrences there is some doubt as to which category they belong. It is, however, clear that there is an approximately equal division between the two categories. As shown in the second column, there are 15 known occurrences in which debris of mantle composition (xenoliths and/or xenocrysts) has been identified. It is noteworthy that a high proportion of these localities are diatremes, and only a few volcanoes, presumably because of the intrinsically higher energy environment of the former. As far as I am aware, mantle materials have not been found in carbonatite localities lacking carbonatite extrusives. From a genetic point of view, the presence of mantle materials in these rocks is highly significant, as discussed later.

TABLE 3

Structure of all occurrences containing extrusive carbonatite and of those in which mantle materials occur

All occurrences		Occurrences containing mantle materials	
Volcano	19	Volcano	3
Volcano?	1	Volcano?	1
Diatreme	15	Diatreme	9
Diatreme/volcano	2	Diatreme/volcano	2
Don't know	2	Don't know	-
Total	39	Total	15

Nature of included mantle materials

Data culled from Church (1995) indicate that spinel lherzolite xenoliths and xenocrysts probably derived from them are the most abundant rock type and phases found in extrusive carbonatite. Mantle amphibole, phlogopite, garnet, Ti-magnetite, apatite and titanite have all been recorded and suggest that metasomatised mantle has been sampled.

OCCURRENCES WHICH INCLUDE INTRUSIVE, BUT NOT EXTRUSIVE, CARBONATITE

There are a number of ways in which the data could have been sorted and correlations explored, but the general categories erected (Table 4), which were considered the most significant, are as follows:

(a) Those with no igneous silicate rocks, other than fenite.
(b) Those with olivinite and/or peridotite.
(c) Those with pyroxenite, but not olivinite and/or peridotite.
(d) Those with melteigite, ijolite or urtite and nephelinite or melanephelinite, but not (b) or (c) above.
(e) Those with nepheline, cancrinite or sodalite syenite and phonolite or tinguaite, but not (b) to (d) above.
(f) Those with syenite, quartz syenite, trachyte or sölvsbergite, but not (b) to (e) above.
(g) Those with melilitolite, melilitite or melilite nephelinite, but not (b) to (f) above.
(h) Those with gabbro, dolerite, essexite, basanite or tephrite, but not (b) to (g) above.
(i) Those with lamprophyre, kimberlite or other igneous silicate rocks, but not (b) to (h) above.

Correlations across these categories were looked for and a number of these will be referred to later. In the initial sorting melteigite-ijolite-urtite and nephelinite and melanephelinite were kept separate but these were later combined. Similarly, nepheline, cancrinite and sodalite syenite and phonolite and tinguaite were eventually combined, as were gabbro, dolerite and essexite and basanite and tephrite. The «Other igneous silicate rocks» group (Table 4) includes glimmerite, phoscorite, alnöite, nelsonite and a number of other rare rocks that, although interesting in their own right, were not taken into consideration for the present exercise. Kimberlite, as discussed later, was selected as a minor but perhaps important rock type.

The first noteworthy point is the diversity of

TABLE 4

Igneous silicate rocks associated with intrusive carbonatites: number of occurrences

Details not known	28	8%
No igneous silicate rocks	68	22%
Olivinite and peridotite	34	11%
Pyroxenite	90	29%
Olivinite/peridotite and/or pyroxenite	94	30%
Gabbro/dolerite/essexite; basanite and tephrite	31	10%
Melteigite-ijolite-urtite; nephelinite and melanephelinite	116	38%
Nepheline/cancrinite/sodalite syenite; phonolite/tinguaite	147	48%
Syenite and quartz syenite; trachyte	109	35%
Melilitolite/melilitite/melilite nephelinite	28	9%
Leucite- and pseudoleucite-bearing rocks.	9	3%
Lamprophyre	42	14%
Kimberlite	7	2%
Other igneous silicate rocks	37	13%

rock types represented in intrusive carbonatite complexes, as given in Table 4. The first column depicts the number of occurrences, out of the total of 337, in which each rock type has been recognised. The second column gives a percentage of the occurrences in which these rocks types occur. The major categories will now be discussed briefly.

Carbonatites with no associated igneous silicate rocks

There are 68 intrusive carbonatite localities with which there are no associated intrusive silicate rocks, that is 22% of the occurrences utilised here (Table 4), and in this feature they are similar to the extrusive carbonatite localities, amongst which there are 10 with neither extrusive nor intrusive igneous silicate rocks i.e. 25%. It is well known that in many carbonatite complexes carbonatite is the last phase to be emplaced and thus may occupy space that it has created by pushing aside silicate rocks emplaced at an earlier time in development of the complex. However, although this scenario may explain some occurrences, it is unlikely to apply to all indicating that, as with the extrusive carbonatites, carbonatite may be intruded free of associated silicate rocks.

Carbonatite occurrences with olivinite/peridotite and pyroxenite

There is a broad spectrum of ultramafic rocks, including peridotite, pyroxenite and some amphibolite amongst carbonatite complexes. As outlined in Tables 4 and 5 there are 34 occurrences with olivinite and/or peridotite all but 4 of which also contain pyroxenite, and there are 90 complexes with pyroxenite. Nearly a third (30%), therefore, of carbonatite intrusions are associated with such ultramafic rocks. As indicated by Table 5, of the 94 complexes with ultramafic rocks 62 (66%) also include ijolite and/or nephelinite, 62 (66%) foid syenite and 41 (44%) syenite. These relatively high percentages indicate that these rock types comprise a distinct series.

TABLE 5
Olivinite/peridotite- and pyroxenite-bearing occurrences

There are 94 such occurrences:
- All but 4 peridotite occurrences also contain pyroxenite
- 62 occurrences include ijolite and/or nephelinite i.e. 66%
- 62 occurrences include foid syenite i.e. 66%
- 41 occurrences include syenite i.e. 44%
- 17 occurrences include melilite-bearing rocks i.e. 18%
- 7 of the melilite-bearing occurrences are associated with ijolite

Carbonatite occurrences with melilite-bearing rocks

Although there are some remarkable carbonatite complexes with melilitolite and other melilite-bearing rocks, the great majority of which are in Russia, particularly in the Maimecha-Kotui province (Kogarko *et al.*, 1995), they only comprise 9%, i.e. 28 occurrences, of the intrusive complexes. This is far short of the 47% of extrusive carbonatite occurrences that are associated with melilite-bearing rocks (Table 2). It is perhaps noteworthy that 17 of the 28 are found in occurrences that also contain ultramafic rocks (Table 5) and 7 are associated with ijolite.

Carbonatite occurrences with ijolite, foid syenite and syenite

Ijolites, including melteigite and urtite, are, as is well known, typical of many complexes and these presumably are the slow cooling equivalents of the nephelinites and melanephelinites of the extrusive association, although fractionation leads to some differences in chemistry and mineralogy of the two suites. There are 54 ijolite-bearing occurrences in complexes that are free of ultramafic rocks (Table 6) which together with the 62 found in complexes with ultramafic rocks (Table 5) makes 116 in total (Table 4) representing more than one third of all complexes.

Nepheline syenite is even more abundant than ijolitic rocks, and again has its extrusive equivalent in phonolites, and is probably the most widespread rock type in carbonatite occurrences. Of the 147 occurrences (i.e. 48% of total – Table 4) 62 are found in complexes containing ultramafic rocks (Table 5), 43 in complexes lacking ultramafic rocks but containing ijolite (Table 6) and there are 42 occurrences with neither associated ultramafic rocks nor ijolites (Table 6).

Although not as abundant as foid syenite, syenite, and to a lesser extent quartz syenite and even granite, is also widespread i.e. 109 occurrences (35%) and is well represented in all associations including both those with and without ultramafic rocks and in association with ijolite, nepheline syenite and gabbro (Tables 4, 5, 6 and 7). As discussed later, it is probable that syenite and trachyte has the most diverse petrogenesis of all rocks of the carbonatite association.

Carbonatite occurrences with gabbro and kimberlite

As shown in Table 4, there are 31 occurrences i.e. 10%, which contain gabbro and these gabbros may, or may not, be nepheline-bearing, indeed some of them are tholeiitic. It seems very improbable that the tholeiitic gabbros are consanguineous, merely spatially and temporally associated with the carbonatites, although the nepheline-bearing gabbroic rocks, essexite, basanite, tephrite etc., may be candidates for a closer petrogenetic association with the carbonatite. Some details of the gabbro-bearing occurrences are given in Table 7 which demonstrate the common association with ultramafic rocks and syenites (>50%) but sparsity of ijolites and foid syenites (<10%) in this association.

A further association that is not common but petrogenetically intriguing is with kimberlite (Table 4). The kimberlite-carbonatite association has a long history of debate but undoubtedly some kimberlites differentiate to carbonate-rich rocks, while for a number of occurrences there have been disputes as to whether the silicate rocks are kimberlite *sensu stricto* or some other sort of mica-rich rock.

TABLE 6

Ijolite and foid syenite occurrences lacking ultramafic rocks

Of the 54 ijolite-bearing occurrences:
- 43 include foid syenite i.e. 80%
- 20 include syenite i.e. 37%

There are 42 occurrences with foid syenite (but lacking ijolite)
of which 25 include syenite i.e. 60%

TABLE 7

Gabbro-bearing occurrences

There are 31 such occurrences of which:
16 occur with ultramafic rocks
16 occur with syenites
3 only are found in ijolite-bearing and
3 in foid syenite-bearing occurrences

DISCUSSION AND PROPOSED MODEL

The diversity and association of silicate rocks found amongst intrusive and extrusive carbonatite occurrences, as outlined above, suggest the existence of not one but six distinct rock series, which are outlined in Table 8. The rock types in rounded brackets represent the principal members of the intrusive (coarse-grained) equivalent series. Peridotite and pyroxenite are abundantly associated with the rocks of the first three of these series, but these ultramafic rocks may be cumulates and do not represent melt compositions, hence they are shown in square brackets in Table 8. The melilitite-nephelinite-phonolite-trachyte and nephelinite-phonolite-trachyte series are

TABLE 8
Rock series indicated by associations

1. [Peridotite-pyroxenite]	- melilitite-nephelinite-phonolite-trachyte (melilitolite)
2. [Peridotite-pyroxenite]	- nephelinite-phonolite trachyte (ijolite)
3. [Peridotite-pyroxenite]	- basanite-trachyte (alkali gabbro)
4.	- phonolite-trachyte (foid syenite)
5.	- trachyte (?) (syenite)
6.	- kimberlite

distinguished because although the rock types of the second series are at many localities associated with melilitite, there are also many localities where melilitite is lacking and nephelinite appears to be the most primitive magma type present. The basanite-trachyte series is generally clearly distinguishable and basanites are rarely associated with rocks of the first two series. The fourth series, phonolite-trachyte, is represented at many localities where there is no evidence of the presence, or former presence, of melilitite or nephelinite, characteristic of the first two series, suggesting their independent generation. This is particularly clear in major intrusive complexes which include nepheline syenite and syenite. The fifth series, involving trachyte, is a problematic one, but there are many localities in which trachyte, or syenite, often of unusual (potassic?) composition, is the only igneous silicate rock manifest. The kimberlite association is a rare but clearly distinct one.

Figure 1 is a diagram which aims to reconcile and explain the six series defined above. Although an attempt has been made to erect a model based solely on the evidence of rock associations, the presence, or absence, of mantle materials and, to a lesser extent, on simple structural observations, inevitably some cognisance has been taken of petrological, particularly petrographical and mineralogical evidence, on known differentiation series. The solid, vertical arrows represent the six series, the origins of which are shown at varying depths in a metasomatised lithosphere. All these rocks, with the probable exception of the kimberlites, it has been argued, on geological evidence, elsewhere (Bailey, 1977; Woolley, 1989), are thought to be generated in the lithosphere. It seems to be generally acknowledged that some sort of metasomatic event in the mantle is necessary for the production of carbonatite and, indeed, for some alkaline rocks. However, it is important to note that all members of the six silicate rock series do occur without associated carbonatites. Whether all these rocks can be generated simply by extreme differentiation processes in a 'normal' mantle, or whether there are necessary, and distinct, types of mantle metasomatism that can lead to suites of alkaline rocks either with or without associated carbonatite are not questions that can be answered by the approach adopted in this paper.

The ultramafic rocks, which may be cumulates, are indicated by the solid black boxes. Carbonatites are shown as being generated in two principal ways: either directly in the mantle or by differentiation at a much shallower depth. The carbonatite sourced directly in the mantle is attested by the presence of mantle xenoliths and xenocrysts in a number of extrusive carbonatite occurrences, which are restricted to three of the series and, in general, these carbonatites are found in diatremes which, presumably, were able to transport dense mantle material to the surface because of the turbulent, highly energetic environment. Evidence for a direct mantle origin for some carbonatites is also furnished by the occurrences with which no igneous silicate rocks occur, the absence of such rocks apparently precluding an origin by

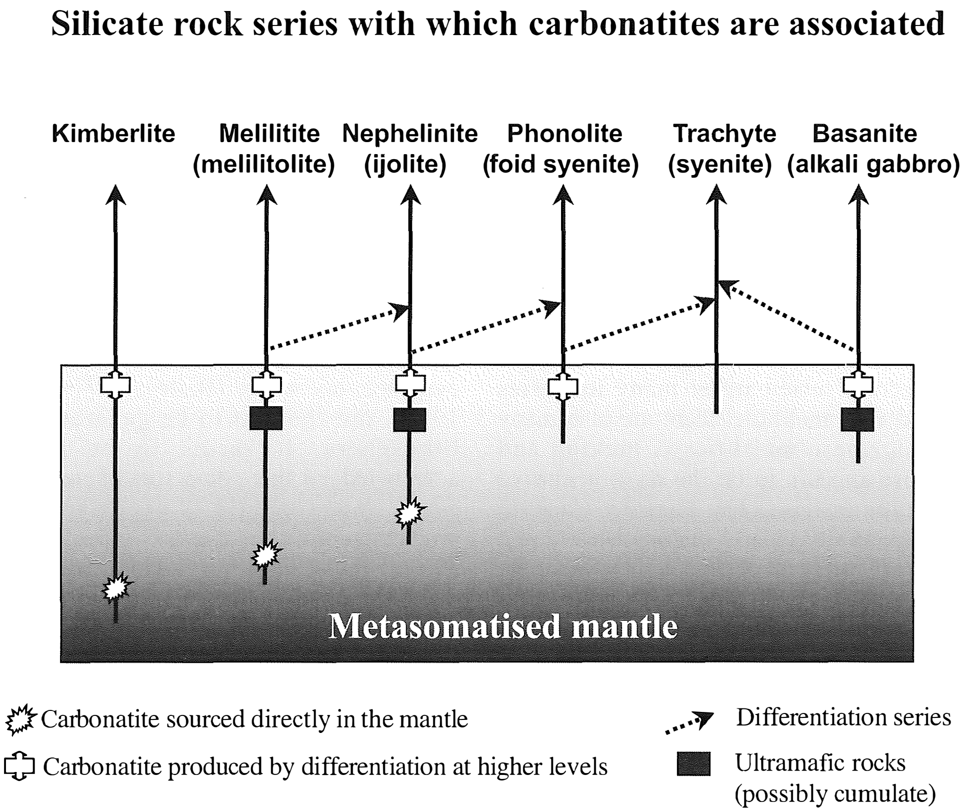

Fig. 1 – Schematic diagram illustrating the six silicate rock series given in Table 7 and indicating proposed relationships to carbonatite and, in some cases, to each other. The diagram also illustrates relative mantle depths of magma generation and, in particular, two levels of carbonatite generation i.e. directly in the mantle and by fractionation at shallower depths. Note that carbonatite sourced in the mantle can pass directly to the surface, and need not be involved in differentiation at a higher level (indicated by open boxes). Ultramafic rocks are associated with three of the series and depicted by the solid rectangles. Known differentiation series are represented by the dotted arrows indicating that three of the series may evolve from more than one type of primary magma source. Shading of the mantle/lithosphere box, denser at greater depths, represents a metasomatic event which is considered a necessary precursor to carbonatite generation and probably to many alkaline silicate rocks.

high level differentiation. The remaining carbonatites, which comprise the great majority and which are found in typical intrusive complexes or volcanoes, are found associated with all six silicate rock series and generated, it is suggested, by differentiation at higher lithosphere levels.

The dotted arrows represent differentiation series amongst the silicate magmas for which evidence of a more primitive parent may be absent. For example, some nephelinites may be either primary magmas or differentiates of melilitite, for the presence of which no evidence is extant. It is possible that the trachyte in some carbonatite occurrences in which this is the sole igneous silicate representative, is a differentiate of either phonolite or basanite. On the other hand some trachytes, quartz trachytes and syenites may be the products of high level melting, perhaps of fenite, although there is also evidence that trachyte may be sourced in the mantle.

In summary, it is proposed that carbonatites are of two principal groups: those generated directly in the mantle and those which have separated from silicate magmas. The latter group, in particular, because of the variability of the silicate melt parents, have a considerable potential for chemical variation, while the carbonatite melts themselves may, presumably, undergo further differentiation before, and during, emplacement.

It was noted earlier that 47% of occurrences with extrusive carbonatite have associated melilite-bearing rocks but only 9% of those with intrusive carbonatite only. Why is this? A possible explanation is that the melilite-bearing rocks are more readily preserved in occurrences dominated by extrusives, many of which are associated with rapidly emplaced diatremes and dyke complexes. In contrast, in the larger complexes, whether large volcanoes or intrusions, there has probably been time for slow differentiation so that the earliest and most primitive members of the melilitite-nephelinite-phonolite-trachyte series, for instance, may be lost, while late thermal and hydrothermal effects can lead to the alteration and replacement of melilite. Similarly, earlier emplaced melilitolites and melilitites can be replaced by later intrusions, carbonatite, in particular, generally being intruded last in complexes of alkaline igneous rocks and carbonatites. It seems probable, therefore, that the greater abundance of melilite-bearing rocks in the extrusive carbonatite association reflects more accurately the close relationship of these two rock types, the relative paucity of melilite rocks in intrusive carbonatite occurrences being an artefact of late replacement processes.

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