A discussion of carbonatite evolution and nomenclature, and the generation of sodic and potassic fenites

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ABSTRACT. Possible evolutionary paths of alkali-rich carbonatite magma may be related to the production of sodic and potassic fenites. It is concluded that the latter are generated not from separate Na- and K-rich carbonatites, but by the earlier preferential loss of Na from a sodi-potassic carbonatite magma. Trends of both Fe and Mg enrichment in carbonatites are illustrated from a number of centres, and ascribed to crystal fractionation, although metasomatism may be partly responsible. Current nomenclature of carbonatites is unsatisfactory and a division into sövites, magnesiocarbonatites and ferrocarbonatites is proposed, based on rock chemistry.

THE possible evolution of carbonatite magmas from initial compositions rich in alkalis, the loss of which causes fenitization, to later liquids which, by fractional crystallization, change from calcium-rich compositions to more magnesian and iron-rich final fractions has recently been discussed by Le Bas (1981). He illustrates this evolutionary path in terms of a triangular plot of $(Na_2O + K_2O)$—CaO—$(MgO + Fe_2O_2{}^T)$ (op. cit., fig. 1), and the principal purpose of this note is to show that if Na_2O and K_2O, and MgO and the iron oxides are plotted separately, instead of being lumped as in Le Bas' diagram, the resulting trends provide further insight into the evolution of these strange liquids, and some problems are highlighted.

This is best achieved by using two triangular plots: one, representing the natrocarbonatite stage, plots Na_2O—K_2O—$(CaO + MgO + FeO + Fe_2O_3 + MnO)$ and the other, the alkali free stage, CaO—MgO—$(FeO + Fe_2O_3 + MnO)$. However, carbonatite evolution does not pass through these stages consecutively, they are merely a graphical convenience.

In fig. 1 are plotted four analyses of the Oldoinyo Lengai natrocarbonatite lavas (Dawson, 1966, Table 4), the only analyses available at present of such magmas. The analyses of alkali carbonate inclusions in apatite of Aspden (1977) used by Le Bas are not utilized here because they are from

ijolites, and there may be differences from carbonatite compositions. As there is little or no alkali present in any known carbonatite intrusions, we must assume that the Lengai magma would have evolved by alkali loss to a composition close to the CaO, MgO, FeO, Fe_2O_3, MnO corner of fig. 1. Loss of alkalis in the same ratio as in the magma i.e. $Na_2O : K_2O$ about 4:1 (1 on fig. 1), would cause fenitization of the surrounding rocks of the type classified by Vartiainen and Woolley (1976, Table 16) as 'Sokli' or 'intermediate' type, that is sodic to sodi-potassic. The magma would evolve along the line a—b on fig. 1.

However, many fenite aureoles are either wholly potassic or sodic in character or contain both sodic and potassic fenites. The principal Malawi carbonatite centres, for example, have outer sodic

FIG. 1. Alternative paths of differentiation of Oldoinyo Lengai natrocarbonatite, and suggested relationship with fenitization. For discussion of trends and hypothetical natrocarbonatite magmas I and II see text. Natrocarbonatite analyses (solid circles) from Dawson (1966, Table 4).

fenite aureoles with inner potassic aureoles adjacent to the carbonatite. The potassic fenites are later than and cut the more sodic fenites, and the order of development is always the same. This was explained in an earlier paper (Woolley, 1969, p. 213) in terms of phonolitic magma causing the more sodic fenitization, and the later emplacement of carbonatite generating the potassic fenites. However, although this sequence of events may have prevailed at some centres, undoubtedly at others all the fenites have been generated by emanations from carbonatite alone, but clearly this cannot be produced by a Lengai-type natrocarbonatite if the alkalis are lost in the same ratio throughout the fenitization process. It could be argued that the alkalis are indeed lost from the carbonatite in such a ratio, and that the potassium is fixed in the inner part of the aureole, the sodium moving further out, but this seems to be unlikely because of the sharp contacts between the two fenite types. Instead it is necessary to postulate the emplacement of a second carbonatite magma enriched in potassium, having a composition lying somewhere in the shaded area labelled II on fig. 1.

This method of carbonatite evolution and fenite development therefore implies the existence of both sodic and potassic carbonatite magmas (I and II on fig. 1) presumably generated deep in the mantle and, in the case of fenite aureoles with both sodic and potassic fenites, the intrusion of both magma types, and always in the same order. This seems most unlikely.

An alternative mechanism invokes the loss of alkalis from a Lengai-type natrocarbonatite but at a higher $Na_2O:K_2O$ ratio than in the magma, such as 'c' on fig. 1. The magma composition would now evolve along a curved path such as d–e with the alkali fraction being lost becoming gradually more potassic (2, 3, and 4 on fig. 1), until the last fraction was almost sodium-free (5 on fig. 1). This is consistent with the field relationships, including the observation that potassium fenitization seems to be generally of more importance at higher structural levels in carbonatite complexes. Further, this model obviates the necessity of postulating the genesis of two distinct natrocarbonatite magmas, deep in the mantle.

Turning now to consideration of calcium, magnesium, and iron in carbonatite magmas, Le Bas discusses the intrusive sequence in western Kenya of sövite through alvikite and beforsite to ferrocarbonatite, which corresponds to the crystallization differentiation sequence determined experimentally by Wyllie (1965). Several workers have discussed similar carbonatite evolutionary sequences and it is generally agreed that field relationships tend to indicate a series from sövite

to more magnesian and iron-rich carbonatites, the best example probably being the three successive plugs of sövite, ankeritic sövite and sideritic carbonatite of Chilwa Island (Garson and Smith, 1958). When, however, analyses of carbonatite from several different areas are plotted in the triangle $CaO-MgO-(FeO+Fe_2O_3+MnO)$ (fig. 2) a broad range of patterns results, and the western Kenya suite (Le Bas, 1977) proves to be rather atypically rich in iron and poor in magnesium. This plot also clearly reveals how meaningless is an 'average' carbonatite analysis (e.g. Gold, 1966).

Data from Fen, Alnö and Sokli (fig. 2a) show rather broad spreads and it is not clear from field observations whether enrichment either in magnesium, or in iron and manganese was sequential or concurrent. Analyses from the Chilwa Province centres of Chilwa Island, Kangankunde, and Tundulu in Malawi (fig. 2b) however, are more revealing in that they portray discrete groups and unexpectedly show no overlap. Of the five analyses available from Chilwa Island, four are of ankeritic sövites and one of a sideritic carbonatite. The sövite has not been analysed but clearly would plot close to the CaO corner, so producing an even more exaggerated trend of Mg enrichment, with final fractions showing strong iron enrichment. It is tempting to speculate that the relatively Ca-poor carbonatites of Kangankunde represent further differentiation of carbonatite magma that was originally similar to that of Chilwa Island. The Mg-poor carbonatites of Tundulu are similar to those of western Kenya, including the final small lobe of Mg enrichment, and it is clear from Garson's (1962) description of Tundulu that the trend away from CaO corresponds generally with the order of emplacement.

Also shown on fig. 2b are the three analyses from Lueshe (Meyer, 1958) including a rauhaugite containing 90% magnesite. Clearly more analyses illustrating this exceptional magnesium enrichment would be valuable. The trends for Ice River and Oka (fig. 2c) show similar $MgO:(FeO, Fe_2O_3, MnO)$ ratios, but a melilite-bearing carbonatite from Oka, is much enriched in Fe and Mg.

As already mentioned the change in the ratios of Na:K and of Ca:Mg:Fe are probably essentially concurrent not consecutive differentiation processes, and take place at a very high level in the crust. Whether there is any correlation between the degree of differentiation reached at any one time in each of the two processes is not at present known. It could be, for instance, that the later stages in the evolution of the alkali part of the system, in which the magma is enriched in potassium, coincides with fractionation to rauhaugite or ferrocarbonatite compositions in the Ca–Mg–Fe
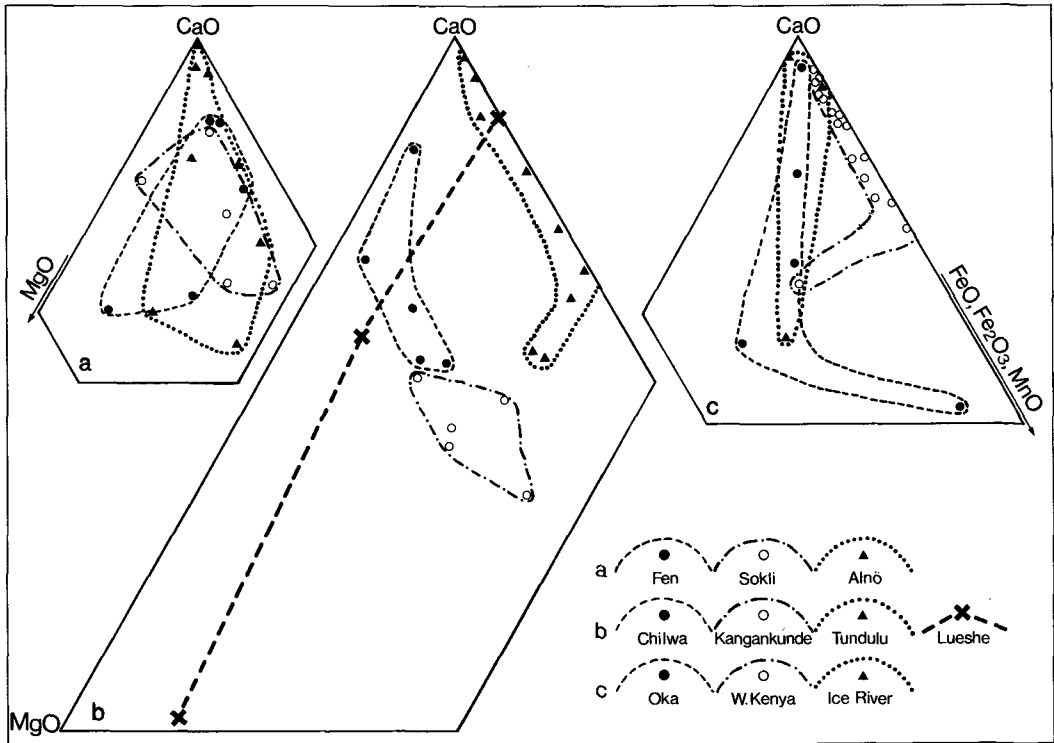
FIG. 2. Plots of carbonatite analyses from a range of complexes in terms of CaO–MgO–(FeO, Fe$_2$O$_3$, MnO) (wt. %) to illustrate variations with and between them. Data sources are: Fen (Brögger, 1921), Sokli (Vartiainen and Woolley, 1976), Alnö (Eckermann, 1948), Chilwa Island (Garson and Smith, 1958), Kangankunde (Garson, 1965), Tundulu (Garson, 1962), Lueshe (Meyer, 1958), Oka (Gold, 1969, quoted in Currie, 1976), W. Kenya (Le Bas, 1977), and Ice River (Currie, 1975).

part of the system, a correlation which it might prove possible to monitor by inclusion studies.

The consensus of opinion as to the mechanism of primary carbonatite magma formation generally favours separation from an initial phonolitic or nephelinitic magma of an alkali carbonate immiscible liquid fraction (Freestone and Hamilton, 1980), but it seems unlikely that the trends of Mg and Fe enrichment discussed in this paper were caused by the separation of successively more magnesian or iron-rich immiscible fractions. Wyllie (1965) observes that synthetic carbonatite magmas are extremely fluid and crystal settling occurs in a few minutes, which would facilitate the separation of residual liquids or accumulated crystal fractions, so that crystallization differentiation might be an effective process in such magmas. So it seems probable that carbonatite magmas are formed initially by separation as immiscible liquids, but evolution then continues by means of crystal fractionation. However, it is likely that late stage metasomatic effects may also be responsible for

some variation in carbonatite compositions, and rocks such as the Lueshe magnesite-rich rauhaugite may have been formed by such a mechanism.

Carbonatite nomenclature. It has already been pointed out that the variation of carbonatite compositions illustrated by fig. 2 makes an average carbonatite analysis meaningless, and it also illustrates why so many carbonatite names were coined in the past. Unfortunately, the nomenclature recently suggested by Streckeisen (1980) does not prove to be very practical. He suggests that carbonatites should be divided as follows:

'(a) calcite-carbonatite (sövite, coarse-grained; alvikite, medium- to fine-grained;
(b) dolomite-carbonatite (beforsite);
(c) ferrocarbonatite (essentially composed of iron-rich carbonate minerals;' (Streckeisen, 1980, p. 204).

This classification poses the following problems:

1. Carbonatites rarely consist of two or more distinct carbonate minerals the modal proportions

of which can be easily determined, say by point counting, even after staining. Many are fine-grained and, because of the extensive solid solution at high temperatures, complex exsolution textures are common (see for example Heinrich, 1966, figures 7-4 to 7-6), while zoning is also abundant, particularly in more Fe-rich compositions.

2. Apart from calcite and dolomite, ankerite is a very common carbonate species in carbonatites. A number of analyses are plotted on fig. 3 from which it is apparent that compositions range from dolomite to Fe-rich ankerite.

3. Although siderite is reported from ferrocarbonatites no analyses appear to have been published. It is probable that in most of these rocks the carbonate is in fact ankerite and much of the Fe is present as oxides.

Taking into consideration the points outlined above together with the range of carbonatite compositions shown on fig. 2, it is suggested that a practical and simple way of classifying carbonatites is by plotting whole rock analyses on the triangle $CaO-MgO-(FeO, Fe_2O_3, MnO)$ (wt. %) divided as shown in fig. 3. A boundary for sövite at 80 % CaO encompasses most of the rocks called sövites included in fig. 2. The line dividing the Mg- and Fe-rich carbonatites also divides the magnesian and Fe-rich carbonatites roughly into two equal populations, providing a simple, though admittedly arbitrary, division.
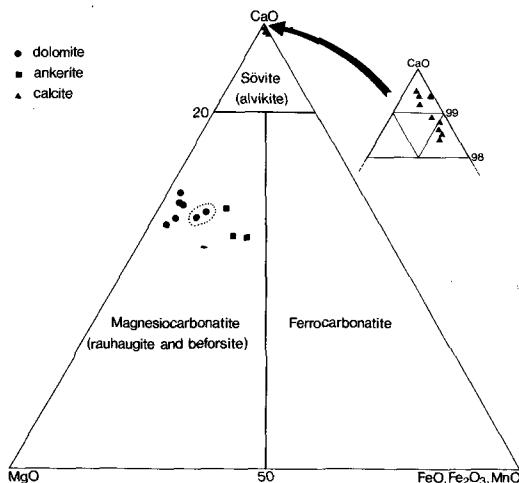

FIG. 3. Suggested classification of carbonatites in terms of $CaO-MgO-(FeO, Fe_2O_3, MnO)$ (wt. %). Analyses of carbonates from carbonatites are plotted and taken from Kapustin (1980) and Barth and Ramberg (1966). The two Barth and Ramberg analyses (circled on the diagram), from the rauhaugite of Fen, are described as ankerites, but by the definition of Deer et al. (1962) (i.e. dolomite = Mg:Fe > 4:1) they are ferroan dolomites.

It does not at present seem practicable to divide dolomitic from ankeritic carbonatites, mainly because little is known about the relationships among the co-existing carbonate phases, and many carbonatites which have been described as dolomitic are almost certainly ankeritic. Lack of information on the compositions of the carbonate phases of ferrocarbonatites makes it impossible at present to define ferrocarbonatites in terms of their carbonate chemistry, but the term needs to be retained as it encompasses a group of carbonatites which are volumetrically and genetically distinct. The retention of the term alvikite for fine-grained calcitic carbonatites could in the long term prove to be unnecessary, though Dr Le Bas (pers. comm.) is of the opinion that they can be distinguished chemically from sövites, so justifying the name.

It is perhaps rather unexpected that the term beforsite, introduced by von Eckermann (1948) for magnesian carbonatite dykes at Alnö, should be recommended by Streckeisen (1980) for dolomitic carbonatite, when the first described and named dolomitic carbonatites were the rauhaugites of Fen (Brögger, 1921). If sövite, the name for the coarse-grained rock is the principal name adopted for calcitic carbonatite then, logically, rauhaugite should be adopted for coarse-grained dolomitic/ ankeritic carbonatite, and the term beforsite either dropped or retained for the hypabyssal variety. However, Le Bas points out that the Fen rauhaugite is a very mixed rock grading variously into sövite and rodberg, and it may have been affected by at least one period of metasomatism. Hence it constitutes an unsatisfactory 'type' dolomitic carbonatite, although the precedence of the name is conceded. On the other hand few carbonatites, except some of the sövites, are homogeneous, and many carbonatites have been altered by sub-solidus changes as demonstrated, for instance, by Vartiainen and Paarma (1979) at Sokli, and as reported in numerous papers on Russian occurrences.

The term beforsite is also unsatisfactory if the nature of the 'type' material is considered. Of the twenty-two analyses of beforsite dykes given by von Eckermann (1948; 1958) no fewer then seventeen have SiO_2 contents greater than 10 %, and eight more than 20 %. The lowest SiO_2 value reported is 2.32 %. These are, therefore, mostly mixed carbonate-silicate rocks and hardly the hypabyssal equivalents of the Fen rauhaugite.

In view of the unsatisfactory nature of the type rauhaugite and beforsite, the term 'magnesiocarbonatite' is recommended for carbonatites in which $MgO > (FeO + Fe_2O_3 + MnO)$. If the nature of the carbonate phase is known the rock may be referred to as dolomitic or ankeritic carbonatite, but this may lead to difficulties if more than one

carbonate phase is present, and if future work should show that ankerite is the principal carbonate phase in ferrocarbonatites.

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