

A supposed sövite from Oldoinyo Lengai, Tanzania: result of extreme alteration of alkali carbonatite lava

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Abstract

A calcite-rich block in nephelinitic agglomerate at Oldoinyo Lengai comprises Sr-calcite, apatite, fluorite, a Ba–Mn oxide akin to romanèchite, and a distinctive Mn–Fe spinel. Formerly reported as sövite, on textural, mineralogical and stable isotope grounds it is now re-interpreted as a highly-altered natrocarbonatite lava. An implication of this study is that natrocarbonatite is not just a modern phenomenon, but has been extruded from Oldoinyo Lengai for at least around 1250 years.

KEYWORDS: sövite, altered natrocarbonatite, Oldoinyo Lengai, Tanzania

Introduction

OLDOINYO LENGAI, situated in the Rift Valley of northern Tanzania, the world's only active carbonatite volcano. The main part of the volcano is built of yellow nephelinitic and phonolitic tuffs and agglomerates (YTA or Unit I) and younger black nephelinitic tuffs and agglomerates (BTA or Unit 3) (Dawson, 1989). Another less-extensive formation that will be referred to below is the so-called Footprint Tuff, that post-dates BTA (Hay, 1989).

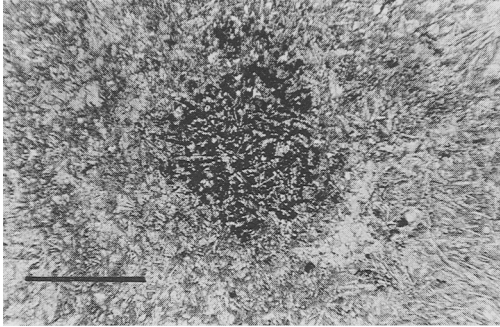
During the 1960 survey of Oldoinyo Lengai, I collected an angular block of fine-grained calcite-rich rock (BD83) embedded in Unit 3 nephelinitic agglomerate on the lower eastern slopes of the volcano. It was identified as a calcite carbonatite by the Tanganyika Geological Survey, and I have reported it as sövite in accounts of the geology of the volcano (Dawson, 1962, 1989). A re-examination of this specimen has been prompted in view of its potential relevance to the origin of alkali carbonate liquids, similar to those erupted in historic times from Oldoinyo Lengai. Gittins (1989) has argued that natrocarbonatite arises by sövite fractionation from an original mixed alkali-calcium carbonate magma.

Because BD83 is texturally similar to both modern and older, partly-altered natrocarbonatite lavas from the volcano, the investigation was extended to a study of the groundmass carbonate and opaque phases of a partly altered natrocarbo-

natite GA47, collected from a down-faulted succession within the crater, the petrography and bulk chemistry of which have been given by Dawson *et al.* (1987). Also examined in this study, are the groundmass phases in another partly-altered lava sample (BD4162) collected from the same locality as GA47 and petrographically identical.

Petrography

In hand-specimen, BD83 is fine-grained, and white in colour, though with distinctive black patches up to 2 mm (Fig. 1). Thin-section examination was carried out by a combination of light optics and back-scattered electron imaging (BSEI). The specimen is inequigranular: it is composed partly of roughly-equidimensional calcite patches up to 1 mm, but in other parts the calcite takes the form of laths and needles being up to 1 mm in length (Fig. 2) The calcite patches, laths and needles are not single crystals but consist of numerous tiny coalescing calcite grains. The individual lathes and needles are *morphologically* very similar to nyerereite quench microphenocrysts in the modern carbonatite lavas. The interstices between the calcite aggregates are sometimes voids but are filled mainly with very fine-grained (up to 50 µm), porous, lattice-like aggregates of apatite (Fig. 3a) The apatite aggregates generally contain a small amount of vermi-



FIGS 1 AND 2. FIG. 1 (*left*). Photomicrograph of romanèchite aggregate. PPL, scale bar is 1 mm. FIG. 2 (*right*). Acicular and tabular calcite aggregates in BD83. PPL, scale bar is 0.5 mm.

form fluorite, which also occurs as isolated equidimensional 3–5 μm grains; it has a very similar BSE reflectivity to the apatite and has only been detected by qualitative EDS microanalysis. Rod-shaped apatites, up to 10 μm long, embedded in some calcite aggregates, have a slightly brighter BSE reflectance than the intergranular, lattice apatite (Fig. 3), probably due to higher concentrations of REE (see Table 4).

The prominent dark spots (Fig. 1) are diffuse aggregates of a phase compositionally dominated by Mn and Ba oxides and most similar to romanèchite; the individual grains, up to 20 μm , are irregular in shape, sometimes spongiform, and are separated from each other by calcite and lattice apatite (Fig. 4a). The margins of the 'romanèchite' aggregates with the surrounding carbonate rock are diffuse (Fig. 4b).

The only other phases identified within the rock are irregularly-shaped grains of Mn–Fe spinel up

to 15 μm , and small (5–10 μm), lozenge-shaped grains of baryte, both of which occur interstitial to the calcite.

A petrographic description of the partly altered natrocarbonatite GA47 has been given by Dawson *et al.* (1987) Specimen BD4162, collected from the same locality is identical to GA47 in that it consists of laths of nyerereite ($[\text{Na}_{0.82}, \text{K}_{0.18}]_2\text{Ca}[\text{CO}_3]_2$) replaced to varying degrees by pirssonite ($[\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}]$). The pirssonite is fringed by linear concentrations of fine-grained apatite and fluorite that parallel the margins of the replaced grains, suggesting diffusion of P and F from the replaced nyerereite. Rounded patches and smaller laths consisting entirely of pirssonite could be pseudomorphs after gregoryite ($[\text{Na}_{0.78}\text{K}_{0.05}]_2[\text{Ca}_{0.17}\text{CO}_3]$) phenocrysts and gregoryite and nyerereite microphenocrysts. The matrix consists mainly of pirssonite and calcite, in roughly equal proportions, but it also contains

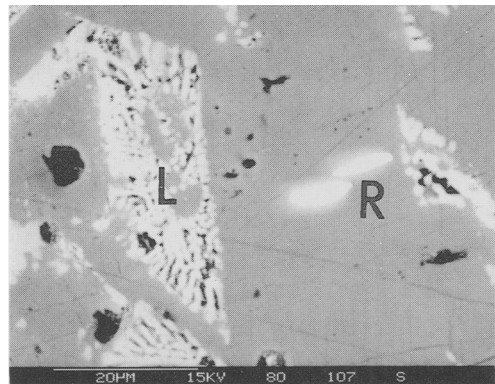
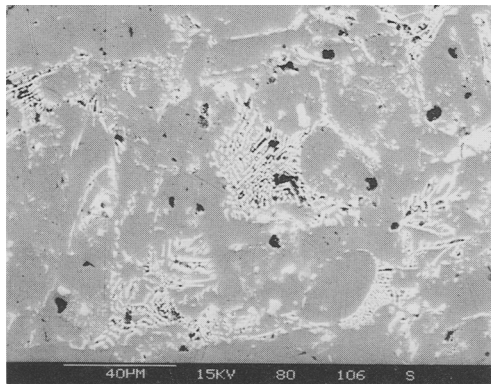


FIG. 3 (*a, left*). BSE image of BD83, showing calcite laths and voids (grey), lattice apatite (high reflectivity-white), and voids (black). (*b, right*) BSE image of lattice apatite (L) and rod apatite (R) in BD83.

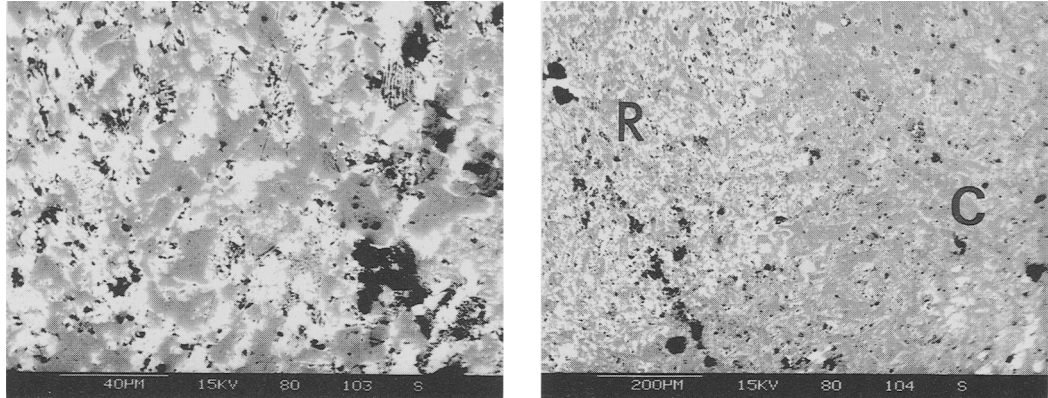


Fig. 4 (a, left), BSE image of romanèchite aggregate, showing irregularly-shaped white romanèchite grains, separated by lattice apatite (white) and calcite (grey). (b, right) BSE image of diffuse margin of romanèchite aggregate (R) (overall brighter reflectivity), with the dominantly calcite matrix (C).

dark-brown, micro-crystalline patches (sometimes wedge-shaped) intergranular to the calcite laths; qualitative analysis indicates Ca, P, Fe and Mn in the patches, which could be interpreted as mixtures of apatite and iron and manganese oxides. In addition there are small amounts (<5 vol.% of the total rock) of anhedral or irregular crystals of nepheline, clinopyroxene, Ti-andradite and Ti-magnetite; their fragmental form suggests that they are xenocrysts.

Bulk chemistry

The bulk chemistry of BD83 is dominated by CaO and CO₂, together with lesser amounts of P₂O₅ and other oxides (Table 1) Most oxides can be explained in terms of the observed mineralogy. The small amounts of Na₂O and K₂O appear too high to be explained by the relatively small modal amounts of xenocrystal nepheline; a possibility is that this may be due to relict alkali carbonates,

Table 1 Analyses of Oldoinyo Lengai carbonatites

	1	2	3		1	2	3		1	3
SiO ₂	<0.10	0.73	0.86	V	123	84	59	La	425	583
TiO ₂	0.01	0.03	0.08	Cr	<10	<10	<10	Ce	498	738
Al ₂ O ₃	0.03	0.25	0.28	Ni	11	12	<10	Pr	30.9	47.3
Fe ₂ O ₃	0.29	1.10	0.67	Cu	18	18	11	Nd	77.5	114.5
MnO	0.25	0.55	0.27	Zn	100	354	87	Sm	4.84	7.50
MgO	0.26	0.49	0.30	Rb	184	55	27	Eu	1.15	1.65
CaO	13.93	25.29	52.47	Sr	11900	12600	6240	Gd	2.57	5.06
Na ₂ O	30.30	24.68	0.38	Y	<5	75	6	Dy	1.13	2.13
K ₂ O	6.55	0.68	0.28	Nb	23	157	24	Ho	0.77	0.38
H ₂ O ⁺	4.51	9.33	0.49	Ba	8830	8180	9040	Er	1.60	2.59
P ₂ O ₅	1.13	0.64	1.46	Pb	89	136	117	Yb	0.43	1.15
SO ₃	3.23	0.20	0.57					Lu	0.07	0.19
CO ₂	33.90	32.71	40.10							
Cl	2.45	0.20	0.04							
F	1.20	1.06	0.18							
Sum	98.14	97.94	98.70							

Analyses by XRF (analyst R.Kanaris-Sotiriou) except H₂O⁺, CO₂, F and Cl (wet methods - analyst A Saxby). Totals include subtraction of oxygen equivalent to F and Cl. REE analyses by ICP (analysts NERC ICP Unit, Royal Holloway and Bedford New College)

1. BD118 natrocarbonatite lava, extruded October 9, 1960.
2. GA47 partly altered natrocarbonatite lava (Dawson et al. 1987).
3. BD83 calcite carbonatite, block in nephelinitic agglomerate; total includes 0.27 wt% REE₂O₃.

Table 2. Oldoinyo Lengai calcites

	1	2	3
FeO	0.04	0.04-0.09	0.02
MnO	0.06	0.00-0.34	0.26
MgO	0.05	0.02-0.08	0.00
CaO	56.4	55.3-56.9	53.2
SrO	0.46	0.18-0.56	1.63
BaO	0.03	0.03-0.10	1.44
Na ₂ O*	0.02	0.00-0.02	0.57
CO ₂	43.21		43.43
Sum	100.21		100.67

*CO₂ calculated.

1. Representative analysis of calcite in BD83.
2. Range of calcite compositions in BD83.
3. Intergranular calcite in BD4162.

though it must be stressed that none has been found in this section. Like other carbonatites in general, BD83 contains high amounts of Sr and Ba (6240 and 9040 ppm respectively), and the *REE*, the latter being dominated by the *LREE*. BD83 has higher absolute concentrations of the *REE* than natrocarbonatite lavas, but has a very similar chondrite-normalised *REE* pattern (Fig. 5).

Stable isotope chemistry. Duplicate analyses of the carbon and oxygen isotopes are $\delta^{13}\text{C}$ 4.16‰ PDB, $\delta^{18}\text{O}$ 24.53‰ SMOW (estimated precision $\pm 0.05\%$ (1 σ)). These values, together with carbon and oxygen isotope values for other carbonatites, are shown in Fig. 6. Compared with the Oldoinyo Lengai natrocarbonatites, BD83 contains considerably heavier oxygen, in this respect closely resembling the values found for calcitic

clasts from the Footprint Tuff that Hay (1989) interprets as altered natrocarbonatites. However, the oxygen is not as heavy as that in calcrites developed within the black tuffs and agglomerates (BTA).

Phase chemistry

The phases were analysed on a Cameca electron microprobe. Standard operating conditions were 20 kV and 20 nA, but for the carbonate analyses the beam current was reduced to 10 nA and the beam was rastered.

Calcite. The carbonate in BD83 (Table 2) consists mainly of calcium carbonate with up to 0.56 wt.% SrO; MnO is the only additional oxide of significance. Intergranular calcite in BD4162 is likewise dominantly CaCO₃ but with higher amounts of SrO (1.63 wt.%) and also significant BaO (1.44 wt.%).

Spinel. The spinel in BD83 (Table 3, analysis 6) belongs to a distinctive set of spinels that occur in all the Oldoinyo Lengai carbonatite lava, regardless of degree of alteration; other members of this set are found in pristine natrocarbonatite, and in partly-altered carbonatite GA47 and BD4162 (analyses 1 to 5). Compared with other Oldoinyo Lengai spinels, these distinctive spinels are low in TiO₂ (generally <2 wt.%), high in MnO (mainly >11 wt.%), high MgO (>2 wt.%), and with a low, but variable, FeO/Fe₂O₃ ratio. BD4162 also contains grains of two other types of spinel—a low MnO (<3 wt.%), low TiO₂ (1 wt.%) spinel with FeO/Fe₂O₃ of 0.4 included within partly replaced nyerereite (also found in GA47) (analysis 7 and 8), and a high-TiO₂ (11 wt.%) spinel with FeO/Fe₂O₃ ratios of ~0.75 (analysis 9)

Table 3. Representative analyses of Oldoinyo Lengai carbonatite spinels and "romanèchite".

	1	2	3	4	5	6a	6b	7	8	9	10	11a	11b	12
SiO ₂	1.47	1.17	0.98	0.37	0.09	0.14	0.26-0.52	0.08	0.18	0.03	0.0-0.06	1.27	1.27-2.10	n.a
TiO ₂	0.82	0.59	0.74	0.26	0.59	1.17	1.17-2.23	1.09	0.89	11.0	9.03-12.8	0.31	0.04-1.74	n.a
Al ₂ O ₃	n.a	0.46	2.16	0.44	1.57	1.49	1.16-1.60	0.20	0.23	0.83	0.06-2.06	0.19	0.19-0.25	1.80
Fe ₂ O ₃	65.6	63.7	65.9	67.8	65.4	65.7	63.6-65.7	66.8	65.7	46.9	43.7-49.1	0.77	0.50-2.85	0.72
FeO	18.1	8.27	0.16	14.6	1.48	16.7	16.0-16.7	28.1	27.7	38.3	33.6-39.1	0	0	0
MnO	11.8	15.2	20.2	12.0	20.3	11.4	9.59-11.4	2.78	2.84	1.21	0.83-1.41	70.6*	68.7-70.6	76.1*
MgO	2.20	3.57	6.67	2.79	5.40	2.46	2.45-2.97	0.52	0.55	1.22	1.16-3.12	0.03	0.03-0.07	0.07
CaO	n.a	2.09	1.71	0.79	1.94	0.90	0.64-1.10	0.45	0.28	0.12		1.65	1.35-2.34	0.45
BaO	n.a	n.a	n.a	n.a	n.a	n.a		n.a	n.a	n.a		12.7	12.1-12.9	11.87
ZnO	n.a	0.31	0.41	0.15	0.39	n.a		0.32	0.34	0.08		n.a		n.a
Sum	99.99	95.37	98.91	99.20	97.16	100.02		99.73	99.78	99.69		90.53		98.71

1. Spinel in natrocarbonatite, erupted November 1988 (recalculated from Dawson et al *in press*).2 and 3. Extremes in compositions of 5-10 μm irregularly-shaped grains in GA47; high CaO and low totals suggests some overlap with carbonate.4 and 5. Extremes in compositions of 5-10 μm irregular grains in BD4162; high CaO and low totals indicates overlap with surrounding carbonate.6a Representative analysis, and 6b range in compositions, of 5-10 μm grains in calcite carbonatite BD83.7. Equant 50 μm spinel included in partly-replaced nyerereite lath, BD4162.8. Equant 70 μm grain in GA47.9. Anhedral 70 μm (?xenocrystal) grain in BD4162.

10. Range of concentrations in spinels in Oldoinyo Lengai ijolites and nepheline syenites (Dawson unpublished data).

11a Representative analysis of, and 11b range in compositions (5 grains) in, small (10 μm) irregular grains of MnBa oxide "romanèchite" in BD83. Total in 11a includes 0.16 % SrO, 2.14 % Na₂O and 0.87 % K₂O. In 11b Na₂O ranges from 1.89 to 2.14% and K₂O from 0.71 to 0.86 %. *Mn expressed as MnO₂ and total iron as Fe₂O₃.12. Romanèchite, Romanèche, France (Perseil and Pinet 1976). Total includes 0.52 wt% Na₂O, 2.12 % K₂O and 5.42% H₂O. *Mn as MnO₂.

Table 4. Oldoinyo Lengai apatites

	1	2	3	4	5	6	7	8
P ₂ O ₅	25.3	25.1	24.1	16.96	30.1	30.4	29.8	30.8
SiO ₂	8.90	10.1	8.49	12.28	1.62	1.41	2.47	2.42
La ₂ O ₃	6.47	7.89	6.40	5.6	0.54	0.59	1.65	1.85
Ce ₂ O ₃	7.49	10.2	8.69	14.4	1.15	1.20	2.60	2.64
Nd ₂ O ₃	1.58	2.16	1.81	8.0	0.05	0.14	0.39	0.44
Pr ₂ O ₃	0.69	0.60	0.47	1.9	0.04	0.01	0.15	0.07
Y ₂ O ₃	0.10	0.16	0.13	0.4	0.00	0.07	n.a	n.a
MnO	0.04	0.09	0.15	n.a	0.38	0.36	n.a	n.a
SrO	2.43	1.25	2.25	n.a	3.71	3.23	3.50	3.63
CaO	42.5	38.5	42.9	28.84	49.3	49.6	42.8	43.7
Na ₂ O	0.24	0.14	0.29	0.21	1.28	0.94	7.85	7.44
K ₂ O	0.12	0.04	0.05	n.a	0.17	0.10	3.00	2.32
F	3.46	2.97	4.41	2.10	8.12	6.60	4.48	5.27
Sum	99.73	98.20	100.14	99.36	96.26	94.65	100.92	99.54

1, 2, 3. Rod-shaped 20 µm grains of britholitic apatite in BD83

4. Thorium britholite, Oka, Quebec (Hughson and Sen Gupta, 1964). Total includes 1.5 wt % Sm₂O₃, 5.62 % ThO₂, 0.13 % FeO, 0.20 % MgO and 0.54 % H₂O.

5,6 Lattice apatite in BD83.

7, 8. Apatites in BD4155, natrocarbonatite extruded November 1988 (Dawson et al *in press*). Analyses contain 1.46 and 1.45 wt% BaO, and 0.77 and 0.61 wt% Cl respectively.

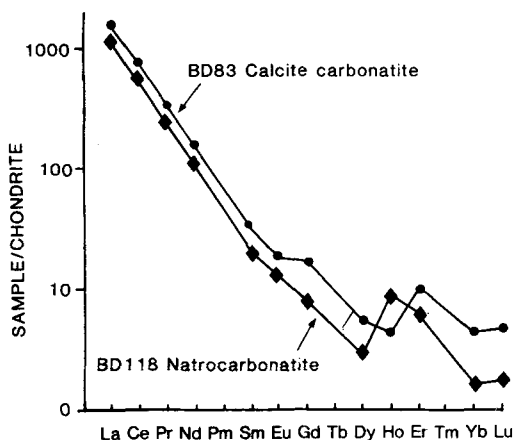


Fig. 5. Chondrite-normalised REE patterns of BD83 and natrocarbonatite BD118 (extruded October 1960). Normalised against chondrite REE values of Taylor and McLellan (1985).

that is similar in composition to spinels in the Oldoinyo Lengai ijolites and nepheline syenites (analysis 10).

'Romanèchite'. Because of the irregular shape and presence of cavities, analysis of the main opaque phase in BD83 has proved difficult;

furthermore, some problems arise in the data processing due to uncertainty as to the oxidation state of Mn—the most abundant element in the mineral. The analyses (Table 3, analyses 11a and 11b) have low totals despite calculating all Mn as MnO₂; this is possibly partly due to the presence of water inherent in many manganese oxides but overlap with surrounding calcite or apatite may account for the high CaO concentrations (1.35 to 2.34 wt. %). The bulk of the analysis comprises the oxides of Ba and Mn, with lower amounts of Si, Sr, Na and K. It is chemically most akin to some members of the isostructural hollandite–cryptomelane–romanèchite group of high-Mn oxides, and finds its closest match in romanèchite from the type-locality Romanèche, France (Table 3, analysis 12) (Perseil and Pinet, 1976), although the French sample contains both Mn⁴⁺ and Mn²⁺ and there are differences in concentrations in some of the minor oxides. This is not surprising since the tunnel structure of the hollandite–romanèchite and todorokite groups allows acceptance of variable amounts of water, Na, Ca, Ba and K (Turner and Buseck, 1979, 1981; Vance and Agrawal, 1982). In the context, some of the Ca found in Oldoinyo Lengai sample might be real.

Apatite. BD83 contains two types of apatite that are both morphologically and chemically

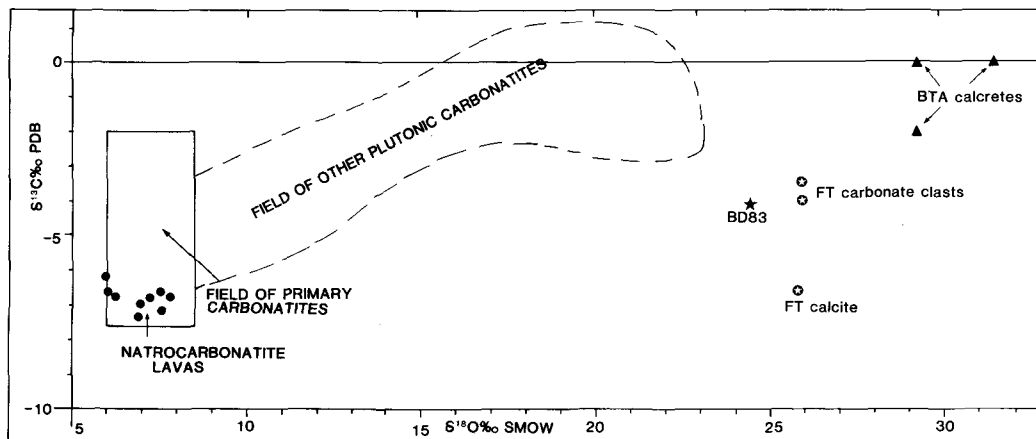


Fig. 6. Plot of $\delta^{18}\text{O}$ vs $\delta^{13}\text{C}$ for Oldoinyo Lengai carbonate rocks. Fields for primary carbonatites and other carbonatites from Sheppard and Dawson (1973) and unpublished data. Natrocarbonatite data from Sheppard and Dawson (1973), O'Neil and Hay (1973), Javoy *et al.* (1988), Hay (1989) and Dawson *et al.* in press. Data for Footprint Tuff (FT) carbonate clasts and calcite, and calcretes developed within the black tuffs and agglomerates (BTA) are from Hay (1989).

distinct. The rod-shaped grains, although showing some variation in composition from grain to grain (Table 4, analysis 1–3), form a high *LREE*, high Si, low P group; the *REE* are dominated by Ce, and the apatite also contains up to 2.43 wt.% SrO. F is up to 4.41 wt.% and the good analytical totals suggest little hydroxyl or carbonate in the lattice. The chemistry indicates some solid solution towards the rare-earth silico-phosphate britholite (ΣREE oxides 60.52, CaO 11.28, P_2O_5 6.48, SiO_2 16.71 wt.%; Winther and Bøggild, 1899) that is related to apatite by the substitution of $\text{REE}^{3+} + \text{Si}^{4+}$ for $\text{Ca}^{2+} + \text{P}^5$. An example of britholitic apatite, though containing Th and a higher percentage of the britholite molecule, is shown for comparison in Table 4 (analysis 4).

Compared with the rod-shaped britholitic apatite, the apatite forming the lattice-like intergranular clusters contain considerably less Si and *REE*, but higher Ca, P, Sr, Na and F. In view of the thinness of the individual apatite filaments and the fluorite intergrowths, the high F concentrations may be due to overlap with fluorite. The two different types of apatite in BD83 are compositionally different from high-alkali fluorapatite that occurs in pristine natrocarbonatite (Table 4, analyses 7–8) (Fig. 7).

Discussion

Chemically BD83 is a calciocarbonatite. However, the textures which range from the fine grain size and lath-shaped morphology of the calcite, to the inter-grain porosity and lattice-like apatite,

are unlike those found in plutonic or hypabyssal sövites. Moreover, minerals of the hollandite-cryptomelane-romanèchite group are typically found in near-surface environments, and the only previously-reported example of the group from carbonatite is hollandite from a weathered carbonatite at Sallanlatva, USSR, where it occurs as a secondary mineral in cavities with limonite, baryte and pyrolusite (Kapustin 1973).

It is noted above that, in containing lath-shaped carbonate crystals, BD83 is *texturally* similar to the modern carbonatite lavas from the volcano. To suggest that BD83 derives from a natrocarbonatite precursor, is to enter a debate that has arisen as to the origin of calcium carbonatite extrusives. Some, such as those at Kerimasi, Tanzania (Mariano and Roeder 1983), Kaiserstuhl, Germany (Keller; 1981, 1989) and Fort Portal, Uganda (Barker and Nixon, 1989), contain platy crystals of unrecrystallised, zoned calcite, and undoubtedly represent extrusion and consolidation of primary calcium carbonate liquid. However, there are others at Kerimasi (Hay, 1983), and also at Tinderet, Kenya (Deans and Roberts, 1984), Homa, Kenya (Clarke and Roberts, 1986) and Kaluwe, Zambia (Turner, 1988), in which the lath-shaped phenocrysts of calcite are polycrystalline aggregates and have been interpreted as pseudomorphs after original crystals of the alkali carbonates nyerereite and gregoryite; on these textural grounds, the rocks are suggested as being altered alkali carbonatite lavas, originally similar to the Oldoinyo Lengai natrocarbonatite lavas. However in the case of

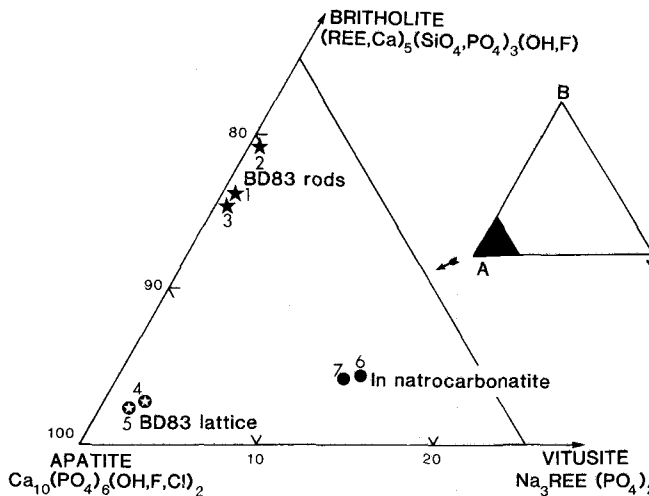


Fig. 7. Compositions of Oldoinyo Lengai apatites. Numbers annotating individual points refer to analyses in Table 4.

the Kaluwe carbonatites, some of the laths are dolomitic and could not derive from natrocarbonatite (Ngwenya and Bailey, 1990).

In a contribution to this debate, Dawson *et al.* (1987) describe the altered alkali carbonatite lava GA47 and show that it is *compositionally* intermediate between pristine alkali carbonatite and calcite carbonatite; they also speculate the more extensive alteration, with further leaching out of the remaining alkalis, might give rise to a calcite rock.

If a convincing case is to be made for a natrocarbonatite protolith for BD83, it is important to be able to recognise two sets of features in BD83, i.e. those that might be inherited from a natrocarbonatite parent and those associated with extensive alteration. Features possibly inherited from a natrocarbonatite precursor are:

1. The texture is similar to that in the natrocarbonatites.
2. The REE concentrations (Table 1) and chondrite-normalised distribution pattern of BD83 (Fig. 5) are very similar to those in the natrocarbonatite lavas.
3. BD83 contains a very distinctive 'tracer' spinel, high in Mn, Mg, and Fe³⁺ (Table 3) that also occurs in both pristine and partly-altered natrocarbonatite lavas at Oldoinyo Lengai.

New features compatible with alteration of the protolith are:

4. The bulk chemistry of BD83 represents the culmination in a 'trend' towards Ca enhancement, and Na, K, Cl and S depletion, already noted in partly altered natrocarbonatite (Table 1).

5. BD83 consists mainly of Sr-bearing calcite, that also makes its appearance in the groundmass of the partly-altered natrocarbonatite (Table 2).

6. The high $\delta^{18}\text{O}$ content of the specimen is indicative of equilibration with meteoric water. This accords with the porous texture of the rock, which itself strongly suggests some leaching process.

It is suggested that these features collectively, if not individually, and the progression of some features from those already documented from partly altered natrocarbonatite (Dawson *et al.*, 1987), provide strong circumstantial evidence for the formation for BD83 by the alteration of a natrocarbonatite precursor. There is, of course, incontrovertible evidence, in the form of relict nyerereite, for a parent natrocarbonatite for the partly altered natrocarbonatites GA47 and BD4162, which are suggested as representing an intermediate stage in the alteration process.

The minerals in the natrocarbonatites (including complex carbonates, FeS-MnS_{ss}, MnFe spinel, sodic sylvite and Na-Si apatite) are highly unusual and metastable solid solutions that result from crystallisation of a dominantly-carbonate high-temperature liquid (Dawson *et al.*, in press). Low-temperature alteration has led to breakdown of the solid solutions to give the relatively simple mineralogy of BD83, with redistribution of some elements and major loss of others.

Wider implications

1. The re-interpretation of BD83 as altered natrocarbonatite means that sövite must be

deleted from the list of rock-types known to exist at Oldoinyo Lengai. A corollary is that models proposing natrocarbonatite generation by fractionation of sövite from a parental alkali-calcite carbonate magma must be argued on theoretical or experimental grounds, in the absence of evidence of the two derivative rock-types existing at the same field-locality.

2. There has been a tendency to regard the extrusion of natrocarbonatite at Oldoinyo Lengai as a modern event. However, the presence of altered natrocarbonatite lava BD83 in the Unit 3 agglomerates, together with the clasts in the Footprint Tuff (Hay, 1989), requires modification of this view. The Unit 3 black tuffs and agglomerates are dated at 1250–2000 a on the basis of their correlation with Namorod Ash of the Olduvai Gorge succession (Hay, *op. cit.*). The inference is that natrocarbonatite eruption has taken place sporadically for at least the past 1250 years, alternating with the more dominant nephelinitic extrusions.

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