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EXTRUSIVE CARBONATITE FROM THE QUATERNARY ROCKESKYLL COMPLEX, WEST EIFEL, GERMANY

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ABSTRACT

Spheroidal carbonate lapilli are present in unconsolidated ash from the upper unit of a diatreme in the Quaternary West Eifel volcanic province of Germany. The cm-sized lapilli are carbonatite autoliths with a groundmass mineralogy dominated (>50%) by polycrystalline quenched carbonate. They are typically nucleated on fragmental material and are concentrically layered around the central nuclei. The carbonatitic groundmass includes clinopyroxene (diopside), melilite, apatite, vishnevite, magnetite, schorlomite and trace sanidine, representing the preserved composition of the erupted melt. The composition of the calcite (SrO ~2%, BaO ~0.5% and La/Yb 125–215) implies a magmatic origin, and the equilibrium assemblage of minerals indicates a high temperature of eruption. The presence of melilite suggests a genetic link with alkali-mafic, melilite-bearing nephelinitic magma erupted as lava and pyroclastic rocks near the diatreme. Sanidine and melilite are widely considered to be incompatible; however, their coexistence in the carbonatitic autoliths and the presence of Or_{70-85} feldspar in syenite xenoliths and their phonolite hosts, as well as megacrysts erupted from the diatreme, indicate that this composition has a broad petrological stability and may form a major reservoir of potassium at low aH_2O conditions in the upper mantle.

Keywords: carbonatite, extrusive, autoliths, nephelinite, melilite, sanidine, Eifel, Germany.

SOMMAIRE

Des lapilli sphéroïdaux de carbonate font partie de cendres non lithifiées de l'unité supérieure d'un diatrème formé par explosion dans la province volcanique de l'Eifel occidental, d'âge quaternaire, en Allemagne. Ces lapilli, centimétriques, sont des autolithes de carbonatite dont la pâte est surtout (>50%) faite de carbonate trempé polycristallin. Cette pâte, en couches concentriques, enrobe un noyau de matériau fragmenté. La pâte carbonatitique contient clinopyroxène (diopside), mélilite, apatite, vishnévite, magnétite, schorlomite et une trace de sanidine, et préserverait la composition du magma lors de l'éruption. La composition de la calcite (~2% de SrO, ~0.5% de BaO, La/Yb entre 125 et 215) implique une origine magmatique, et l'assemblage de minéraux en équilibre suppose une température élevée d'éruption. D'après la présence de mélilite, nous soupçonnons un lien génétique avec une suite mafique et alcaline, et en particulier avec un magma néphélinique à mélilite, mis en place sous forme de lave et de produits pyroclastiques près du diatrème. On considère généralement l'association de sanidine et de mélilite comme exemple de paire incompatible; toutefois, elles semblent coexister dans les autolithes carbonatitiques. Ce fait, et la présence de feldspath de composition Or_{70-85} dans des xénolithes syénitiques et leurs hôtes phonolitiques, de même que sous forme de mégacristaux dans les tufs de la diatrème, montrent que cette composition possède un champ étendu de stabilité pétrologique, et pourrait bien former un réservoir majeur de potassium sous conditions de faible activité de H_2O dans le manteau.

(Traduit par la Rédaction)

Mots-clés: carbonatite, extrusion, autolithes, néphélinite, mélilite, sanidine, Eifel, Allemagne.

INTRODUCTION

Studies of carbonatites and related rocks have shown that extrusive carbonatites are not as widespread as their intrusive counterparts, and yet they are probably closer to a true melt composition. Extrusive carbonatite magmatism will be potentially explosive and accompanied by rapid discharge of magma. Therefore, preserved effusive carbonatites (especially lapilli, ash eruptions and melt droplets) have probably undergone little interaction with lithologies other than their source region. The low viscosity of carbonatitic melts (Treiman & Schedl 1983) also encourage efficient separation from source rocks and rapid rate of eruption.

Carbonatite magmatism from the Rockeskyll complex (West Eifel, Germany) erupted autoliths judged to be compositionally close to the original

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melt. Their proximity to alkaline mafic rocks allows further constraints to be placed on magma genesis.

Geological Setting

The Quaternary West Eifel volcanic field covers an area of approximately 600 km^2 and was active from 0.6 to 0.01 Ma. The field comprises some 250 eruptive centers (Büchel 1993) dominated by alkali-mafic lavas and pyroclastic rocks. Within the West Eifel field, three phonolitic centers have been identified (Büchel 1993), one of which is located in the Rockeskyll complex, northeast of Gerolstein (Fig. 1). In contrast, the neighboring volcanic field of the East Eifel is dominated by more felsic rock-types, attributed by Schmincke *et al.* (1983) to a differing tectonic regime; they considered the East Eifel to be characterized by the development of a subsurface magma chamber, absent in the West Eifel.

The occurrence of phonolitic rock-types at Rockeskyll was noted by Hopmann (1914), who commented on the similarity of the center to the volcanism of the Laacher See in the East Eifel. Parallels were drawn after finding syenite, phonolite and sanidine fragments in the tuffs and fields to the east of Kyllerkopf. However, he made no mention of any genetic links with the alkali-mafic deposits of Kyllerkopf, described by Haardt in the same year (1914).

A far clearer volcanological picture is now possible at Rockeskyll owing to extensive quarrying, a common feature of the West Eifel landscape. Quarrying has exposed numerous horizons of maar deposits and revealed the limits of the crater walls. Detailed mapping, coupled with existing magnetic data (Mertes 1982), has enabled the identification of several eruptive centers (I, II and III) within the Rockeskyll complex (Fig. 2). The quarry exposures are shown in Figure 3, which highlights the two principal centers, Kyllerkopf hill (center III), dominated by alkali-mafic lavas and pyroclastic rocks, and the Auf Dickel center (II) toward the northeast. Carbonatite volcanism is restricted to Auf Dickel and forms the only known carbonatite in the West Eifel. At Auf Dickel, 10- to 15-m cuttings expose a partly eroded diatreme that cuts through the upper ash and some lower, bedded, but reworked pyroclastic material. A diatreme origin is suggested by the erupted products, fragmental carbonatite and syenite xenoliths, and by carbonatitic

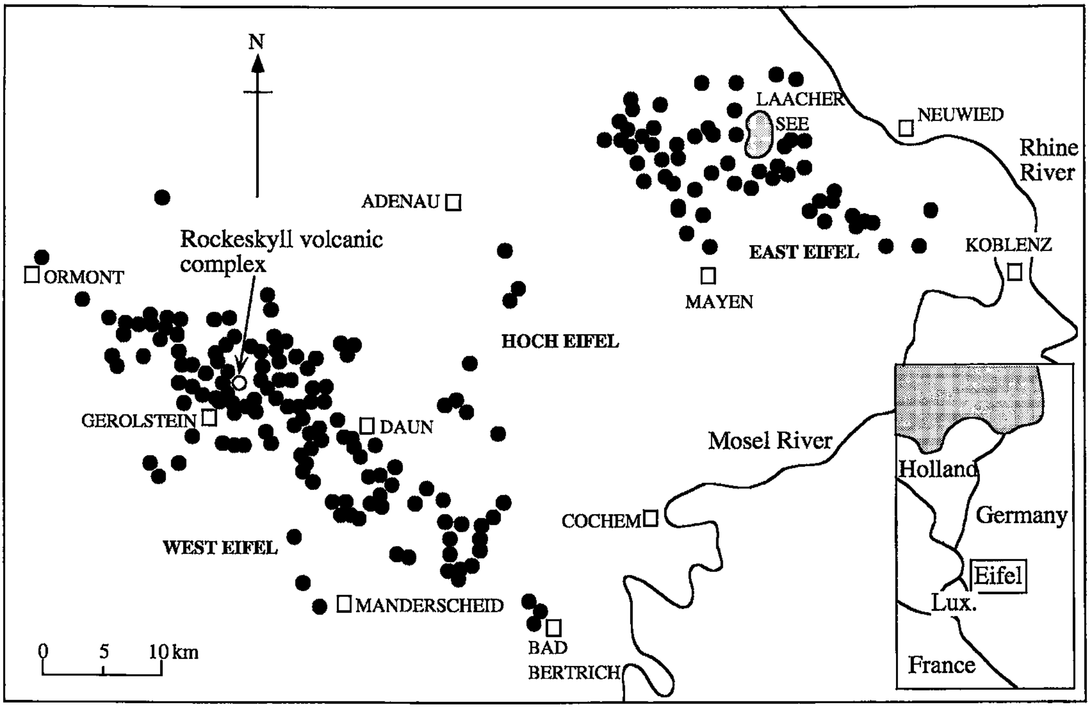

FIG. 1. Distribution of Quaternary volcanic centers from the East and West Eifel fields (adapted from Mertes & Schmincke 1983).

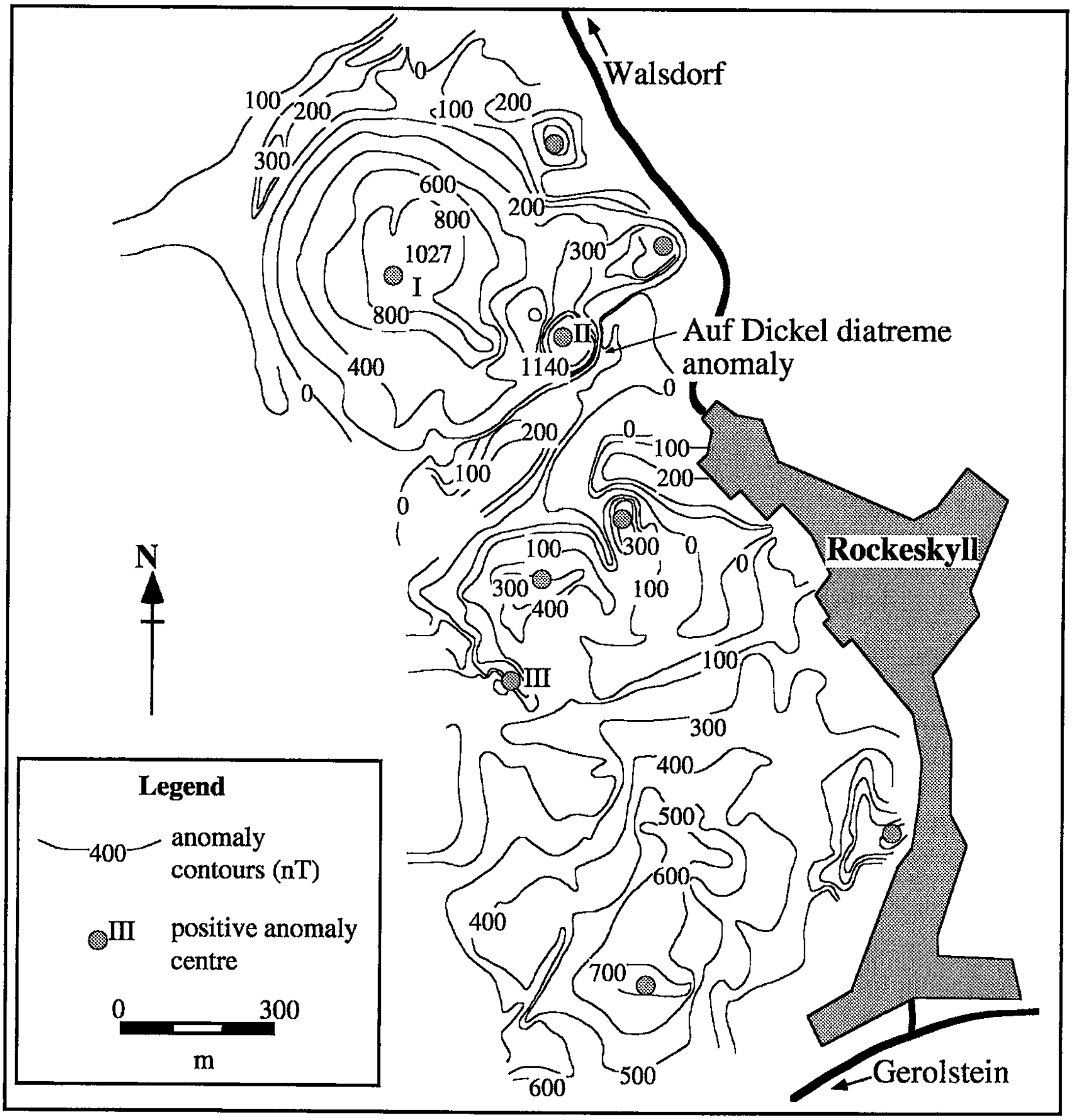

FIG. 2. Magnetic anomaly map of the volcanic complexes north and west of Rockeskyll village (adapted from Mertes 1982).

autoliths, which are common in diatreme eruptions. This interpretation is reinforced by existing magnetic data of the region (Mertes 1982), clearly showing a positive magnetic high of 1140 nT near the site of the present exposures (Fig. 2). Büchel (1978) noted that a positive magnetic anomaly exists over many maar craters and volcanic edifices, and has been attributed to a "lava plug" remaining in the fossilized conduit. The upper ash unit of the diatreme, which hosts the erupted xenoliths and autoliths, is devoid of bedding, and the presence of slump structures within the unit may indicate water-driven slumping of primary deposits back into a depression created by the diatreme. However, such features are also considered to be a primary characteristic of tuffisite pipes (*e.g.*, Schwabian field; Cloos 1941), and are a result of fluidized emplacement. The proximity of the vent site is indicated by the abundance of erupted xenoliths and pyroclastic material, which decreases sharply away from Auf Dickel.

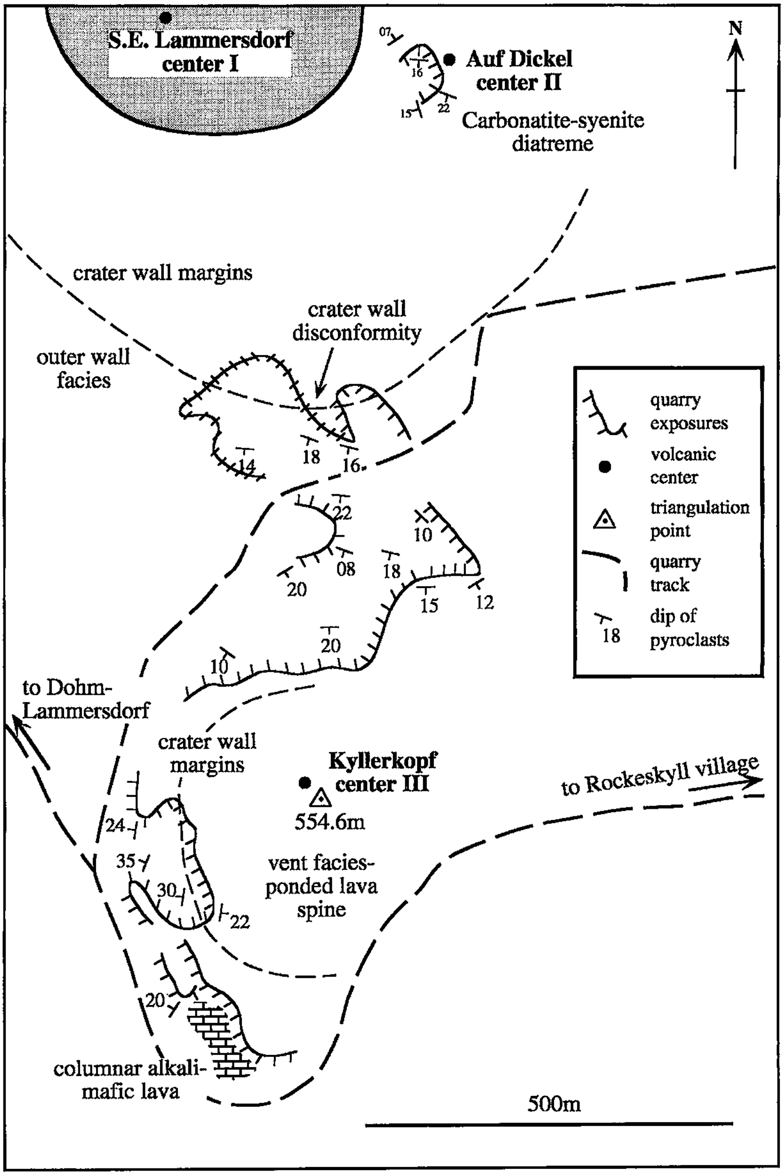

FIG. 3. Quarry exposures and volcanic complexes of the area north and west of Rockeskyll.

THE AUF DICKEL DIATREME: ERUPTED PRODUCTS

The composition of magmas erupted throughout the West Eifel is dominantly alkaline and mafic. However, the erupted products at Auf Dickel are distinctive in their felsic and carbonatitic character. The tuffisite ash that forms the upper unit of the diatreme is host to a wide range of alkaline and carbonatitic rock-types; fragmental xenoliths of syenite, mafic syenite, phonolite and biotite–calcite carbonatite are common, as are megacrysts of water-clear sanidine and diopsidic pyroxene. The extrusive carbonatite is erupted as lapilli, which are spheroidal to ellipsoidal; these are termed *autoliths* (Fig. 4) since they are interpreted to be cognate with the host, carbonate-rich ash. The autoliths are carbonatitic, with more than 50% calcium carbonate constituting the groundmass. They are erupted in large numbers, but do not form any preserved horizons of lapilli.

Pelletal lapilli, including nucleated autoliths, are common in diatreme eruptions, and are reported from the Urach and Deckentuff pipes of the Hegau, southern

Germany (Keller *et al.* 1990). Bailey (1989) also reported magmatic lapilli from the diatreme breccias of Rufunsa (Zambia), and they are widely recognized from kimberlitic diatremes (Ferguson *et al.* 1973).

ANALYTICAL PROCEDURES

Electron-microprobe analyses were performed on a JEOL JXA–8600 Superprobe with Link analytical AN10/85s analyzer and LEMAS automation at the Department of Geology, University of Bristol. Analysis was by wavelength-dispersion methods, with beam conditions 15 kV, 15 nA (5 nA for carbonate) and a diameter of 5 μm (15 μm for carbonate). Data were reduced by ZAF correction procedures.

The carbonate fraction was leached using 0.5 M acetic acid and was analyzed for the rare-earth elements (*REE*) and other trace elements (Ba, Rb, Th, Nb, Ta, Sr, Zr, Hf, Y) on separate runs, with the same solution. Analyses were performed using a VG PlasmaQuad ICP–MS instrument at the University of Bristol. The solutions for *REE* analysis were prepared with Re and Ru as internal standards. Blank solutions and international rock standards also were run as a control on instrument behavior. For trace-element analysis, we used In as an internal standard. Each solution was analyzed three times during the same run, with a sample-uptake period of 3 minutes followed by a 20-second wash period in 5% HNO_3 + orthophosphoric acid. The *REE* concentrations were normalized to the chondritic values of Nakamura (1974), and the remaining trace elements to the chondrite values of Thompson *et al.* (1984).

PETROCHEMISTRY OF THE AUTOLITHS

Over one hundred autoliths have been recovered from the Auf Dickel tuffisite ash and from the soil above the quarry face. They are concentrated at the locality marked by the positive magnetic anomaly (center II) in Figure 2 and are distributed sparsely in nearby fields. Many of the collected samples have been sliced to investigate their internal structure, to ascertain whether they are nucleated, what is the composition of the nucleus, and to check for the presence or absence of concentric zoning. Thin sections of twenty-five randomly chosen autoliths have been prepared for mineralogical and electron-microprobe analysis (EMPA); their mineral composition, nucleus composition and morphology are listed in Table 1. The autoliths fall into two textural categories, although chemically they are very similar. Distinction is made on the basis of grain size, with one group characterized by coarse crystalline calcite and melilite, whereas the other group is very fine-grained, the phases only discernible by EMPA. The coarsely crystalline autoliths are best observed under cathodoluminesence, where the ragged calcite laths are easily identified as the dominant luminescing phase (Fig. 5). The back-scattered electron image (Fig. 6) highlights the groundmass mineralogy of the finer-grained autoliths, with phenocrysts of melilite, apatite, schorlomite and calcite. Only two of the samples sectioned exhibit coarser-grained minerals, and both are cored by zoned fragments of clinopyroxene and dominated by ragged laths of calcite, characteristic of quenched carbonate (Keller 1989). Microprobe analyses of the calcite (Table 2)

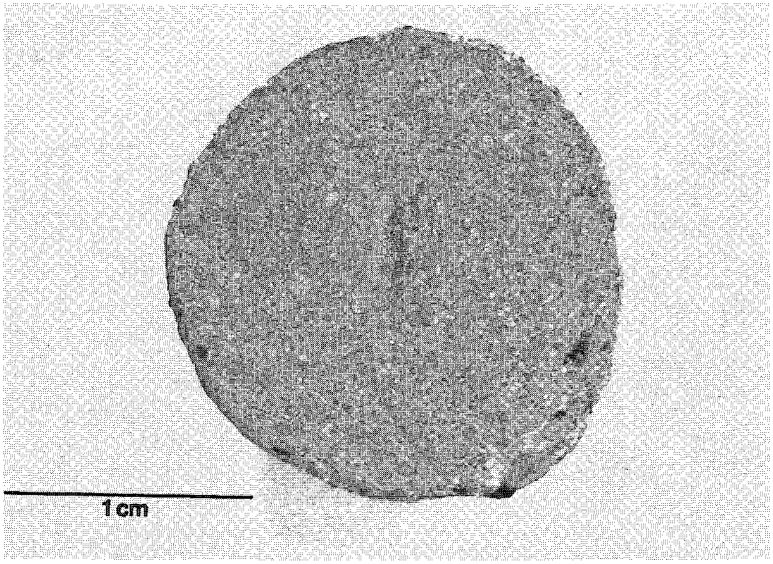

FIG. 4. Carbonatitic, nucleated autolith (SQlap1) from the Auf Dickel diatreme.

TABLE 1. SUMMARY OF AUTOLITH MINERALOGY, MORPHOLOGY AND NUCLEUS COMPOSITION

Sample	Nucleus	Composition	Groundmass Mineralogy	long axis (mm)	short axis (mm)
AD1	yes	amph	cc, vh, ap, mt, mel, cpx	26	23
AD2	yes	cpx	cc, vh, cpx, ap, mt, schl, idd, mel	26	26
AD3	no	-	cc, mel, cpx, ap, mt, schl	21	20
AD4	yes	cpx+ap	cc, cpx, mel, san, ap, mt, schl, vh	31	27
AD5	yes	amph+ap+cpx	cc, cpx, mel, san, ap, mt, schl, vh	18	18
AD6	no	-	cc, ap, cpx, vh, mt	20	20
AD7	yes	cpx	cc, mel, ap, cpx, vh, mt, schl	20	17
AD8	no	-	cc, cpx, ap, idd, vh, mt	18	17
AD9	yes	ap+cpx+vh fragment	cc, mel, vh, cpx, ap, mt	22	20
AD10	yes	mafic-rich fragment	cc, ap, cpx, mt, vh, idd	18	15
AD11	yes	cpx	cc, mel, cpx, ap, schl, mt	16	12
AD12	no	-	cc, mel, cpx, ap, idd, vh, mt, schl	17	16
AD13	yes	amph+cpx	cc, mel, ap, cpx, vh, idd, mt	16	15
AD14	yes	cpx	cc, mel, ap, vh, cpx, mt, schl, idd	16	11
AD15	yes	cpx	cc, mel, cpx, ap, vh, mt, idd	15	14
AD16	no	-	cc, mt, cpx, ap, mel, vh	17	16
AD17	yes	cpx+ap+mt	cc, ap, cpx, vh, mt, idd, mel	23	17
AD18	yes	cpx+mt	cc, cpx, ap, mel, vh, mt, idd, schl	21	19
AD19	yes	lithic fragment	cc, cpx, mel, ap, vh, mt, idd	26	22
AD20	no	-	cc, cpx, ap, mel, vh, mt	43	34
RKK77	yes	lithic fragment	cc, ap, cpx, mt, vh, idd	40	30
SQlap1	yes	cpx	cc, mel, cpx, ap, vh, schl, mt	16	15
SQlap2	yes	vh	cc, cpx, san, idd, ap, vh, mt, mel, schl	16	15
SQlap3	no	-	cc, cpx, ap, idd, mt, vh, mel	17	15

cc, calcite; vh, vishnevite; cpx, clinopyroxene; schl, schorlomite; ap, apatite; mt, magnetite; san, sanidine; mel, melilite; amph, kaersutite; idd, iddingsite.

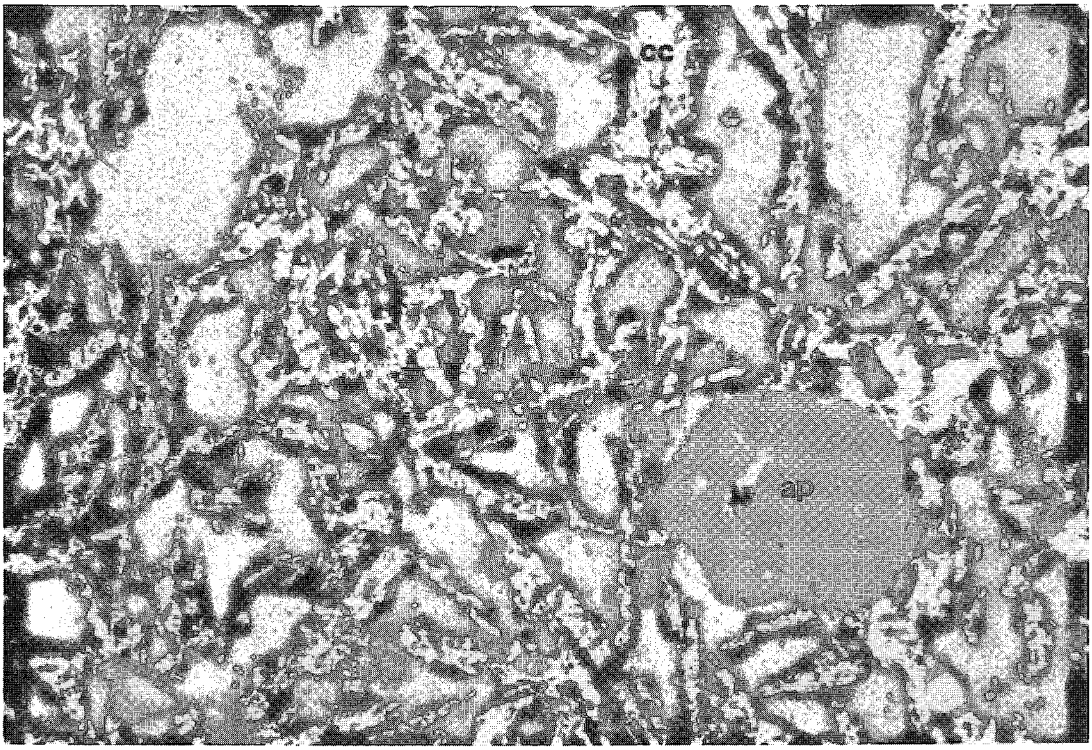

FIG. 5. Cathodoluminescence photomicrograph of autolith SQlap1; luminescing phases are calcite, cc (laths) and apatite, ap (euhedra). Field of view is 4.5 × 1.5 mm.

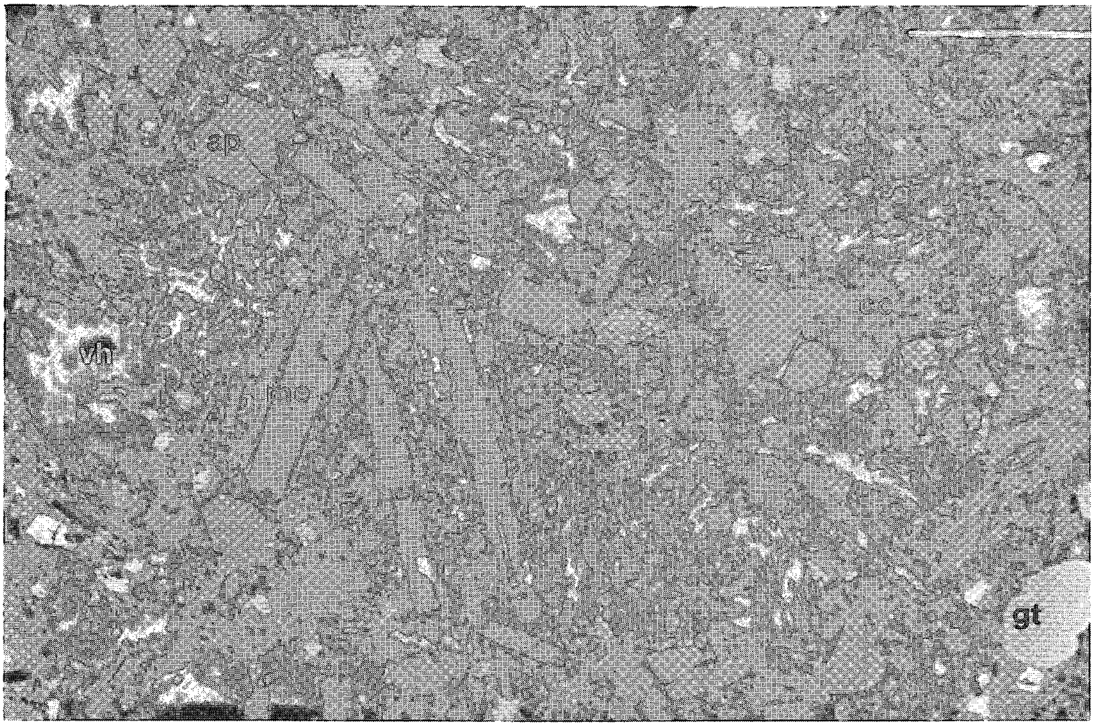

FIG. 6. Back-scattered electron image of autolith (AD5) groundmass. Melilite (me), apatite (ap), schorlomite (gt), calcite (cc) and vishnevite (vh). Scale bar: 100 μm.

reveal high levels of Sr (1.7% SrO) and Ba (0.4% BaO), indicative of primary magmatic carbonate (Ngwenya & Bailey 1990).

Modal analyses have been determined for the two coarser-grained samples, AD11 and SQlap1, excluding the xenocrystic clinopyroxene, vishnevite and the nucleus (Table 3). Mass-balance calculations using modal proportions and microprobe data have allowed the determination of their bulk chemistry; these are listed, with that of other extrusive carbonatites, in Table 4.

TABLE 2. REPRESENTATIVE RESULTS OF ELECTRON MICROPROBE ANALYSES OF MINERAL PHASES FROM A RANGE OF AUTOLITHS

	AD1 cpx	AD5 cc	AD13 ap	SQlap3 vh	SQlap1 mel	AD14 mel	AD5 schl	AD4 mt
SiO_2	46.94	0.07	2.28	36.56	47.94	43.22	28.10	2.51
TiO_2	1.79	na	na	bd	na	na	15.05	7.51
Al_2O_3	5.78	bd	bd	24.48	9.43	8.29	3.26	2.67
Cr_2O_3	0.04	na	na	na	na	na	na	na
FeO^*	10.49	0.37	0.39	1.39	4.89	5.91	18.05	75.99
MnO	0.49	0.18	bd	na	0.29	0.38	0.43	1.63
MgO	10.68	0.07	bd	0.18	4.53	5.24	1.27	1.63
CaO	23.95	57.20	55.31	8.93	29.04	31.95	32.72	na
Na_2O	0.57	0.05	0.37	10.14	3.74	4.65	0.24	na
K_2O	na	0.22	na	4.31	0.38	0.25	0.05	na
ZrO_2	na	na	na	na	na	na	0.26	bd
P_2O_5	na	0.12	37.05	na	0.21	0.20	na	na
SrO	na	1.79	0.76	0.45	na	1.05	0.29	0.49
BaO	na	0.36	bd	0.39	na	na	na	na
Nb_2O_5	na	na	na	na	na	na	0.59	na
SO_3	na	na	0.65	4.49	na	na	na	na
F	na	bd	1.69	bd	na	na	na	na
Total	100.69	60.02	99.18	91.15	100.45	101.21	100.30	95.27

FeO^*: total iron reported as FeO. Symbols: na: not analyzed, bd: below detection, cpx: clinopyroxene, cc: calcite, ap: apatite, vh: vishnevite, mel: melilite, schl: schorlomite, mt: magnetite. Compositions reported in wt.% oxides.

The finer-grained samples are characterized by mm-sized phenocrysts and xenocrysts of vishnevite, clinopyroxene, melilite and apatite in a groundmass of the same composition. They occur as subhedral and euhedral crystals and commonly form cores to smaller lapilli included within the autolith groundmass. The

TABLE 3. MODAL ANALYSES OF COARSELY CRYSTALLINE CARBONATITIC AUTOLITHS

phase	SQlap1	AD11
calcite	56.8 %	53.1 %
melilite	7.2	5.7
groundmass cpx	10.1	4.0
apatite	5.2	5.7
vishnevite	12.3	25.7
schorlomite	1.9	2.7
magnetite	1.7	3.0
groundmass	5.0	0.4
number of counts	714	636

TABLE 4. COMPOSITIONS OF EXTRUSIVE CARBONATITES (ALL EXCEPT ROCKESKYLL DATA TAKEN FROM BAILEY 1993)

	Oldoinyo Lengai Tanzania	Kerimasi Tanzania	Fort Portal Uganda	Rockes-kyll (AD11)	Rockes-kyll (SQlap1)	Kaiser-stuhl Germany	Uyannah (U.A.E.)	Polino Italy
SiO_2	nd	0.39	13	13.3	15.8	0.45	7.45	16.2
TiO_2	0.11	tr.	1.74	1.16	0.75	0.03	1.01	0.52
Al_2O_3	0.09	0.07	3.03	7.38	5.45	0.15	1.75	3.91
Fe_2O_3	0.28¶	0.34¶	7.93	nd	nd	0.98¶	8.3	3.69
FeO	nd	nd	4.44	6.11*	5.49*	nd	3.12	1.31
MnO	0.04	0.22	0.4	0.2	0.07	0.41	0.46	0.07
MgO	0.53	0.21	8.55	0.9	1.91	0.36	3.27	7.31
CaO	13.9	54	36	39.1	38.9	52.6	40.5	38.7
Na_2O	32.2	0.1	0.73	2.8	1.92	0.04	0.23	0.05
K_2O	8.27	0.05	0.2	1.3	0.22	0.5	0.14	0.5
P_2O_5	0.9	1.82	3.32	2.55	2.34	1.56	7	0.6
H_2O	tr.	nd	3.45	0.7	0.2	1.16	1.2	3.12
CO_2	34.7	41.8	14.8	21.3	22.2	39.8	24.6	24.1
F	2.93	nd	0.08	0.2	0.13	0.54	nd	nd
Cl	4.21	nd	nd	nd	nd	nd	nd	nd
SO_3	2.18	nd	nd	1.6	0.9	nd	nd	nd
SrO	1.53	0.4	0.63	1.14	1.25	0.67	nd	nd
BaO	1.04	0.2	0.15	0.4	0.46	0.15	nd	nd
Total	102.91	99.6	98.45	100.14§	98.01§	99.4	100.23	100.08

Compositions reported in wt.% oxides. Symbols: nd: no data, tr: trace, Fe_2O_3¶: total iron reported as Fe_2O_3, FeO*: total iron reported as FeO, §: mass–balance calculation from modal analyses and electron–microprobe data.

TABLE 5. CHEMICAL COMPOSITION OF SANIDINE FROM AUF DICKEL ROCKS

	megacryst (DKB 87)	syenite (RKK25/1)	phonolite (KQS6)	autolith (AD5)
SiO_2	65.03	65.05	64.29	66.43
Al_2O_3	18.28	19.26	19.01	16.06
MgO	bd	bd	bd	0.41
FeO*	0.20	0.20	0.15	2.25
CaO	0.05	0.03	0.07	0.22
Na_2O	3.17	2.63	2.63	0.49
K_2O	13.36	12.49	12.60	13.93
BaO	1.16	0.77	1.02	0.18
Total	101.65	100.92	100.86	100.07
An	0.23	0.15	0.35	0.62
Ab	25.94	23.86	23.55	14.02
Or	71.21	73.79	73.67	78.03
Ce	1.92	1.41	1.85	7.64*

Compositions reported in wt.% oxides. Symbols: bd: below detection, FeO*: total iron reported as FeO, An: anorthite ($CaAl_2Si_2O_8$), Ab: albite ($NaAlSi_3O_8$), Or: orthoclase ($KAlSi_3O_8$), Ce: celsian ($BaAl_2Si_2O_8$). *$KFeSi_3O_8$ end–member.

larger grains of clinopyroxene (>1 mm diameter) are pale brown to green and commonly are zoned, whereas the smaller (<1 mm diameter) fragments of clinopyroxene are typically green-cored. The fine-grained groundmass has been analyzed by EMPA and has revealed a mineral assemblage consistent with the coarser samples (Table 2): calcite (AD5), clinopyroxene (AD1), melilite (SQlap1, AD14), apatite (AD13), vishnevite (SQlap3), magnetite (AD4) and euhedra of the titanium-rich garnet schorlomite (AD5). These phases constitute an equilibrium assemblage and are considered to represent the composition of an erupted melt.

The two textural types also coexist within the same sample. Finer-grained autoliths commonly have an outer concentric rim of coarser crystalline carbonatite, similar to the textures observed in samples AD11 and SQlap1. These textures may indicate autolith nucleation and accretion occurring at more than one level in the diatreme. If autolith growth takes place within the diatreme neck itself, it is possible that the finer-grained autoliths nucleate at higher levels in the diatreme column and are quenched prior to recirculation within a fluidization cell. However, there appears to be no systematic mineralogical variation in the carbonatite between coarser and finer lithologies, and analyses of groundmass pyroxene from the core to rim have not revealed any marked chemical changes.

MELILITE AND SANIDINE: AN INCOMPATIBLE ASSEMBLAGE?

The absence of plagioclase with melilite in magmatic rocks has been noted by Yoder (1973), although their coexistence has been reported from hybrid rocks and in metamorphic rocks. Yoder (1973) and Soulard (1992) have demonstrated experimentally that in olivine-free melts, melilite and plagioclase can exist in equilibrium. The apparent incompatibility of alkali feldspar and melilite also has been illustrated (Yoder 1985), although an example has been reported in a melilite nephelinite in Djebel Targou, Morocco (Velde & Rachdi 1988). Another possible example has been noted by Stoppa & Cundari (1995).

Microlaths (<100 μm) of sanidine coexisting with melilite have been noted in two of the finer-grained carbonatitic autoliths (AD4, AD5). The sanidine is chemically similar to the water-clear sanidine erupted as megacrysts and present within the syenite xenoliths (Table 5), with the exception of the FeO content, which is significantly higher in the sanidine of the autolith. Bailey & Schairer (1966) attributed the high-Fe nature of the alkali feldspars to their higher-temperature genesis, where the structure is expanded, and Fe can be accommodated. This observation is congruent with the likely high-temperature source regions of the carbonatitic autoliths and the lower-temperature source of the syenite xenoliths, erupted from the Auf Dickel diatreme. Velde & Rachdi (1988) attributed the coexistence of sanidine and melilite to the anomalously high Sr in the nephelinitic melt. This proposal was based on the high Sr content of the melilite (12% SrO), which was judged to be the only phase able to crystallize from a Sr-rich, silica-undersaturated melt, since the coexisting nosean can only accommodate up to 2% SrO; the P_2O_5 content of the melt was too low to allow sufficient apatite to crystallize and accommodate the excess Sr. However, this explanation for the occurrence of K-feldspar and melilite by Velde & Rachdi (1988) is now regarded as not entirely satisfactory (D. Velde, pers. comm., 1993).

The petrogenetic scenario at Rockeskyll has few parallels with the nephelinite of Morocco. Although the Sr content of the carbonatite is high, it partitions strongly into the calcite and the apatite, whereas the melilite rarely contains more than 1% SrO (Table 2). The occurrence of sanidine in the autoliths of Auf Dickel as <100 μm laths has only been identified following detailed EMPA. Conditions favorable to the crystallization of sanidine are high activities of K, Si and low activity of H_2O, whereas conditions favorable to melilite include high Na in the melt and an alkalinity ratio [(Na+K)/Al] greater than 0.8. Early crystallization of melilite, accompanied by calcite, will have driven the melt toward a Si- and K-rich composition; providing the aH_2O is low, following the crystallization of vishnevite, then conditions may favor the formation of sanidine.

Sanidine is present in many of the alkaline rocks at Rockeskyll and Auf Dickel. Its occurrence in syenite, phonolite, carbonatite and as water-clear megacrysts indicates that the composition Or_{70-85} has a broad stability. Potassic feldspar of Or_{70-85} composition has been reported from other alkaline-carbonatite provinces: Rufunsa, Zambia (Liyungu 1992), Laacher See, East Eifel (Taylor *et al.* 1967), Polino, Italy (Stoppa & Lupini 1993) and northeastern Scotland (Aspen *et al.* 1990). Sanidine (Or_{83-99}) from a coesite–grospydite xenolith (Sharp *et al.* 1992) and from diamond (Novgorodov *et al.* 1990) testifies to its stability at higher pressures and confirms it may form a major potassic phase at conditions where hydrous phases are unstable (Bailey 1987).

CARBONATITE CHEMISTRY AND THE CALCIFICATION HYPOTHESIS

Three autolith samples were selected for trace-element analysis, to determine the abundances of large-ion lithophile elements (*LILE*) and high-field-strength elements (*HFSE*) in the carbonate fraction. The samples AD1, AD2 and AD4 are ellipsoidal and 2.5 to 3 cm in diameter. Only AD4 is nucleated on a core, hence the powdered samples are dominated by groundmass mineralogy and as such are closer in composition to an erupted melt. To eliminate the xenocrystic material from analysis and to isolate the carbonate fraction, the samples were acid-leached in 0.5 M acetic acid for 90 minutes at 200°C. The leachates revealed carbonate levels of 58%, 65% and 68% in samples AD4, AD1 and AD2, respectively, similar to the calcite modes of the crystalline autoliths (AD11, SQlap1; Table 2).

The results (Fig. 7) for the three samples are plotted with the average carbonatite of Nelson *et al.* (1988). The high levels of the *LILE* are characteristic of calciocarbonatites, whereas the low levels of the *HFSE* are the result of the resistance to leaching of the schorlomite garnet and magnetite, as these are the major depository minerals for the heavy rare-earth elements (*HREE*), Zr, Ti, Nb, Ta and Hf. The *HFSE* levels in the average carbonatite of Nelson *et al.* (1988) are indicative of the presence of pyrochlore, garnet and magnetite in the carbonatite.

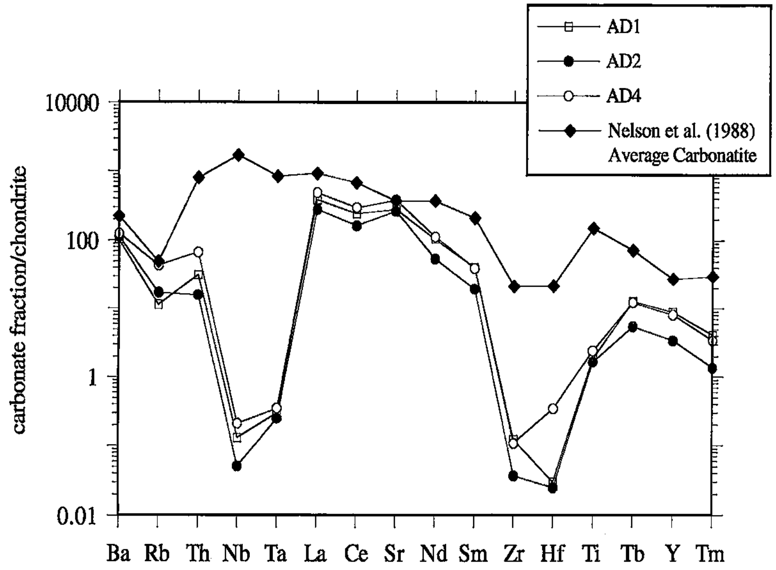

FIG. 7. Variation diagram for the acid-soluble fraction of Auf Dickel autoliths compared to the average carbonatite of Nelson *et al.* (1988).

The *LILE*-enriched signature and the Sr, Ba levels in the calcite unequivocally classify the carbonate as magmatic, making it distinct from altered alkali carbonatites (Hay & O'Neil 1983). The carbonatite volcano of Oldoinyo Lengai in northern Tanzania erupts alkali carbonatite lavas (Dawson 1962). The alkali-carbonate minerals nyerereite and gregoryite are water-soluble and hygroscopic, and therefore highly susceptible to removal under surface conditions, where they are often assumed to be replaced by calcite. This has prompted suggestions that many calciocarbonatites are replacements of a primary alkali carbonatite. The calcite laths within the Rockeskyll autoliths are polycrystalline, with ragged, feathery margins, a texture that might be compared with pseudomorphs of alkali carbonate (Hay & O'Neil 1983). The replacement hypothesis is dependent upon percolating solutions of meteoric water crystallizing calcite at low temperature, which would involve the rejection of Sr (Shearman & Shirmohammadi 1969), Ba and other incompatible elements. However, the high levels of these elements in the Rockeskyll carbonates seem to rule out a low-temperature calcification of alkali carbonatite. Also, the pristine nature of the melilite indicates minimal alteration of the Auf Dickel autoliths, whereas the abundance of apatite (Table 3) indicates a far higher solubility of F than is possible in alkali carbonate melts (Gittins & Jago 1991). In summary, the polycrystalline nature of the calcite may be a primary quench-related feature or a result of inversion from a high-temperature to a low-temperature form.

ORIGINS OF CARBONATITE AND THE ALKALI-MAFIC CONNECTION

Bailey (1993) listed known occurrences of extrusive carbonatites (Table 4) and reported their field associations with silicate rock-types. Although all carbonatites are not associated with silicate rock-types, the occurrence of carbonatite in association with nephelinite, melilitite and phonolite is widespread (Le Bas 1977), and the role of CO_2 in the genesis of all such magma-types is paramount (Bailey 1974).

The scenario at Rockeskyll is the familiar association of carbonatitic, nephelinitic and phonolitic magma-types. Spatial links between these lithotypes are clear, with carbonate and felsic magmatism restricted to the diatreme, and alkali-mafic lavas and pyroclastic units to the neighboring eruptive center of Kyllerkopf hill. However, the mineral assemblages imply genetic links among carbonatite, the alkali-mafic rocks and the felsic rocks.

The presence of melilite in the carbonatitic autoliths and the capping lavas of Kyllerkopf hill indicates possible links between source regions. Experimental work by Lloyd (1985) on olivine melilitite indicated that Ca (and, by inference, other cations) as well as Na and K promote the crystallization of melilite. Yoder (1973) also remarked upon the importance of Ca, and specifically carbonate, in the crystallization of melilite, and commented on its association with limestone, marble and carbonatite. The case for a genetic link between melilite- and carbonate-bearing magmas is strong and has been proposed for the eruptive suites at Kerimasi, Tanzania (Mariano & Roeder 1983) and the Kaiserstuhl in Germany (Keller 1984). The Kaiserstuhl alkaline complex consists of olivine nephelinite, melilitite, tephrite, phonolite and carbonatite, and as such presents parallels to the Quaternary volcanic rocks of Rockeskyll. Keller (1984) proposed a close genetic link between carbonatite and calcite – melilite – haüyne nephelinite ("bergalite") at Kaiserstuhl. This observation was supported by Schleicher *et al.* (1990), who showed the Sr-isotope systematics of the melilite-bearing melts and the carbonatites to be consistent with a genetic link, with "bergalite" forming the intermediate composition. Isotopic evidence from the Rockeskyll complex also is compatible with a genetic link between the carbonatitic rocks of Auf Dickel and the melilite nephelinite of Kyllerkopf hill. Carbonatitic autoliths have a $^{87}Sr/^{86}Sr$ value of 0.70421 ± 0.00014, and the capping melilite nephelinite lava from Kyllerkopf hill has a $^{87}Sr/^{86}Sr$ value of 0.70451 ± 0.00012 (Riley 1994).

Gittins (1989) commented on the problems associated with the origin of carbonatitic magmas and rejected ideas involving crystal fractionation from a carbonated alkali-mafic magma on the grounds that CO_2 activity is too low to allow abundant carbonate to crystallize. He highlighted the problems of trace-element budgeting between carbonatitic and nephelinitic magmas. The evidence supporting primary carbonate melts is now growing in support (*e.g.*, Bailey 1989). Dalton & Wood (1993) have demonstrated experimentally that calcium carbonate melts can be produced by reacting near-solidus carbonate melts from mantle peridotite with depleted mantle wallrock. Primary melts from mantle lherzolite (>25 kbar) have Ca/(Ca + Mg) values of 0.72–0.74. Reaction of these melts with depleted mantle assemblages (lherzolite, harzburgite) at lower pressure drives the melt composition to a Ca/(Ca + Mg + Fe + Na) value of up to 0.95, providing the wallrock (lherzolite, harzburgite) is converted to wehrlite (olivine + clinopyroxene). These results confirm that Ca–Mg carbonate melts may erupt directly from the mantle and that calcium carbonate melts are the product of reaction with mantle peridotite.

Wehrlite compositions are enriched in the *LILE* relative to depleted mantle assemblages. Therefore, they provide a possible parent for mantle-derived nephelinitic and melilite-bearing melts without the problem of requiring an ultra-low degree of partial melting of a lherzolitic composition in order to concentrate the required incompatible elements. The problem with low-degree partial melting is apparent when the volume of alkali-mafic magma erupted in the West Eifel is considered. Within a time span of only 0.5 Ma, 1.7 km^3 (Mertes & Schmincke 1983) of dominantly nephelinitic, leucititic and melilite-bearing magmas were erupted; therefore, melt production would have to be far higher than the minute fractions of melt proposed to concentrate the *LILE* from a depleted mantle source. This petrogenetic problem was approached by Frey *et al.* (1978), who used a pyrolite starting composition with the *LILE* at 6–9 times chondritic values and inferred fractions of 4–7% partial melt to generate olivine melilitite and olivine nephelinite. Wehrlite and trace-element-enriched lherzolite from the West Eifel are characterized by *LILE* contents at 10–30 times chondritic values (Fenwick 1991). Hence even a larger degree of partial melting can be envisaged than that proposed by Frey *et al.* (1978), thus providing a suitable model for alkali-mafic magma production in the West Eifel.

Recent attempts to explain events of mantle enrichment have implicated carbonate melts to produce the observed mineralogical and geochemical changes. Green & Wallace (1988), Thibault *et al.* (1992), Fenwick (1991), Yaxley *et al.* (1991) and Ionov *et al.* (1993) all looked to mantle-derived carbonate melt and alkaline silicate melt as a viable mechanism for producing enrichment in the *LILE* and converting depleted mantle assemblages to wehrlite and ultimately olivine clinopyroxenite. The appearance of *REE*-rich phases (monazite, apatite) and, in some cases, remnant pockets of carbonate (Ionov *et al.* 1993) in mantle xenoliths all point to interaction of depleted mantle with a melt with a signature that is carbonatitic. The implications are that interaction with carbonate melt and also an alkali-rich component acts as a precursor to the genesis of alkali-mafic magma, a link that is upheld by field observations in the West Eifel. The dominantly alkali-mafic eruptive rocks are accompanied by suites of lherzolite, harzburgite, wehrlite and olivine clinopyroxenite xenoliths with trace-element signatures indicative of interaction with carbonate melt (Fenwick 1991, Thibault *et al.* 1992).

CONCLUSIONS

1. Extrusive carbonatites, erupted as autoliths from an explosive diatreme pipe, represent the only known carbonatite of the West Eifel. The autoliths have typically nucleated on crystal or lithic fragments and are characterized by groundmass mineralogy of calcite, melilite, diopside, vishnevite, apatite, schorlomite, magnetite and trace sanidine. The groundmass constitutes an equilibrium assemblage and is considered to represent the composition of the erupted melt.
2. The calcification hypothesis is not deemed valid for the autolith carbonates. The carbonate chemistry retains its magmatic signature, with La/Yb ratios of 125–215 and Sr and Ba contents in the calcite of 1.7% SrO and 0.4% BaO, respectively. The pristine nature of the melilite seems to rule out any interaction between the autoliths and meteoric water.
3. Genetic links between the carbonate magma and melilite nephelinite of a neighboring center are inferred from Sr-isotope chemistry and the melilite connection. Partial melting of peridotite and wallrock reaction are favored to explain the origin of carbonatitic magma and provide the source rocks for the associated alkali-mafic magmas.
4. The petrologically incompatible assemblage of melilite and sanidine is reported from the groundmass of the carbonatite autoliths. The sanidine composition is close to that of the feldspar erupted as megacrysts and within the syenites and phonolites from the diatreme pipe (Or_{70-85}). Sanidine from other carbonatite – alkaline provinces (Rufunsa, Zambia; Laacher See, Germany; northeastern Scotland) and diamond-bearing eruptive rocks testify to its broad petrological stability, it may form a major reservoir of potassium in the upper mantle.

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