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Mineralogy and petrology of some Tertiary leucite–rhönite basanites from central France

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SUMMARY. The composition of the various phases present in the rhönite-bearing leucite basanites of the southern part of the Sillon Houiller district have been determined with the electron microprobe. Clinopyroxenes show strong progressive enrichment in Al_2O_3 and TiO_2, maximum values being 13 % and 6 % respectively. These extreme compositions are comparable to others found in feldspathoidal lavas from other provinces, and can be explained by the low silica content of the liquids they crystallized from, and high cooling-rates. Rhönite composition is similar to those previously determined in various terrestrial occurrences. The chemical compositions of the lavas differ from those of basanites, and are intermediate as far as Ca, Al, and Si contents between basanites and melilite-bearing basic lavas. The presence of rhönite can be explained by bulk composition, but is not a consequence of a particularly high Fe and/or Ti content. Xenoliths are absent from these lavas, so that there is no petrographic indication of possible contamination. It is tentatively concluded that the high K/Na ratio is primary.

RECENT volcanism in France is mostly located in the Massif Central. Its extension is limited to the east by the Rhône valley, and to the west by the Sillon Houiller fault of Hercynian age (Grolier and Letourneur, 1968). Some of the volcanic provinces (Brousse, 1961; 1971) are essentially basaltic (Aubrac, Devès, Cézallier, Sioule, Sillon Houiller) whereas in other districts basalts are associated with felsic rocks (Velay, Chaîne des Puys, Mont Dore, Cantal, Coirons). Most of the lavas traditionally called basalts are, in fact, basanites and contain variable proportions of modal feldspathoids such as nepheline, leucite, and/or an intermediate member of the sodalite group of minerals (Tournon and Velde, 1971; Velde, 1973); analcime may at times be present. The Sillon Houiller district as defined by Brousse (1961) includes a number of outcrops of probable Tertiary age on either side of the fracture zone. Leucite is present, and abundant, in most of the lavas, and a detailed study (Magonthier, 1974) has shown that the area includes two types of leucite-bearing basanites:

To the north (Sillon Houiller north and Sioule district), where leucite is generally found as veins and vug fillings and around ultrabasic xenoliths, as originally described by MacKenzie and Rahman (1968).

To the south of the town of Bort les Orgues seven outcrops of strongly undersaturated lavas occur, probably being small extrusions. Beside leucite they contain notable amounts of rhönite. The description of these lavas is the object of the present paper.

Fig. 1 shows the position of these seven outcrops, and the localization of the two sub-provinces mentioned above with respect to the fracture zone.

Rock descriptions. The leucite basanites are for the most part holocrystalline, with, in rare instances, minor amounts of glass. Olivine and sahlite occur as phenocrysts, the latter being a strong brown and conspicuously zoned. The groundmass is composed of sahlite, rhönite, leucite, and opaques. Accessory phases always include plagioclase, and at times nepheline, apatite, phlogopite, and glass. Calcite and montmorillonite sometimes fill veins and small vugs.

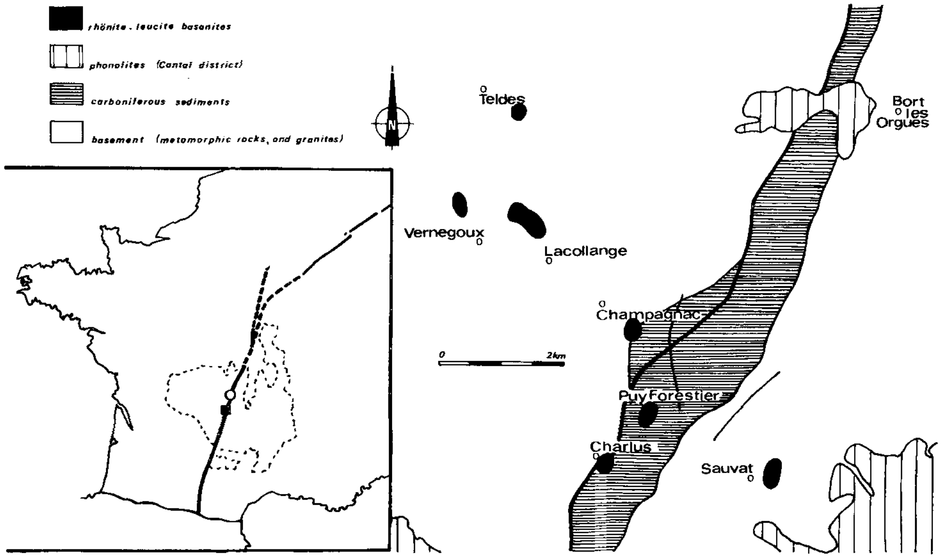


FIG. 1. Position of the Sillon Houiller district with respect to the Sillon Houiller fault zone. Northern part, open circle; southern part, solid square. Location of the seven outcrops studied on a schematic map of the area south of Bort-les-Orgues.

A representative modal analysis from Puy Forestier has 12·13 % olivine phenocrysts, 3·83 % clinopyroxene phenocrysts, and a groundmass with 40·17 % clinopyroxene, 14·83 % rhönite, 11·73 % leucite, 12·35 % groundmass, 2·55 % opaques, 2·04 % olivine, and 0·34 % plagioclase. This shows that the volume of the groundmass is important relative to the phenocrysts. The clinopyroxene phenocrysts are titaniferous sahlites up to 4 mm long either as isolated crystals or as star-shaped aggregates. All contain opaque inclusions, more rarely olivine and, exceptionally, altered amphibole. They are strongly zoned, sector zoning being frequent in the aggregate crystals, and often twinned. Olivine (1·5 to 20 μm) is never as abundant as clinopyroxene. The largest crystals are frequently rounded or even corroded; they are usually little altered, but sometimes partly replaced by yellow green phyllites. Former amphiboles can be recognized, though they are completely transformed and replaced by an association of rhönite+opaques+clinopyroxene+plagioclase.

Leucite appears either as euhedral crystals (Vernegoux, Lacollange, Sauvat, Charlus) or as irregular patches (Teldes, Puy Forestier). When euhedral, the crystals reach a maximum size of 200 μm and inclusions (generally apatite and clinopyroxene) are usually grouped in the centre of the crystals. In the other type (Puy Forestier) leucite forms 4 mm diameter poikilitic patches where it is the only salic phase. The disposition is quite similar to that illustrated in basanites from various other provinces of the Massif Central (Tournon and Velde, 1971). Rhönite appears as euhedral microphenocrysts (average 100 μm; up to 200 μm in Teldes), which are difficult to distinguish from titanomagnetite in thin section. Rhönite also appears as smaller anhedral crystals with strong polychroism (purple brown to deep green). In Puy Forestier, rhönite forms palm-shaped associations of branching curved crystals, 60 μm long, a usual quenched crystal morphology.

Other phases in the groundmass are, in decreasing order of abundance, leucite, plagioclase, titanomagnetite, rare apatite, and Ti-phlogopite. Titanomagnetite forms 50 μm crystals; plagioclases, usually euhedral, are found as 100 μm long laths, but at times they also form irregular patches. Calcite, also found in patches, can at times contain abundant hematite inclusions.

Mineral descriptions

Five samples (Teldes, Puy Forestier, Champagnac, Lacollange, Sauvat) have been studied using a CAMECA electron microprobe. Standards were natural minerals of known compositions. Results have been corrected using a FORTRAN program written by Rucklidge and Gasparrini (1969).

TABLE I. *Leucite and rhönite compositions in leucite–rhönite lavas*

	Leucite					Rhönite				
	1	2	3	4	5	6		7	8	9
SiO_2	54.54	55.23	54.44	54.75	54.23	23.50	(23.98-22.95)	24.49	24.18	24.82
TiO_2	0.24	0.28	0.19	-	-	9.46	(9.84- 8.86)	8.88	8.96	8.71
Al_2O_3	23.10	23.67	23.03	23.27	23.43	17.82	(18.73-16.98)	18.40	18.36	18.77
Fe_2O_3*	1.00	-	-	-	-	-		-	-	-
FeO†	-	-	-	-	-	22.50	(24.46-22.43)	22.56	23.10	22.32
MgO	-	-	-	-	-	12.01	(12.59-11.55)	12.50	12.18	12.29
CaO	0.40	0.48	0.35	0.35	0.51	12.42	(12.62-11.95)	12.59	12.67	12.62
Na_2O	0.52	0.65	0.52	0.56	0.36	1.02	(1.17- 0.90)	0.89	0.93	1.18
K_2O	20.48	20.26	19.82	20.08	20.22	-		0.13	0.17	-
Total	100.28	100.57	98.35	99.01	98.75	98.73		100.44	100.55	100.71

	Atoms per 6 oxygen				
	1	2	3	4	5
Si	1.979	1.987	1.999	2.000	1.988
Ti	0.006	0.007	0.011	-	-
Al	0.988	1.003	0.996	1.002	1.012
Fe^{3+}	0.027	-	-	-	-
Ca	0.015	0.018	0.014	0.013	0.020
Na	0.038	0.055	0.037	0.040	0.026
K	0.949	0.930	0.929	0.936	0.945

* Total iron as Fe_2O_3.
† Total iron as FeO.

1: Puy Forestier, N = 18.
2: Teldes, N = 11.
3: Lacollange, N = 16.
4: Champagnac, N = 6.
5: Sauvat, N = 7.
6: Puy Forestier, N = 13.
7: Lacollange, N = 10.
8: Lacollange (rhönite in altered amphibole crystals.
9: Champagnac, N = 12.

All analyses are averages of N probe analyses, except for Na_2O and K_2O in nos. 1 to 5, which are maximum values.
For anal. 6 the range of observed values is given.

Minor *plagioclase* is ubiquitous in the leucite–rhönite lavas. The euhedral crystals have a bytownite core with a sharp boundary against a thin anorthite zone, which is surrounded by andesine. If the abrupt change is due to a rapid pressure decrease this would imply that the plagioclase cores were formed before the eruption of the lava. The anhedral plagioclases do not seem to have a homogeneous composition or a regular zoning pattern.

Leucite is close to the ideal with a very low sodium content (Table I). There is no compositional difference between the euhedral and anhedral crystals.

Olivine forms phenocrysts and is in the groundmass, where it may be completely replaced by iddingsite (Lacollange). The cores are Fo_{85}, but can be as iron-rich as

Fo_{82} (Lacollange). The rims are more variable, from Fo_{77} (Champagnac) to Fo_{72} (Teldes, Lacollange, Puy Forestier). The composition of the most iron-rich crystals in the groundmass varies from Fo_{79} (Champagnac) to Fo_{71} (Puy Forestier). There is no evidence to indicate the presence of any olivine xenocrysts.

Rhönite has a constant composition in the rocks studied, within each rock sample as well as between samples, as indicated by the range of values observed in one of the analysed specimens (Table I). Compositions are close to the previously published analyses of rhönite (Cameron *et al.*, 1970; Grunhagen and Seck, 1972; Kyle and Price, 1975) but not to that found in the Allende meteorite (Fuchs, 1971). This agrees with the view of Cameron *et al.* (1970) that there is a limited range of possible solid solution for rhönites formed at magmatic temperatures near the earth's surface.

The only opaque phase found with rhönite is *titanomagnetite*. Its composition seems to be quite variable from 62 to 70 % total iron (as FeO), and TiO_2 between 14 and 30 %. Ilmenite, present in the leucite-bearing lavas of the northern Sillon Houiller district (Magonthier, in press) has not been found in the rhönite-bearing lavas.

Clinopyroxenes are quite variable (Table II); there is a peculiar trend of evolution of clinopyroxenes in these lavas that is typical of feldspathoidal basic lavas in general, though not of alkali basalts. Three of the five rocks studied show abundant idiomorphic phenocrysts from 1 to 4 mm. The other two have 0·4 to 1·5 mm phenocrysts with cores richer in iron than the cores of the larger phenocrysts. To show the fullest range of variation, plots have been made of a sample containing large phenocrysts from Lacollange.

TABLE II. *Representative clinopyroxene analyses*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SiO_2	49.27	46.44	42.99	39.73	48.50	44.53	42.05	38.06	48.12	46.05	42.92	39.50	47.67	44.83	41.92	40.30	46.44	43.97	41.35	39.20
Al_2O_3	5.99	8.25	10.45	13.39	6.60	8.56	10.72	13.57	5.41	7.03	10.74	13.21	6.47	7.25	10.61	12.22	6.04	8.74	11.11	12.25
FeO*	4.35	6.93	7.30	8.47	5.24	6.96	7.51	9.57	6.43	7.29	7.46	8.93	4.84	7.11	7.33	8.60	6.63	7.91	8.40	8.80
MnO	0.12	0.13	0.15	0.12	0.09	0.09	0.10	0.10	0.13	0.16	0.19	0.15	0.11	0.14	0.15	0.14	-	-	-	-
MgO	15.44	13.50	11.50	10.37	15.43	12.76	11.60	9.85	14.37	13.13	11.40	10.05	14.87	12.97	11.30	10.87	13.95	12.31	11.26	10.88
CaO	22.86	22.73	23.43	23.50	21.98	23.52	23.16	22.96	23.30	23.42	23.10	22.90	22.97	23.37	23.13	22.69	23.44	23.34	23.18	23.06
Na_2O	0.45	0.35	0.41	0.44	0.59	0.45	0.54	0.46	0.33	0.41	0.51	0.44	0.44	0.38	0.43	0.61	0.25	0.45	0.40	0.31
TiO_2	1.14	2.35	3.74	4.68	1.01	2.71	3.95	5.88	1.86	2.49	3.48	4.92	1.42	3.75	4.04	4.57	2.26	3.09	3.80	4.91
Sum	99.62	100.68	99.97	100.70	99.44	99.58	99.63	100.45	99.95	99.98	99.80	100.10	98.79	99.80	98.91	100.00	99.01	99.81	99.50	99.41
Si	1.803	1.704	1.601	1.475	1.777	1.655	1.569	1.426	1.776	1.707	1.600	1.480	1.763	1.673	1.579	1.504	1.733	1.637	1.550	1.476
Al^{iv}	0.197	0.296	0.399	0.525	0.223	0.345	0.431	0.574	0.224	0.293	0.400	0.520	0.237	0.319	0.421	0.496	0.266	0.363	0.450	0.524
Al^{vi}	0.061	0.061	0.060	0.062	0.062	0.030	0.041	0.026	0.011	0.014	0.071	0.064	0.046	0.000	0.50	0.042	-	0.021	0.041	0.020
Fe^{3+}	0.105	0.130	0.159	0.233	0.148	0.197	0.207	0.250	0.134	0.169	0.171	0.211	0.144	0.136	0.173	0.241	0.157	0.202	0.224	0.248
Fe^{2+}	0.028	0.083	0.069	0.030	0.013	0.020	0.028	0.050	0.064	0.057	0.062	0.069	0.006	0.086	0.058	0.028	0.050	0.044	0.039	0.029
Mn	0.004	0.004	0.005	0.004	0.003	0.003	0.003	0.003	0.004	0.005	0.006	0.005	0.003	0.004	0.005	0.004	-	-	-	-
Mg	0.842	0.738	0.638	0.574	0.842	0.707	0.645	0.550	0.790	0.725	0.633	0.561	0.820	0.721	0.634	0.605	0.776	0.683	0.629	0.611
Ca	0.896	0.894	0.935	0.935	0.863	0.936	0.926	0.922	0.921	0.930	0.922	0.920	0.910	0.935	0.934	0.908	0.937	0.931	0.931	0.930
Na	0.032	0.025	0.030	0.032	0.042	0.032	0.039	0.033	0.024	0.029	0.037	0.032	0.032	0.028	0.031	0.044	0.018	0.032	0.029	0.023
Ti	0.031	0.065	0.105	0.131	0.028	0.076	0.111	0.166	0.052	0.069	0.098	0.139	0.040	0.105	0.114	0.128	0.063	0.087	0.107	0.139

* Total iron asFeO; in the atomic ratios, Fe^{2+} and Fe^{3+} have been calculated following Hamm and Vieten (1971).

Analyses 1 to 4, Teldes; 5 to 8, Lacollange; 9 to 12 Champagnac; 13 to 16, Puy Forestier; 17 to 20, Sauvat.

The clinopyroxenes in the rhönite-bearing lavas are remarkably rich in Al_2O_3 and TiO_2 and low in silica. As crystallization proceeds, the chemical evolution is towards enrichment in Al and Ti (fig. 2). The correlation is very strong in both cases, and the last formed crystals (microlites, or outer rims of the phenocrysts) are the most enriched

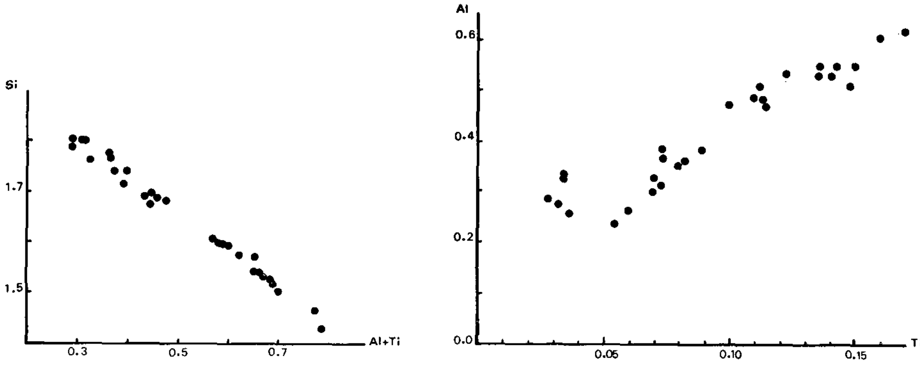
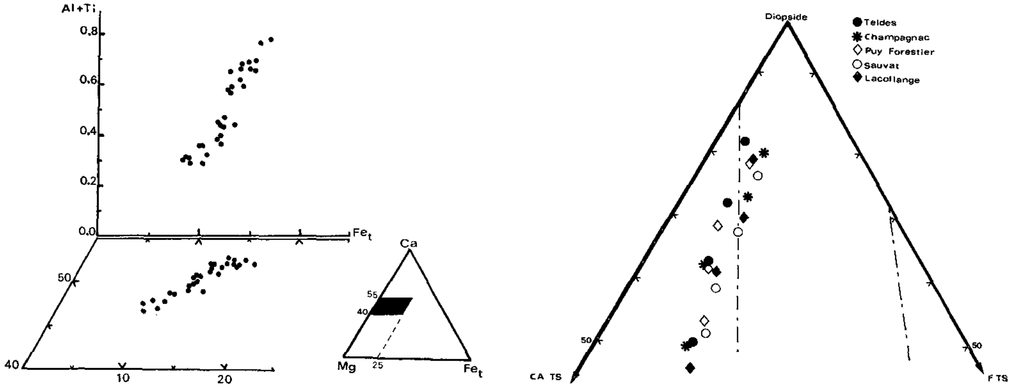


FIG. 2. Variation of Si versus Al_t+Ti and of Al_t versus Ti in clinopyroxenes from Lacollange where Al_t is total Al.



FIGS. 3 and 4: FIG. 3 (left). Variations in total iron represented in Ca–Mg–Fe_t diagram and concomitant variations in Ti+Al contents of the clinopyroxenes from Lacollange. FIG. 4 (right). Representative analyses of clinopyroxenes listed in Table II plotted on the diopside:Ca-Tschermak:ferri-Tschermak triangle. Dotted lines are the experimentally determined limits of solid solution at low pressure (Huckenholz *et al.*, 1974).

in Al and Ti. There is a break between the composition of the phenocryst cores and the linear trend of the rest of the crystals, which might be due to a change in the pressure during crystallization, with the cores contemporaneous with those of the olivines and plagioclases. Fig. 3 shows the enrichment in total iron (with the most iron-rich crystals being the latest) with increase in the total Al+Ti content. In rocks lacking large phenocrysts, the cores of the largest crystals do not plot as closely to the Ca–Mg side of the triangular diagram as they do in the sample from Lacollange. Accordingly, the compositional hiatus shown in fig. 2 is not apparent.

The Na content of the clinopyroxene is always small, which follows the work of Huckenholz *et al.* (1974), who showed that in potassic lavas the trend of clinopyroxene crystallization is towards enrichment in ferri-Tschermak molecule rather than towards acmite-rich compositions.

Since these lavas are very strongly silica-undersaturated, the low silica content of the liquid is the obvious explanation for the low Si of the clinopyroxenes. However, Akella and Boyd (1972) have shown that the activity of silica is probably not as important in determining the Si content of clinopyroxenes at high pressure as it is at low pressure. Gupta *et al.* (1973) have shown that the silica content of the liquid was the determining factor for the solubility of the $CaTiAl_2O_6$ molecule in diopside at one bar. It is obvious, however, that the $CaTiAl_2O_6$ substitution does not alone explain the composition of the clinopyroxene observed here. The calculation of end-member molecules (after partitioning total iron between Fe^{3+} and Fe^{2+} following Hamm and Vieten, 1971) brings out a high proportion of $CaFe_2^{3+}SiO_6$ (ferri-Tschermak) and $CaAl_2SiO_6$ (Ca-Tschermak) around 20 % (Table II). In the clinopyroxenes studied, the Ca-Tschermak component is always more abundant than ferri-Tschermak molecule. In fig. 4 the trend is quite regular, but does not lie in the area of clinopyroxene solid solution determined experimentally at one bar in the simple system.

This trend towards high Al, Ti, and Fe^{3+} contents is extremely constant for clinopyroxenes studied so far in Central France (Magonthier, in press; Velde and Frain de la Gaulayrie, 1974, unpublished) and it is important to examine whether this is a regional characteristic or whether it is a more general character of basic alkali lavas.

This same trend (towards high Al and Ti) exists in clinopyroxenes from melilite-free olivine nephelinites (Gramse, 1970). Also Lowder (1973) shows that Al and Ti increase towards the edges of phenocrysts and in groundmass pyroxenes relative to the phenocrysts in one ne-normative sample, whereas this trend is reversed for other lavas that are hy+ol normative. Stormer (1972) points out that Al is higher in groundmass clinopyroxenes than in phenocrysts and states that Al reaches extreme values in feldspathoidal lavas (5 to 18 % ne). Best and Brimhall (1974) also state that for rocks of alkali basalt parentage the groundmass pyroxenes have rims markedly enriched in Ti, Fe, and Al, and at least some clinopyroxenes in ankaramites appear to be rich in the ferri-Tschermak molecule. Morawski *et al.* (1975) have described sector-zoned Ti-augite phenocrysts in titaniferous alkali basalts from the Central Pacific basin, with marked outward increase in Ti, Al, and calculated Fe^{3+}. Finally, Tracy and Robinson (1975) have reported sahlite overgrowths on orthopyroxene and augite occurring at the contact between ultrabasic nodules and alkali basalts from Tahiti. They show that there is a strong trend to lower Si and higher Al and Ti.

The values found are very close to those reported here for the Sillon Houiller area. It appears that high Al, Ti, and Fe^{3+} values are found frequently in strongly undersaturated (feldspathoid-bearing) lavas. Either the clinopyroxene compositions reflect the low silica content of the liquid from which they crystallized or they represent metastable crystallization that is restricted to silica-deficient bulk compositions. A metastable trend has been advocated to explain the Al and Ti-enrichment of some lunar clinopyroxenes (Biggar *et al.*, 1971) and there is experimental evidence to support the hypothesis (O'Hara and Schairer, 1963; Lofgren *et al.*, 1974). Although slowly cooled undersaturated intrusions do not show these trends, the usual presence of kaersutitic amphibole makes comparison with lavas difficult. The effect of high cooling-rates on clinopyroxene compositions cannot yet be fully assessed, but existing data indicate that they induce high Al, and to a lesser extent high Ti (Mevel and Velde, in preparation).

In any case, it seems that the composition of the liquid is a strong controlling factor on the composition of the clinopyroxenes and that silica-poor pyroxenes can only appear in nepheline-normative bulk compositions.

Chemical composition of the lavas

The analysed lavas (Table III) do not contain any inclusions, nor any obvious xenocrysts. They are strongly undersaturated. Their SiO_2, TiO_2, and Na_2O contents are low, but they are rich in K_2O and CaO compared with other leucite basanites (Magonthier, in press). Their normative composition (absence of ab; quasi-absence of or; possible normative larnite) shows a similarity with the normative composition of melilite-bearing basic lavas.

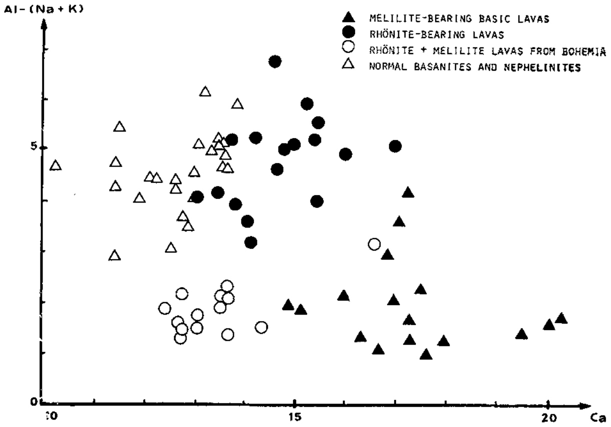


FIG. 5. Composition of different basic lavas represented in terms of Al—(Na+K) versus Ca (all in mole %). No attempt was made to present an exhaustive collection of analyses. (Sources of the data: Ficke, 1961; Kyle and Price, 1975; Hernandez, 1973; Lacroix, 1923; Magonthier, 1974; Velde et Frain de la Gaulayrie, 1974; Velde et Thièbaut, 1973; Shrbeny and Machacek, 1974; unpublished).

Kyle and Price (1975) conclude that the crystallization of primary rhönite cannot be explained 'in terms of unusual temperature, oxygen fugacity or silica activity'. If lavas in which rhönite appears exclusively as a transformation product of primary kaersutite are excluded, a plot of Ca against Al—(Na+K) permits the distinction of three groups of rocks (fig. 5): melilite basalts, rhönite-bearing lavas, and undersaturated basanites and nephelinites. Analogous and separate fields appear on a diagram showing the Si content versus Al—(Na+K).

The presence of primary rhönite in a lava can then be interpreted as a consequence of bulk composition, as is that of melilite, and cannot be considered as due to unusual physical conditions. The factors that are critical to the crystallization of rhönite would appear to be low Ca and high Al contents relative to melilite-bearing lavas, and, for a given Al (and alkali) content, silica percentages intermediate between the extreme undersaturation of melilite ankaratrites and the common level of undersaturation of normal basanites. Although rhönite is a Ti-rich phase, the Ti content of the lava is not critical to the appearance of rhönite. Rhönite-free lavas from the northern part of the Sillon Houiller (Magonthier, in press) are always richer in Ti than the rhönite-bearing basanites from the southern part of the district. It would also be reasonable to assume that rhönite could be more frequent than so far reported, but has been overlooked in many instances, mistaken as it can easily be for an opaque phase.

TABLE III. *Compositions and C.I.P.W. norms of the leucite–rhönite lavas from the Sillon Houillier South; and comparison with a lherzite.*

	1	2	3	4	5	6	7	8	9	10
SiO_2	41.58	42.67	40.89	41.22	41.00	42.52	41.88	41.00	38.76	39.68
Al_2O_3	14.34	14.83	14.72	15.71	14.80	14.94	15.04	14.80	14.05	16.89
Fe_2O_3	5.34	5.39	2.46	2.45	5.34	5.53	4.93	-	-	-
FeO	6.57	5.65	7.74	7.82	6.22	5.60	6.31	11.02*	9.72*	10.15*
MnO	0.16	0.11	0.12	0.13	0.12	0.16	tr.	-	-	-
MgO	9.90	9.35	10.04	10.93	8.79	10.40	8.14	8.79	15.10	10.09
CaO	12.66	12.80	13.27	12.00	13.01	12.33	13.42	13.01	10.30	12.38
Na_2O	2.52	2.48	2.23	2.80	2.49	2.51	2.81	2.49	2.62	3.15
K_2O	2.64	2.51	2.20	2.62	2.46	2.33	2.47	2.46	1.36	1.64
TiO_2	2.86	2.69	2.88	2.48	3.09	2.65	2.96	3.09	5.20	6.25
P_2O_5	0.41	0.33	0.20	0.40	0.36	0.38	0.25			
H_2O+	0.92	1.03	1.64	1.53	1.32	0.64	1.38			
H_2O-	0.50	0.47	0.70	0.19	0.62	0.30	0.28			
Sum	100.40	100.31	99.09	100.28	99.62	100.29	99.87			
Or	0.94	8.63	-	-	1.58	9.86	0.66			
An	20.02	21.92	23.66	22.56	21.94	22.62	21.13			
Lc	11.50	4.86	10.19	12.14	10.16	3.06	10.93			
Ne	11.55	11.37	10.22	12.84	11.41	11.51	12.88			
Di	31.64	30.93	26.28	20.65	31.65	28.27	34.55			
Ol	9.21	7.41	14.42	18.54	6.49	10.10	4.71			
Ln	-	-	2.48	2.65	-	-	-			
Mt	7.74	7.81	3.57	3.55	7.74	8.02	7.15			
Il	5.43	5.11	5.47	4.71	5.87	5.03	5.62			
Ap	0.95	0.75	0.46	0.93	0.83	0.88	0.58			

1. Champagnac.
2. Vernegoux.
3. Teldes.
4. Puy Forestier.
5. Charlus.
6. Lacollange.
7. Sauvat.

8 to 10, for comparison:

8. Phlogopite-bearing lherzite (Conquéré, 1971b, p.41).
9. Rhönite-bearing lava.
10. Lherzite modified by subtraction of 17 wt.% Fo_{90}.

* Total iron as FeO.

Origin of leucite–rhönite lavas

These lavas form a homogeneous group with an intermediate composition between that of undersaturated basanites and that of melilite ankaratrites. They differ from leucite basanites on various grounds of major and trace element chemistry (Magonthier, in press) and mineralogy. Furthermore, whereas leucite basanites from the northern part of Sillon Houiller usually contain abundant inclusions (crustal material as well as peridotite nodules), inclusions are conspicuously absent from the rhönite-bearing basanites.

The composition of nephelinites and basanites has often been compared with that of amphibole-bearing ultrabasic rocks (e.g. Lacroix, 1917). The origin of many such rocks, including that of lherzites (an ultramafic hornblendite with minor spinel, phlogopite, and garnet), the closest compositional analogs of the lavas studied here, is probably partial fusion of spinel peridotite in the presence of small amounts of water, and subsequent fractionation of the liquids formed (Conquéré, 1971*b*; Best, 1974). Peridotites from the Pyrenees contain lherzite veins up to 5 cm in width. Partial melting could form larger bodies of magma (Best, 1974).

If we compare (Table III) the composition of a phlogopite-bearing lherzite with those of the leucite–rhönite lavas, major differences are found in Ti, Mg, and K. The Mg content can be adjusted by correcting for the precipitation of olivine. Ti is variable in lherzites, but seems to be positively correlated with K, as it is in amphiboles (Conquéré, 1971*b*). It thus appears difficult to solve the problem of excess titanium. The Na/K ratio cannot be changed by any simple process of crystal fractionation either; it should be assumed that the value close to unity already obtained in the first liquid formed, and it seems necessary to suppose that the potassium content of the source material was higher than is generally the case for peridotites. Contamination is not a likely source of K as most basaltic rocks in France have K_2O below 1·75 % and Na_2O/K_2O ratios well above unity.

It seems then that the rhönite-bearing lavas originated by partial fusion of a phlogopite-bearing spinel peridotite at depth followed by limited fractionation upon ascent by crystallization of olivine. The outcrops are situated on a major fracture zone and it is important to note that rhönite-bearing lavas in France seem preferentially associated with great vertical faults, just as melilite-bearing basic lavas are in general. It is also significant that the Lherz massif, where lherzites have been described (Conquéré, 1971*b*), is situated on the extension of the Sillon Houiller fracture zone to the south (Cogné *et al.*, 1966).

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