Potash-rich volcanic rocks from southern Spain

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Summary. Several restricted outcrops of potash-rich volcanic rocks occur in the Spanish provinces of Murcia and Almeria, where they form intrusive pitchstones or surface lavas among country rocks consisting of Tertiary and Quaternary sediments: the volcanic rocks include jumillites and verites from the type localities of Jumilla and Vera and it is these rocks that have been investigated. Jumillites are basic lavas, sometimes coarse-grained, rich in MgO, CaO, K_2O, TiO_2, and P_2O_5, poor in SiO_2, Al_2O_3, and Na_2O and they contain important, if minor, concentrations of Cr_2O_3, BaO, SrO, and ZrO_2. Their mineralogy is distinctive: chrome diopside, forsterite, titaniferous phlogopite, kataphorite, and sanidine, with rare leucite. Verites, typically, are black pitchstones or pitchstone breccias that range from basic to acid in composition; they are more variable in their chemistry than jumillites, but in part this variation might be due to introduction of silicate and carbonate into some of the verites during extensive hydrothermal alteration, which has undoubtedly affected their initial chemistry. Mineralogically, verites are simpler than jumillites and have fewer phenocrysts: forsterite, some diopside, phlogopite, and, occasionally, leucite. Certain mineralogical and compositional similarities of jumillites and verites suggest they may have originated from the same type of parental magma. Their mineralogy and chemistry also relate the jumillites and verites to phlogopite-bearing potash-rich volcanics from East Africa, America, and Australia and it seems possible that all these rocks might have a common parent in mica peridotite or mica pyroxenite.

THE basic and intermediate alkaline lavas and near-surface intrusive rocks of southern Spain are comprised of jumillites, fortunites, and verites: they are found in the provinces of Murcia and Almeria and they occur in fairly widely separated localities. The most southerly occurrences of these alkaline rocks are those of the verites that form a series of hill or valley outcrops near the village of Vera, south-west of the town of Murcia; fortunites were reported by Osann (1906) to occur near the old road to Fortuna from Orihuela that lies to the east of Murcia, but on a visit in 1964 to the given locality the present author was unable to find the outcrops described; the jumillites, which are probably the best-known members of this group of rocks, are post-Miocene lavas that lie about 40 km north-north-west of Fortuna and appear in exposures on or near the main road in the country between

TABLE I. Analyses and norms of jumillites: nos. 1 to 8 from exposures near the main road between Jumilla and Hellin, Murcia, Spain (anal. G. D. Borley); nos. *a* and *b* from Osann (1906)

	1	2	3	4	5	6	7	8				Norms		
	J1	J4	J7	J9	J11	J12	J17	J16	a	b		Average of nos. 1 and 2	Average of nos. 3 and 4	Average of nos. 5, 6, 7, and 8
SiO_2	45·53	45·64	51·25	51·52	47·07	46·96	46·43	47·03	50·78	48·81	Q	—	—	—
Al_2O_3	8·5	8·2	9·1	8·6	7·2	6·4	7·2	7·2	9·10	8·17	Or	21·7	38·9	28·9
Fe_2O_3	2·93	3·44	1·45	2·58	3·03	3·90	2·97	2·87	2·96	3·46	Ab	13·1	8·9	8·9
FeO	4·31	3·83	4·21	3·28	3·19	2·64	3·36	3·33	3·64	3·22	An	4·7	—	—
MgO	14·86	14·65	15·79	15·55	16·88	16·80	16·72	17·37	14·29	14·84	Ne	—	—	0·1
CaO	9·06	8·95	4·25	4·14	7·90	7·77	7·45	6·77	5·29	7·06	Ac	—	6·0	2·6
Na_2O	1·5	1·6	2·2	2·0	1·4	1·5	1·4	1·4	1·05	1·71	Di	20·1	7·4	17·5
K_2O	3·6	3·8	6·4	6·8	5·0	5·1	5·2	4·7	7·39	5·73	Hy	0·5	3·7	1·6
H_2O+	4·1	3·6	0·8	0·8	2·9	3·1	3·1	3·8	2·53	3·46	Ol	21·5	25·9	24·4
H_2O-	1·13	0·66	0·37	0·40	0·52	0·77	0·74	1·22	—	—	Mt	4·4	—	3·1
CO_2	0·6	0·8	0·6	0·8	1·2	0·8	0·9	0·1	0·5	0·81	Ilm	3·0	2·6	2·6
TiO_2	1·57	1·51	1·37	1·42	1·32	1·66	1·52	1·32	1·28	1·34	$CaCO_3$	1·6	1·6	1·2
*ZrO_2	0·12	0·10	0·03	0·08	0·09	0·08	0·09	0·10	—	—	Ap	4·4	2·7	3·9
P_2O_5	1·82	2·04	1·16	1·25	1·78	1·90	1·73	1·45	1·31	1·39	Vols.	4·7	1·3	4·4
Cr_2O_3	n.d.	0·04	0·13	0·15	0·10	0·10	0·13	0·13	—	—				
MnO	0·11	0·12	0·07	0·09	0·10	0·11	0·10	0·08	0·09	tr.				
†BaO	0·41	0·41	0·40	0·39	0·48	0·53	0·63	0·59	—	0·25				
*SrO	0·22	0·25	0·13	0·14	0·19	0·18	0·18	0·15	—	0·09				
Totals	100·3	99·7	99·7	100·0	100·4	100·3	99·6	99·8	100·21	100·34				

* Determined by X-ray fluorescence. A. Z. Smith. † Spectrographic determination. R. Berlin.

Hellin and Jumilla. Country rocks in all these areas consist of bare, sometimes arid, nearly flat lying, Tertiary and supposed Quaternary sediments, but a series of faults also brings the most westerly verite exposures close to the metamorphosed Pre-Cambrian basement rocks of Sierra de Bedan.

Jumillites attracted attention as far back as the eighteenth century as they were associated with apatite deposits that have been quarried out until recently, but it was in the late nineteenth and early twentieth centuries that they were first described in any detail. Osann (1906) discussed fortunites and jumillites, reviewed earlier papers on the same subject, and presented some analyses of rocks and minerals. Washington (1903) gave an analysis of verite and classified it as a dosodic akerose. These earlier writers drew attention to some of the similarities between the Spanish alkaline rocks and those of the Leucite Hills in America. More recent publications are those of Fuster and Pedro (1953) who discussed some of the verites, and the explanation of the Jumillite Sheet (No. 869) published by the Geologico Minero de España (1961) in which brief reference was made to the jumillite lavas. A new study of jumillites and related types seemed to be timely, and visits were made to Jumilla in 1963 by Dr. I. Gibson, formerly of Imperial College, and to Jumilla, Fortuna, and Vera in 1964 by the author, in order to make collections of the lavas. Rocks collected in these visits and analysed by the author form the basis of discussion in this paper.

As previously mentioned, *jumillites* outcrop as small, hilly exposures, along the road between Jumilla and Hellin; fresh specimens are usually possible to collect as the road cuts through some of the exposures. Several samples of each of three types of jumillite were collected: A heavy, coarse-grained, brown variety in which large plates of potash feldspar, bright green pyroxene, golden-brown flakes of mica, and a near colourless olivine were clearly visible; despite its texture, which is that of a plutonic rock, this variety appears to be a surface flow and not an intrusion. A fine-grained, light-grey rock containing small, scattered phenocrysts of ferromagnesian minerals and 'pockets' of golden-brown mica that appears to be of post-lava crystallization origin. And a fine-grained dark-grey to black rock that again has only scattered ferromagnesian phenocrysts. All three types are of basic composition (table I).

Petrography. Specimens J11, J12, and J17 are coarse-grained varieties of the first type that are essentially similar in their mineralogy and only J11 will be described. Thin sections of J11 contain early formed,

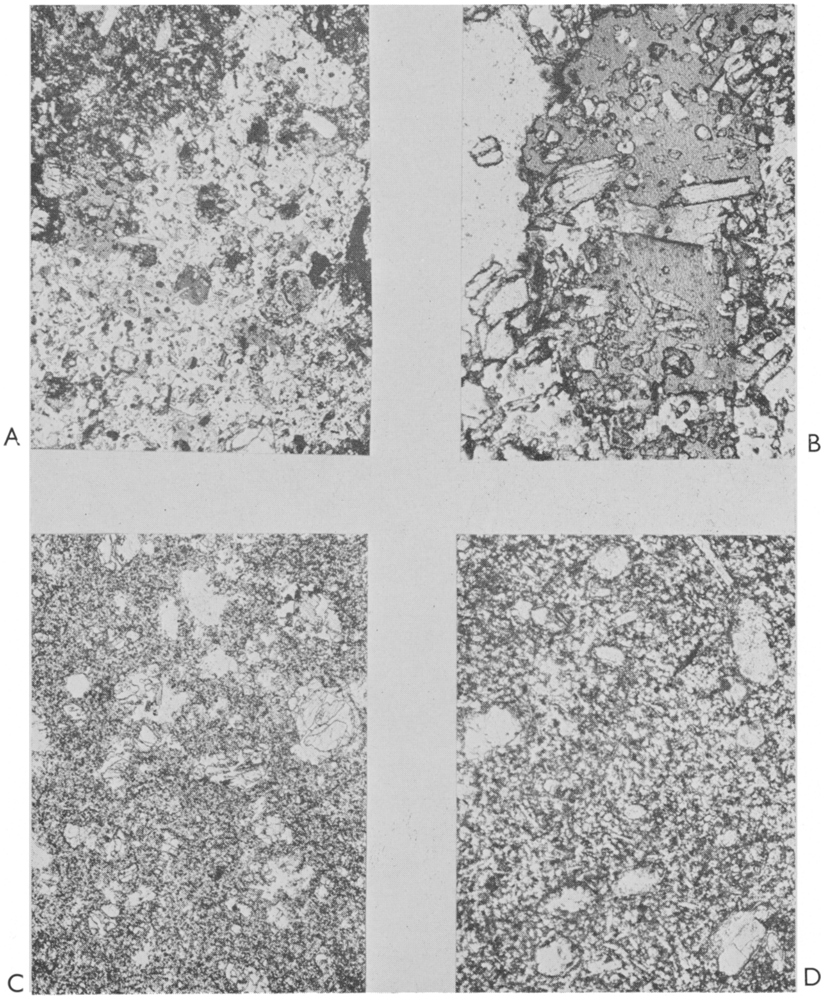

Fig. 1. *a*. Jumillite J12. Large colourless sanidine, poikilitically enclosing phlogopite, pyroxene, etc. (Crossed nicols, ×20.) *b*. Jumillite J16. Crystal of phlogopite showing sieved nature of the mica. (Plane polarized light, ×55.) *c*. Jumillite J9. Phlogopite and pyroxene in a glassy groundmass. (Plane polarized light, ×20.) *d*. Jumillite J4. Altered ferromagnesian minerals in glassy groundmass. (Plane polarized light, ×20.)

idiomorphic, colourless crystals of olivine (Fo 85·5$\pm$3 %)[1] between 1·5 mm and 2 mm in size, that have been slightly altered to iron oxides and show some marginal serpentinization. Colourless or watery-green chrome-bearing diopside occurs in two generations: early formed crystals that are generally slightly smaller in size than those of the olivine, and a later generation of extremely minute laths and tabulae that may have marginal zones of bright-green and presumably soda-enriched material. Some alteration of pyroxene to calcite has taken place. Poikilitic, and often ragged, crystals of titaniferous phlogopite are abundant and are strongly pleochroic from α pink and β yellow to γ red-brown, and many grains show basal lamellar twinning. These phlogopite grains contain numerous inclusions of minute, second generation diopside, together with leucite and apatite. Also present in the rock are glomerophytic grains of leucite associated with a near isotropic base, and late-formed interstitial amphibole that occurs in small grains *c.* 0·1 mm in size, and has the optics of kataphorite, α straw-yellow to γ pinky-brown. All these early formed minerals are poikilitically enclosed by large optically continuous plates of sanidine, the last major constituent to crystallize (fig. 1, *a* and *b*). Specimen J16 is also a coarse-grained variety of jumillite, but it differs slightly from the others in having a higher proportion of pyroxene and less olivine (Fo 87$\pm$3 %). J7 and J9 are samples of the light-grey lava, second type of which is also the most potash-rich of the jumillites (table I). In thin section they contain lightly altered colourless phenocrysts of olivine (Fo 88 and Fo 87 for J7 and J9 respectively) and, more rarely, diopsidic pyroxene; laths of phlogopite (α pale straw, β golden yellow, γ reddish-brown), pyroxene, and kataphoritic amphibole occur in a near-isotropic groundmass (fig. 1*c*). J1 and J4 represent the fine-grained dark-grey third type of lava. Thin sections show the rock to have a slightly coarser texture than either J7 or J9 and also show extensively serpentinized phenocrysts of olivine (Fo 89) that are about 1 mm in size. Pyroxene occurs as watery green phenocrysts up to 1 mm in size that are much less altered than those of olivine. One or two lath-shaped phenocrysts of mica are present and these are almost completely resorbed and replaced by iron-oxides. The groundmass, as with lavas of the second type, is almost isotropic and contains small grains of phlogopite (α pale-straw, β golden-yellow, γ reddish-brown), watery-green pyroxene, kataphoritic amphibole, and abundant iron oxides.

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[1] Diffractometer determination using Δd_{174}: Jambor and Smith (1964). Determined by R. Curtis, Imperial College.

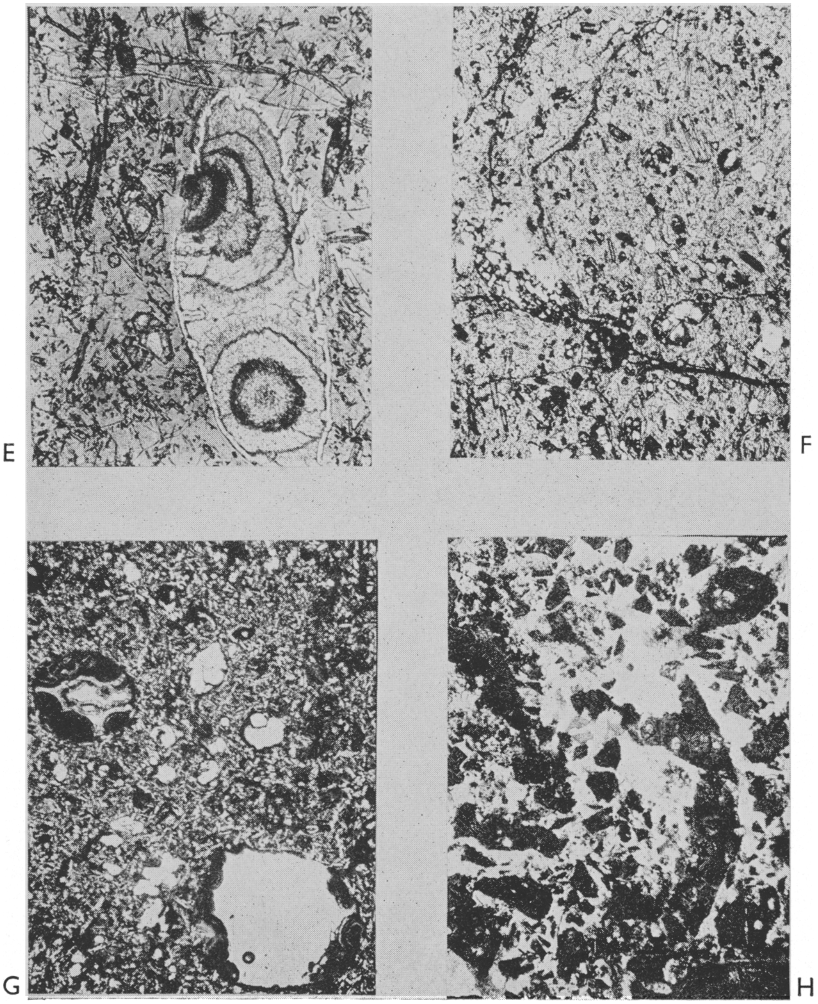

FIG. 2. *e*. Verite V2 (*b*). Calcite-filled amygdales with phlogopite laths and pyroxene set in glass. (Plane polarized light, × 55.) *f*. Verite V5 ii (*a*). Phlogopite laths and altered olivine, etc., in glassy base. *g*. Verite V4*a*. Altered vesicular verite with remnants of ferromagnesian minerals. (Plane polarized light, × 20.) *h*. Verite V3*a*. Clear calcite and other alteration products in glassy base. (Crossed nicols, × 20.)

The group of rocks known as *verites* occurs in a number of separated outcrops along a line that extends for several kilometres east and west of the main road from Vera to Almeria, about 7 km south-south-west of Vera. The most westerly of the outcrops forms a prominent hill, Maria Cabeza, that lies just east of the fault scarp, which brings the Tertiary sediments that form the country rock against Pre-Cambrian basement complex; and the most easterly outcrop, near the coast close to Garrucha, is formed mainly of blocks of disintegrating verite breccia that are being rapidly reduced to dust. Between these extremes, which are *c.* 12 km apart, lies an extensive outcrop of verite that appears a little to the east of the main road and forms a small, gorge-like dry valley. Here the verite is a massive black obsidian containing calcite- and silica-filled amygdales. Occasional flow textures may be observed on the top surface of the verite but generally this obsidian seems to have been intrusive just below the surface of Mesozoic sediments. Alteration of the verites, by hydrothermal solutions rich in silica and, possibly, carbonate, has been extensive, particularly in the area of Maria Cabeza where much of the rock is crumbly and almost totally altered. Samples of verite were collected from four localities: the gorge exposure immediately east of the main road; a stream section of an outcrop a few kilometres west of the main road; the area of Maria Cabeza; the eastern outcrops near the coast at Garrucha.

Petrography. Verites from the gorge exposure, e.g. V1, V1b, V1c, are black obsidians associated with rare verite breccias. Thin sections of the obsidian show a pale-brown glass that contains abundant euhedral to subhedral phenocrysts of olivine (Fo 90·5 to Fo 91·5) that are often broken or are being slightly altered to serpentine or mosaics of calcite crystals. Scattered, unaltered laths or plates of phlogopitic mica also occur as phenocrysts, which are strongly pleochroic (α colourless, β yellow, γ red-brown), but occasional elongate laths of near colourless mica are also found and these are very altered and oxidized. Vesicles are sporadically developed and they are usually infilled with calcite. In samples of verite from the stream exposure west of the main road, e.g. V2, mica is a much more abundant phenocryst and it forms euhedral basal plates of pinky-brown colour: rare grains of this mica appear to have been recrystallized. Olivine (Fo 89) is still a major constituent but the grains are frequently broken and altered and are sometimes completely pseudomorphed by calcite mosaics or serpentine (fig. 2*e*). A number of specimens were examined from exposures in the area of Maria Cabeza. Verite V3 comes from beneath the main rock face of the hill where the outcrops are formed of dark-grey crumbly material. It is an altered, broken, and dirty-looking brown glass in thin section, with calcite filling the network of cracks and vesicles that form a large part of the rock. Large fractured, pseudomorphed olivines, and corroded phlogopite grains that are almost the same colour as the glass are all that remains of the original minerals (fig. 2*h*). Samples V4, V4 (i), and V4 (ii) from the main hill were also originally obsidians and very similar in thin section to verites V1, V1b, and V1c, i.e. olivine-bearing obsidians (Fo 91·5) with minor phlogopite, but they are now much altered. Small hexagonal, or near hexagonal, almost isotropic grains in the glass may be altered leucites. The most interesting verite from Maria Cabeza is a crystalline variety not found elsewhere, e.g. V4a and V4b. Thin sections show a rock rich in phlogopite and potash feldspar that occurs in small untwinned or Carlsbad-twinned grains. The presence of feldspar is a distinguishing feature of this verite and reference to table III shows that the rock has a high potash content. Patches of pinky-brown glass occur in some of the sections and all the latter show heavy iron staining. Again, as in V4 (i), etc., some small hexagonal or rounded grains appear to be altered leucites (fig. 2*g*). The last exposure from which samples were collected was that near the coast at Garrucha, where obsidian V5 and breccia V5 (*a*) were obtained. No special new features were seen in thin sections of either, the obsidian containing phlogopite as the main mineral constituent with some pseudomorphed olivine grains, set in a pinky-grey vesicular glass (fig. 2*f*).

Chemistry. Analyses of jumillite are given in table I, including those taken from Osann (1906), and complete or partial analyses of minerals from the lavas are given in table II. Verite analyses by the present author together with analyses taken from Fuster (1953), are given in table III. A number of interesting features distinguish the chemistry of the jumillites: the combination of very high magnesia with moderately high to high potash contents; the low silica, alumina, and total iron contents, high titania, phosphorus, and high potash:soda ratio; of the minor constituents, chrome, zirconia, and baria are all high. The curious chemistry of the rocks makes for a distinctive mineralogy that is most striking in the coarse-grained jumillite: forsteritic olivine, chrome-bearing diopside, titaniferous phlogopite, and sanidine. A large part of the chrome in the analysed rocks appears to have entered the pyroxene lattice whilst a large part of the titania and baria have entered the phlogopite (table II). Titaniferous phlogopite appears to be restricted to potash-rich rocks of this type, e.g. the titaniferous phlogopite from the Australian lamproites reported by Wade and Prider (1940). The distribution of baria and chrome between phlogopite and diopside from the jumillites is of special interest when compared with that given for pyroxenes and phlogopite from the wyomingite of Leucite Hills by Cross (1897), where both baria and chrome were reported as being in the phlogopite. Chrome-bearing diopsides are generally found in magnesia-rich rocks, especially those of kimberlitic affinities, e.g. Holmes (1936). Phosphorus is high in the jumillites and most of it has presumably entered apatite; the small amount of soda present has probably gone predominantly into the kataphorite although a little is present in both the diopside and the phlogopite. Table I shows the presence of a minor amount of normative nepheline ($\leqslant 1\,\%$) in some of the jumillites; none has been identified modally and it appears likely that it is accounted for chemically by the presence of kataphorite. Leucite is not present in the norms of the jumillites, which are rich in normative orthoclase, and it is obvious that the little that is present was formed above the orthoclase inversion temperature and was 'frozen' into the glassy base with which it is associated, or into the early formed ferromagnesian minerals.

TABLE II. Complete or partial analyses of minerals from jumillites (G. D. Borley anal.)

	Pyroxenes			
	J17	J12	J16	J11
SiO_2	52·26			
TiO_2	0·73			
Al_2O_3	1·94			
Fe_2O_3	1·08	0·98	0·95	0·78
Cr_2O_3	0·54			
FeO	2·29	1·95	2·15	2·62
MnO	0·07	0·08	0·08	0·10
CaO	22·80	23·26	23·14	22·96
MgO	16·73	16·71	16·09	16·72
K_2O	0·18			
Na_2O	0·87			
	99·48			

J17 Formula calculated to 6 oxygens	
Si	1·922
Al^{iv}	0·050
Al^{vi}	0·034
Ti	0·020
Fe^{3+}	0·030
Cr	0·016
Fe^{2+}	0·070
Mn	0·002
Ca	0·901
Mg	0·917
K	0·008
Na	0·062
Z	1·97
WXY	2·06
Atomic %	
Ca	47·5
Mg	47·5
Fe	5·0

	Phlogopite J11
SiO_2	38·99
TiO_2	8·43
Al_2O_3	8·20
Fe_2O_3	1·24
FeO	6·41
MnO	0·03
CaO	0·60
MgO	19·31
BaO	1·85*
K_2O	8·75
Na_2O	0·85
H_2O+	n.d.
H_2O-	1·34
P_2O_5	0·15
	96·15
Cr	100 ppm

* Spectrographic determination by Mr. R. Berlin.

TABLE III. Analyses of verites

	1 V1	2 V1b	3 V1c	4 V2	5 V3	6 V4a	7 V5	8 V5a	9	10	11	12	13	14	15	16	c
SiO_2	53·96	53·24	55·79	51·40	59·90	51·59	58·88	53·56	49·33	55·03	58·08	56·24	61·88	61·15	71·81	68·49	57·13
Al_2O_3	11·3	10·8	11·4	10·6	14·1	10·4	12·5	11·0	9·24	6·59	9·25	10·17	11·34	13·33	10·05	10·42	10·28
Fe_2O_3	0·73	1·00	1·21	1·39	1·85	4·08	1·86	1·73	2·28	4·17	2·93	0·84	2·38	4·39	1·78	2·62	1·90
FeO	3·52	3·45	3·19	3·21	1·19	1·32	2·19	1·76	2·99	3·43	1·42	1·96	1·55	0·96	1·16	1·30	4·11
MgO	8·61	8·00	7·11	6·68	1·95	3·40	5·15	3·31	8·36	7·72	2·64	5·31	5·50	3·14	1·67	3·60	9·73
CaO	3·67	5·20	3·94	6·33	2·75	7·70	2·75	8·10	3·86	4·48	5·13	6·47	3·92	1·82	1·37	1·88	3·37
Na_2O	3·1	3·0	3·2	3·3	3·9	1·2	2·9	2·2	2·74	2·59	3·71	1·86	1·02	1·61	1·14	1·18	2·56
K_2O	3·5	3·4	3·8	3·4	3·9	6·1	5·5	4·4	2·46	4·03	7·71	7·00	5·57	7·75	7·18	7·21	6·07
H_2O+	4·8	4·5	4·8	4·8	5·9	4·6	4·5	5·4	4·52	3·94	3·24	4·85	2·65	2·62	0·74	0·62	2·55
H_2O-	0·47	0·46	0·50	0·66	1·48	1·06	0·62	1·34	0·94	0·62	0·80	1·50	1·09		0·69	0·49	—
CO_2	4·4	5·3	3·6	6·7	0·8	6·2	0·5	5·1	10·50	3·80	2·35	0·85	0·26	0·16	0·08	0·07	0·07
TiO_2	1·30	1·24	1·33	1·12	1·46	1·22	1·41	1·23	1·23	1·28	1·05	1·32	1·43	1·44	1·21	1·30	1·60
ZrO_2	0·08	0·09	0·10	0·09	0·12	0·07	0·10	0·09	—	—	—	—	—	—	—	—	—
P_2O_5	0·55	0·54	0·47	0·71	0·63	0·52	0·74	0·56	1·27	2·07	1·20	1·55	0·88	1·11	0·84	1·05	0·82
MnO	0·07	0·06	0·04	0·07	0·03	0·07	0·05	0·08	0·15	0·07	n.d.	0·04	0·05	0·04	ind	0·04	0·09
SrO	0·06	0·06	0·06	0·05	0·08	0·07	0·07	0·06	0·15*	0·15*	0·21*	0·19*	0·09*	0·15*	0·15*	0·11*	—
Totals	100·1	100·3	100·6	100·6	100·0	99·6	99·7	99·9	100·02	99·97	99·72	100·15	99·61	99·67	99·87	100·38	100·28

* BaO

Norms:

	1	2	3	4	5	6	7	8
Qtz	3·3	3·2	6·1	1·4	15·4	7·6	9·5	9·8
Or	20·6	20·0	22·2	20·0	22·8	36·1	26·1	32·8
Ab	26·2	25·2	27·2	27·8	33·0	10·0	18·3	24·6
An	6·7	6·1	5·6	4·2	9·5	5·0	7·2	4·7
Di	6·4	12·9	8·3	18·2	0·9	18·4	17·9	3·8
Wo	—	—	—	—	—	2·7	2·8	—
Hy	22·4	17·6	16·5	10·7	4·4	—	—	11·4
Mt	0·9	1·4	1·9	2·1	—	0·9	2·6	2·8
Hm	—	—	—	—	1·8	3·5	—	—
Il	2·4	2·3	2·4	2·1	2·6	2·3	2·3	2·7
Ap	1·3	1·3	1·3	1·7	1·3	1·3	1·3	1·7
Water $+CO_2$	9·7	10·3	8·9	12·2	8·2	11·9	11·8	5·6
Totals	99·9	100·3	100·4	100·4	99·9	99·5	99·8	99·9

Nos. 1, 2, and 3. Verites (obsidians) V1, V1b, and V1c. Outcrops immediately east of the main road, Vera to Almeria, *c.* 7 km SSW. of Vera, Province of Almeria, S. Spain.

No. 4. Verite V2. From stream exposure west of main road above.

No. 5. Altered Verite V3. Beneath main face of the hill Maria Cabeza, *c.* 5 km west of main road.

No. 6. Altered Verite V4a. From lower part of hill Maria Cabeza.

Nos. 7 and 8. Verites V5 (obsidian) and V5a (breccia). Disintegrating outcrops several kilometres east of the main road, near the coast north of Garrucha.

Nos. 9–16. Verites from Vera area, taken from Fuster and Pedro (1953).

c. Fortunite from Fortuna area, taken from Osann (1906).

The verites analysed by the author (table III) show a greater variation in chemical composition than the jumillites and often differ considerably from the latter in mineralogy; they have generally more silica and alumina, less magnesia, phosphorus, and titania, and have a wider spread of total alkali contents with more variable potash:soda ratios than the jumillites. The analysis of a fortunite given by Osann (1906), and reproduced in table III (c), shows that there is a considerable affinity between fortunites and verites. Total iron contents of the verites are low, as are those of the jumillites; their carbonate content is often high, as seen from the analyses of the author and from those given for comparison in table III (9–16) of Fuster and Pedro (1953). This carbonate is undoubtedly of secondary origin as is probably some of the silica in the high-silica verite analyses given by Fuster and Pedro, as the latter authors report the presence of opal and chalcedony, as well as calcite, in amygdales. Analyses of verites made by the present author (table III, 1–8) fail to match any of the high phosphorus figures for verites given by Fuster and Pedro (table III, 9–16). Despite the much lower magnesia contents of the verites than the jumillites, the forsterite contents of the olivines in the former are slightly higher than in the latter (Fo 89–91·5 and Fo 85·5–89 for verites and jumillites respectively) and this must be due to the paucity of pyroxene in the verites resulting in an increased concentration of magnesia in their olivines.

Relationship of jumillites and verites. Fuster and Pedro (1953) considered that the jumillites and verites were related rocks. Allowing for the extensive hydrothermal alteration of some of the verites, it is possible that by subtraction of olivine or diopside or both, from, say, basic jumillite magma of J1 type (table I, 1) that a basic verite magma of type V1 (table III, 1) could be obtained. However, subtraction of these minerals would not produce a magma with the approximately 1:1 potash:soda ratio of the more basic verites and neither would it account for the decrease of baria that takes place in the latter lavas. Unfortunately, there are no reports of nodules of olivine, or any other type of accumulate, occurring in verite lavas and certainly the author has found none: neither is there any indication of jumillite types of material occurring as intrusives, as lavas, or as xenoliths in the lavas in the area of Vera. At the moment therefore the author considers the relationship between the two lava types must remain conjectural: it should be pointed out, however, that Osann (1906) in discussing the fortunites, which are chemically allied to the verites, reported that olivine nodules were common in the former.

TABLE IV. Analyses of rocks with affinities to jumillites and verites

	a	b	c	d	e	f	g	h	j	k	l	m		o
SiO_2	43·35	44·39	42·59	47·33	45·48	31·80	44·36	35·37	43·58	45·18	41·71	47·50	51·07	45·77
Al_2O_3	9·67	6·37	3·82	6·84	3·16	3·41	6·97	6·50	8·08	9·31	8·55	9·62	9·93	8·94
Fe_2O_3	5·26	5·11	2·55	0·02	6·28	5·19	5·10	7·23	5·00	6·31	2·51	3·37	2·72	3·63
FeO	2·65	4·86	4·96	5·62	4·07	3·48	4·22	5·00	5·77	4·08	9·79	4·74	1·19	7·13
MgO	15·74	14·20	33·84	19·31	22·10	24·69	21·46	14·08	12·91	10·77	14·65	13·00	10·31	12·96
CaO	12·20	17·02	2·84	16·99	6·16	10·04	4·00	16·79	8·88	8·56	11·74	9·00	4·87	11·56
Na_2O	0·44	0·50	0·26	0·41	1·32	0·29	nil	1·32	0·90	1·73	0·60	1·96	0·82	1·40
K_2O	4·74	2·35	2·58	0·88	4·84	4·32	8·04	4·09	5·99	6·93	3·65	3·28	9·92	4·60
H_2O^+	0·59	0·35	2·96	0·55	2·02	5·59	1·27	2·78	1·95	1·01	1·41	3·90	2·19	0·95
H_2O^-	0·07	0·05	0·63	0·21	2·56	0·63	0·26	1·15	1·15	0·55	0·16	0·90	2·04	0·18
CO_2	0·04	0·04	0·25	0·02	0·15	7·65	0·89	0·09	0·11	0·17	0·16	—	—	—
TiO_2	4·38	3·91	1·60	1·26	1·30	1·40	2·70	3·87	4·64	4·36	2·15	1·85	2·13	0·76
P_2O_5	tr.	0·26	0·22	0·21	0·08	1·49	0·16	0·74	0·62	0·51	1·62	1·05	1·53	1·52
Cl	tr.	0·04	0·05	tr.	—	—	—	0·02	—	—	—	—	—	—
F	0·11	0·04	0·12	0·01	—	—	—	0·16	—	—	—	—	—	—
S	tr.	0·02	0·18	0·01	—	—	—	0·35	—	—	—	—	—	—
Cr_2O_3	0·05	0·03	0·23	0·32	—	—	—	0·01	—	—	—	—	—	—
V_2O_3	0·04	0·05	0·01	0·04	—	—	—	0·03	—	—	—	—	—	—
NiO	0·04	0·01	0·21	0·04	—	—	—	0·19	—	—	—	—	—	—
MnO	0·09	0·10	0·10	0·12	0·05	—	0·09	0·24	0·21	tr.	0·24	tr.	0·04	0·13
BaO	0·30	0·16	0·13	0·03	—	—	0·42	0·25	0·32	0·30	0·50	—	0·57	0·26
SrO	none	0·03	0·02	none	—	—	—	0·04	—	—	—	—	—	—
Others	—	—	—	—	—	—	—	0·14	—	0·10	0·38	—	0·33	—
	99·79	99·89	100·15	100·22	99·57	99·98	99·94	100·36	100·25	99·87	99·82	100·17	99·66	99·79
Less O	0·04	0·03	0·11	0·01	—	—	—	0·15	—	—	—	—	—	—
	99·75	99·86	100·04	100·21	99·57	99·98	99·94	100·21	100·25	99·87	99·82	100·17	99·66	99·79

a. Biotite-pyroxenite, Bufumbira } Ejected blocks
b. ,, ,, ,, }
c. ,, peridotite, Bunyuruguru
d. ,, -augite-peridotite, Bufumbira
e. Kimberlite, Premier Mine, Kimberley, Africa } from Holmes (1950). Nos. 2, 3, 6, and 7, p. 775.
f. Micaceous kimberlite, Lion Hill Dyke, Orange Free State, S. Africa
g. Average of four mica-pyroxenite xenoliths in kimberlite, Kimberley } from Wade and Prider (1940). Nos. 2, 3, and 4, p. 85.
h. Katungite, Katunga volcano; from Holmes (1936). No. E, p. 395.
j. Leucite basalt, El Capitan, New South Wales
k. ,, ,, Byrock, New South Wales } from Harvey and Joplin (1940), Nos. 1 and 111, p. 439.
l. Biotite-pyroxenite, Newry Complex, Seeconnell, Co. Down, N. Ireland.
m. Leucite basalt, Todilta Park, Navajo Province, Arizona; from Williams (1936), No. 6, p. 166.
n. Orendite, Leucite Hills, Wyoming; from Washington (1917), p. 592.
o. Shonkinite, Lower Shonkin Sag; from Hurlbut and Griggs (1939), No. 3, p. 1071.

Affinities of the Spanish basic potash-rich lavas with other lavas. In seeking affinities of the Spanish lavas with basic potash-rich lavas elsewhere, a number of distinct chemical features of the jumillites in particular, as they are the less altered rocks, have to be kept in mind, e.g. the low alumina contents of the jumillites, their potash:soda ratios of 2 or more, their high MgO:CaO ratios and high MgO contents, their high concentrations of TiO_2 and P_2O_5, and their moderate contents of BaO and Cr_2O_3. Considering these characteristics, it seems that lavas most likely to be comparable with the Spanish ones are to be looked for in the Vesuvian province of Italy (Rittmann, 1933); the Leucite Hills, Wyoming (Cross, 1897, and Hague, 1889), Navajo, Arizona (Williams, 1936), and Montana (Hurlbut and Griggs, 1939) provinces of America;

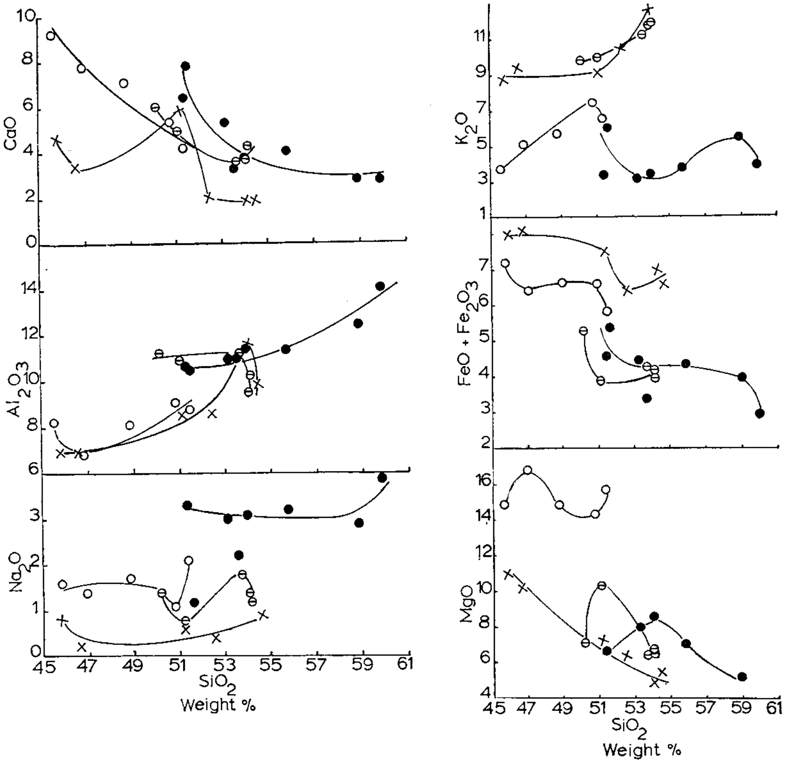

FIG. 3. Oxide variation diagrams for jumillites, verites, and related rocks. ⊖ Leucite Hills; ○ jumillites; × West Kimberley; ● verites.

the West Kimberley province of Australia; in various of the East African provinces of basic potash-rich lavas, e.g. Bunyaruguru, Bufumbira, and Katunga; and in some of the inclusions in kimberlite pipes (Williams, 1932). Table IV gives analyses of rocks that may be compared with the Spanish lavas. Of the non-Spanish rocks mentioned above, those of the Vesuvius area tend to be exceptionally rich in leucite and there is no doubt that the high percentage of limestone fragments in the extruded rocks of the area give credence to Rittmann's (1933) suggestion that assimilation of basement limestones by trachytic magma gave rise to the sequence of lavas observed. The Spanish rocks are not leucite-rich and there is no evidence in the jumillite lavas that assimilation of carbonate rocks has played any part in modifying the composition of the parent magma. Of the East African rocks, the Bufumbira lavas (Holmes and Harwood, 1937) are much richer in alumina than those of Spain and they tend to have higher CaO contents compared with MgO. Although much more basic than the verites the Bufumbira rocks have more affinities with the latter than with jumillites. The Katunga lavas, e.g. table IV (h) discussed by Holmes (1937 and 1950) are more basic and richer in CaO than the jumillites; to obtain jumillite from Katungite of type (h) in table IV it would be necessary to subtract melilite from the latter, and although melilite-bearing lavas occur in a number of the Italian basic potash-rich lava provinces (e.g. Washington, 1927), none have been reported in the Jumilla or Vera areas of Spain. Of the mica-pyroxenites, mica-peridotite, and kimberlite in table IV (a, b, e, f, g, and l), the mica pyroxenite from kimberlite (g) is extremely rich in potash and total iron compared with the Spanish lavas, the two kimberlites (e, f) have comparatively high iron contents, and all these rocks with the exception of (f) and (l) tend to have low phosphorus contents (an important point when considering the affinities of jumillites). The mica-pyroxenite (l) is of interest as it shows some similarities to the jumillites, and might be considered a slightly more basic, iron-rich variety of jumillite of type J1 (table I, no. 1). Two of the best studied groups of lavas (intrusive and extrusive) of basic-potash type outside the East African areas are those of West Kimberley (Australia) and the Leucite Hills (U.S.A.): an analysis of orendite from the latter area is given in table IV (n). Mineralogically these two groups of rocks have some similarities to jumillites and verites, as they contain diopsidic pyroxene, phlogopite, and leucite, but they lack the abundant olivine of the Spanish lavas. Variation diagrams that show the differences between the West Kimberley and Leucite Hills lavas and those from Spain are given in fig. 3. Trends of various oxides plotted against silica for all four groups of lavas tend to be irregular, but part of the irregularity, at least for the verites and the West Kimberley lamproites, may be due to their degree of alteration. A few things are clear, however, from the diagrams: the basic nature of the jumillites compared with the other lavas, the high potash content of the Leucite Hills and West Kimberley rocks, and the alumina-poor nature of the jumillites and West Kimberley lamproites. In terms of minor elements the West Kimberley lavas are distinct from the others as their titania and baria contents (maxima of 7·34 % and 2·04 % respectively) are exceptionally high (Wade, 1937). Although, therefore, the four lava groups have many superficial chemical and mineralogical resemblances to one another it seems that their differences are important enough to rule out their having been formed by the same mechanism from a single parental type.

Most authors, e.g. Williams (1936), Holmes (1952), Rittman (1933), and Larsen (1940), have concluded that potash-rich basic lavas owe their curious chemical characteristics to processes of assimilation of other materials (e.g. limestones, granitic xenoliths, granitic feldspar) by basic, trachytic, or carbonatite magmas, although Prider (1960) still considers that differentiation from a primary peridotite magma or formation of lamproite magma by a process such as the 'zone-refining' one of Harris (1957) is the most likely explanation of the West Kimberley lamproites. The widespread acceptance of the idea that assimilation of granite or limestone by basic and ultrabasic magmas could account for the basic potash-rich lavas in certain areas is due in part to the abundant supporting field evidence for the hypothesis. In Spain the verites outcrop close to basement complex rocks and they often have high CO_2 contents, although part of this may be derived from limestones at high level by percolating waters; the composition of verite magma at depth might then conceivably have been modified by extraneous components. But in the area of Jumilla there is no indication that granites or basement rocks occur (unless at considerable depth) and there is no evidence in the rocks themselves that assimilation of granite or limestone has played any part in their formation. Like Prider (1960), therefore, the present author thinks that in the absence of supporting field evidence, a differentiation-assimilation origin for jumillites is unacceptable, and a differentiation origin from, possibly, a mica-pyroxenite type of parent is one that most fits in with the present chemical, mineralogical, and field data. In this connexion, modification by tectonic forces of the differentiation processes that give rise to basic potash-rich magmas seems likely, as many rocks of this type occur in areas where there has been considerable tectonic disturbance.

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