TWO LAMPROPHYRE DIKES NEAR SANTAQUIN AND MOUNT NEBO, UTAH

BY

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Shorter contributions to general geology, 1918

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INTRODUCTION.

No description of lamprophyre dikes in Utah has heretofore been published,[1] and this paper is presented as an addition to the petrology of the State. The two dikes here described are on the west slope of the Wasatch Mountains, near Santaquin and Mount Nebo, and were noted by the writer in 1912, while he was engaged in a reconnaissance of the ore deposits of central Utah.

LOCAL GEOLOGY.

STRATIGRAPHY.

The steep western front of the Wasatch Mountains in the Santaquin and Mount Nebo region exposes rocks of pre-Cambrian, Paleozoic, and Tertiary age, whose relations are complicated by overthrust and block faulting.[2] (See fig. 13.)

The pre-Cambrian is represented by reddish gneissoid granite with pegmatite veins and included bodies of schist, exposed for 2 miles or more along the lower west slope of the main range southeast of Santaquin. This granite is overlain unconformably by Cambrian quartzite, dipping 28° E., which does not appear to be over 800 feet thick (aneroid measurement). The quartzite is prominent along the middle west slope east of Santaquin and about 5 miles northeast of Mona. It passes upward into Cambrian shale, which corresponds to the Ophir formation to the north and west, and this is followed by a great thickness of limestones, the lower beds of which are probably

of Cambrian age and the higher beds certainly of Mississippian age. The upper Mississippian includes thin quartzite beds intercalated with limestone and shale. The limestones form the greater part of the range throughout the region, occupying most of the summit areas and upper western slopes and extending down to the west base of the range in the Mount Nebo mining district northeast of Mona.

The Tertiary rocks include coarse reddish conglomerate and concretionary limestone, which rest unconformably upon the Mississippian. They veneer the low ridges south and southwest of Santaquin and are very extensive on the east slope of the main range. These rocks are overlain by a coarse latite or andesite breccia, most of whose outcrops have been reduced to aggregates of loose cobbles.

DIKE ROCKS.

The only intrusive rocks noted in the region are the two lamprophyre dikes that form the subject of this paper. The northern dike is east of Santaquin, on the Black Balsam claim. It cuts pre-Cambrian granite, is 3 feet thick, trends northeastward, and dips about 70° SE. It is closely paralleled for part of its course by a vein of calcite and fluorite which contains a little chalcopyrite, galena, and corresponding oxidation minerals. The southern dike is south of the mouth of Bear Canyon, northeast of Mona, on the property worked by the Eureka Leasing & Mining Co. in 1912. It cuts Mississippian limestone, is 4 feet wide, strikes N. 45°–50° E., and has a vertical dip.

There is no local evidence by which these dikes can be correlated with other igneous rocks. From their petrographic character, however, and their lack of deformation, it is

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[1] B. S. Butler has informed the writer that he has noted several biotite lamprophyre dikes during his recent detailed studies of the Cottonwood and Park City area in Utah.

[2] Loughlin, G. F., Reconnaissance in the southern Wasatch Mountains, Utah: Jour. Geology, vol. 21, pp. 447–451, 1913.

assumed that they represent a late stage of the Tertiary volcanic period, which is well represented by latites or andesites on Long Ridge, by granodiorite and quartz diorite to the north in the Cottonwood-American Fork region.[2] Lamprophyre dikes in the last-named

5   0   5 MILES

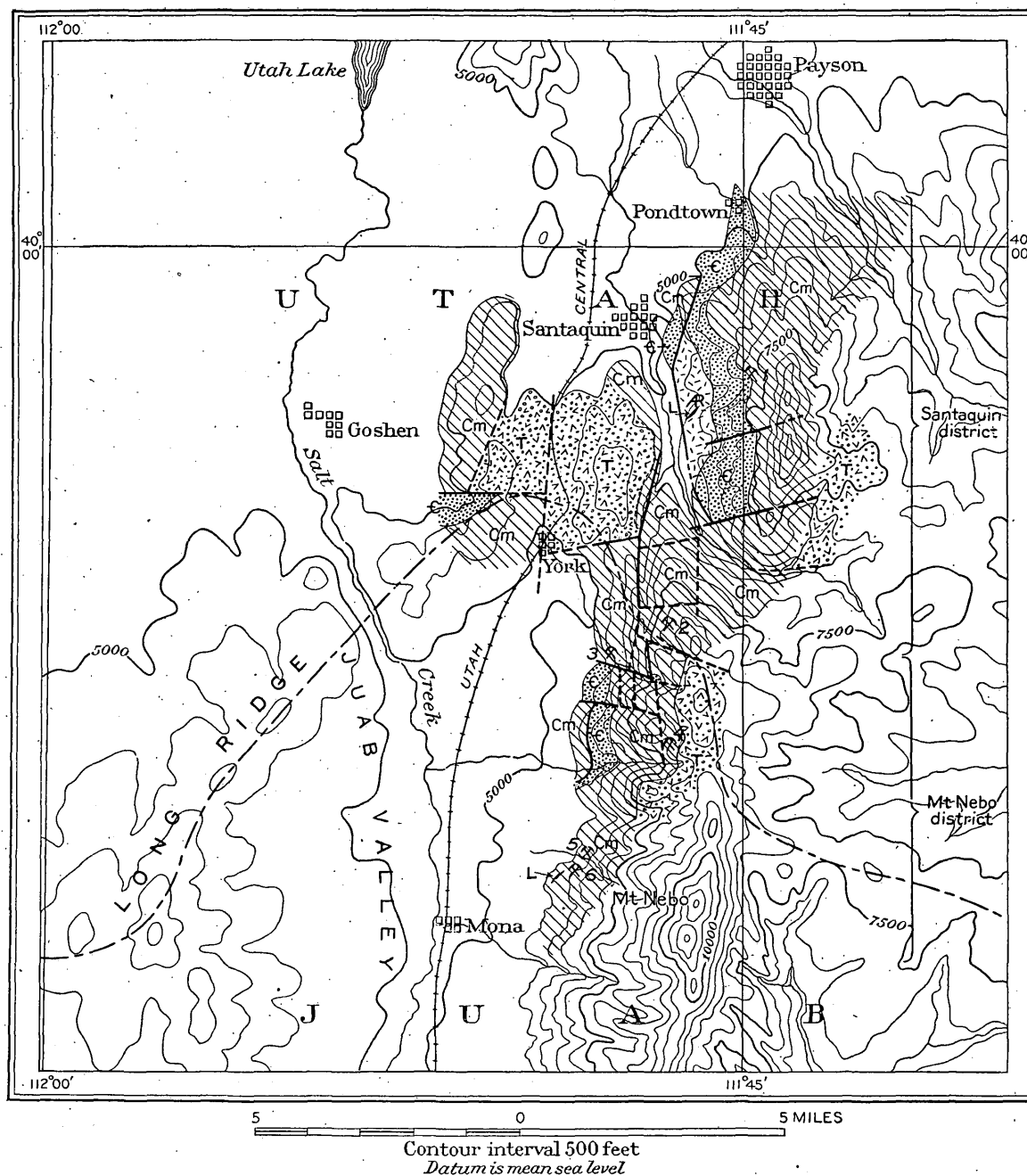Contour interval 500 feet
Datum is mean sea level

FIGURE 13.—Geologic map of the Santaquin and Mount Nebo region, Utah. Æ, pre-Cambrian granite; €, Cambrian quartzite; Cm, Mississippian and earlier limestones; T, Tertiary conglomerate and volcanic rocks; L, lamprophyre dikes. List of mines: 1, Union Chief; 2, Santaquin Chief and Santaquin King; 3, Big Nebo; 4, Eva and Nebo Highland; 5, Spider; 6, Freddie Lode (Eureka Leasing Co.).

west of Mona; by rhyolites, latites, and monzonite farther west, in the Tintic district,[1] and region, according to Butler, are the latest of the intrusive rocks.

[1] Lindgren, Waldemar, and Loughlin, G. F., Geology and ore deposits of the Tintic mining district, Utah: U. S. Geol. Survey Prof. Paper 107, pp. 42–75 (in press).

[2] Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 174–177, 1916.

STRUCTURE.

The attitude of the strata is for the most part homoclinal, with a prevailing dip of about 30° E., but some folds with steep to vertical dips are prominent east and northeast of Mona.

The most striking structural features of the region have been produced by overthrust and block faulting. The overthrusts are exposed, though not very clearly, east and south of Santaquin, near the north and south ends of the pre-Cambrian granite area; also along the west base of the range about 5 miles northeast of Mona. At all these places Mississippian limestone is overridden by Cambrian quartzite. The overthrust northeast of Mona clearly antedates the block faulting, as shown in figure 13. The relation of the overthrusts to local folding is not clear. They may be synchronous with or later than the folding, which elsewhere in Utah is assigned to post-Jurassic time but clearly antedates the intrusions of monzonite and related rocks with which ore deposits are genetically connected. The writer's investigations in the Cottonwood-American Fork [1] and West Tintic [2] districts, however, have proved that the overthrusts in those districts are older than the igneous intrusions and any accompanying deformations, which are probably of early Tertiary age, and he provisionally correlates the overthrusts in the Santaquin and Mount Nebo region with those in the districts mentioned.

The block faulting is marked by normal faults of northward and east-northeastward trends, most of which coincide in position with canyons. These faults were formed by the disturbances that caused the main uplift of the Wasatch Mountains and the ranges of the Great Basin. They are later than the volcanic breccia and presumably later than the two lamprophyre dikes and the ore deposits of the region, but there is no means of comparing the age of the dikes with any local faulting.

THE DIKES.

MEGASCOPIC CHARACTER.

The rocks are dark gray to black, dense, and porphyritic. Biotite is the only conspicuous

[1] Loughlin, G. F., op. cit., pp. 440-443. Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 178-179, 1916.
[2] Butler, B. S., and Loughlin, G. F., Ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111 (in press).

megascopic mineral, forming irregular scales and tablets 3 millimeters or less in diameter. These phenocrysts constitute about 20 per cent of the rock and give it the characteristic luster of lamprophyre. Alteration products of olivine, consisting largely of calcite in small thinly scattered spots, are visible on close inspection of the dike near Santaquin. The application of dilute hydrochloric acid produces brisk effervescence in both rocks.

MICROSCOPIC CHARACTER.

NORTHERN DIKE.

The northern dike, as seen in thin section, consists of a prevailingly glassy groundmass crowded with phenocrysts of augite, biotite, olivine, and magnetite and minute crystals of apatite. Phenocrysts 0.5 to 1 millimeter in diameter constitute about 25 per cent of the rock. Feldspar is present only in the groundmass. The feldspar and glass form less than 50 per cent of the rock. Calcite, fibrous monoclinic amphibole, and chalcedonic quartz are alteration products.

Augite is the most abundant microscopic phenocryst, making up about 35 per cent of the rock. It forms typically twinned prismatic automorphic grains. The main part has an extinction angle $(c \wedge \dot{c})$ between 45° and 50°, whereas that of a narrow marginal zone is about 5° greater. These angles do not accord with Rosenbusch's statement [3] that the pyroxenes of lamprophyres are of the diopsidic variety, and this is one characteristic in which the two dikes are exceptional. The augite is very free from alteration.

Olivine in hypautomorphic crystals as much as 2 millimeters long originally formed about 3 per cent of the rock. These crystals are now mostly altered to aggregates of calcite and a finely fibrous to platy monoclinic amphibole. A few crystals are replaced by serpentine and calcite. No secondary magnetite accompanies the alteration products.

Biotite forms many irregular to automorphic brown grains and tablets, most of them less than 0.5 millimeter long but some more than 1 millimeter. The larger phenocrysts have borders that are darker brown than the main part, a common feature in the biotite of lampro-

[3] Rosenbusch, H., Elemente der Gesteinslehre, p. 233, 1906.

phyres. All the biotite is of distinctly later growth than augite and olivine. As a whole it is free from alteration, but a few of the larger phenocrysts contain a little calcite.

Magnetite is present in fine grains, mostly of square outline, thickly scattered throughout the section. It is for the most part of later growth than the three minerals just described. No inclusions of it are found in the augite or olivine except along their margins, and very few are found in the biotite.

Apatite forms many small typical prisms. They appear to be mostly inclosed in biotite, but many in the groundmass may have been overlooked, owing to their close resemblance to the smallest augite crystals in transmitted light. No pyrite was identified in this section, although the chemical analysis signifies the presence of 0.24 per cent.

Feldspar is present in places, forming a poikilitic matrix for the minerals already described. It occurs in divergent or radiating aggregates, as shown by its extinction, but each aggregate appears to be a homogeneous crystal in other respects. Its mean index of refraction is a little above 1.52 and, together with the diverging habit, suggests albite. The isotropic groundmass has an index of refraction a little above 1.51. In a few places it forms small rounded areas free from phenocrysts and resembling an isotropic mineral such as analcite; but in some of these areas incipient growths of feldspar are recognizable, and no gelatinization was obtained by evaporation with hydrochloric acid. There is no sharp boundary between these rounded areas and the rest of the groundmass.

Chalcedonic quartz forms a few small irregular aggregates in the groundmass and is closely associated with calcite.

SOUTHERN DIKE.

The southern dike, as seen in thin section, consists of phenocrysts of biotite, augite, apatite, and magnetite in a groundmass of feldspar which has a distinctly diverging or radiating habit. Alteration products are pyrite, calcite, chalcedonic quartz, chlorite, and hematite.

In this rock biotite is more abundant than augite, constituting about 20 per cent of the section. It forms hypautomorphic crystals, the largest of which are not much over 1 millimeter in diameter. Its pleochroism, as a whole, is from medium brown to white. The borders of the crystals are darker brown than the main part. The central parts of some crystals are olive-colored. Alteration products, which are very scarce, include calcite and chlorite. The biotite crystallized later than the augite.

Augite forms hypautomorphic grains, none more than 1 millimeter long. The more prominent grains constitute about 5 per cent of the rock. Some grains show a little alteration to calcite, and some have fringes and veinlets of a very finely fibrous mineral, probably amphibole.

Apatite forms prominent though small typical prisms, the largest 0.2 millimeter long. Magnetite is present only as fine grains of square outline, some of which are altered to hematite.

The radiating feldspar which makes up the groundmass has a mean index of refraction a little above 1.52 and a large axial angle and is optically positive. These properties all indicate albite. No orthoclase was recognized. Little or no isotropic material is present in the groundmass.

Pyrite forms a few irregular grains as much as 0.3 millimeter in diameter, which may be impregnations of the groundmass rather than primary crystals.

Calcite, besides impregnating augite and biotite, forms a few small round to irregular aggregates impregnating the groundmass. Some of these are accompanied by chalcedonic quartz and some by pyrite.

CHEMICAL COMPOSITION.

The chemical composition of the northern (Santaquin) dike is shown by the analysis in column 1 of the accompanying table, which includes also the most closely corresponding analyses given by Washington.[1]

[1] Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 14, pp. 315-317, 1903. A second edition (Prof. Paper 99) of this work has been issued since the completion of the present paper.

Chemical analyses of lamprophyre from Santaquin, Utah, and rocks of similar composition.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	45.59	45.47	46.67	48.36	51.68	48.73	52.09[b]	48.66	44.27	46.47	49.45	50.79
Al_2O_3	12.02	13.07	12.64	12.42	14.07	11.92	11.93	12.36	10.73	15.97	14.41	15.26
Fe_2O_3	3.84	6.72	6.13	5.25	4.71	4.79	1.84	3.08	3.63	5.97	3.39	3.29
FeO	5.05	12.43	10.17	2.48	4.57	4.56	7.11	5.86	5.87	4.27	5.01	5.54
MgO	7.09	2.80	5.64	9.36	7.72	5.93	12.48	8.09	5.87		8.26	6.33
CaO	10.21	6.79	11.48	8.65	6.65	9.24	7.84	9.97	10.80	10.54	6.73	5.73
Na_2O	1.82	2.04	1.64	1.46	2.45	2.62	2.04	2.71	1.07	1.69	2.54	3.12
K_2O	3.90	3.36	2.31	3.97	4.16	2.47	3.01	5.15	4.43	4.83	4.69	2.79
H_2O+	3.59	6.06	2.64	5.54	2.09	1.52	.35	1.46	3.23	2.32	2.43	2.74
H_2O-	1.64											
CO_2	1.91					5.80	.16				.61	2.97
TiO_2	1.67			1.18	1.08	1.34	.73	.97	1.37	1.33	1.23	1.02
ZrO_2	None.											
P_2O_5	1.33	.52	.74	.84	.72	.32	.34	1.07	.83	.73	1.12	.35
MnO	.16	.21	.19	.13	Trace.	.36	.15	.13	.06	.01	.13	.07
BaO	.20			.29		Trace.		.40	.48			
SrO	.16							.09	.18			
S	.13				.13	.34						
Cr_2O_3	Not det.	.28	.34	Trace.			.10					
NiO							.07					
Cl						.11						
Li_2O					Trace.	Trace.						
Sum	100.31	99.85	100.49	99.93	100.03	100.05	100.24	100.00	100.00	100.00	100.00	100.00
Specific gravity	[a]2.755	2.331	2.703				2.94					

[a] Apparent specific gravity. The apparent specific gravity of the southern (Mona) dike is 2.680.

1. Albite minette, Black Balsam claim, Santaquin, Utah. George Steiger, analyst.
2, 3. Basalt, Assab, near Massowa, Abyssinia. Ricciardi, L., Soc. geol. italiana Boll., vol. 5, p. 59, 1886.
4. Absarokite, Clarks Fork, Yellowstone National Park. Iddings, J. P., Jour. Geology, vol. 3, p. 938, 1895; U. S. Geol. Survey Mon. 32, pt. 2, p. 329, 1899.
5. Absarokite, Two Ocean Pass, Yellowstone National Park. Iddings, J. P., U. S. Geol. Survey Mon. 32, pt. 2, p. 329, 1899.
6. Kersantite, Big Horn Pass, Yellowstone National Park. Iddings, J. P., U. S. Geol. Survey Mon. 32, pt. 2, p. 70, 1899.
7. Kentallenite, Glen Shira, Argyllshire, Scotland. Hill, J. B., and Kynaston, H., Geol. Soc. London Quart. Jour., vol. 56, p. 537, 1900.
8. Average shonkinite. Daly, R. A., Am. Acad. Arts and Sci. Proc., vol. 45, p. 228, 1910.
9. Average missourite. Daly, R. A., op. cit., p. 229.
10. Average leucite basalt. Daly, R. A., op. cit., p. 229.
11. Average minette. Daly, R. A., op. cit., p. 233.
12. Average kersantite. Daly, R. A., op. cit., p. 233.

The noteworthy features of this analysis are low SiO_2 and relatively high alkalies, with K_2O in excess of Na_2O, which class the rock with alkaline varieties rather than normal basalt; also the high content of H_2O, CO_2, TiO_2, and P_2O_5. The H_2O+ is only in part accounted for by biotite and the fibrous amphibole to which olivine is altered, and the remainder is evidently present in the isotropic groundmass, partly in small bubble inclusions and partly in solid solution. CO_2 is present in calcite, which was introduced either at the close of consolidation or somewhat later, at the time of ore deposition. The TiO_2 is definitely referred to fine rutile needles in biotite and is doubtless present as a minor component of biotite, augite, and magnetite. The fact that the finely powdered rock is almost entirely picked up by a weak hand magnet is proof that little or no free ilmenite is present. The high P_2O_5 is attributable to abundant apatite, which is a characteristic feature of lamprophyres and certain other rocks of similar chemical composition.

Apparent discrepancies between the analysis and the mineral composition (mode) of the rock are the high CaO (about 6.5 per cent available for silicates), in contrast to the absence of calcic plagioclase, and the relatively high K_2O, in contrast to the absence of recognizable orthoclase. In the calculation of the mode, however, the CaO is found to be just sufficient

to satisfy augite. The K_2O in excess of that required by biotite evidently belongs to the glassy groundmass.

The difference between the norm and mode is shown below. The orthoclase in the norm includes the large quantity of K_2O actually present in biotite, the albite includes the small quantity of Na_2O in augite, and the anorthite includes much of the CaO and all of the Al_2O_3 in augite. The diopside and hypersthene and part of the olivine, magnetite, and ilmenite in the norm are actually present in augite and biotite.

Calculated mineral composition of lamprophyre dike at Santaquin, Utah.

Norm.		Mode.	
Orthoclase	22. 80	Orthoclase molecule [1]	11. 12
Albite	15. 20	Albite	12. 05
Anorthite	13. 34	Anorthite	None.
Diopside	14. 73	Augite	35. 04
Hypersthene	8. 85	Biotite	21. 27
Olivine	3. 69	Olivine	1. 04
Magnetite	5. 57	Magnetite	2. 78
Ilmenite	3. 19	Ilmenite	. 91
Apatite	3. 02	Apatite	3. 02
Pyrite	. 24	Pyrite	. 24
Calcite	4. 30	Calcite	4. 30
Water (+)	3. 59	Chalcedony	3. 90
Water (−)	1. 64	Water (+) unassigned	2. 83
		Water (−)	1. 64

As no analyses of the augite or biotite were made, the calculation of the mode is only approximate. The assumed composition of these two minerals is based on analyses of augites and biotites from rocks that are similar in composition to the Santaquin lamprophyre.[2] According to this assumption the CaO not present in apatite and calcite is exactly the amount required by the augite, a condition perfectly in accord with the optical character of the augite and the only recognizable feldspar, albite. The absence of modal anorthite causes the ratios of Al_2O_3 to K_2O (1.9) in biotite and of Al_2O_3 to CaO (0.30) in augite to be higher than the average for these minerals, but no higher than in some of the analyses tabulated by Cross, Iddings, Pirsson, and Washington.[2]

The low percentage of olivine in the mode compared to that estimated in thin section is doubtless due to small errors in the assumed

[1] In glassy groundmass.
[2] Cross, Whitman, Iddings, J. P., Pirsson, L. V., and Washington, H. S., Quantitative classification of igneous rocks, tables 12 and 14, 1903.

MgO and FeO contents of biotite and augite. The rather high percentage of chalcedony is attributed to similar errors in the assignment of silica.

Further evidence to confirm some of the foregoing statements was afforded by treating the rock with strong hydrochloric acid and evaporating to dryness. The constituents dissolved are shown in the second column below.

Partial analyses of constituents of lamprophyre dikes soluble in hydrochloric acid.

	Dike at Santaquin.			Dike at Mona: Soluble in HCl.
	Per cent in complete analysis.	Soluble in HCl.	Difference.	
$Al_2O_3+P_2O_5$	13. 35	10. 13	3. 22	4. 10
Fe_2O_3	3. 84	7. 42		5. 31
FeO	5. 05			
MgO	7. 09	4. 51	2. 58	4. 22
CaO	10. 21	5. 41	4. 80	5. 52
TiO_2	1. 67	. 95	. 72	. 51
CO_2	1. 91	1. 91	. 00	

In the Santaquin dike there is only about 1.9 per cent soluble CaO in excess of that in calcite and apatite, and this may as well have come from slight corrosion of augite as from any undetected sodic plagioclase. The soluble magnesia is mainly that derived from olivine and biotite; the iron from olivine, biotite, and magnetite; the titanic oxide from biotite and magnetite. The alumina is derived largely from biotite, but the proportion can not be told without determining the soluble alkalies. The soluble MgO and CaO indicate roughly the ratio in augite, which is only slightly less than that assumed in the calculation of the mode. Microscopic examination of the insoluble residue showed it to consist mostly of augite and scales of isotropic silica left by biotite, with small amounts of albite, fibrous amphibole, and glassy groundmass.

The soluble portion of the dike near Mona agrees well with that of the Santaquin dike as regards MgO and CaO. Its lower content of Al_2O_3 and Fe_2O_3 is due in part to the incomplete decomposition of biotite, shown by microscopic examination of the residue, and perhaps in part to the greater insolubility of its thoroughly crystallized feldspathic groundmass.

CLASSIFICATION.

According to the quantitative classification the Santaquin dike is designated by the coordinates III.5.3.3 (kentallenose). The excess of K_2O over Na_2O is only a little lower than that of III.5.3.2 (absarokose). According to its mode, it belongs to the minette-kersantite group of lamprophyres. It differs from typical minette and kersantite, however, in possessing a largely isotropic groundmass and in this respect resembles monchiquite or analcite basalt; but the isotropic material has too high an index of refraction for analcite, is not readily soluble, and does not gelatinize in hydrochloric acid. The rock differs further from minette in containing no recognizable orthoclase or anorthoclase, although its mode shows that one or both of these minerals would appear if crystallization were completed. It differs more markedly from kersantite in the absence of a conspicuous amount of anorthite molecule in the feldspar and is best designated by the name vitrophyric "albite minette." The name "albite minette" is equally applicable to the dike near Mona.

In chemical composition the Santaquin dike differs considerably from the minettes represented in the superior analyses tabulated by Washington.[1] These are designated in the quantitative system by II.5.2.3 (monzonose), II.5.2.4 (akerose), and II.5.3.2 (not named). They differ from the Santaquin rock in having higher SiO_2 and Al_2O_3, lower Fe_2O_3, FeO, and CaO, and two of the three have lower MgO and higher Na_2O. Of the minettes analyzed since the publication of Washington's tables in 1903, a rock described by Ransome[2] is lower than the Santaquin rock in SiO_2 and Al_2O_3 and higher in K_2O, TiO_2, and especially P_2O_5, corresponding to the coordinates III.6.1.2 (washingtonose). Another minette, described by Cross,[3] resembles this one more closely than the Santaquin rock. Of the analyzed minettes described by Daly,[4] two are designated monzonose and one III.5.2.2 (prowersose). The latter, an olivine-augite minette, agrees with the Santaquin rock rather closely in percentages of SiO_2, Al_2O_3, Na_2O, and K_2O, and in having a glassy ground-mass. A lamprophyre between minette and kersantite, described by Schrader,[5] is designated by the coordinates II.5.3.3 (shoshonose). These differences in classification show that the relatively few rocks sufficiently similar in mineral composition to be classed as minette vary considerably in relative amounts of chemical constituents.

There is closer agreement between the Santaquin dike and three of the four inferior analyses of minette tabulated by Washington,[6] although these show considerably more Al_2O_3.

Compared with Daly's average of 10 analyses of minette[7] (column 12, p. —)the analysis of the Santaquin rock is rather low in SiO_2 and Al_2O_3, about normal in Fe_2O_3 and MgO, high in CaO, and rather low in alkalies, though similar in the Na_2O–K_2O ratio. High H_2O and and P_2O_5 are characteristic of several minettes, as is high TiO_2 to a less extent.

One analysis of altered kersantite (column 6, p. —) is very similar to that of the Santaquin rock except in the ratio of Na_2O to K_2O and in low P_2O_5. Most analyses of kersantite, however, are higher in SiO_2 and Al_2O_3 and lower in iron oxides MgO and CaO.[8]

SIMILAR ANALYSES OF OTHER ROCKS.

Analyses 2, 3, 4, 5, and 7 in the table on page— represent other rocks which in some respects agree more closely with the Santaquin rock than the minettes and kersantites, whose analyses are given. With the exception of Nos. 2 and 3, which are termed basalt, the rocks represented by these analyses are the uncommon absarokite and kentallenite. All except No. 4 (absarokose) belong to the subrang kentallenose. The Santaquin rock differs from the absarokites in its abundance of biotite and from both absarokite and kentallenite in its lack of calcic plagioclase.

Although single analyses of shonkinite differ in various ways from that of the Santaquin rock, falling in groups II.6.2.3, III.6.1.1, and III.6.2.3 of the quantitative system, Daly's average analysis of shonkinite (column 8) is

[1] Washington, H. S., op. cit., pp. 255, 263, 265.

[2] Ransome, F. L., An apatitic minette from northeastern Washington: Am. Jour. Sci., 4th ser., vol. 26, pp. 337–339, 1908.

[3] Cross, Whitman, Dike rocks of the Apishapa quadrangle, Colo.: U. S. Geol. Survey Prof. Paper 90, pp. 18–20, 1915.

[4] Daly, R. A., Geology of the North American Cordillera at the forty-ninth parallel: Canada Geol. Survey Mem. 38, pp. 306–312, 1912.

[5] Schrader, F. C., Mineral deposits of the Cerbat Range, Black Mountains, and Grand Wash Cliffs, Mohave County, Ariz.: U. S. Geol. Survey Bull. 397, pp. 32–33, 1909.

[6] Washington, H. S., op. cit., p. 397.

[7] Daly, R. A., Average chemical compositions of igneous rock types; Am. Acad. Arts and Sci. Proc., vol. 45, p. 233, 1910.

[8] Washington, H. S., op. cit., pp. 227, 251, 259, 265, 269, 271, 281, 315, 317, 411, 413.

very similar, as are his average analyses of missourite and leucite basalt.[1] The similarity of the minettes of the Highwood Mountains to the shonkinites of the same region was pointed out by Pirsson.[2] The relatively low content of water, especially H_2O+, in shonkinites may be attributed in part to its escape during relatively prolonged crystallization as well as to freedom from alteration.

CORRELATION AND GENESIS.

Minettes and kersantites are generally regarded as mafic products, complementary to aplites, of the differentiation of granitic and dioritic magmas and are found closely associated with large intrusive masses of these rocks. The nearest mass of post-Cambrian granite or granodiorite to Santaquin and Mona is about 35 miles to the north, in the Cottonwood and American Fork mining region,[3] and the only other intrusive mass within an equal distance is the monzonite stock of the Tintic mining district, 18 miles to the west.[4] The fact that the dike near Mona cuts Carboniferous limestone precludes correlation with the pre-Cambrian granite of the Santaquin district. Correlation of the dikes with certain intrusive stocks is therefore impossible. As the Cottonwood and Tintic stocks, above mentioned, were intruded in Tertiary time, and as the extensive sheets of lavas in central Utah were erupted in Tertiary time, it is inferred that the two dikes also are of Tertiary age.

The volcanic breccia in the Santaquin district is of latitic or andesitic character, as are the greater part of the volcanic rocks to the west as far as the Tintic district. The only rhyolites of the region are closely related to the monzonite and latite of the Tintic district in both occurrence and composition. It seems probable, therefore, that the two minettes under discussion are genetically related to a monzonitic magma represented by the latite breccias and flows of the region. The norm of the Santaquin dike (p. 106) is monzonitic as regards ratio of feldspar, though high in femic minerals.

The isolation of the Santaquin dike from other intrusive rocks prevents more than general speculation regarding its origin, which may be attributed, first, to a concentration of femic constituents and normative calcic plagioclase in a monzonite magma; second, to conditions that caused the crystallization of abundant biotite and aluminous augite instead of less aluminous mafic minerals and calcic plagioclase. It may be assumed, in accordance with Bowen's hypothesis,[5] that at some stage in the period of monzonitic intrusions and eruptions parts of the magma undergoing gravitative differentiation became enriched in alkalies, water, and other volatile constituents, which both increased fluidity and lowered the temperatures of crystallization. Further differentiation was thus promoted, and separation of the heavier constituents continued. These constituents may have been redissolved to some extent by sinking to a depth where the temperature was high enough, thus forming a basic submagma relatively high in alkalies and water. Whether or not this happened, final crystallization took place as follows: Olivine crystallized until the temperature became too low for it to exist in equilibrium with the magma; then, instead of hypersthene, diopside, and calcic plagioclase, the more complex mineral, augite, formed. Although augite contains very little water, the fact that it does not crystallize from dry fusions indicates that water and other volatile constituents of the magma may have been the factors that determined its crystallization. The zonal character of the augite, showing an increase in content of alumina as it grew, is of interest in view of the absence of the anorthite molecule in the feldspar of the rock. At still lower temperature biotite, a hydrous mineral that probably contains fluorine, crystallized, perhaps overlapping the period of later augite in the groundmass to some extent. After the larger biotite crystals had nearly attained their growth, magnetite crystals begin to form, but the magma solidified before they could attain any considerable size.

The position of apatite in the order of crystallization is not so definite as that of any of the

[1] Daly, R. A., op. cit., pp. 228, 229.

[2] Pirsson, L. V., Petrography and geology of the igneous rocks of the Highwood Mountains, Mont.: U. S. Geol. Survey. Bull. 237, pp. 145–146, 1905.

[3] Butler, B. S., and Loughlin, G. F., A reconnaissance of the Cottonwood-American Fork mining region, Utah: U. S. Geol. Survey Bull. 620, pp. 175–176, 1916.

[4] Lindgren, Waldemar, and Loughlin, G. F., Geology and ore deposits of the Tintic mining district, Utah: U. S. Geol. Survey Prof. Paper 107, pp. 64–69 (in press).

[5] Bowen, N. L., The later stages of the evolution of the igneous rocks: Jour. Geology, supplement to vol. 23, No. 8, pp. 41–61, 1915.

other minerals, owing to the small size of its crystals. They are clearly older than the large biotite crystals but are not found inclosed in olivine or augite.

Crystallization of feldspar, partial in the Santaquin dike and complete in the Mona dike, marked the final stage of consolidation. Considerable of the water and other volatile matter not entering into biotite was retained in the rock, either as minute fluidal inclusions or dissolved in the glass groundmass. The retention of water and other volatile matter may be an important factor in rendering lamprophyres especially subject to hydration and carbonatization. Olivine is evidently unstable in their presence, even at high temperatures. Other minerals or glass in equilibrium with them at high temperatures are subject to attack by them at low temperatures, and the long time since consolidation, supplemented by dynamic disturbances that caused fracturing, would favor hydration and carbonatization. The presence of metalliferous deposits in contact with or close by the Santaquin and Mona dikes leaves the source of water and carbon dioxide in their alteration products in doubt, but the suggestion may be worthy of consideration in the study of other lamprophyres.

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