

duced with the camera in the normal position and pairs of front reflection lines produced with the camera in the rotated position. Table 1 shows a comparison of the correction factors obtained for three different patterns of silicon using both methods. It can be seen that the agreement in this case is good to one part per thousand.

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WAIRAKITE IN WEST INDIAN SPILITIC ROCKS

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INTRODUCTION

An occurrence of wairakite in spilitic rocks from St. Thomas, Virgin Islands, is of special interest for several reasons. In the first place, this is the first record of this rare zeolite from spilitic rocks. Secondly, this is the first instance in which wairakite can be shown to be replacing albite and not a more calcic feldspar; therefore, the lime for the zeolite in this case was not derived from the plagioclase. Thirdly, if the hypothesis of an essentially primary origin for this mineral is accepted, then some rather interesting and important conclusions can be drawn regarding the chemical and physical conditions prevailing during the final stages of consolidation of this spilitite.

The oldest rocks of St. Thomas are the keratophyres and spilites of the Water Island Formation. This formation consists of about eighty per cent keratophyre (including quartz keratophyre) flows and pyroclastics and twenty per cent spilitite flows. The age is pre-Upper Cretaceous and the volcanic rocks appear to have escaped regional metamorphism. These rocks have been described elsewhere (Donnelly, 1959, and in MS). Wairakite was originally found in a poorly exposed spilitite

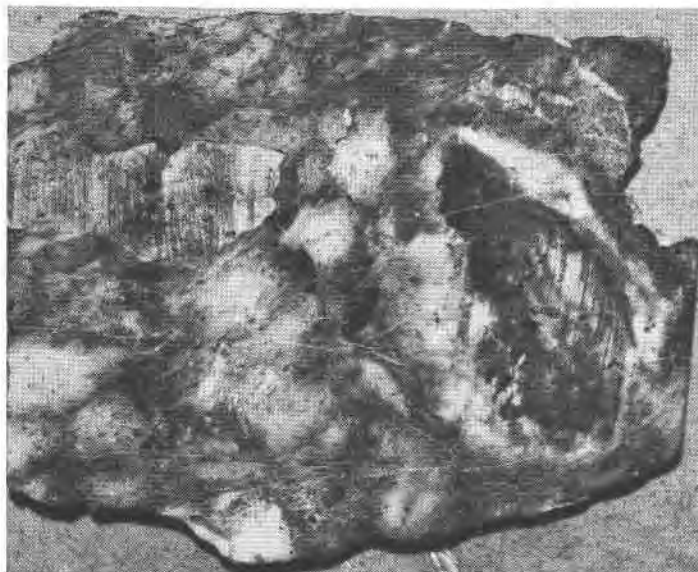


FIG. 1. Polished section of wairakitic rock, showing two keratophyre xenoliths. The larger of the two has a well-developed rim of wairakite, but the other shows no rim. White patches in the center of the section are smaller, completely replaced xenoliths. Length of section 5 inches.

flow at Nadir, St. Thomas. Later field work showed that there were probably many occurrences of this mineral in spilite flows, but these occurrences could not be confirmed because the samples were lost during shipping. The original occurrence is a spilite flow about fifty feet in thickness and crowded with xenoliths of keratophyre. In many parts of the flow there is no megascopic reaction of the spilite with the xenoliths, but in a few places the xenoliths are found to be replaced by a chalky white mineral (Fig. 1). This mineral was determined as wairakite by its optical and x -ray properties (Tables 1, 2) and by partial chemical analyses

TABLE 1. OPTICAL PROPERTIES OF WAIRAKITE FROM ST. THOMAS AND WAIRAKI

	St. Thomas	Wairaki (Steiner)
	n (mean) $1.502 \pm .001$	α $1.498 \pm .001$
γ - α	.0015 to .0025	γ $1.502 \pm .001$
$2V_{\gamma}$	50° to $66^{\circ} \pm 5^{\circ}$.004
	$r > v$	70° to 105° , av. 90°
		$r > v$

Polysynthetic twinning parallel to $\{110\}$ in both cases.

TABLE 2. X-RAY DATA FOR WAIRAKITE FROM ST. THOMAS AND WAIRAKI

hkl^1	St. Thomas		Wairaki (Coombs)	
	d Å	I	d Å	I
(200)	6.84	40	6.85	40
(211)	5.57	100	5.57	80
Impurity?	3.65			
(400)	{ 3.39 3.42	{ 95 100	{ 3.39 3.42	{ 60 100
(411) (330)	{ 3.202 3.061	{ 20 10	{ 3.21 3.04-3.06	{ 10B 10B
(332)	{ 2.913 2.898	{ 40 30	{ 2.909 2.897	{ 50 30
?	2.783	10B		
?	2.766	10B		
(431) (510)	2.674	20	{ 2.680 2.67	{ 40 10
(521)	(Quartz)		{ 2.50 2.489	{ 10 40
(611) (532)	{ 2.454 2.414 2.000 1.999	{ 10 10 5B 5B	2.215	40
(640)	{ 1.895 1.889	{ 10B 10B	{ 1.895 1.886	30B
(633) (721) (552)	1.855	10B	{ 1.867 1.857 1.844	{ 10 30 10
(732) (651)	{ 1.759 1.706	{ 15 5B	1.722-1.732	40B
(741) (811) (554)			1.680	20B
?	1.673	5B		

¹ Note: (hkl) values based on analogy with isometric analcime, according to scheme of Coombs.

(showing high CaO and low Na₂O contents) of those portions of the rock which were especially rich in this mineral. The subsequent field identifications of this mineral were based on its chalky white appearance, and on its occurrence rimming keratophyre xenoliths in spilite flows.

PETROGRAPHY

The mineralogy of the Virgin Islands spilites is typical for the rock type generally: albite microlites set intersertally in a chloritic matrix with fresh diopside phenocrysts and numerous amygdules containing epidote, prehnite, chlorite, calcite and quartz. The thicker flows are commonly highly altered (apparently both before and after consolidation) and the early minerals irregularly replaced by calcite, quartz and (rarely) muscovite. The original intersertal textures are generally preserved during alteration, but commonly they are destroyed. The mineralogical and textural characteristics of these spilites supports the thesis that these rocks represent the crystallization of a hydrous andesitic magma in an environment in which the separation of the volatile phase was retarded by the pressure of superincumbent sea water. At any rate, there appears to be a stage late in the consolidation of the rock during which albite has formed and most of the lime and much of the alumina content of the magma is still in a mobile form. Much of this will crystallize later as amygdular prehnite, epidote, chlorite or calcite, depending largely on the physical conditions prevalent at the time and upon the partial pressure of carbon dioxide in the system. In the case of the wairakitic spilite-keratophyre hybrids, this material has apparently reacted with the siliceous xenoliths to form the relatively siliceous zeolite, wairakite.

The wairakite-bearing rock has the microscopic appearance of a highly altered spilite, with no trace of the intersertal texture remaining. Wairakite occurs as ill-defined patches and streaks intimately mixed with quartz, chlorite, mica?, epidote (rare) and opaques including pyrite. There is also an amorphous substance which is nearly colorless and has an average index of refraction of about 1.62. The xenoliths have been altered from a normal keratophyre (albite phenocrysts in a fine-grained groundmass of quartz and albite with minor opaques and chlorite) to an intimate mixture of quartz and wairakite, with much of the same high-index amorphous material as occurs in the altered spilite itself.

With the exception of the occurrence of the wairakite which rims keratophyre xenoliths, there are few of the conventional petrographic criteria for replacement. However, the occurrence of wairakite replacing the large (to 2 mm) albite phenocrysts in the keratophyre is instructive in this

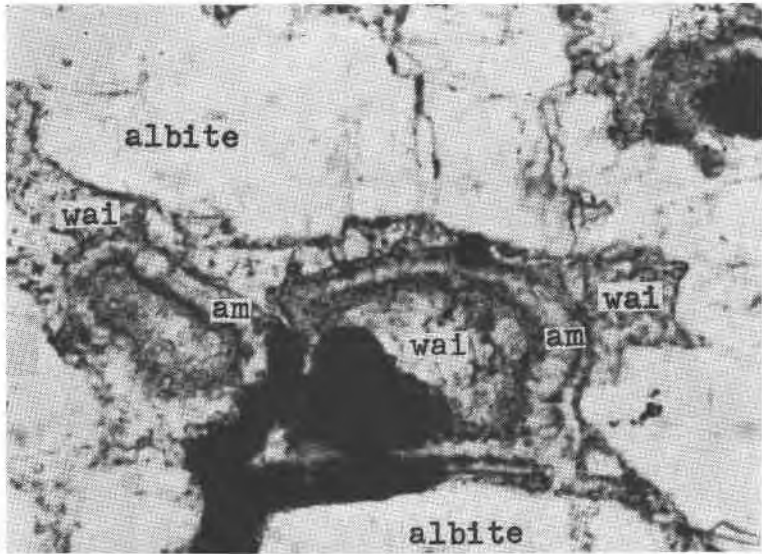


FIG. 2. Photomicrograph of a portion of an albite phenocryst within a keratophyre xenolith, showing the occurrence of wairakite (wai) between the amorphous substance (am) and the host albite. Plane light, $\times 400$.

regard. Large phenocrysts (Fig. 2) are rounded, embayed, and preferentially replaced along prominent cleavages. The replacing materials are wairakite and the same amorphous, high index material found in the groundmass of the spilite. The relationship between the two is that wairakite always occurs between the albite host and the amorphous material, and both of these materials show rounding, apparently as a result of replacement by wairakite. The petrographic criteria suggests that the wairakite occurs here as a reaction between the albite and the amorphous material, and it would be interesting to identify this material. The relatively high index (about 1.62) of this nearly colorless material suggests that it is probably relatively high in lime, magnesia, iron or a combination of these. *X*-ray diffraction of a carefully picked sample shows only low-angle scattering, which indicates very small particle size. In many cases the material shows very small domains of birefringence, but these cannot be resolved into crystalline forms, and they appear to result from microfractures within the amorphous material. Microchemical confirmation of the belief that this material contains lime is not practical because it is always intimately surrounded with wairakite. Nevertheless, I suspect it to represent the late magmatic material which was responsible for the replacement of the keratophyre and its phenocrysts. Its present

composition, of course, may be significantly different from its original composition. The reaction between the material (assuming it to contain lime) and the keratophyre can be written as follows:



This reaction may have gone much further in the matrix of the keratophyre than within individual albite phenocrysts because of the unlimited available SiO_2 in the matrix as contrasted with the possibly limited amount of available SiO_2 contained within the replacing material itself.

OPTICAL PROPERTIES

Optical properties are summarized in Table 1. It may be noted that these properties are very similar to those recorded by Steiner (1955), with the possible exception of the optic angle. This was measured in the present study by measuring 2E according to the Mallard method with an oil immersion lens and correcting for index of refraction. Only a mean index of refraction could be measured because of the fine grain size and low birefringence of the wairakite. The birefringence was measured with a Berek compensator calibrated with co-existing quartz grains oriented on the universal stage.

Fine polysynthetic twinning parallel to $\{110\}$ was very striking, although in many cases the lamellae were so thin that they approached the limit of optical resolution. Although no crystal faces were seen, the nature of the twinning supports Coombs' (1955) contention that the mineral crystallized with cubic symmetry and twinned during transformation to monoclinic symmetry.

X-RAY PROPERTIES

The *x*-ray pattern (Table 2) was obtained on a Phillips Norelco diffractometer using filtered Cu radiation. The *d* values obtained compare very well with those reported by Coombs except that in a few parts of the pattern I was able to resolve more peaks than Coombs, whereas in other regions Coombs was able to resolve more. The most likely explanation for this is that the angular lattice parameters for my material probably differ by a small amount from those of the original Wairaki specimens.

CHEMICAL RELATIONSHIPS

Table 3 shows chemical analyses of the wairakitic rock, a typical spillite, and a typical keratophyre, all from St. Thomas. Inspection of the analyses shows that the wairakitic rock is not a simple mixture of these two rock types. If silica is taken as the fixed oxide, then the wairakitic rock is too high in alumina, lime and potash, and too low in magnesia and soda.

If this rock resulted from magmatic reaction with a xenolith, then one would expect a diffusion gradient to be established with respect to those minerals which are forming in the reaction zone. In this case, the formation of wairakite and mica created a chemical gradient for lime, alumina and potash, and these migrated into the zone of reaction. Albite and chlorite were replaced, and soda and magnesia in the wairakitic rock are relatively low. These chemical relationships might have resulted from later hydrothermal alteration, or metasomatism, but they could not have resulted from a simple mechanical mixing of the two rock types. Although the chemical data are not by themselves a proof of the hypothesis of xenolithic reaction, they are at least consistent with this idea.

SIGNIFICANCE OF WAIRAKITE FOR THE SPILITE PROBLEM

The scarcity of wairakite in nature suggests that it may be formed during unusual conditions. The first two reported occurrences (Steiner, 1955, 1958) were very similar: alteration of plagioclase of intermediate composition by hot springs. A subsequent discovery that wairakite occurred replacing andesine in Eocene tuffaceous rocks of Washington (Waters, pers. comm.; Wise, 1959) showed that this mineral can occur in very low grade metamorphic rocks, although in the latter case the mineral replaced was andesine. The St. Thomas occurrence is unique for two reasons. In the first place, albite is the mineral being replaced. I should note here that much keratophyric albite apparently crystallizes as high temperature albite and oligoclase and reacts with the magma to form quasi-low temperature albite, but that the Virgin Island keratophyres are almost universally low in lime (Table 3). Therefore, it is highly unlikely that much lime could have been obtained from the rock or from the plagioclase phenocrysts. Secondly, only keratophyre xenoliths show this reaction. There is abundant late amygdular quartz along with a number of lime-alumina silicates (epidote, prehnite, pumpelleyite) in other spilites, but these minerals never show any tendency to react to form wairakite, even in those rocks which have undergone low-grade contact metamorphism around small plutons. Also wairakite is not found replacing the labradorite or calcic bytownite phenocrysts in the overlying Louisenhoj tuffs and breccias. The restriction of this zeolite to some xenoliths of keratophyre within thick spilite flows indicates that a late magmatic process is responsible for its formation.

Recent work by Koizumi and Roy (1960) on the synthesis and stability of the calcium zeolites is of interest here. These workers found 1) that wairakite was favored by a siliceous environment, and that 2) wairakite forms most readily between the temperatures of 410 and 460° C., although it formed frequently in their experiments at about 350° C. and

TABLE 3. CHEMICAL COMPOSITIONS OF THE WAIRAKITIC ROCK, A TYPICAL SPILITE AND A TYPICAL KERATOPHYRE FROM ST. THOMAS

	W-20 spilite	ST-163 ¹ wairakitic rock	ST-128 keratophyre
SiO ₂	56.60	65.93	72.45
Al ₂ O ₃	14.65	16.32	11.31
Fe ₂ O ₃	1.94	1.00	1.11
FeO	4.62	3.15	3.60
MgO	6.36	2.39	2.99
CaO	6.01	2.81	.53
Na ₂ O	4.07	2.82	4.19
K ₂ O	.87	1.30	.33
H ₂ O—	.30	.18	.11
H ₂ O+	3.20	2.86	2.02
CO ₂	.39	.09	.03
TiO ₂	.50	.45	.42
P ₂ O ₅	.05	.08	.10
MnO	.14	.08	.06
BaO	.00	nd	nd
Total	99.70	99.46	99.25

Doris Thaemlitz, analyst.

¹ Corresponding to about 32% quartz, 25% albite, 21% wairakite, 12% muscovite, 8% aluminous chlorite and 2% oxides.

rarely as low as 300° C. Thus the occurrence of the St. Thomas wairakite is explained by a siliceous environment (silica-rich xenoliths) and relatively low temperatures of consolidation. This last conclusion is consistent with independent evidence for low temperatures: lack of visible baking effects, scarcity of chilling phenomena, abundance of bent albite lamellae, etc. The characteristics of this occurrence are also consistent with the hypothesis of a primary origin of these spilites: the occurrence of a rather large number of phases, and especially of phases of apparent world-wide rarity, is more easily explained by assuming a volcanic, *i.e.* non-equilibrium, origin for the rock than a metamorphic. I predict, however, that wairakite will not be found in many spilitic rocks for several reasons. In the first place, low carbon dioxide pressures are probably required (calcite is almost absent from this rock, though it is generally abundant in other spilites, including several with keratophyre xenoliths), and in the second place mild metamorphism will probably destroy this mineral. Thirdly, slightly higher temperatures will favor the formation of epidote. However, wairakite should be looked for, and any occurrence of analcime in spilites should be carefully verified.

ACKNOWLEDGMENT

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CHOOSING PRECESSION SCREEN SETTINGS

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The layer-line screen setting in the Buerger precession technique is usually obtained from tables like those in the International Tables for X-ray Crystallography (1959, p. 197) or by a graphic solution of the equation

$$\frac{r_s}{s} = \tan \cos^{-1} (\cos \bar{\mu} - d^*) \quad (1)$$

where, using the symbolism of Buerger (1944), r_s is the radius of the annular aperture in the layer-line screen, s is the layer-line screen's correct setting, $\bar{\mu}$ is the desired precession angle, and d^* is the spacing in reciprocal lattice units (r.l.u.) between those reciprocal lattice planes that are parallel to the film. The nomograms used for the graphic solution of Equation (1) are usually constructed for a particular value of $\bar{\mu}$ (15°, 20°, 25°, or 30° being the usual values). To photograph as large a portion of the reciprocal lattice as possible, a value of $\bar{\mu}$ other than the four cited may be desired. Two nomograms exist that permit s to be determined for any value of $\bar{\mu}$ between 0° and 35°, that of Evans, *et al.* (1949) and that of Tavora (1951). Both are complex to use and do not

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