

LARNITE, SCAWTITE, AND HYDROGROSSULAR FROM TOKATOKA, NEW ZEALAND

BRIAN MASON, *The American Museum of Natural History,*
New York 24, N.Y.

ABSTRACT

Near Tokatoka, North Auckland, New Zealand an andesite dike, probably of Pliocene age, has metamorphosed the surrounding limestone of the Onerahi Formation (Lower Tertiary). A marked mineralogical zoning parallel to the contact is noteworthy; from the contact outwards these zones consist largely of (1) hydrogrossular, thickness 6 inches; (2) larnite, thickness 30 inches; (3) scawtite, thickness 10 inches. Other minerals recognized include cristobalite, opal, spurrite, gehlenite, and wollastonite. The minerals are described in detail, and the maximum temperature during metamorphism is estimated to be about 800°.

INTRODUCTION

Near Tokatoka, North Auckland, New Zealand (approx. latitude 36° S, longitude 174° E) numerous small bodies of intermediate and basic igneous rocks intrude the country rock, which is mainly argillaceous limestone of the Onerahi Formation (Lower Tertiary). The regional geology has been mapped by the New Zealand Geological Survey (Ferrari, 1934). While searching the country rock for fossils my brother, Mr. A. P. Mason, observed an andesite dike well exposed in a small quarry opened for road material and drew my attention to it. It proved to have produced a well-defined zone of contact metamorphism in the enclosing limestone. Natural exposures are poor in this region, and it was a fortunate chance that this quarry was observed shortly after it had been opened.

The exact location according to the National Grid is N27/533560, and it is 2.1 miles due east of the Tokatoka Hotel. The andesite dike forms the backbone of a narrow ridge. When visited in December 1953 the quarry was about 20 feet deep and had been opened for about 50 feet along the strike (N. 20° E., dip 60° SE) of the dike.

The dike is about 12 feet thick, and consists throughout of a fine-grained grey andesite. No attempt was made to trace its extension beyond the quarry, but according to Ferrari's map it can be followed for about 400 yards before it is obscured by Recent swamp deposits. The zone of contact metamorphism in the enclosing limestone is clearly marked by the presence of a band of dense black rock which does not effervesce with acid—the larnite zone.

Detailed collection from the contact zone on the east side of the quarry showed that the contact with the andesite is a sharp one (Fig. 1). At the

contact itself the limestone has been changed to a white rock consisting largely of hydrogrossular. This rock continues for about six inches from the contact, when it passes rapidly into dense black larnite rock. This zone is about thirty inches wide, and is followed by a greyish-white band, about ten inches wide, of rock consisting mainly of scawtite. Beyond this scawtite zone is pale grey limestone, seamed with narrow (1 mm. and



FIG. 1. Close-up of contact between andesite and limestone; the hammer head rests on the knife-sharp contact.

less) white veinlets of grossularite and wollastonite. On the western side of the quarry a similar sequence was found, except that the scawtite zone was not observed; it may be present but has been overlooked.

MINERALOGY AND PETROLOGY

Andesite: In hand specimen the andesite is an aphanitic grey rock; it was mapped as basalt by Ferrar, evidently on megascopic appearance. In thin section it is seen to consist largely of oligoclase laths (average dimensions 0.1×0.02 mm.) with a marked trachytic texture. The only other minerals present are rare plagioclase (An_{60}) phenocrysts, minute (0.01 mm. diameter) crystals of magnetite, and interstitial pale green ferromagnesian silicate, specifically indeterminable but probably chlorite. The density of the rock is 2.62. The andesite shows no chilled margin against the country rock and the grain size of the feldspar is not noticeably smaller towards the contact.

The chemical composition and norm (calculated according to Barth, 1952, p. 80) are given in Table 1. This confirms the classification of the rock as an andesite, with trachytic affinities as indicated by the presence of 14% orthoclase in the norm. Orthoclase was not recognized in thin sections, although if present it could easily be overlooked. In chemical and mineralogical composition and in mode of occurrence this rock resembles kullaite, from Kullen near Kristianstad in southern Sweden.

TABLE 1. ANALYSIS AND NORM OF ANDESITE, ONE INCH FROM CONTACT WITH LIMESTONE

(Analyst: Doris Thaemlitz, Rock Analysis Laboratory, University of Minnesota; Lab. No. R2213)

	Weight, per cent	Mol. Prop.	Norm	
SiO ₂	51.90	8607	Or	14.5
TiO ₂	0.82	102	Ab	43.5
Al ₂ O ₃	17.01	1664	An	17.3
Fe ₂ O ₃	2.95	185	Cn	2.5
FeO	5.00	696	Σ salic	77.8
MnO	0.17	24		
MgO	3.67	910	Di	6.8
CaO	5.26	938	Hy	5.0
BaO	1.26	82	Ol	5.4
Na ₂ O	4.58	739	Mt	3.3
K ₂ O	2.34	248	Il	1.2
P ₂ O ₅	0.28	20	Ap	0.5
CO ₂	0.15			
H ₂ O+	3.34		Σ femic	22.2
H ₂ O-	1.25			
S	0.06			
	100.04			

A noteworthy feature of the chemical analysis is the unusually high content of barium, which is presumably present in the feldspar, since no specific barium minerals were noted in thin sections. Von Engelhardt (1936), who studied the geochemistry of barium, recorded that rocks of the syenite-trachyte family show the largest concentration, averaging about 0.2% BaO. The presence of 1.26% BaO in the Tokatoka andesite is intriguing, since other igneous rocks from this region do not show unusual amounts of barium; it can hardly have been derived by assimilation, since barium was not detected in the limestone, and in any case there is no evidence of assimilation having taken place.

Limestone: The limestone is a pale grey fine-grained rock, compact but well jointed, and it breaks down rapidly by weathering. It is very uniform in texture and shows no trace of fossils. It belongs to the Onerahi Formation, which covers large areas in North Auckland, but whose age is not precisely known; various ages, from Upper Cretaceous to Oligocene, have been ascribed to it, and it may extend through a considerable time interval.

TABLE 2. ANALYSES OF LIMESTONE, (1) UNALTERED, AND (2) SLIGHTLY ALTERED

(1) Onerahi limestone, near Kaiwaka, North Auckland (*N.Z. Geol. Surv. Bull.* 22, 61).

(2) Onerahi limestone, eight feet from contact with andesite dike.

(Analyst: Doris Thaemlitz, Rock Analysis Laboratory, University of Minnesota; Lab. No. R2214).

	(1)	(2)	Mol. Prop.	Grossularite	Scawtite	Wollastonite	Calcite
SiO ₂	17.48	19.51	3248	927	1101	1220	
Al ₂ O ₃	3.01	2.59	254	309			
Fe ₂ O ₃	1.61	0.88	55				
FeO	—	0.20	28				
MgO	0.78	0.56	139	927	1285	1220	5496
CaO	41.49	50.04	8923				
CO ₂	32.00	25.00	5680		184		5496
H ₂ O+	3.03	0.66	367		367		
H ₂ O—	—	0.12					
P ₂ O ₅	—	0.10					
TiO ₂	—	0.14					
MnO	—	0.05					
	99.40	99.85					

In thin section the limestone is seen to be a structureless aggregate of irregular grains of calcite, averaging about 0.03 mm. in diameter. The fine grain and the complete absence of any trace of fossils suggest that the limestone was formed by inorganic precipitation.

A sample of the limestone eight feet from the contact with the dike was selected for analysis (Table 2). This limestone appeared to be completely unaltered except for some microscopic veinlets of garnet; the residue from dissolving the rock in dilute acid gave an *x*-ray powder pattern of grossularite with $a=11.90\text{\AA}$. A cursory examination of the analysis, however, shows that it cannot be interpreted as a mixture of calcite and grossularite; there is an excess of CaO and a deficiency of CO₂. A careful examination of thin sections of this rock showed that associated

with the grossularite are patches of a fibrous or prismatic mineral with low birefringence; wollastonite was suspected, and was confirmed by the recognition of the strongest lines of wollastonite in an x-ray powder photograph of the analysed material. Reexamination of the thin sections also showed the presence of some scawtite, which is similar in appearance to calcite, but has brighter interference colors. The mode calculated from the analysis is calcite 55%, grossularite 14%, wollastonite 14%, and scawtite 15%; the deficiency from 100% is due to a slight excess of CaO, and the other oxides present which are not used in the calculated mode.

In view of the somewhat metamorphosed state of the analysed sample, an analysis of typical unmetamorphosed Onerahi limestone has been selected from the literature and is also given in Table 2. It can be seen that the beginning alteration is essentially a decarbonation, the silica and alumina necessary for the formation of grossularite, wollastonite, and scawtite being provided by the impurities in the limestone.

Hydrogrossular zone: The innermost contact zone against the dike is four to six inches thick, and consists of white massive material, often chalky in appearance and very light and porous. Thin sections of this material showed tiny (0.01 mm. diameter) rounded isotropic grains with high refractive index in a turbid, isotropic or slightly anisotropic groundmass of low refractive index. X-ray powder photographs served to identify the rounded grains as hydrogrossular, and the groundmass as cristobalite (the high-temperature or beta-form) probably admixed with opal. The cristobalite was identified by the strong lines with d -values 4.15, 2.53, and 1.64; the presence of opal is suggested by a diffuse halo in the powder photographs at $d=4.0$.

The x-ray powder photograph of hydrogrossular is similar to that of grossularite, but the lines are weaker and back reflections seldom appear even after long exposure. The cell dimensions vary considerably from specimen to specimen, the range being from 11.95 Å to 12.24 Å; considering hydrogrossular as a phase in the two-component system $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ — $\text{Ca}_3\text{Al}_2(\text{OH})_{12}$, this indicates a compositional range from 25% to 65% of the $\text{Ca}_3\text{Al}_2(\text{OH})_{12}$ component, according to Yoder's data (1950, fig. 14). The composition bears no obvious relation to the location of the material with respect to the contact; different samples from the hydrogrossular zone have cell dimensions ranging from 11.95 Å to 12.24 Å, and hydrogrossular with $a=12.17$ Å occurs as disseminated grains in the scawtite zone. The garnet in veinlets in the limestone, beyond the scawtite zone, has $a=11.90$ Å and is evidently close to grossularite in composition; the slightly greater cell dimensions than pure grossularite ($a=11.85$ Å) are probably due to a small amount of ferric iron replacing aluminum, rather than the presence of hydroxyl.

Four names are current for minerals with composition between $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ and $\text{Ca}_3\text{Al}_2(\text{OH})_{12}$ —hirschite (Cornu, 1905), plazolite (Foshag, 1920), grossularoid (Belyankin and Petrov, 1941), and hydrogrossular (Hutton, 1943). Later work, especially that of Yoder (1950), has shown that a continuous series exists between the above components, and that the individual species that have been described are simply random compositions within this series. Under these circumstances a single name is adequate. In this paper hydrogrossular is accepted as the most satisfactory name, although hirschite has priority. The name hydrogrossular indicates clearly the nature of the mineral. The variation in cell dimensions for samples taken from a single small hand specimen shows that the composition of hydrogrossular can vary greatly over a short distance. Thus specific formulas such as have been derived for plazolite and hirschite misrepresent the true composition; a satisfactory formula is that suggested by Hutton— $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_{3-m}(\text{OH})_{4m}$. Although Hutton introduced the name hydrogrossular for compositions intermediate between grossularite and hirschite (and plazolite), it seems reasonable to extend the name to include the latter minerals also.

A sample of the material from the inner contact zone was analysed chemically (Table 3). The hydrogrossular in this sample had the largest cell dimensions, $a = 12.24 \text{ \AA}$, indicating a composition approximately $\text{Ca}_3\text{Al}_2(\text{SiO}_4)(\text{OH})_8$, according to Yoder's data. When the chemical analysis is interpreted in these terms, it indicates a composition approximately 59% cristobalite and opal, 40% hydrogrossular, and 1% calcite. The SO_3 and P_2O_5 shown by the analysis may well be present as SO_4 groups and PO_4 groups in the hydrogrossular, since the garnet structure is known to tolerate the introduction of other four-coordinate cations in place of silicon.

On cursory consideration the presence of silica in the form of cristobalite rather than quartz appears anomalous, since the temperature of formation of the material was certainly far outside the stability field of cristobalite in the system SiO_2 . However, the material was probably formed rapidly under non-equilibrium conditions, through the agency of hot magmatic gases; also the cristobalite may be stabilized by the presence of foreign ions buttressing the open structure of this mineral and preventing its inversion to quartz.

Larnite zone: The larnite zone is very prominent, forming a band about thirty inches thick, dark grey to almost black in color, hard, flinty, and very tough. The dark color is not due to the larnite, but to the presence of a small amount of very fine-grained magnetite. Pure larnite is presumably white. It is interesting to note that the original larnite from Larne is grey from the presence of finely divided spinel.

Thin sections of this rock show the larnite as an aggregate of tiny rounded grains, seldom greater than 0.02 mm. in diameter. On this account the optical properties are not easily determined, and in immersion liquids only the maximum and minimum refractive indices were measured: $\alpha = 1.71$, $\gamma = 1.73$. The identification was originally made on

TABLE 3. ANALYSIS OF HYDROGROSSULAR-CRISTOBALITE ROCK, FROM CONTACT WITH ANDESITE DIKE

(Analyst: Eileen H. Oslund, Rock Analysis Laboratory, University of Minnesota; Lab. No. R2215)

	Weight per cent	Mol. Prop.	Calcite	Hydrogrossular	Cristobalite Opal
SiO ₂	59.03	9789		924	8865
Al ₂ O ₃	8.15	797			
Fe ₂ O ₃	2.03	127		924	
FeO	0.19	26			
MgO	3.25	806			
CaO	13.63	2430	139		
CO ₂	0.61	139	139		
H ₂ O+	7.02	3900		3696	204
H ₂ O-	4.48	2489			2489
TiO ₂	0.29				
MnO	0.09				
BaO	0.10				
Na ₂ O	0.13				
K ₂ O	0.08				
SO ₃	0.59				
P ₂ O ₅	0.22				
	99.89				

the *x*-ray powder photograph, which agreed with that given by Brownmiller and Bogue (1930) for synthetic beta dicalcium silicate. This has been confirmed by Dr. Della M. Roy of the Pennsylvania State University, who very kindly ran the Tokatoka larnite on an *x*-ray diffractometer and compared the record with that for a sample of beta dicalcium silicate prepared in her laboratory. She also detected a small amount of gehlenite intermixed with the larnite.

The larnite rock also contains some spurrite, which occurs as porphyroblasts up to about 0.15 mm. in diameter; a little scawtite in isolated patches; and a small amount of finely divided magnetite. The density of the rock varies somewhat from sample to sample on account of variable mineral composition; the maximum density measured, probably for material nearly pure larnite, was 3.26.

A sample of the larnite rock was analysed chemically, and the results are given in Table 4. Assuming ideal compositions corresponding to the accepted chemical formulas of the minerals, the calculated mode is 59% larnite, 21% spurrite, 11% gehlenite, 5% scawtite, and 1% magnetite, the deficiency from 100% being due to excess H_2O+ and other oxides not used in the calculation.

TABLE 4. ANALYSIS OF LARNITE ROCK, EIGHT INCHES FROM MARGIN OF ANDESITE DIKE

(Analyst: Eileen H. Oslund, Rock Analysis Laboratory, University of Minnesota; Lab. No. R2216)

	Weight per cent	Mol. Prop.	Magnetite	Gehlenite	Scawtite	Spurrite	Larnite
SiO ₂	30.89	5123		408	383	958	3374
Al ₂ O ₃	4.17	408		408			
Fe ₂ O ₃	0.89	56	56	} 816			
FeO	0.54	75	56				
MgO	0.72	179			447	2395	
CaO	57.26	10208					
CO ₂	2.39	543			64	479	
H ₂ O+	1.60	888			128		
H ₂ O-	0.66						
Na ₂ O	0.17						
K ₂ O	0.09						
TiO ₂	0.21						
P ₂ O ₅	0.14						
MnO	0.06						
BaO	0.00						
SO ₃	0.38						
	100.17						

The beta form of dicalcium silicate is rather difficult to preserve in synthetic preparations, since it undergoes an inversion below 675° to the gamma form. The gamma form has the olivine structure and is considerably less dense than the beta form. The increase of volume on inversion causes solid masses of the beta form to fall to powder. This feature was observed on the original larnite when it was heated or hammered (Tilley, 1929, p. 82). The larnite from Tokatoka does not invert to gamma dicalcium silicate on heating or hammering. This reluctance to invert is probably the result of the presence of foreign ions in solid solution inhibiting the change, a feature characteristic of the beta dicalcium silicate from slags (Mason, 1945, p. 179).

This appears to be the third record of beta dicalcium silicate as a mineral, and the first outside Great Britain. Besides the original discovery at Scawt Hill, it has been found in a dolerite-chalk contact at Ballycraigy, also in the Larne district (McConnell, 1955), and on the island of Muck in Scotland (Tilley, 1947).

Scawtite zone: A zone about ten inches thick between the larnite zone and the limestone consists essentially of scawtite. The scawtite rock is greyish-white, dense and flinty and with a marked conchoidal fracture. It effervesces in cold dilute hydrochloric acid, but less actively than the limestone. Thin sections show that the rock is an aggregate of very small grains of scawtite, the individual diameters being seldom greater than 0.01 mm. On this account the optical properties are not easily determined, and only the maximum and minimum refractive indices were measured: $\alpha = 1.60$, $\gamma = 1.62$. The mineral was identified from its x-ray powder photograph, which agrees with that given for scawtite from Ballycraigy by McConnell (1955). The scawtite rock also contains some hydrogrossular as small disseminated grains, a little magnetite, and occasional patches of calcite, which can be distinguished from the scawtite by its higher birefringence.

A chemical analysis of the scawtite rock is given in Table 5. The calculated mode (using a composition halfway between $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ and $\text{Ca}_3\text{Al}_2(\text{OH})_{12}$ for the hydrogrossular, as indicated by its cell dimensions, $a = 12.17\text{\AA}$) is 66% scawtite, 17% hydrogrossular, 12% calcite, and 2% magnetite. When the analysis is recalculated in this way a small amount of CaO and $\text{H}_2\text{O}+$ remains unaccounted for. In addition there is the 0.70% SO_3 , which has not been identified with a specific mineral; it may conceivably be present as sulphate groups in the structure of the hydrogrossular.

This is the fifth record of scawtite, the other localities being Scawt Hill (Tilley, 1930) and Ballycraigy (McConnell, 1955) in Northern Ireland; near Neihart, Montana (Taylor, 1935); and Crestmore, California (Murdoch, 1955).

PARAGENESIS

The source of the heat which produced the metamorphism is clearly the magma from which the andesite crystallized. The temperature at which magma of this composition flows freely (and the narrowness of the dike indicates that the magma did flow freely) is uncertain. Zies (1941) has recorded that the temperature of the andesitic lava of the extruding dome at the volcano of Santiaguito in Guatemala was about 700°; this was the temperature at the top of the dome, and the tempera-

tures within the magma channel were undoubtedly higher. Probably the temperature of the magma at Tokatoka was at least 800°–900°.

The pressure due to the overlying rock was certainly quite low, since there is no evidence for any great thickness having been removed by erosion since the igneous activity. Many of the small igneous intrusions in this region of North Auckland reached the surface and gave rise to lava flows.

TABLE 5. ANALYSIS OF SCAWTITE ROCK, 3½ FEET FROM THE MARGIN OF THE ANDESITE DIKE

Analyst: Doris Thaemlitz, Rock Analysis Laboratory, University of Minnesota; Lab. No. R22127)

	Weight per cent	Mol. Prop.	Magnetite	Hydro- grossular	Scawtite	Calcite
SiO ₂	32.22	5343		606	4737	
Al ₂ O ₃	4.13	404		404		
Fe ₂ O ₃	1.23	77	77			
FeO	0.33	46	46			
MgO	0.80	198	31			
CaO	45.34	8083		} 1212	5530	1182
CO ₂	8.68	1972				790
H ₂ O+	5.77	3203		1212	1580	
H ₂ O+	0.14					
Na ₂ O	0.01					
K ₂ O	0.04					
TiO ₂	0.23					
P ₂ O ₅	0.15					
MnO	0.07					
BaO	0.20					
SO ₃	0.70					
	100.04					

It is thus reasonable to conclude that during the active flow of magma through the dike conduit the temperature at the margin was above 800°, and the rock pressure was comparatively low. According to Yoder (1950) the association larnite-gehlenite in a metamorphosed limestone indicates a temperature of formation of 800°; at lower temperature the association would be larnite-grossularite for compositions low in Al₂O₃, or grossularite-gehlenite for compositions higher in Al₂O₃.

From these two lines of evidence it therefore seems probable that the maximum temperature in the larnite zone, which extends as far as two feet from the margin of the dike, was at least 800°. However, the larnite

zone does not extend to the dike itself; along the margin of the dike there is a band of hydrogrossular-cristobalite rock up to six inches thick. Yoder's studies show that hydrogrossular of this composition is formed at about 500°.

We thus have the apparent contradiction of a lower temperature zone at the margin of the dike, followed by a higher temperature zone further out. This contradiction is resolved, however, if the hydrogrossular-cristobalite zone is the result of late metasomatism of the inner part of the larnite zone. Their relative compositions suggests such a relationship; the hydrogrossular-cristobalite rock is highly hydrated and silicated with reference to the other metamorphic zones, and it is reasonable to ascribe this to the introduction of SiO_2 and H_2O during the ultimate cooling and crystallization of the andesite. On this hypothesis the larnite zone originally extended to the margin of the dike, and the innermost part was converted to hydrogrossular and cristobalite by later introduction of silica, water, and some alumina.

The presence of scawtite as a rock-forming mineral constituting a distinct metamorphic zone seems to be unique among the few occurrences of this mineral. At other localities scawtite is found lining veins or vesicles in contact-altered limestones, and evidently is of late hydrothermal origin. At Tokatoka it is the principal mineral in a zone about ten inches thick between the larnite zone and the limestone, and also occurs in sporadic patches further out in the apparently unaltered limestone.

It might be suggested that the scawtite is not a primary metamorphic product but is secondary after some pre-existing mineral (as hydrogrossular in the inner contact zone is evidently secondary after larnite and gehlenite). The differences in composition between the larnite rock and the scawtite rock are not great, being essentially an increase of CO_2 and H_2O and decrease of CaO in the latter. These differences can be interpreted as the result either of metasomatism of the larnite rock, or of a lower temperature of metamorphism, within which scawtite formed as a stable phase in a chemical environment essentially the same as that which gave rise to the larnite-gehlenite association closer to the intrusion. The latter interpretation is favored, mainly because of the apparently primary nature of the scawtite; thin sections indicate that it originated by the direct replacement of the limestone, rather than by metasomatism of the larnite rock.

Another possibility is that scawtite is secondary after wollastonite. The formula of scawtite ($6\text{CaSiO}_3 \cdot \text{CaCO}_3 \cdot 2\text{H}_2\text{O}$) shows that in composition it is essentially a somewhat carbonated and hydrated wollastonite, and its structure is probably related to that mineral (McConnell, 1955). Hydration of a wollastonite-calcite rock could conceivably give

rise to scawtite. This is a plausible hypothesis, since the original presence of a wollastonite zone might be expected. However, no trace of residual wollastonite was seen in the scawtite rock, and the evidence favors a primary origin for the scawtite.

An interesting feature which deserves comment is the variation in composition of the garnet in the contact zone. The material in the inner contact zone is hydrogrossular of variable composition, and hydrogrossular also occurs disseminated through the scawtite zone, but the garnet in the tiny veinlets in otherwise unaltered limestone is close to grossularite in composition and is evidently not hydrated. Thus the garnet does not increase regularly in hydration from the contact outwards, which would be expected were it produced along a line of steadily diminishing temperature. The reason for the hydrated nature of the garnet in the inner contact zone has already been discussed in the description of hydrogrossular. The anhydrous nature of the grossularite in the limestone suggests that it formed at comparatively high temperatures. A reasonable explanation is that it was produced by the action of hot gases escaping from the magma, an explanation supported by the occurrence of the mineral along narrow veinlets, which were probably microscopic joints in the limestone serving to channel the gases from the intrusion. The presence of wollastonite with the grossularite in the veinlets indicates that they were formed at temperatures above 500°, from the data of Harker and Tuttle (1956) on the calcite-wollastonite reaction.

Tilley (1950) has recently discussed the progressive metamorphism of siliceous limestones (Fig. 2). He recognizes successive steps of progressive decarbonation giving rise to the following mineral associations: (1) wollastonite-calcite; (2) wollastonite-tilleyite-calcite; (3) wollastonite-spurrite-calcite; (4) spurrite-rankinite; (5) spurrite-larnite. The succession at Tokatoka is not as complete as this scheme; rankinite and tilleyite have not been found, and wollastonite occurs only in small amount with grossularite in veinlets in the limestone. The association wollastonite-calcite is represented at Tokatoka by the association scawtite-calcite. Thus we have the larnite-spurrite zone followed by a scawtite-calcite zone; between them there may well be a transitional zone of spurrite-scawtite, equivalent to the wollastonite-spurrite-calcite association of Tilley's scheme. The occurrence of scawtite instead of the usual association wollastonite-calcite is the most interesting feature of the Tokatoka paragenesis. Evidently some peculiarity either in physical conditions or chemical composition or both favored the formation of scawtite, and it appeared in the sequence of metamorphism where

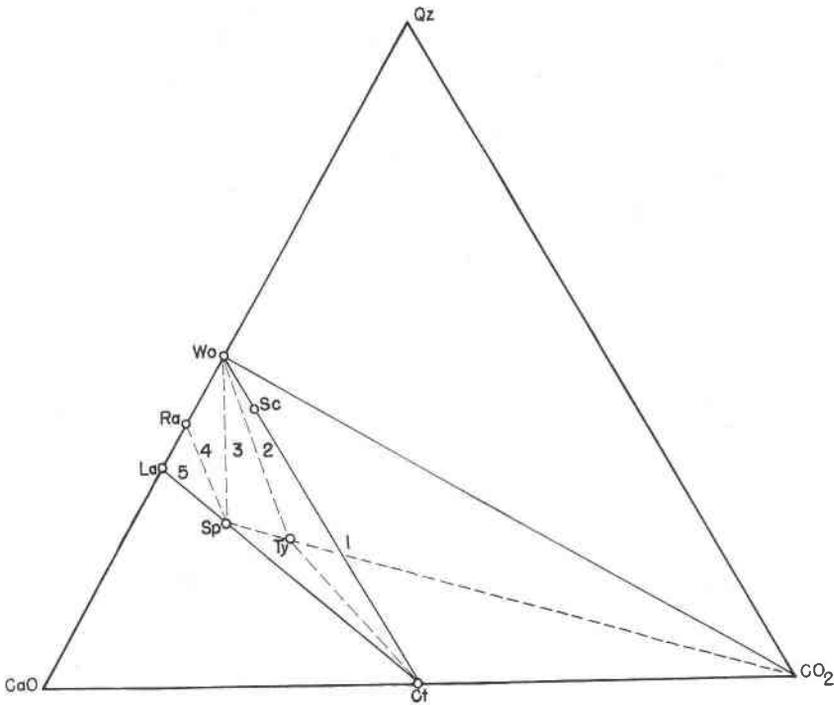


FIG. 2. Progressive decarbonation in the system $\text{CaO-SiO}_2\text{-CO}_2$ in thermal metamorphism (after Tilley, 1951); Qz=quartz, Ct=calcite, Wo=wollastonite, Ty=tilleyite, Sp=spurrite, Ra=rankinite, La=larnite, Sc=scawtite.

wollastonite would normally be expected. Perhaps an unusually high H_2O pressure, either emanating from the intrusion or resulting from a high water content in the limestone, favored the hydrated mineral scawtite over the anhydrous wollastonite.

ACKNOWLEDGMENTS

In addition to the persons mentioned in the text, I am indebted to Mr. Leineweber, of the Johns Manville Research Center, for making a preliminary spectrographic analysis and an x -ray diffractometer record of the hydrogrossular-cristobalite rock; and to Dr. R. N. Brothers, of Auckland University College, for the photograph of the quarry. My thanks are also due to the John Simon Guggenheim Memorial Foundation, as the field work was carried out during the tenure of a fellowship from this organization.

REFERENCES

- BARTH, T. F. W. (1952), *Theoretical petrology*. John Wiley and Sons, New York.
- BELYANKIN, D. S., AND PETROV, V. P. (1941), The grossularoid group: *Am. Mineral.*, **26**, 450-453.
- BROWNMILLER, L. F., AND BOGUE, R. H. (1930), The x-ray method applied to a study of the constitution of Portland cement: *Am. Jour. Sci.*, **20**, 241-264.
- CORNU, F. (1906), Beiträge zur Petrographie des Böhmisches Mittelgebirges: *Tschermaks Min. Petr. Mitt.*, **25**, 249-268.
- ENGELHARDT, W. VON (1936), Die Geochemie des Barium: *Chemie der Erde*, **10**, 189-246.
- FERRAR, H. T. (1934), The geology of the Dargaville-Rodney subdivision: *New Zealand Geol. Surv. Bull.*, **34**, 86 pp.
- FOSHAG, W. F. (1920), Plazolite, a new mineral: *Am. Mineral.*, **5**, 183-185.
- HARKER, R. I., AND TUTTLE, O. F. (1956), Experimental data on the P-T curve for the reaction: calcite + quartz \rightleftharpoons wollastonite + carbon dioxide: *Am. Jour. Sci.*, **254**, 239-256.
- HUTTON, C. O. (1943), Hydrogrossular, a new mineral of the garnet-hydrogarnet series: *Trans. Royal Soc. New Zealand*, **73**, 174-180.
- MASON, B. (1945), Basiska martinslaggers mineralogiska byggnad: *Jernkontorets Annaler*, **129**, 171-1847.
- McCONNELL, J. D. C. (1955), A chemical, optical and x-ray study of scawtite from Ballycraig, Larne, North Ireland: *Am. Mineral.*, **40**, 510-514.
- MURDOCH, J. (1955), Scawtite from Crestmore, California: *Am. Mineral.*, **40**, 505-509.
- TAYLOR, J. H. (1935), A contact metamorphic zone from the Little Belt Mountains, Montana: *Am. Mineral.*, **20**, 120-128.
- TILLEY, C. E. (1929), On larnite (calcium orthosilicate, a new mineral) and its associated minerals from the limestone contact-zone of Scawt Hill, Co. Antrim: *Mineral. Mag.*, **22**, 77-86.
- (1930), Scawtite, a new mineral from Scawt Hill, Co. Antrim: *Mineral. Mag.*, **22**, 222-224.
- (1947), The gabbro-limestone contact of Camas Mor, Muck, Inverness-shire: *Bull. Comm. Geol. Finlande*, **140**, 97-106.
- (1951), A note on the progressive metamorphism of siliceous limestones and dolomites: *Geol. Mag.*, **88**, 175-178.
- YODER, H. S. (1950), Stability relations of grossularite: *Jour. Geol.*, **58**, 221-253.
- ZIES, E. G. (1941), Temperatures of volcanoes, fumaroles, and hot springs, in "Temperature, its measurement and control in science and industry." Reinhold Publishing Corp., New York.

Manuscript received November 16, 1956.