

## BURIAL METAMORPHISM OF THE KARMUTSEN VOLCANIC ROCKS, NORTHEASTERN VANCOUVER ISLAND, BRITISH COLUMBIA

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**ABSTRACT.** The Upper Triassic Karmutsen volcanic rocks of northeastern Vancouver Island consist of close-packed pillows, pillow breccias, and massive flows of oceanic tholeiite. They have undergone diagenesis and burial metamorphism. Chemical alteration depleted Na, Si, Ca, and Al from aquagene tuffs and pillow rims. The bulk compositions of flows and pillow cores remain relatively unchanged. Prehnite-pumpellyite facies mineral assemblages albite + chlorite + pumpellyite + sphene + magnetite  $\pm$  quartz  $\pm$  prehnite  $\pm$  epidote occur on a regional scale. The primary Fe-Ti oxides in most Karmutsen volcanic rocks were unmixed into ilmenite and magnetite at relatively high  $f_{O_2}$  condition during cooling, and ilmenite lamellae were then replaced by sphene during burial metamorphism. Chemographic analyses indicate that local equilibrium has been approached in most mineral assemblages under high  $\mu_{H_2O}$  and low  $\mu_{CO_2}$ . Metamorphic albitization and pumpellyitization of primary plagioclase occurred in flows and pillow cores but not in tuffs and pillow rims. The variable composition of pore fluid during recrystallization of primary Fe-Ti oxides was responsible for the selective albitization. Field relations and mineral paragenesis suggest that the burial metamorphism occurred at temperatures of about 250° to 350°C, lithostatic pressures of 1 to 2.5 kb, and a high  $\mu_{H_2O}$ . The spilitic features of the Karmutsen volcanic rocks are metamorphic and not metasomatic or deuteric; most "petrographically spilitic rocks" described in the literature may actually be metabasalts.

### INTRODUCTION

The Upper Triassic Karmutsen volcanic rocks occur extensively on Vancouver Island (fig. 1). Although metamorphosed, they retain remarkably well their original igneous textures and chemical compositions. The lithologic and chemical similarities of Karmutsen volcanic rocks and recent ocean floor basalts have been documented (Kuniyoshi, 1971). The Karmutsen volcanic rocks had been subjected to post-eruptive submarine weathering, diagenesis, and burial metamorphism before they were intruded by the Jurassic Island Intrusions (fig. 1). The thermal effect of the intrusions in the contact aureoles has been described by Kuniyoshi and Liou (1976). Most of the Karmutsen volcanic rocks, however, are free apparently from contact metamorphism. This note is devoted to the pre-intrusive regional burial metamorphism on northeastern Vancouver Island. Interesting aspects in low-grade metamorphism — alteration of some igneous minerals including Fe-Ti oxides and selective albitization of primary plagioclase — will be described in detail in this paper.

### REGIONAL GEOLOGY AND PETROGRAPHY

Vast areas of Vancouver Island are occupied by the Lower Mesozoic Vancouver Group, the dominant unit of which is the Upper Triassic Karmutsen Subgroup, a more than 6000 m thick succession of basaltic pillows, pillow breccias, and massive flows. The Karmutsen Subgroup is underlain by a Middle Triassic sediment-sill unit and Permian and older sedimen-

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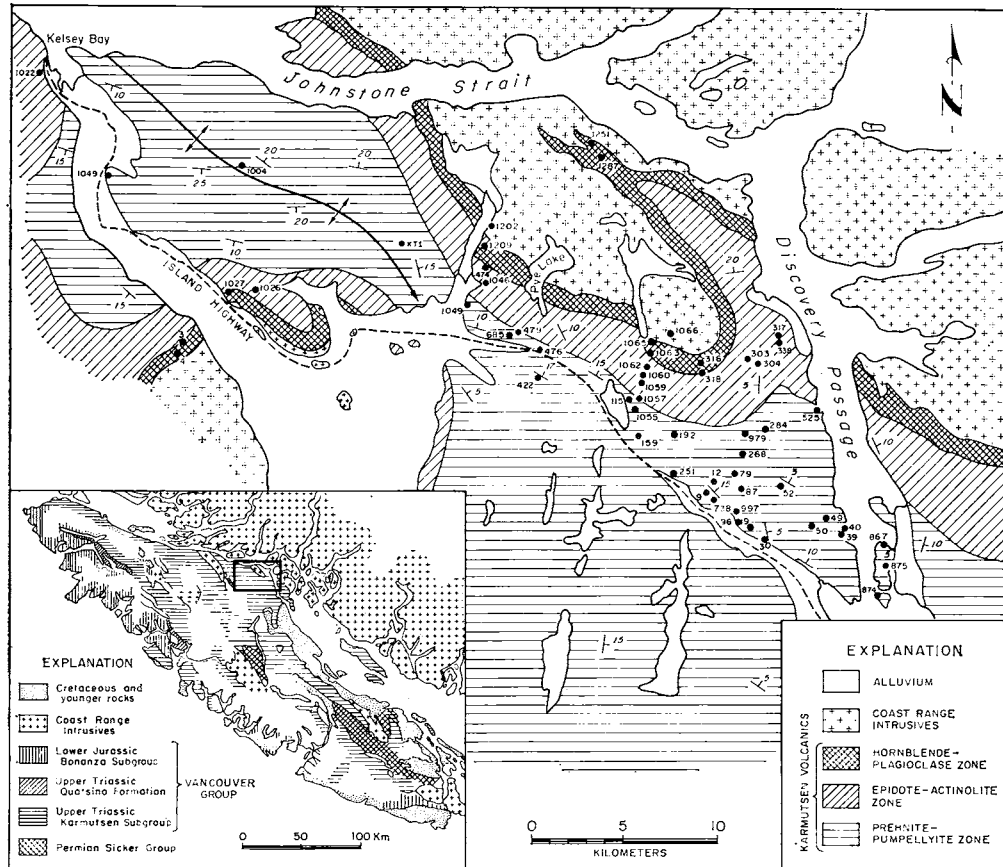


Fig. 1. Simplified geologic and metamorphic map of northeastern Vancouver Island, showing the distribution of the Karmutsen volcanic rocks, Coast Range Intrusions, contact metamorphic zones, and some sample localities.

tary and volcanic rocks of the Sicker Group and is overlain successively by the Uppermost Triassic Quatsino Limestone (300 m), the Parson Bay Formation (400 m), the Lower Jurassic Harbledown Formation (500 m), and the Bonanza Volcanics (2400 m) on northern Vancouver Island (Carlisle, 1972; Muller, Northcote, and Carlisle, 1974). The whole section is intruded by the 148 to 181 m.y. old Island Intrusions (Carson, 1973) and is unconformably overlain by the Upper Cretaceous Nanaimo Group. On northeastern Vancouver Island, where the post-Karmutsen overburden has been largely eroded and only the upper two thirds (4300 m) of the Karmutsen Subgroup is exposed, the maximum possible depth of pre-Cretaceous burial to the upper part of the Karmutsen Subgroup is about 3600 m, and to the lower part about 7900 m, corresponding roughly to 1 kb and 2.4 kb, respectively. The generalized geologic map and the sample localities in the study area are shown in figure 1.

A three-fold stratigraphic subdivision of the Karmutsen volcanic rocks has been well established (for example, Carlisle, 1972). In our study area, a thickness of about 1500 m of the exposed, lower Karmutsen is composed of closely packed basaltic pillows. The middle Karmutsen, about 610 m thick, is characterized by pillow breccias, an aggregate of whole or fragmented pillows in a cogenetic tuffaceous matrix or "aquagene tuff". The lower three fourths of this unit consist of well stratified broken pillow breccias, and the upper quarter is mainly isolated pillow breccias where pillows are widely separated in aquagene tuff. The upper Karmutsen, about 2200 m thick, is dominated by amygdaloidal massive flows with minor pillow breccia layers.

The petrographic features and chemical composition of some metamorphic minerals in the three Karmutsen rock types are described below. Modes of the representative flows are listed in table 1; chemical compositions of the representative rocks along with their mineral assemblages are shown in table 2; some mineral compositions analyzed by electron microprobe are listed in table 3.

*Close-packed pillows.*—Close-packed pillow lava is composed of pillows and interstitial matrix. Pillows are tightly packed, and the matrix is less than 10 percent of the total volume. Pillows have a chilled rim, 1 to 2 cm thick. The rim was originally a glassy material in which intratelluric and newly nucleating crystals were sparsely distributed. Although the basaltic glass is now entirely replaced by chlorite and other minerals, the earlier presence of the primary glass is still recognizable in Karmutsen pillow rims and tuffs. Toward the pillow interior, the modal proportions of plagioclase, pyroxene, and Fe-Ti oxides increase. The pillow core is typically porphyritic or glomero-porphyritic with an intersertal to intergranular groundmass consisting of plagioclase microlites, tiny granules of augite, and interstitial glass alteration.

The matrix between closely packed pillows consists of secondary quartz and fragments of metamorphosed pillow rims. Within the inter-pillow fillings, dark green pumpellyite occurs in variolitic aggregates

TABLE 1  
Modes and specific gravity of representative Karmutsen flows

Sample no.	K50	K79	K135	K166	K268	Average
Albite	40	33	35	17	41	33.4
Augite*	26	32	23	31	18	25.7
Pumpellyite	13	11	15	22	22	16.7
Chlorite	15	20	16	15	13	15.8
Epidote	—	—	3	2	tr	1.0
Quartz	tr	tr	—	4	tr	0.8
Magnetite and ilmenite	6	4	—	—	6	3.2
Sphene and leucoxene	tr	tr	8	9	tr	3.4
Points counted	2167	3154	3319	3353	2074	
Specific gravity**	2.98	2.91	2.86	3.06	2.94	2.95

\* Relict primary mineral.

\*\* Measured with the Jolly balance.

TABLE 2  
XRF bulk rock compositions and mineral contents of some Karmutsen pillows, aquagene tuffs, and massive flows\*

	Pillow core				Aquagene tuff				Massive flow					
	K479	K867A	K867B	K867C	K875C	K422A	K9	K19	K39	K50	K52	K251	K1049	K1055
SiO <sub>2</sub>	49.9	53.9	47.1	47.3	39.2	43.2	47.4	49.5	47.6	47.1	46.2	47.3	46.6	45.2
TiO <sub>2</sub>	1.77	1.40	1.39	2.06	2.52	1.98	2.00	1.85	1.55	1.54	2.48	1.94	1.18	1.54
Al <sub>2</sub> O <sub>3</sub>	14.4	14.8	14.8	13.4	16.0	15.8	14.1	14.0	14.3	14.4	14.0	15.6	16.5	14.1
Fe <sub>2</sub> O <sub>3</sub> **	11.5	10.6	13.1	14.3	17.8	14.4	13.2	12.9	11.1	13.2	14.1	11.8	10.5	12.4
MgO	5.65	5.35	7.84	10.5	11.7	9.62	6.95	5.80	7.50	7.50	6.15	5.75	7.24	10.6
CaO	11.9	11.5	10.2	7.10	5.38	9.77	11.2	10.0	13.1	9.96	9.50	10.3	11.5	11.4
Na <sub>2</sub> O	2.31	2.46	1.98	0.55	0.49	0.58	1.89	3.17	1.46	2.98	2.42	3.17	2.89	1.02
K <sub>2</sub> O	0.37	0.76	0.60	0.79	1.92	0.32	0.14	0.28	0.01	0.03	0.05	0.21	0.06	0.03
H <sub>2</sub> O	1.67	1.35	3.13	5.41	4.94	5.12	3.88	2.66	4.17	2.06	4.03	3.14	3.74	5.00
Total	99.47	101.21	100.14	101.41	99.95	100.79	100.76	100.16	101.29	98.77	98.93	99.21	100.21	101.29
Quartz		—	v	v	v	v	v	—	—	—	v	v	v	v
Albite	v	v	v	v	v	v	v	v	v	v	v	v	v	v
Plagioclase***						An75								
Pumpellyite	v	v	v	v	v	v	v	v	v	v	v	v	v	v
Prehnite	v	v	v	v	v	v	v	v	v	v	v	v	v	v
Epidote	—	—	v	—	—	—	—	—	—	—	—	—	—	v
Chlorite	v	v	v	v	v	v	v	v	—	v	v	v	v	v
Wt mica			—			—		—	—	—	—	—	—	—
Laumontite	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Sphene							v	—	—	—	v	v	—	v
Magnetite		v					v	v	—	v	v	v	v	v
Calcite														
Hydrogarnet	v					—								

\* All sections contain relict augite; \*\* total Fe as Fe<sub>2</sub>O<sub>3</sub>; \*\*\* relict plagioclase remains.

Relative mineral abundance: v: more than 5 percent in volume; —: less than 5 percent present in a section.

aligned around the pillow margin, and fan and bow-tie-shaped prehnite fills spaces between pumpellyite varioles (pl. 1-A). Quartz is commonly surrounded by prehnite. These textural relations suggest the sequence of crystallization of pumpellyite, prehnite, and quartz in that order. Epidote and calcite may occur in the center of interstitial quartz. In some cases, one may find large prismatic crystals of epidote within the quartz interstices. Two such epidote aggregates were found to possess high  $\text{Fe}^{+3}$  content (ps value ranges from 29 to 33) according to the X-ray determination method of Myer (1965).

In the pillow interiors, chlorite, pumpellyite, albite, and sphene are abundant metamorphic minerals, replacing primary plagioclase, Fe-Ti oxides, and interstitial glass. Igneous pyroxene is unaltered or at most only partially altered to chlorite. Although albitization of plagioclase is more or less pervasive in most pillows, relict calcic plagioclase (An 40-60) is present in small pillows and particularly in pillow margins. However, where pumpellyite occurs within the feldspar, no calcic plagioclase is left. Pumpellyite and chlorite occur abundantly also in amygdules and mesostatis of close-packed pillows. Prehnite, quartz, and phengite are major accessories. Trace epidote and calcite occur in pillow cores.

*Pillow breccia.*—Pillows of pillow breccia are metamorphosed in much the same way as close-packed pillows described above. In aquagene tuff, about 80 percent of which was composed of glassy fragments ranging from 0.5 to 3 mm in diameter, primary augite is unaltered, and calcic plagioclase (An 65-80, table 4) is almost invariably not albitized (pl. 1-B) and is replaced only partially by white mica. Sideromelane particles are completely replaced by nearly isotropic green chlorite. Shard fragments are typically rimmed by light-colored chlorite, which contrasts with the dark green or brown chlorite of the fragment interior and suggests previous palagonitization of fragment rims prior to chloritization. Greenish chlorite

TABLE 3  
Microprobe analyses of some burial metamorphic  
minerals of the Karmutsen volcanic rocks

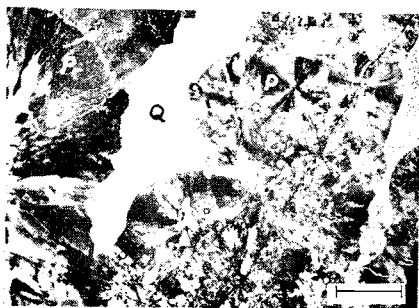
Minerals	Pumpellyite			Chlorite				Prehnite		Albite		
	Sample no.	K39	K39*	K40	K40	K251	K479	K479**	K997	K738	K39	K40
SiO <sub>2</sub>	38.0	38.0	37.8	28.5	27.5	28.5	27.5	28.5	45.5	67.0	67.5	
TiO <sub>2</sub>	—	0.1	0.1	—	—	1.9	—	—	—	—	—	—
Al <sub>2</sub> O <sub>3</sub>	22.7	22.5	22.0	16.0	15.0	14.3	15.9	14.4	24.5	21.0	20.8	
FeO <sup>+</sup>	8.8	8.7	8.5	20.8	27.5	25.8	26.0	23.0	—	—	—	—
Fe <sub>2</sub> O <sub>3</sub> <sup>++</sup>	—	—	—	—	—	—	—	—	1.8	—	—	—
MnO	0.2	0.2	0.2	0.3	0.4	0.2	0.2	0.3	—	—	—	—
MgO	1.9	1.9	2.0	18.3	14.0	12.5	14.1	17.1	—	—	—	—
CaO	22.7	22.3	22.9	0.4	0.5	0.3	0.2	0.5	25.9	0.1	0.2	
Na <sub>2</sub> O	0.1	—	—	0.2	—	—	—	—	—	11.4	11.3	
Anhydrous												
Total	94.3	93.7	93.5	84.5	84.9	83.5	83.9	83.8	97.8	99.5	99.8	

\* Pumpellyite inclusion in albitized plagioclase; \*\* chloritized tachylite (?) inclusion in augite of aquagene tuff.

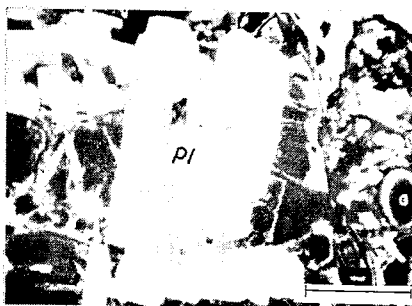
† and †† Total Fe as FeO and Fe<sub>2</sub>O<sub>3</sub> respectively.

PLATE I

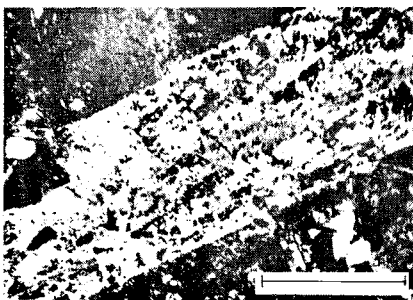
Photomicrographs of some Karmutsen burial metamorphic rocks. Bar scale represents 0.5 mm in length.



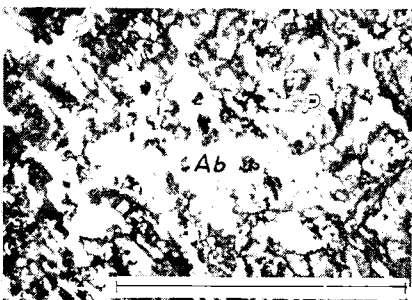
A



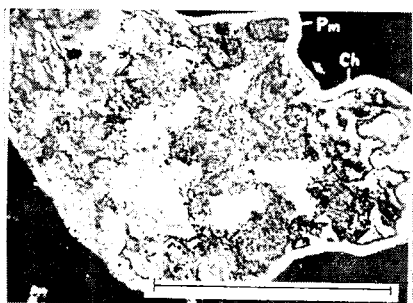
B



C



D



E



F

A. Variolitic pumpellyite aggregates (P), prehnite (Pr), and quartz (Q) in the fillings of the close-packed pillow (K1001c) (crossed nicols).

B. Fresh phenocryst of plagioclase (Pl) (An64) in the Karmutsen aquagene tuff. Globule (G) is also shown (K875C) (open nicol).

C. Pumpellyite + albite intergrowth replacing euhedral, twinned calcic plagioclase in the Karmutsen flow (K199) (crossed nicols).

D. Pumpellyite (P) + albite (Ab) replacing a large plagioclase crystal in the Karmutsen flow (K1049). Note pumpellyite crystals align parallel to the cleavage of plagioclase (open nicol).

E. Prehnite (Pr)-pumpellyite (Pm)-chlorite (Ch)-wairakite (Wr) assemblage in an amygdale of pillow core (K874A-1). Note the chlorite rimmed around the amygdale, and the crystallization sequence being chlorite first, then pumpellyite, prehnite, and finally wairakite (open nicol).

F. Acicular pumpellyite (P) and chlorite (Ch) in a quartz (Q)-rich amygdale in the Karmutsen flow (K1055-2); note abundant fluid inclusions in quartz (open nicol).

after sideromelane has only small amounts of CaO (0.2 to 0.5 wt percent, table 3). In some tuff fragments, tiny granules of hydrogarnet were identified by X-ray diffraction. The mesostasis surrounding the fragments consists largely of chlorite, prehnite, quartz, and, less commonly, albite, wairakite, and pumpellyite.

*Massive flows.*—Eighty to ninety percent of the massive flows are composed of plagioclase, augite, and iron oxides, and the rest of amygdules and interstitial groundmass. The flows are predominantly medium-grained and diabasic or porphyritic with an intergranular or diabasic groundmass. With the exception of augite, all primary phases in the flows are replaced extensively by metamorphic minerals. Incipient and complex alteration of augite to chlorite + epidote was found along fractures, at the crystal periphery, or in scattered small patches.

The amygdaloidal appearance is characteristic of most massive flows. Chlorite, pumpellyite, quartz, prehnite, and epidote are the most common amygdule minerals. Calcite, white mica, albite, laumontite, wairakite, and copper minerals occur sporadically in small amounts. The most common mineral assemblages in amygdules are pumpellyite + chlorite  $\pm$  epidote  $\pm$  prehnite  $\pm$  quartz. In typical amygdules, chlorite occurs in rims, and quartz, with bundles of pumpellyite needles, fills cores, or pumpellyite occupies cores surrounded by chlorite (pl. 1-E).

Plagioclase in the massive flows is in subhedral intergrowth with augite and ranges in size from 0.15 to 2.00 mm long. It is almost completely replaced by albite and pumpellyite with lesser amounts of chlorite and phengite (pl. 1-C, -D). The composition of remnant, unaltered plagioclase is An 50 to 70. Over 90 percent of massive flows contain plagioclases with the albite composition. Albite has always a pale brownish, dusty appearance. The maximum symmetrical extinction angle ( $X \wedge c$ ) of albite-

TABLE 4

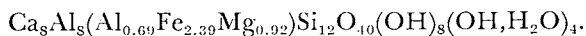
Optical data and compositions of some plagioclases from Karmutsen volcanic rocks by using universal stage after method of Slemmons (1962a)

Rock type	Sample no.	TA $\wedge$ X	TA $\wedge$ Y	Twin law	2V <sub>z</sub>	Average composition
Flow	K 30 (1)	89	72	Albite	82	An 00
"	K 30 (2)	88	20	Carlsbad	80	An 00
"	K 87	87	15	Carlsbad	86	An 00
"	K 115	87	74	Albite	79	An 00
"	K 284	86	87	Ab-carls	84	An 01
"	K 268 (1)	85	16	Carlsbad	86	An 02
"	K 268 (2)	87	75	Albite	85	An 02
Aquagene tuff	K 338	57.5	59	Pericline	89	An 80
"	K 474 (1)	61	59	Albite	98	An 82
"	K 474 (2)	59	60	Albite	98	An 85
"	K 476 (1)	63	63	Albite	84	An 76
"	K 476 (2)	64.5	31	Ab-carls	80	An 67
"	K 517	64	65	Albite	83	An 71
"	K 525	32	88	Carlsbad	88	An 80

twinned plagioclase is determined to be 15° to 18° by the universal stage, corresponding to An 03 to An 00 according to Slemmons' (1962a) curves, which is consistent with some microanalyses shown in table 3. The optical data and compositions of some plagioclases are presented in table 4. Carefully measured values of  $2V_z$  average between 79° and 85°, indicating low-temperature, ordered albite (Slemmons, 1962b). Zoning and compositional variation in a single albite grain were not detected.

Pumpellyite occurs in amygdules, interstices, and as inclusions in plagioclase and constitutes on the average 10 to 30 percent (in volume) of most Karmutsen massive flows (table 1). In amygdules and interstitial fillings, pumpellyite may occur as mono-mineralic aggregates, but most commonly it is accompanied by quartz and chlorite in stellate aggregates of tiny needles or clusters of isolated needles in quartz (pl. 1-F). Pumpellyite also occurs abundantly as products of alteration of primary calcic plagioclase. In some cases, pumpellyite prisms are aligned parallel to plagioclase cleavage (pl. 1-D), and in others they are randomly but evenly distributed within the crystals (pl. 1-C). Pumpellyite and chlorite tend to be more common in smaller groundmass laths than in larger phenocrystal plagioclases. In some thin sections, microlitic plagioclase of the groundmass is completely replaced by pumpellyite.

Pumpellyite is distinguished by its strong pleochroism in the elongated Y direction and by a characteristic second-order greenish purple birefringence. The pleochroic color is deep green in Y and colorless or light green in X and Z in common pumpellyite. Amygdule pumpellyite has  $\beta = 1.700 \pm 0.003$  and indicates iron-rich pumpellyite, corresponding to  $Fe^{+2}/Fe^{+3} = 11/100$  according to Seki's diagram (1961). Three microanalyses shown in table 3 give pumpellyite composition very close to

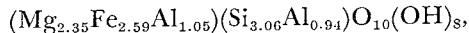


Prehnite often occupies the entire space of large amygdules, but its occurrence is rather sporadic, and it is much less abundant than pumpellyite. It appears as fan-shaped radiating aggregates showing bow-tie structure or as small needle-like poikilitic clusters in quartz. The hand specimen of amygdule prehnite is commonly pinkish due to minute inclusions of native copper (Surdam, ms) and is easily recognized in the field. The optical properties of this pink prehnite are  $\alpha = 1.608$ ,  $\beta = 1.617$ ,  $\gamma = 1.633$  (all  $\pm 0.003$ ),  $2V(+)$  = 60° to 65°. The chemical composition (table 3) indicates appreciable substitution of  $Fe^{+3}$  for Al in the Karmutsen prehnite; similar observations have been made by Surdam (ms, 1969).

Epidote is commonly present in amygdules and veins and partly replaces augite. It occurs as anhedral grains included in quartz or chlorite. However, it does not occur in all flows, and, where present, it generally constitutes less than 3 percent of the rock. The measured optical properties,  $\alpha = 1.730$ ,  $\beta = 1.759$ ,  $\gamma = 1.773$  (all  $\pm 0.003$ ),  $2V(-)$  = 79°, suggest a high  $Fe^{+3}$  content (Ps32 after Myer, 1965).

Green chlorite, constituting 10 to 20 percent of the Karmutsen flows, occurs abundantly as radiating fibrous aggregates in amygdules and as

tiny flaky inclusions in albitized plagioclase. Chlorites are recognized as secondary minerals after some pyroxene and plagioclase or as products of late vein and amygdule-filling processes. The composition of chlorite is very close to



in agreement with that of chlorite regarded as of burial metamorphic origin (Zen, 1974).

Quartz is present in most amygdules and veinlets but is not found in every thin section. Generally, amygdule-free massive flows do not contain quartz. Low birefringent white mica, presumably phengite (Surdam, ms), is fairly common as tiny flaky inclusions in amygdaloidal quartz. Laumontite (or wairakite) occurs as tiny subhedral grains, poikilitically enclosed by quartz in some amygdules. Primary Fe-Ti oxide minerals are invariably replaced by lamellar sphene and magnetite, as described in the next section.

#### SPHENE-MAGNETITE INTERGROWTHS

The primary Fe-Ti oxides of the Karmutsen flows are invariably replaced by magnetite and sphene. The primary opaques appear to have been unmixed into ilmenite and magnetite during cooling, and ilmenite lamellae were then replaced by sphene during burial metamorphism. Although lamellar intergrowths of magnetite-ilmenite and magnetite-ülvospinel are common and well-known in igneous rocks (for example, Deer, Howie, and Zussman, 1965), the magnetite-sphene microgrowth in the prehnite-pumpellyite facies metabasalts has not been described adequately. Some previous investigators briefly mentioned replacement by sphene of iron oxide (Cann, 1969) and ilmenite lamellae (Zen, 1974, p. 216) in metabasalts.

Opaque minerals invariably constitute 5 to 10 percent (in volume) of most Karmutsen massive flows, occurring mainly as subhedral grains, ranging from 0.1 to 1 mm in grain size. They are more abundant and coarser-grained in metamorphosed flows than in pillows. Two types of magnetite-sphene intergrowths have been recognized: (1) magnetite-sphene microintergrowths in typical flows, in which plagioclase has been extensively altered to albite and pumpellyite, and (2) primary Fe-Ti oxide with sphene inclusions in some Karmutsen pillows and flows, in which plagioclase is not albitized.

Plate 2 illustrates electron beam scanning photographs of an opaque grain of the first type, which is very common in the flows. This grain (K1055) is composed of two distinct compositional domains, Ti-rich and Fe-rich phases, in super-fine lamellae in three directions apparently controlled by the crystal structure of the original host. From the distribution patterns of Fe, Ti, Ca, and Si, the Ti-rich phase is considered to be sphene and the Fe-rich phase magnetite. Semi-quantitative electron probe analyses and X-ray diffraction patterns support this identification.

Plate 3 shows electron beam scanning photographs of unaltered primary Fe-Ti oxides (second type) in a relatively fresh massive flow (K96). This very anhedral grain consists of an apparently homogeneous Fe-Ti oxide and granular inclusions of sphene. The Fe-Ti phase does not show any exsolution texture on this scale of magnification (1 cm = 20 microns) and is considered to be a homogeneous magnetite-ülvospinel solid solution.

Buddington and Lindsley (1964) and Davidson and Wyllie (1968) have advanced the theory, based on experimental and observational works, that the common magnetite-ilmenite intergrowth in igneous rocks is caused by oxidation and "exsolution" of the ülvospinel component of originally homogeneous ülvospinel-magnetite solid solution during cooling, rather than by simple exsolution of ilmenite-magnetite solid solution. As discussed in detail by these authors, various textural and compositional relationships among Fe-Ti oxides of igneous rocks depend upon different temperatures and partial pressures of oxygen during cooling of magma.

In gabbro and diabase, which cool relatively slowly, Fe-Ti oxide intergrowth would be either ilmenite-magnetite under conditions of high  $f_{O_2}$  or ilmenite-magnetite-ülvospinel under low  $f_{O_2}$ . The Karmutsen magnetite-sphene microintergrowths may represent such a primary texture; Ti-oxide (ilmenite or ülvospinel) is now replaced by sphene, but Fe-oxide (magnetite) has survived. The replacement of Ti-oxide by sphene is considered to have taken place during burial metamorphism, because this phenomenon is intimately related to the metamorphic albitization and pumpellyitization of primary plagioclase. The  $TiO_2$  content (5-10 wt percent) of the magnetite certainly indicates that the lamellar magnetite is not metamorphic but primary, because metamorphic magnetite of the greenschist facies contains only 0.03 to 0.69 wt percent  $TiO_2$  (Abdullah and Atherton, 1964).

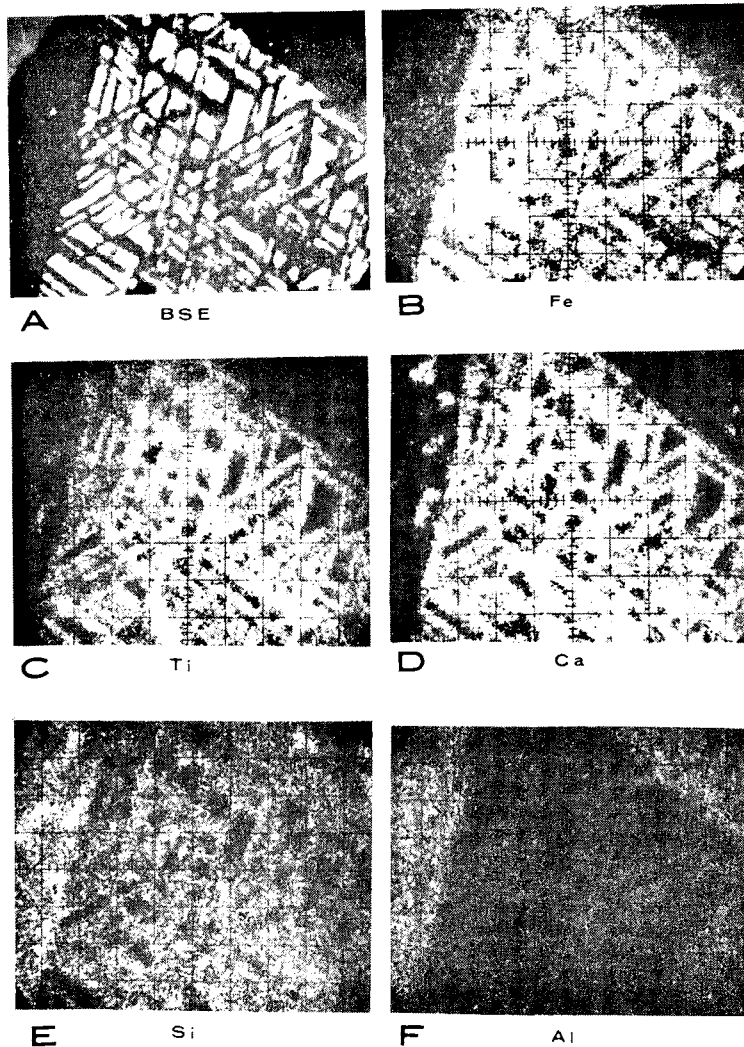
Primary Fe-Ti oxides in most of the Karmutsen flows and some of the pillow cores have followed the alteration history as described above. However, in the relatively unaltered Karmutsen rocks (for example, K96), in which homogeneous Fe-Ti oxide and granular sphene inclusions occur (pl. 3), sphene probably represents former ilmenite formed by "internal granule exsolution" (Buddington and Lindsley, 1964, p. 323). The extremely anhedral form of this grain suggests that  $f_{O_2}$  was too low initially to precipitate oxides during crystallization of pyroxene and plagioclase, and only the residual melt accumulated enough oxygen to crystallize oxides in the interstices between silicates. Because of the low  $f_{O_2}$ , the oxidation of the ülvospinel component to make lamellar magnetite-ilmenite intergrowths did not occur during cooling of this particular lava.

#### CHEMICAL COMPOSITIONS

About 200 rock samples representing the three Karmutsen rock types, (1) aquagene tuffs, (2) pillows, and (3) massive flows, were analyzed by

## PLATE 2

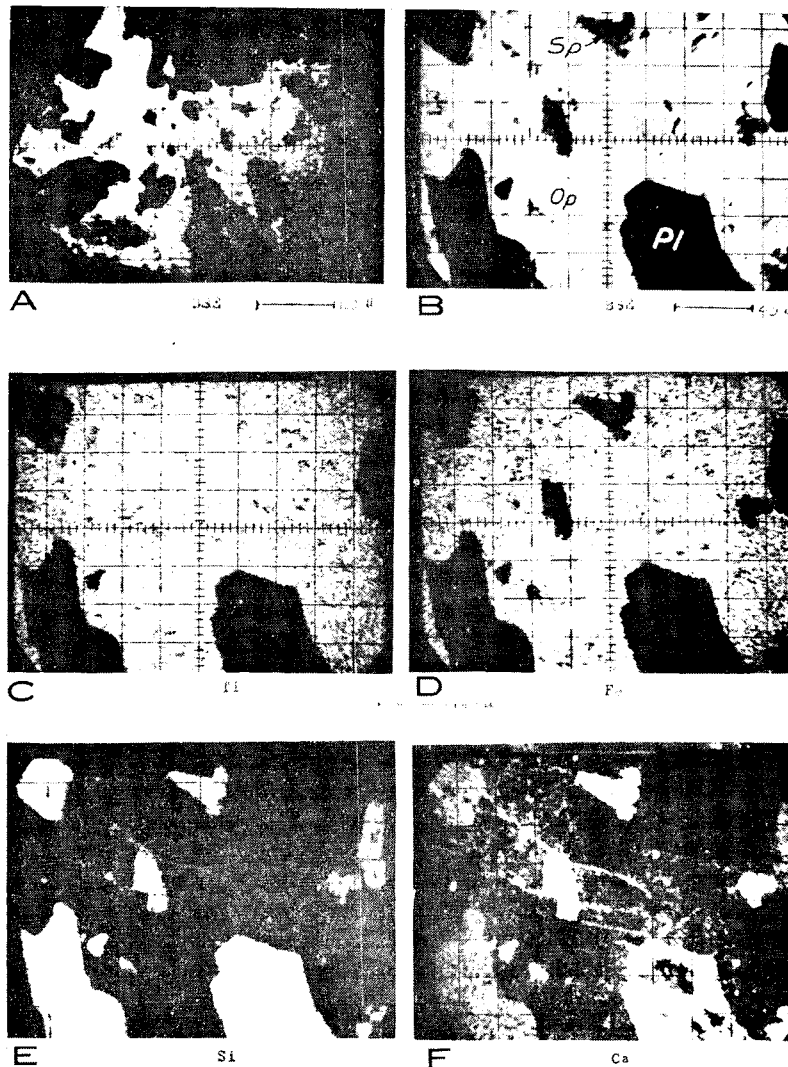
Scanning electron probe pictures of an opaque grain composed of lamellar sphene and magnetite in an albitized pumpellyite-rich metabasalt (K1053). Microprobe operated at 15 kv and 0.02 ma.



A. Back scattering electron beam picture; B. Fe  $K_{\alpha}$  radiation (200,000 counts); C. Ti  $K_{\alpha}$  radiation (140,000 counts); D. Ca  $K_{\alpha}$  radiation (200,000 counts); E. Si  $K_{\alpha}$  radiation (150,000 counts); F. Al  $K_{\alpha}$  radiation (70,000 counts).

PLATE 3

Scanning electron probe pictures of an opaque grain in an unalbitized flow (K96). Microprobe operated at 15 kv and 0.02 ma.



A. Back scattering electron beam picture. The right side of this grain is shown enlarged in (B) to (F); B. Back scattering electron beam picture; C. Ti  $K_{\alpha}$  radiation (370,000 counts); D. Fe  $K_{\alpha}$  radiation (200,000 counts); E. Si  $K_{\alpha}$  radiation (200,000 counts); F. Ca  $K_{\alpha}$  radiation (150,000 counts).

(sp = sphene; Op = Fe-Ti oxide; pl = plagioclase)

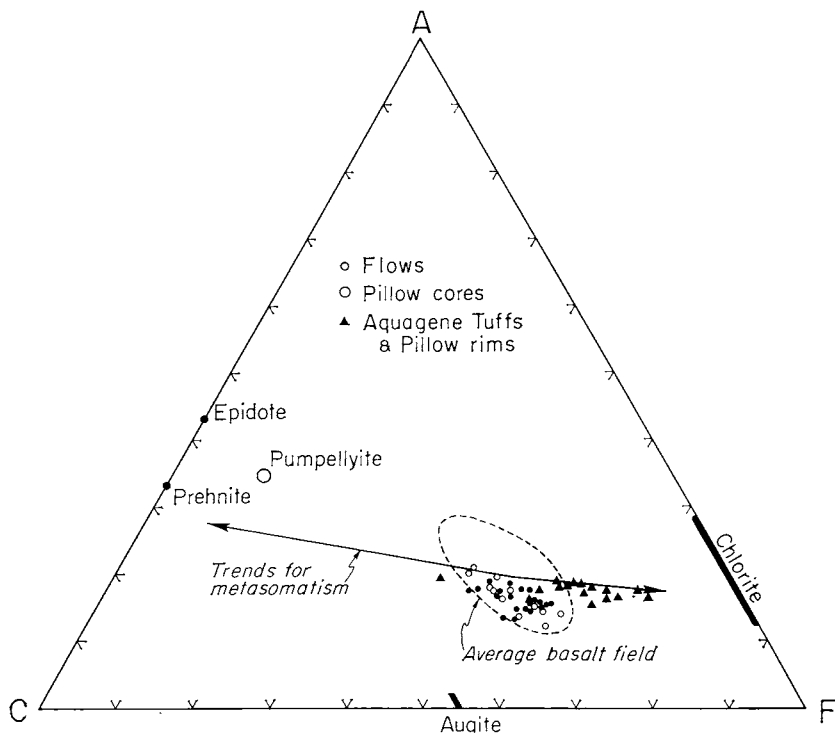


Fig. 2. ACF plot of some Karmutsen flows, pillow cores, and aquagene tuffs. Compositional field of average basalt compiled by Smith (1968) after Coombs' (1963) data, and trends of chemical variation during the burial metamorphism in "domains" described by Smith (1968) are also shown. Compositions of epidote, pumpellyite, prehnite, chlorite, and augite are plotted.

A =  $\text{Al}_2\text{O}_3 - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ ; C = CaO; F = FeO + MgO + MnO.

In order to plot XRF data of the Karmutsen volcanic rocks,  $\text{Fe}_2\text{O}_3/\text{FeO}$  ratios were assumed to be 1/10.

X-ray fluorescence techniques for major elements, and the total  $\text{H}_2\text{O}$  content determined as loss at ignition. Representative chemical analyses are presented in table 2 and figure 2. In order to avoid possible metasomatic effect of the granitic Island Intrusions, the rocks in the thermal aureole are excluded from the present discussion.

It is noticeable from table 2 that the chemical compositions of the Karmutsen aquagene tuffs differ significantly from the associated pillow cores and massive flows. In particular, consistently lower  $\text{SiO}_2$  and  $\text{Na}_2\text{O}$  and higher total Fe, MgO, and  $\text{H}_2\text{O}$  in aquagene tuffs are the most noticeable. The significant compositional variations may be caused by differential leaching of Na, some Si, Ca, and Al, and little or no Mg, Fe, Ti, and K from the originally glass tholeiites (that is, pillow rims and aquagene tuffs) during diagenesis and burial metamorphism (Kuniyoshi, Carlisle, and Liou, 1975).

Karmutsen pillow cores and massive flows are compositionally homogeneous and are H<sub>2</sub>O-rich compared with fresh submarine volcanic rocks. For example, Moore (1970) reported about 0.25 (0.06-0.42) wt percent H<sub>2</sub>O in fresh, K-poor oceanic basalts. Most H<sub>2</sub>O in the Karmutsen is apparently post-eruptive addition. If the bulk compositions of massive flows and pillow cores are recalculated assuming a lower H<sub>2</sub>O content, for example, 1 wt percent, the variations of major oxides are very small. When plotted on the ACF diagram of figure 2, the overall compositions of Karmutsen flows and pillow cores fall within the average basalt field of Coombs (1963).

On the ACF diagram (fig. 2), the compositions of aquagene tuffs and pillow rims lie toward the chlorite composition. Such compositional variations are consistent with the mineral assemblages listed in table 2, as aquagene tuffs and pillow rims are enriched in chlorite as secondary minerals. Smith (1968) studied the chemistry of alteration domains in Ordovician basic lava and observed two diverging trends away from the basaltic field: domains enriched in albite-chlorite and domains enriched in prehnite-pumpellyite or pumpellyite-epidote (fig. 2). Smith (1968) suggested that such features resulted from rearrangement of chemical components of basaltic rocks during burial metamorphism. No such trends were found in Karmutsen flows and pillows, but Karmutsen aquagene tuffs show a trend similar to the chlorite-enriching trend of Smith. The occurrence of secondary minerals in veins and amygdulites certainly indicates remobilization of material within flow and pillow bodies during diagenesis and burial metamorphism but in a much lesser scale than in the Ordovician lavas of Australia.

#### BURIAL METAMORPHISM

*General statement.*—The portion of the Karmutsen Subgroup that is free from contact metamorphism is exposed for a maximum thickness of 4400 m in the present area. Depth-controlled variations in metamorphic minerals or mineral assemblages were not found. Although the possibility of subtle but consistent differences in the ratios or in the composition of minerals has not been investigated, it appears valid to include all exposed Karmutsen volcanic rocks in this area within the prehnite-pumpellyite facies.

The normal sequence of burial metamorphism with increasing depth is characterized by zeolite → prehnite-pumpellyite → pumpellyite-actinolite → greenschist facies, as recognized in meta-volcanic and meta-volcaniclastic rocks in New Zealand (Coombs, 1954; Bishop, 1972; Kawachi, 1975). Greenschist facies burial metamorphic rocks are not found in the Karmutsen Subgroup in this area, either because the deeper, higher grade metamorphic rocks are not exposed or because the Karmutsen Subgroup did not reach greenschist facies conditions during burial. Neither are zeolite facies rocks, characterized by heulandite, analcime, and laumontite without pumpellyite and prehnite, exposed in the present area. Possibly zeolitic rocks in the uppermost Karmutsen Subgroup have been

eroded away in some parts of the area. Asihene (ms) also found no zeolite facies rocks in the 4700 m of the Texada Formation correlative with the Karmutsen volcanic rocks on Texada Island.

On the other hand, Surdam (ms, 1973) has described a recognizable depth-controlled distribution of alteration minerals in the Karmutsen volcanic rocks of the Buttle Lake area, 50 km south of the present area. There, the glassy phase in aquagene tuffs in the upper 2100 m of the section is altered to zeolitic assemblages, analcime, and laumontite with the exclusion of albite and pumpellyite, and that in the lower section to prehnite. Surdam maintains that, although largely overlapping, the glass alteration by hydration occurred in the laumontite stability field in the upper section and in the prehnite field in the lower section and explains the overlapping occurrence of these minerals in terms of ionic equilibria.

Except in the proximity of the granitic intrusions, the pumpellyite-bearing Karmutsen volcanic rocks described in this note appear to be free from intrusive effects. We have examined the possible thermal overprint even in rocks appreciably removed from exposed granitic rocks. The large spatial extent of the pumpellyite-bearing assemblages (fig. 1) and no apparent changes in texture (extent of recrystallization and grain size), in mineral assemblages, and in compositions of the constituent minerals suggest that the sequence was metamorphosed during burial on a regional scale.

*Mineral assemblages.*—The most common mineral assemblages in the studied area are albite + chlorite + pumpellyite + sphene + magnetite  $\pm$  quartz  $\pm$  epidote  $\pm$  prehnite. Calcite bearing assemblages are restricted only to rare amygdules and veinlets. The following rare associations were also observed in amygdules and veinlets: albite + quartz + chlorite + pumpellyite + laumontite (in flow) or wairakite (in tuff) and albite + quartz + chlorite + epidote + calcite. Inasmuch as partially replaced igneous pyroxene and plagioclase are abundant in the Karmutsen rocks, these metastable relicts indicate that complete textural and chemical equilibrium was not attained in the rock as a whole. Nevertheless, the discussion below suggests that phase equilibrium was approached in the most thoroughly recrystallized metamorphic mineral assemblages.

At least 9 metamorphic minerals (shown in table 2) are present in the Karmutsen volcanic rocks, although a thin section normally contains only 5 to 6 of them. These minerals may be described by 12 components:  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{MnO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{CO}_2$ . For graphical analysis these components could be simplified to 4 by the following general considerations: (1)  $\text{SiO}_2$  is considered to be in excess; the common occurrence of quartz in the Karmutsen amygdules and tuff interstices justifies this assumption, although in specific small domains it may be invalid. (2)  $\text{Na}_2\text{O}$ ,  $\text{TiO}_2$ , and  $\text{K}_2\text{O}$  are considered to be retained only in albite, sphene, and white mica, respectively. (3)  $\text{FeO}$ ,  $\text{MgO}$ , and  $\text{MnO}$  are considered as isomorphic components in solid solu-

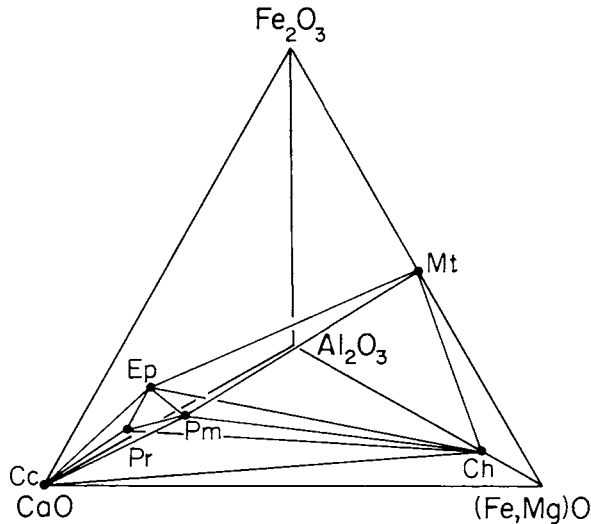


Fig. 3. Some observed four-phase mineral assemblages in pumpellyite-bearing rocks of the Karmutsen plotted in the  $\text{Al}_2\text{O}_3$ -poor portion of the tetrahedron  $\text{Fe}_2\text{O}_3$ - $\text{Al}_2\text{O}_3$ - $\text{CaO}$ - $(\text{Fe},\text{Mg},\text{Mn})\text{O}$ . Four phase assemblages (with or without albite, quartz, and sphene), Pm-Ch-Ep-Mt, Pm-Ch-Pr-Mt, Pm-Ch-Ep-Pr, Pm-Ch-Cc-Mt, Pm-Ep-Cc-Mt, Pr-Ep-Ch-Cc were observed in the Karmutsen metabasalt. Incompatible assemblages Ep-Pr-Cc-Mt, Ep-Pm-Pr-Cc, Ch-Ep-Pr-Mt, Pm-Ep-Ch-Cc, Ep-Pm-Pr-Cc were not found. (Pm = pumpellyite; Ch = chlorite; Pr = prehnite; Ep = epidote; Cc = calcite; Mt = magnetite).

tions and may be combined into a single component  $(\text{Fe},\text{Mg},\text{Mn})\text{O}$ . (4)  $\text{H}_2\text{O}$  and  $\text{CO}_2$  may be considered either as excess components or as mobile components with chemical potential externally fixed. In either case, these volatiles are indifferent in our chemographic consideration. We are now left with 4 components:  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ , and  $(\text{Fe},\text{Mg},\text{Mn})\text{O}$ .

In figure 3, metamorphic minerals of the Karmutsen volcanic rocks are located in the 4-component tetrahedron. The  $\text{Fe}^{+3}/(\text{Fe}^{+3}+\text{Al})$  ratio for epidote is considered to be about 0.3 from the X-ray diffraction study and for pumpellyite and prehnite about 0.2 and 0.05 respectively from the microprobe analyses (table 3, and Surdam, 1969). The observed four-phase assemblages excluding albite, quartz, mica, and sphene are shown in the diagram. With or without the excess and accessory phases (quartz, albite, sphene, and white mica), these compatible assemblages were actually found in the flows, amygdules, or interstices, although commonly only 2 or 3 out of 4 possible phases occur together. The diagram also predicts incompatible assemblages which are indeed not commonly found.

These considerations, if the assumptions are valid, suggest that most mineral assemblages in the Karmutsen volcanic rocks have approached phase equilibrium at least within the limited domains at relatively constant temperature, pressure, and other external variables. The uniformity in compositions for coexisting pumpellyite, chlorite, and epidote in

different modes of occurrence in Karmutsen meta-volcanic rocks (Schiffman, personal commun., 1975) also supports this suggestion.

*Physical conditions of metamorphism.*—The metamorphic facies characterized by prehnite and pumpellyite in meta-volcanics and metagraywackes is called “prehnite–pumpellyite metagraywacke facies” (Coombs, 1960, 1961) or “prehnite–pumpellyite facies” (Seki, 1961). The mineral assemblages of the Karmutsen volcanic rocks resemble those found in the rocks of this facies in New Zealand and Japan. Therefore, the metamorphic condition of the Karmutsen volcanic rocks is considered to correspond to the prehnite–pumpellyite facies.

The stability of individual minerals of the prehnite–pumpellyite facies depends on temperature, load pressure, fluid pressure, and chemical composition including  $H_2O$  and  $CO_2$  in the rock. Liou (1970, 1971a, b) experimentally determined stability relations of prehnite, laumontite, wairakite, and lawsonite for the  $CaO-Al_2O_3-SiO_2-H_2O$  system where  $P_{fluid} = P_{total} = P_{H_2O}$ . Such P–T fields can be taken as individual petrogenetic grids, although we are fully aware that such a simplified system seldom represents natural rocks; the presence of other elements (such as Fe, Mg, and Na) and the relation of  $P_{H_2O}$  and  $P_{total}$  significantly modify the experimentally determined temperature of reactions and cause the stability fields of various key minerals to overlap one another.

Nevertheless, the experimentally determined stability relations are most valuable for approximating the physical conditions of metamorphism. The approximate range of pressure in the Karmutsen volcanic rocks of this area can be inferred as 1 to 2.5 kb from the thickness of the overlying Upper Triassic and Jurassic strata in other areas. The prehnite–pumpellyite–chlorite–quartz assemblage was experimentally demonstrated to be stable up to  $345^\circ \pm 20^\circ C$  (Nitsch, 1971), although prehnite itself is stable up to  $400^\circ C$  (Liou, 1971a). Stilbite transforms to laumontite at  $190^\circ C$  at  $P_{H_2O}$  of 1 to 2.5 kb (Liou, 1971c). These temperatures can be considered as maximum and minimum in the burial metamorphism of the Karmutsen volcanic rocks. Considering the possible effect of other elements and the variable  $P_{H_2O}$  in these rocks, one can only suggest that the Karmutsen volcanic rocks in this area were probably subjected to temperatures from  $250^\circ$  to  $350^\circ C$  during burial metamorphism. Epidote is sparse, and hematite is even less common; this suggests that the metamorphism took place at relatively low  $f_{O_2}$ , certainly within the field of magnetite stability.

#### SELECTIVE ALBITIZATION

Primary calcic plagioclase in almost all massive flows and most pillow cores of the Karmutsen Subgroup is invariably altered to pure albite and pumpellyite plus lesser amounts of chlorite and phengite, whereas that in the aquagene tuff and pillow rims is replaced only partially by white mica, and most of the plagioclase crystals remain fresh (pl. 1-B, -C, -D). What caused such a contrasting alteration of primary plagioclase? The origin of albitic plagioclase in igneous-looking rocks has been con-

troversial in the past and is a main issue of the problem of whether spilites are igneous, deuteritic, seawater metasomatic, or burial metamorphic in origin (for a review, see Amstutz, 1974). Although current opinion predominantly favors a metamorphic origin (for example, Coombs, Horadyski, and Nayer, 1970; Hekinian, 1971; Reed and Morgan, 1971; Vallance, 1965, 1974a, b; Battey, 1974; Smith, 1974), the alteration process is not well understood.

There is little doubt that albite and pumpellyite intergrowths were formed from originally calcic plagioclase in the Karmutsen massive flows and pillows during prehnite-pumpellyite facies burial metamorphism. The pure albite composition, the low temperature form, and lack of zoning for plagioclases in the flows and most pillow cores strongly support this suggestion. The occurrence of predominantly calcic plagioclase in unaltered submarine pillowed basalts and the abundance of subophitic augite intergrown with plagioclase (now replaced by pumpellyite and albite in the Karmutsen massive flows and pillows) rule out the magmatic or deuteritic origin of the albite. This fact, plus abundantly unaltered calcic plagioclase in the Karmutsen aquagene tuff, which was permeated by seawater, certainly excludes a metasomatic origin involving introduction of Na from the seawater during cooling or diagenesis. Moreover, the chemical data described in this paper and elsewhere (Kuniyoshi, Carlisle, and Liou, 1975) show a significant loss of Na from aquagene tuff to the ocean or to interstitial solutions during diagenesis. Therefore, the albitization in the Karmutsen volcanic rocks and related reactions must have taken place during burial metamorphism.

The metamorphic recrystallization of albite and pumpellyite takes place within the calcic plagioclase crystals. The alteration can be considered to involve only the anorthite component of plagioclase; the albite component remains unaltered as anorthite decomposes to pumpellyite and kaolinite according to the hypothetical reaction:  $4 \text{ anorthite} + 5\text{H}_2\text{O} = 2 \text{ pumpellyite} + \text{kaolinite}$ . However, the alteration is not isochemical but involves the introduction of Fe, Mg, and other elements to make pumpellyite. Calculation of the chemical balance for the reaction  $\text{plagioclase (An 70)} + \text{Fe} + \text{Mg} + \text{H}_2\text{O} = \text{albite} + \text{pumpellyite}$  at constant volume is shown in table 5. Three cases were considered: (1) at constant CaO, (2) at constant Na<sub>2</sub>O, and (3) at fixed volume ratio of albite (66 percent) and pumpellyite (34 percent), which represent average volume relations of typical altered plagioclase in the Karmutsen massive flows. The results indicate that some introduction of Si, Fe, Mg, Na, and H<sub>2</sub>O and removal of Al are required for albitization and pumpellyitization of calcic plagioclase in all cases, and Ca is added at constant Na<sub>2</sub>O and removed at the fixed volume ratio. Necessary elements for the alteration were probably supplied from decomposition of earlier formed zeolites, interstitial glass, and ilmenite. The alteration of calcic plagioclase releases Al<sub>2</sub>O<sub>3</sub> and CaO, which enter amygdules and interstices to crystallize pumpellyite, prehnite, chlorite, epidote, or calcite during meta-

morphism. Occurrence of these minerals in amygdules and veins indicates considerable mobility of Ca and Al components.

The albitization of igneous plagioclase has been widely reported in burial metamorphic sequences in many areas (for some references, see Zen and Thompson, 1974). The completeness of the alteration has been shown to be related roughly to the depth of burial and thus to increased temperature and pressure. No doubt, heat is necessary to activate the hydration reaction. However, incompletely altered plagioclase is also known to occur abundantly in rocks that have undergone burial metamorphism (for example, Dickinson, 1962). As described, completely albitized plagioclase is found only within pillow bodies, whereas unaltered plagioclase occurs in aquagene tuffs at the same stratigraphic horizon in the upper Karmutsen Subgroup. Therefore, it appears that P-T conditions alone do not determine plagioclase alteration.

Dickinson (1962) explained the variable alteration of the Jurassic andesitic tuffs in Oregon in terms of the availability of water; unequal distribution of interstitial water was given as the chief reason for the selective albitization. It is conceivable that a more extensive reaction may be facilitated by the infiltration of a hydrous fluid phase during burial. However, this concept does not explain the lack of albitization of Karmutsen aquagene tuffs which were water-soaked in comparison with pillow cores and consequently have a higher water content.

TABLE 5

Calculated chemical budget for albitization and pumpellyitization of calcic plagioclase (An 70) at constant volume in three different schemes: (1) at constant CaO, (2) at constant Na<sub>2</sub>O, and (3) at given albite/pumpellyite ratio of 66/34

Weight percent	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO*	MgO	CaO	Na <sub>2</sub> O	H <sub>2</sub> O	Density**
Plagioclase (An70)	50.9	31.5	—	—	14.1	3.54	—	2.7
Albite	68.8	19.4	—	—	—	11.8	—	2.6
Pumpellyite***	37.9	22.4	8.7	1.9	22.7	—	6.4	3.2
<hr/>								
Weight (grams)								
1 cc Plagioclase (An70)	1.374	0.850	—	—	0.380	0.096	—	2.7
<hr/>								
I. At constant CaO								
0.477 cc albite	0.853	0.241	—	—	—	0.146	—	1.235
0.523 cc pumpellyite	0.635	0.375	0.146	0.032	0.380	—	0.107	1.674
Gain or loss	+0.113	-0.234	+0.146	+0.032	0	+0.050	+0.107	
<hr/>								
II. At constant Na <sub>2</sub> O								
0.31 cc albite	0.560	0.158	—	—	—	0.096	—	0.814
0.69 cc pumpellyite	0.837	0.495	0.192	0.042	0.501	—	0.141	2.208
Gain or loss	+0.023	-0.197	+0.192	+0.042	+0.121	0	+0.141	
<hr/>								
III. At given albite/pumpellyite ratio of 66/34								
0.66 cc albite	1.181	0.333	—	—	—	0.202	—	1.716
0.34 cc pumpellyite	0.412	0.244	0.095	0.021	0.247	—	0.070	1.088
Gain or loss	+0.219	-0.273	+0.095	+0.021	-0.133	+0.106	+0.070	

\* Total Fe as FeO; \*\* density values of plagioclase, albite, and pumpellyite are from Deer, Howie, and Zussman (1963); \*\*\* average composition of 3 pumpellyite analyses (table 3).

It is proposed here that the composition of the fluid, in particular the concentration of Fe and Mg ions in the fluid, is a critical factor in the reaction. There is a direct relationship between albitization of plagioclase and alteration of primary Fe-Ti oxides in the Karmutsen volcanic rocks. In the albitized massive flows and pillow cores, primary Fe-Ti oxides are invariably replaced by magnetite and sphene. The primary oxides must have unmixed into ilmenite and magnetite during cooling. During burial metamorphism, ilmenite was replaced by sphene, thereby freeing Fe into the fluid. The formation of sphene involves introduction of Ca and Si and removal of Fe ions from the Ti-rich phase into the fluid (ilmenite+Ca+Si→sphene+Fe). Si and Ca were perhaps supplied from decomposition of early formed diagenetic zeolites in amygdules or from alteration of calcic plagioclase. Thus the interstitial pore fluid in the flows and pillow cores was highly charged with Fe<sup>+2</sup> ions and was able to convert the anorthite component of plagioclase to pumpellyite (+chlorite). In the aquagene tuffs and pillow rims, most of the Fe was retained not in the form of oxide but in quenched solution in sideromelane glass (opaques are very rare in the aquagene tuff). As glass is least stable during diagenesis and burial metamorphism, it is readily converted to clay minerals and chlorite. Thus Fe was likely fixed in the structure of chlorite during the early stage of metamorphism and was not available in the pore fluid (Carlisle and Kuniyoshi, 1966; Kuniyoshi, 1972). This Fe-poor fluid was evidently unable to alter calcic plagioclase to albite and pumpellyite in the aquagene tuffs and the pillow rims.

#### DISCUSSION

Karmutsen metavolcanic rocks are of interest in connection with the problem of spilite origin. Extensive albitization and pumpellyitization of calcic plagioclase, accompanied by alteration of Fe-Ti oxides to sphene and magnetite, in the Karmutsen flows and pillow cores have resulted in spilitic characteristics. In addition to albite, pumpellyite, and sphene, the rocks contain primary clinopyroxene, interstitial chlorite, and variable amounts of epidote, prehnite, and magnetite. Therefore, based on their present mineralogy, these Karmutsen metabasaltic rocks can be classified as spilites.

Chemically the present rocks are considered not typically spilitic. Spilites are generally distinguished from basalts by higher Na<sub>2</sub>O and lower CaO contents. Sundius (1930) shows 4.93 and 6.89 wt percent as average Na<sub>2</sub>O and CaO contents of spilites, respectively. On the other hand, a complete chemical gradation from normal tholeiite basalt to spilite has been suggested (Fairbairn, 1934; Battey, 1956; Vallance, 1960). The term "spilite" is generally applied to sodium-rich, albite-bearing, basic, igneous-looking rocks. But the definition or acceptance of the term seems to differ considerably among authors. Some petrologists emphasize mineral association, and others a chemical or genetic connotation. The ambiguity in the definition makes the problem of the genesis of "spilites," more difficult (for reviews, see Vallance, 1960; Fiala, 1974; Amstutz, 1974).

Concerning the origin of spilites, whether magmatic (for example, Amstutz, 1968; Amstutz and Patwardhan, 1974; Bamba, 1974), seawater diffusion (for example, Park, 1946), metasomatic (for example, Gilluly, 1935), autometasomatism (for example, Vozar, 1974), hydrothermal degradation (Vallance, 1974a, b), or metamorphic (Cann, 1969; Smith, 1969, 1974; Coombs, Horadyski, and Nayer, 1970; Coombs, 1974), opinions are still widely split. The Karmutsen "spilitic" rocks apparently are metamorphosed tholeiitic basalts. Most of the described "typical spilites" in literature (for references, see Amstutz, 1974) very much resemble these rocks petrographically, and they may be of similar genesis. The invariable occurrence of albite + chlorite + quartz + sphene + magnetite  $\pm$  pumpellyite  $\pm$  prehnite  $\pm$  epidote  $\pm$  hematite in spilites suggests that all spilites are more or less metamorphosed in the zeolite, prehnite-pumpellyite, or greenschist facies conditions (for details, see Coombs, 1974). Extremely sodium-rich spilites may require another explanation, possibly involving metasomatism (Gilluly, 1935).

Unfortunately, the decision to classify an albitized rock as spilite, keratophyre, or metabasalt seems to impose a petrogenetic opinion upon the rock terminology. Those who favor a metamorphic origin may be inclined to name the rock metabasalt (Coombs, 1974) or greenstone and reject the term spilite, whereas those who claim a magmatic origin use the term spilite (for example, Battey, 1956; Donnelly, 1963; Amstutz, 1968; Amstutz and Patwardhan, 1974; Bamba, 1974). In fact, the possibility of a metamorphic origin for spilites in general may have been overlooked, because such rocks would be lumped with "metabasalt" (for example, Ernst, 1965; Coombs, 1974). If virtually all spilites are proven to be metamorphosed basalts, as previously considered by Fairbairn (1934), Smith (1969, 1974), Cann (1969), and Coombs (1974), the term spilite should be abandoned or used as a synonym of Na-rich metabasalts. If, on the other hand, the existence of unmetamorphosed volcanic spilites can be proven, the term spilite should be used only for such rocks. In our opinion most "petrographically spilitic rocks" are actually metabasalts.

#### ACKNOWLEDGMENTS

We are indebted to Doctors D. Carlisle and W. G. Ernst of the University of California, Los Angeles, and Y. Seki of Saitama University, Japan for their critical review of the initial manuscript and for their helpful suggestions for improvement. Research for this project was initiated at the University of California, Los Angeles and financial support for the field mapping and chemical analyses was partially supported by the University of California, Los Angeles. Final research was completed at Stanford University with support by an NSF grant (GA37177/Liou).

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