PETROLOGY OF THE MONTEREGIAN INTRUSIONS OF MOUNT YAMASKA, QUEBEC

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ABSTRACT

Two major intrusions of the igneous complex of Mount Yamaska are shallow-seated, vertical pipe-like in form, and subsiliceous calcic basaltic in composition. They are strongly differentiated, with ultramafic rocks at their cores and progessively more felsic rocks towards their boundaries. The older intrusion, 2.8 square miles in area, has differentiates ranging from ultramafic "older yamaskite" through gabbro to silica-saturated akerite. On its southwestern margin is the younger intrusion, which is 0.3 square mile in area and has differentiates ranging from ultramafic "younger yamaskite" to nepheline-bearing essexite. Differentiation trends of the intrusions are discussed in light of the known phase relations.

INTRODUCTION

Mount Yamaska is situated between latitudes 45° 25′ and 45° 29′ north, and longitudes 72° 50′ and 72° 54′ west. It is one of a classical group of nine hills in the St. Lawrence lowland, which have core of intrusive rocks of related types that constitute the Monteregian petrographic province (Adams 1903 ; Dresser & Denis 1944). The igneous rocks intruded folded sedimentary formations of Lower Paleozoic age. The intrusions range in age from 135 to 70 million years according to recent age determinations (Larochelle 1962 ; Fairbairn *et al.* 1963).

The igneous core of Mount Yamaska is nearly circular in plan and about two miles in diameter (3.18 square miles in area). It consists of rocks ranging from ultramafic to highly felsic in character. In the most important previous study of the rocks, Young (1906) concluded that they are products of differentiation in a single body of magma forming a stock or a volcanic neck. Detailed mapping (1 inch to 400 feet scale) by the writer, however, revealed multiple injection of two main intrusive phases and two minor phases, and several related dykes. The two main intrusions are vertical pipe-like in form, basanitic or subsiliceous basaltic in composition, and are strongly differentiated with ultramafic rocks at their core and increasingly more felsic rocks towards their outer margin. The older intrusion occupies 89 per cent of the area of the igneous core of the mountain, and has differentiates ranging from yamaskite (ultramafic), through gabbro to akerite (monzonitic), designated as the older yamaskite-gabbro-akerite rock series (see Fig. 1). The younger main body intrudes the southwestern margin of the older, occupies 9 per cent of the area of the igneous core, and has differentiates ranging from yamaskite to essexite, designated as the younger yamaskite-essexite rock series. This paper deals mainly with the differentiation of the two main intrusions.

The intrusions had little effect on the attitude of surrounding formations, mainly shales and some sandstone, which strike northerly and commonly dip steeply to the east. At the immediate contact however, minor irregularities are common, and locally shatter-zone breccia is seen. The zone of contact metamorphism is 500 to 1,500 feet thick on the north and south sides of the igneous core, where the boundary of the core runs along the peaks of arcuate high ridges, rising steeply up to 1,000 feet above the St. Lawrence lowland. On the east and west sides of the core however, the zone is less than 200 feet thick, and the boundary is exposed close to the level of the lowland. The intrusions, like other Monteregian intrusions, are considered shallow-seated from their general geologic setting (Gold 1963). This is also supported by the transitional or intermediate character of the structural state of the feldspars (Pouliot 1962), which indicate that the rocks presently exposed crystallized at a pressure of about 1,000 bars (roughly equivalent to a depth of two miles).

The two minor intrusive phases are of augite porphyritic rock and nepheline syenite. The augite porphyritic rock is heterogeneous because of a number of small mineral aggregates and sedimentary inclusions, and it has a pronounced flow texture. It is intrusive into hornfels through which it is irregularly distributed, and the two are therefore mapped together (Fig. 1). It is apparently related to the essexite, possibly contaminated by the country rock, although it is intruded and surrounded by the younger yamaskite-essexite phase. Apparently the youngest intrusive phase is nepheline syenite, which occurs as a small body intrusive into the older yamaskite (Fig. 1), and as dykes cutting other igneous rocks. Several dykes of other compositions occur within and nearby the igneous core, and these include yamaskite, gabbro, essexite, diorite, bostonite, and syenite-aplite. They are evidently genetically related to the Monteregian igneous activity, though their relative ages are uncertain.

Previous work

Soon after Adams (1903) wrote his general account of the Monteregian petrographic province, Young (1906) published a detailed account of the geology and petrography of Mount Yamaska with a geological map on

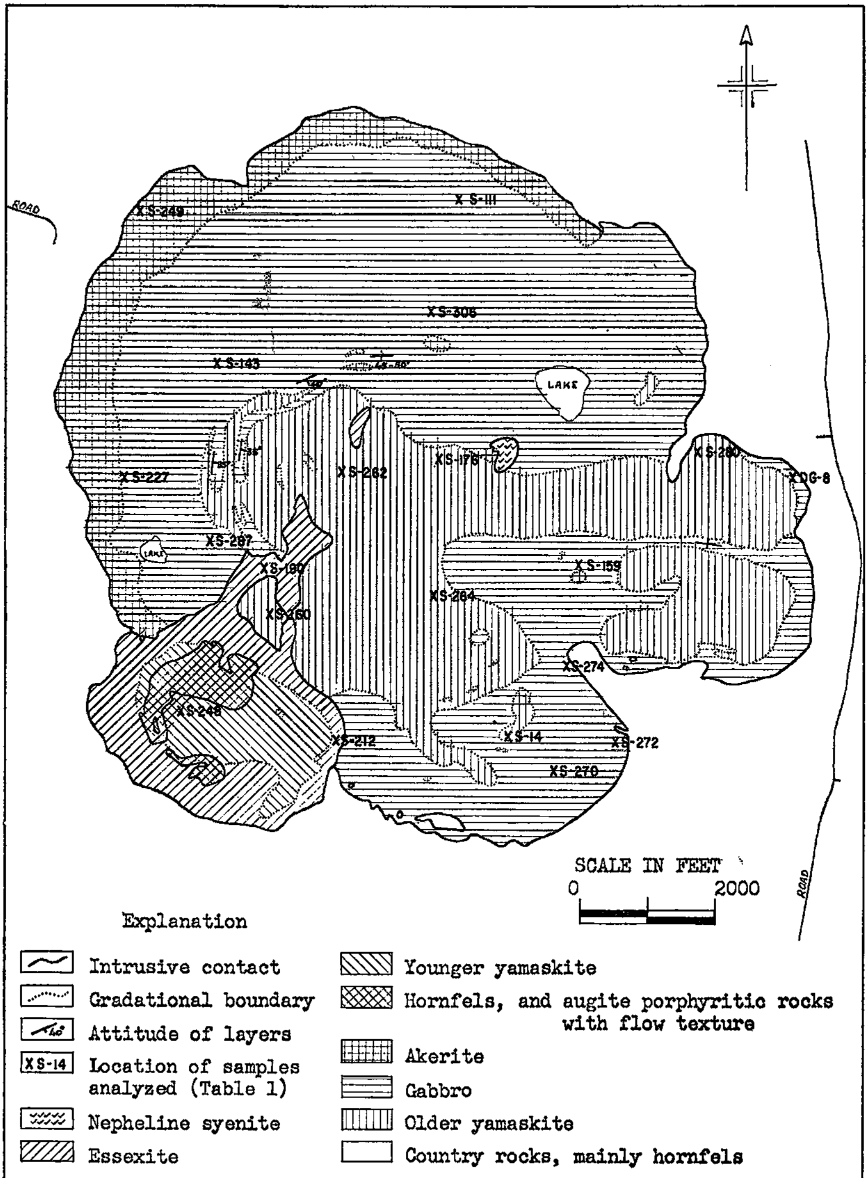

Fig. 1. Geological map of Mount Yamaska, Quebec.

scale 1 inch to ¼ mile. The igneous rocks of Mount Yamaska have been studied in more recent years as a part of two general studies of the Monteregian intrusions; one by Pouliot (1962) who studied the thermal history from the structural state of feldspars, and the other by Beall (1962) who investigated pyroxenes and discussed differentiation trend of the intrusions with reference to the system calcium tschermak's molecule-forsterite-monticellite-silica. Nickel (1958) described ulvöspinel-magnetite intergrowth in a sample from Mount Yamaska. Larochelle (1962) carried out a paleomagnetic study of Mount Yamaska.

OLDER YAMASKITE-GABBRO-AKERITE ROCK SERIES

Extreme differentiation of the older main intrusive phase has produced a series of rocks which can be classified into three groups, namely yamaskite, gabbro and akerite, which constitute 30, 60 and 10 per cent of the area of the intrusion respectively (Fig. 1). They encompass a considerable range in the chemical and mineralogical compositions, as can be seen from the chemical and modal analyses of 20 rocks presented in Tables 1 and 2. (See Fig. 1 for location of the rocks.) Transitional varieties between yamaskite and gabbro, and between gabbro and akerite, are encountered in the field. Molecular norms calculated from the chemical analyses, are given in Table 3, and it is seen that normative nepheline appears in all of eight yamaskites, in eight out of ten gabbros, and in one of the two akerites. The rock series as whole is therefore subsiliceous basaltic or basanitic in character. The two gabbros which do not contain normative nepheline, contain a small amount of normative hypersthene, and one of them contains normative olivine. Model nepheline however, is not seen in any of the 20 rocks, nor in thin sections of 155 other rocks of the series examined by the writer, with an exception, of a border phase of gabbro containing accessory nepheline, restricted to the extreme southeast corner of the intrusion, the locality where Young (1906) found traces of sodalite or analcite in a similar rock. Modal quartz on the other hand, is widely distributed as an accessory mineral in akerites and in the border phases of gabbro in the northeastern part of the intrusion. The appearance of normative nepheline in rocks of this series is due to the presence of silica-undersaturated minerals titanaugite, kaersutite and titanbiotite (see Tables 4 and 5 for their chemical analyses and norms). A study of thin sections shows that the composition of plagioclase in rocks of this series varies from highly calcic in ultramafic and mafic rocks to sodic in felsic rocks, and this is also seen from a triangular diagram

TABLE. 1. CHEMICAL ANALYSES * OF IGNEOUS ROCKS OF MOUNT YAMASKA, QUEBEC.

Rock Group	←——— Older Yamaskite							———→	←——— Gabbro			———→
Sample Number	S–176	S–262	Y–III	S–264	Y–IV	S–14	S–260	S–280	DG–8	S–270	S–287	S–306
SiO_2	32.67	32.52	39.97	31.72	36.24	35.57	34.99	37.80	40.59	43.15	40.98	39.75
Al_2O_3	8.45	9.33	8.68	8.77	9.05	9.84	10.45	11.84	15.30	15.19	17.66	16.59
TiO_2	8.92	7.36	4.05	6.88	7.12	6.44	6.84	5.00	5.66	6.12	5.55	5.28
Fe_2O_3	8.99	9.34	8.63	10.44	10.64	10.70	8.78	7.28	5.15	3.94	5.10	3.52
FeO	9.05	9.55	7.99	7.60	9.58	10.45	8.77	7.85	8.20	8.73	6.70	7.17
MnO	0.87	0.39	0.19	0.31	0.29	0.19	0.23	0.17	0.53	0.19	0.11	0.16
MgO	8.55	12.56	10.32	8.01	7.75	8.66	8.46	9.25	7.12	6.48	6.16	6.64
CaO	15.70	13.26	15.18	18.33	14.97	13.66	15.14	13.83	11.71	11.53	13.50	13.34
Na_2O	1.60	2.36	1.19	1.24	1.05	0.99	2.20	2.06	2.51	2.60	1.47	3.00
K_2O	0.60	0.90	0.74	0.31	0.43	0.41	0.90	0.86	0.98	0.65	n.d.	0.65
P_2O_5	2.23	2.76	0.10	5.50	1.01	0.19	2.97	0.35	0.34	0.17	0.11	2.81
H_2O+	0.61	—	0.57	1.01	0.65	1.10	—	0.51	0.54	—	0.83	0.83
CO_2	0.11	0.17	1.15	—	—	0.15	0.17	0.71	—	—	—	—
FeS_2	—	—	1.01	—	0.97	—	—	—	—	—	—	—
Total	98.35	100.50	99.77	100.12	99.75	98.35	99.90	97.51	98.63	98.75	98.17	99.74

Rock Group	←——— Gabbro					———→	←— Akerite	—→	Yama-skite	←—— Essexite		——→
Sample Number	S–143	S–274	S–159	S–111	S–227	S–272	Y–I	S–249	S–248	S–212	S–190	Y–II
SiO_2	42.61	43.71	43.35	43.44	45.44	50.36	57.75	58.13	35.07	39.25	41.48	43.91
Al_2O_3	18.00	16.79	16.96	17.73	16.73	15.99	17.50	17.65	8.40	13.59	16.07	19.63
TiO_2	4.25	5.41	3.69	3.36	3.26	3.17	1.53	1.59	6.94	5.51	4.87	3.80
Fe_2O_3	4.30	4.31	6.31	4.86	4.91	1.93	2.92	1.69	9.60	5.63	5.17	4.16
FeO	6.22	7.50	6.00	6.00	5.87	7.89	2.94	4.00	8.57	8.11	7.22	5.55
MnO	0.16	0.19	0.23	0.62	0.77	0.26	0.19	0.33	0.22	0.80	0.63	0.07
MgO	6.05	5.11	5.36	5.40	4.84	3.34	1.70	1.86	9.92	6.05	5.44	5.20
CaO	13.53	10.23	9.34	9.70	8.90	7.51	3.86	3.74	15.40	12.30	10.29	9.49
Na_2O	2.09	2.99	3.70	4.17	4.46	4.58	5.08	6.27	1.58	3.94	4.76	4.49
K_2O	0.58	0.67	1.41	1.00	1.24	2.29	3.51	3.99	0.62	1.06	2.01	1.51
P_20_5	0.28	0.21	1.33	1.54	1.47	0.82	1.05	0.43	1.90	1.94	1.46	0.32
H_2O+	0.87	0.71	1.02	0.62	0.82	—	0.37	—	—	0.47	0.68	0.53
CO_2	0.23	—	—	—	0.15	0.41	0.55	0.66	—	—	0.22	0.51
FeS_2	—	—	—	—	—	—	0.21	—	—	—	—	0.64
Total	99.17	97.83	98.70	98.44	98.86	98.55	99.16	100.34	98.22	98.65	100.30	99.81

* Analyses of samples Y-I, Y-II, Y-III, and Y-IV, reproduced from Young (1906, p. 40 H) ; analyses of the rest of the samples performed by Mrs. H. I. Soutar, using rapid silicate analytical methods, at the Geochemical Laboratory, McGill University, Montreal. Locations of these samples are given in Figure 1.

† Younger yamaskite.

TABLE 2. MODAL ANALYSES OF ROCKS OF TABLE 1.

Rock Group	←Older Yamaskite							→←	Gabbro→			
Sample Number	S–176	S–262	Y–III	S–264	Y–IV	S–14	S–260	S–280	DG–8	S–270	S–287	S–306
Plagiol.	0.10	6.10	2.00	0.00	15.00	6.85	2.36	12.03	42.08	58.12	50.55	51.40
Alk. Feld.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	tr.	0.00	0.00	0.00	0.00
Olivine	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.64	0.00	1.15
Augite	44.35	19.30	57.00	50.60	43.40	58.53	45.10	42.11	18.24	26.36	30.10	7.39
Hnbl.												
Brown	30.15	50.60	29.00	15.30	21.20	12.79	38.98	35.69	24.00	tr.	3.65	21.90
Green	0.00	0.00	0.00	0.00	0.00	2.76	0.00	0.00	0.00	0.00	4.65	0.00
Biotite	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	4.97	4.00	0.00	0.45
Opaques	14.05	10.70	8.00	19.80	19.10	17.85	8.84	8.92	8.40	8.88	10.60	7.40
Apatite	5.95	6.00	0.20	14.30	1.30	0.13	4.63	0.35	0.60	0.00	0.00	5.40
Sphene	4.90	7.20	0.00	0.00	0.00	0.03	0.10	0.84	1.73	0.00	0.00	0.00
Hercynite	0.00	0.00	0.00	0.00	0.00	0.27	0.00	tr.	0.00	0.00	0.50	0.00
Calcite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	tr.	0.05	0.00	0.00	0.00
Secondary	0.50	0.00	3.50	0.00	0.00	1.08	0.00	tr.	0.00	0.00	0.00	0.00
Points counted	2000	5000	—	4000	—	2891	3517	2869	2012	2500	2000	2000
IC number per 2 cms.	91	29	—	39	—	24	45	20	57	29	31	75

Rock Group	←Gabbro					→←	Akerite →		Yamaskite †	← Essexite →		
Sample Number	S–143	S–274	S–159	S–111	S–227	S–272	Y–I	S–249	S–248	S–212	S–190	Y–II
Plagiocl.	55.99	59.07	52.69	58.42	59.30	61.04	43.76	62.46	0.00	30.93	22.62	31.50
Alk. Feld.	0.00	0.00	0.00	0.00	0.00	14.40	25.06	23.49	0.00	0.00	1.67	15.50
Nepheline	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.43	10.67	7.50
Olivine	1.49	3.18	0.00	0.00	0.61	2.00	0.00	0.00	0.00	0.00	0.00	0.00
Augite	12.32	21.29	1.40	0.48	tr.	10.91	0.86	0.03	51.90	28.99	10.99	4.00
Hnbl.												
Brown	16.11	1.03	32.63	34.15	31.90	0.00	0.00	5.66	31.15	28.75	46.97	26.00
Green	4.67	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biotite	0.36	3.78	2.38	0.15	2.26	6.43	11.83	4.24	tr.	0.00	tr.	1.00
Opaques	7.07	11.17	6.35	4.15	4.30	4.58	6.00	1.64	12.65	4.71	4.32	4.00
Apatite	1.27	0.19	3.17	2.64	1.63	0.50	2.25	0.00	4.05	1.10	0.57	1.50
Sphene	tr.	0.00	0.50	0.00	0.00	0.00	0.00	0.56	0.25	0.10	2.15	6.50
Calcite	0.12	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zircon	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
Quartz	0.00	0.00	0.00	0.00	0.00	0.00	7.92	1.46	0.00	0.00	0.00	0.00
Pyrite	—	—	—	—	—	—	1.25	—	—	—	—	0.10
Secondary	0.57	0.29	0.06	0.00	0.00	0.17	0.00	0.40	0.00	0.00	0.00	2.00
Points counted	4000	2739	3025	2047	2700	5354	—	2810	2000	2929	4005	—
IC number per 2 cms.	30	40	46	44	79	42	—	42	45	45	33	—

* Modal analyses given in volume percentages of minerals. Modal analyses of the samples other than Y–I, II, III & IV, performed by the writer, using "Swift" point counter and spacing of three points per millimeter. Modal analyses of Y–I, II, III & IV are reproduced here from Young (1906, pp. 21H, 26H & 33H).

Abbreviations — Plagiocl.: Plagioclase, Alk. Feld.: Alkali Feldspar; Hnbl.: Hornblende; IC number: Identity change number of major mineral identity changes along a unit length of lines (Chayes 1956, p. 72); tr.: trace amount.

† Younger yamaskite.

Table 3. Molecular Norms* of Rocks of Table 1.

Rock Group	Older Yamaskite								Gabbro			
Sample Number	S-176	S-262	Y-III	S-264	Y-IV	S-14	S-260	S-280	DG-8	S-270	S-287	S-306
Or	0.0	0.0	4.5	2.0	2.5	2.5	6.0	4.4	6.0	4.0	0.0	3.5
Ab	0.0	0.0	3.0	7.0	6.5	4.5	2.0	0.0	12.5	21.0	14.0	18.9
An	15.5	12.5	17.3	18.8	20.5	23.0	16.8	21.0	28.8	29.0	44.0	31.0
Lc	0.4	2.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0
Kp	1.8	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ne	9.3	12.9	4.8	3.0	2.1	3.0	11.1	12.0	6.6	1.8	0.0	5.1
Di	43.2	29.2	48.8	31.2	42.8	39.6	33.2	38.4	23.2	23.6	20.4	13.6
Hy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.8	0.0
Ol	3.2	15.9	5.1	6.1	1.4	5.0	6.0	6.5	8.3	7.1	0.0	10.3
Pr	—	—	0.5	—	0.5	—	—	—	—	—	—	—
Mt	4.8	8.1	9.6	4.2	8.4	12.2	7.2	8.1	5.6	4.5	3.9	3.8
Hm	3.6	1.3	0.0	4.9	2.3	0.0	1.6	0.0	0.0	0.0	1.4	0.0
Il	13.4	10.4	6.0	10.2	10.8	9.6	9.8	7.4	8.2	8.8	8.2	7.6
Ap	4.8	5.9	0.3	12.6	2.1	0.4	6.4	1.1	0.8	0.3	0.3	6.3
Total	100.0	100.0	99.9	100.0	99.9	99.9	100.1	100.1	100.0	100.1	100.0	100.1
% Salic	27.0	29.2	29.6	30.8	31.6	33.0	35.9	38.6	53.9	55.8	58.0	58.5

Rock Group	Gabbro						Akerite		Yamaskite †	Essexite		
Sample Number	S-143	S-274	S-159	S-111	S-227	S-272	Y-I	S-249	S-248	S-212	S-190	Y-II
Q	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0
C	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Or	3.5	4.0	8.5	6.0	7.5	14.0	21.0	23.5	2.0	6.5	12.0	9.0
Ab	15.1	28.0	26.0	27.5	33.9	39.4	46.0	50.1	0.0	10.9	11.1	18.5
An	39.3	32.0	26.3	27.5	22.5	16.5	13.5	8.0	14.8	16.8	16.5	29.3
Lc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0
Ne	2.7	0.0	4.5	6.6	4.2	1.8	0.0	3.3	9.3	15.3	19.5	13.2
Di	22.8	16.0	9.6	9.6	10.4	12.8	0.0	6.4	43.2	26.8	20.0	12.4
Hy	0.0	2.0	0.0	0.0	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0
Ol	5.2	4.8	10.2	9.5	8.3	6.9	0.0	4.0	5.9	5.7	5.3	6.5
Pr	—	—	—	—	—	—	0.1	—	—	—	—	0.3
Mt	4.7	4.8	6.8	5.3	5.3	2.1	3.2	1.7	6.3	6.0	5.6	4.4
Hm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0
Il	6.2	8.0	5.2	4.8	4.6	4.6	2.2	2.2	10.4	8.0	6.8	5.6
Ap	0.5	0.5	2.9	3.2	3.2	1.9	2.1	0.8	4.0	4.0	3.2	0.8
Total	100.0	100.1	100.0	100.0	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
% Salic	60.6	64.0	65.3	67.6	68.1	71.7	81.0	84.9	27.3	49.5	59.1	70.0

* Molecular norms calculated according to Niggli's rules given by Barth (1959, pp. 76-82)

TABLE 4. CHEMICAL ANALYSES* OF TITANAUGITES, KAERSUTITES, AND TITANBIOTITE, FROM IGNEOUS ROCKS** OF MOUNT YAMASKA, QUEBEC.

Rock Group	Older Yamaskite				Gabbro				Essexite	
Sample Number	S-264	S-262	S-280	S-14	S-143	S-274	S-159	S-272	S-212	S-190
	Titan-augite	Titan-augite	Titan-augite	Titan-augite	Titan-augite	Titan-augite		Titan-augite	Titan-augite	
SiO_2	44.0	45.52	44.35	46.37	47.84	47.38		50.17	45.12	
Al_2O_3	8.62	8.32	8.05	4.74	5.39	4.11		3.30	6.66	
TiO_2	4.52	4.10	3.31	3.21	2.16	2.06		1.16	3.82	
Fe_2O_3	4.51	4.47	4.05	3.17	3.03	2.72		1.15	3.82	
FeO	3.07	3.80	3.33	4.82	4.67	6.04		10.03	5.00	
MnO	0.17	0.23	0.09	0.14	0.23	0.23		0.60	0.26	
MgO	12.44	11.34	12.79	13.50	14.36	13.46		13.93	11.26	
CaO	21.80	21.42	21.47	22.11	21.51	21.75		20.06	21.57	
Na_2O	1.16	1.12	0.65	0.70	0.69	0.82		0.37	1.36	
K_2O	0.11	n.d.	0.18	n.d.	n.d.	0.05		n.d.	n.d.	
P_2O_5	0.16	0.22	0.03	0.03	0.07	0.06		0.04	0.22	
Total	100.56	100.54	98.30	98.79	99.95	98.68		100.81	99.09	
	Kaers-utite	Kaers-utite	Kaers-utite		Kaers-utite		Kaers-utite	Titan-biotite	Kaers-utite	Kaers-utite
SiO_2	39.86	39.24	39.62		41.48		40.96	37.38	39.88	40.35
Al_2O_3	12.11	12.71	12.26		12.18		12.13	13.67	12.08	12.05
TiO_2	6.49	6.03	5.66		5.25		5.06	4.86	5.86	5.06
Fe_2O_3	5.00	4.05	3.82		2.29		3.01	1.43	4.09	4.11
FeO	6.62	9.05	10.02		8.41		7.71	17.63	10.67	10.69
MnO	0.21	0.32	0.15		0.17		0.25	0.17	0.42	0.38
MgO	11.14	10.59	10.53		12.69		12.76	11.19	9.98	8.63
CaO	12.08	11.95	11.54		11.14		11.31	1.47	12.08	12.03
Na_2O	2.80	2.94	3.08		2.32		2.93	0.42	2.87	2.97
K_2O	1.37	1.34	1.57		1.44		1.10	9.46	1.99	2.02
P_2O_5	0.22	0.27	0.07		0.10		0.20	0.04	0.18	0.27
H_2O+	0.99	0.62	0.60		1.02		0.53	1.53	0.61	0.59
Total	98.89	99.11	98.92		98.49		97.95	99.25	100.71	99.15

* Analyst: Mrs. H.I. Soutar, the Geochemical Laboratory, McGill University.

** For chemical and modal analyses of the rocks, see Tables 1 and 2.

TABLE 5. MOLECULAR NORMS* OF TITANAUGITES, KAERSUTITES, AND TITANBIOTITE, OF TABLE 4.

Rock Group	←Older Yamaskite→			←Gabbro→					←Essexite→	
Sample Number	S-264	S-262	S-280	S-14	S-143	S-274	S-159	S-272	S-212	S-190
	Titan-augite	Titan-augite	Titan-augite	Titan-augite	Titan-augite	Titan-augite		Titan-augite	Titan-augite	
Or	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	
Ab	0.0	0.0	0.0	0.0	0.0	0.0		3.5	0.0	
An	18.0	18.0	19.0	10.0	11.8	7.5		7.3	12.5	
Lc	0.0	0.0	0.0	0.0	0.0	0.0		0.0	0.0	
Ne	6.3	6.0	3.6	3.9	3.6	4.5		0.0	7.5	
Kp	0.3	0.0	0.6	0.0	0.0	0.2		0.0	0.0	
Wo	0.0	3.6	0.0	0.0	0.0	0.0		0.0	6.3	
Di	56.0	63.2	60.0	74.0	74.2	76.8		73.6	64.2	
Hy	0.0	0.0	0.0	0.0	0.0	0.0		3.2	0.0	
Ol	4.8	0.0	4.5	1.5	3.6	3.5		9.6	0.0	
Cs	5.8	0.0	4.3	2.7	0.5	1.8		0.0	0.0	
Mt	0.0	0.9	0.9	3.3	3.3	2.8		1.2	4.1	
Hm	3.1	2.5	2.3	0.0	0.0	0.0		0.0	0.0	
Il	5.0	5.8	4.8	4.6	3.0	2.9		1.6	5.4	
Ru	0.7	0.0	0.0	0.0	0.0	0.0		0.0	0.0	
Total	100.0	100.0	100.0	100.0	100.0	100.0		100.0	100.0	
	Kaers-utite	Kaers-utite	Kaers-utite		Kaers-utite		Kaers-utite	Titan-biotite	Kaers-utite	Kaers-utite
C	0.0	0.0	0.0		0.0		0.0	0.2	0.0	0.0
Or	8.5	4.0	2.0		8.5		6.5	0.0	0.0	3.0
Ab	0.5	0.0	0.0		2.5		2.8	0.0	0.0	0.0
An	16.8	18.0	15.3		19.0		17.0	7.3	14.5	14.0
Lc	0.0	3.2	6.0		0.0		0.0	29.8	7.6	7.6
Ne	15.3	16.2	17.1		11.4		14.5	2.4	15.6	16.5
Kp	0.0	0.0	0.0		0.0		0.0	12.4	1.5	0.0
Di	34.4	32.8	34.0		29.6		31.2	0.0	36.0	36.8
Ol	10.8	12.8	13.5		19.2		17.6	39.4	12.2	10.4
Mt	2.7	4.4	4.1		2.4		3.2	1.5	4.4	4.5
Hm	1.8	0.0	0.0		0.0		0.0	0.0	0.0	0.0
Il	9.2	8.6	8.0		7.4		7.2	7.0	8.2	7.2
Total	100.0	100.0	100.0		100.0		100.0	100.0	100.0	100.0

* Molecular norms calculated according to Niggli's rules given by Barth (1959, pp. 76-82).

(Fig. 2) by Pouliot (1962), who determined the plotted feldspar compositions using refractive indices and fusion method. Following the classical generalizations by Bowen (1928) regarding crystallization of plagioclase from basaltic melts, it is concluded here that the intrusion differentiated from early crystallized yamaskites, through gabbros to the late stage border phases of gabbro and akerite. Thus the differentiation of a subsiciliceous balsaltic magma has lead to the crystallization of silica-saturated rocks at a late stage.

A considerable increase in SiO_2 content from gabbro to akerite is seen from the chemical analyses, and is also shown on a variation diagram (Fig. 3), in which oxide percentages are plotted against the proportion of normative salic constituents. The proportion of salic constituents, calculated from the norm, provides a good index of variation in a series of igneous rocks, because differentiation in general, leads to the separation of the lighter, more siliceous, and more alkalic minerals from the heavier ferromagnesian minerals (Tyrrell, 1926). A study of the variation diagram and the modal analyses shows that the chemical variation, in general,

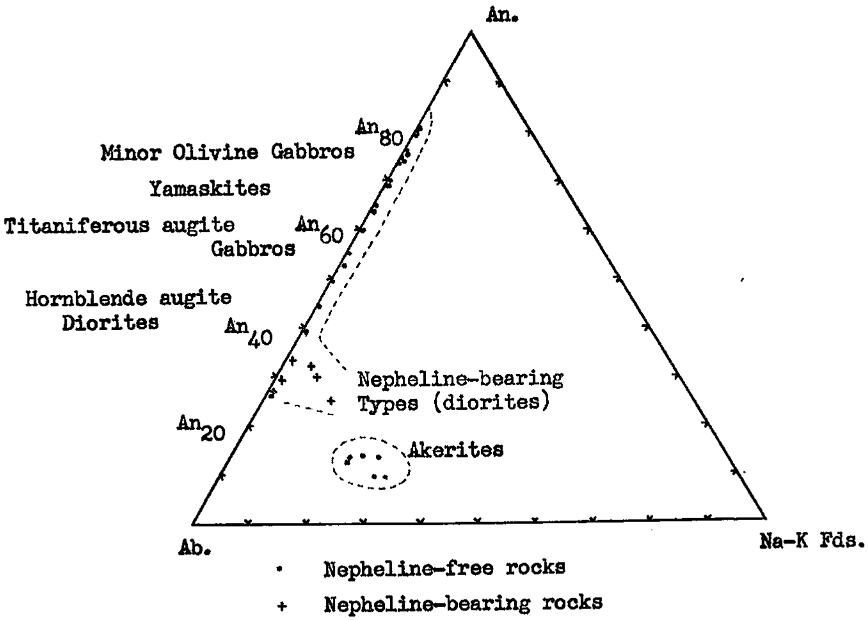

FIG. 2. Feldspar compositions of igneous rocks from Mount Yamaska, Quebec. Reproduced from Pouliot (1962, Fig. 4.4, p. 127A). The nepheline-free rocks are of the older yamaskite-gabbro-akerite series, and the nepheline-bearing rocks are of the younger yamaskite-essexite series.

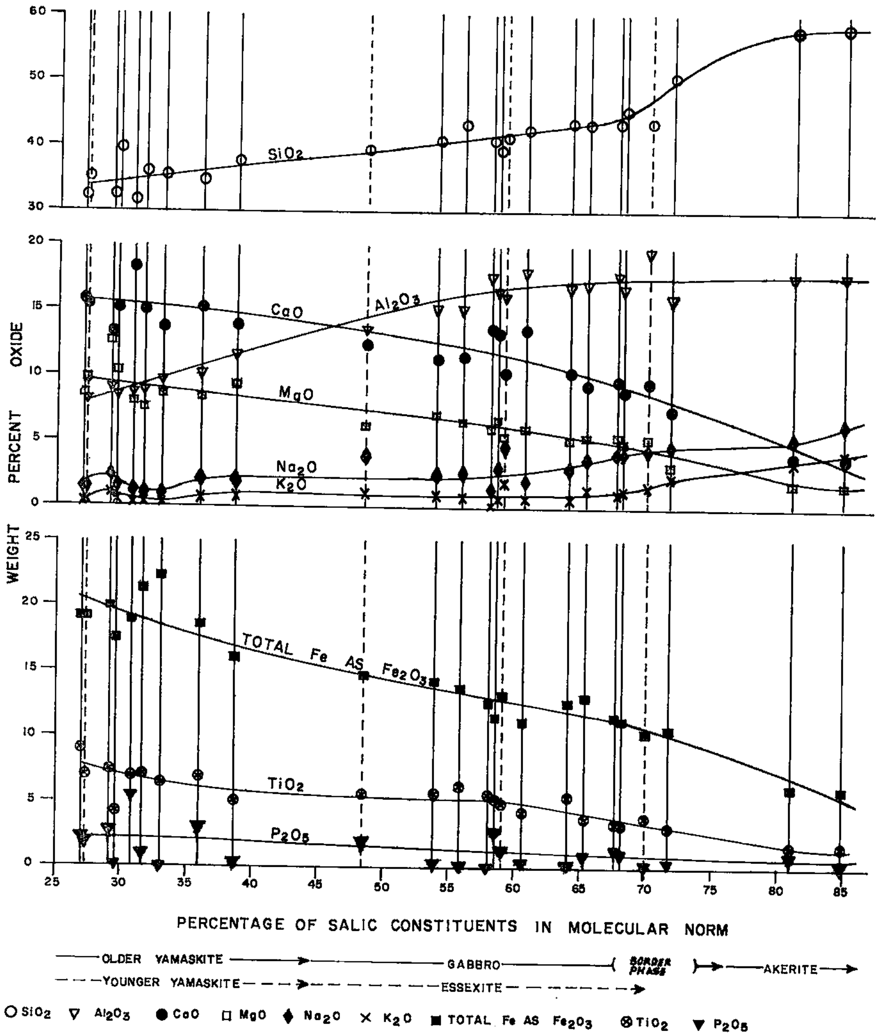

Fig. 8. VARIATION DIAGRAM OF THE OLDER YAMASKITE – GABBRO – AKERITE ROCK SERIES AND THE YOUNGER YAMASKITE – ESSEXITE ROCK SERIES OF MOUNT YAMASKA, QUEBEC.

DATA FROM TABLES I AND 3.

SOLID VERTICAL LINES REPRESENT POSITIONS OF ROCKS OF THE OLDER YAMASKITE – GABBRO – AKERITE SERIES, AND DASHED VERTICAL LINES REPRESENT POSITIONS OF ROCKS OF THE YOUNGER YAMASKITE – ESSEXITE SERIES.

CURVES SHOW VARIATIONS IN THE OLDER YAMASKITE — GABBRO — AKERITE ROCK SERIES.

reflects the variation in relative abundances of individual mineral phases in the rocks. There are however, complicating factors, such as variation in composition of the mineral phases during differentiation, zoning in crystals, and the presence of minerals such as hercynite ($FeAl_2O_4$) whose alumina content is allotted to the salic constituents in the norm calculation. Complexity of mineralogical variations in this rock series can be seen from the description of the rock groups and the discussion of composition of the important mafic silicates titanaugite and kaersutite, that follow.

Older yamaskite

The term 'yamaskite' was first introduced by Young (1906) for the ultramafic rocks of Mount Yamaska, composed chiefly of titanaugite, brown hornblende (kaersutite), iron-titanium oxides, and small but variable amounts of highly calcic plagioclase and apatite, and locally of olivine, sphene, biotite, hercynite and pyrite. He gave chemical and modal analyses of two varieties of yamaskite, one feldspar-poor and the other feldspar-rich, which grade into one another in the field (see Y-III and Y-IV in Tables 1 and 2). Johanssen (1937) included the feldspar-rich yamaskite in his strictly mineralogical classification, assigning the name 'yamaskite' to the Family 3421 P. The feldspar-poor yamaskite has been included by him in the Family 4211, and the same rock was used by Washington (1917) to name the sub-range to which it belongs as 'yamaskose'. The yamaskite differs from 'jacupirangite' (Derby 1891) in the presence of calcic plagioclase and hornblende, and the absence of nepheline. It differs from 'perknite' (Turner 1901) in the absence of orthopyroxene. This is significant because, as pointed out by Wilkinson (1956), the absence of orthopyroxene and the presence of titaniferous augite are two of the distinctive features of rocks crystallized from the alkaline olivine basalt magma.

The rocks grouped as older yamaskite occupy a large area in the central and east-central parts of the mountain (Fig. 1). They vary considerably in their mineral composition (Table 2), although their chemical composition appears to fall within a limited range (Table 1). Titanaugite is generally predominant, and is the first or one of the first minerals to have crystallized. In thin section, it is pale to dark mauve in colour, and commonly exhibits zoning and hair-like opaque exsolution lamellae, arranged in one or two sets. Similar lamellae in titanaugite from a gabbro are identified as ilmenite, by comparison of its *x*-ray powder pattern with that of concentrate of titanaugite from another gabbro in which such lamellae are rare or absent. Coarse zoned crystals of titanaugite are common in yamaskites from the eastern part of the mountain. Yamaskites with up to 50 volume per cent kaersutite are seen in the central part of the mountain, and these contain little or no plagioclase, no olivine nor hercynite, but contain notable amounts of apatite and sphene. Small amounts of highly calcic plagioclase (An_{85} to An_{65}), usually less than 25 volume per cent, occur in yamaskites adjacent to gabbro, and these contain a relatively small amount of kaersutite. In the southern part of the mountain the plagioclase laths have a preferred vertical orientation imparting a foliation which is nearly parallel to the boundary with gabbro. In the northwestern part of the older yamaskite outcrop area, layering with gabbro is common, and the laths of plagioclase are generally subparallel to the layers. Olivine (Fo_{80}), hercynite, and magnetite-ulvöspinel-ilmenite-hercynite(-pleonaste) intergrowth are observed along this layered zone. The zone is broad and semicircular, with dips commonly between 40 and 60 degrees towards the centre. Elsewhere the transition between the older yamaskite and gabbro is abrupt or gradational over a zone up to 50 feet wide. Local occurrences of yamaskite within gabbro are seen and these grade into the gabbro.

Gabbro

The most abundant rock type in the igneous complex of Mount Yamaska is a medium to coarse-grained gabbro, characterized by subparallel euhedral laths of plagioclase that impart a trachytic texture to the rock. Young (1906) described these rocks as one of his two main varieties of essexite, even though he noted the absence of nepheline and the presence of only a small amount of alkali feldspar in them. He thought that they graded into his other variety of essexite, which is granular to porphyritic and contains nepheline and a notable amount of alkali feldspar. The latter is essexite according to definitions by Sears (1891) and Washington (1899), but is restricted to the southwestern part of the igneous complex where it is intrusive into the trachytic gabbro.

Plagioclase commonly constitutes 50 to 60 volume per cent of the gabbro. In gabbros adjacent to the yamaskites, composition of plagioclase generally ranges between An_{80} and An_{60}, and in the layered zone plagioclase composition of An_{85-75} is common. Plagioclase compositions in the large area of massive gabbro range from An_{65} to An_{50} in its inner parts, and from An_{50} to An_{30} in its outer parts. Other minerals are interstitial to plagioclase. Titanaugite is the chief mafic mineral in the gabbros near the older yamaskite, and also in the southern part of the intrusion. Kaersutite predominates in gabbros closer to the akerite area, where they approach diorite in composition. Kaersutite locally is abundant in gabbros in the eastern part of the mountain. It poikilitically encloses all other minerals and thus appears to be the last mineral to have crystallized. Olivine is found in accessory amounts in gabbros near the older yamaskite, and shows 2V close to 90°, indicating the composition close to Fo_{80}. Biotite is subordinate to kaersutite in the northwestern part of the mountain, but prevails almost to the exclusion of it in gabbros in the southeastern part of the mountain. It is a titanium-rich variety (Table 4). Magnetite, usually with abundant exsolution lamellae of ilmenite, is the chief accessory mineral. In the layered zone between the gabbro and the older yamaskite, magnetite-ulvöspinel intergrowth with hercynite(-pleonaste) lamellate is observed. Hercynite locally occurs as small irregular grains associated with the oxide minerals. Other accessory minerals include apatite, ilmenite, pyrite, green hornblende, locally traces of zircon, and sphene in kaersutite-rich gabbros.

The gabbroic rocks show considerable variation in texture and mineralogy in a narrow zone along their contact with the sedimentary country rock. These border phases of gabbro are characterized by the presence of biotite and alkali feldspar, and they are thus close to akerite in composition. Small amount of quartz is found in gabbro in the extreme northeastern corner of the intrusion. In the southeastern corner of the intrusion, traces of sodalite or analcite have been reported by Young (1906) and traces of nepheline are seen in gabbro locally at the contact with the sedimentary country rock. Along the southern contact of the intrusion, needles of apatite and elongate patches of oxide minerals are seen in the titanaugite and oxide-rich gabbroic rocks. Along the northwestern half of the boundary, the gabbro grades laterally into the akerite ; the transition zone is 10 to 50 feet wide, and is vertical.

Akerite

Brögger (1890) first introduced the term 'akerite' for an augite monzonite having characteristic eugranitic texture in which rectangular tablets of feldspar are well developed. Barth (1944) pointed out that the definition of akerite was mostly textural rather than mineralogical. Young (1906) applied the name to mineralogically and chemically similar rocks from Mount Yamaska, although texturally they differ somewhat from the original akerite.

The akerite occupies a long, narrow, semicircular border zone along the northwestern half of the intrusion. The rock is medium to coarse-grained, massive, with subhedral granular texture, and contains over 70 per cent feldspars. The amount of mafic minerals is variable, usually between 10 and 20 per cent, but increases to 35 per cent near the gabbro boundary. Biotite is the predominant mafic mineral except near the gabbro boundary where kaersutite predominates. Other mineral phases in akerite include diopsidic pyroxene, green hornblende, magnetite, ilmenite, apatite, sphene, quartz, pyrite, calcite and zircon. Akerites are characterized by common association of plagioclase ($An_{15\text{-}20}$) and alkali feldspar ($Or_{70\text{-}75}Ab_{25\text{-}30}$) which usually vary in amounts 50 to 65 per cent and 15 to 30 per cent by volume respectively (Pouliot 1962). Plagioclase is commonly zoned, with more calcic core often showing albite twinning.

Composition of titanaugite

Analyses of seven titanaugites given in Table 4, show that there is a considerable variation in the chemical composition of the mineral, from the older yamaskites through gabbros to a border phase of gabbro, which shows a corresponding gradual increase in silica and decrease in alumina and titania. Recalculation of the analyses on the basis of 6 oxygens, given in Table 6, reveals that the substitution of Al (and ferric iron where necessary) in the Z-site for Si is highest in titanaugites from the older yamaskites, and decreases through gabbro to the border phase of gabbro. Substitution of Al in the Z-site requires substitution of trivalent or tetravalent cations in the *Y*-site to maintain the electrical neutrality. The available cations are aluminum, titanium, and ferric iron. It is seen from Table 6 that the higher the aluminum substitution in the Z-site the higher the amount of titanium in the *Y*-site. Verhoogen (1962) has deduced from the thermodynamic considerations that the solubility of titanium in pyroxene increases with increasing activity of alumina, decreasing activity of silica and higher temperature. The observed variation of titanium in the titanaugites of the older yamaskite-gabbro-akerite rock series is consistent with this generalization. Verhoogen has pointed out however, that titanium would not be available for large scale substitution in pyroxenes under conditions of low partial pressure of oxygen, where it would combine with ferrous iron to form ilmenite. It is seen from Table 6 that there is insufficient titanium in the *Y*-site to balance the charge requirements caused by aluminum substitution in the Z-site, and it is necessary to include the aluminum and ferric iron in the *Y*-site for the purpose. The contribution of titanium towards the charge balance would be even smaller if part of it is considered trivalent. Trivalent titanium is considered to be the cause of the characteristic mauve colour of titanaugites (Verhoogen 1962). Low partial pressure of oxygen would also favour the trivalent state of titanium. The presence of notable amounts of such minerals as ulvöspinel and hercynite in some of the older yamaskites and gab-

TABLE 6. FORMULAE OF TITANAUGITES, ON THE BASIS OF 6 OXYGENS, AND OF KAERSUTITES AND TITANBIOTITE, ON THE BASIS OF 24 OXYGENS, OF TABLE 4.

Rock Group	Older Yamaskite				Gabbro				Essexite	
Sample Number	S-264	S-262	S-280	S-14	S-143	S-274	S-159	S-272	S-212	S-190
	Titan-augite	Titan-augite	Titan-augite	Titan-augite	Titan-augite	Titan-augite		Titan-augite	Titan-augite	
Si	1.643	1.697	1.683	1.760	1.783	1.805		1.874	1.720	
Al	0.357	0.303	0.317	0.212	0.217	0.184		0.126	0.280	
Fe^{+3}	0.000	0.000	0.000	0.028	0.000	0.011		0.000	0.000	
Mn	0.005	0.007	0.003	0.005	0.007	0.007		0.019	0.009	
Z	2.000	2.000	2.000	2.000	2.000	2.000		2.000	2.000	
Al	0.023	0.062	0.043	0.000	0.020	0.000		0.019	0.019	
Ti	0.127	0.115	0.094	0.092	0.060	0.059		0.033	0.109	
Fe^{+3}	0.127	0.125	0.116	0.062	0.085	0.067		0.032	0.109	
Fe^{+2}	0.096	0.119	0.106	0.153	0.146	0.192		0.313	0.159	
Mn	0.005	0.007	0.003	0.005	0.007	0.007		0.009	0.009	
Mg	0.692	0.630	0.723	0.763	0.797	0.764		0.775	0.640	
Ca	0.864	0.844	0.871	0.897	0.855	0.884		0.800	0.869	
Na	0.084	0.081	0.048	0.052	0.050	0.060		0.027	0.100	
K	0.005	0.000	0.009	0.000	0.000	0.002		0.000	0.000	
X + Y	2.023	1.983	2.013	2.024	2.020	2.035		2.018	2.014	
$Al_{Z/Al}$	93.95	83.01	88.01	100.00	91.56	100.00		86.90	93.64	
	Kaers-utite	Kaers-utite	Kaers-utite		Kaers-utite		Kaers-utite	Titan-biotite	Kaers-utite	Kaers-utite
Si	6.042	6.022	6.089		6.246		6.255	5.885	6.080	6.248
Al	1.958	1.978	1.911		1.754		1.745	2.115	1.920	1.752
Z	8.000	8.000	8.000		8.000		8.000	8.000	8.000	8.000
Al	0.205	0.321	0.310		0.407		0.438	0.421	0.250	0.447
Ti	0.739	0.696	0.653		0.594		0.581	0.575	0.671	0.589
Fe^{+3}	0.570	0.468	0.441		0.260		0.345	0.169	0.469	0.478
Fe^{+2}	0.838	1.161	1.288		1.059		0.984	2.320	1.360	1.384
Mn	0.027	0.041	0.019		0.022		0.032	0.023	0.054	0.050
Mg	2.515	2.420	2.411		2.846		2.903	2.624	2.266	1.990
Ca	1.915	1.906	1.884		1.775		1.807	0.238	1.933	1.936
Na	0.823	0.874	0.917		0.676		0.868	0.129	0.848	0.891
K	0.264	0.262	0.308		0.277		0.215	1.899	0.386	0.398
X + Y	7.896	8.149	8.231		7.916		8.177	8.398	8.237	8.163
OH	1.000	0.634	0.615		1.024		0.539	1.606	0.621	0.610

bros indicates that the partial pressure of oxygen was low during their crystallization.

It is apparent from Table 6 that ferric iron and sodium decrease with decrease in aluminum substitution in the Z-site. Generally, sodium is assigned to acmite ($NaFe^{+3}Si_2O_6$) or jadeite ($NaAlSi_2O_6$) in pyroxene calculations (see Le Bas 1962; Beall 1962; Yoder & Tilley 1962). Yagi (1953) observed that the trend of crystallization of pyroxenes in alkalic rocks of Morotu district, Sakhalin, is as follows : diopsidic augite→titanaugite→titaniferous soda augite→aegirine augite→aegirine. Recalculation of Yagi's pyroxene analyses in terms of acmite and jadeite, tschermak's molecule, diopside, and hedenbergite, by Yoder & Tilley (1962) showed the same fractionation trend towards an increase in proportion of acmite molecule in the pyroxene towards later stages of crystallization. Recalculation of Mount Yamaska pyroxenes in the same terms (see Table 7) shows that the proportion of acmite molecule decreases towards later stages of crystallization, a trend opposite to that observed by Yagi. It is suggested that part or all of sodium in this case, may be allotted to the tschermak's molecule as in $Na(K)Ti^{+4}SiAlO_6$ or $Na(K)Ti^{+3}Si_2O_6$, which can explain the decrease of sodium and titanium with decrease in aluminum substitution in the Z-site.

Composition of kaersutite

Composition of five kaersutites, coexisting with titanaugite, are given in Table 4. Recalculation of these in terms of 24 oxygens (Table 6), shows that the amounts of Ti, Fe^{+3}, Ca, and Al (in the Z-site), decrease

TABLE 7. COMPOSITION OF TITANAUGITES FROM MOUNT YAMASKA, IN TERMS OF ACMITE (+ JADEITE), TSCHERMAK'S MOLECULE, HEDENBERGITE, AND DIOPSIDE.

Rock Group	Older yamaskite ⟶ Gabbro ⟶ Border phase of gabbro							Essexite
Sample number	S-264	S-262	S-280	S-14	S-143	S-274	S-272	S-212
ACMITE : $NaFeSi_2O_6$ (+ JADEITE : $NaAlSi_2O_6$)	9 —	8 —	6 —	5 —	5 —	6 —	3 —	10 —
TSCHERMAK'S MOLECULE $Ca(Mg)Al_2SiO_6$	36	30	32	24	22	19	13	28
HEDENBERGITE $CaFeSi_2O_6$	10	13	11	16	15	20	33	17
DIOPSIDE $CaMgSi_2O_6$	45	49	51	55	58	55	51	45

and that of Si, Mg, and Al (in the *Y*-site), increase with the increasing feldspathic character of the rocks. It is significant that the variation of Al (in the Z-site) and Ti of the kaersutites corresponds, in general, to the variation of these cations in the coexisting titanaugites. Thus changes in magma chemistry during differentiation of the older yamaskite-gabbro-akerite rock series is reflected in the compositions of the coexisting major silicate phases, namely plagioclase, titanaugite and kaersutite.

YOUNGER YAMASKITE-ESSEXITE ROCK SERIES

Differentiation of the younger of the two main intrusions, has produced rocks ranging from ultramafic yamaskite through mafic essexite to felsic essexite. These are mapped as younger yamaskite and essexite, and they represent 35 and 65 percent, respectively, of the area of the intrusion (Fig. 1). They encompass a range in chemical composition similar to the one by the older yamaskite and gabbro, as can be seen from Table 1 and the variation diagram (Fig. 3). The proportion of normative nepheline in the rocks ranges from 9 to 20 per cent (see Table 3), which clearly underlines the subsiliceous basaltic or basanitic character of the rock series as a whole.

Mineralogically, the younger yamaskites are very similar to the kaersutite-rich older yamaskite, but the essexites differ from gabbros in the presence of modal nepheline and alkali feldspar, each amounting from 5 to 10 per cent in the felsic essexites (see Table 2). The essexites contain relatively greater proportion of kaersutite (30 to 50 per cent) and smaller proportion of plagioclase (20 to 40 per cent) than the gabbros. Kaersutite is chemically similar to the kaersutite in gabbro, except for small differences such as MgO content (see Table 4). The two kaersutites analyzed show a tendency towards increase in Si and Al (in the *Y*-site), and decrease in Al (in the Z-site) and Ti, with increasing feldspathic character of the rock, as is the case with kaersutites from the older yamaskites and gabbros (see Table 6). The similarity of titanaugite in essexite to those of older yamaskite and gabbro (Tables 4 and 6), also reflects overall similarities in composition of the melts from which they crystallized, with minor differences in abundances of some of the constituents such as soda. Plagioclase composition in younger yamaskite is close to An_{55}, and that in mafic essexite ranges between An_{55} and An_{40}. In felsic essexites, where plagioclase coexists with alkali feldspar, its composition varies from An_{40} to An_{20} and lower, although the core of some of the zoned plagioclase may be as calcic as An_{50} (see also Fig. 2). It is therefore concluded, as in case of the older main intrusion, that the younger main intrusion differentiated from early crystallized younger yamaskites, through mafic essexites to the late stage felsic essexites. The trend of differentiation of this basanitic intrusion, unlike the older intrusive phase, is towards late stage silica-undersaturated, nepheline-bearing rocks.

The variation diagram (Fig. 3) shows that although the two rock series have overall chemical similarities, there is a slightly different trend of variation in soda, potash, silica and alumina, in the younger rock series than in the older one. Thus the essexites contain nearly twice as much soda as gabbros with comparable salic constituents, but the difference practically disappears in the range of the border phases of gabbro. The essexite within this range contains lower silica and higher alumina than the border phases of gabbro. These chemical characters and mineralogical features indicate that there are small but significant differences in the initial bulk composition of the magmas from which the two rock series crystallized.

Younger yamaskite

The ultramafic rocks found at the core of the younger main intrusion are similar to the kaersutite-rich older yamaskites, but differ in that they grade into the nepheline-bearing essexite which intrudes the older yamaskite, gabbro and akerite, and are therefore grouped separately as younger yamaskite.

The central part of younger yamaskite consists of medium to coarse-grained rocks with abundant euhedral crystals of titanaugite, and large, irregular, poikilitic crystals of kaersutite. The rocks contain minor amounts of plagioclase, iron-titanium oxides, apatite, and sphene. Plagioclase (An_{55} to An_{40}) amounts to less than 15 per cent, and occurs as small subhedral to euhedral crystals, which appear to have crystallized contemporaneously and/or later than kaersutite. Iron-titanium oxides form small irregular patches, and their proportion decreases from 12 to 5 per cent towards the essexite boundary. Apatite and sphene occur commonly as euhedral crystals. Closer to the essexite boundary, kaersutite becomes as abundant as or predominates over titanaugite, and tends to form euhedral crystals, commonly twinned. Neither olivine nor hercynite were observed in the thin sections examined; biotite is rare. A narrow zone of porphyritic younger yamaskite along the western boundary, west of the area of hornfels and augite porphyritic rock, consists of phenocrysts of titanaugite set in a medium to fine-grained matrix of kaersutite, iron-titanium oxides, titanaugite, plagioclase, apatite and sphene.

Younger yamaskite contains xenoliths of and intrudes the hornfels and flow-textured augite porphyritic rocks as dykes and apophyses. The younger yamaskite grades into mafic essexite ; the transition zone is 10 to 50 feet wide along the eastern and southern boundaries, and is vertical. The transition is more abrupt on the west side.

Essexite

Nepheline-bearing gabbroic rocks, mapped as essexite by the writer, underlie a pear-shaped area around younger yamaskite, and an isolated small body 2,000 feet to the north-northeast. Porphyritic texture is common, particularly among the more felsic rocks near the outer margin. Phenocrysts of titanaugite and kaersutite, up to 5 millimeters long, are embedded in a fine to medium-grained granular matrix. Seriate texture is common in the mafic essexites, adjacent to the younger yamaskite. Larger crystals are commonly of titanaugite, some of kaersutite, and rarely of plagioclase. Titanaugite and kaersutite together constitute 30 to 70 per cent of the essexites, and though their relative proportions vary considerably, kaersutite generally predominates. Kaersutite usually occurs as large poikilitic crystals subhedral to euhedral in outline, and occasionally contains irregular grains of titanaugite. Plagioclase occurs as small, randomly oriented laths. Mafic essexites contain little or no nepheline or alkali feldspar, but felsic essexites contain up to 10 per cent of each, occurring as irregular patches. Opaque minerals in essexites vary from 2 to 10 per cent, and include abundant magnetite with ilmenite lamellae, ilmenite, hematite, and pyrite. Hercynite (–pleonaste) occurs as lamellae in some magnetite crystals. Apatite and sphene commonly occur as euhedral crystals, in amounts 1 to 3 per cent of each, locally reaching up to 7 per cent. Apatite is usually found as inclusions in kaersutite, and sphene is closely associated with iron-titanium oxides, and locally surrounds them. Biotite occurs as an accessory mineral. Local occurrences of sodalite (or analcime) and altered olivine, and traces of other secondary minerals such as calcite, sericite, zeolite and muscovite, are seen in thin sections.

Coarse pegmatitic patches carrying kaersutite, nepheline, alkali feldspar, apatite, sphene, and titanaugite, are locally developed in the essexite. Layering of dark and light coloured minerals is seen in restricted areas of the essexite and the layers dip steeply or vertically. Xenoliths of metasediments (predominantly hornfels), flow-textured augite porphyry, older yamaskite, gabbro and akerite, occur in the essexite mass, particularly near its outer margin. Dykelets and patches of essexite intruding the country rock are common at the boundary of the essexite area.

Differentiation Trends of the Two Main Intrusive Phases

It is evident from the overall chemical and mineralogical similarities, close association in time and space, and similar mode of intrusion, that the two main intrusive phases of the Mount Yamaska complex are genetically related. Differentiation trends of the two intrusions are however, different. The older one differentiated from the early crystallized yamaskite, through gabbro to late stage silica-saturated border phases of gabbro and akerite. The younger one differentiated from early crystallized yamaskite to the nepheline-bearing essexite. Furthermore, the older intrusion crystallized abundant plagioclase of highly calcic composition during early stages of crystallization, whereas the younger intrusion crystallized relatively smaller amount of more sodic plagioclase, and abundant kaersutite, although both the intrusions crystallized in generally similar physical environments. Therefore, despite the overall chemical similarities between the two rock series, some small but significant differences in the initial bulk composition of the magmas from which they crystallized must be expected.

It is impossible to determine accurately the composition of the two magmas. It would be desirable however, to have some estimate of their composition in order to compare and contrast their differentiation paths. The desired estimates are obtained from the weighted average compositions of the two rock series as outlined in Table 8. The average compositions are calculated by first averaging the available analyses of the main rock groups of the series, and then weighing the averages against the areas occupied by the rock groups. A requirement of this procedure that the rocks mapped extend vertically in a pipe-like body, is supported by the attitude of boundaries and flow foliation of the two bodies, except the layered zone in the older intrusion which is restricted in extent. Other methods for deducing the composition of the magmas, introduced more uncertainties. For example, chilled margins are lacking in these intrusions. There are only a few dykes and they cannot be definitely correlated with the intrusions and regarded as representative of their composition. It is difficult to use the method of liquid line of descent (Nockolds & Allen 1953), because of considerable scatter in the variation diagram (Fig. 3). Attempts to use other indices for variation diagram in order to obtain smoother curves were not successful. Therefore, the estimates given in Table 8 are considered useful for a comparative study, although it is realized that the number of analyses available is limited, and that the composition of the rocks may vary vertically in the plutons. The estimates are used in the discussion of phase relations which follows.

The system diopside-calcium tschermak's molecule-nepheline-silica

The CIPW norms of the average composition of the two rock series given in Table 8, show that the normative diopside, anorthite, albite and nepheline, together constitute about 65 per cent of both the norms. Expressing albite in terms of nepheline and silica, and recalculating to 100 the proportions of the four components, gives the following:

The older yamaskite-gabbro-akerite rock series: $Di_{30.9}An_{35.4}Ne_{20.2}Si_{13.5}$
The younger yamaskite-essexite rock series: $Di_{41.3}An_{28.3}Ne_{24.4}Si_{6.0}$

Furthermore, the proportion of anorthite can be expressed in terms of calcium tschermak's molecule and silica, as follows:

The older yamaskite-gabbro-akerite rock series: $Di_{30.9}Ca\text{-}Tsch_{27.8}Ne_{20.2}Si_{21.1}$
The younger yamaskite-essexite rock series: $Di_{41.3}Ca\text{-}Tsch_{22.2}Ne_{24.4}Si_{12.1}$

These compositions are considered representative of compositions of the magmas of the two rock series. Their trend of differentiation can be best studied with reference to this four component system. The plot of the two compositions in a tetrahedron representing the system is shown in Fig. 4. The approximate field boundary between diopside and plagioclase in the tetrahedron is shown by a dashed line on the plane diopside-albite-anorthite.

In general, compositions of basaltic magmas lie closer to the join diopside-calcium tschermak's molecule than to the join nepheline-silica in the tetrahedron. During crystallization differentiation, composition of a basaltic magma varies in the direction of the join nepheline-silica, which is generally the direction of the decreasing temperature, as indicated by an arrow on the dashed line in the tetrahedron. The course of differentiation however, may be in the direction of nepheline, or albite, or silica, depending mainly on the initial bulk composition of the magma. This has been discussed by Barth (1931; 1936; 1952) with reference to the system olivine (+diopside)-anorthite-nepheline-silica. Yoder & Tilley (1962) have emphasized the importance of two equilibrium thermal divides which are parts of the system diopside-calcium tschermak's molecule-nepheline-silica. One of equilibrium thermal divides is along the join anorthite-albite in the ternary system anorthite-nepheline-silica, and the other is along the join albite-diopside in the ternary system diopside-nepheline-silica. Very slight differences in the initial bulk composition may yield liquids, which differentiate towards silica on one hand, or towards nepheline on the other. They have also pointed out that the join diopside-albite is not a binary, and the above generalization is true only in a broader sense. Crystallization of aluminous diopside, containing calcium (+ magnesium)

TABLE 8. AVERAGE CHEMICAL COMPOSITIONS OF THE OLDER YAMASKITE-GABBRO-AKERITE ROCK SERIES AND THE YOUNGER YAMASKITE-ESSEXITE ROCK SERIES, AND THEIR CIPW NORM.

The Older Yamaskite–Gabbro–Akerite Rock Series				Average of the series	CIPW norm of the average
Rock Group	Older Yamaskite (Average of 8)	Gabbro (Average of 10)	Akerite (Average of 2)		
SiO_2	35.19	43.34	57.94	42.36	
Al_2O_3	9.55	16.69	17.58	14.64	or : 6.67
TiO_2	6.58	4.58	1.56	4.88	ab : 19.39
Fe_2O_3	9.35	4.43	2.30	5.69	an : 23.35
FeO	8.86	7.03	3.47	7.22	ne : 2.84
MnO	0.33	0.32	0.26	0.32	di : 20.43
MgO	9.20	5.65	1.78	6.33	ol : 5.06
CaO	15.01	10.93	3.80	11.45	mt : 8.35
Na_2O	1.59	3.16	5.68	2.94	il : 9.27
K_2O	0.64	0.95	3.75	1.14	ap : 2.69
P_2O_5	1.89	0.91	0.74	1.19	
Total	98.10	97.99	98.86	98.16	98.05
Percent Area	30	60	10		

The Younger Yamaskite–Essexite Rock Series				
Rock Group	Younger Yamaskite (One Analysis)	Essexite (Average of 3)		
SiO_2	35.07	41.55	39.28	
Al_2O_3	8.40	16.43	13.62	or : 7.23
TiO_2	6.94	4.73	5.50	ab : 8.38
Fe_2O_3	9.60	4.99	6.60	an : 18.07
FeO	8.57	6.96	7.52	ne : 11.08
MnO	0.22	0.50	0.40	di : 26.35
MgO	9.92	5.56	7.08	ol : 3.85
CaO	15.40	10.69	12.34	mt : 9.51
Na_2O	1.58	4.40	3.41	il : 10.49
K_2O	0.62	1.53	1.21	ap : 3.36
P_2O_5	1.90	1.24	1.47	
Total	98.22	98.58	98.43	98.32
Percent Area	35	65		

tschermak's molecule, may lead to differentiation towards silica which otherwise would have been towards nepheline (Yoder & Tilley 1952). Hytonen & Schairer (1961) have observed that the maximum amount of calcium tschermak's molecule in solid solution with diopside in equilibrium with anorthite at 1135°C, is 28 per cent. De Neufville & Schairer (1962) have estimated from their study of the join diopside-calcium tchermak's molecule, that stable pyroxene may contain a maximum of about 40 per cent calcium tschermak's molecule in solid solution at one atmosphere. Because of extensive substitution of aluminum in diopside that can occur, the region of compositions capable of differentiating towards silica is increased (see also Beall 1962).

Augite is the first major phase to have crystallized from the magmas of the two main intrusive phases of Mount Yamaska, and there is considerable amount of aluminum substitution in the pyroxene (Tables 4 and 6). The composition of the magmas lie close to the plane anorthite-albite-diopside defined by the joins anorthite-albite and diopside-albite in the tetrahedron representing the system diopside-calcium tschermak's molecule-nepheline-silica (Fig. 4). They also fall on the nepheline side of the two equilibrium thermal divides, and this is seen more clearly in Figure 5, which shows the plots of the two compositions in the triangular diagrams of the systems anorthite-nepheline-silica and diopside-nepheline-silica. Because of their subsiliceous character, both the magmas are in general expected to differentiate towards nepheline. The magma of the older intrusion however, lies closer to the thermal divides and farther away from nepheline, relative to the position of the magma of the younger intrusion. Only a small amount of silica enrichment is sufficient to shift the position of the magma across the thermal divides anorthite-albite and diopside-albite, towards silica. The silica enrichment due to abundant early crystallization of aluminous pyroxene could force the magma to differentiate towards silica, which otherwise would have differentiated towards nepheline. In case of the magma of the younger intrusion however, it is seen that (Fig. 5 B) even if all the calcium tschermak's molecule were considered to enter diopside, the silica enrichment would not be sufficient to overcome the initial deficiency of silica to cause it to cross the equilibrium thermal divide diopside-albite. The magma would therefore differentiate towards nepheline.

Crystallization of plagioclase and kaersutite

Approximate liquidus relations in the system anorthite-nepheline-silica are given by Schairer (1957, see Barth, 1962). Beall (1962) has discussed liquidus relations in the system, and has shown that for the same ratio of Na AlO_2 to $CaAl_2O_4$ in the melt, the low silica melt crystallizes highly calcic plagioclase in contrast to the high silica melt. This can be visualized roughly by referring to Fig. 5A as follows. In melts such as estimated magma composition of the two intrusions of Mount Yamaska, whose compositions lie on the nepheline side of the join anorthite-albite, the com-

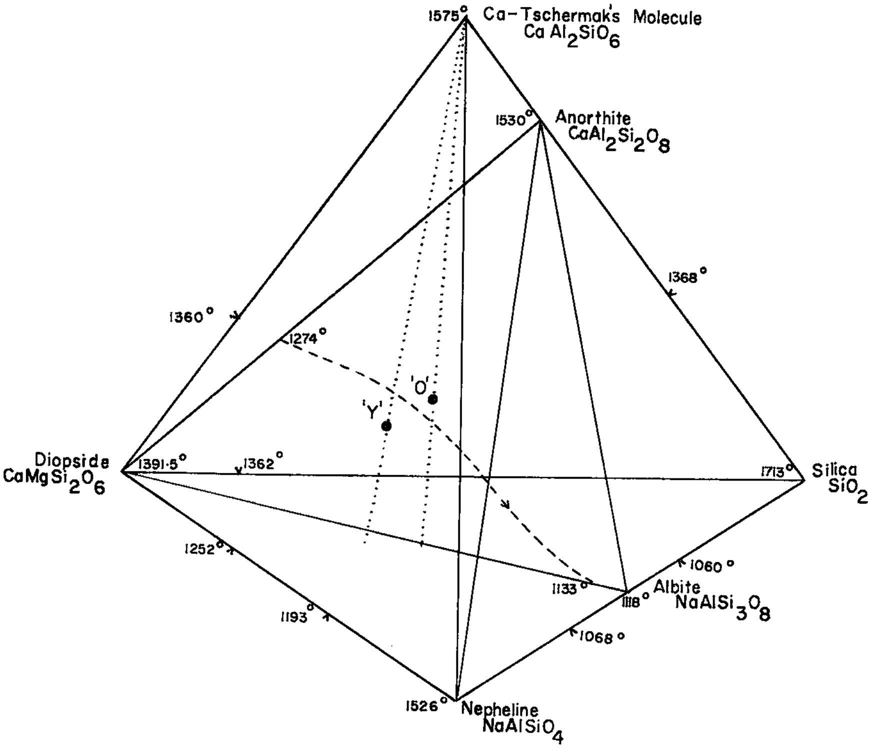

FIG. 4. The system diopside-calcium tschermak's molecule-nepheline-silica.

Circles marked 'O' and 'Y' represent approximately average compositions of the older yamaskite-gabbro-akerite rock series and the younger yamaskite-essexite rock series respectively.

References for the experimental data on parts of the system at 1 atmosphere :

'The join diopside-calcium tschermak's molecule', de Neufville & Schairer (1962, p. 57).

'The system diopside-calcium tschermak's molecule-silica', Clark, Schairer & de Neufville (1962, p. 66).

'The system diopside-nepheline-silica', Schairer & Yoder (1960, p. 278).

'The join diopside-nepheline', Schairer, Yagi & Yoder (1962, p. 97).

'The system anorthite-nepheline-silica', Schairer (1957, p. 232).

'The system diopside-anorthite-albite', Bowen (1915, p. 167).

'The join diopside-anorthite', Osborn (1942, p. 758).

position of the first crystallizing plagioclase is obtained by projecting a line from the nepheline apex through the point representing the composition of melt onto the join anorthite-albite. The point of intersection on the join anorthite-albite is read on the plagioclase liquidus in the well-known equilibrium diagram of the system anorthite-albite given by Bowen (1928), and the corresponding composition of the crystallizing plagioclase is

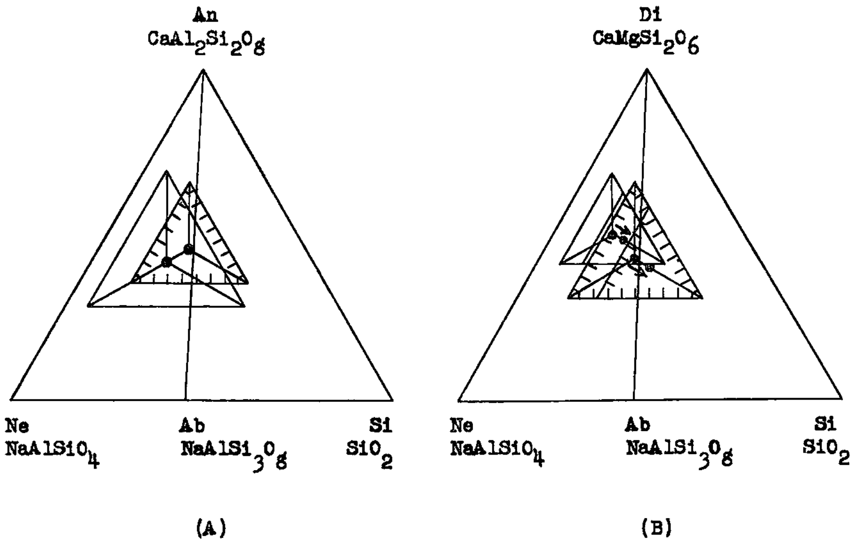

Fig. 5. Average compositions of the two rock series of Mount Yamaska with reference to the systems (A) anorthite-nepheline-silica and (B) diopside-nepheline-silica.

△ Average composition of the older yamaskite-gabbro-akerite rock series : $Di_{30.9}\ An_{35.4}\ Ne_{20.2}\ Si_{13.5}$

△ Average composition of the younger yamaskite-essexite rock series : $Di_{41.3}\ An_{28.3}\ Ne_{24.4}\ Si_{6.0}$

The 'error of closer' in the system anorthite-nepheline-silica represents the proportion of diopside.

The 'error of closer' in the system diopside-nepheline-silica represents the proportion of anorthite. Note the reduction in the size of the 'error of closer' and a shift in the position of its centre towards silica, when the proportion of anorthite is expressed in terms of calcium tschermak's molecule and silica.

read from the solidus. The approximation involved in arriving at the composition of the first plagioclase crystallizing from a melt in this manner is small, and geologically insignifiant, as pointed out by Smith (1963) with regard to the analogous system diopside-anorthite-albite. In the case of melts with the same ratio of nepheline to anorthite as the two magmas, but lying on the silica side of the join anorthite-albite, the composition of the plagioclase at the beginning of crystallization is obtained by projecting a line from the silica apex in the same manner, and is relatively richer in albite than that obtained for the subsiliceous magmas, with the same ratio of nepheline to anorthite. The greater the deficiency of silica in the melt, the more calcic the composition of the first plagioclase crystallizing from the melt. Furthermore, the silica-undersaturated melts (*i.e.* those lying on the nepheline side of the join anorthite-albite) in the plagioclase field, begin crystallization with very calcic plagioclase, which causes considerable enrichment of soda in the melt, whereas this effect is not achieved in the silica-saturated melts.

Crystallization of highly calcic plagioclase from the magma of the older intrusion can be attributed to its subsiliceous basaltic character. Furthermore, extreme differentiation of the magma has lead to a considerable enrichment of soda (and also potash) relative to lime and alumina, in the residual melt (Fig. 3). Beall (1962) has pointed out that the enrichment of soda in a melt crystallizing highly calcic plagioclase causes non-equilibrium between the crystals and the melt, and unless a continuous and complete crystal-liquid reaction takes place, zoning will result. Sharply-zoned crystals of plagioclase are common in the rocks of the older intrusion.

Highly calcic plagioclase is not found in rocks of the younger intrusion, despite its overall chemical similarity with the older intrusion. Two reasons can be given for this : (a) the initial low content of anorthite in the magma of the younger intrusion, as compared with the magma of the older intrusion, and (b) inhibition of crystallization of plagioclase due to high dissolved water content in the magma of the younger intrusion, which favoured the crystallization of kaersutite instead of plagioclase. Differences in the initial bulk composition of the two magmas are too small to account for the differences in compositions and abundances of plagioclase crystallized from them. The main factor of importance therefore is the role of dissolved water in crystallization of the two magmas.

Ringwood (1959) has explained the crystallization of hornblende from magmas in terms of preferential Al-OH ordering. In dry magmas Al^{+3} crystallizes out principally as $(AlO_4)^{-5}$ groups in the anorthite component of plagioclase. In the presence of water, not only the temperature of crystallization is lowered, but also crystallization of anorthite, and to a lesser extent, that of albite, is inhibited because of the preferential Al-OH ordering. Accordingly, Al_2O_3 will tend to accumulate in the residual magma, whilst the CaO which would have crystallized in anorthite, enters pyroxene. Thus the field of pyroxene is widened, and the cotectic approaches closer to the plagioclase side, whilst at the same time the plagioclase that crystallizes is more sodic. Experimental work on the system diopside-anorthite-water by Yoder (1954) supports this interpretation. Ringwood further suggests that high concentration of $(OH)^{-1}$ and $Al(O,OH)_6$ groups eventually lead to the crystallization of hornblende, and where potassium is high, they lead to the crystallization of biotite (see also Yoder 1965).

The effect of dissolved water, as outlined above, explains the abundance of kaersutite and small amount of plagioclase of sodic composition in rocks of the younger intrusion. Inhibition of crystallization of anorthite-rich plagioclase results in availability of Ca and Al. This favoured crystallization of the calcium-rich mineral, sphene, and probably of apatite, in these rocks. The presence of $(OH)^{-1}$ probably further aided crystalllization of apatite. Kaersutite is commonly subhedral or euhedral towards nepheline, alkali feldspar, and some sodic plagioclase, in these rocks. These textural relations are consistent with the interpretation of crystallization of the younger intrusion under the influence of high content of dissolved water. Abundance of xenoliths, some of which are very large blocks, strongly suggests that the present level of erosion is within the roof-zone of the intrusion. Loss of magmatic water to the country rock was probably minimal because of the metamorphism of the fine-grained sediments of the country rock to impervious hornfels.

The older intrusion is much larger than the younger intrusion, yet it has relatively fewer xenoliths. It is therefore suggested that the intrusion reached the surface and thereby lost much of its dissolved water content. Even if it did not reach the surface, it could have so disturbed the roof under near surface conditions that much of the water could escape through fissures. In any event, local concentrations of water in an intrusion of this size are expected, and crystallization of kaersutite-rich older yamaskite can be explained on this basis. The presence of kaersutite (and also biotite) in the gabbro near the akerite area, in the border phases of gabbro, and in akerite, can be attributed to the increase in content of water in the magma from which abundant titanaugite and plagioclase have crystallized, and the prevailing lower temperatures at later stages of differentiation when kaersutite (and biotite) is a stable phase. It is also significant that hercynite (and possibly ulvöspinel) is restricted to the older yamaskites and gabbros that are rich in titanaugite and highly calcic plagioclase. Preferential Al-OH ordering is likely to inhibit crystallization of hercynite (and possibly also of ulvöspinel because of higher oxygen pressure due to the presence of water). Hercynite is not found in the kaersutite-rich rocks.

Mechanism of Differentiation and Mode of Emplacement

Both of the main intrusive phases of Mount Yamaska occur as vertical pipe-like bodies and have concentrations of earlier crystallized minerals at the central parts and progressively lower temperature assemblages towards the margins of the intrusions. Thus fractional crystallization must have played an important role in the differentiation of these intrusions. Crystallization in shallow-seated intrusions such as these, however, should commence at the border unless prevented by some factor or factors, such as gravity, convection, diffusion, flowage differentiation, filter pressing and gas streaming. Young (1906) expressed the opinion about what he thought was a single intrusion in Mount Yamaska, that it was partly or wholly differentiated before reaching its present position, and from the movements during the crystallization, indicated by the distribution and texture of the rocks, it would appear that the differentiation took place *in situ*. Young's view seems applicable to both the main intrusive phases of Mount Yamaska, because much of their crystallization appears to have taken place *in situ*, allowing for movements of a crystal mush. There is a gradual variation in composition of the main mineral phases of the two rock series crystallized from the intrusions. There is also a lack of fragments or crystals of deep-seated origin, or resorption of crystals. Zoning of titanaugite however may indicate that a proportion of this mineral may have crystallized at a considerable depth ; the proportion of such crystals is however, small. On the other hand, the transitional or intermediate character of the structural state of the feldspars in the rocks indicates that both the intrusions crystallized at a shallow depth (Pouliot 1962).

From the above considerations, it appears to the writer that the observed distribution of rocks in the two intrusions may be due in part to the tendency of volatiles (mainly steam) and alkalis in the magma to diffuse towards the regions of lowest temperatures and pressures, as suggested by Kennedy (1955) and in part probably due to flowage differentiation, as suggested by Bhattacharji & Smith (1964), which takes place due to mechanical properties of partially crystallized magma flowing through a vertical column. Concentration of volatile constituents may also have occurred in the roof zone of the magma chamber from which the intrusions are derived, probably in the upper mantle where the magma originated, or more likely in the crust where a reservoir of magma undergoing differentiation was formed and was tapped at different points and different times. Concentration of the volatiles may have initiated the intrusion by brecciation of roof. Release of pressure by brecciation may lead to further concentration of volatiles, and then to more brecciation. Movement of magma would soon follow the brecciation, and the process could eventually lead to the emplacement of the intrusion. Brecciation of the country rock is common at the boundary of the intrusions.

The majority of the Monteregian intrusions, like the two intrusions of Mount Yamaska, are basanitic or alkalic basaltic in composition, but some others are syenitic in composition. The syenitic intrusions are spatially associated with the basanitic intrusions, but are younger. A few of the syenitic intrusions are comparable in size to them (Dresser & Denis 1944), and therefore could not have been derived from the *in situ* differentiation of the basanitic intrusions. It is thus indicated that the parent magma in the reservoir was undergoing differentiation, and the batches of magma derived from it at different points and times, differed in composition from each other to a varying degree. Herein lies an explanation for the small differences in the initial bulk composition of the two major intrusions of Mount Yamaska, which differ in age in so far as the older intrusion had completely solidified before the younger intrusion took place.

CONCLUSIONS

The two main intrusions of the igneous complex of Mount Yamaska are vertical, pipe-like in form, and subsiliceous calcic basaltic in character. The trend of differentiation of the older intrusion is from the ultramafic, older yamaskite, through gabbro, to the border phases of gabbro and silica-saturated akerite, as seen from the variation in composition of plagioclase and progressive decrease in aluminum substitution in the Z-site of titanaugite and kaersutite of these rocks. The trend of differentiation of the younger intrusion is from ultramafic, younger yamaskite, to the nepheline-bearing essexite. The different trends of differentiation of the two intrusions is due to small but significant differences in their initial bulk composition, which probably lay close to and on the nepheline side of the equilibrium thermal divides along joins anorthite-albite and diopside-albite in the system diopside-calcium tschermak's molecule-nepheline-silica. Early crystallization of aluminous diopside (titanaugite) caused silica enrichment sufficient to force the magma of the older intrusion to differentiate towards silica, but it was not sufficient to overcome the initial deficiency of silica in the magma of the younger intrusion, which therefore differentiated towards nepheline. Highly calcic plagioclase, as found in the older intrusion, is expected to crystallize from the subsiliceous calcic basaltic magmas, but in case of the younger intrusion it was probably inhibited by high dissolved water content which favoured the crystallization of kaersutite instead.

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