EVOLUTION OF THE WHITE MOUNTAIN MAGMA SERIES

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PART I. DATA

PROBLEM

In recent years, a number of intensive field and laboratory studies of the rocks of the White Mountain district in New Hampshire have been carried out. One result of these investigations is to show that there exists in this area a group of rocks with marked alkaline affinities (3)* to which the name White Mountain magma series has been applied (5, p. 56). The various rock types of this group form a definite series, and wherever found in the area they possess the same relative ages. Such a sequence is of greatest importance to petrology and necessitates an explanation. Accordingly, the writers have undertaken a study of this problem, the results of which are presented in this paper. It is not pretended that this work is complete or that the problem has been entirely solved. Certain definite conclusions have been reached, however, and it is hoped that these may lead to a more complete understanding of the evolution of the White Mountain magma series.

The writers are especially indebted to Professor Marland Billings of Harvard University for his valuable assistance in preparing this paper. Several of the major ideas presented here were first suggested by Professor Billings, and these have led to a clearer understanding of many of the intricate problems encountered in the course of the work. The writers also wish to thank Professor Esper S. Larsen, Jr., and Professor R. A. Daly for their many helpful suggestions and criticisms. The new mineral analyses quoted here were made by F. A. Gonyer of Harvard University.

In the course of these investigations the writers have limited themselves entirely to those areas with which they are personally familiar, either from a field study or from a study of rock collections. These areas include the North Conway quadrangle, the Ossipee Mountains, the Belknap Mountains, Pleasant Mountain in Maine, the Franconia quadrangle, the Percy quadrangle, Tripyramid Mountain, and Red Hill. The rock types of each of these

* Numbers in parentheses refer to bibliography at end of paper.

TABLE 1. DATA ON THE PLUTONIC ROCKS OF THE WHITE MOUNTAIN MAGMA SERIES

NAME	GABBRO	NORITE	DIORITE	QUARTZ DIORITE	MONZODIORITE	MONZONITE	NEPHELITE SYENITE	ANALCITE SYENITE
DISTRIBUTION	TRIPYRAMID MTN. BELKNAP MTNS.	TRIPYRAMID MTN.	NORTH CONWAY QUAD. PLEASANT MTN. FRANCONIA REGION	FRANCONIA REGION	BELKNAP MTNS.	TRIPYRAMID MTN. PLEASANT MTN.	RED HILL	PLEASANT MTN.
SIZE OF BODIES	FEW SQ.FT. TO 0.25 SQ. MI.	NOT KNOWN	FEW SQ.FT. TO 0.2 SQ. MI.	1.5 SQ. MI.	0.25 TO 2 SQ. MI.	RING-DIKE - 2.5 MI. DIAMETER SMALL MASS - 0.01 SQ. MI.	NOT KNOWN	0.03 SQ. MI.
SHAPE OF BODIES	IRREGULAR	NOT KNOWN	SMALL STOCKS AND DIKES	ROUGHLY CIRCULAR	INCOMPLETE RING-DIKES	IRREGULAR AND RING-DIKE	NOT KNOWN	SMALL PERIPHERAL BAND ON MAIN STOCK
TOTAL AREA AND PER CENT OF MAGMA SERIES	0.10 SQ. MI. 0.02 %	VERY SMALL	0.25 SQ. MI. 0.055 %	1.5 SQ. MI. 0.33 %	4.0 SQ. MI. 0.87 %	2.6 SQ. MI. 0.57 %	VERY SMALL	0.03 SQ. MI. 0.007 %
TEXTURE	HYPIDIOMORPHIC, GRANULAR BELKNAPS - DIABASIC	HYPIDIOMORPHIC, INEQUIGRANULAR	HYPIDIOMORPHIC, INEQUIGRANULAR	HYPIDIOMORPHIC, INEQUIGRANULAR	HYPIDIOMORPHIC, EQUIGRANULAR TO SUBPORPHYRITIC	HYPIDIOMORPHIC, INEQUIGRANULAR	HYPIDIOMORPHIC, GRANULAR	ALLOTRIOMORPHIC, INEQUIGRANULAR
DIAMETER OF GRAINS	5 - 10 MM.	1 - 3 MM.	1 - 4 MM.	2 - 3 MM.	DARK MINERALS - 0.5 MM. REST 2 - 5 MM.	1 - 5 MM.	2 - 5 MM. AVG. 2 - 3 MM.	0.5 - 5 MM.
COLOR	DARK GRAY TO BLACK	DARK MOTTLED	DARK MOTTLED	LIGHT GRAY MOTTLED	LIGHT GRAY	GRAY	LIGHT GRAY	LIGHT GRAY
MODE	TRIPY. / BEL. LAB. 63.0 / 49.0 HBD. — / 22.0 AUG. 14.0 / 18.0 IL. 6.7 / 5.0 BI. 5.0 / — OL. 10.0 / — OR. .5 / — ACC. 0.8 / 6.0 100.0 / 100.0 ACC. - PY. TI. AP. CHL. HY	QTZ. 3.0 LAB. 56.5 OR. 3.0 HY. 10.0 DI. 5.6 BI. 6.0 AP. 4.4 MT. 11.0 ACC. 0.5 100.0	P.M. / F. AND. 62.0 / 65.0 BI. 17.5 / 12.0 AUG. 15.5 / 8.0 AP. 1.5 / TR. MT. 4.0 / TR TI. TR. / TR. CHL. — / 14.0 ACC. — / 1.0 100.5 / 100 0 ACC.- HBD. PY. QTZ	AND. 63.0 OR. 2.0 BI 15.0 HBD. 9.0 QTZ. 10.0 ACC. 1.0 100.0 ACC. - AP MT	I / II / III AND. — / — / 72.0 OLIG. 61.0 / 61.0 / — OR. 21.0 / 20.0 / 12.0 AUG. 7.0 / 5.0 / — BI. 4.0 / 10.0 / 3.0 HBD. 3.0 / 2.0 / 7.0 QTZ. 2.0 / — / 4.0 ACC 2.0 / 2.0 / 2.0 100.0 / 100.0 / 100.0 ACC.- DI AP MT. ZR. CHL.	TRIPY. / P.M. AND. 40.0 / 47.0 MP. — / 40.0 OR. 40.0 / — HBD. 12.0 / — DI. 3.0 / — AUG. — / 1.5 BI. — / 8.0 ACC. 5.0 / 3.0 100.0 / 99.5 ACC. - AP IL. MT TI ALL.	OR. 36.0 AB. 37.0 NEPH. 14.0 SOD. 5.0 HBD. 7.0 ACC. 1.0 100.0 ACC. - AP. ZR. DI. BI. AEG. MT. CANCRINITE. WOHLERITE	I / II / III MP. 80.5 / 82.0 / 84.0 OLIG. 3.5 / 2.5 / — ANAL. 6.5 / 6.5 / 7.5 HBD. 7.5 / 5.5 / 4.5 TI. 2.5 / 2.5 / 1.5 MT. 0.6 / 0.5 / 1.5 AP. TR. / 0.7 / TR. ZR. TR. / TR. / TR. 100.6 / 100.2 / 99.0
CHEMICAL COMPOSITION	TRIPY. / BEL.				MODE I			MODE I
SiO_2	48.04 / 43.94	48.67			56.66		58.30	60.96
TiO_2	2.56 / 4.13	2.12			1.55		.10	.60
Al_2O_3	20.10 / 16.17	16.88			19.03		21.38	19.20
Fe_2O_3	2.32 / 3.96	4.98			2.67		1.05	1.24
FeO	6.13 / 10.06	6.37			4.88		2.04	1.63
MnO	.09 / —	—			—		TR.	18
MgO	4.68 / 5.05	4.62			1.86		.22	.55
CaO	11.52 / 9.59	8.63			4.82		.95	1.86
Na_2O	3.01 / 2.93	3.85			4.52		8.66	7.07
K_2O	79 / 1.51	1.26			3.62		6.06	5.54
H_2O^+	.42 / 1.42	.32			60		.45	.58
H_2O^-	— / 13	.02					35	.04
ZrO_2	ND / ND	ND			ND		02	.07
P_2O_5	.15 / .69	1.85			ND		.04	.14
Cl	ND / CO_2 .09	ND			ND		.35	BaO .06
S	.08 / ND	ND			07		.08	ND
TOTALS	100.06 / 99.67	99.57			100.37		100.05	99.80

ABBREVIATIONS

AB - ALBITE; ACC - ACCESSORIES; AEG - AEGIRINE; ALL - ALLANITE; ANAL - ANALCITE; AND - ANDESINE; AP - APATITE; AST - ASTROPHYLLITE; AUG - AUGITE; BI - BIOTITE; CHL - CHLORITE; DI - DIOPSIDE; FAY - FAYALITE; FL - FLUORITE; HAST - HASTINGSITE; HBD - HORNBLENDE; HED - HEDENBERGITE; HY - HYPERSTHENE; IL - ILMENITE; LAB - LABRADORITE; MP - MICROPERTHITE; MT - MAGNETITE MAY INCLUDE IL; NEPH - NEPHELINE; OL - OLIVINE; OLIG - OLIGOCLASE; OR - ORTHOCLASE; PY - PYRITE; PYROX - PYROXENE; QTZ - QUARTZ; RIEB - RIEBECKITE; SOD - SODALITE; TI - TITANITE; ZR - ZIRCON

NAME	SYENITE	QUARTZ SYENITE	QUARTZ SYENITE ALBANY TYPE	GRANITE PORPHYRY	HASTINGSITE GRANITE	RIEBECKITE GRANITE	BIOTITE GRANITE
DISTRIBUTION	NORTH CONWAY; FRANCONIA REG.; BELKNAP MTNS.; RED HILL; PLEASANT MTN.; PERCY QUAD.; TRIPYRAMID MTN.	NORTH CONWAY; BELKNAP MTNS.	NORTH CONWAY QUAD.; BELKNAP MTNS.; OSSIPEE MTNS.; FRANCONIA REGION	FRANCONIA REGION	NORTH CONWAY QUAD.; PERCY QUAD.	NORTH CONWAY QUAD.; PERCY QUAD.	NORTH CONWAY QUAD.; PERCY QUAD.; OSSIPEE MTNS.; FRANCONIA REGION; BELKNAP MTNS.; TRIPYRAMID
SIZE OF BODIES	0.10 - 20.0 SQ. MI.	1.5 - 6.0 SQ. MI.	WIDTH - 0.25 - 1.5 MI. DIAMETER - 8 - 9 MI.	WIDTH 1 - 3 MI. 43.2 SQ. MI	STOCKS - 1.5 TO 4.0 MILES IN DIAMETER. RING-DIKES - WIDTH 0.25 - 1.0 MI. LENGTH 1 - 4 MI.		STOCKS: 1 - 5 MI. IN DIAMETER A FEW SMALL RING-DIKES
SHAPE OF BODIES	RING-DIKES AND IRREGULAR STOCKS		RING-DIKES	IRREGULAR RING-DIKE	N.C. - IRREGULAR P - INCOMPLETE RING-DIKES	N.C. - SMALL IRREG. BODIES P. - INCOMPLETE RING-DIKES	LARGE STOCKS OF IRREGULAR SHAPE, AND VARYING SIZE. A FEW SMALL RING-DIKES.
TOTAL AREA AND PER CENT OF MAGMA SERIES	43.1 SQ. MI. 9.41 %	7.5 SQ. MI 1.64 %	39.9 SQ. MI 8.71 %	43.2 SQ. MI 9.43 %	ALL GRANITES 315.5 SQ. MI. 68.9 %		
TEXTURE	HYPIDIOMORPHIC, GRANULAR. SOME PORPHYRITIC SOME TRACHYTIC		PORPHYRITIC, GROUND MASS PANALLOTRIOMORPHIC TO HYPIDIOMORPHIC GRANULAR	PORPHYRITIC, GROUND MASS PANALLOTRIOMORPHIC	HYPIDIOMORPHIC, GRANULAR	HYPIDIOMORPHIC, GRANULAR TO MICROPEGMATITIC	HYPIDIOMORPHIC, GRANULAR. SOME PHASES PORPHYRITIC
GRAIN SIZE	0.5 - 5.0 MM.		DARK MINERALS: 0.5 - 1.2 MM. REST: 1.0 - 8.0 MM.	GROUND MASS: 0.06 - 0.3 MM. PHENOCRYSTS: 5.0 - 8.0 MM. DARK MINERALS: 0.6 - 1.4 MM.	0.5 - 3.0 MM.	0.5 - 3.0 MM.	0.5 - 10.0 MM. PHENOCRYSTS OFTEN UP TO 1.5 CM.
COLOR	GRAY, GREEN, BLUISH		DARK GRAY, GREEN OR PINK	DARK GRAY AND PINK	LIGHT GRAY TO WHITE	SNOWY WHITE, MOTTLED	PINK TO GREEN, SPOTTED WITH DARK MINERALS
MODE	BEL. / PERCY / P.M. / TRIPY QTZ. — / 1.6 / 3.0 / 1.0 OR 47.0 / — / — / — MP — / 86.6 / 83.0 / 80.0 OLIG 42.0 / — / 7.0 / — LAB — / — / — / 6.5 BI 2.0 / — / 1.5 / 1.0 HBD 7.0 / 3.2 / TR / 6.0 HED — / 3.4 / — / — PYROX — / — / 1.5 / 1.0 FAY — / 1.9 / — / — ACC 2.0 / 2.9 / 3.3 / 4.5 100.0 / 99.6 / 99.3 / 100.0	BEL. / N.C. QTZ 8.0 / 6.3 OR 40.0 } 75.9 OLIG 39.0 } BI 2.0 / 0.4 HBD 7.0 / — HAST — / 12.6 HED — / 3.6 ACC 2.0 / 1.2 100.0 / 100.0	N.C. / BEL. / F QTZ 12.6 / 15 0 / 13.8 MP } / / 59.1 OR } 74.1 / 71.0 / 17 1 OLIG } / 12.0 / 2.7 HAST 12.3 / 12.0 / 3.8 HED — / — / 2.4 FAY — / — / 0.6 BI 0.5 / — / — ACC 0.5 / 2.0 / 0.5 100.0 / 100.0 / 100.0 ACC: MT. AP. ZR. AL. FL	AVG. MODE QTZ 26.5 MP 23.5 OR 34 9 OLIG 1.4 HAST 6 1 HED 5.1 FAY 1.0 BI 1.2 ACC 0.6 100.0 ACC: FL. ALL. AP. ZR. MT	N.C. / PERCY QTZ 17 4 / 24.0 MP } 72.6 / 66.5 OLIG } / 0.5 HAST 8.3 / 8.0 HED — / 0.4 BI 0.6 / — ACC 1.1 / 0.6 100.0 / 100.0 ACC: AL. AP. ZR. FL. MT. AEG	N.C. / PERCY QTZ 39.4 / 38.5 MP } 54.0 / 53.8 OLIG } / 0.7 RIEB 5.5 / 5.8 BI — / 0.7 AST 1.1 / — ACC — / 0.5 100.0 / 100.0 ACC: ZR. MT. IL. TI. AP FL	N.C. / BEL. / PERCY / F. QTZ 26.7 30.0 / 23.0 39.0 / 34.2 35.1 / 25.9 26.5 MP — — / 44.4 39.2 / 55.3 } 69.8 OR 69.4 68.4 / 37.0 } 56.0 / — — / — — OLIG 34.0 / 16.6 21.9 / 15.3 } BI 3.0 1.6 } 4.0 / 3.0 4.2 / 2.8 2.9 / 1.4 HAST 0.2 — } / — — / — — / 1.6 ACC 0.7 — / 2.0 2.0 / 0.1 0.9 / 0.6 0.6 100.0 100.0 / 100.0 100.0 / 100.0 100.0 / 100.0 100.0 ACC: FL. ALL. MT. IL. AP HBD
CHEMICAL COMPOSITION	BEL. / TRIPY. / P.M.	N.C.	N.C. / BEL.				NORTH CONWAY: RED PHASE / BALDFACE PHASE / BLACK CAP PHASE / RED PHASE
SiO_2	60.75 / 62.12 / 63.32	62.24	64.40 / 66.14	71.88			70.45 / 73.65 / 72.35 / 73.01
TiO_2	0.63 / 0.84 / 0.52	0.87	0.88 / 0.51	0.25			0.69 / 0.22 / 0.39 / ND
Al_2O_3	19.55 / 15.57 / 18.75	15.82	16.75 / 17.04	13.64			14.87 / 13.73 / 12.48 / 13.73
Fe_2O_3	1.54 / 2.16 / 1.24	1.94	1.31 / 1.24	1.36			1.07 / 0.23 / 1.22 / 0.44
FeO	2.98 / 2.59 / 1.77	4.69	3.44 / 2.10	1.99			1.54 / 0.95 / 1.25 / 1.48
MnO	ND / TR / 0.11	0.24	0.05 / —	0.03			— / TR / 0.03 / 0.09
MgO	0.81 / 0.86 / 0.71	0.07	0.62 / 0.21	0.17			0.35 / 0.11 / 0.42 / 0.01
CaO	2.29 / 2.37 / 2.03	2.65	1.85 / 1.62	0.90			1.28 / 0.90 / 1.19 / 0.94
Na_2O	4.89 / 6.78 / 6.04	4.80	4.44 / 4.88	3.73			4.28 / 4.47 / 3.78 / 3.50
K_2O	5.90 / 4.79 / 4.88	6.26	4.96 / 5.54	5.61			4.16 / 4.27 / 5.98 / 5.62
H_2O^+	0.08 / 0.48 / 0.36	0.56	1.05 / 0.41	0.29			0.65 / 0.77 / 0.60 / 0.18
H_2O^-	0.24 / 0.09 / 0.06	0.07	0.22 / —	—			0.50 / 0.56 / 0.17 / 0.05
ZrO_2	ND / ND / 0.05	ND	ND / ND	ND			ND / ND / ND / ND
P_2O_5	0.13 / 0.23 / 0.16	0.14	0.11 / 0.08	TR			0.04 / TR / 0.27 / ND
Cl	ND / ND / SrO 0.03	ND	ND / ND	ND			ND / ND / N D / ND
S	ND / ND / BaO 0.11	ND	ND / ND	0.02			ND / ND / ND / ND
TOTALS	99.79 / 100.88 / 100.24	100.35	100.08 / 100.08	99.87			99.88 / 99.86 / 100.11 / 99.05

regions is shown in some detail in Figure 1. It is entirely possible, and in fact likely, that such areas as Mount Ascutney in Vermont, the Burnt Meadow Mountains in Maine, and the Pawtuckaway Mountains of New Hampshire also contain rocks belonging to this magma series, but due to the fact that they have not been studied by the present investigators, they will not be considered in this discussion.

Briefly, the method of attack consisted of both field and laboratory studies. The field studies served to determine the sizes of rock bodies and the age relations of the various rock types of the series. In the laboratory the mineralogy and chemistry of the rocks, and the optics and chemistry of the minerals were determined. Particular emphasis was given to the evolution of the mineral species, for the writers feel that such a method of attack must be adopted if problems in the evolution of igneous rocks are to be solved.

Rocks

Petrography and Chemistry. The rocks of the White Mountain magma series may be classified into three main groups: volcanic rocks, plutonic rocks, and dike rocks. The volcanic rocks consist of flows, tuffs, and breccias of basalt, andesite, trachyte, and rhyolite. The plutonic rocks are gabbro, norite, diorite, quartz diorite, monzodiorite, monzonite, nephelite syenite, analcite syenite, syenite, quartz syenite, quartz syenite (Albany type), granite porphyry, hastingsite granite, riebeckite granite, and biotite granite. The dike rocks are listed below. The distribution of the volcanic and plutonic rocks is shown in Figure 1. For the sake of simplicity, all the granites have been indicated with one pattern, and the monzodiorites and monzonites with another pattern. All the other rocks have been mapped with separate patterns. The data have been obtained from the published works of Billings (3), Kingsley (26), Jenks (23), Pirsson and Rice (33), Pirsson and Washington (31 and 32), and the unpublished works of Modell (28), Williams (40), Chapman (9), Billings (6), and Page (29). Mount Monadnock, Vermont, and a number of bodies in which the different rock species have not been distinguished are shown on the map, but they were not considered in the present study. Since the map was prepared, Dr. A. W. Quinn of Brown University has completed a study of Red Hill.

Lack of space prohibits a complete description of each rock type;

accordingly, most of the data have been listed in tabular form. Table 1, which is self-explanatory, gives the most important characteristics of the plutonic phases, together with their modes and chemical analyses. The rocks are listed according to age as nearly as possible, except that the quartz syenite (Albany type) has been placed before the granite porphyry. This was done so that the quartz syenite and the quartz syenite (Albany type) might be compared more easily. Many of the data are new and are published here for the first time. Those for the Belknaps, Percy, and Franconia regions are from the unpublished works of Modell, Chapman, and Williams respectively. The following chemical analyses are also new: gabbro from Tripyramid Mountain, monzodiorite from the Belknaps, Albany quartz syenite from the Belknaps, and granite porphyry from the Franconia quadrangle.

The chief characteristics of the volcanic rocks, which cover about 30 square miles, are shown in Table 2. The dikes belonging to the magma series are very abundant and consist of olivine diabase, kersantite, diorite, camptonite, spessartite, augite syenite porphyry, porphyritic syenite, syenite porphyry, bostonite, hastingsite sölvsbergite, paisanite, hastingsite granite, biotite granite, aplite, and quartz porphyry. A list of their chemical analyses is given in Table 3.

TABLE 2

VOLCANIC ROCKS OF THE WHITE MOUNTAIN MAGMA SERIES*

NAME	*Basalt*	*Andesite*	*Trachyte*	*Rhyolite*
DISTRIBUTION	Ossipee Mtns.	Ossipee Mtns. Franconia Quad.	North Conway Pleasant Mtn. Belknap Mtns.	North Conway Ossipee Mtns. Belknap Mtns. Franconia Quad.
TEXTURE	Porphyritic	Trachytic and porphyritic	Trachytic and porphyritic	Porphyritic
GRAIN SIZE	Dense groundmass	Dense groundmass	Dense groundmass	Dense groundmass
COLOR	Black	Black	Gray, black, red, purple	Red, gray, yellow, brown, pink
MINERALS	Labradorite Augite-diopside Amphibole	Andesine Alkali feldspar Amphibole	Orthoclase Oligoclase Albite	Microperthite Soda-orthoclase Albite

TABLE 2 (*Continued*)

Magnetite	Apatite	Soda-orthoclase	Oligoclase
Titanite	Magnetite	Microperthite	Quartz
Pyrite	Epidote	Quartz	Hastingsite
Epidote	Chlorite	Zircon	Biotite
Calcite	Sericite	Magnetite	Fayalite
Chlorite	Leucoxene	Biotite	Fluorite
		Apatite	Zircon
		Clinozoisite	Magnetite
		Augite	Riebeckite
		Hornblende	Aegirine-augite
		Titanite	Hornblende
		Epidote	Apatite
		Chlorite	Titanite
			Allanite
			Chlorite
			Epidote

CHEMICAL ANALYSES OF VOLCANIC ROCKS OF WHITE MOUNTAIN MAGMA SERIES

	1	2	3	4	5	6	7
SiO_2	49.04	57.85	65.05	75.38	73.33	72.25	72.05
TiO_2	3.74	2.34	.25	nd	nd	nd	.23
Al_2O_3	18.10	16.30	16.80	11.85	12.95	13.40	14.72
Fe_2O_3	2.31	3.16	4.97	1.78	.98	1.10	1.02
FeO	6.69	5.10	1.12	.88	1.66	1.53	1.46
MnO	.08	.10	tr	.10	1.13	.11	tr
MgO	3.68	2.68	.20	none	none	none	.15
CaO	10.72	5.50	1.68	.33	.98	.74	.79
Na_2O	2.53	3.00	3.94	3.68	3.46	4.27	4.42
K_2O	1.09	2.92	5.22	5.37	5.61	5.56	4.00
H_2O+	1.72	.61	.30	.50	.30	.31	.55
H_2O-	.12	.10	.45	.15	.11	.10	.55
P_2O_5	.08	.13	tr	nd	nd	nd	nd
Totals	99.90	99.80	99.98	100.02	99.51	99.37	99.94

1. Basalt—Bald Knob, Ossipee Mountains (26, p. 159).
2. Andesite—Cold Brook, Ossipee Mountains (26, p. 159).
3. Trachyte—South Moat Mountain, North Conway quadrangle (3, p. 97).
4. Quartz porphyry—south slope Mt. Pequawket, North Conway quadrangle (30, p. 408).
5. Quartz porphyry—east slope Mt. Pequawket, North Conway quadrangle (30, p. 409).
6. Quartz porphyry—summit Mt. Pequawket, North Conway quadrangle (30, p. 409).
7. Riebeckite quartz porphyry—Dry Brook, Albany, North Conway quadrangle (3, p. 95).

* These rocks occur in part as tuffs and breccias.

TABLE 3

CHEMICAL ANALYSES OF DIKE ROCKS OF WHITE MOUNTAIN MAGMA SERIES

	1	2	3	4	5	6	7	8	9	10
SiO_2	69.51	50.75	50.59	76.65	52.95	42.73	41.63	42.77	41.94	58.25
TiO_2	.29	3.05	2.60	.05	3.90	4.30	3.95	2.35	4.15	tr
Al_2O_3	15.06	17.31	17.74	12.89	14.96	14.50	13.26	14.06	15.36	18.22
Fe_2O_3	1.25	2.08	3.54	.89	2.44	4.03	3.19	2.72	3.27	1.07
FeO	1.63	8.13	7.54	1.11	7.03	7.28	9.92	8.34	9.89	5.96
MnO	?	tr	tr	nd	tr	.19	.27	.15	.25	.10
MgO	.05	3.48	3.92	.20	3.86	5.46	7.31	9.72	5.01	tr
CaO	.31	6.77	6.85	.48	6.76	8.46	8.86	11.47	9.47	1.51
Na_2O	6.02	4.14	4.25	3.71	4.95	3.11	2.49	1.89	5.15	4.19
K_2O	5.48	2.87	2.79	5.50	1.64	2.28	3.32	1.43	.19	5.59
H_2O+	.23	.56	.55	.15	.55	3.08	} 1.35	2.74	3.29	.85
H_2O-	.11	none	none	.08	.09	.36				
P_2O_5	tr	.10	.27	nd	.76	.93	none	none	none	none
S	nd	nd	nd	nd	.05	.18	none	none	none	none
CO_2	none	none	nd	nd	none	3.76	5.20	1.62	2.47	4.75
ZrC_2	.01	nd	nd	nd	.02	nd	none	none	none	none
Totals	99.95	99.14	100.55	100.71	100.16	100.60	100.75	99.26	100.44	100.49

1. Paisanite—Horne Farm Quarry, Red Hill (32, p. 441).
2. Lamprophyre—Black Cascade, Tripyramid Mountain (33, p. 424).
3. Lamprophyre—Norway Rapids, Tripyramid Mountain (33, p. 424).
4. Aplite—southwest slope of Mt. Belknap (31, p. 440).
5. Spessartite—Belknap Mountains (31, p. 455).
6. Camptonite—summit of Mt. Gunstock, Belknap Mountains (31, p. 495).
7. Diabase—Campton Falls, New Hampshire (20, p. 156).
8. Olivine diabase—Campton Falls, New Hampshire (20, p. 150).
9. Diortite—Campton Falls, New Hampshire (20, p. 156).
10. Syenite—Campton Falls, New Hampshire (20, p. 156).

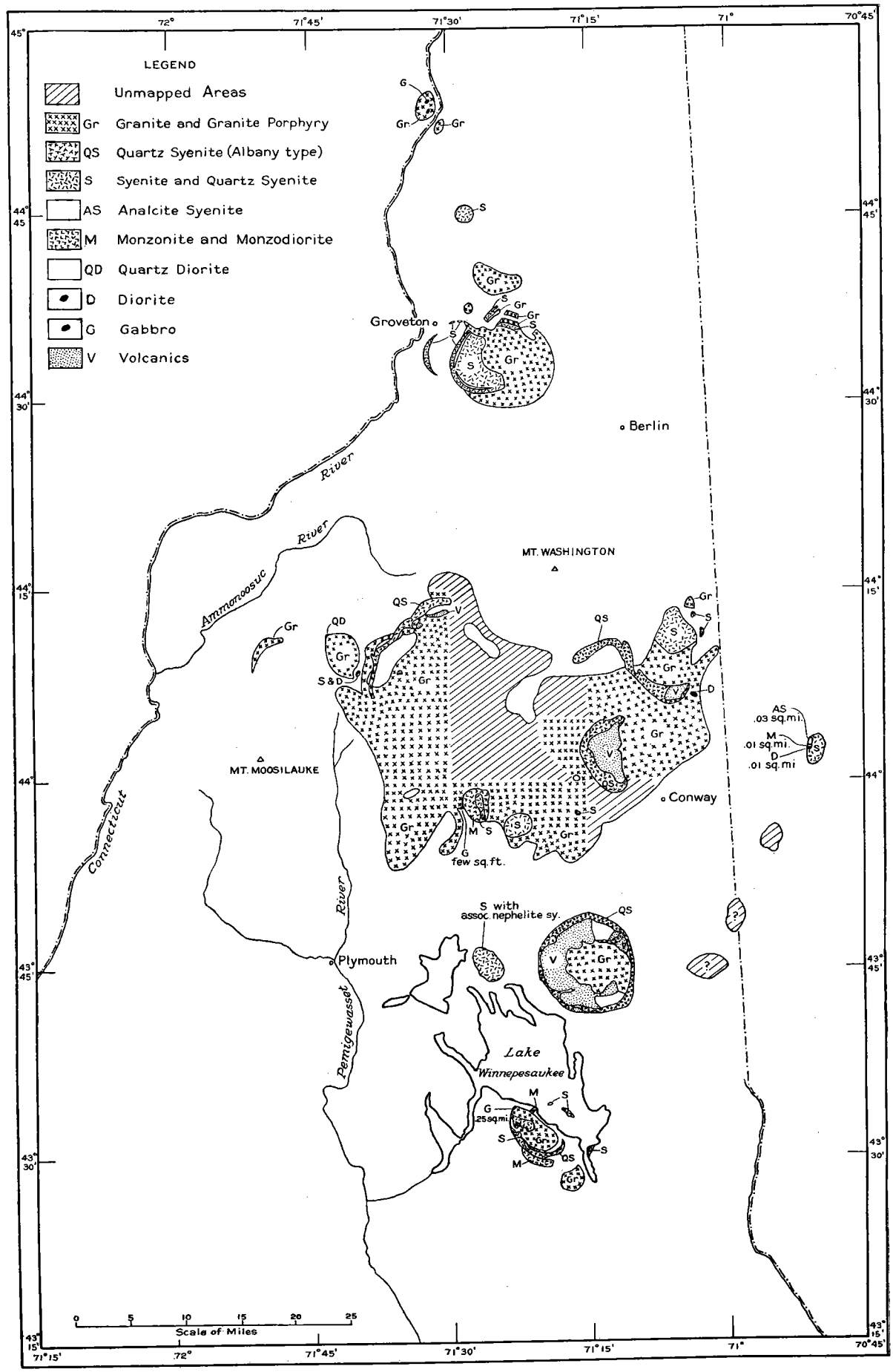

FIG. 1. Map showing distribution of the White Mountain magma series.

Due to the magnitude of the task, the writers have deemed it advisable to confine their studies to the plutonic phases of the White Mountain magma series, and have been forced to neglect the extrusive and dike rocks. A complete theory, however, must ultimately consider these too.

AREAL EXTENT OF PLUTONIC PHASES. The writers have calculated the number of square miles of area underlain by each of the rock types. They have also determined the percentage of each type with respect to the magma series as a whole. The results are shown in Table 4. The figures are given to several decimals in order to represent the rarer types. For the more common types the decimals have no significance. It should be clearly understood that these figures are based only upon those areas studied in recent years, and do not include areas such as the Crawford Notch and Plymouth quadrangles for which sufficient data are not available.

TABLE 4

TABLE SHOWING AREAL EXTENT OF PLUTONIC ROCK TYPES AND PERCENTAGE OF EACH COMPARED TO TOTAL MAGMA SERIES

NAME	SQUARE MILES	PER CENT OF MAGMA SERIES
Granite	315.50	68.9000
Granite porphyry	43.30	9.4300
Quartz syenite (Albany type)	39.90	8.7100
Quartz syenite	7.50	1.5400
Syenite	43.10	9.4100
Analcite syenite	0.03	0.0066
Nephelite syenite	?	?
Monzonite	2.60	0.5700
Monzodiorite	4.00	0.8700
Quartz diorite	1.50	0.3300
Diorite	0.25	0.0546
Norite	?	?
Gabbro	0.10	0.0218
Total	457.78	

The relative proportions of the various rock types as they are seen today in the White Mountain region may not necessarily represent the proportions of those types as magmas. They are rather a function of specific gravities. Granite, being the lightest of the magmas in the region has a greater tendency to rise, and thus, at the present level, is more abundant than any of the other types, whereas gabbro forms only a very minor proportion of those observed at the surface.

Age Relations. The most important data furnished by field relations as to the evolution of the magma series pertains to the relative ages of the different rock types. Although the data from any one area are by no means complete, the facts collected from the whole region indicate that there is a definite succession of rocks beginning with the volcanics.

There is ample evidence that the so-called Moat volcanics are older than most of the plutonic rocks of the White Mountain magma series. In the North Conway quadrangle, all the plutonic phases of the series present, except the diorite, cut the volcanics. In the Ossipee Mountains, the Albany quartz syenite cuts the volcanics and, furthermore, contains inclusions of the latter. On Pleasant Mountain, the volcanics are definitely older than the augite syenites and syenites. Thus, the Moat volcanics are clearly older than the syenites and more siliceous rocks, but, unfortunately, there is no direct evidence as to their age relative to the gabbro, diorite, and monzonite. However, fragments of the plutonics have never been found in the Moat volcanics.

It is certain that the gabbro and diorite of the series are older than the biotite granite since they are cut by the latter in the Belknap Mountains. In the Belknap Mountains, also, some of the diorite occurs as inclusions in the monzodiorite. There are no data on the age of either the norite or quartz diorite. At Pleasant Mountain, the analcite syenite cuts the monzonite and is, in turn, cut by the syenite. The relative age of the nephelite syenite at Red Hill is not known, but until evidence to the contrary is found, it seems probable that it has the same relative age as the analcite syenite of Pleasant Mountain. For the most part, the quartz syenite is younger than the syenite. The Albany quartz syenite is probably essentially contemporaneous with the other quartz syenite. In the North Conway and Percy quadrangles, the latter is found locally grading into the hastingsite granite. In the Percy quadrangle, the hastingsite granite, in turn, grades into the riebeckite granite. Evidence from the Franconia region shows that the granite porphyry is older than the quartz syenite (Albany type) since it is intruded by the latter. In all areas where the Conway biotite granite occurs it is definitely the youngest plutonic present since it cuts most of the other plutonic phases. In most areas, the dikes are younger than the biotite granite, but at Pleasant Mountain, some are older than the diorite.

In summary, the rocks of the White Mountain magma series may be listed chronologically (oldest at bottom) as shown in Table 5. The relative ages of those types shown in brackets are not well known.

TABLE 5

ROCKS OF THE WHITE MOUNTAIN MAGMA SERIES LISTED

According to Age (Oldest at Bottom)

Vent agglomerate of the Belknaps
Biotite granite
Riebeckite granite
Hastingsite granite
Quartz syenite (Albany type)
Granite porphyry
Quartz syenite
Syenite
[Nephelite syenite and analcite syenite]
Monzonite
Monzodiorite
[Quartz diorite]
Diorite
[Norite]
Gabbro
Volcanics—definitely older than syenite and younger rocks. Age relative to analcite syenite and older rocks unknown.

Dikes

Inspection of this table shows features which are characteristic of many comagmatic regions. As evolution proceeds, there is a gradual decrease in the percentage of ferromagnesian minerals and anorthite, and a corresponding increase in the alkali feldspars, and, in the final stages, quartz. Chemically this means a decrease in iron, magnesium, and lime and an increase in soda, potash and silica.

LOCUS OF ORIGIN OF ROCK TYPES. It is clear to those who are most familiar with the White Mountain magma series that the different rock types did not originate at the levels where we now see them. They formed at some depth below the present surface of the earth and were then injected into higher levels. Little differentiation took place in the bodies now exposed to view. The evidence for this is that the contacts between different members of the White Mountain magma series are relatively sharp—in many instances they show a knife-edge sharpness. It is true that in some localities gradational contacts exist, but these are usually confined to zones a few feet wide and are insignificant when compared to the size of the rock-bodies as a whole.

MECHANICS OF INTRUSION. It is not the purpose of this paper to discuss the mechanics of intrusion of the White Mountain magma series, but a brief statement is desirable. Evidence from the Ossipee Mountains, North Conway quadrangle, Percy quadrangle, Belknap Mountains, Franconia quadrangle, and Tripyramid Mountain shows that the plutonic rocks of the series occur as stocks and irregular ring-dikes, and that cauldron subsidence has been the dominant mechanism of intrusion.

MINERALS

INTRODUCTORY STATEMENT. Practically all discussions of magmatic differentiation are concerned merely with rock types. The writers are convinced, however, that a far more fundamental study is essential, and that the evolution of the individual minerals must be thoroughly investigated. In this belief, an attempt has been made to determine by chemical and optical methods the composi-

TABLE 6

MINERALS OF THE WHITE MOUNTAIN MAGMA SERIES

OLIVINE GROUP
- Olivine (hyalosiderite)
- Fayalite

PYROXENE GROUP
- Diopside-hedenbergite series
- Aegirine series
- Augite
- Enstatite-hypersthene series

AMPHIBOLE GROUP
- Hornblende
- Hastingsite
- Riebeckite

BIOTITE GROUP

PLAGIOCLASE GROUP
- Albite
- Oligoclase
- Andesine
- Labradorite

ORTHOCLASE

ANORTHOCLASE

MICROPERTHITE

QUARTZ

FELDSPATHOIDS
- Analcite
- Cancrinite
- Nephelite
- Sodalite

ACCESSORIES
- Allanite
- Apatite
- Astrophyllite
- Fluorite
- Ilmenite
- Magnetite
- Pyrite
- Titanite
- Woehlerite
- Zircon

tion of the essential minerals in all the plutonic phases of the White Mountain magma series. Obviously, to do this by chemical means entirely would be very expensive and laborious. Consequently, certain key minerals have been chosen for chemical analysis and their optical properties determined. From these data, supplemented by information contained in the textbooks of optical mineralogy, it has been possible to determine the chemical composition of most of the minerals in the White Mountain magma series.

A list of the minerals of this magma series is shown in Table 6.

The essential minerals are the feldspars, olivines, pyroxenes, amphiboles, biotites, and quartz. Quartz first becomes important in the quartz syenites and granites, although it first appears in the quartz diorite, which is of very limited extent.

FELDSPARS. The usual relations were found in the feldspars—calcic and intermediate plagioclases in the gabbros, diorites, and monzonites; alkali feldspars (albite-oligoclase, orthoclase, anorthoclase, and microperthite) in the monzonites, syenites, and granites.

BIOTITE. Three new chemical analyses have been made of biotites from the White Mountain magma series. One of these is from the gabbro of Tripyramid Mountain, a second is from the monzodiorite of the Belknap Mountains, and a third from the Conway granite of the Percy quadrangle. The chemical compositions and optical data are given in Tables 7 and 8.

It will be observed that in passing from the gabbro to the granite, there is a systematic decrease in silica, titania, alumina, and magnesia, and a systematic increase in ferric iron, ferrous iron, manganese, and lime. The potash and minor oxides are not so regular in their variation. The most striking change is the increase in the iron-magnesia ratio. The available data suggest a continuous reaction series with no sharp discontinuity.

OLIVINE. The olivine (hyalosiderite) in the gabbro of Tripyramid Mountain has been isolated and analyzed. The results are given in Table 7 and the optical properties in Table 8. It is about 40% fayalite and 60% forsterite. Unfortunately, the fayalite from the more siliceous rocks could not be separated for analysis. Optical data had to be employed to determine the chemical composition, and typical data on fayalite from a syenite are given in Table 8. They indicate fayalite, with 10% forsterite and 90% fayalite. As in the biotites, there is a great increase in iron relative to magnesia in going from the basic end of the series to the siliceous. Olivine

TABLE 7

CHEMICAL COMPOSITION OF THE MINERALS OF THE WHITE MOUNTAIN MAGMA SERIES

	1	2	3	4	5	6	7	8	9
SiO_2	37.74	35.88	33.48	47.58	46.56	37.40	46.98	34.96	none
TiO_2	5.22	4.17	2.94	.37	1.83	3.20	1.49	none	48.90
Al_2O_3	16.31	14.96	13.64	1.16	2.48	12.34	1.29	none	none
Fe_2O_3	none	2.33	8.00	2.60	6.24	4.16	11.93	none	9.80
FeO	15.52	20.88	23.54	24.21	27.27	25.84	23.38	36.77	38.97
MnO	.06	.18	1.02	.59	1.08	1.24	.24	.52	.36
MgO	14.23	10.04	4.97	3.34	1.35	2.20	.13	27.04	2.03
CaO	.04	.12	.56	18.80	6.15	9.72	1.91	none	nd
Na_2O	.44	.36	.53	.47	4.17	1.80	8.90	nd	nd
K_2O	8.88	9.20	7.80	.21	1.37	1.36	2.74	nd	nd
H_2O+	1.17	.80	2.63	.34	1.27	tr	1.10	nd	nd
H_2O-					nd	.60	none	—	—
F	.45	1.58	.95		—	—	—	—	—
	100.06	100.50	100.06						
Less O for F	.19	.66	.40						
Total	99.87	99.84	99.66	99.67	99.77	99.86	100.09	100.58	100.06

1. Biotite from gabbro (7052)*, Black Cascade, Tripyramid Mountain.
2. Biotite from monzodiorite (609), one-third mile northwest of Ames station, Belknap Mountains.
3. Biotite from granite (19287), granite quarry one mile south of Beech Hill, Percy quadrangle.
4. Hedenbergite from syenite (19258), east slope of knoll south of Burnside Brook at elevation 2160 feet, Percy quadrangle.
5. Hornblende from syenite (19247), in Moore Brook at elevation 2000 feet, Percy quadrangle.
6. Hastingsite from quartz syenite (18299), Jackson Falls, Jackson, North Conway quadrangle (3, p. 110).
7. Riebeckite from granite (19274), ¼ mile N.E. of small swamp on Mill Mt., Percy quadrangle.
8. Hyalosiderite from gabbro (7052), Black Cascade, Tripyramid Mountain.
9. Ilmenite from gabbro (7052), Black Cascade, Tripyramid Mountain.

* Numbers in parentheses refer to Harvard University rock collections. F. A. Gonyer, analyst of all except specimen 6.

(hyalosiderite) occurs in the gabbro, fayalite in the syenites and granites. Members of the olivine series have not been observed in the diorites or monzonites. There is, apparently, a definite stage corresponding to the intermediate types, in which members of the olivine series could not exist in equilibrium.

PYROXENES. The pyroxenes of the White Mountain magma series belong to four groups: (1) enstatite-hypersthene, (2) aege-

TABLE 8

OPTICS OF MINERALS OF THE WHITE MOUNTAIN MAGMA SERIES

		1	2	3	4	5	6	7	8	10	11	12	13	14
INDICES	α	1.596	1.599	1.606	1.730	1.688	1.698	1.691	1.721	1.690	1.691	1.687	1.670	1.812
	β	1.656	1.665	1.671	1.736	1.699	1.719	1.694	1.750	1.695	1.698	1.697	—	1.849
	γ	1.656	1.665	1.672	1.755	1.704	1.722	1.699	1.765	1.716	1.718	1.703	1.689	1.860
SIGN		−	−	−	+	−	−	+	−	+	+	−	−	−
OPTIC ANGLE		5°	small	small	60°	35°	47°±3°	large	85°±2°	60°±3°	60°	70°	medium	48°
DISPERSION		$r<v$ weak	$r<v$ —	$r<v$ weak	$r>v$ med.	$r>v$ strong	med. strong	$r>v$ strong	$r>v$ weak	weak	$r>v$ weak	$r<v$ weak	$r>v$ med.	$r>v$ —
ORIENTATION		$X\wedge c=$ 4°	$X\wedge c=$ 3°	$X\wedge c=$ 3°	$Y=b$ $Z\wedge c=$ 45°	$Y=b$ $Z\wedge c=$ 25°	$Y=b$ $Z\wedge c=$ 20°	$Z=b?$ $X\wedge c=$ 3°–5°	?	$Y=b$ $Z\wedge c=$ 40°	$Y=b$ $Z\wedge c=$ 43°	$Z=c$	$Y=b$ $Z\wedge c=$ 17°	?
PLEOCHROIM		Z=Y >X	Z=Y >X	Z=Y >X	Z>Y =Y	Z>Y >X	Y>Z >X	X>Z >Y				X=Y =Z	Y>Z >X	

1–8 refer to analyzed specimens—same numbers as in Table 7.

10. Diopside from gabbro (7052), Black Cascade, Tripyramid Mountain.
11. Diopside from syenite porphyry (19665), north peak of Cape Horn, west of Percy quadrangle.
12. Hypersthene from norite (7048), Black Cascade, Tripyramid Mountain.
13. Hornblende from diorite, one mile east of Mt. Pequawket (3, p. 103).
14. Fayalite from syenite (19246), ridge north of Cummings Brook, elevation 1710 feet, Percy quadrangle.

rine, (3) augite, and (4) diopside-hedenbergite. Hypersthene is relatively rare, being found only in the norite of Tripyramid Mountain. Aegerite is also rare, having been observed in a riebeckite granite on Bartlett Haystack in the Crawford Notch quadrangle. Available data indicate that most of the so-called augite in the White Mountain magma series probably belongs to the diopside-hedenbergite series. The problem thus resolves itself into a study of the diopside-hedenbergite series. One new analysis was made for the present paper, the pyroxene from syenite in the Percy quadrangle, which was found to be hedenbergite. This analysis is given in Table 7, the optical properties in Table 8. It is 90% hedenbergite, 10% diopside.

Attempts to obtain clean material for an analysis of the pyroxene of the gabbro from Tripyramid Mountain were unsuccessful. The optics were obtained, however, and are shown in Table 8. Winchell's curve (41, p. 184) indicates that it is diopside-hedenbergite with 68% diopside, 32% hedenbergite.

Optical data were also obtained on pyroxenes from the norite from Tripyramid Mountain, with the results shown in Table 8. According to Winchell's curve (41, p. 177), they indicate a hypersthene with about 24% $FeSiO_3$ and 76% $MgSiO_3$.

In a syenite porphyry from the Cape Horn ring-dike of the Percy quadrangle two pyroxenes were observed. One is very rare and occurs as phenocrysts, the other is in the groundmass. The optical properties of the pyroxene occurring as phenocrysts are given in Table 8. It is very similar to the pyroxene from the Tripyramid gabbro. The groundmass pyroxene, however, is a hedenbergite.

The above facts indicate that the pyroxenes of the White Mountain magma series belong largely to the diopside-hedenbergite series, and that in the gabbro the pyroxene is about 68% diopside, 32% hedenbergite; in the syenite (except for the rare phenocrysts) and granite the pyroxene is about 10% diopside, 90% hedenbergite. There is thus a great increase in iron relative to magnesia in going from the basic to the siliceous end of the series. Since, however, pyroxenes intermediate in composition between those of the gabbro (68% diopside) and the syenite (10% diopside) have not been observed, and since both occur in a syenite porphyry, the former as phenocrysts, the latter as the groundmass, we are led to believe that a discontinuity in the series may exist.

Amphiboles. Three analyses of amphiboles from the White

Mountain magma series are available, two of which are new. One is a soda hornblende from a syenite in the Percy quadrangle and the second is a riebeckite from a riebeckite granite in the same area. A third analysis is of a hastingsite from the North Conway quadrangle. It will be observed that all three are very rich in iron relative to magnesia. Unfortunately, amphiboles in the more basic rocks could not be successfully separated for chemical analysis. Billings (4, p. 293) has shown, however, from a study of the whole New England-Quebec alkaline province that the amphiboles in the basic rocks have a much lower iron-magnesia ratio than those from the siliceous rocks.

The following facts may be noted: (1) Riebeckite is confined to the granites. (2) Hastingsite is confined to the syenites, quartz syenites, and granites. (3) The range of the sodic hornblende is unknown. Riebeckite is younger than hastingsite, for in some specimens the former has been observed as a shell about the latter.

Ilmenite. The opaque mineral ilmenite from the gabbro from Tripyramid Mountain was studied in polished section by the writers, and was found to be a homogeneous ilmenite. This mineral was also separated by the writers and analyzed by F. A. Gonyer; the analysis is given in Table 7.

Quartz. Consideration of a number of important facts in regard to the occurrence of quartz may be helpful in explaining later the means whereby it has originated.

In the first place, silica-deficient femags are found mainly in the siliceous rocks. Hastingsite and biotite—both minerals low in silica—are the principal dark minerals of the granites, the rocks in which quartz is most abundant. Such an association strongly suggests that the origin of quartz is in some way related to the crystallization of the silica-poor femags.

Secondly, with the exception of a small body of quartz diorite in the Franconia region, quartz is not present in the White Mountain magma series in any quantity until the quartz syenite stage. It is of the greatest importance to remember that it is also in the syenite stage that hastingsite and fayalite first appear, and pyroxene becomes unimportant.

In the third place, the rocks of the so-called New Hampshire magma series which occur in the same general area as the White Mountain magma series, but are somewhat older, represent a case in point. In these rocks, which include quartz diorite, granodiorite,

quartz monzonite, and granite, biotite is the only ferromagnesian mineral present in any amount, and it occurs in all types. In contrast to the White Mountain magma series, quartz appears very early in these rocks. In other words, the appearance of biotite is accompanied by the simultaneous appearance of quartz. This fact alone is strong evidence that quartz is, in part, the result of the crystallization of biotite, a silica-poor femag.

Work by F. S. Miller (27) on the basic rocks of the San Luis Rey quadrangle, California, shows a very similar relation between biotite and quartz. Biotite, which appears in these rocks when the anorthite content of the plagioclase reaches about 56%, is closely accompanied by the appearance of quartz. Apparently, the two are closely related in origin. Miller has further found that many of the gabbroid rocks contain nodular masses composed of pyroxene and calcic plagioclase. These basic nodules grade out into a zone composed of plagioclase, pyroxene, biotite, and quartz. Farther from the center of the nodules the pyroxene has changed to hornblende, and quartz and biotite have become more abundant. The quartz and biotite appear together and increase in amount proportionally.

PART II. THEORY

Theories of Origin of Rock Types

Introductory Statement. Many theories have been developed to explain the great diversity of igneous rocks, particularly in such a consanguineous group as the White Mountain magma series. Some theories are based primarily on differentiation—that is, a primary magma of uniform composition is supposed to break up into subsidary fractions of varying composition. Other theories involve the mixing of two different magmas, or the assimilation of solid rock by magma. Still other theories are based on the melting up of rock in place, either in whole or in part, the latter being known as selective fusion.

Theories of Differentiation. In recent years, a number of theories of differentiation have been presented by petrologists. These include principally liquid immiscibility, gaseous transfer, and fractional crystallization. These theories have been summarized by Daly in his "Igneous Rocks and the Depths of the Earth" (12, pp. 319–332).

According to the theory of liquid immiscibility, differentiation takes place in the magmatic state by the separation of liquid phases of different compositions. The crystallization of these phases gives rise to different rock types. Bowen (7, pp. 7–19) and Grieg (18) have shown, however, that the evidence is decidedly against limited miscibility in natural magmas. Accordingly, we can dismiss this method of differentiation without further comment.

Fenner (14, p. 743) is one of the chief advocates of gaseous transfer. He considers that the gases responsible for differentiation form a separate bubble phase and rise from lower to higher levels in the magma, making selective transfer of materials from lower to higher levels. Bowen (7, pp. 7–19) and others, although realizing that gases may play an important role during the cooling of a magma, believe it very unlikely that notable differentiation of the molten material would accompany this action. The present writers are of the opinion that this process has certainly not been operative to any great extent in the formation of the White Mountain magma series.

Fractional crystallization is the theory of differentiation most widely accepted at present. According to this theory, different rock types are formed by the early crystallization of minerals which are richer in lime, iron, and magnesia than the magma from which they separate. If these minerals are isolated from the magma by gravitative settling or by the squeezing out of the residual magma itself, different rock types are produced. For a more detailed discussion of this theory, the reader is referred to Bowen's "Evolution of the Igneous Rocks" (7).

Theories of Assimilation and Pure-melting. Daly (12, p. 287) has strongly emphasized the importance of both assimilation and pure-melting in the formation of igneous rocks. He defines magmatic assimilation as "the mutual solution of magma with solid rock, with other magma, or with foreign gas, so that a new magma with at least some approach to chemical homogeneity results." In other words, the assimilation of granitic material by gabbroic magma would produce a magma of some intermediate composition. Since differentiation of the syntectic magma accompanies and follows assimilation, the resulting rocks are not the readily identifiable products of addition. Magmatic assimilation may be either high-level or abyssal (intracrustal or in the substratum).

By pure melting the writers mean melting up of older rocks without contamination by magmas, solutions or gases. It may be complete or partial and in the latter case may be called selective fusion. The last minerals to crystallize in the original formation of rocks (quartz and feldspars) would, in general, be the first to go into mutual solution when blocks submerged in a magma reach a level where sufficiently high temperatures are available. The liquid thus formed might either rise as an independent mass because of its low specific gravity or it might become incorporated in the surrounding magma.

Theories of Origin of Alkaline Rocks. A great many theories have been proposed to explain the origin of the alkaline rocks. Among the writers responsible for these are Becke (2), Jensen (24), Evans (13), Goldschmidt (17), Barth (1), Foye (15), Harker (19), Shand (34, 35), Holmes (21, 22), Smyth (36, 37), Gillson (16), Kennedy (25), Daly (11), and Bowen (7). Due to a lack of space none of these will be considered here. For a complete discussion of any of the theories the reader is referred to the above authors.

Outline of Theory Accepted. The writers propose to show that none of the processes, outlined above, operating alone is capable of producing the complete White Mountain magma series, but that a combination of fractional crystallization, pure melting, and assimilation is necessary. They will show that, although it is qualitatively possible to produce the White Mountain magma series by fractional crystallization, it is quantitatively impossible.

The writers will first consider the evolution of the minerals of the White Mountain magma series and then the mechanics of differentiation through fractional crystallization. They will then discuss the quantitative difficulties involved in deriving all the rocks by this process alone, and, after a consideration of assimilation and pure-melting, will describe in greater detail the theory accepted.

Evolution of the Minerals of the White Mountain Magma Series

Feldspars. The general variation of feldspar composition is a well-known fact. In the White Mountain magma series, the feldspars follow the general rule, with calcic plagioclase appearing in the gabbro and becoming increasingly richer in alkalies as the rock becomes more siliceous. Alkali feldspars (orthoclase, micro-

perthite, and anorthoclase) first appear in the monzonites, but become abundant only in the syenites and granites. The liquidus-solidus diagram of the plagioclase feldspars is well known, whereby the plagioclase crystallizing from a magma is more calcic than the magma from which it crystallized. The importance of this fact is discussed further on a later page.

Biotite, Olivine, Pyroxenes, Amphiboles. On earlier pages it has been pointed out that the iron-magnesia ratio in the ferro-magnesian minerals is much higher in the siliceous rocks of the White Mountain magma series than in the basic. J. H. L. Vogt has made similar observations: "The low-melting components of the ferro-magnesian silicates which are rich in iron and the low-melting albite component of the plagioclase are all enriched in the rocks of the rest-magma direction" (39, p. 123). In an even earlier paper (38, pp. 151–152) he gave reasons for believing that the liquidus-solidus curve of the olivine series is similar to that of the plagioclase series. This deduction has been confirmed by recent experimental work by Bowen and Schairer (8, p. 153).

A diagrammatic curve for olivine, pyroxene, and biotite, similar to the liquidus-solidus curve for plagioclase feldspar is shown in Figure 2. It is intended to show that the magnesia-iron ratio is much higher in the solid phase than in the liquid phase with which it is in equilibrium. If complete reaction occurs, the final solid phase will have the same composition as the original liquid. If, however, reaction is incomplete, the final liquid will have a lower magnesia-iron ratio than the original liquid. Differentiation will proceed, therefore, in the direction of rocks with a low magnesia-iron ratio. The amphiboles will follow the same general rules.

Quartz. It has been pointed out that (1) the silica-deficient femags of the White Mountain magma series are found mainly in the most siliceous rocks, (2) quartz does not appear in any quantity in the White Mountain magma series until the quartz syenite stage, (3) in the older New Hampshire magma series, biotite and quartz appear very early in the evolution of the series, and (4) in the San Luis Rey quadrangle of California biotite and quartz appear simultaneously.

These facts indicate that the formation of free silica in the White Mountain magma series is, at least in part, related to the evolution of silica-poor dark minerals. It is, apparently, a process taking place in the late stages of differentiation. The writers believe that

in the late stages of the evolution of the White Mountain magma series potential metasilicates, such as members of the diopside-hedenbergite series and common hornblende broke down to give orthosilicates such as fayalite, hastingsite, and biotite, with the

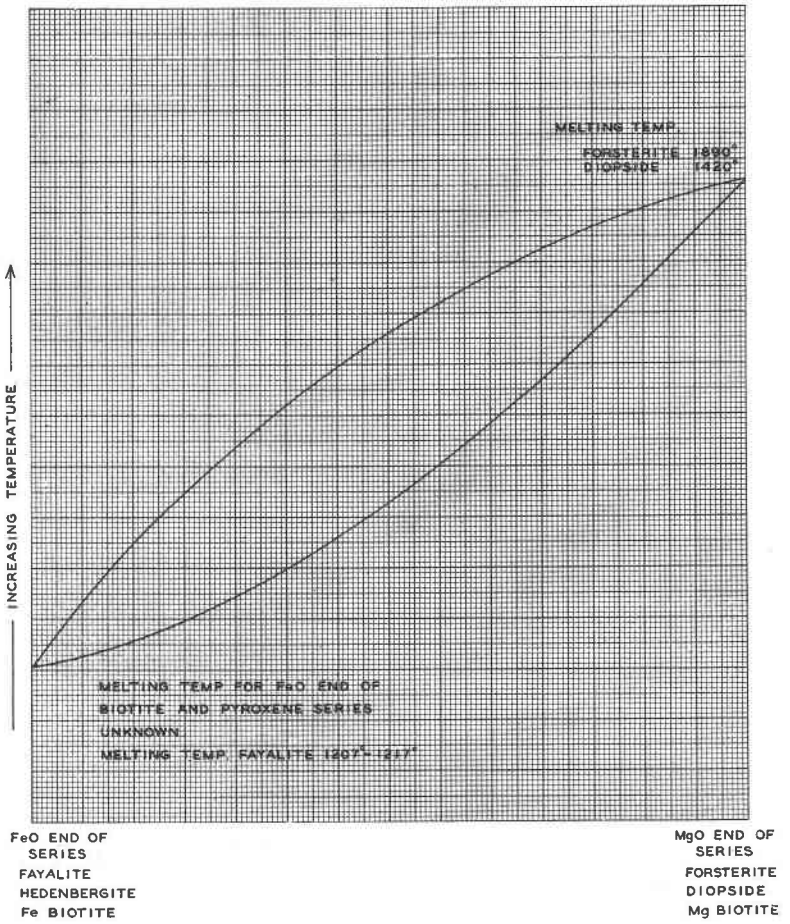

FIG. 2. Diagrammatic liquidus-solidus cure for forsterite-fayalite, diopside-heden-bergite, and biotite series. Modified after Vogt. Since this figure was prepared Bowen and Schairer have presented a similar diagram (8).

release of free silica to form quartz. The alkali feldspars were also involved in this process in certain reactions also with the release of free silica. By further fractional crystallization, a relatively small amount of quartz might be concentrated to form granites.

Theoretical Evolution of the White Mountain Magma Series by Fractional Crystallization

Process. Let us summarize, in the light of the above facts, the theoretical evolution, by fractional crystallization, of a gabbroic magma such as that which gave rise to the White Mountain magma series. To begin with, we may assume a great chamber of gabbro, some distance below the surface, which is in the process of cooling. As cooling proceeds, olivine, pyroxene, and calcic plagioclase begin to crystallize first. In this early stage of differentiation it is obvious that the ferromagnesian minerals separate out in far greater proportion than in the later stages, since the amount of dark minerals in each succeeding rock type has become less and less. Whether or not there is opportunity for reaction between the magma and these early-formed crystals is of the greatest importance. Since crystallization, with perfect reaction, of a gabbroic magma would result in the formation of a gabbro, it is evident that in the production of the observed series, reaction has not been complete.

The minerals which crystallize early, having a specific gravity which is generally greater than the liquid, tend to settle into the depths. The residual liquor left behind now has a different composition than at first. Intrusions of the magma into the country rock, which would originally have resulted in gabbro, now produce some such rock as diorite. Further crystallization and settling of minerals causes the magma to become progressively less mafic until it has finally attained the composition of a granite. Intrusion of the magma at appropriate intervals produces the various rock types of the series.

The chemical changes which take place in the magma during the course of differentiation are of fundamental importance. These include: (1) a decrease in the amount of lime and an increase in the amount of alkalies in the magma, (2) the enrichment of the magma in iron relative to magnesia, and (3) the absolute enrichment of the magma in silica, especially in the late stages of differentiation.

The decrease in the amount of lime is due, as we have seen, to the early separation of calcic plagioclase and pyroxene. Calcic plagioclase and sodic plagioclase form a continuous reaction series and the early crystallization of the former causes the magma to become enriched in the latter. The amount of potash is also increased in the magma as differentiation proceeds. The more calcic

plagioclase is found, accordingly, in the less siliceous rocks, whereas the soda and potash feldspars are concentrated in the late differentiates.

Accompanying this process is the steady increase in the amount of iron relative to magnesia from the more mafic rocks to the granites. We have already considered the means by which the change takes place. It is the result of the early separation of minerals of the biotite, olivine, and pyroxene series which are high in magnesia relative to iron (magnesia-rich biotite, hyalosiderite, and diopside). This causes a relative increase in the iron-magnesia ratio of the magma itself. As crystallization proceeds, the minerals formed become relatively poorer in magnesia and relatively richer in iron, until in the late stages (syenites and granites) they are high in iron compared to magnesia (iron-rich biotite, fayalite, and hedenbergite). There is evidence that there is a similar iron-magnesia-ratio change in the hornblende system.

The rather sudden increase in the silica content of a magma by differentiation has already been pointed out. As a rule, quartz first appears in the White Mountain magma series in the syenite stage. It is also in this stage that hedenbergite and silica-deficient hastingsite first appear, and the possible origin of quartz by reactions involving these minerals has been considered. In the granites, quartz is present in great abundance. The fact that it is accompanied by biotite and hastingsite (minerals low in silica) suggests that it is, in part, closely related in origin to these two minerals.

By thus emphasizing the simultaneous appearance of silica-deficient femags with quartz in the later stages of the evolution, the writers do not wish to imply that silica-deficient femags are confined to the siliceous end of the series. Olivine is found in the gabbro, and biotite appears all through the series.

Derivation of Rock Types. It is possible to derive the series from gabbro through monzonite, syenite, and granite by the subtraction of crystals as shown below in Table 9. There are several primary assumptions on which the development of this series is based. In the first place, in order to simplify the method, biotite was omitted all the way through the calculations, largely because it is in general a late mineral to crystallize. Secondly, as shown in the liquidus-solidus diagram for the plagioclases, the feldspar which crystallized in a given magma will be richer in anorthite than

the magma. For this reason, a feldspar more calcic than the normal plagioclase of the magma was subtracted in each case. A similar relation holds for the iron-magnesia ratio of the ferromagnesian minerals. This is brought out in the curve shown in Figure 2. Thus, in each case, a ferromagnesian mineral was subtracted which had relatively more magnesia to iron than the normal mineral for the rock type. Otherwise, the minerals subtracted had the compositions of the analyzed minerals of the various rocks, as shown above. Ferric iron has been converted to ferrous iron so that the iron could be handled as a total in the ferrous state. Minor constituents have been omitted from the calculations.

TABLE 9

DERIVATION OF ROCK TYPES FROM A GABBRO MAGMA BY FRACTIONAL CRYSTALLIZATION

(For details see text)

	GABBRO	MONZONITE	SYENITE	GRANITE
SiO_2	48.04%	58.00%	63.60%	71.40%
TiO_2	2.56	1.38	.61	.55
Al_2O_3	20.10	16.10	16.20	14.32
FeO	8.21	6.45	4.05	2.10
MgO	4.68	2.03	.80	.21
CaO	11.52	7.82	3.13	2.10
Na_2O	3.01	4.60	6.04	3.31
K_2O	.79	3.69	5.66	5.78
Total	98.91%	100.07%	100.09%	99.77%

MINERALS SUBTRACTED TO CHANGE:

	GABBRO TO MONZONITE	MONZONITE TO SYENITE	SYENITE TO GRANITE
Orthoclase	— %	— %	20.02%
Albite	17.00	5.24	19.91
Anorthite	36.00	11.95	5.00
Pyroxene	10.00	16.00	—
Olivine	10.00	—	—
Ilmenite	4.50	2.00	—
Hastingsite	—	—	13.00
Total	77.50%	35.19%	57.93%

The development of this series was accomplished by starting with the analyzed gabbro and subtracting minerals present in the gabbro, with the qualifications given above. The resulting rock was a typical monzonite. By repeating the process, a syenite and a granite were derived. All of the calculations were made on the

basis of molecular proportions. The following table shows the analyses of the rocks and the minerals subtracted to form the rock next in the series. Under the gabbro, the minerals subtracted to form the monzonite are given; the derived monzonite analysis is shown and below that, the minerals subtracted to form the syenite et cetera.

On the way through this series the diorite and monzodiorite would be developed, and by a similar process the biotite granites would be formed from the hastingsite granite.

The analcite and nephelite syenites are definitely off the main line of descent shown in the above table. Special conditions are necessary to explain their presence. Both of these rocks form small bodies and there is no available field evidence which offers a clue as to their origin. Daly (12, p. 510) has suggested the possibility of the assimilation of lime-bearing rocks in the region, but does not exclude the possibility of the role of gaseous transfer. A third method by which these rocks might be formed, which would be consistent with fractional crystallization, is based upon Bowen's theory of the incongruent melting of orthoclase to form felds- pathoids.

Quantitative Difficulties. An objection to the derivation of the various rock types of the White Mountain magma series by fractional crystallization is based on the belief that tremendous quantities of gabbro would be necessary to produce the syenites and granites, and, thus, there should be large quantities of basic rocks beneath the White Mountain area. According to isostasy, such a region should be a lowland and not a mountainous area. It is possible to compute roughly the necessary quantity of gabbro to produce the known rocks of the White Mountain magma series. This may be done in several ways, one of which is by direct application of the figures in Table 9. There can be little doubt that the plutonic bodies observed at the surface extend down at least a mile, and probably much farther. We may thus readily calculate the volume of the various plutonic bodies in the uppermost mile of the earth's crust, for the areal extent in square miles in that case is equivalent to the volume in cubic miles.

Since the known areal extent of the granite and granite porphyry is 358.8 square miles, there would be 358.8 cubic miles of granite and granite porphyry. Referring to Table 9, if 77.5% of the gabbro is removed, the remaining 22.5% is monzonite; if 35.19% of that is removed, 14.9% of syenite remains; 57.93% of

the constituents of the syenite removed leaves 6.3% of granite. Thus, to produce 358.8 cubic miles of granite, 5700 cubic miles of gabbro would be necessary. Similarly, 90.5 cubic miles of syenite and quartz syenite would require 607 cubic miles of gabbro, and 2.6 cubic miles of monzonite would require 11.5 cubic miles of gabbro. Thus, to produce all of the rock types by fractional crystallization of a gabbro, 6318 cubic miles of gabbro would be required. If this gabbro were spread out under the whole area shown in Figure 1—about 9000 square miles—it would have a thickness of 0.7 miles.

These figures, however, give a minimum. They assume an efficiency which undoubtedly does not exist. In the second place, these figures are based on the assumption that the plutonic rocks of the magma series are only one mile in thickness. The differentiates are probably actually more than a mile thick. It is doubtful, nevertheless, if they ever extended very high above their present highest point. Some of the coarse plutonic phases hold up mountains which are only about 1000 feet lower than the highest point in the region (Mount Washington, 6290 feet). Billings (3, p. 128) has shown that the surface on which the volcanic members of the magma series were deposited was at least a little higher than Mount Washington and possibly much higher. Assuming that the ancient surface was a mile or more above Mount Washington, the plutonic rocks could not have extended very far above their present highest position since coarsely crystalline rocks cool at some depth. There is no means, however, of knowing the depth to which the plutonic differentiates extend. It seems logical to assume, however, that these rocks probably extend at least 3 or 4 miles below the present surface. If the mechanics of ring-dike intrusion as outlined by Anderson (10) are correct, the vertical dimension of a ring-dike would be approximately the same as the diameter of the ring itself. In view of this fact, the plutonics of the ring-dikes and associated stocks might extend down at least 8 or 10 miles.

If the above facts are true, a tremendous quantity of parent gabbroic magma would be required. The total area of the map (Figure 1) showing the White Mountain magma series is 9000 square miles. If the magma were confined entirely beneath the area covered by this map, it would extend all the way to the basaltic substratum. It is difficult to understand how so much gabbroic rock could now underlie this part of New England and yet allow the

country to stand so high isostatically. Furthermore, there is some question as to whether the relatively thin crust would have been stable over such a large molten mass.

Assimilation and Pure-melting. Consideration of the effects of assimilation in producing rock types involves several factors. The depth at which the process takes place, the character of the material to be assimilated, the chemical composition of the magma, and the temperature of the magma all play important parts in the process. Conditions become more favorable for assimilation with increasing depth, higher initial temperature and lower melting temperature of the assimilated material, and increasing temperature of the magma. Thus, with sufficient depth and temperature, there can be no doubt as to the effectiveness of assimilation. Assimilation alone will not explain the character of the rocks observed in the White Mountain magma series. By the assimilation of siliceous sediments and granites it would be possible to account for a series from gabbro through possibly monzodiorite, but to produce the syenites and granites, it would be necessary to assimilate prohibitive amounts of material. Moreover, mixing an older granite with gabbro could never produce a granite.

Many of the objections to assimilation, such as the heat problem, also apply to pure-melting as the sole means of deriving the White Mountain magma series. Pure-melting may be complete or partial. Complete melting of older rocks can not explain the series. There are no known older rocks in the region with the same composition as the White Mountain magma series. Moreover, in complete melting granite would be generated first, gabbro last and the sequence would be precisely the reverse of that observed. Selective fusion of older rocks as the sole process is also eliminated for the last reason given above.

Theory of Rock Evolution Accepted

From a consideration of all the foregoing facts, it appears that although fractional crystallization alone is qualitatively capable of producing all the rock types of the White Mountain magma series, quantitatively it is not adequate. Too great an amount of the parent magma is required to produce all the siliceous differentiates. It has also been shown that assimilation alone cannot possibly explain the origin of certain of the more siliceous rocks of the series, and that pure-melting as the sole process is open to the same ob-

jections as assimilation and to several others. In view of these facts, the writers have concluded that fractional crystallization and assimilation have gone on together with selective fusion, and that each has helped to produce the rock sequence of the magma series.

Qualifications as to the depth at which differentiation by fractional crystallization took place are necessary. According to Stokes' Law, and assuming that the viscosities given by Daly (12, p. 193) for moderate depths in the earth are of the right order of magnitude, the rate of settling of an olivine crystal 0.5 mm. in diameter, at depths of from 30 to 40 miles in the crust, is practically negligible in the time available. Thus, fractional crystallization becomes important only at some distance above the substratum. It is impossible to calculate this distance because there are no available data on viscosities at various depths in the crust.

On the basis of the facts and assumptions discussed above, the evolution of the White Mountain magma series is believed to have resulted from the invasion of the crust by basaltic magma, largely by stoping; melting and assimilation of the stoped blocks; and fractional crystallization of the original magma and the liquids formed by melting and assimilation. The evolution was complex in that these processes were operating essentially simultaneously at different levels in the crust. At the deeper levels, pure-melting and assimilation were important, because there sufficient heat was available for those processes. Higher in the crust, fractional crystallization was going on—at first in the basaltic magma alone, and later in the liquids formed by selective fusion and assimilation, which moved upward continuously as they formed. The gabbros and diorites were probably derived directly from the original basaltic magma, but the other rock types resulted from fractional crystallization of the original magma contaminated by assimilated and melted older rocks. The sequence, however, was definitely controlled by fractional crystallization.

The syntectic magma underwent fractional crystallization and differentiation in the following way. Due to early separation of calcic feldspars and a failure of reaction, the alkali feldspars concentrated in the late differentiates. Similarly, due to the separation of magnesia-rich ferromagnesian minerals, iron increased relative to magnesia in the later differentiates. Quartz had a dual origin. In part it appeared due to the separation of silica-deficient femags. Much of the quartz, however, is merely older quartz which was

present in the pre-existing granites and schists, was incorporated in the syntectic magma and then concentrated in the later differentiates.

Nature of the Magma Chamber

The exact size, shape and location of the chamber or chambers in which differentiation occurred is problematical. One hypothesis pictures a single, large chamber, roughly circular in ground-plan and underlying practically all of central and northern New Hampshire and part of eastern Vermont and western Maine. Locally, however, there were cupolas extending up from the main chamber to within a few miles of the surface. These cupolas, which existed directly beneath the areas now containing rocks of the magma series, were the chief agents localizing the cauldron subsidence and igneous intrusion. An alternative theory is possible. It may be assumed that instead of one large magma chamber at depth with cupolas extending up from it, there was a separate, narrow, cylindrical chamber underlying each local area of intrusion.

Future Work

The problem of the evolution of the White Mountain magma series is, of course, intimately tied up with similar problems in other areas. Information gathered elsewhere will shed light on our problem in the White Mountains. The work of the Geophysical Laboratory at Washington is also of prime importance, and gives us much of our most significant data. More specifically in the White Mountain district the following additional data should be gathered:

(1) Analyses of more minerals, particularly those ends of the pyroxene, amphibole, and olivine series which are as yet not analyzed. The writers are of the opinion that additional mineral analyses are of much more importance than rock analyses.

(2) Additional field data on the age relations of the plutonic rocks. The chronological position of some of the intrusive rocks is still unknown.

(3) Additional data on the size, shape, and mechanics of intrusion of the rock bodies. Large areas of the White Mountain magma series are exposed in the Crawford Notch, Plymouth, and Mount Washington quadrangles, but they have not been studied since the Hitchcock Survey sixty years ago. The Division of Geological Sciences of Harvard University will probably undertake this study during the next few years.

(4) The importance of deuteric and hydrothermal processes should be considered much more fully.

(5) The genetic relations of the volcanic and dike rocks to the plutonics must be considered.

(6) Seimological and other data may give more information as to the depths to which the granite and syenite masses extend.

Physical data of importance include:

(1) Viscosity of magmas under high pressure, in order to determine the rate of crystal settling under the influence of gravity.

(2) Investigation in the laboratory of the presumed liquidus-solidus relation existing between iron and magnesia in the ferromagnesian minerals as proposed in this paper.

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