PETROLOGY AND GEOCHEMISTRY OF GRANITIC ROCKS:

CAPE ANN, MASSACHUSETTS

by

Paul Pelke

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 1971 (c.c. June 1973)

Signature of Author _____
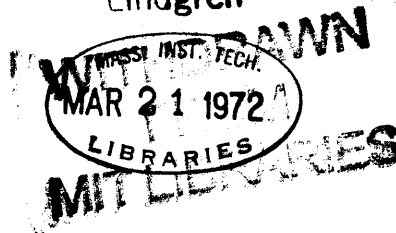Department of Earth and Planetary Sciences
August 16, 1971

Certified by _____
Thesis Supervisor

Accepted by _____
Chairman, Departmental Committee
on Graduate Students

PETROLOGY AND GEOCHEMISTRY OF GRANITIC ROCKS;

CAPE ANN, MASSACHUSETTS

by

Paul Pelke

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

ABSTRACT

The abundances of REE, Ba, Sr, Sc, Th, and Ta have been determined for the Cape Ann Granite, the Nordmarkite Granite inclusions within the Cape Ann, the Beverly Syenite and two Misery Island Syenites. Stained Slab modal analyses have been obtained for the Cape Ann and Nordmarkite Granites.

The Modal data indicates that the Cape Ann Granite is rather homogeneous, while the Nordmarkite Granite was more heterogeneous. The Nordmarkite Granite also shows heterogeneity in the trace element abundances.

The Eu, Ba, and Sr abundances of the Nordmarkite Granite are compatible with an origin from a basic magma. Whether the granite is a megagranophyre or is a product of feldspar fractional crystallization is open to question. The modal homogeneity of the Cape Ann Granite, its sheet like geometry, with denser rocks beneath, and its composition are interpreted as implying a possible origin as an imiscible liquid. The Beverly Syenite was tested as a possible cumulate phase of the Cape Ann and Nordmarkite Granites. On the basis of calculations, the Beverly Syenite could not be a cumulate of either granite. A cumulus-residuum relationship between the Beverly and the Cape Ann was found to be possible but not probable, due to distribution coefficient limitations.

Thesis Supervisor: F.A. Frey

Title: Assistant Professor

TABLE OF CONTENTS

ACKNOWLEDGMENTS

INTRODUCTION

The purpose of this study is to investigate the hetero-
geneity of the granitic rocks on Cape Ann, Massachusetts in
terms of their modal and trace element (Rare Earth Elements
[REE], Ba, Sr, Th, Ta, and Sc) abundances. This investiga-
tion is limited to the town of Rockport and the eastern half
of the town of Gloucester, which is located some 50 miles
northeast of Boston (Figure 1).

Buma, et al, (1971), considered the REE abundances of
the Cape Ann Granite, in particular the Eu and heavy REE,
as indicative of a granitic magma that originated from a
basic magma as a result of extensive feldspar crystalliza-
tion. This work further tests that hypothesis, and examines
the relationship of the earlier granitic inclusions to the
Cape Ann Granite.

Samples of bedrock were collected on a 1/2 mile grid,
slabbed, stained for modal analysis, and thin sectioned.
Instrumental Neutron Activation Analysis (INAA) was used to
determine abundances of REE, Ba, Th, Ta, and Sc of selected
samples. The Sr abundances of the selected whole rock powders
was determined using x-ray fluorescence. The perthite of
each selected sample was homogenized, sanidinized, and the
composition determined by x-ray diffraction.

In order to further elucidate the relationship between
the Cape Ann Granite and other rocks in the area, the REE,

Figure 1 -- Sketch map of Northeastern Massachusetts
            showing the location of the Cape Ann
            Granite, Beverly Syenite, and Misery
            Islands Syenite.

N.H.

MASS.

CAPE ANN GRANITE

MISERY ISLANDS

BEVERLY SYENITE

0   5   10   15 KILOMETERS

BOSTON
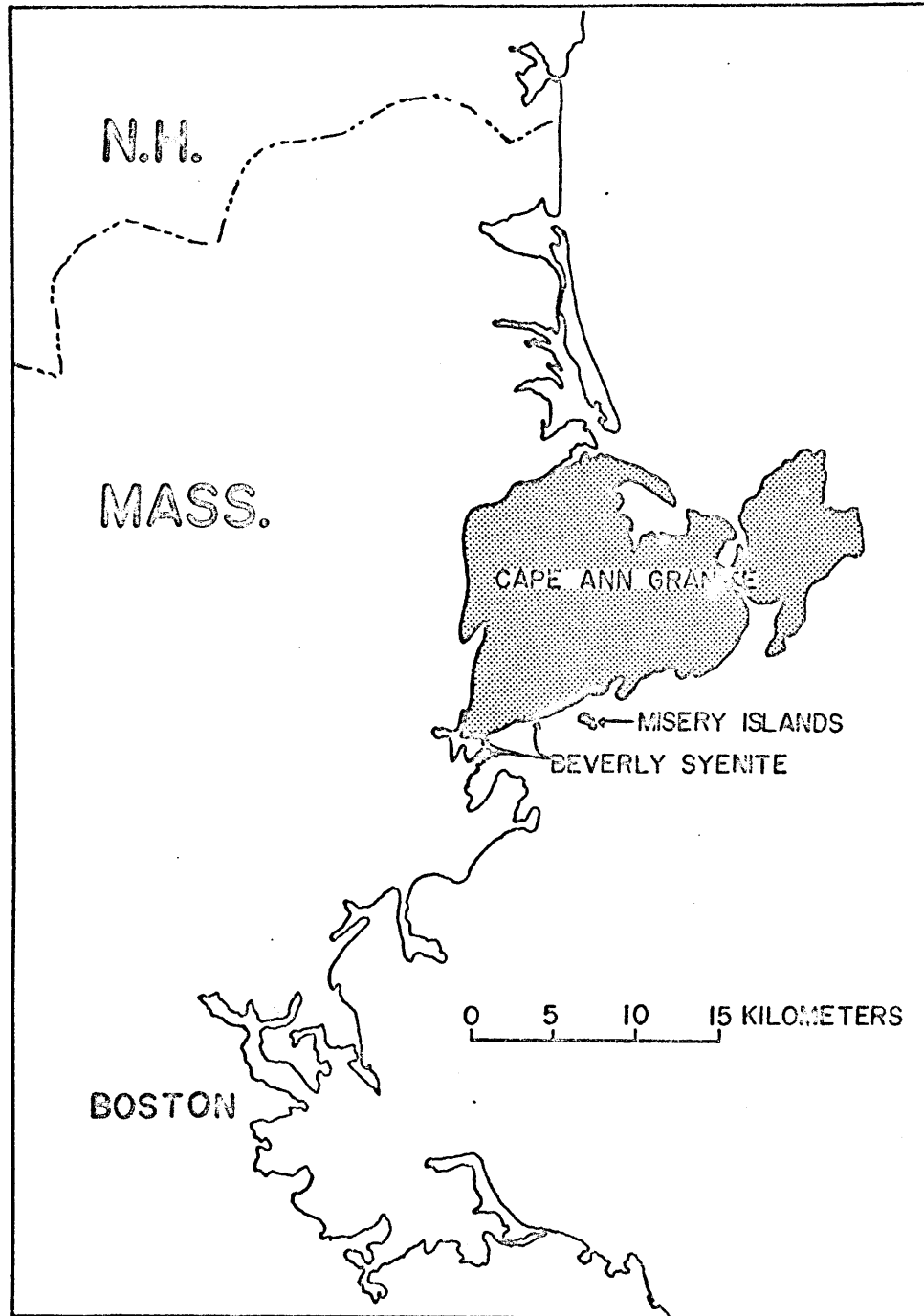
Ba, Sr, Th, Ta, and Sc abundances of the Beverly Syenite, a fragment of Anorthosite from a basalt dike near Lane's Cove, and of two syenitic dikes from the Misery Islands were determined. Thin sections but not stained slabs were prepared of these samples.

PREVIOUS WORK

The first rigorous study of the granitic rocks at Cape Ann was part of an investigation of the petrographic province of Essex County (Washington, 1899). Most of the previous work has been concerned with Eastern Massachusetts, in particular Essex County (Sears, 1905, Clapp 1910, 1921, Emerson, 1917, LaForge 1932). Warren and McKnistry (1924) investigated the granitic rocks at Cape Ann and interpreted the geology. The most recent work in the area has been done by Toulmin (1964), who studied Salem Quadrangle.

The geographic name, Cape Ann Granite, was first used by Clapp (1910), and followed by Toulmin (1964) and Buma et al (1971). Other workers had termed the Cape Ann, Peabody, and Quincy Granites, all Quincy, following Crosby (1876). Warren and McKnistry (1924) also used the term Cape Ann Granite and called the granitic inclusions Nordmarkite. This nomenclature will be used in this work.

The only previous geochemical work was that done by Buma et al (1971). The Cape Ann Granite was one of five

New England Granites studied by them, the other four being the Peabody, Quincy, Narragansett Pier, and the Westerly. The Cape Ann, as well as the Peabody and the Quincy, was interpreted as resulting from an H_2O poor basic magma as a result of extensive feldspar crystallization. A radiometric age of the Cape Ann Granite has been determined by Zartman and Marvin (1971). The Pb^{207}/Pb^{206} zircon age, termed the most reliable by the authors, is 452 ± 10 my.

GEOLOGY

The geology of Cape Ann is summarized by figures 2 & 3. The oldest rocks are a suite of granitic inclusions within the Cape Ann Granite termed Nordmarkite Granite by Warren and McKinstry (1924). The Nordmarkite inclusions are exposed along the western coast from Lane's Cove in the north, to Wigwam Point (Annisquam Lighthouse) in the south. From Davis Neck south, the inclusions are subordinate to the younger granite. The other major occurrence is between Gloucester and Rockport. Several isolated inclusions occur to the north of Lane's Cove, at Andrew's Point, where the Nordmarkite Granite is associated with a large fayalite bearing pegmatite dike, and along the coast between Andrew's Point and Pigeon Cove. Such contacts as those in figure 2 are gradational in the field from Nordmarkite Granite with abundant dikes of Cape Ann Granite, grading into massive

Figure 2 -- Geologic Map of Cape Ann, Massachusetts

SYMBOLS

/₇₀ Strike and Dip of Basalt Dikes

/₈₅ Strike and Dip of Pegmatite Dikes

/ Strike of Vertical Basalt Dikes

/ Strike of Vertical Pegmatite Dikes

⊗ Nordmarkite Granite Inclusion

Andrew's Point

Lane's Cove

Pigeon Cove

Pzn

Pzca

42°40'

Wigwam Point

ROCKPORT

Pzcaa

Pzca

Og

Pzn

Pzca

EXPLANATION

Og   Glacial Deposits

Pzcaa Cape Ann Granite with abundant aplites
Pzca   Cape Ann Granite

Pzn   Nordmarkite Granite

All contacts are gradational

Pzca

Pzn
Pzca

Brier Neck

42°37'30"

GLOUCESTER

70°40'

70°37'30"

Figure 3 -- Summary of Geology. Solid lines represent observed field evidence for relative ages (oldest on bottom). Dashed line with question mark indicates uncertain relative age. The solid line between the Cape Ann Granite and Beverly Syenite is drawn on the basis of the map pattern and an indication of an increase in SiO_2 content of the rocks with time (see text).

BASALT DIKES

APLITES - PEGMATITES

POST CAPE ANN-
GRANITE DIKES

CAPE ANN GRANITE

#450

BASALT DIKES

ANORTHOSITE

?   ?

NORDMARKITE GRANITE

BEVERLY SYENITE

?

MISERY ISLAND SYENITE M-2

MISERY ISLAND SYENITE M-1
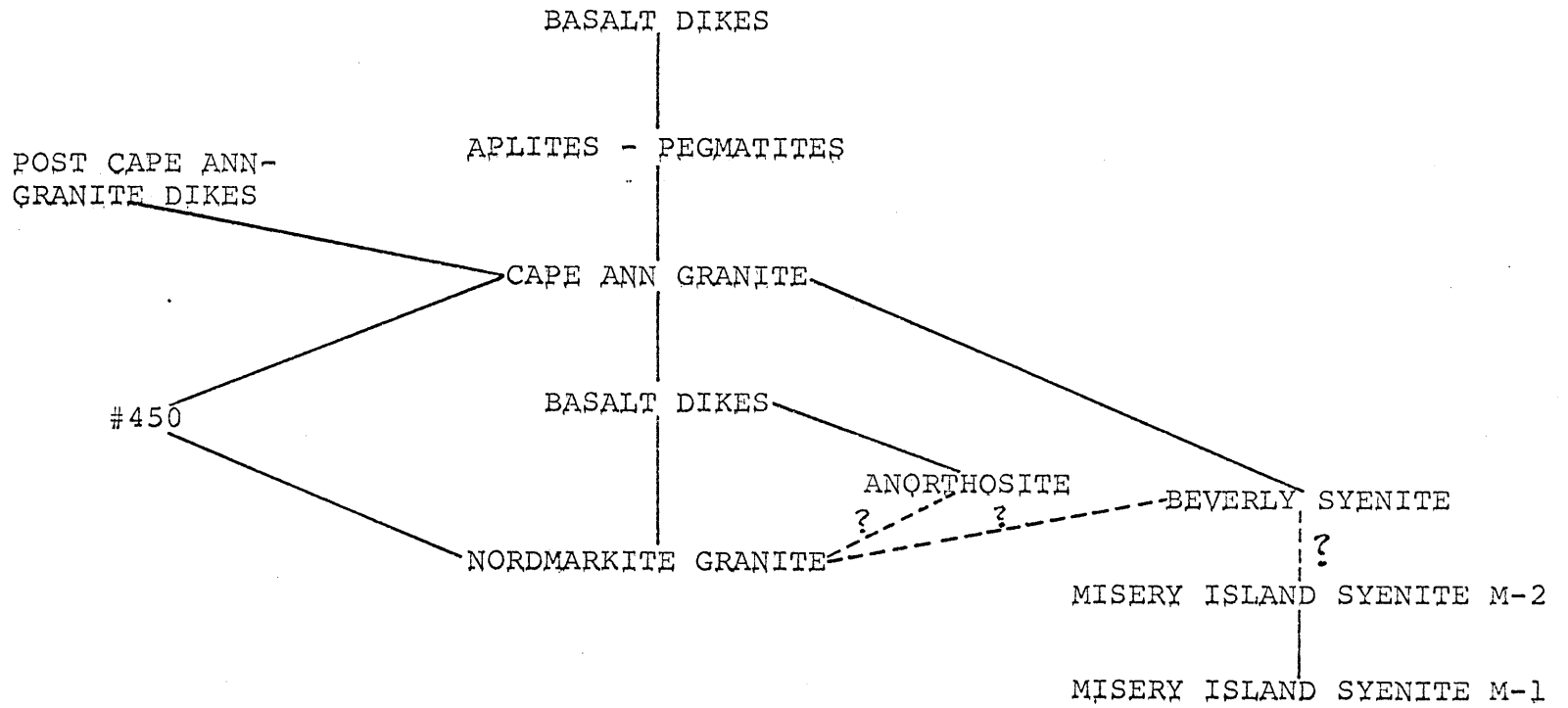
Cape Ann Granite containing inclusions of Nordmarkite.

The Nordmarkite Granite is cut by basaltic dikes which are truncated by the Cape Ann Granite. They are of two types: one type has abundant xenocrysts of plagioclase up to 7cm. long, and in one dike a fragment of anorthosite (An 53) 1.5 x 3m. is exposed; the other type is a "normal" basalt dike. Both types, as well as basalt dikes intruding the younger Cape Ann Granite, are vertical or near vertical, are generally oriented north-south or east-west, and are fragmented and surrounded by the country rock. The "pulled apart" nature seems to come about from the dikes being intruded at a time when the cooling granites would fracture under the short term stresses of dike intrusion, but would respond plasticly by flowing as a result of the long term stresses within the granite pluton (Toulmin, 1964). In short, the model is intrusion, solidification, and then fragmentation. The granite, near some of the basalt dikes, has developed a foliation and lineation in response to these long term stresses, but these areas are never large compared to the size of the dikes.

Between the time of the emplacement of the Nordmarkite and the subsequent intrusion of the Cape Ann Granite, there is evidence of minor granitic igneous activity. At Lane's Cove, near a pod of fayalite bearing pegmatite, there is a rock (#450) which intrudes the Nordmarkite and is itself cut

by the Cape Ann Granite. The total outcrop area of this
rock is no more than 15 sq. m., and is the only exposure
seen within the area investigated. The age relationship
to the post Nordmarkite basalt dikes is unknown.

The Cape Ann Granite is by far the major rock type
at Cape Ann. It is greenish gray on fresh surfaces and
whitish on weathered surfaces. There is some aplitic and
pegmatitic material associated with the Cape Ann Granite.
Pegmatites occur at Andrew's Point and at Lane's Cove.
Small aplite veins tend to occur fairly frequently near the
Nordmarkite Granite, and sparsely elsewhere. On the eastern
shore of the Cape, from Rockport to Brier Neck, there is
relatively abundant aplitic material mixed in with the Cape
Ann Granite - this is an area free from Nordmarkite inclu-
sions. The aplitic areas sometimes contain megacrysts of
perthite, quartz, and amphibole. The Cape Ann Granite is
also cut by basalt dikes exhibiting characteristics similar
to the pre-Cape Ann basalt dikes, except that the plagio-
clase xenocrysts are absent

At Wigwam Point, there occurs a post-Cape Ann Granite
dike. It contains the same minerals as the Cape Ann Granite,
except that it contains approximately 50% modal quartz. In
outcrop it has the same color and texture as the Cape Ann
Granite. The dikes occur also just south of Wigwam Point.
The total area is about 20 sq. m. This rock is not seen

elsewhere in the area investigated, and has an unknown age relationship to the post Cape Ann Granite basalt dikes.

The entire area mapped is covered by a veneer of glacial deposits. Usually there is abundant outcrop. An exception to this is the region between Gloucester and Rockport. Here in the area mapped as glacial deposits, outcrop accounts for less than ∿2% of the total area. The thickness is difficult to estimate, but it is certainly on the order of 15-30 m at the greatest, and much less on the average.

GEOLOGIC HISTORY

One of the most striking features of the Nordmarkite-Cape Ann Granite Sequence is the overall increase in the silica and quartz contents (Tables 1, 2, 4). It should be noted that #450 appears to be comparable to the Cape Ann Granite in terms of quartz content and that the post Cape Ann Granite dike is distinctly more quartz rich - 50%. The implication is of a process or series of processes involving an increase in quartz content over time. Hence the suggestion is that the Beverly Syenite may be pre-Cape Ann, perhaps even pre-Nordmarkite. The Cape Ann Granite - Beverly Syenite contact is sharp, not affording a relative age determination (Toulmin, 1964). Toulmin (1964) also notes an increasing quartz content in the Beverly Syenite as the contact with the Cape Ann Granite is approached.

The geometry of the Cape Ann pluton is rather recti-
linear as suggested by figure 1. Gravity measurements
(Joyner, 1963), indicates that the pluton is shallow, some-
what like a sheet, with denser rocks beneath. The presence
of the dikes (pulled apart), implies that there was a con-
temporaneous presence of two magmas. The denser rocks at
depth may be correlative with the dikes. If this is the
case, then the Nordmarkite and Cape Ann Granite may be a
mega-granophyre, or may be an imiscible liquid, with the
denser rocks being the cognate liquid.

The late Ordivician age of the Cape Ann Granite
(Zartman and Marvin, 1971), coupled with its undeformed
texture, carries interesting implications for Northern
Appalachian geology. The age is clearly earlier than the
Acadian orogeny. About 80 km to the west, the Acadian meta-
morphic isograds are up to sillimanite grade (Thompson and
Norton, 1968). Yet, this event did not seem to affect the
Cape Ann Granite. The reason why may lie in the interpreta-
tion of a broad system of faults (Skehan, 1968), between
the Cape Ann Granite and the Acadian metamorphic terrain.
Although such interpretation is beyond the scope of this
work, they may be related to events such as those described
by Bird and Dewey (1970). If that is the case, the Cape Ann
Granite may have been part of an entirely different tectonic
environment, than rocks affected by the Acadian Orogeny.

It is clear, that more field and geochemical studies are in order, to resolve this question.

SAMPLING

Sampling was carried out with two objectives in mind: first, random sampling on a 1/2 mile grid attempting to discern petrologic variations, and second, specific sampling for REE, Ba, Sr, Th, Ta, and Sc abundance determinations. The petrologic sample grid, as set up, contained 51 potential stations where bedrock samples could be made. Of these, at 28 no bedrock was present, at 19 samples of Cape Ann Granite was obtained, while at only 4 was there the Nordmarkite Granite (Figure 4). Enough rock was taken in each case to cut and stain a slab at least ten times the average longest dimension of a perthite crystal square. The average length of a perthite crystal is about .80 cm. and the area required is slightly less than 10 sq. in. The grid size used for modal analysis was 10 divisions to the inch.

For trace element analysis, the samples were chosen to help elucidate the relationship between the Nordmarkite and the Cape Ann Granite. Two samples (#59 & 63) of the Cape Ann Granite were chosen from different locations than those of Buma et al. (1971), as a further check on the homogeneity of the granite. Two samples (#48 & #470) of the Nordmarkite were taken from near Lanesville, one (#54) from

Figure 4 -- Sample Locality Map - Circled samples were
        analyzed for REE, Ba, Sr, Th, Ta, and Sc
        and Or contents of Perthites.

SAMPLE LOCALITY MAP

0   No Bedrock Sample Obtained

16 Bedrock Sample for Modal Analysis

(54) Geochemical Sample
(Also Modal Analysis Sample if on Grid)

the large body between Gloucester and Rockport, and one (AP) from the inclusion associated with the aplite and fayalite bearing pegmatite at Andrew's Point. A locally representative sample of the Beverly Syenite was taken from the foot of Woodbury Street in Beverly (Field Trip E, Stop #5, NEIGC 1965 Guidebook), to check Toulmin's (1964) hypothesis that the Beverly is a feldspar cumulate of the Cape Ann Granite. A sample (#450) of a granitic rock intermediate in age between the Nordmarkite and the Cape Ann Granite from Lane's Cove was also chosen. An anorthosite inclusion from a basalt dike in the Nordmarkite near Lane's Cove was analyzed. And finally, two "syenitic" dikes from the Misey Islands were analyzed to see if they might have any relation to the processes involved in the formation of the Nordmarkite and Cape Ann Granites. In each case, approximately 5 kg. of rock was collected and crushed. After a whole rock powder was separated, heavy liquids were used to obtain perthite separates for homogenization and sanidinization.

PETROGRAPHY

The Nordmarkite is a medium to coarse grained rock, with the major minerals being perthite, quartz, plagioclase, ferrohastingsite, aegeritic pyroxene, and biotite. The modes obtained from stained slabs are given in table 1. The biotite is abundant only in sample #48, where it is

TABLE 1

NORDMARKITE GRANITE MODAL DATA

No.	Quartz	Perthite	Plagioclase	Mafic [1]	An in Plag
470	5.0	62.8	18.6	13.6	An20 - An11
47	9.0	80.1	4.4	6.5	An16 - An 8
54	10.2	64.0	11.6	14.2	An16 - An 8
55	11.0	71.4	8.7	8.9	An11 - An 4
AP	11.3	63.2	15.0	10.5	An10 - An 4
48	12.0	74.7	5.1	8.1	An11 - An 4

1. Includes ferrohastingsite, aegeritic pyroxene, biotite
    and accessories.

essentially the only hydrous phase present. In the other samples ferrohastingsite is the principle hydrous phase with some biotite. Other minerals present include fayalite, hedenbergite, albite-oligioclase, magnetite, ilmenite, zircon, apatite, fluorite, allanite, iddingsite, and perhaps grunnerite. The allanite is occasionally overgrown with aegeritic pyroxene. The aegeritic pyroxene may by rimmed by ferrohastingsite, which may in turn be rimmed by biotite. The fayalite is often enclosed by aegeritic pyroxene or amphibole. In many cases only its decomposition products remain, iddingsite, which, in places, has been further altered to magnetite and grunnerite (?). Zircons tend to be poikilitically enclosed by the ferrohastingsite. The perthite is euhedral, quartz euhedral to anhedral, most being subhedral, and the ferrohastingsite filling in the interstices between the perthite and quartz grains. Some of the perthite grains are cored by plagioclase. This is most evident in stained slabs. In thin section the central plagioclase is highly altered.

Sample #450, the rock intermediate in age between the Nordmarkite and the Cape Ann Granite, has a porphyritic texture. Its mode is as follows: 17.9% quartz phenocrysts, 7.9% perthite phenocrysts, 8.7% plagioclase, .9% mafics, and 64.6% groundmass. The major mafics are biotite and ferrohastingsite, both being about equally abundant. The

overall abundance of mafics is greater than suggested by the mode, because they are more abundant in the groundmass. Acessory minerals include iddingsite, magnetite, ilmenite, zircon, and fluorite.

The Cape Ann Granite is medium to coarse grained, tends to be equigranular, but is distinctly porphyritic in places. In hand specimen, a typical equigranular rock appears to have euhedral perthite grains suspended in quartz. Under the microscope, the quartz resolves into many small crystals rather than one larger one, and also tends to contain plagioclase (An 12-An3). Modes are given in table 2.

The two samples (#59 & 63) selected for trace element analysis are quite different from this description. They lack groundmass, and are more even grained, with interlocking quartz and perthite crystals. What plagioclase there is, is more Ab rich (An3-5), and occurs only along grain boundaries. Ferrohastingsite, which is the principle mafic, always occurs anhedrally, in the interstices between the perthite and quartz crystals, poikilitically enclosing the zircons. Acessories include fayalite, hedenbergite, magnetite, biotite, ilmenite, zircon, allanite, riebeckite, sphene, apatite, and fluorite.

The texture of samples #59 & 63 is interpreted as being a late stage texture. It should be added that these two samples were chosen randomly, in order to get a geographical distribution with respect to previous trace element analysis (Buma, et al, 1971).

TABLE 2

CAPE ANN GRANITE MODAL DATA

No.	Quartz	Perthite	Plagioclase	Mafic [1]	An Range
61	20.4	67.6	3.6	8.4	An 10-3
56	22.7	67.5	3.4	6.4	An 11-5
57	23.9	67.2	2.9	6.2	An 10-4
51	25.0	66.3	2.9	5.9	An 5-2
26	25.5	62.0	6.4	6.1	An 12-4
44	26.6	62.6	4.5	6.3	An 6-4
12	27.4	63.8	4.3	4.7	An 8-4
53	27.4	64.5	4.2	3.9	An 6-3
59	27.5	68.5	1.2	2.8	An 4-3
34	27.6	65.0	1.7	5.7	An 5-3
16	28.2	62.8	5.0	4.0	An 10-2
13	28.4	60.3	6.9	4.4	An 5-3
18	29.3	64.1	0.9	5.7	An 11-3
4	30.6	61.2	5.0	4.3	An 8-3
52	30.6	63.6	2.0	3.8	An 5-2
63	30.7	63.0	1.8	4.8	An 4-3
33	31.6	53.3	11.8	3.3	An 12-3
1	31.8	61.7	3.7	3.0	An 5-3
50	32.3	63.4	1.4	3.0	An 7-4

1. Principally ferrohastingsite, plus accessories.

PETROLOGICAL INTERPRETATION

The 19 samples of the Cape Ann Granite that were slabbed
and stained form a rather coherent group (Table 2). For the
quartz content, the high value was 32.2%, low 20.4%, mean
27.6%, median 27.6%, and the standard deviation is 3.14%.
From textures, it appears that the rocks with the three low-
est quartz contents may be "hybrid", that is, contain partially
assimilated Nordmarkite granite. With these values deleted,
the low quartz content becomes 25.0%, mean 28.8%, median
28.3%, and the standard deviation becomes 2.2%.

For total feldspar, similar results are obtained - for
all the samples the mean feldspar content is 67.5%, high
71.2%, low 64.8%, and standard deviation of 2.4%. Deleting
the values corresponding with the three lowest quartz contents
the values become: mean 66.9%, standard deviation 1.9%, high
69.2%, low 64.8%. As might have been anticipated, the lowest
quartz contents correspond with the highest feldspar contents.
The amount of mafic minerals tends, in a general way, to de-
crease with an increasing in quartz content.

The mineral cyrstallization of the Cape Ann Granite
would begin with perthite and allanite, proceeding to quartz
and zircon, and ending with ferrohastingsite. The allanite
ceased crystallizing early and zircon crystallization ended
before the formation of amphibole. This is concomitant with
the fact that in general aplites are scarce - it took a long

time to build up enough H_2O pressure to enter the stability field of a hydrous mineral.

The homogeneity of the Cape Ann Granite implies that no internal differentiation within the magma took place. This probably was a function of the viscosity of the magma. In terms of a possible origin of the magma, a single large scale process rather than a series of small ones is implied.

In sample #450 the crystallization sequence is suggested by the relative amounts of quartz and perthite phenocrysts to be quartz followed by perthite, followed by chilling. The groundmass contains euhedral zircons, smaller than those in the Cape Ann Granite, not enclosed by ferrohastingsite, and also euhedral biotite, indicating enough H_2O pressure to stabilize that mineral before entering a residual state.

The Nordmarkite Granite is more complex. It is much more heterogeneous, and contains plagioclase rimmed by perthite. Thus either the plagioclase is xenocrystic, or the liquid passed from a two feldspar plagioclase-alkali feldspar field into a one feldspar perthite field. Stained slabs suggest that perthite may have been crystallizing simultaneously with the plagioclase because some of the perthite crystals are certainly as large as the overgrown plagioclase crystals. A clear cut decision cannot be made. The liquid later passed into a two alkali feldspar field due to the intersection of the solvus and solidus as a result of rising H_2O pressure. Hence, the ferrohastingsite

is less strictly relegated to the interstices as compared to the Cape Ann Granite. Sample #48 appears to be the most volatile rich on the basis of abundance of biotite.

ANALYTICAL METHODS

The determination of the REE, Ba, Sc, Ta, Th abundances was carried out using an instrumental neutron activation technique similar to the one described by Gordon, et al (1968). The equipment used included a Ge(Li) detector of 13cc. volume, and a Ge(Li) low energy photon system (LEPS). Peak integration followed the method outlined by Denechaud (1969). This method using only one full width at half maximum, tends to minimize the two sources of error present: the statistical counting error, and the error in the placement of the baseline. Interferences with the Tb 962-966 kev peaks and the Gd 97.43 kev peak required special handling for abundance determinations. For Tb, whole peak integration with subtraction of the interfering Eu peak was used, while for Gd, only the half width at half maximum from the low energy side of the peak was used to avoid interference by the Pa peak. Errors, determined by duplicate analyses of #59, #48, and the Beverly Syenite are given in table 3.

X-ray fluorescence was used in the determination of the Sr abundances. The values are good to at least ±10%,

TABLE 3

| | Cape Ann Granite | | | |
	"Cape Ann" [1]	#59 [2]	63	#450
La	71 ± 7	77.9	113	38.6
Ce	169 ± 12	174 ± 5	228	96.0
Nd	---	85.7 ± 1.7	97.8	42.6
Sm	15 ± 1	16.4 ± 0.8	17.4	9.44
Eu	1.52 ± 0.26	.334 ± 0.03	438	0.234
Gd	---	15.9 ± 0.3	15.6	7.96
Tb	2.0 ± 0.2	1.92 ± 0.41	2.0	1.65
Yb	5.2 ± 0.7	2.37 ± 0.09	5.20	3.46
Lu	0.86 ± 0.07	.779 ± 0.03	0.910	0.584
Sc	1.23 ± 0.39	.654 ± .066	0.534	0.498
Th	13.1 ± 3.0	14.9 ± 0.7	10.5	17.4
Ta	3.4 ± 0.5	4.74 ± 0.27	4.26	4.22
Ba	---	<20	<20	<20
Sr	---	< 5	< 5	< 5
Ba/Sr	---	---	---	---
Eu/Eu* [3]	0.35	0.07	0.08	0.09
Sm/Eu	9.87	49.1	39.7	40.3
Or Content [4]	---	57	52	60

1. From Buma, et al, in press. Values represent average
    of 3 different samples. The ± values represent the
    average deviation from the mean.

2. Values are the average of two duplicate analyses. The
    ± values represent the deviation from the average.

3. Observed Eu abundance divided by interpolated abundance.

4. Or content (Or + Ab = 100) of homogenized perthite
    separate in %.

TABLE 3

Continued

NORDMARKITE GRANITE

	48 [2.]	AP	54	470
La	294	82.7	46.9	50.2
Ce	567 ± 9	152	111	111
Nd	253 ± 3	66.0	63.8	60.0
Sm	37.2 ± 1.0	13.6	12.6	11.6
Eu	2.11 ± 0.09	0.526	3.18	5.12
Gd	29.2 ± 1.8	8.36	11.0	9.72
Tb	3.22 ± 0.02	1.96	1.06	0.948
Yb	3.38 ± 0.05	3.84	3.60	3.04
Lu	1.22 ± 0.02	0.714	0.780	0.632
Sc	2.52 ± 0.27	2.24	4.40	5.68
Th	17.5 ± 0.6	28.2	4.10	4.54
Ta	4.49 ± 0.05	7.90	2.60	2.64
Ba	296 ± 3	178	859	1149
Sr	16.6	37.8	72.0	85.5
Ba/Sr	17.8	4.71	11.9	13.3
Eu/Eu* [3.]	0.20	0.13	0.84	1.48
Sm/Eu	17.6	25.9	3.96	2.27
Or Content [4.]	51	70	40	39

2. Values are the average of two duplicate analyses. The ± values represent the deviation from the average.

3. Observed Eu abundance divided by interpolated abundances.

4. Or content (Or + Ab = 100) of homogenized perthite separate in %.

TABLE 3

Continued

	Beverly Syenite 2.	Misery Island Syenites M-1	M-2	Anorthosite
La	23.3	55.7	30.2	10.7
Ce	50.1 ± 1.6	129	72.0	22.7
Nd	22.8 ± 0.4	60.4	30.8	12.3
Sm	4.02 ± 0.22	12.9	5.34	2.99
Eu	1.05 ± 0.09	2.56	0.454	1.65
Gd	4.56 ± 0.30	13.7	5.64	2.73
Tb	0.386 ± 0.03	1.82	0.588	---
Yb	0.933 ± .005	2.14	1.56	0.540
Lu	0.319 ± .009	0.74	0.260	0.102
Sc	2.47 ± 0.03	9.26	0.542	4.68
Th	6.79 ± 0.02	6.40	8.14	0.853
Ta	2.84 ± 0.11	2.76	3.50	0.532
Ba	322 ± 10	1321	81.2	447
Sr	88.6	149	33.3	926
Ba/Sr	3.63	8.87	2.44	0.483
Eu/Eu* 3.	0.76	0.60	0.26	1.70
Sm/Eu	3.83	5.04	11.8	1.81
Or Content 4.	35	60	37	---

2. Values are the average of two duplicate analyses. The ± values represent the deviation from the average.

3. Observed Eu abundance divided by interpolated abundance.

4. Or content (Or + Ab = 100) of homogenized perthite separate in %.

based on duplicate counts of the standard rock G-1. G-1 was also the standard used for the abundance determinations in the unknowns.

Perthite separates of each sample were ground and then homogenized and sanidinized in a hydrothermal bomb at 1/2 kb. and 850°C or at 1 atm and 1000°C in a muffle furnace. The Or contents were determined by measuring the postion of the $\overline{2}01$ peak (Wright, 1968).

RESULTS

The results of the trace element chemical analysis are given in table 3, and the REE distributions are presented graphically in figures 5, 6, 7. Compilations of REE data for Granitic rocks are given by Haskin et al (1966) and Herrman (1970). The light REE abundances increase generally with increasing SiO_2 content, or in other words, with increasing differentiation (Zielinski and Frey, 1970; Schnetzler and Philpotts, 1970; Le Maitre, 1962).

The two analyses of the Cape Ann Granite are comparable to those done previously (Buma et al, in press), except for the increased negative Eu anomalies, which is consistent with the samples lacking a groundmass and being more even-grained. Sample #450 exhibits a Eu anomaly essentially identical to that of the Cape Ann Granite (#59 & 63). The Nordmarkite Granite forms a series from #470 and #54, which

Figure 5 -- Comparison plot for Cape Ann Granite and
#450. Stippled area indicates range of
values for four composite granites (60-70%
SiO_2, >70% SiO_2, Western North America
Precambrian and Finnish Precambrian). Data
from Haskin et al (1966, 1968). "Average of
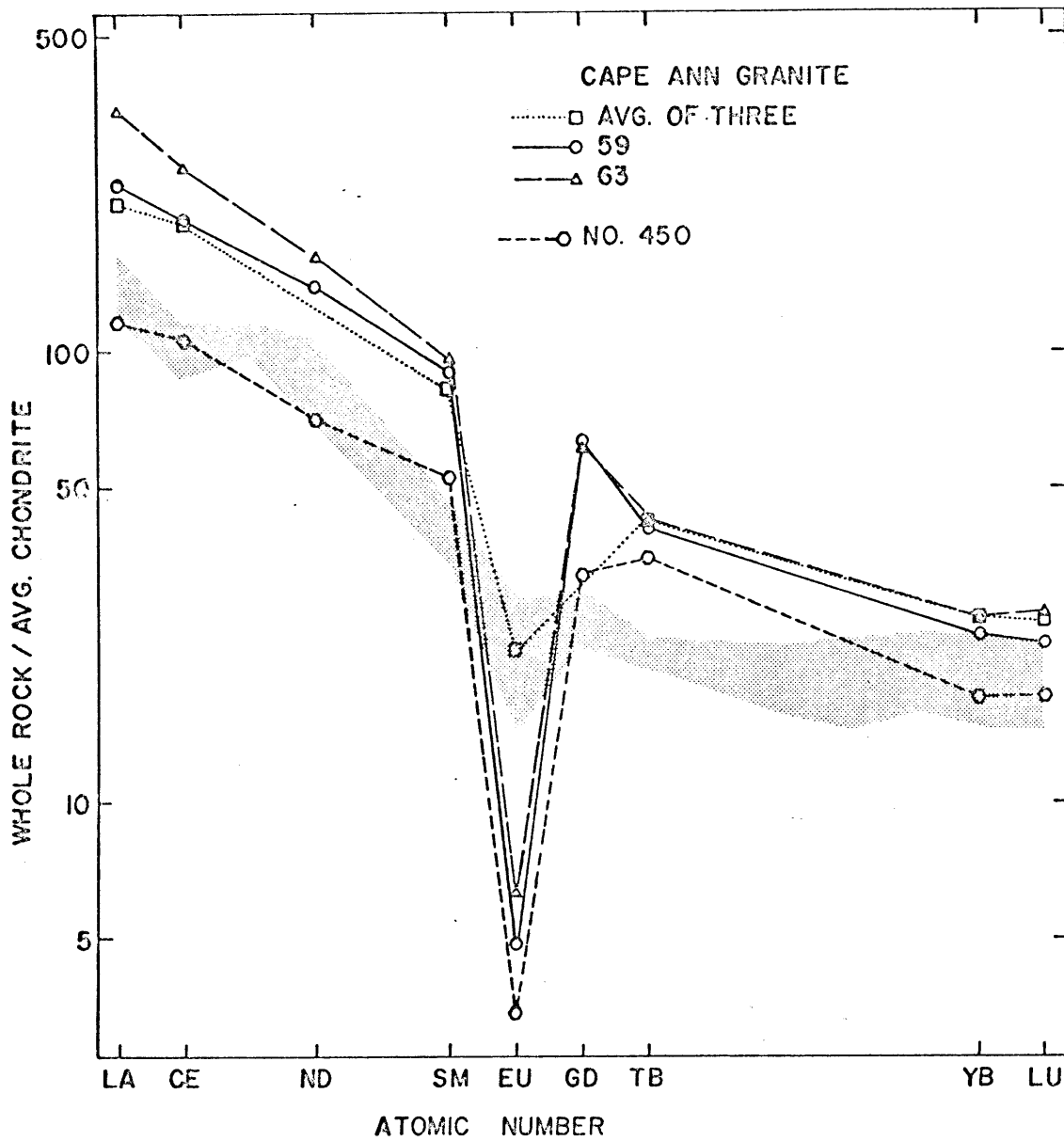three"is from Buma et al(1971).

Figure 6 -- Comparison plot for Nordmarkite Granite.

Stipple area indicates range of values of
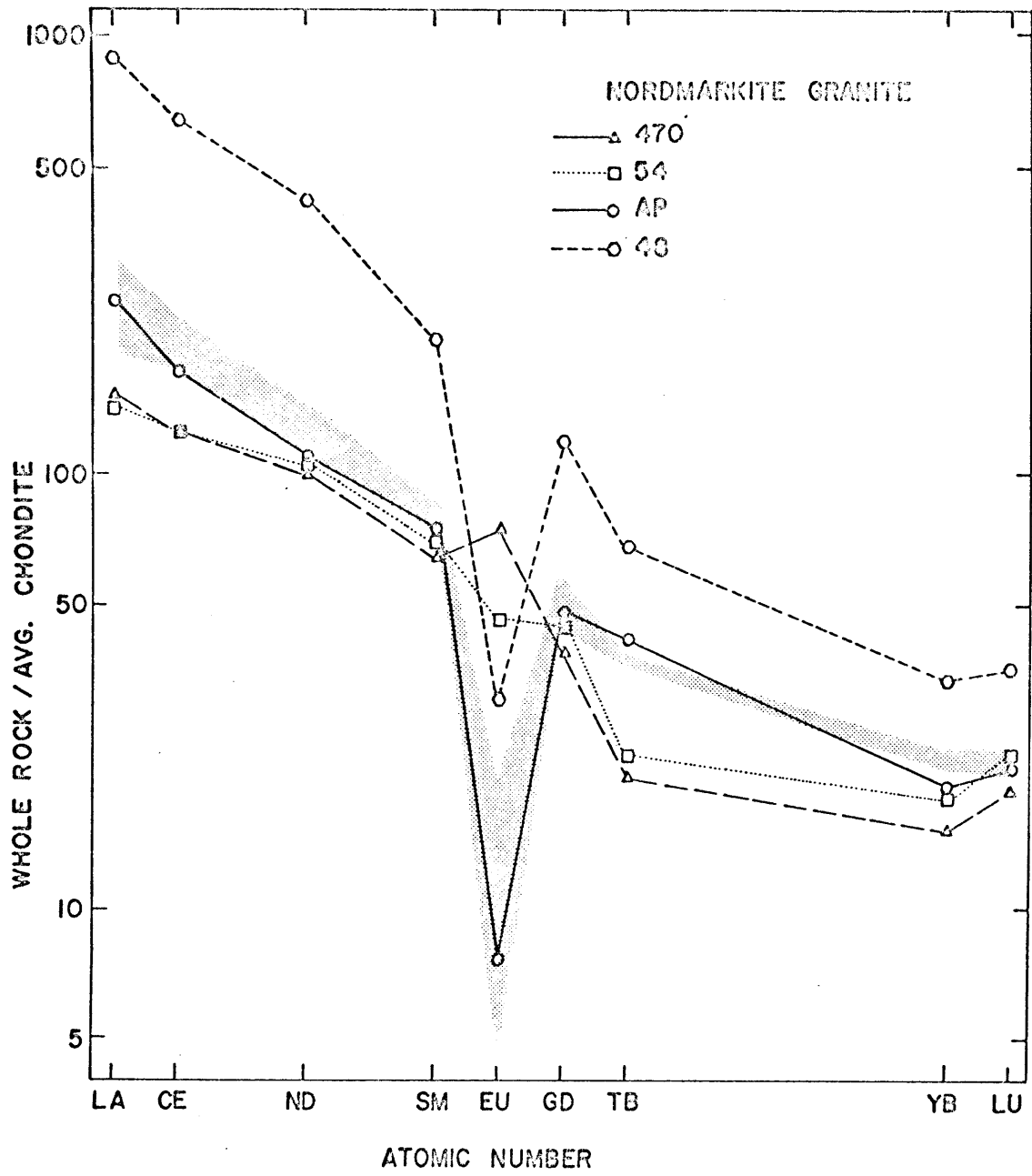
Cape Ann Granite from Fig. 5.

Figure 7 -- Comparison plot of Beverly Syenite, Misery
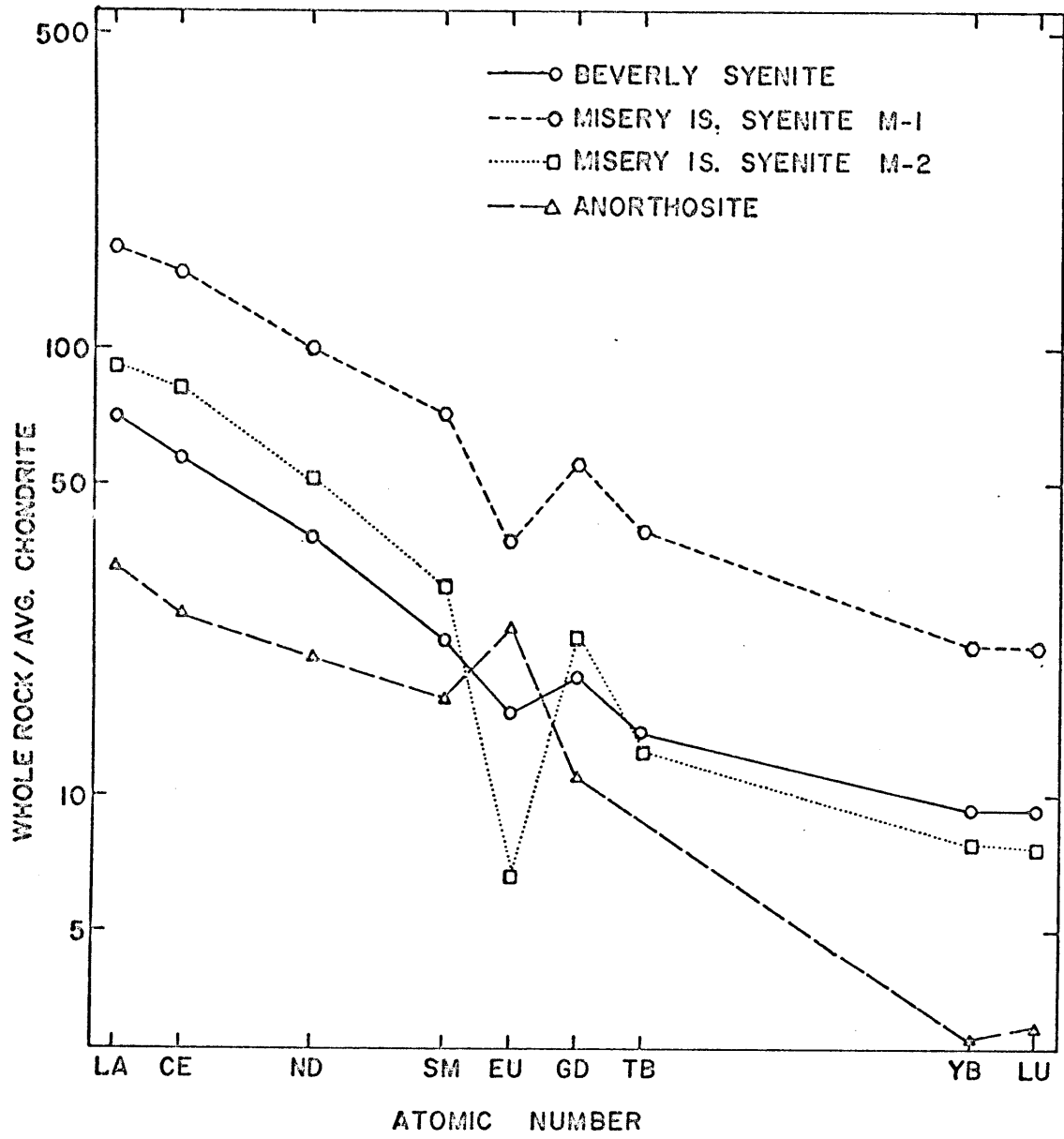
Islands Syenites and Anorthosite.

exhibit a Eu enrichment and a slight depletion respectively, to #48 and AP, which approach the Eu anomalies of the Cape Ann Granite (#59 & 63). The Misery Islands Syenites and the Beverly Syenite show moderate to large negative Eu anomalies.

BARIUM AND STRONTIUM

The Ba and Sr abundances in residual magmas are largely controlled by feldspar crystallization (Berlin and Henderson, 1968, 1969; Philpotts and Schnetzler, 1970). The concentration of Ba in a residual liquid is also controlled by biotite, due to its solid-liquid distribution coefficient of 6.4 (Philpotts and Schnetzler, 1970). Biotite appears not to have been important in the crystallization history of the granitic rocks at Cape Ann, except for the possible exception of sample number 48, which will be discussed later.

The solid-liquid distribution coefficient for Sr in plagioclase varies from 1.3 to 2.8 as the An content varies from An 97 to An 46 (Philpotts and Schnetzler, 1970). The Ba distribution coefficient varies from 0.05 to 0.6, generally increasing with increasing Ab content, but not systematically. For alkali feldspar (Or 74), the distribution coefficient for Ba is 6.1 and for Sr is 3.8.(Philpotts and Schnetzler, 1970).

In light of these distribution coefficients, extensive plagioclase crystallization would lead to relative Sr deple- tion and large Ba enrichment. Using the following equation (Haskin et al, 1970)

$$\frac{(Ba/Sr)_{RES.}}{(Ba/Sr)_{SYS.}} = (1 - x)^{D_{Ba} - D_{Sr}} \qquad (1.)$$

and assuming $D_{Ba} - D_{Sr}$ tends to a maximum, then 65% of a basaltic magma with an initial Ba/Sr ratio of 0.8 would have to crystallize as plagioclase in order for a residual liquid to have a Ba/Sr ratio such as that of #470. Then, after the onset of alkali feldspar crystallization, this liquid would become more rapidly depleted in Ba than Sr, which is reflected in smaller Ba/Sr ratios. Such a model may explain the Ba/Sr ratios of the Nordmarkite Granite.

In table 4 this variation in the Ba and Sr concentra- tions is compared to other parameters. The quartz content is seen to rise with increasing differentiation as does the Or-content of the alkali feldspars. The Eu/Eu* is seen to decrease. There is some ambiguity in the relationship between #48 and AP and this will be discussed later. The overall implication is, however, that the Nordmarkite series, from #470 through #48 represent increasing differentiation of a liquid derived from extensive feldspar (plagioclase + alkali) crystallization from a gabbroic magma.
     feldspar

TABLE 4

SYSTEMATIC VARIATIONS IN NORDMARKITE CHEMISTRY

No.	Quartz Content (%)	OR-Content of K-Feldspar (%)	Ba (PPM)	Sr (PPM)	$\frac{Eu}{Eu^*}$ [1]	Ba/Sr	Sm/Eu
470	5.0	39	1149	85.5	1.48	13.3	2.27
54	10.2	40	859	72.0	0.84	11.9	3.96
AP	11.3	70	178	37.8	0.13	4.71	25.9
48	12.0	51	296	16.6	0.20	17.8	17.6

1. "Eu*" is the interpolated value between Sm and Gd.

The two Cape Ann Granite samples (#59 & 63) and sample #450 contain concentrations of Ba and Sr below the detection limit of the techniques used. For neutron activation analysis, Denechaud (1969) gives a method for calculating an upper limit for the elemental abundance based on each channel used for calculation of abundances, having to have at least one standard deviation of counts above background in order to be detectable. For Ba these calculations yield 20 ppm for the upper limit. The detection limit for Sr with the equipment and the method used is approximately 5 ppm (Fairbairn, pers. comm.). The overall implication is that these rocks are all extremely differentiated, resulting from processes involving plagioclase and alkali feldspar cyrstallization.

SCANDIUM, TANTALUM, AND THORIUM

The chemistry of Sc has been summarized by Frondel (1970). Sc is concentrated principally in pyroxenes, amphiboles, and dark micas, and in general is considered to decrease with increasing differentiation. Ta was found to be enriched in residual liquids by Rankama (1944), and little new information has been added since. The geochemistry of Th has been discussed by Rogers and Adams (1969). They found that in a large number of differentiation sequences there was only one in which the Th content

decreased towards the younger rocks.

The abundances of Sc, Ta and Th are tabulated in table 3. For the Nordmarkite Granite, the behavior of these three elements is consistent with the hypothesis of differentiation. Again, the relationship between #48 and AP is ambiguous, but the overall trend is evident. The concentrations of these elements in the Cape Ann Granite Samples (#59 & 63) and in sample #450, appears to be consistent with the implication that these samples represent extremely differentiated liquids.

APPLICATION TO THE ORIGIN AND HISTORY OF GRANITES

In considering table 4, the most striking feature is the sympathetic variation between the five parameters tabulated. Thus, in the Nordmarkite Granite, a trend towards increasing modal quartz content in the rock, increasing Or content of the perthites, and decreasing abundances of Ba, Sr, and Eu is correlated with increasing differentiation. This is consistent with the known geochemical behavior of these elements. In general the abundances of Sc, Th, and Ta also support this hypothesis. On the basis of these variations, the relationships between the Nordmarkite Granite, the Cape Ann Granite, and the Syenites will be elucidated.

The Cape Ann Granite samples #59 & 63 and sample #450,

on the basis of increased modal quartz, generally high Or

contents of the perthites, and greater depletions of Ba,

Sr, and Eu strongly imply that these rocks are more differ-

entiated than the Nordmarkite Granite. It is interesting

to note that prior analysis of the Cape Ann Granite (Buma,

et al., 1971) yielded a Eu/Eu* value of 0.35 for an average

of three samples from the pluton. The values in this study

are 0.07 for #59, and 0.08 for #63. Thus, the Cape Ann

Granite cannot be merely a later stage product of the same

process that produced the Nordmarkite Granite, but it appears

that it stemmed from another process. Sample #450 has a

Eu/Eu* value of 0.09, comparable to the samples of the

Cape Ann Granite analyzed, but less than the values reported

by Buma et al (1971). #450 is a rock intermediate in age

between the Cape Ann Granite and the Nordmarkite Granite.

In table 3, the various elemental abundances of the

Beverly Syenite and the Misery Islands Syenites are reported,

and can be compared to the other rocks analyzed. Consider

the Beverly Syenite. Toulmin (1964) proposed that the

Beverly was a cumulate of the Cape Ann. This hypothesis can

now be tested in light of the geochemical data in table 3.

The method used to test the hypothesis was analogous

to that used by Haskin et al (1970). The Sm/Eu ratio of

the Beverly was tested using the following equation:

$$\frac{(Sm/Eu)_{BEV.}}{(Sm/Eu)_{SYS.}} = \frac{1 - (1 - x)^{D_{Sm}}}{1 - (1 - x)^{D_{Eu}}} \qquad (2.)$$

to discover if the Beverly was a cumulate of the Cape Ann or Nordmarkite. The Ba/Sr ratio was also used in comparing the Beverly to the Nordmarkite but not to the Cape Ann, because this ratio was not determined in the samples analyzed previously (Buma, et al, 1971), and because the low abundances of Ba and Sr in samples #59 and 63 are not indicative of a unique process.

The results of the calculations suggest that the Beverly cannot be a cumulate of either the Cape Ann or the Nordmarkite. This is based on the ratios of the Sm/Eu value of the Beverly to that of the rock being tested as the liquid not being among the solution set of the equation, calculated from the known distribution coefficients for given values of x (fraction completion of the process). For details of the calculation see appendix A.

Certain limitations and assumptions that were made in making these calculations should be pointed out. First, equation 2 above compares the cumulate phase to the overall system compositions. For the Nordmarkite Granite, samples #54 and #470 were considered to be fairly representative of the original liquid. This is not known diagnostically, because the samples have essentially the same texture, and hence it is impossible in the field to determine the

relative abundance of say sample #54 within the Nordmarkite.
Thus the composition of the original Nordmarkite liquid is
open to question.

For the Cape Ann Granite, the original liquid compo-
sition appears to be better known. In the previous anal-
ysis (Buma, et al, 1971), three samples were taken from the
pluton. The variation of the trace elements in these samples
was found to be rather samll (Table 3). Thus, the Sm/Eu
ratio found by Buma, et al, (1971) may be considered to be
fairly representative of the original liquid. In fact,
calculations show that the Sm/Eu ratio of sample #59 is
representative of a residual liquid after ~80% of an
original liquid of composition of that found by Buma, et
al, (1971) has solidified.

It is interesting to note that in the solution set
to equation 2 given in Appendix A, the ratio $\dfrac{(Sm/Eu)_{BEV.}}{(Sm/Eu)_{SYS.}}$

remains below 0.02 up to x = 0.40. Using this information
one may calculate the Sm/Eu ratio of the original system
from which the Beverly might be a cumulate, accounting for
up to 40 weight per cent. This ratio is 192 and increases
slightly for smaller x. Now consider the Cape Ann Granite
crystallizing from the residual liquid left from the Beverly
Crystallization, assuming the Beverly accounts for 5% of
the original system. The Sm/Eu ratio of the cumulate will

be taken as 10 (Buma, et al, 1971), and the Sm/Eu ratio of
the system (Beverly residual liquid) as 200. Thus from
the solution set in the appendix, $x = 95\%$. The Cape Ann
Granite might then represent a 95% solidification of the
Beverly residual liquid.

This result is somewhat suspect, however. There are
syenitic dikes in the Beverly Syenite which do not cut the
Cape Ann Granite (Toulmin, 1964). This is somewhat sug-
gestive that the Beverly may belong to a separate magmatic
event. Another problem area is the distribution coefficients.

The assumption is made that the distribution coeffi-
cients used for the derivative (cumulate) phase solely controls
the abundance of the trace element in the solid and liquid.
In the calculations, the distribution coefficients for
alkali feldspar (Schnetzler and Philpotts, 1970) were used.
This assumption is valid for Eu, but not Sm. Sm is con-
centrated by zircon and amphibole (Buma, et al, 1971).
Hence, the abundances of Sm taken from the whole rock anal-
yses will reflect the Sm in the mafics, while the Eu is
concentrated by the feldspars. In the Cape Ann Granite,
the amphibole occupies the interstices between the perthite
and quartz crystals; it is a residual liquid in its own right.
This is not the case in the Beverly, the mafics do not in
general have such a relationship to the other minerals, and
they are more varied of type (Toulmin, 1964). The problem
of determining the actual distribution coefficients during

the crystallization of these rocks is indeed formidable.

The calculations do not confirm or deny a cumulus-residuum

relationship between the Beverly and the Cape Ann Granite.

But if the cumulus-residuum relationship exists then start-

ing material was already significantly more Eu depleted

than the Cape Ann Granite.

The Misery Islands syenites also appear to occupy

such a position geochemically. But considering the field

relations, one can definitely say that they are not cumu-

lates, because they certainly were liquid when intruded,

based on lack of foliation or lineation. The country rock

containing the dikes is a greenschist, and has been mapped

as the Beverly Contact Zone (Toulmin, 1964). The islands

are one mile offshore from Cape Ann Granite. The absolute

ages of the greenschist or the dikes are unknown. Consider-

ing the known data and all the unknown data, any positive

correlation between the granites and syenites must be

deemed speculative.

What then is the relationship between the Nordmarkite

and the Cape Ann Granite? The Nordmarkite exhibits the

trends shown in table 4, and seems to be a coherent body,

that is, a reasonable and logical hypothesis may be made

relating the samples to each other as part of a magmatic

process. The stained slabs suggest that during crystalli-

zation the Nordmarkite Granite magma left a two feldspar

field (plagioclase-alkali feldspar) and entered the alkali feldspar field, causing the overgrowth of perthite on the plagioclase. On the other hand, the plagioclase may be xenocrystic, having originated in the parent magma. The Nordmarkite probably was a mega-granophyre, forming a roof over a more basic magma at depth which was continuing to differentiate. This allows a fair amount of heterogeneity in the granophyre itself, as well as the possibility of internal differentiation. It also supplies a magma source for the dikes cutting the Nordmarkite, and would explain the presence of the anorthosite (An 53) which would be a "raft" in the solidifying magma below.

The magma at depth would continue to fractionate, eventually leaving a magma whose major constituents are SiO_2, Al_2O_3, FeO, K_2O, and Na_2O, and depleted in MgO and CaO. Assuming that the magma is above 1150°C, further cooling might lead to the intersection of the region of liquid imiscibility in figure 8, and the magma would split Si-rich and Fe-rich liquids (Roedder, 1951; Roedder and Weiblein, 1970). The K enrichment in the high silica liquid over the silica poor one would be 25 to 1, and the Na enrichment would be about 3 to 1 (table 5). Terrestial basalts contain an order of magnitude more Na_2O than lunar basalts, hence the composition after such a splitting would be similar to that of the Cape Ann Granite (table 6).

Figure 8 -- Preliminary Diagram for system leucite-
      fayalite-silica (Roedder, 1951).

PRELIMINARY
DIAGRAM

Approximate Temperatures
A and A′   1140° C
B and B′   1150°
C   1270°
D   <1100°
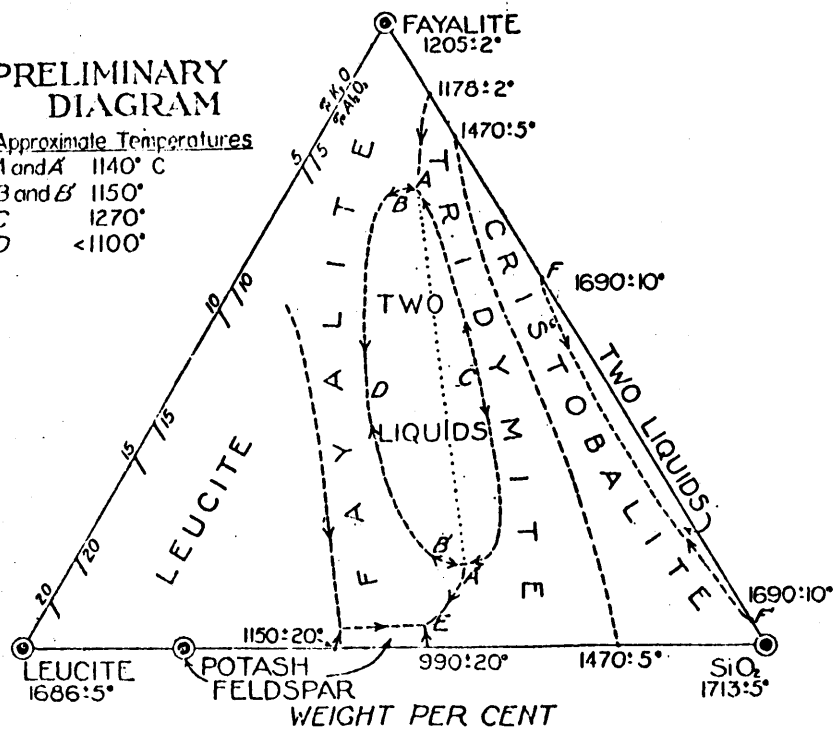
TABLE 5

CHEMICAL COMPOSITIONS OF SOME LUNAR IMISCIBLE LIQUIDS

	High Silica Glass[1].	High Iron Glass[2].
SiO_2	75.4	44.1
Al_2O_3	11.5	3.0
FeO	2.5	30.6
MgO	0.26	2.1
CaO	1.8	10.7
K_2O	6.5	0.26
Na_2O	0.37	0.13
TiO_2	0.52	4.0

$$\frac{K_2O \ High \ Silica}{K_2O \ High \ Iron} = 25.0$$

$$\frac{Na_2O \ High \ Silica}{Na_2O \ High \ Iron} = 2.85$$

1. Average of 33 (Roedder & Weiblein, 1970)
2. Average of 6 (Roedder & Weiblein, 1970)

TABLE 6

SELECTED CHEMICAL ANALYSES

	High Silica Lunar Glass	Cape Ann Granite		Nordmarkite Granite		
	1.	2.	3.	4.	5.	6.
SiO_2	75.4	72.56	77.61	69.42	63.36	66.60
TiO_2	.52	.25	.25	.20	tr.	.76
Al_2O_3	11.5	13.21	11.94	15.15	16.58	15.05
Fe_2O_3	--	.78	.55	1.49	.90	1.07
FeO	2.5	2.14	.87	3.50	3.24	4.42
MnO	--	.05	--	.10	tr.	tr.
MgO	.26	.12	tr.	.09	.45	.36
CaO	1.8	.89	.31	.96	1.85	2.21
K_2O	6.5	5.53	4.98	5.12	5.27	5.42
Na_2O	.37	3.82	3.80	3.35	3.97	4.03
H_2O	--	.29	.23	.47	.35	.41

1. Average of 33 (Roedder and Weiblein, 1970)

2.-6. (Warren and McKinstry, 1924)

Thus the Cape Ann Granite would be the product of
a single large event, leading to a fairly homogeneous magma.
It would be a dry, hot magma as required by the paucity of
aplites and the perthite. This theory is not forced by the
data, that is, one may invoke crystal fractionation and get
to the same point. But this theory, in light of experi-
mental work, certainly is elegant and intriguing, and seems
to be suggested by overall data.

Zartman (Zartman and Marvin, 1971) not only dated the
Cape Ann Granite, but obtained other miscellaneous New
England ages as well. In particular, a Rb-Sr age from a
phologopitic biotite from the Salem Gabbro-Diorite yields
an age of 460 ± 15 my. The age of the Cape Ann Granite
was found to be 452 ±10 my. by Pb-Pb zircon ages. Joyner
(1963) found the Cape Ann Granite to be shallow and under-
lain by denser rock from gravity studies. Toulmin stated
that in Salem Quadrangle the Cape Ann's lower contact was
gently dipping to the north. Hence, the evidence implies
that the Salem Gabbro Diorite may represent either the
cognate liquid itself or another part of the parent magma,
with the cogante liquid directly beneath the Cape Ann
Granite.

Sample #450 is unique in that it is the only rock inter-
mediate in age between the Nordmarkite and the Cape Ann
Granite, and it is the only rock with distinctly porphyritic
texture in the area. Its mode is 17.9% quartz phenocrysts,

7.9% perthite phenocrysts, 8.7% plagioclase, .9% mafics
(biotite, ferrohastingsite), 64.6% groundmass. The sug-
gestion is that quartz was the first mineral to begin
crystallization (based on modal amounts), but this is not
conclusive. It should be pointed out that the texture of
the Cape Ann Granite might result from quartz beginning to
crystallize early and ending early, until the residual
stages are reached. Such relationships are exhibited by
figure 8. Sample #450 also contains iddingsite in thin
section, which is usually interpreted as the decomposition
product of fayalite. If #450 is interpreted in light of
figure 8, then the liquid must be inside the potash feld-
spar field, due to the size of the phenocrysts. Thus the
quartz would remain inert until the residual stage is
reached.

A rock such as #450 cannot be directly representative
of an imiscible liquid, because such phenomena have been
described only in anhydrous systems. The abundance of bio-
tite and the occurrence of two alkali feldspars in the
groundmass indicate that the rock is fairly hydrous. The
porphyritic texture indicates chilling, i.e., intrusion
into relatively cold country rock. The origin of this
magma most likely rests in the origin of the Cape Ann
Granite itself. After magma splitting took place, the
highly siliceous magma would be beneath the solidified
roof granophyre above. Due to the temperature of the

magma (1100°) some partial melting must have taken place.

Melting processes fractionate trace elements more effective-

ly than fractional cyrstallization (Gast, 1968). Hence,

the upper most part of the Cape Ann liquid might be depleted

in REE, due to the partial melting of the roof granophyre.

This fraction, being the first to be intruded into the

country rock might solidify, and later be engulfed by the

major pulse of the intrusion. This is consistent with the

field evidence -- #450 shows foliation and lineation, indi-

cating forceful intrusion, while the Cape Ann Granite itself

is equigranular, suggesting emplacement by stoping.

SAMPLE #48

Sample #48 is unique in several ways: it has the largest

overall REE abundance of any sample analyzed, and it is by

far the most hydrous of any Nordmarkite or Cape Ann Granite

sample. The rock contains more allanite than any other,

and more apatite. The amount of zircon appears to be similar

to other rocks. The allanite is subhedral to anhedral sug-

gesting that its origin is not xenocrystic, that is, the REE

which formed the allanite was a function of liquid composition.

The zircons and apatite are both euhedral. In other thin

sections, the large, euhedral zircons are confined almost

entirely to poikilitic enclosure in the ferrohastingsite.

In sample #48 the majority of the zircons occur with the

rest of the mafics, but not poikilitically enclosed, and a significant number occur in the finer grained portions of the thin section (quartz-feldspar).

This rock probably represents the final residuum of the Nordmarkite. This is compatible with the volatiles becoming concentrated in the more residual minerals on a thin section scale. The REE abundances also are indicative of an extremely differentiated liquid.

SUMMARY AND CONCLUSIONS

This study has attempted to elucidate the relationship between the Cape Ann Granite, the Nordmarkite Granite and the Beverly Syenite. The Nordmarkite was found to be rather heterogeneous both in terms of trace element abundances (Eu, Ba, Sr) and in modal amounts of constituent minerals. The variations were found to be correlative with a hypothesis of increasing differentiation from #470 to #48. Whether this rock was a product of fractional crystallization of a basic magma or merely a mega-granophyre, cannot be determined unequivocally.

The Cape Ann Granite was found to be more homogeneous than the Nordmarkite. The two analyses compare favorably with work done previously, except for Eu. The texture of the two samples analyzed differ from that of the bulk of the Cape Ann Granite. The texture is interpreted as being

a later stage texture, and this is confirmed by the in-
creased Eu depletion. The general lack of aplites or peg-
matites, appearance of perthite, the geometry of the pluton
as a whole, and its homogeneity are considered to suggest
that the Cape Ann Granite may be an imiscible liquid with
the denser rocks beneath it being the cognate liquid.

The Beverly Syenite was modeled as a cumulate of the
Cape Ann Granite as well as the Nordmarkite. One of the
problems and limitations of this model was in attempting to
make a reasonable assumption about the trace element compo-
sition of the original liquids. Calculations showed that
the Beverly could not be a cumulate assuming the granites
to be representative of original liquids. Calculations
were also performed to discover if the Beverly and the Cape
Ann Granite had a cumulate-residuum relationship. Results
of these calculations showed such a relationship possible,
but in light of the assumptions on the distribution coeffi-
cients, it cannot be considered probable.

The distribution coefficients for alkali feldspar were
assumed to be representative of the cumulate material. The
actual distribution coefficient between the cumulate and
liquid is difficult to estimate. Consider Sm. Sm is con-
centrated by the mafics (zircon, amphibole, and pyroxene).
Hence, if any mafic mineral crystallizes with feldspar then
the Sm concentration cannot be calculated using the distri-
bution coefficient for feldspar. But one cannot reliably

determine a representative distribution coefficient to use in making the calculations. The variation on the distribution coefficients with composition in plagioclase is rather well documented. It also seems reasonable to expect variation in the distribution coefficients of the mafics with composition. These variations have not yet been reported. Hence, the real distribution coefficients are essentially unknown.

Another paramount problem is in recognizing whether or not a particular granite may result from liquid imiscibility. Certain criteria can be set forth that seem to be indicative of such an imiscible liquid:

1) Compositionally, the granite should contain 70% SiO_2, be almost entirely depleted in CaO and MgO and have a low (4 wt.%) FeO content, in accordance with experimental work and lunar results.

2) The granite must be hot and dry, i.e. it must contain perthite and have few aplites and pegmatites.

3) The granite should contain fayalite or its decomposition products.

4) Such a granite should be relatively homogeneous, because a magma with a high SiO_2 content and no H_2O cannot allow much major element transport or crystal settling.

It should be pointed out that the REE distribution itself may be characteristic, but this is certainly speculative.

Also at Cape Ann, dense rocks of similar age are associ-
ated with the granite. This adds more weight to the argu-
ment that the Cape Ann Granite is in fact an imiscible
liquid, but in general such data may be lacking. Both the
distribution coefficients and the granitic imiscible liquids
are problems that deserve much more work.

APPENDIX A

The equation (Haskin et al, 1970) used for testing the Beverly Syenite as a possible cumulate of various Granitic liquids is

$$\frac{(Sm/Eu)_{BEV}}{(Sm/Eu)_{LIQ}} = \frac{1 - (1 - x)^{D_{Sm}}}{1 - (1 - x)^{D_{Eu}}} \qquad (A-1)$$

where $(Sm/Eu)_{BEV} = \dfrac{\text{concentration of Sm}}{\text{concentration of Eu}}$ in the Beverly

Syenite

D_{Sm} = Sm solid-liquid distribution coefficient for alkali feldspar

x = fraction crystallized as alkali feldspar, $0 < x < 1$

The equation cannot be solved explicitly for x, given the rest of the variables, but $\dfrac{(Sm/Eu)_{BEV}}{(Sm/Eu)_{SYS}}$ ratios can be

calculated for given values of x, and values of D_{Sm} (0.018) and D_{Eu} (1.13) (Schnetzler and Philpotts, 1970). The same procedure can be followed to generate ratios for D_{Ba} (6.12), D_{Sr} (3.87) and x. (Philpotts and Schnetzler, 1970). These ratios are given in tables I and II.

To discover if the Beverly Syenite is a cumulate of a liquid with a Sm/Eu or Ba/Sr ratio equal to any of the granite samples analyzed, one need only divide the ratio

TABLE I

x	$(1 - x)^{D_{Sm}}$	$(1 - x)^{D_{Eu}}$	$\dfrac{(Sm/Eu)_{BEV}}{(Sm/Eu)_{SYS}}$
.01	.9998	.989	.0160
.02	.9996	.977	.0161
.03	.9995	.966	.0162
.04	.9993	.955	.0163
.05	.9991	.944	.0164
.10	.998	.888	.0169
.15	.997	.832	.0174
.20	.996	.777	.0179
.25	.995	.722	.0186
.30	.994	.668	.0193
.35	.992	.615	.0200
.40	.991	.561	.0208
.45	.989	.509	.0223
.50	.988	.457	.0228
.55	.986	.406	.0240
.60	.984	.355	.0254
.65	.981	.305	.0269
.70	.979	.257	.0289
.75	.975	.209	.0312
.80	.971	.162	.0343
.85	.966	.117	.0387
.90	.959	.074	.0448
.95	.948	.034	.0544
.96	.944	.026	.0578
.97	.939	.019	.0624
.98	.932	.012	.0688
.99	.920	.005	.0796

TABLE II

x	$(1 - x)^{D_{Ba}}$	$(1 - x)^{D_{Sr}}$	$\dfrac{(Ba/Sr)_{BEV}}{(Ba/Sr)_{SYS}}$
.01	.940	.962	1.579
.02	.884	.925	1.547
.03	.830	.889	1.532
.04	.779	.854	1.514
.05	.731	.820	1.494
.10	.525	.665	1.418
.15	.370	.533	1.349
.20	.255	.422	1.289
.25	.172	.328	1.232
.30	.113	.251	1.184
.35	.072	.189	1.144
.40	.044	.138	1.109
.45	.026	.099	1.081
.50	.014	.068	1.058
.55	.008	.045	1.039
.60	.004	.029	1.026
.65	.002	.017	1.015
.70	.0006	.009	1.008
.75	.0002	.005	1.005
.80	.00005	.002	1.002
.85	9×10^{-6}	.0006	1.0006
.90	7×10^{-7}	.00013	1.00013
.95	1×10^{-8}	9×10^{-6}	1.000009

for the Beverly by the ratio of the sample and see whether that value is among the solution set. If it is, then a corresponding value of x can also be obtained from the table.

The $\dfrac{(Sm/Eu)_{BEV}}{(Sm/Eu)_{LIQ}}$ and $\dfrac{(Ba/Sr)_{BEV}}{(Ba/Sr)_{LIQ}}$ are given below for the ratios as given in table 3 for each sample in the left column treated as a liquid.

Sample	$\dfrac{(Sm/Eu)_{BEV}}{(Sm/Eu)_{LIQ}}$	$\dfrac{(Ba/Sr)_{BEV}}{(Ba/Sr)_{LIQ}}$
470	1.69	.273
54	.967	.305
AP	.148	.771
59	.078	--
63	.096	--
"Cape Ann"	.388	--

For Sm-Eu the only rock which fits according to the solution set is #59, and this rock is interpreted to have late stage fracture with respect to the Cape Ann Granite as a whole. Hence it is unlikely that it is representative of the original liquid composition. Considering Ba-Sr, all Nordmarkites give numbers too low. If the Ba/Sr ratio of the Cape Ann Granite were ≥ 4 then the Beverly might be modeled as a cumulate, but this is unknown. Thus one cannot call any of the samples representative of the original liquid.

Now consider a possible residuum-cumulate relationship between the Cape Ann Granite and Beverly Syenite. Noting that the value of the ratio $\dfrac{(Sm/Eu)_{BEV}}{(Sm/Eu)_{SYS}}$ remains less than

.02 for x<.35. The $(Sm/Eu)_{SYS}$ ratio can be calculated for $(Sm/Eu)_{BEV}$ = 3.82 and is found to be 192, assuming the BEV/SYS ratio is 0.02. This means that the liquid that the solid Beverly Syenite would crystallize from would be more Eu-depleted than the most Eu-depleted granite.

Now applying the following equation (Haskin, et al, 1971)

$$\frac{(Sm/Eu)_{RES}}{(Sm/Eu)_{SYS}} = (1 - x)^{D_{Sm} - D_{Eu}} \qquad (A-2)$$

the Sm/Eu ratio of a residual liquid can be calculated after a fraction x has crystallized as the Beverly Syenite, assuming $(Sm/Eu)_{SYS}$ = 192. These values are tabulated below.

x	(Sm/Eu) Residual Liquid
.05	203
.10	216
.15	230
.20	246

From Figure 1, it appears that the Beverly Syenite comprises less than 5% of the total area of exposure of the

Cape Ann Granite and Beverly Syenite. Thus the Beverly

can be considered to represent less than 5% of the total

system. The Cape Ann Granite then may be considered to

crystallize from a liquid in which the Sm/Eu ratio is ~200.

If the Sm/Eu ratio of the Cape Ann Granite is taken as ~10

(Buma et al, 1971), then the Cape Ann would represent ~95%

solidification of such a residual liquid.

REFERENCES

Berlin, R., and Henderson, C.M.B.: Reinterpretation of Sr and Ca fractionation trends in plagioclases from basic rocks. Earth and Planet. Sci. Lett. 4, 79-83 (1968).

Berlin, R., and Henderson, C.M.B.: The distribution of Sr and Ba between the alkali feldspar, plagioclase and groundmass phases of porphyritic trachytes and phonolites. Geochim. Cosmochim. Acta 33, 247-255 (1969).

Bird, J.M., and Dewey, J.F.: Lithosphere plate - continental margin tectonics and the evolution of the Appalachian Orogen. Bull. Geol. Soc. Amer. 81, 1031-1060 (1970).

Buma, G., Frey, F.A., and Wones, D.R.: New England Granites: Trace element abundances. (In press) (1971).

Clapp, C.H.: The igneous rocks of Essex County, Massachusetts. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts (1910).

Clapp, C.H.: Geology of the igneous rocks of Essex County, Mass. U.S. Geol. Surv. Bull. 704, (1921).

Denechaud, E.B.: Rare-earth activation analysis: Improvement and application to Stretishorn Dike and Duluth Complex. Ph.D. thesis, University of Wisconsin (1969).

Emerson, B.K.: Geology of Massachusetts and Rhode Island. U.S. Geol. Surv. Bull. 597, (1917).

Frondel, C.: Scandium. In Handbook of Geochemistry, edited by K.H. Wedepohl. Springer-Verlag, Berlin (1970).

Gast, P.W.: Trace element fractionation and the origin of tholeiitic and alkaline magma types. Geochim. Cosmochim. Acta 32, 1057-1066 (1968).

Gordon, G.E., Randle, K., Goles, G.G., Corliss, J.B., Beeson, M.H., and Oxley, S.S.: Instrumental activation analysis of standard rocks with high resolution gamma ray detectors. Geochim. Cosmochim. Acta 32, 369-396 (1968).

Haskin, L.A., Allen, R.O., Helmke, P.A., Paster, T.P., Anderson, M.R., Korotev, R.L., and Zweifel, K.A.: Rare earths and other trace elements in Apollo 11 lunar samples. In Proceedings of Apollo 11 Lunar Science Conference Vol. 2, edited by A.A. Levinson, pp. 1213-1231, Pergamon (1970).

Haskin, L.A., Frey, F.A., Schmitt, R.A., and Smith, R.H.: Meteoritic, solar and terrestrial rare-earth distributions. Physics and Chemistry of the Earth, Vol. 7, 169-321. Pergamon, New York (1966).

Haskin, L.A., Haskin, M.A., Frey, F.A., and Wildeman, T.R.: Relative and absolute terrestrial abundances of the rare earths. In Origin and Distribution of the Elements, edited by L.H. Ahrens, pp. 889-912. Pergamon, New York (1968).

Herrmann, A.G.: Yttrium and the lanthanides. In Handbook of Geochemistry, edited by K.H. Wedepohl. Springer-Verlag, Berlin (1970).

Joyner, W.B.: Bravity in North Central New England. Bull. Geol. Soc. Amer. 74, 831-858 (1963).

LaForge, L.: Geology of the Boston area, Massachusetts. U.S. Geol. Surv. Bull. 839 (1932).

LeMaitre, R.W.: Petrology of volcanic rocks, Gough Island, South Atlantic. Bull. Geol. Soc. Amer. 73, 1309-1340 (1962).

Philpotts, A.R.: Imiscibility between critically under-saturated basic and oversaturated felsic magmas. (Abstract) Transactions Am. Geoph. Union 51, 438 (1970).

Philpotts, J.A., and Schnetzler, C.C.: Phenocryst-matrix partition coefficients for K, Rb, Sr, and Ba, with applications to anorthosite and basalt genesis. Geochim. Cosmochim. Acta 34, 307-322 (1970).

Philpotts, J.A., Schnetzler, C.C., and Hart, S.R.: Submarine basalts: Some K, Rb, Sr, Ba, REE, H_2O and CO_2 data bearing on their alteration, modification by plagioclase and possible source materials. Earth and Planet. Sci. Lett. 7, 293-299 (1969).

Rankama, K.: On the geochemistry of tantalum. Comm. Geol. Finlande Bull. 133 (1944).

Roedder, E.; Low temperature liquid imiscibility in the system $K_2O-FeO-Al_2O_3-SiO_2$. Amer. Min. 36, 282-286 (1951).

Roedder, E., and Weiblen, P.W.: Lunar petrology of silicate melt inclusion, Apollo 11 rocks. In Proceedings of the Apollo 11 Lunar Science Conference Vol. 1, pp. 801-817 (1970).

Rogers, J.J.W., and Adams, J.A.S.: Thorium. In Handbook of Geochemistry, edited by K.H. Wedepohl. Springer-Verlag, Berlin (1969).

Schnetzler, C.C., and Philpotts, J.A.: Partition coefficients of rare-earth elements between igneous matrix material and rock-forming mineral phenocrysts - II. Geochim. Cosmochim. Acta 34, 331-340 (1970).

Sears, J.H.: The physical geography, geology, mineralogy and paleontology of Essex County, Massachusetts, The Essex Institute, Salem, Mass. (1905).

Skehan, J.W.: Fracture tectonics of southeastern New England as illustrated by the Wachusett-Marlborough Tunnel, eastern Massachusetts. In Studies of Appalachian Geology, Northern and Maritime, edited by E. Zen, W. White, J. Hadley, and J.B. Thompson, pp. 281-290. Interscience, New York (1968).

Thompson, J.B., and Norton, S.A.: Paleozoic regional metamorphism in New England and adjacent area. In

Studies of Appalachian Geology, Northern and Maritime, edited by E. Zen, W. White, J. Hadley, and J.B. Thompson, pp. 319-327. Interscience, New York (1968).

Toulmin, P., III: Bedrock geology of the Salem quadrangle and vicinity, Massachusetts. U.S. Geol. Surv. Bull. 1163-A (1964).

Warren, C.H., and McKinstry, H.E.: The granites and pegmatites of Cape Ann Massachusetts. Amer. Acad. Arts and Sciences Proc. 49, 203-330 (1924).

Washington, H.S.: The petrographical province of Essex County, Massachusetts. J. Geol. 6, 787-808 (1898); 7, 53-64, 105-121, 284-294, 463-482 (1899).

Wright, T.L.: X-ray and optical study of alkali feldspar II. Am. Min. 53, 88-104 (1968).

Zartman, R.E., and Marvin, R.F.: Radiometric age of the Quincy, Cape Ann and Peabody Granites from Eastern Mass. Bull. Geol. Soc. Amer. 82, 937-958 (1971).

Zielinski, R.A., and Frey, F.A.: Gough Island: Evaluation of a fractional crystallization model. Contrib. Mineral. and Petrol. 29, 242-254 (1970).