

MEDDELELSER OM GRØNLAND

UDGIVNE AF

KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND

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MELTING RELATIONS OF
UNDERSATURATED ALKALINE ROCKS
FROM SOUTH GREENLAND

COMPARED TO THOSE OF AFRICA AND CANADA

BY

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WITH 16 FIGURES AND 11 TABLES IN THE TEXT

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Abstract

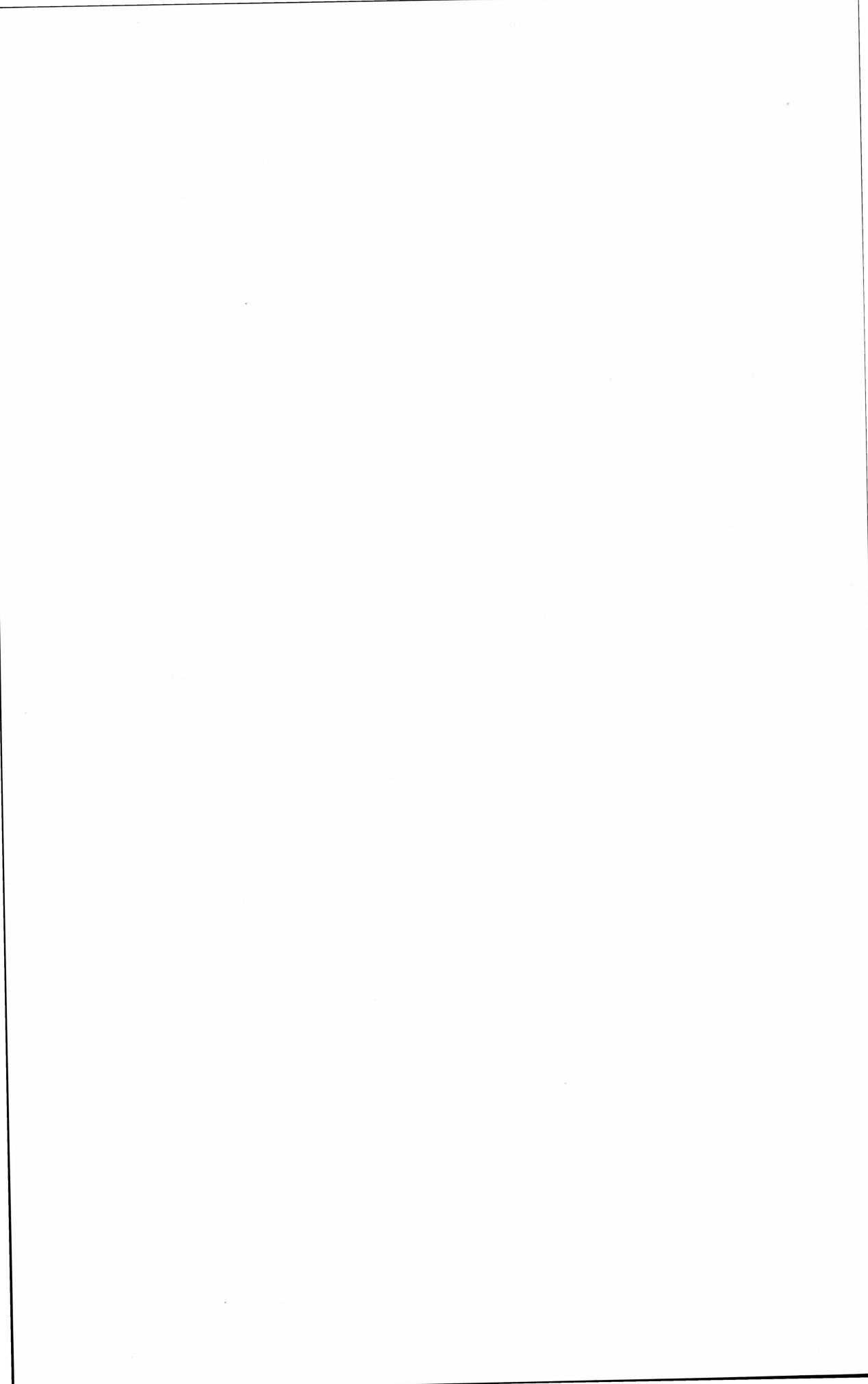
Sixteen volcanic and plutonic undersaturated alkaline rocks of diverse compositions from Greenland, Africa and Canada have been examined petrographically and their melting relations determined at 1 atmosphere pressure in air; 4 samples have been melted in an argon (non-oxidizing) environment and 6 samples at water vapour pressures up to 2070 bars. At 1 atmosphere pressure, liquidus temperatures range from 1120° to 1230° C; in the non-oxidizing atmosphere, liquidus temperatures are similar but iron-bearing minerals remain in the same oxidation state as in the unheated rock. Water vapour pressures lower liquidus temperatures by as much as 300° C with the initial 1000 bars pressure being most effective.

For the majority of samples the sequence of crystallization is nepheline, feldspar and pyroxene at 1 atmosphere pressure. Argon atmosphere and water vapour pressure alters this sequence for some rocks. There is a direct relationship between the melting intervals and chemistry of the rocks. Rocks showing aplitic trends (USSING, 1912) and high volatile contents have much longer melting intervals. A comparison of the melting data of the rocks studied with data from pertinent synthetic systems indicates high liquidus temperatures for many of these rocks when compared to synthetic systems at 1 atmosphere, but good agreement was found between the hydrothermally melted rocks and the synthetic systems at equivalent pressures.

For some of the specimens, tie-lines between coexisting nephelines and feldspars have been determined for the unheated rocks and for rocks heated to 975° C. When plotted on the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$, the slopes of the tie-lines compare favourably with those suggested by TILLEY (1958) for rocks from plutonic and volcanic environments. Relationships between liquidus temperatures, chemistry and petrography are discussed.

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INTRODUCTION

Recently, a number of investigations have been made to determine the melting relations and crystallization sequences of various rock types in an attempt to elucidate their genesis. Because of their importance as possible parents of many igneous rocks much of this work has been concerned with various types of basalts; it has been shown that a wide variety of rocks, such as pyroxenite, eclogite and amphibolite, when melted yield liquids of basaltic composition (YODER and TILLEY 1962; TILLEY, YODER and SCHAIRER 1965). Studies of non-basaltic rocks have been mainly carried out on granites and pegmatites (GORANSON 1932, JAHNS and BURNHAM 1957). BARKER (1965) has reported melting relations on litchfieldites from Maine at water vapour pressures up to 2 kilobars, and PIOTROWSKI, EDGAR and FLEET (1965) have investigated the melting behaviour of similar rocks from Blue Mountain, Ontario at atmospheric pressure.

This paper presents the results of melting experiments in air at one atmosphere, in an inert gas (argon) at one atmosphere, and at water vapour pressures of up to 2070 bars for sixteen specimens of alkaline undersaturated rocks from localities in Greenland, Africa and Canada. Choice of specimens has been made on the basis of their "igneous" origin (no samples of obvious metasomatic origin have been investigated), their lack of excessive alteration, and their variation in chemical composition. Samples of plutonic type are represented by lichfieldites, nepheline syenites, melteigites, naujaites, ijolites, pulaskites and foyaites; volcanic types are represented by phonolites, melanephelinites and nephelinites.

The objectives of this study were: —

- (1) To determine the liquidus temperatures and range of crystallization for rocks of different chemical compositions, and to compare these temperatures with crystallization sequences deduced from field and petrographic evidence.
- (2) To investigate the trends of liquidus temperatures with varying compositions for comagmatic rocks;
- (3) To compare the liquidus temperatures of these rocks with those deduced from appropriate synthetic systems;
- (4) To determine changes in the compositions of coexisting nepheline and feldspar during crystallization.

The authors are indebted to professor, Dr. H. SØRENSEN (University of Copenhagen), Dr. B. G. J. UPTON (University of Edinburgh) and Dr. C. H. EMELEUS (University of Durham) for providing samples from South Greenland which were collected during the investigations organised by the Geological Survey of Greenland in this area, and to the Director of this Survey, mag. scient. K. ELLITSGAARD-RASMUSSEN, for permission to work on this material. For the material from Africa the authors are indebted to Dr. M. J. LE BAS (University of Leicester) and Mr. R. W. BARTHOLEMEW (Geological Survey, Tanzania).

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PETROGRAPHY AND CHEMISTRY

Sample Locations

Details of the sample locations, names and donors are given in Table I. The majority of these samples are described elsewhere and no details of their geological setting are repeated here. Included in Table I are the latest published references to these rocks. Sample numbers of the donors have been retained to facilitate reference to published reports of these rocks.

Table I. *Sample Names and Locations.*

| Sample No. | Name | Locality | Donor | Reference |
|------------|------------------------|-------------------------------------|-----------------------|----------------------|
| 57044 | Naujaite | Himaussaq Intrusion, S. Greenland | Prof. Dr. H. SØRENSEN | SØRENSEN (1958) |
| 57033 | Green ijavrite | — | — | SØRENSEN (1958) |
| 57070 | Foyaite | — | — | SØRENSEN (1958) |
| | | | | FERGUSON (1964) |
| 50241 | Nepheline syenite | Tugtutôq Island, S. Greenland | Dr. B. G. J. UPTON | UPTON (1964) |
| 30640 | — | — | — | — |
| 30681 | — | — | — | — |
| 27113 | Foyaite | Grønnedal-Íka Complex, S. Greenland | Dr. C. H. EMELEUS | EMELEUS (1964) |
| K 14 | Melteigite | Ruri-Usaki Complex, Kenya | Dr. M. J. LE BAS | PULFREY (1950, 1954) |
| K 15 | Ijolite | — | — | — |
| K 2 | Nepheline syenite | — | — | — |
| K 18 | Phonolitic nephelinite | — | — | McCALL (1958) |
| K 5 | Melanephelinite | — | — | PULFREY (1950, 1954) |
| DH 940 | Phonolite | Rungwe Volcano, S. Tanzania | R. W. BARTHOLEMEW | HARKIN (1960) |
| U 880 | Phonolite | Sadiman Volcano, N. Tanzania | — | — |
| BM 1 | Litchfeldite | Blue Mountain, Ontario, Canada | Collected by authors | HEWITT (1960) |
| BM 5 | Litchfeldite | — | — | — |

Chemical analyses and CIPW norms for these samples are given in Table II. Wherever feasible modal analysis have been performed and are presented in Table III. A brief description of the petrography of these samples is given below.

Petrography

57041 — Naujaite, Ilímaussaq Intrusion. In hand specimen this rock is characterized by coarse grain size and poikilitic texture. Aegirine, arfvedsonite, eudialyte and feldspar poikilitically enclose euhedral grains of nepheline and sodalite. In thin section, sodalite occurs as dodecahedrons. Feldspar is microcline with exsolved albite showing multiple twinning. In some cases the feldspar is altered to analcite and commonly contains microlites of aegirine. Aegirine also occurs as large poikilitic anhedra showing patchy deep green to pale brown colour. Arfvedsonite has a similar occurrence but is commonly zoned. Aenigmatite is present as dark brown to opaque anhedra, generally smaller than the aegirine. FERGUSON (1964) has given optical properties for both the aegirine and aenigmatite. Large poikilitic anhedra of eudialyte with enclosed sodalite inclusions are common. When unaltered the eudialyte is a pale pink colour. Nepheline occurs as subhedral rectangular phenocrysts, up to 1 cm in diameter, enclosing microlites of aegirine and arfvedsonite. Some of the nepheline is altered to analcite and natrolite. Accessory minerals are apatite, biotite, fluorite, pyrite and pyrrhotite.

The coarse-grained nature of this specimen did not permit accurate modal analysis (in thin section). From a field analysis, FERGUSON (1964) determined approximate mineral proportions as: dark minerals (aegirine, arfvedsonite, aenigmatite) 20 %, eudialyte 4 %, feldspar 23 %, nepheline 14 %, sodalite 39 %. However modal analyses of the Ilímaussaq naujaites vary within wide limits (personal communication — professor H. SØRENSEN).

Chemical analysis of this sample (Table II) indicates a chlorine content which, when recalculated as halite and combined with available nepheline in the CIPW norm, is in fair agreement with the sodalite content given by FERGUSON.

In the specimens studied sodalite did not have the characteristic blue colour and could only be detected as sodalite by X-ray diffraction or in thin section. Correlation between the mode of this rock and the CIPW norm cannot be expected because of minerals such as eudialyte, aenigmatite etc. not allowed for in the standard norm calculation.

57033 — Lujavrite, Ilímaussaq Intrusion. This rock is strongly fissile, fine to medium-grained and pale green in colour. Poikilitic aggregates of arfvedsonite up to 10 mm in diameter are common, along with smaller

phenocrysts of eudialyte. In thin section microcline with plaid twinning and albitic feldspar with multiple twinning make up about one half of the section. Other minerals are aegirine, as bent and fractured needles oriented parallel to the fissility; arfvedsonite, as poikilitic anhedra enclosing all the other common minerals; and nepheline, as rectangular phenocrysts. Natrolite occurs as interstitial aggregates, most probably of secondary origin. Arfvedsonite is altered to acmite pyroxene and nepheline to natrolite and analcime.

The fissility and fine-grained nature of this sample did not warrant modal analysis. FERGUSON (1964) has estimated mineral proportions to be microcline 25 %, albite 15 %, aegirine 28 %, nepheline 13 %, eudialyte, 10 %, arfvedsonite 8 %, and sodalite 1 %. Although, as in the previous rock, the CIPW norm (Table II) cannot be compared with the estimated mode because of the presence of minerals such as arfvedsonite, eudialyte etc., the amounts of nepheline, feldspar and acmite in the norm are in fair agreement with those of the mode.

57070 — Foyaite, Ilímaussaq Intrusion. This rock is coarse-grained, holocrystalline and mesocratic, containing stubby laths of feldspar and semipoikilitic aggregates of pyroxene and amphibole. Anhedra of sodalite are partly altered to analcime. In thin section, the major minerals are crypto- and micro-perthitic feldspar, pyroxene (mainly aegirine-augite), arfvedsonite, nepheline and natrolite. Nepheline is altered to zeolites and possibly pectolite with natrolite pseudomorphing nepheline. FERGUSON (1964) has reported zoning in the pyroxenes with increased soda content toward the rims. No estimation of the percentage minerals for this sample are given by FERGUSON and the degree of alteration did not warrant modal analysis.

Detailed descriptions of the geology of the Ilímaussaq region have been given by USSING (1912), SØRENSEN (1958) and FERGUSON (1964). FERGUSON believed that augite syenite and alkali acid magmas formed the intrusion, and that the augite syenite magma followed a peralkaline course of *in situ* differentiation which, aided by volatile enrichment, produced the agpaitic rocks — lujavrite, naujaite, sodalite foyaite and kakortokite. All of the specimens used in the present study are agpaitic¹⁾: The later alkali acid magma was injected into the partially differentiated augite syenite magma in the upper part of the magma chamber. The differentiates of this magma are alkali granites and quartz syenites. The

¹⁾ The definition of an agpaitic rock as used throughout this paper is that of Gerasimovskii (1956) *i.e.* a rock in which $\frac{\text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{Al}_2\text{O}_3} \geq 1$ (as molecular proportions). Other definitions have been proposed notably by USSING (1912) and FERSMAN (1929, 1939). These are discussed by SØRENSEN (1960).

Table II. *Chemical Analysis and C.I.P.W.*

| Wt. percent | No. BM 1 ¹⁾ | BM 5 ¹⁾ | 50241 ²⁾ | 30640 ²⁾ | 30681 ²⁾ | U 880 ³⁾ | DH 940 ³⁾ |
|--|------------------------|--------------------|---------------------|---------------------|---------------------|---------------------|----------------------|
| SiO ₂ | 57.02 | 59.33 | 58.53 | 57.51 | 54.17 | 50.42 | 56.30 |
| Al ₂ O ₃ | 23.48 | 22.61 | 17.42 | 16.54 | 19.34 | 20.60 | 21.42 |
| Fe ₂ O ₃ | 0.84 | 1.27 | 3.08 | 4.32 | 6.00 | 4.41 | 3.20 |
| FeO | 1.52 | 0.85 | 4.56 | 4.56 | 1.86 | 1.93 | 0.52 |
| MgO | 0.11 | 0.05 | 0.47 | 0.27 | 0.24 | 0.53 | 0.51 |
| CaO | 0.51 | 0.94 | 2.43 | 2.37 | 1.74 | 5.92 | 1.65 |
| Na ₂ O | 10.03 | 9.94 | 5.82 | 6.15 | 7.71 | 7.53 | 8.40 |
| K ₂ O | 4.97 | 4.24 | 5.74 | 5.89 | 5.32 | 3.71 | 5.36 |
| H ₂ O + | 0.66 | 0.37 | 0.64 | 1.19 | 2.70 | 3.38 | 1.28 |
| H ₂ O— | 0.05 | 0.04 | 0.08 | 0.20 | 0.12 | 0.18 | 0.20 |
| TiO ₂ | 0.03 | 0.03 | 0.71 | 0.54 | 0.37 | 0.54 | 0.53 |
| P ₂ O ₅ | 0.02 | 0.01 | 0.16 | 0.10 | 0.10 | 0.09 | 0.04 |
| MnO | 0.04 | 0.04 | 0.17 | 0.20 | 0.17 | 0.23 | 0.32 |
| S | — | — | n. d. | n. d. | 0.02 | — | — |
| Cl | — | — | n. d. | n. d. | 0.02 | — | — |
| CO ₂ | 0.36 | 0.44 | n. d. | n. d. | n. d. | 0.48 | 0.07 |
| Total | 99.66 | 99.83 | 99.81 | 99.84 | 99.88 | 99.65 | 99.80 |
| Or | 29.36 | 25.08 | 34.4 | 35.8 | 32.7 | 21.83 | 31.61 |
| Ab | 39.20 | 48.16 | 43.8 | 42.1 | 36.2 | 26.85 | 35.04 |
| An | 0.28 | 3.94 | 4.4 | — | 2.6 | 12.60 | 5.31 |
| Lc | — | — | — | — | — | — | — |
| Ks | — | — | — | — | — | — | — |
| Ne | 24.68 | 19.43 | 3.3 | 5.9 | 16.7 | 18.81 | 19.09 |
| Cor | 1.90 | 0.20 | — | — | — | — | — |
| Ac | — | — | — | — | — | — | — |
| Wo | — | — | — | 4.3 | 1.6 | 5.46 | — |
| Di | — | — | 5.8 | 0.8 | 1.3 | 2.84 | 2.23 |
| Ol | 1.80 | 0.35 | 2.2 | 5.0 | — | — | 0.17 |
| Mt | 1.28 | 1.88 | 4.4 | 4.7 | 5.5 | 5.40 | 1.18 |
| Il | 0.05 | 0.04 | 1.4 | 1.4 | 0.8 | 1.02 | 1.00 |
| Hm | — | — | — | — | 2.3 | 0.67 | 2.38 |
| Ap | 8.8 | — | 0.3 | 0.3 | 0.3 | tr. | — |
| Ct | 0.84 | 0.25 | — | — | — | — | — |
| Ne | — | — | — | — | — | 0.42 | 0.16 |
| 2CaO.SiO ₂ | — | — | — | — | — | — | — |
| Recalculated to Q-Ne-Ks. | | | | | | | |
| Q | 33.57 | 35.61 | 42.83 | 41.47 | 35.89 | 32.22 | 36.87 |
| Ne | 48.40 | 49.01 | 33.15 | 34.19 | 42.38 | 49.41 | 40.87 |
| Ks | 18.03 | 15.37 | 24.02 | 24.34 | 21.73 | 18.37 | 22.26 |

¹⁾ Analyst: M. E. L. FLEET.²⁾ Analyses from UPTON (1964).³⁾ Analyses by Technical Services, Toronto, Canada.⁴⁾ Analyst: K. RAMLAL.⁵⁾ Includes ZrO₂ = 0.086; additional normative mineral — Zircon 0.18.

Norms of Alkaline Rocks.

| K 2 ⁴⁾ | K 5 ³⁾ | K 14 ³⁾ | K 15 ³⁾ | K 18 ³⁾ | 57041 ⁴⁾ | 57033 ³⁾ | 57070 ⁴⁾ | 27113 ⁴⁾ |
|---------------------|-------------------|--------------------|--------------------|--------------------|---------------------|---------------------|---------------------|---------------------|
| 49.75 | 38.10 | 40.62 | 39.80 | 48.16 | 47.05 | 52.96 | 50.59 | 51.50 |
| 19.05 | 8.76 | 9.26 | 14.22 | 22.22 | 21.34 | 15.52 | 17.09 | 16.80 |
| 3.77 | 8.30 | 9.95 | 5.96 | 3.84 | 3.59 | 7.73 | 5.85 | 6.15 |
| 1.48 | 8.13 | 4.64 | 2.06 | 2.71 | 3.08 | 2.18 | 4.68 | 4.68 |
| 1.16 | 7.49 | 8.02 | 1.73 | 0.78 | 0.03 | 0.02 | 0.38 | 1.04 |
| 4.74 | 16.61 | 17.82 | 21.53 | 4.87 | 2.68 | 0.88 | 1.94 | 4.53 |
| 9.02 | 3.85 | 3.08 | 7.20 | 8.46 | 14.43 | 11.60 | 10.04 | 7.56 |
| 5.79 | 1.89 | 1.24 | 3.08 | 5.02 | 3.67 | 3.36 | 3.48 | 4.87 |
| 2.32 | 2.36 | 2.06 | 1.36 | 2.40 | { 1.03 | 3.04 | 0.07 | 1.04 |
| — | 0.32 | 0.14 | 0.14 | 0.24 | | 0.10 | 4.31 | — |
| 0.59 | 3.00 | 2.08 | 1.62 | 0.69 | 0.27 | 0.32 | 0.42 | 0.17 |
| 0.29 | 0.88 | 0.79 | 0.38 | 0.16 | 0.09 | 0.01 | 0.17 | 0.11 |
| 0.21 | 0.26 | 0.30 | 0.37 | 0.27 | 0.12 | 0.15 | 0.24 | 0.36 |
| — | — | — | — | — | — | 0.07 | 0.02 | 0.06 |
| — | — | — | — | — | 2.57 | 0.02 | 0.21 | — |
| 1.52 | 0.17 | 0.07 | 0.45 | 0.14 | 0.16 | 0.06 | 0.16 | 0.54 |
| 99.76 ⁵⁾ | 100.12 | 100.07 | 99.90 | 99.96 | 99.69 ⁶⁾ | 99.85 ⁷⁾ | 99.79 ⁸⁾ | 99.54 ⁹⁾ |
| 34.47 | — | — | 8.39 | 29.56 | 20.57 | 20.02 | 20.53 | 28.91 |
| 5.24 | — | — | 0.10 | 9.49 | 5.24 | 24.63 | 21.60 | 19.91 |
| — | 1.11 | 8.24 | — | 8.71 | — | — | — | — |
| — | 2.62 | 5.72 | 7.64 | — | — | — | — | — |
| — | 4.51 | — | — | — | — | — | — | — |
| 31.67 | 17.61 | 13.67 | 30.29 | 32.73 | 46.01 | 19.60 | 25.43 | 21.30 |
| — | — | — | — | — | — | — | — | — |
| 9.24 | — | — | 3.56 | — | 10.63 | 22.18 | 13.30 | 4.16 |
| 0.12 | — | 8.26 | — | 2.76 | 0.12 | — | — | 0.23 |
| 9.49 | 47.08 | 43.08 | 9.29 | 6.39 | 9.89 | 1.46 | 7.30 | 15.04 |
| — | — | — | — | — | — | 2.24 | 3.43 | — |
| 0.93 | 12.06 | 8.70 | 3.10 | 5.56 | — | — | 1.81 | 6.73 |
| 1.06 | 5.78 | 3.95 | 3.10 | 1.31 | 0.61 | — | 0.79 | 0.30 |
| — | — | 4.54 | 2.59 | — | — | — | — | — |
| 0.67 | 2.04 | 2.19 | — | 0.37 | 0.34 | — | 0.37 | 0.34 |
| 3.50 | 0.40 | — | — | — | 0.40 | 0.10 | 0.03 | 1.20 |
| — | — | 0.16 | 0.17 | 0.33 | — | — | — | — |
| — | 4.13 | — | — | — | — | — | — | — |
| — | — | — | — | — | — | — | — | — |
| — | — | — | — | — | — | — | — | — |
| — | — | — | — | — | — | — | — | — |

⁶⁾ Includes $ZrO_2 = 0.36$; additional normative minerals — Zircon 0.55, n.s. 0.24, halite 4.21.

⁷⁾ Includes $ZrO_2 = 1.11$, F = 0.72; additional normative minerals — Zircon 1.65, fluorite 1.48, pyrite 0.12, n.s. 2.81.

⁸⁾ Includes $ZrO_2 = 0.15$, additional normative minerals — Zircon 0.22, pyrite 0.06, halite 0.33.

⁹⁾ Includes $ZrO_2 = 0.130$; additional normative mineral — Zircon 0.18.

specimen used in this study are therefore according to FERGUSON differentiates of an earlier magma.

50241, 30640, 30681 — Nepheline syenites, Tugtutôq, S. Greenland.

The three samples from this locality occur as a dike 555 m in width and 20 km in length, consisting of a narrow margin of syenogabbro and a late central intrusion of syenite; the latter shows a longitudinal variation from larvikite-type augite syenite in the south-west to soda-rich nepheline syenite in the north-east (UPTON, 1964). UPTON believes that these variations can be explained as due to crystal fractionation.

Since the samples used in this study were supplied as powders, their descriptions are taken from UPTON (1964). The rocks are mesocratic and moderately coarse-grained. In 50241, the feldspar occurs as cryptoperthitic subhedral grains, tabular parallel to 010, whereas in 30640 the feldspar is antiperthitic. Subhedral fresh nepheline occurs interstitially with the feldspar and also in a matrix of analcite and thomsonite. In 50241, the pyroxene is zoned with the core consisting of ferrohedenbergite. Barkevikite reaction rims surround the pyroxene. In 30640 the pyroxene is a zoned aegirine-augite with γ_{Ae} increasing from 60° to 70° from core to rim. Amphibole is minor in this sample. Sample 30640 has not been described but from its locality probably corresponds to UPTON's soda-rich nepheline syenite.

Analyses and CIPW norms are given in Table II.

27113 — Foyaite, Grønnedal-Íka Complex, S. Greenland. In hand specimen this rock shows well-developed lamination due to the parallel alignment of tabular crystals of alkali feldspar. Nepheline, aegirine-augite and biotite occur interstitially. In thin section, the alkali feldspar can be identified as microcline microperthite. Nepheline, partially altered to fibrous cancrinite, occurs interstitially to the feldspar. Aegirine-augite forms poikilitic aggregates. Dark brown pleochroic biotite is commonly intergrown with magnetite. Accessory amounts of calcite are also found. Modal analysis of this sample is given in Table III.

The geology of this complex has been described in detail by EMELEUS (1964). The complex consists of foyaite, nepheline syenite and carbonatite. The foyaite, represented by sample 27113, is believed to be an igneous cumulate in which alkali feldspar and nepheline crystallized early to form the cumulus phase with the other minerals crystallizing from the trapped interstitial liquid.

K14 — Melteigite, Ruri-Usaki Complex, Kenya. In hand specimen this rock is very dense, fine-grained melanocratic. The principal constituents in thin section are subhedral aegirine-diopside, magnetite and garnet with minor amounts of nepheline and accessory perovskite, biotite, apatite,

Table III. *Modal Analysis.*

| | 50241 ¹⁾ | 30640 ¹⁾ | 30681 ¹⁾ | 27113 | K 2 | K 15 | K 14 | K 18 | BM 1 | BM 5 |
|---------------|---------------------|---------------------|---------------------|-------|------|------|------|------|-------|-------|
| K-Na..... | 79.2 | 72.4 | 41.4 | 34.8 | 24.8 | — | — | 17.5 | 19.50 | 24.94 |
| Feldspar.... | — | — | — | — | — | — | — | — | 43.42 | 54.04 |
| Albite..... | — | — | — | — | — | — | — | — | — | — |
| Nepheline... | 7.6 | 5.0 | 23.4 ²⁾ | 31.4 | 47.7 | 57.6 | 4.4 | 26.3 | 30.30 | 19.62 |
| Pyroxene... | 4.3 | 8.1 | 14.6 | 22.8 | 21.3 | 23.5 | 72.3 | 7.6 | tr. | — |
| Amphibole... | 5.0 | 0.5 | — | — | — | — | — | — | 1.47 | — |
| Biotite..... | — | — | — | 8.2 | — | — | 0.7 | — | 0.10 | 0.30 |
| Muscovite... | 0.5 | — | — | — | — | — | — | — | — | — |
| Garnet..... | — | — | — | — | — | 5.3 | 8.6 | 0.6 | — | — |
| Wollastonite. | — | — | — | — | — | 3.6 | — | — | — | — |
| Analcite..... | 0.4 | 2.8 | 27.1 | — | — | — | — | — | — | — |
| Natrolite.... | — | — | — | — | 2.0 | — | — | — | — | — |
| Ore..... | 3.0 | 2.5 | 3.8 | 0.3 | — | 5.3 | 12.2 | — | 0.10 | 0.43 |
| Perovskite... | — | — | — | — | — | 0.2 | 1.0 | — | — | — |
| Sphene..... | 0.2 | — | — | — | — | — | — | 0.2 | — | — |
| Alteration... | — | 7.0 | 27.1 | 2.2 | 4.2 | 6.0 | — | 0.3 | 6.60 | — |
| Groundmass. | — | — | — | — | — | — | — | 47.5 | — | — |
| Others..... | — | — | — | 0.6 | — | 1.1 | 0.7 | — | 0.76 | 0.79 |

¹⁾ from UPTON (1964).²⁾ includes 10.6 percent gieseckite.

calcite and zeolites (Table III). The magnetite is titaniferous and occurs as large aggregates interstitial to the pyroxene, which PULFREY (1950) believes to be due to replacement. The melanite garnet has a similar occurrence. Nepheline occurs as relatively fresh interstitial anhedral crystals.

K 15 — Ijolite, Ruri-Usaki Complex, Kenya. This rock represents a wollastonitic ijolite and is one of four types of ijolite found in this locality. In hand specimen it is coarse-grained mesocratic. Principal constituents are nepheline, as large, fresh idiomorphic crystals and less commonly as small, anhedral grains interstitial to the larger crystals; and interstitial aggregates of slightly altered subidiomorphic aegirine-diopside showing a patchy colour variation suggestive of zoning. PULFREY (1950) gives an analysis of this mineral. Minor constituents are garnet, rimming inclusions in the nepheline and pyroxene; large prisms of wollastonite; and ore minerals. Accessories are interstitial calcite and zeolites with apatite and perovskite. Modal analysis of this specimen is given in Table III.

K 2 — Nepheline syenite, North Ruri, Kenya. In hand specimen, this rock is medium-grained, grey coloured and contains phenocrysts of feldspar and nepheline recognizable on weathered surfaces. In thin section, the predominant minerals are platy crystals of orthoclase containing

euhedral nepheline inclusions, zoned nepheline, zoned aegirine-diopside with cores of augite, and sphene. The nepheline shows all stages of replacement by cancrinite and calcite. Natrolite and sphene occur in the groundmass as fibrous aggregates and euhedral crystals respectively. Proportions of minerals are given in Table III.

K 18 — Phonolitic Nephelinite, Ruri-Usaki, Complex, Kenya. In hand specimen this rock is a mesocratic, medium to coarse-grained, porphyritic nephelinite. In thin section, idiomorphic crystals of nepheline and feldspar are well developed. Zoned pyroxene phenocrysts have aegirine-diopside cores and aegirine rims. Garnet is rare and occurs as aggregates associated with the pyroxene. Apatite and magnetite are accessories. The phenocrysts are set in a very fine-grained groundmass of pyroxene, nepheline and feldspar. Alteration is very minor. Modal analysis is given in Table III.

K 5 — Melanephelinite, Ruri-Usaki Complex, Kenya. This is a dark grey, dense porphyritic rock containing phenocrysts of aegirine-augite and altered olivine. In thin section the most conspicuous feature is the abundant magnetite, varying in size from minute grains up to small phenocrysts, occurring evenly throughout the section. Aegirine-augite occurs as subhedral prismatic phenocrysts and as smaller grains scattered throughout the groundmass. Minor olivine occurs as badly altered phenocrysts and in the groundmass. The fine-grained nature of this sample did not warrant modal analysis.

Chemically this rock is very similar to K 14 (Table II).

The geology of the Ruri-Usaki district of Kenya has been described in detail by PULFREY (1950, 1954). This district consists of a varied suite of Tertiary carbonatite and alkaline rocks which have formed ring complexes around four volcanic vents. The generalized sequence of intrusion consists of early ijolite and nepheline syenites, carbonatite intrusions, and finally phonolitic nephelinite plugs and dikes.

DH 940 — Phonolite, Rungwe Volcanies, S. Tanzania. In hand specimen this phonolite is dense, dark-grey in colour with occasional phenocrysts of platy feldspar in a trachytic matrix. In thin section this rock is holocrystalline and porphyritic. The dominant phenocrysts are orthoclase microperthite but less commonly phenocrysts of euhedral to subhedral nepheline and aegirine containing magnetite inclusions are observed. The groundmass consists of feldspar microlites with interstitial nepheline, granular pyroxene, and rare crystals of sphene. The fine grain size of the specimen did not make modal analysis feasible.

U 880 — Phonolite, Sadiman Volcano, N. Tanzania. This specimen is a dense, dark green, porphyritic rock characterized by abundant nepheline phenocrysts and rarer subhedral pyroxene phenocrysts. In thin sec-

tion the texture is holocrystalline and porphyritic with phenocrysts of nepheline, aegirine-augite, wollastonite and sphene in a dense groundmass of feldspar, nepheline, pyroxene and magnetite.

Sample DH 940 is from the Rungwe volcanics located near the junction of the Eastern and Western Rift systems in Southern Tanzania. The geology of this area has been described in detail by HARKIN (1960). U 880 is from the Sadiman Volcano, west of the Ngorongoro Crater, approximately 20 miles east of Gregory Rift Valley.

BM 1, BM 5 — Litchfieldites, Blue Mountain, Ontario, Canada. These rocks are uniformly massive, medium-grained and leucocratic in hand specimen. The major minerals are microcline, albite and nepheline with accessory magnetite, biotite, hastingsite, aegirine, muscovite, calcite, corundum (rare), zircon and apatite. In thin section the texture is generally granitic although a distinct foliation can be found in some samples of this type of rock. Albite (An_{1-5}) and microcline occur as subhedral grains while nepheline is commonly interstitial to the feldspars. The feldspars are generally very fresh but nepheline may show minor alteration. The lack of alteration and very minor amounts of accessory minerals make these two rocks ideally suited for melting experiments. Their normative albite, orthoclase and nepheline contents when recalculated to nepheline, kalsilite and quartz, are greater than 90 percent. Thus they can be directly compared to synthetic liquidus relations in Petrogeny's Residua System ($NaAlSiO_4$ — $KAlSiO_4$ — SiO_2).

Chemical and modal analysis of these samples are given in Tables II and III respectively. Chemically both are very similar. However BM 1 is a ferrohastingsite-rich sample whereas BM 5 contains no amphibole.

The Blue Mountain complex outcrops in the Grenville province of the Canadian Shield and consists mainly of nepheline syenites (litchfieldites) and leucosyenites surrounded by Precambrian granites, orthogneisses and paragneisses. The litchfieldite occurs as an elongate pear-shaped body striking ENE and approximately 6 miles long. Many workers have investigated this body. The general geology of the area and a summary of the hypothesis of its origin have been given by HEWITT (1960).

Chemistry

Analyses and CIPW norms of the 14 analysed rocks (Table II) show that they represent a wide diversity of composition with SiO_2 contents ranging from 39.80 (K 18) to 59.33 (BM 5) weight percent. This range almost covers the compositional spectrum of alkaline undersaturated rocks. In addition three of the samples have agpaitic characteristics and show distinctively different melting features from those with non-agpaitic tendencies.

EXPERIMENTAL METHODS

a) Sample Preparation

The size of sample chosen for the melting experiments was dependant on the availability of material (some of the samples donated were small) and the heterogeneity of the rock. Whenever possible samples were of sufficient size to give a fair representation of the rocks.

Prior to melting, all samples were crushed in a mechanical grinder to pass through a 100 mesh sieve and then ground under acetone for two hours in a mechanical agate mortar. The powder was then remixed and reduced in size by the method of "coning and quartering" until a 5-10 g sample was obtained. The rock powder was then dried at 105° C for 1 hour and stored in a sealed container.

b) Apparatus

(i) *Melting Experiments at One Atmosphere*: All runs at one atmosphere were done in conventional 12 inch long Pt-wound vertical resistance furnaces. Temperatures were controlled by Pt-10 % Rh thermocouples, calibrated at the melting points of NaCl(801° C) and Au(1063° C), and recorded on a potentiometer. Desired temperatures were obtained by varying the input voltage using a transformer. Temperature measurements are believed to be accurate to within $\pm 10^{\circ}$ C. For runs carried out in an argon atmosphere, the furnaces were modified to permit the slow flowage of argon throughout the run, the rate of argon being controlled by means of a micrometer-type valve. The procedure used for each run was to suspend about 100 mg of sample, wrapped in Pt foil on a loop of fine Pt-wire. This charge was held at a fixed temperature for the desired length of time. At the end of the experiment the samples was quenched by passing a current through the Pt-wire, thus dropping the sample into a dish of mercury.

Detailed descriptions of this type of furnace, their operation and quenching procedures are given by FAUST (1936).

(ii) *Hydrothermal Experiments*: Melting experiments were carried out at water vapour pressures up to 2,070 bars using cold-seal pressure vessels (TUTTLE, 1949) and the sealed-tube technique of GORANSON (1931).

Ratios of distilled water to powdered rock were kept constant at 1:6 by weight in all runs. The presence of water at the end of each run indicated that the experiments had taken place under conditions of excess water. Temperatures, recorded on previously calibrated chromel-alumel thermocouples, are believed to be accurate to within $\pm 5^\circ$ C. Pressures were recorded on a Bourdon type pressure gauge and are believed accurate to within ± 4 percent of the stated values.

(iii) *Identification of Products.* At the end of each experiment the charge was removed from its container and examined optically using a standard petrographic microscope and the appropriate refractive index oils. A Philips high angle X-ray diffractometer with filtered copper radiation was used to confirm the optical observations. For routine identification the diffractometer was set to scan at $1^\circ 2\theta$ per minute at a chart speed of $\frac{1}{2}$ inch per minute. For the determination of the compositions of the nephelines and feldspars, described below, the diffractometer was run at $\frac{1}{4}^\circ 2\theta$ per minute with a chart speed of $\frac{1}{4}$ inch per minute.

(iv) *Determination of Mineralogical Composition.* Compositions of alkali feldspars and nephelines were determined for certain samples before heating and during the melting interval in order to ascertain what changes, if any, had taken place. Lack of proven X-ray diffraction methods, and the fine-grained nature of the heated products (making optical methods impractical) did not permit determination of other crystalline phases.

Alkali feldspar compositions were determined using the $\Delta 2\theta$ ($\bar{2}01$ - $KBrO_3$ $_{111}$) method of ORVILLE (1963). For the unheated specimens, the feldspars were separated by hand picking, and, when perthitic, homogenized at 1050 - 1080° C for 36 hours at atmospheric pressure. The accuracy of this method is believed to be within ± 2 mole percent Or (ORVILLE, 1963).

Nepheline compositions were determined using the X-ray method of HAMILTON and MACKENZIE (1960) which involves measurement of the positions of the $20\bar{2}2$ and $21\bar{3}0$ nepheline reflections using an internal standard (Si_{111}). The reflections are reproducible to $\pm 0.02^\circ 2\theta$. Although this method will determine nepheline compositions as represented in the system SiO_2 - $NaAlSiO_4$ - $KAlSiO_4$ it does not allow for the amount of calcium or other constituents. However, WILKINSON (1965) has shown that chemically determined compositions and compositions determined by this X-ray method are in good agreement.

(v) *Evaluation of Experimental Procedure:* Two important problems arise in the experimental procedure used in this study. Of prime importance is whether the liquidus temperatures and crystallization temperatures of the various minerals represent equilibrium conditions. The easiest criteria to establish equilibrium is to approach liquidus temperatures from

the low temperature assemblage (rock powder) and the high temperature assemblage (glass). If liquidus temperatures are the same using both methods, they be considered are representing equilibrium. However, FYFE (1960) has shown that it is impossible to give absolute proof whether such equilibrium represents stable or metastable conditions.

Wherever feasible this test of equilibrium was applied in the present study. However, in a number of samples this could not be used for the following reasons:

- (1) presence of minerals with high fusion temperatures, such as corundum and hematite, which were not melted; in these samples no absolute liquidus temperature was attained;
- (2) presence of minerals with volatile constituents, such as sodalite, biotite and hornblende which will release their volatiles on heating and cannot recrystallize on cooling from a glass;
- (3) presence of minerals such as aegirine, which melt incongruently and may not when cooled reform the original mineral. For example, BAILEY and SCHAIRER (1966, p. 124) have shown that hematite produced by the incongruent melting of acmite in the system acmite-jadeite- $\text{Na}_2\text{O} \cdot 4\text{SiO}_2$ enters into the nepheline and albite structures. There is a strong possibility that similar phenomena will take place in the present experiments.
- (4) Rates of crystallization of different minerals vary according to temperature composition, structure and to the viscosity of their liquids. For example, under atmospheric conditions albite and orthoclase will not crystallize from liquids of their own composition but with the addition of magnetite they crystallize readily (DAY and ALLEN, 1905).

Within the limits of experimental error, it was possible to show that equilibrium temperatures had been attained in a number of samples. Liquidus temperatures obtained from the glass assemblages were slightly higher than those obtained from the powdered rocks. One exception to this was sample U 880 in which there was a 40–60° C temperature difference. No reasonable explanation for this discrepancy can be offered at the present time. Under hydrothermal conditions, where the system is closed and volatiles cannot escape, liquidus temperatures from the high and low temperature assemblages were within 10° C of one another. It seems probable that in the majority of samples liquidus temperatures represent equilibrium conditions.

The second problem in the experimental procedure used in this study involves the reaction of iron-bearing minerals with the Pt-container of the charge, and the oxidation of ferrous iron during heating in air at atmospheric pressure. In both cases, the PO_2 which occurs during the crystallization of the rock cannot be maintained and changes in the oxidation state may influence the mineral stabilities (TILLEY, YODER, and SCHAIRER, 1965, p. 375).

For the temperatures and times of runs used in this study it is believed that loss of iron due to alloying with the Pt-containers is not a serious problem and consequently did not warrant the use of special alloys (MUAN, 1962). KENNEDY (1948, p. 533) found that only 0.09 percent iron alloyed with the Pt-containers at temperatures and times similar to those of the present study.

Oxidation of iron due to heating in air is a more serious problem and is a function of the amount of iron and the minerals it forms (controlling the initial ferrous-ferric ratio), the temperature and duration of the experiment, the particle size of the starting material, and the size of the charge. Samples with a high iron content were run in an argon atmosphere, and, although the partial pressure of oxygen could not be controlled, it was sufficiently low to prevent oxidation of magnetite in runs of 16 hours duration. Estimation of the extent of oxidation can be made by considering the initial ferrous-ferric ratios, temperatures, and durations of the experiments. High concentrations of ferrous iron and high temperatures will, of course, favour rapid oxidation. KENNEDY (1948) has shown that for rocks with $\text{FeO} > \text{Fe}_2\text{O}_3$ there is generally an initial decrease in FeO within the first few hours of heating. In the present experiments, only five of the sixteen samples had $\text{FeO} > \text{Fe}_2\text{O}_3$ and of these two were investigated under an argon (non-oxidizing) atmosphere.

For large charges with very fine-grained starting material, longer times will be required for reactions to go to completion. Charge and particle sizes are difficult to evaluate but it is believed that the 100 mg samples of -100 mesh material used in this study are sufficiently small to permit reactions to go to completion but large enough to prevent excessive oxidation. However, possible changes in the ferrous-ferric ratios due to oxidation and alloying of iron with the Pt cannot be completely eliminated when interpreting the results.

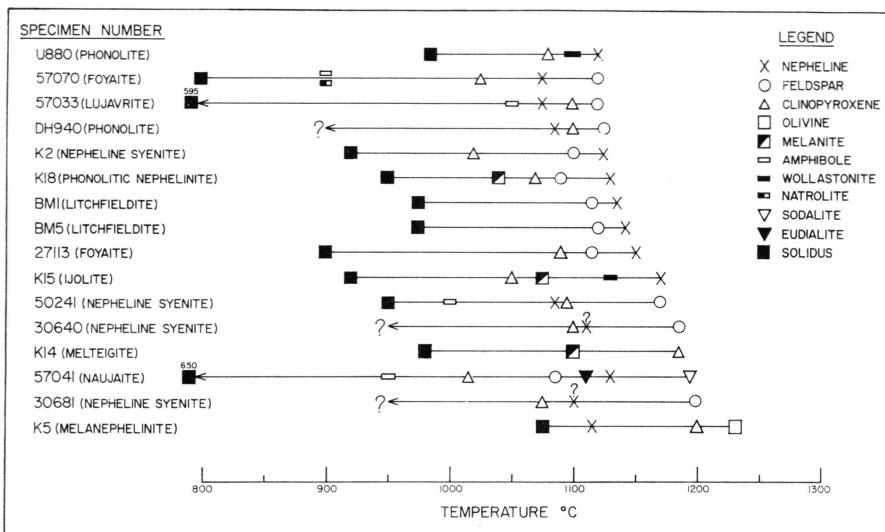


Fig. 1. Melting relations at 1 atmosphere in air.

RESULTS

(a) Experiments at One Atmosphere Pressure in Air

Results of heating experiments at one atmosphere pressure in air are given in Table IV and summarized in Fig. 1, where the samples have been arbitrarily arranged in order of increasing liquidus temperatures.¹⁾ The range of liquidus temperatures (1120°–1230° C) is very low considering the chemical variability of the rocks studied. The intrusive rocks have a slightly lower range of liquidus temperatures (1120°–1195° C) than the extrusive rocks.

In an attempt to show whether there was any correlation between the chemistry of these rocks and their liquidus temperatures, numerous chemical parameters were plotted against liquidus temperatures for the Kenyan rocks (Samples K 2, K 5, K 14, K 15 and K 18 — representing an ijolitic type), the Ilímaussaq rocks (Samples 57033, 57041, and 57070 — representing an agpaitic type), and the Tugtutôq rocks (Samples 30640, 30681, and 50241 — representing a non-agpaitic type). The only parameters showing any trends are weight percent SiO_2 , Al_2O_3 , TiO_2 and

¹⁾ Liquidus temperature is defined here as that temperature at which the rock is completely melted *exclusive* of minor amounts of high melting minerals such as magnetite, hematite, corundum, sphene and apatite.

Table IV. *Results of Experiments at 1 Atmosphere in Air.*
 (Only experiments indicating a phase change are listed).
 Results are listed in the same sequence as given in Fig. 1.

| Temp. (° C) | Time (hours) | Products ¹⁾ |
|---------------------------------------|-----------------|---------------------------------------|
| U 880 Phonolite, Tanzania | | |
| 1125 | 20 | Gl. |
| 1113 | 17 | Gl., Ne. |
| 1085 | 13 | Gl., Ne., Wo. |
| 1076 | 23 | Gl., Ne., Wo., Clpx., Fp(?) |
| 1055 | 23 | Gl., Ne., Wo., Clpx., Fp. |
| 978 | 6 | Gl., Ne., Wo., Clpx., Fp. |
| 970 | 6 | Ne., Wo., Clpx., Fp. |
| 57070 Foyaite, Ilmaussaq, Greenland | | |
| 1128 | 24 | Gl. |
| 1112 | 24 | Gl., Fp. |
| 1075 | 24 | Gl., Fp., Ne. |
| 1040 | 22 | Gl., Fp., Ne., Clpx. |
| 941 | 25 | Gl., Fp., Ne., Clpx. |
| 890 | 24 | Gl., Fp., Ne., Clpx., Nat., Amph. |
| 820 | 24 | Gl., Ne., Clpx., Nat., Amph. |
| 610 | 78 | Gl. (?), Ne., Clpx., Nat., Amph. |
| 57033 Lujavrite, Ilmaussaq, Greenland | | |
| 1128 | 19 | Gl. |
| 1102 | 6 | Gl., Fp. |
| 1095 | 17 | Gl., Fp., Clpx. |
| 1062 | 23 | Gl., Fp., Clpx., Ne., Eud. (?) |
| 1042 | 24 | Gl., Fp., Clpx., Ne., Eud. (?), Amph. |
| 907 | 6 | Gl., Fp., Clpx., Ne., Eud., Amph. |
| 646 | 41 | Gl., Fp., Clpx., Ne., Eud., Amph. |
| 580 | 76 | Fp., Clpx., Ne., Eud., Amph. |
| DH 940 Phonolite, Tanzania | | |
| 1140 | 22 | Gl. |
| 1123 | 24 | Gl., Fp. |
| 1082 | 23 | Gl., Fp., Clpx. |
| 1070 | 18 | Gl., Fp., Clpx., Ne. |
| 945 | 9 | Gl. (?), Fp., Clpx., Ne. |
| 870 | 14 | Fp., Clpx., Ne. |

¹⁾ Abbreviations: Gl. = glass, Ne. = nepheline, Fp. = feldspar, Clpx. = clinopyroxene, Wo. = wollastonite, Nat. = natrolite, Amph. = amphibole, Eud. = eudialyte, Mel. = melanite, Sod. = sodalite, Ol. = olivine. Iron oxide, usually as hematite, is present in many of the runs but has not been listed.

(continued)

Table IV (cont.).

| Temp. (° C) | | Time (hours) | Products |
|----------------|------------------------------------|-----------------|----------------------------|
| K 2 | Nepheline Syenite, Kenya. | | |
| 1128 | | 24 | Gl. |
| 1112 | | 24 | Gl., Ne. |
| 1090 | | 24 | Gl., Ne., Fp. |
| 1000 | | 23 | Gl., Ne., Fp., Clpx. |
| 957 | | 24 | Gl., Ne., Fp., Clpx. |
| 948 | | 24 | Ne., Fp., Clpx. |
| K 18 | Phonolitic Nephelinite, Kenya. | | |
| 1140 | | 23 | Gl. |
| 1124 | | 24 | Gl., Ne. |
| 1101 | | 24 | Gl., Ne. |
| 1083 | | 25 | Gl., Ne., Fp. |
| 1055 | | 30 | Gl., Ne., Fp., Clpx. |
| 1038 | | 24 | Gl., Ne., Fp., Clpx., Mel. |
| 967 | | 22 | Gl., Ne., Fp., Clpx., Mel. |
| 904 | | 24 | Ne., Fp., Clpx. |
| BM 1 | Litchfieldite, Ontario. | | |
| 1138 | | 52 | Gl. |
| 1127 | | 24 | Gl., Ne. |
| 1115 | | 24 | Gl., Ne., Fp. |
| 972 | | 26 | Gl., Ne., Fp. |
| 951 | | 19 | Ne., Fp. |
| BM 5 | Litchfieldite, Ontario. | | |
| 1146 | | 24 | Gl. |
| 1133 | | 22 | Gl., Ne. |
| 1127 | | 24 | Gl., Ne. |
| 1115 | | 24 | Gl., Ne., Fp. |
| 993 | | 25 | Gl., Ne., Fp. |
| 929 | | 36 | Ne., Fp. |
| 27413 | Foyaite, Grønnedal-Íka, Greenland. | | |
| 1155 | | 28 | Gl. |
| 1146 | | 20 | Gl., Ne. |
| 1127 | | 20 | Gl., Ne. |
| 1108 | | 44 | Gl., Ne., Fp. |
| 1083 | | 26 | Gl., Ne., Fp., Clpx. |
| 915 | | 9 | Gl., Ne., Fp., Clpx. |
| 870 | | 14 | Ne., Fp., Clpx. |

(continued)

Table IV (cont.).

| Temp. (° C) | | Time (hours) | Products |
|----------------|---|-----------------|---|
| K 45 | Ijolite, Kenya. | | |
| 1180 | | 15 | Gl. |
| 1161 | | 25 | Gl., Ne. |
| 1142 | | 23 | Gl., Ne. |
| 1112 | | 24 | Gl., Ne., Wo. |
| 1083 | | 25 | Gl., Ne., Wo. |
| 1066 | | 24 | Gl., Ne., Wo., Mel. |
| 1037 | | 24 | Gl., Ne., Wo., Mel., Clpx. |
| 937 | | 24 | Gl., Ne., Wo., Mel., Clpx. |
| 898 | | 24 | Ne., Wo., Mel., Clpx. |
| 50241 | Nepheline Syenite, Tugtutôq, Greenland. | | |
| 1175 | | 24 | Gl. |
| 1165 | | 17 | Gl., Fp. |
| 1100 | | 24 | Gl., Fp. |
| 1080 | | 26 | Gl., Fp., Clpx., Ne(?) |
| 1048 | | 24 | Gl., Fp., Clpx., Ne. |
| 1022 | | 21 | Gl., Fp., Clpx., Ne. |
| 981 | | 26 | Gl., Fp., Clpx., Ne., Amph. |
| 932 | | 30 | Fp., Clpx., Ne., Amph. |
| 30640 | Nepheline Syenite, Tugtutôq, Greenland. | | |
| 1195 | | 26 | Gl. |
| 1183 | | 22 | Gl., Fp. |
| 1108 | | 23 | Gl., Fp. |
| 1096 | | 20 | Gl., Fp., Clpx., Ne(?) |
| 1082 | | 23 | Gl., Fp., Clpx., Ne. |
| 998 | | 26 | Gl.(?), Fp., Clpx., Ne. |
| K 14 | Melteigite, Kenya. | | |
| 1190 | | 26 | Gl. |
| 1180 | | 15 | Gl., Clpx. |
| 1120 | | 24 | Gl., Clpx. |
| 1095 | | 19 | Gl., Clpx., Mel. |
| 986 | | 24 | Gl.(?), Clpx., Mel. |
| 57041 | Naujaite, Ilmaussaq, Greenland. | | |
| 1200 | | 18 | Gl. |
| 1187 | | 8 | Gl., Sod. |
| 1146 | | 6 | Gl., Sod. |
| 1120 | | 24 | Gl., Sod., Ne. |
| 1095 | | 17 | Gl., Sod., Ne., Eud. |
| 1080 | | 26 | Gl., Sod., Ne., Eud., Fp. |
| 1022 | | 21 | Gl., Sod., Ne., Eud., Fp., Clpx. |
| 932 | | 30 | Gl., Sod., Ne., Eud., Fp., Clpx., Amph. |
| 646 | | 41 | Gl.(?), Sod., Ne., Eud., Fp., Clpx., Amph. |

(continued)

Table IV (cont.).

| Temp. (°C) | | Time (hours) | Products |
|---------------|---|-----------------|-------------------------|
| 30681 | Nepheline Syenite, Tugtutôq, Greenland. | | |
| 1201 | | 22 | Gl. |
| 1195 | | 26 | Gl., Fp. |
| 1108 | | 23 | Gl., Fp. |
| 1096 | | 20 | Gl., Fp., Ne.(?). |
| 1082 | | 23 | Gl., Fp., Ne. |
| 1070 | | 26 | Gl., Fp., Ne., Clpx. |
| 945 | | 23 | Gl.(?), Fp., Ne., Clpx. |
| K 5 | Melanephelinite, Kenya. | | |
| 1236 | | 22 | Gl. |
| 1226 | | 21 | Gl., Ol. |
| 1200 | | 18 | Gl., Ol., Clpx. |
| 1130 | | 32 | Gl., Ol., Clpx. |
| 1095 | | 20 | Gl., Ol., Clpx., Ne. |
| 1055 | | 30 | Gl.(?), Ol., Clpx., Ne. |

$\text{FeO} + \text{Fe}_2\text{O}_3$ / $\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}$. These are plotted on Fig. 2, and discussed in a later section.

Nepheline or feldspar is the primary crystalline phase¹⁾ at the liquidus in the majority of samples, although some rocks had pyroxene, olivine or sodalite as primary crystalline phases. In most samples the primary phase was closely followed by the second phase. Similar results were found by YODER and TILLEY (1962) in their experiments on the melting of basalts. As discussed later, there is fair agreement between the experimental melting sequence and the crystallization sequence as deduced from textural relations in the unheated rocks.

The temperature range between the beginning of melting (solidus) and the liquidus could only be obtained with any degree of accuracy for twelve of sixteen samples. Optically, it is very difficult to determine the first few percent of glass and the solidus temperatures shown in Fig. 1 should be regarded as those at which significant melting begins. The most significant aspect of these results is that the rocks from the Ilímaussaq Intrusion, representing agpaitic crystallization, have a much lower solidus temperature than non-agpaitic rocks. Melting intervals ranged from 140° C

¹⁾ Primary crystalline phase is either the last mineral which remains unmelted as the temperature is increased or the first mineral to crystallize as the temperature is lowered from that of the liquidus, exclusive of those minerals listed above.

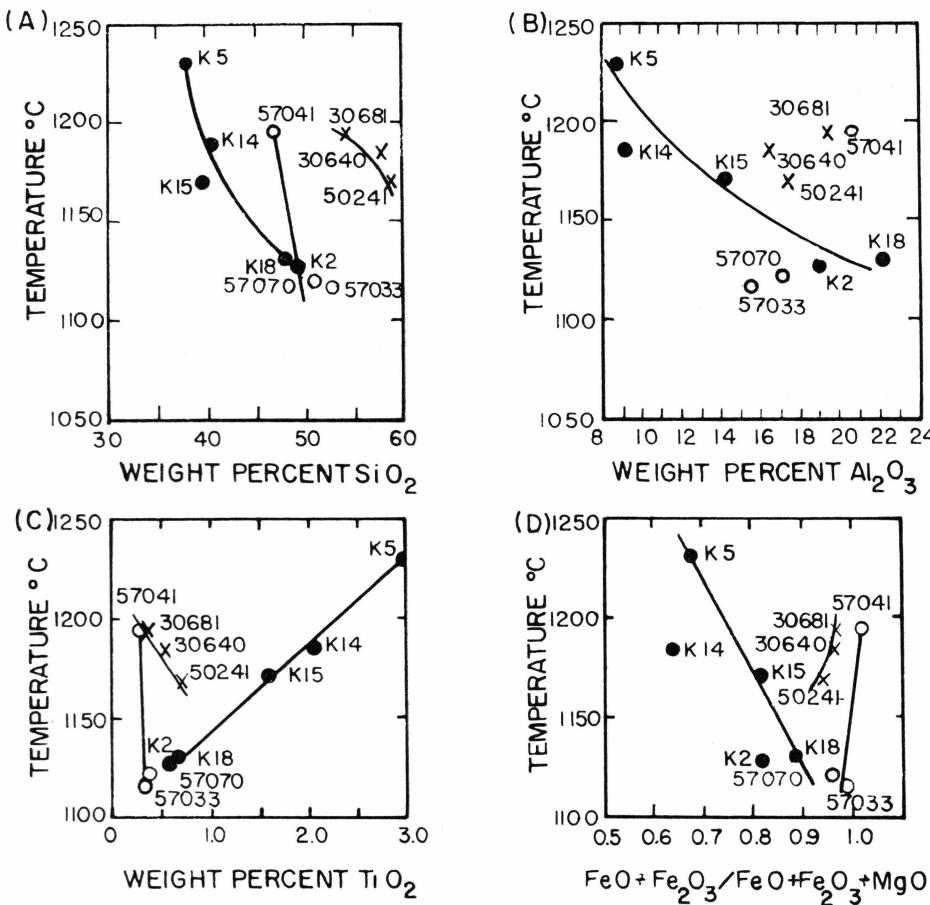


Fig. 2. Liquidus temperatures plotted against chemical composition for comagmatic rocks. Shaded circles represent Kenyan rocks; open circles rocks from Ilímaussaq, Greenland; crosses rocks from Tugtutôq, Greenland.

to 545°C with extrusive rocks generally having much smaller melting intervals than the intrusive rocks.

(b) Experiments at One Atmosphere in Argon

Results of melting experiments in an argon atmosphere are given in Table V and shown in Fig. 3. Although no analysis of the foyaite (27113) was available, its mineralogy (biotite, aegirine-augite and magnetite) suggests that it has a higher iron content than the other three samples. Comparison of the results shown in Figs. 1 and 3 suggests that the non-oxidizing conditions have slightly lowered liquidus temperatures

Table V. *Results of Experiments in an Argon Atmosphere.*
 (Only experiments indicating a phase change are listed).
 Results are listed in the same sequence as given in Fig. 3.

| Temp. (° C) | Time (hours) | Products ¹⁾ |
|--|-----------------|---|
| U 880 Phonolite, Tanzania. | | |
| 1110 | 24 | Gl. |
| 1106 | 5 | Gl., Ne. |
| 1085 | 7 | Gl., Ne., Wo., Clpx. |
| 1065 | 5 | Gl., Ne., Wo., Clpx., Fp.(?). |
| 983 | 5 | Gl.(?), Ne., Wo., Clpx., Fp. |
| 27113 Foyaite, Grønnedal-Íka, Greenland. | | |
| 1133 | 15 | Gl. |
| 1122 | 5 | Gl., Fp. |
| 1091 | 5 | Gl., Fp., Ne., Clpx. |
| 1074 | 6 | Gl., Fp., Ne., Clpx., Bio. |
| 920 | 6 | Gl., Fp., Ne., Clpx., Bio. |
| 912 | 5 | Fp., Ne., Clpx., Bio. |
| BM 4 Litchfieldite, Ontario. | | |
| 1146 | 6 | Gl. |
| 1130 | 6 | Gl., Ne. |
| 1110 | 24 | Gl., Ne. |
| 1102 | 5 | Gl., Ne., Fp. |
| 977 | 5 | Gl., Ne., Fp. |
| 952 | 13 | Ne., Fp. |
| 57041 Naujaite, Ilimaussaq, Greenland. | | |
| 1195 | 11 | Gl. |
| 1173 | 12 | Gl., Sod. |
| 1122 | 5 | Gl., Sod. |
| 1091 | 5 | Gl., Sod., Ne. |
| 1047 | 5 | Gl., Sod., Ne., Fp., Eud. |
| 1010 | 5 | Gl., Sod., Ne., Fp., Eud. |
| 970 | 5 | Gl., Sod., Ne., Fp., Eud., Amph., Clpx. |
| 860 | 6 | Gl., Sod., Ne., Fp., Eud., Amph., Clpx. |

¹⁾ Abbreviations are the same as Table IV. Magnetite is an ubiquitous phase in all runs.

for the phonolite (U 880) and foyaite (27113) by 10° C and 25° C respectively and may have lowered the liquidus temperatures of the naujaite (57041). In the latter case, the presence of very minor amounts of isotropic sodalite makes its identification difficult when large amounts of glass are also present. Within the limits of experimental error, the liquidus

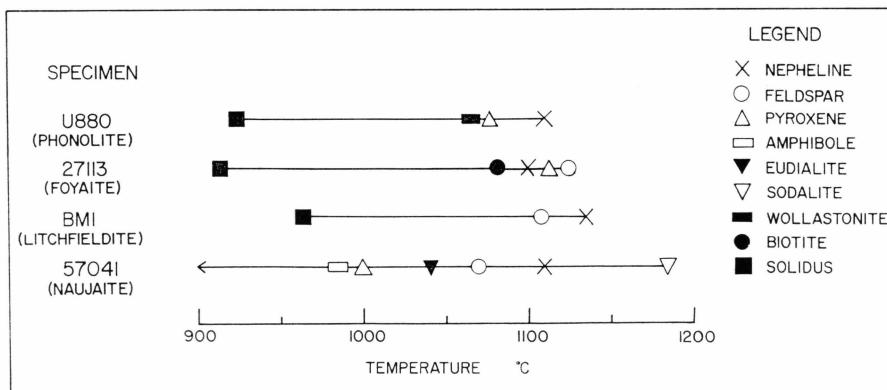


Fig. 3. Melting relations in an argon atmosphere.

temperature of the litchfieldite (BM 1), containing the least iron, has remained the same. These results suggest that an oxidizing atmosphere raises the melting temperature and that there is a correlation between liquidus temperature and iron content of the rock. These results are in agreement with those of TILLEY, YODER and SCHAIRER (1965), for the melting of basalts in a reducing environment.

For three of the samples (BM 1, U 880, and 57041) the primary phase is the same as in the atmospheric runs, but sample 27113 has feldspar rather than nepheline as the primary phase in the argon atmosphere runs. In the litchfieldite (BM 1) with low iron content, the sequence of crystallization remains the same, whereas in the other rocks the sequence of crystallization has been altered to varying extents (Fig. 1 and 3).

In an argon atmosphere, the beginning of melting is similar to that of the atmospheric runs in all samples except U 880 in which the beginning of melting was 30° C lower than in the atmospheric runs.

(c) Experiments under Hydrothermal Conditions

In order to duplicate more precisely the probable conditions of formation of most alkaline rocks, six samples were melted hydrothermally at water vapour pressures up to 2070 bars PH_2O . Lack of suitable equipment did not permit liquidus determinations of the more "basic" rocks due to their higher liquidus temperatures. The samples investigated were the three rocks from Ilímaussaq, Greenland (Nos. 57041, 57033, 57070)¹ the litchfieldites from Blue Mountain, Ontario (Nos. BM 1 and BM 5), and the phonolite from Kenya (No. DH 940). The rocks from Ilímaussaq were selected because of their agpaitic characteristics and also in order to determine whether the long melting interval found in the atmospheric

¹) These experiments were done by Mr. M. K. Sood.

Table VI. *Results of Experiments Under Water Vapour Pressure.*
(Only experiments indicating a phase change are listed).

| Temp. (° C) | PH ₂ O (bars) | Time (hours) | Products ¹⁾ |
|----------------|-----------------------------------|-----------------|--|
| 57041 | Naujaite, Ilimaussaq, Greenland. | | |
| 910 | 1,030 | 8 | Gl. |
| 895 | 1,030 | 6 | Gl., Sod. |
| 865 | 1,030 | 48 | Gl., Sod., Ne.(?). |
| 845 | 1,030 | 48 | Gl., Sod., Ne., Eud. |
| 800 | 1,030 | 48 | Gl., Sod., Ne., Eud., Fp. |
| 745 | 1,030 | 96 | Gl., Sod., ¹ Ne., Eud., Fp., Clpx. |
| 685 | 1,030 | 96 | Gl., Sod., Ne., Eud., Fp., Clpx., Amph. |
| 500 | 1,030 | 336 | Gl., Sod., Ne., Eud., Fp., Clpx., Amph., Bio. |
| 450 | 1,030 | 336 | Gl.(?), Sod., Ne., Eud., Fp., Clpx., Amph., Bio. |
| 430 | 1,030 | 400 | Sod., Ne., Eud., Fp., Clpx., Amph., Bio. |
| 880 | 2,070 | 8 | Gl. |
| 870 | 2,070 | 9 | Gl., Sod. |
| 57033 | Lujavrite, Ilimaussaq, Greenland. | | |
| 885 | 1,030 | 48 | Gl. |
| 875 | 1,030 | 48 | Gl., Fp. |
| 845 | 1,030 | 48 | Gl., Fp., Clpx. |
| 775 | 1,030 | 72 | Gl., Fp., Clpx., Ne.(?). |
| 750 | 1,030 | 80 | Gl., Fp., Clpx., Ne., Amph., Eud. |
| 430 | 1,030 | 336 | Fp., Clpx., Ne., Amph., Eud. |
| 870 | 2,070 | 10 | Gl. |
| 860 | 2,070 | 11 | Gl., Fp., Clpx.(?). |
| 57070 | Foyaite, Ilimaussaq, Greenland. | | |
| 885 | 1,030 | 48 | Gl. |
| 875 | 1,030 | 48 | Gl., Fp. |
| 865 | 1,030 | 48 | Gl., Fp., Ne.(?). |
| 850 | 1,030 | 48 | Gl., Fp., Ne., Clpx.(?). |
| 820 | 1,030 | 60 | Gl., Fp., Ne., Clpx. |
| 765 | 1,030 | 72 | Gl., Fp., Ne., Clpx., Amph. |
| 450 | 1,030 | 336 | Gl.(?), Fpm., Ne., Clpx., Amph. |
| 430 | 1,030 | 460 | Fp., Ne., Clpx., Amph. |
| 870 | 2,070 | 8 | Gl. |
| 865 | 2,070 | 10 | Gl., Fp., Clpx.(?). |
| BM 1 | Litchfieldite, Ontario. | | |
| 930 | 340 | 72 | Gl. |
| 910 | 340 | 67 | Gl., Fp. |
| 890 | 690 | 50 | Gl. |

¹⁾ Abbreviations are the same as Table IV. Iron oxide, usually as hematite, is an ubiquitous phase in many samples.

(continued)

Table VI (cont.).

| Temp. (° C) | PH ₂ O (bars) | Time (hours) | Products |
|------------------------------|--------------------------|-----------------|----------|
| BM 1 Litchfieldite, Ontario. | | | |
| 860 | 690 | 72 | Gl., Fp. |
| 848 | 1,030 | 72 | Gl. |
| 834 | 1,030 | 95 | Gl., Fp. |
| 825 | 2,070 | 61 | Gl. |
| 800 | 2,070 | 72 | Gl., Fp. |
| BM 5 Litchfieldite, Ontario. | | | |
| 938 | 340 | 24 | Gl. |
| 928 | 340 | 24 | Gl., Fp. |
| 870 | 1,030 | 92 | Gl. |
| 860 | 1,030 | 97 | Gl., Fp. |
| 857 | 2,070 | 6 | Gl. |
| 830 | 2,070 | 36 | Gl., Fp. |
| DH 940 Phonolite, Tanzania. | | | |
| 910 | 520 | 48 | Gl., Fp. |
| 880 | 690 | 120 | Gl. |
| 860 | 790 | 120 | Gl., Fp. |
| 860 | 1,030 | 68 | Gl., Fp. |
| 860 | 1,380 | 72 | Gl. |
| 850 | 1,380 | 96 | Gl., Fp. |
| 845 | 1,660 | 72 | Gl., Fp. |
| 860 | 2,070 | 10 | Gl. |

runs persisted under hydrothermal conditions. The litchfieldites were investigated because they are very similar in composition to the litchfieldite from Maine used by BARKER (1965) for his hydrothermal melting experiments, and because their compositions correspond very closely to those of the synthetic system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2\text{-H}_2\text{O}$ investigated by HAMILTON and MACKENZIE (1965). Sample DH 940 was selected because it represents a fairly typical phonolite and corresponds chemically to the litchfieldites from Blue Mountain, Ontario. This sample was also chosen because its mineralogical composition can be represented by the synthetic system $\text{CaMgSi}_2\text{O}_6\text{-NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-H}_2\text{O}$ (EDGAR, 1964a).

Results of the hydrothermal experiments are given in Table VI and plotted on Figs. 4-9. For comparison with data from synthetic systems the "granite" minima obtained from the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{(-H}_2\text{O)}$ (TUTTLE and BOWEN, 1958) [Curve A]; the "nepheline syenite" minima obtained from the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ (SCHAIRER and BOWEN, 1935; HAMILTON and MACKEN-

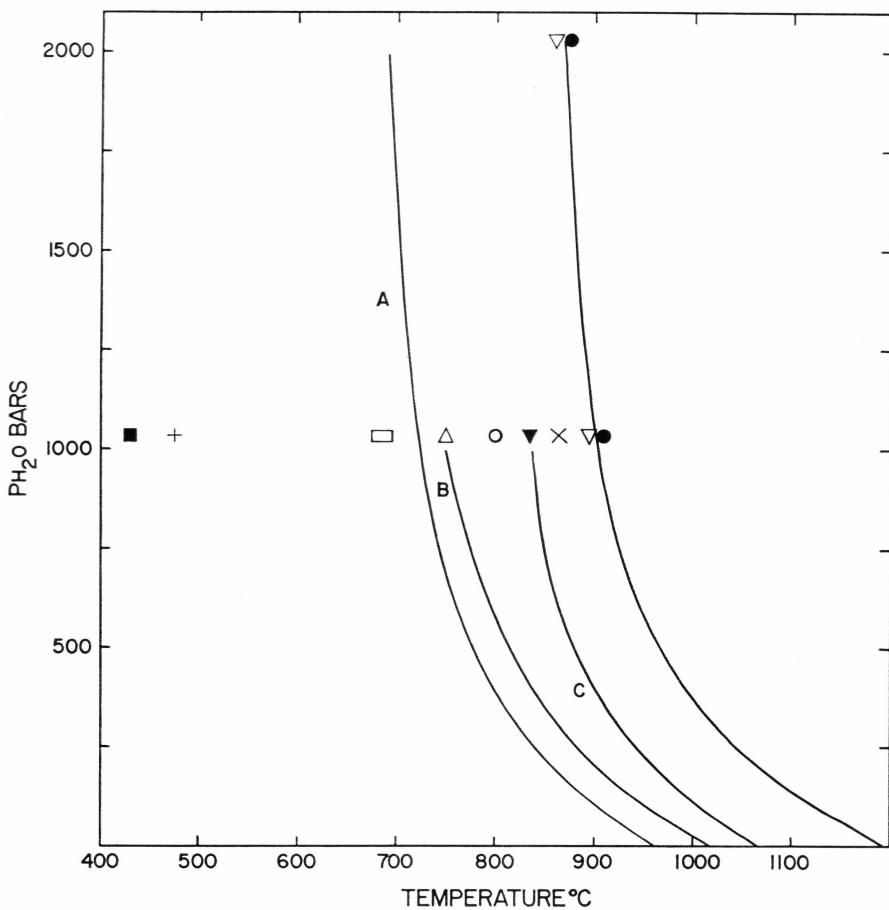


Fig. 4. Melting relations for sample 57041 at water vapour pressures up to 2070 bars. Symbols are the same as in Fig. 1. Curve A represents minima in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{(-H}_2\text{O)}$ after TUTTLE and BOWEN (1958), curve B represents minima in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after SCHAIRER and BOWEN (1935) and HAMILTON and MACKENZIE (1965), curve C the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after GREIG and BARTH (1938) and EDGAR (1964 b).

ZIE, 1965) [Curve B]; and the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ (GREIG and BARTH, 1938; EDGAR 1964b) [Curve C] have been included.

Liquidus temperatures for the Ilímaussaq rocks range from 910°C for the naujaite (57041) to 885°C for the foyaite (57070) and lujavrite (57033) at 1030 bars PH_2O . The solidus temperatures for these rocks range from 430°C to 475°C . Thus the long melting interval remains under conditions of water vapour pressure. The crystallization sequence under hydrothermal conditions is also very similar to that of the one

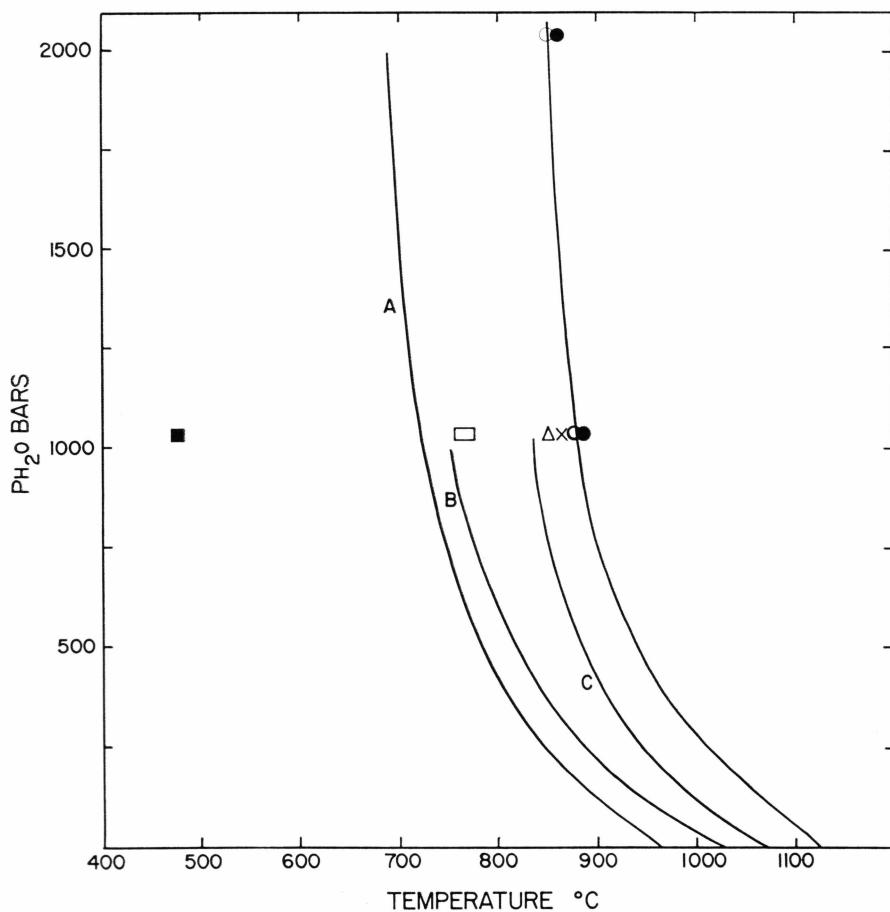


Fig. 5. Melting relations for sample 57033 at water vapour pressures up to 2070 bars. Symbols are the same as in Fig. 1. Curve A represents minima in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{(-H}_2\text{O)}$ after TUTTLE and BOWEN (1958), curve B represents minima in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after SCHAIRER and BOWEN (1935) and HAMILTON and MACKENZIE (1965), curve C the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{ (-H}_2\text{O)}$ after GREIG and BARTH (1938) and EDGAR (1964 b).

atmosphere runs with the exception that natrolite was not observed in 57070 and biotite is a minor phase at low temperatures in 57041 under hydrothermal conditions. Increase in hematite content (an ubiquitous phase at all temperatures) between the temperature of crystallization of the last major mineral and the solidus temperature indicates that the glass probably decreases in iron content with decreasing temperature. Similarly it may be expected that there is a change in the compositions of the crystalline phases, particularly nepheline and feldspar, on cooling. This was not investigated for the Ilmaussaq rocks but, as explained in a later section, was determined for the Blue Mountain, Ontario litchfieldites.

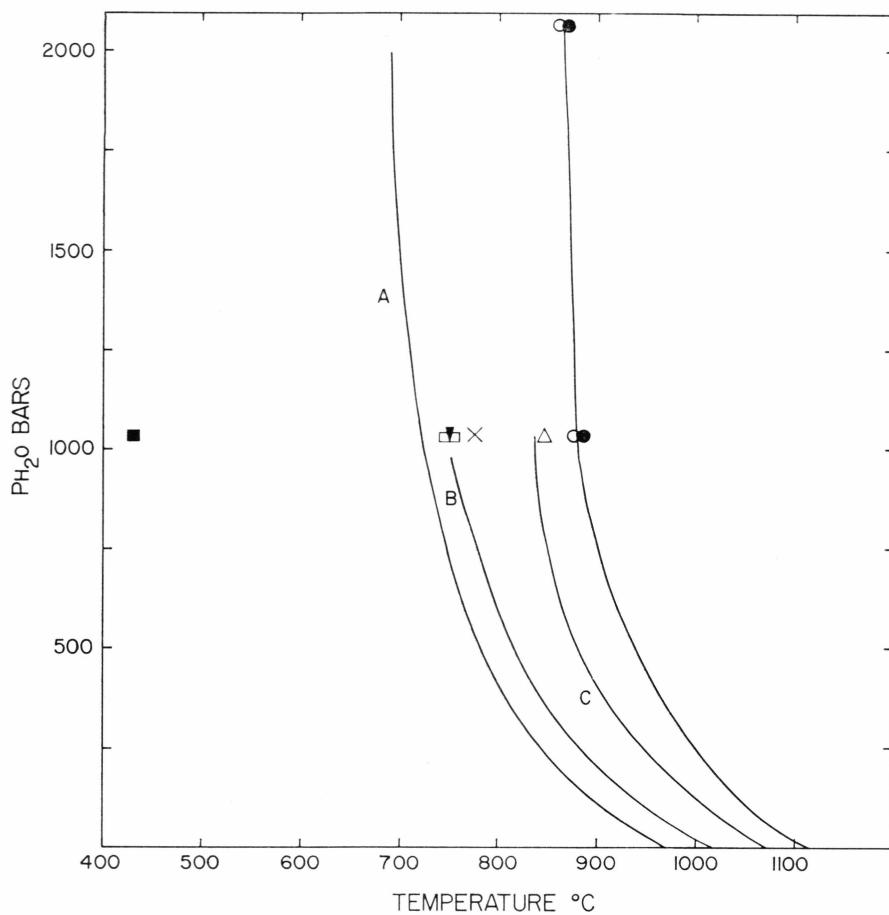


Fig. 6. Melting relations for sample 57070 at water vapour pressures up to 2070 bars. Symbols are the same as in Fig. 1. Curve A represents minima in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{(-H}_2\text{O)}$ after TUTTLE and BOWEN (1958), curve B represents minima in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after SCHAIER and BOWEN (1935) and HAMILTON and MACKENZIE (1965), curve C the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after GREIG and BARTH (1938) and EDGAR (1964 b).

The presence of water vapour at 2070 bars pressure lowers liquidus temperatures in the Blue Mountain, Ontario litchfieldites by approximately 300°C in comparison to the liquidus temperatures at atmospheric pressure. Initial 1000 bar PH_2O increment is sufficient to produce most of this temperature lowering, with the increase from 1000 bars to 2000 bars PH_2O having only a very minor effect. The difference in liquidus temperatures of the two samples is approximately $20\text{--}25^\circ\text{C}$ at all pressures investigated, with sample BM 5 having the higher liquidus. In Figs. 7 and 8 the liquidus for the litchfieldite from Litchfield, Maine,

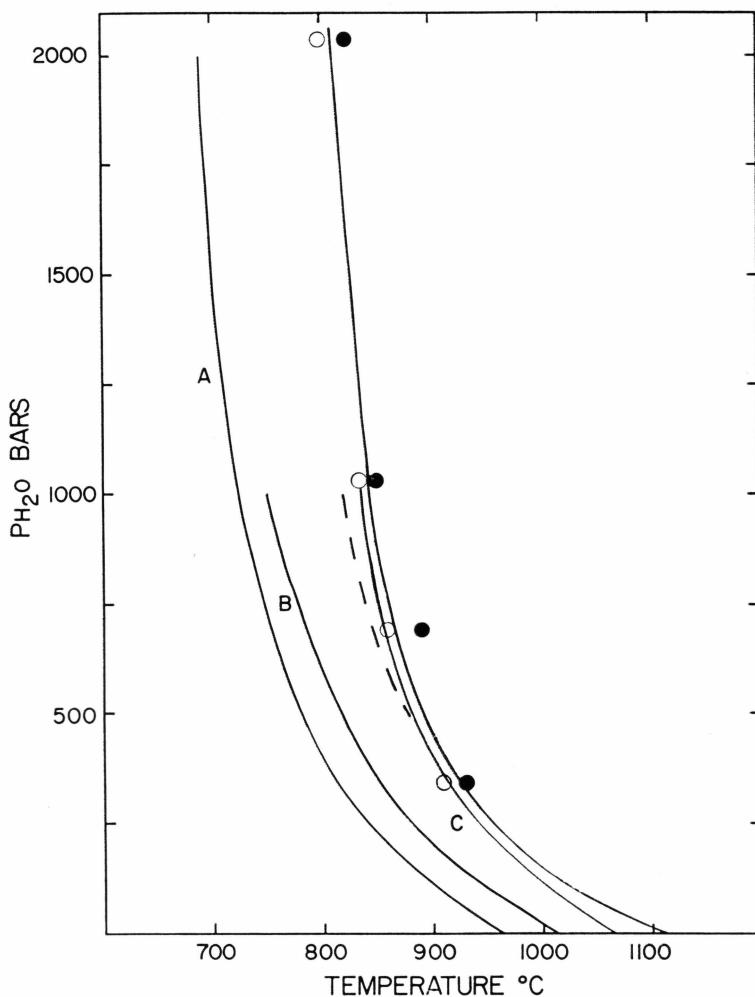


Fig. 7. Melting relations for sample BM 1 at water vapour pressures up to 2070 bars. Shaded circles represent all liquid runs, open circles runs containing crystals and liquid. Curve A represents minima in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{(-H}_2\text{O)}$ after TUTTLE and BOWEN (1958), curve B represents minima in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after SCHAIRER and BOWEN (1935) and HAMILTON and MACKENZIE (1965), curve C the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after GREIG and BARTH (1938) and EDGAR (1964b). Broken curve represents minimum melting for litchfieldite from Litchfield, Maine from BARKER (1965).

determined by BARKER (1965) has been included. This sample is very similar in composition to the Ontario sample and has a fairly similar liquidus temperature.

The primary phase at the liquidus for both litchfieldites is an albitic feldspar, very closely followed by nepheline a few degrees lower. This is in contrast to the runs at atmospheric pressure in which nepheline is the

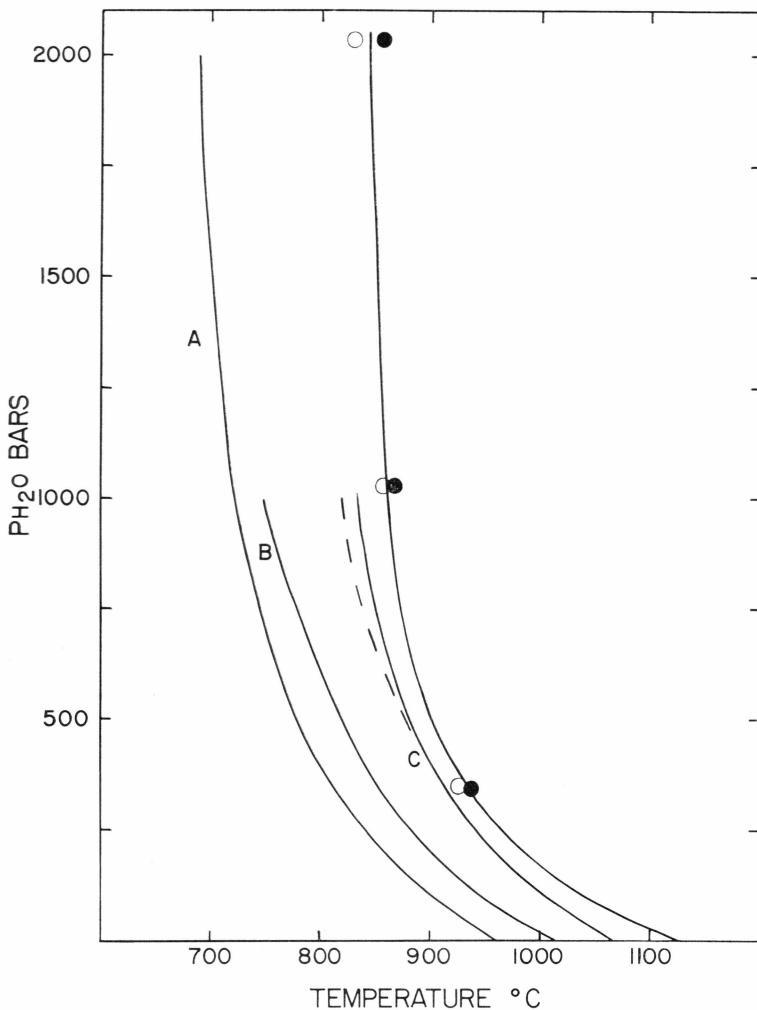


Fig. 8. Melting relations for sample BM 5 at water vapour pressures up to 2070 bars. Shaded circles represent all liquid runs, open circles runs containing crystals and liquid. Curve A represents minima in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{(-H}_2\text{O)}$ after TUTTLE and BOWEN (1958), curve B represents minima in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after SCHAIRER and BOWEN (1935) and HAMILTON and MACKENZIE (1965), curve C the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{(-H}_2\text{O)}$ after GREIG and BARTH (1938) and EDGAR (1964b). Broken curve represents minimum melting for litchfieldite from Litchfield, Maine from BARKER (1965).

primary phase. YODER and TILLEY (1962) found similar results with basalts, and HAMILTON *et al.* (1963) reported that the crystallization sequences of basalts were dependent on the type of buffer used.

The phonolite sample (DH 940) has melting relationships very similar to those of the litchfieldites, with feldspar being the primary phase at the liquidus.

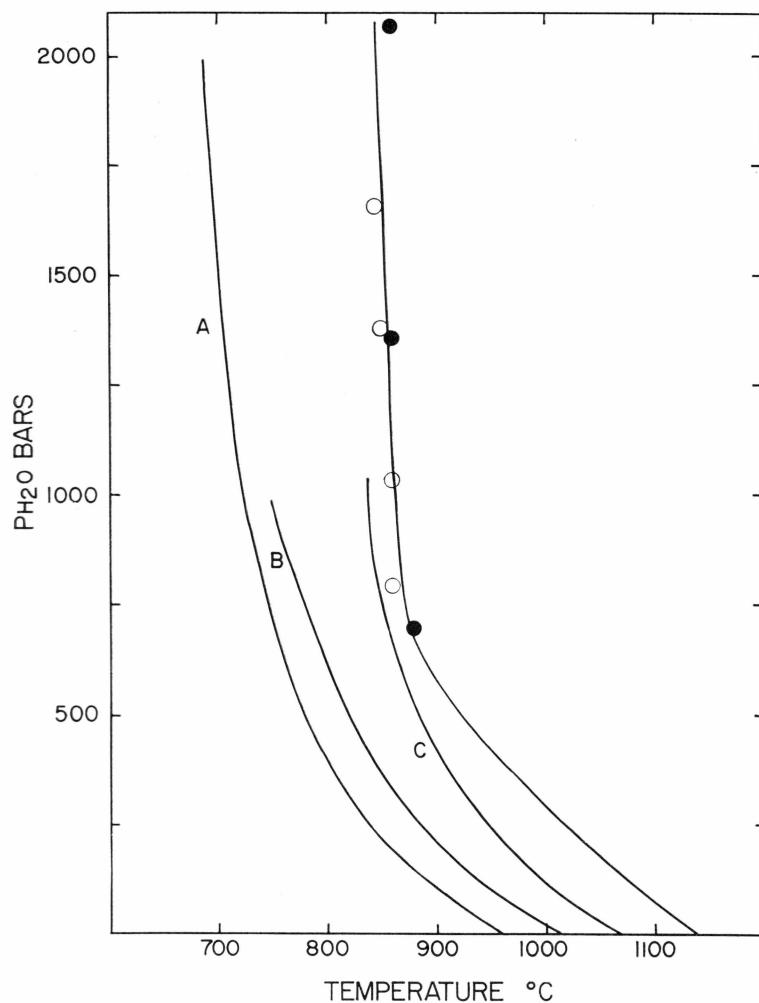


Fig. 9. Melting relations for sample DH 940 at water vapour pressures up to 2070 bars. Shaded circles represent all liquid runs, open circles runs containing crystals and liquid. Curve A represents minima in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2$ ($-\text{H}_2\text{O}$) after TUTTLE and BOWEN (1958), curve B represents minima in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8$ ($-\text{H}_2\text{O}$) after SCHAIRER and BOWEN (1935) and HAMILTON and MACKENZIE (1965), curve C the minima in the system $\text{NaAlSiO}_4\text{-NaAlSi}_3\text{O}_8$ ($-\text{H}_2\text{O}$) after GREIG and BARTH (1938) and EDGAR (1964b).

The beginning of melting has not been determined for the litchfieldites and phonolite. From analogy with the Ilímaussaq rocks, which have similar melting intervals under both atmospheric and hydrothermal conditions, it can reasonably be assumed that these samples also have melting intervals similar to those of the atmospheric experiments.

(d) Feldspar and Nepheline Compositions Before and After Melting

Results of X-ray determinations of the compositions of nephelines and feldspars separated from the unheated rocks are given in Table VII as weight percentages nepheline, kalsilite and quartz and as orthoclase and albite respectively. The feldspar compositions for the nepheline

Table VII. Nepheline and Feldspar Compositions of Unheated Rocks.

| Sample No. | Nepheline | Nepheline Kalsilite | Silica | Na Na + K | Ortho- clase | Feldspar Albite | Anorthite |
|---------------------|----------------|------------------------|--------|--------------|-----------------|--------------------|-----------|
| 57041 | 78.5 | 15.5 | 6.0 | 0.84 | 68 | 32 | — |
| 57033 | 75.0 | 20.5 | 4.5 | 0.79 | 83 | 17 | — |
| 57070 | not determined | — | — | — | 88 | 12 | — |
| 50241 ¹⁾ | 78.0 | 17.0 | 5.0 | 0.82 | 41.5 | 53.0 | 5.5 |
| 30640 ¹⁾ | not determined | — | — | — | 46.5 | 54.0 | 0.0 |
| 30681 ¹⁾ | not determined | — | — | — | 46.0 | 50.5 | 3.5 |
| 27113 | 83.5 | 9.0 | 7.5 | 0.90 | 55 | 45 | — |
| K 14 | 73.0 | 24.0 | 3.0 | 0.75 | not determined | — | — |
| K 15 | 72.0 | 24.5 | 3.5 | 0.75 | not determined | — | — |
| K 2 | 78.0 | 18.0 | 4.0 | 0.81 | 88 | 12 | — |
| K 18 | 79.0 | 14.5 | 6.0 | 0.84 | 69 | 31 | — |
| K 5 | 67.0 | 31.0 | 2.0 | 0.68 | not determined | — | — |
| DH 940 | 79.5 | 14.5 | 6.0 | 0.85 | 47 | 53 | — |
| U 880 | 73.5 | 22.5 | 4.0 | 0.77 | not determined | — | — |
| BM 1 | 73.5 | 22.5 | 4.0 | 0.77 | 82 | 18 | — |
| BM 5 | 73.0 | 23.5 | 3.5 | 0.76 | not determined | — | — |

¹⁾ Compositions determined by UPTON (1964); nepheline by X-ray method, feldspar by chemical analysis.

Table VIII. Compositions of Coexisting Nepheline and Feldspar as a Function of Temperature for Blue Mountain Ontario Litchfieldite (BM 1).

| Temp. (° C) | Time (hours) | Nepheline | Na Na + K | Feldspars | |
|----------------|-----------------|--|--------------|------------------------------------|-------------------------------------|
| 975 | 26 | Ne ₈₀ Ks _{13.7} Q _{6.7} | 0.86 | Ab ₉₁ Or ₉ ; | Ab ₆₆ Or ₃₄ |
| 925 | 23 | Ne ₈₀ Ks _{13.7} Q _{6.7} | 0.86 | Ab ₉₁ Or ₉ ; | Ab ₆₆ Or ₃₄ |
| 825 | 48 | — | — | Ab ₁₀₀ ; | Ab ₈₄ Or ₂₆ ; |
| 580 | 36 | Ne _{58.7} Ks _{17.7} Q ₆ | 0.83 | Ab ₁₀₀ ; | (2); |
| unheated | | Ne _{53.7} Ks _{22.7} Q ₄ | 0.77 | Ab ₁₀₀ ; | (2); |
| | | | | | Ab ₁₀ Or ₉₀ |

¹⁾ In all runs below 825° C, three feldspars are present — a very soda-rich alkali feldspar and a perthite.

²⁾ Composition could not be determined due to overlapping albite reflection.

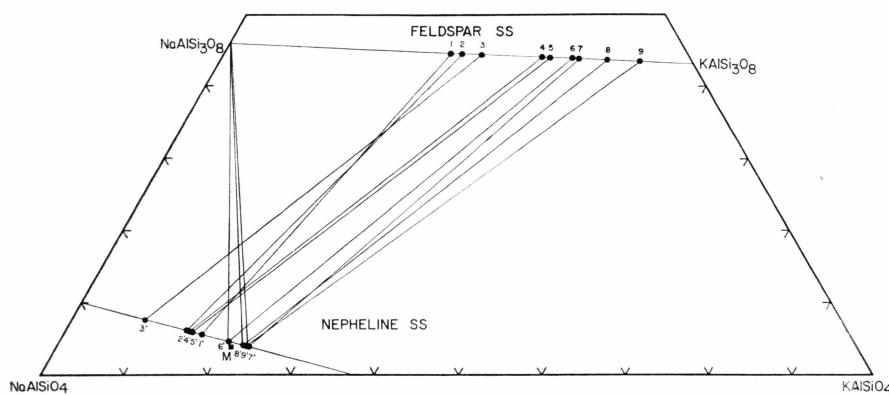


Fig. 10. Nepheline-feldspar tie lines for unheated rocks plotted in the system nepheline-kalsilite-orthoclase-albite. Nepheline compositions plotted on the field boundary indicating the limit of nepheline solid solution at 700° C and $\text{PH}_2\text{O} = 1000$ bars. (HAMILTON and MACKENZIE, 1960).

| | |
|----------------------------|-----------|
| M — Morozewicz composition | 5 — 57041 |
| 1 — 50241 | 6 — 57033 |
| 2 — DH 940 | 7 — BM 5 |
| 3 — 27113 | 8 — BM 1 |
| 4 — K 18 | 9 — K 2 |

Primed numbers refer to nepheline compositions, unprimed numbers to feldspar compositions.

syenites from Tugtutôq, Greenland were determined by chemical analysis (UPTON, 1964). Tie-lines joining coexisting nepheline and feldspar compositions, plotted in the system NaAlSiO_4 - KAISiO_4 - $\text{NaAlSi}_3\text{O}_8$ - KAISi_3O_8 , are shown in Figure 10. The nepheline compositions, with the exception of the foyaite (No. 27113) and the melanephelinite (No. K 5), have compositions which are not too far removed from the theoretical Morozewicz composition ($\text{Ne}_{75}\text{Ks}_{21}\text{Q}_4$), toward which the composition of the nepheline adjusts in response to falling temperature. The feldspar in many of the samples is potash-rich, although in three of the rocks (Nos. 57033, BM 1, and K 2) there is a very soda-rich feldspar in addition to a perthitic feldspar.

Feldspar and nepheline compositions were also determined for the Ontario litchfieldite BM 1 as a function of temperature up to 975° C. Results of these determinations are given in Table VIII, and plotted in Fig. 11. With decreasing temperature, the composition of the nepheline becomes less soda-rich as the bulk composition of the feldspars becomes richer in the albite component.

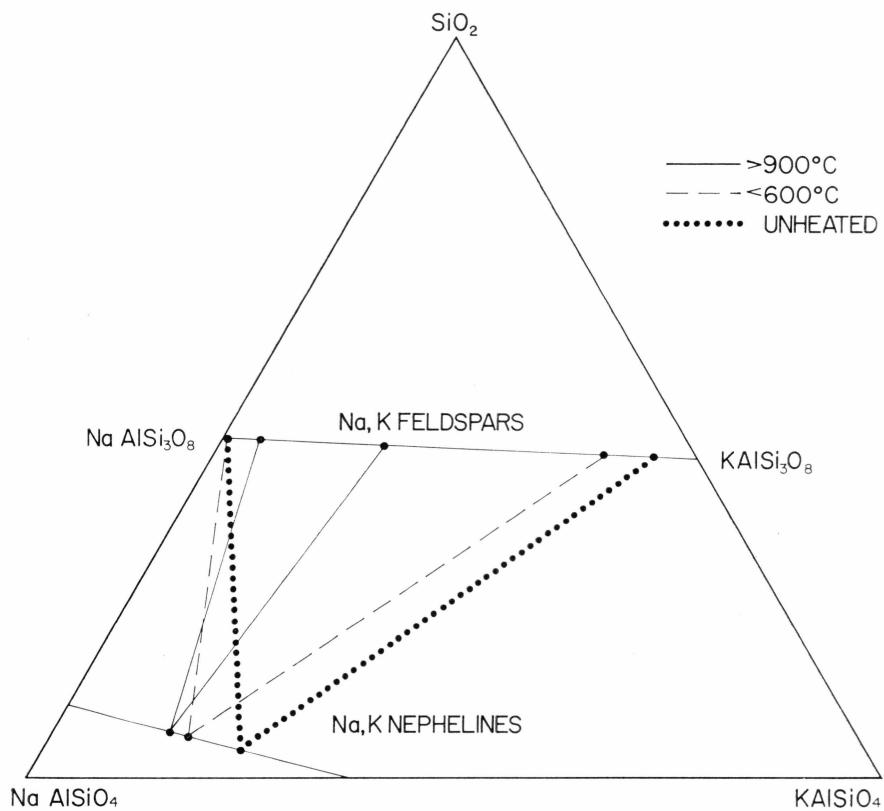


Fig. 41. Tie lines for coexisting nepheline and feldspar in Sample BM 1 at various temperatures.

DISCUSSION OF RESULTS

(a) Introduction

In this study an attempt has been made to elucidate the genesis of alkaline undersaturated rocks using laboratory techniques (principally melting relations) applied to natural materials whose compositions and field relationships are well known. The value of this approach has been most recently demonstrated in investigations of basalts and other basic rocks (YODER and TILLEY, 1962; GREEN and RINGWOOD, 1966). The assumption in these studies is that melting relationships of the rocks reflect initial crystallization temperatures, sequences of crystallization and final consolidation temperatures of the magmas from which they have formed. In addition, one of the most important aspects of such studies is that they test the applicability of using simplified synthetic systems to describe the genesis of complex natural systems.

Although data of this type are of obvious importance, the limitations of this approach in addition to those of the experimental method described earlier, should be recognized. These are as follows: —

- a) Many of the experiments were done at atmospheric pressure, or under water vapour pressure conditions, whereas in nature other volatiles are undoubtedly important, particularly in the genesis of alkaline rocks.
- b) No attempt has been made to precisely control oxygen pressures, although it has been shown that oxygen fugacities may be important in the genesis of these rocks (EDGAR and NOLAN, 1966).
- c) The duration of the heating experiments were much shorter than the cooling and consolidation process of the natural magmas. Thus metastability may be present. (See p. 13).
- d) The initial samples represent only the final stages of a process that in nature may have been approached in several different ways.

(b) Melting Relations at One Atmosphere

Under both atmospheric and hydrothermal experiments, the range of liquidus temperatures is small considering the variability in composition of the rocks studied (Figs. 1, 2, 4-9). Although no definitive correlation can be made, the nepheline syenites and phonolites, containing higher SiO_2 percentages, have slightly lower liquidus temperatures than rocks with lower SiO_2 contents. In the nepheline syenites and phonolites, the

first phase to crystallize is nepheline or feldspar with only a small temperature interval between the first and second phases, possibly indicating that many of these rocks have compositions which are not far removed from cotectic boundaries when plotted on synthetic systems. Most of the other rocks studied consist of assemblages containing four or more principal constituents, any one of which can be the first phase to crystallize.

The results of solidus determinations indicate that there is a strong correlation between the melting interval and volatile content of the rocks (Table IX). Rocks with high percentages of volatile-bearing minerals have

Table IX. *Modal Content of Volatile-Bearing Minerals, Melting Intervals and Agpaitic Indices.*

| Specimen No. | Name | Modal Volatile Bearing Minerals ¹⁾ | Melting Interval (° C) | Agpaitic Index |
|--------------|------------------------|---|------------------------|----------------|
| 57041 | Naujaite | 49.0 ²⁾ | 545 | 1.29 |
| 30681 | Nepheline syenite | 37.7 ²⁾ | 245 | 0.99 |
| 57033 | Lujavrite | 19.0 ²⁾ | 500 | 1.47 |
| 27113 | Foyaite | 6.0 | 250 | 1.06 |
| 50241 | Nepheline Syenite | 5.6 ³⁾ | 220 | 0.91 |
| 30640 | Nepheline Syenite | 3.3 ³⁾ | 235 | 1.00 |
| BM 1 | Litchfieldite | 2.3 | 160 | 0.93 |
| K 2 | Nepheline Syenite | 2.0 ³⁾ | 205 | 1.11 |
| K 14 | Melteigite | 0.7 | 215 | 0.69 |
| BM 5 | Litchfieldite | 0.3 | 170 | 0.92 |
| K 15 | Ijolite | 0.0 | 250 | 1.07 |
| 57070 | Foyaite | — | 320 | 1.18 |
| U 880 | Phonolite | — | 130 | 0.79 |
| K 18 | Phonolitic nephelinite | — | 182 | 0.87 |
| K 5 | Melanephelinite | — | 160 | 0.95 |

¹⁾ Exclusive of very fine-grained constituents.

²⁾ From FERGUSON (1964).

³⁾ From UPTON (1964).

the longest melting interval. The Ilímaussaq rocks (Nos. 57041, 57033 and 50241), which have followed an agpaitic course of crystallization, have the lowest solidus temperatures and largest melting intervals, those rocks with the highest agpaitic index (GERASIMOVSKIY, 1956) producing longest melting intervals. This correlation is particularly significant since volatiles have long been recognized as important in the genesis of alkaline rocks. SØRENSEN (1962) has estimated the final consolidation temperature of the residual lujavrite magma in the Ilímaussaq complex to be as low as 400° C, a value corroborated by the present work.

Of the remaining nepheline syenites, in which there is good evidence that the volatile content was lower, the solidus temperatures are much higher and the melting intervals shorter.

In the Kenyan rocks, consisting of the comagmatic plutonic rocks, melteigite and ijolite, the primary member melteigite (KING and SUTHERLAND, 1960) has a higher solidus than the ijolite. This is consistent with the cooling temperatures associated with plutonic crystallization (TURNER and VERHOOGEN, 1960, p. 65). The volcanic rocks, melanephelinite and phonolite, have higher solidus temperatures. For the remaining rocks there is no definite correlation between solidus temperatures and rock type.

As noted previously, the experiments in the non-oxidizing (argon) atmosphere affect liquidus temperatures only slightly. The most pronounced difference between the oxidizing and non-oxidizing environments is the preservation of magnetite and differences in the crystallization temperatures of iron-bearing minerals (principally aegirine, aegirine-augites, arfvedsonite and biotite) under the latter conditions.

Under non-oxidizing conditions, the melting temperatures of the iron-bearing pyroxenes in the phonolite (U 880) and foyaite (27118) are raised by about 10° C, a value very close to the limits of experimental error. However in the naujaite (57041), the crystallization temperature of the pyroxene is lowered by about 50° C. BAILEY (1963) found that a pressure of 1000 bars PH_2O and a low PO_2 lowered the melting of pure acmite by 60° C, in comparison to conditions of high PO_2 at the same PH_2O .

The arfvedsonite in sample 57041 crystallizes about 40° C higher under non-oxidizing conditions. This is in agreement with the results of ERNST (1962) who found that decreased PO_2 and/or increased temperature raised the stability of this mineral. Similarly the biotite in sample 27113 has an increased crystallization temperature under non-oxidizing conditions. This increased stability of biotite may be due to its intimate intergrowth with magnetite.

The only significant difference in crystallization temperatures of felsic minerals was the nepheline of sample 27113 which melts about 50° C lower in the non-oxidizing environment. This may be due to solid solution of Fe_2O_3 in the nepheline under oxidizing conditions as suggested by BAILEY and SCHAIRER (1963, p. 126).

Variation in the crystallization temperatures of any one mineral in different samples in non-oxidizing conditions depends on the bulk iron (ferrous and ferric) content of the samples, and on differences in iron content of the minerals themselves. Petrologically, the earlier crystallization of nepheline under oxidizing conditions will produce a residual magma with increased silica. Thus under high PO_2 conditions the differentiates

of such a magma will be more siliceous than under low PO_2 conditions. The importance of PO_2 in the genesis of alkaline undersaturated rocks has been stressed by many recent workers (*cf.* NOLAN, 1966).

(c) Hydrothermal Melting

Water vapour pressure considerably lowers liquidus temperatures of all samples investigated, with the initial 1000 bars PH_2O producing the most significant decrease. For the Ilímaussaq rocks (57041, 57033, 57070), the sequence of crystallization at 1030 bars PH_2O is the same as in the experiments at one atmosphere. As in these runs, the melting interval at this pressure extends for several hundred degrees, with the main crystalline phases appearing about 100°C below the liquidus temperature. The long temperature interval between the last crystallizing phase and the solidus temperature suggests that the coexisting minerals, particularly the nepheline and feldspar are probably changing composition by interaction with the residual liquid. The only phase to appear in the hydrothermal experiments is minor biotite in the naujaite (57041) at about 485°C at 1030 bars PH_2O . The presence of biotite may be related to the decrease in iron content of the glass with falling temperature. Comparison of the liquidus temperatures of the agpaitic Ilímaussaq rocks with those of the non-agpaitic rocks (Figs. 4-9) shows that the former have slightly higher liquidus temperatures. This may be due to their higher alkali, volatile and rare-earth constituents. The much longer melting interval in which the residual liquid can react with crystalline phases will certainly produce a larger variation in the possible differentiation processes which can take place in these rocks in comparison to those with shorter melting intervals.

Under hydrothermal conditions, feldspar is the primary phase at the liquidus for the Blue Mountain, Ontario litchfieldite (BM 1 and BM 5) in contrast to nepheline under atmospheric conditions. This change can be explained by examining the plotted compositions of these samples on the nepheline-kalsilite-orthoclase-albite system at one atmosphere pressure (Fig. 14) and at 1000 bars PH_2O (Fig. 15). At 1000 bars PH_2O , the effect of water vapour pressure is to shift the minimum and the nepheline-feldspar cotectic boundary. At this pressure the compositions of these rocks plot well within the primary phase field of feldspar, whereas at atmospheric pressure, both plot close to the minimum on the nepheline-feldspar cotectic. Therefore, at 1000 bars PH_2O both samples should have feldspar on the liquidus surface.

For comparative purposes, the liquidus curves for three synthetic systems and for the liquidus for the litchfeldite from Maine (BARKER,

1965) have been included in Figs. 7 and 8. The liquidus for the Ontario litchfieldite is in fairly good agreement with the liquidus for the minima in the nepheline-albite system (Curve C), and also with the Maine, litchfieldite liquids curve (dotted). Although there is a close correspondence in composition between the Ontario litchfieldites and the synthetic "nepheline syenite" curve (Curve B), there is a large temperature discrepancy. Possible reasons for this will be discussed in the following section. YODER and TILLEY (1962) suggest that the "nepheline syenite curve" may cross the "granite" curve (Curve A) at approximately 1400 bars PH_2O . The liquidus curves for the rocks studied do not cross the "granite" curve up to 2070 bars PH_2O , and indeed show no tendency to do so even if extrapolated to higher pressures.

The liquidus curve for the Tanzanian phonolite (DH 940) is very similar to those of the Blue Mountain litchfieldites. Feldspar is the primary phase at the liquidus.

(d) Comparison of Melting Experiments with Synthetic Systems

It is common practice for petrologists to plot the compositions of their rocks on various appropriate synthetic systems. From comparison with these systems it is possible to deduce the trends of differentiation, the possible processes of origin of the rock, and in some cases the temperatures of crystallization. (The latter usage seems particularly dubious since only rarely can the pressure of crystallization be accurately estimated). Only in very rare cases, if ever, are the mineralogical constituents of the rock exactly the same as those of the simplified system and it is normally considered justified to compare rock compositions with synthetic systems, provided the rock contains a minimum of 80 percent of the normative minerals of the synthetic system (e.g. TUTTLE and BOWEN, 1958).

In order to compare liquidus temperatures of the rocks of the present study with those of synthetic systems of similar composition, the criterion of 80 percent or more normative minerals in the rocks when compared to the synthetic systems has been used. On this basis, nine of the sixteen rocks can be plotted on appropriate synthetic systems. The rocks from Ilmaussaq have been plotted on the system diopside-nepheline-albite (modified from the system diopside-nepheline-silica investigated by SCHAIRER and YODER (1960), and from the same system at 1000 kg/cm^2 PH_2O (EDGAR, 1964a). Using the procedure of EDGAR, normative orthoclase and albite have been considered as albite, and diopside and acmite present in approximately equal amounts have been plotted as diopside. This is justifiable in view of the similarity between the diopside-neph-

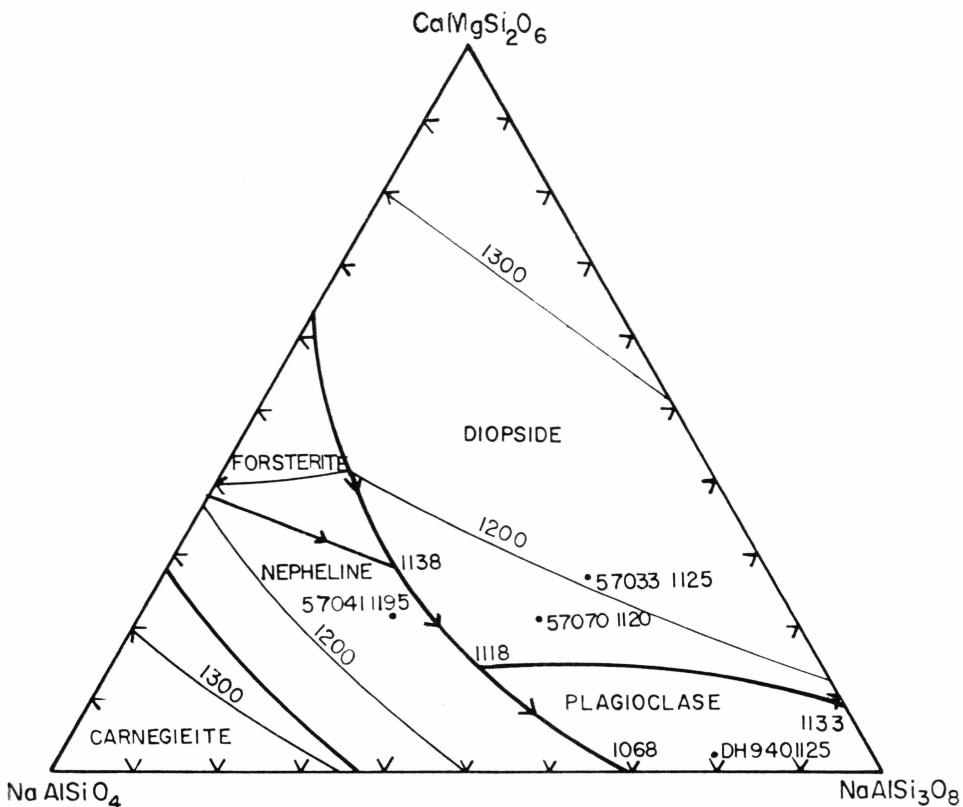


Fig. 12. Samples 57041, 57033, 57070 and DH 940 plotted in the system diopside-nepheline-albite at 1 atmosphere. (System reconstructed from data of SCHAIRER and YODER, 1960).

line-albite and (diopside₅₀-acmite₅₀)-nepheline-albite systems (NOLAN, 1966). The Tanzanian phonolite DH 940 has also been plotted on this system.

The nepheline syenites from Tugtutôq and the Ontario litchfieldites have been plotted on the silica undersaturated portion of the system nepheline-kalsilite-silica (SCHAIRER, 1950; HAMILTON and MACKENZIE, 1965). The Ontario samples are particularly suited for the comparison with this system as they contain more than 92 percent normative nepheline, albite and orthoclase. Modally this percentage is even higher.

The three Ilmaussaq rocks and the phonolite (DH 940) are plotted on the system diopside-nepheline-albite at 1 atmosphere pressure in Fig. 12. Two of the Ilmaussaq samples, which are agpaitic (57041 and 57033), do not plot close to the minima on this system which lies on the nepheline-albite join. Similar tendencies for other agpaitic rocks have been noted by EDGAR (1964a, p. 581). The phonolite (DH 940) plots close to the minima on the synthetic system.

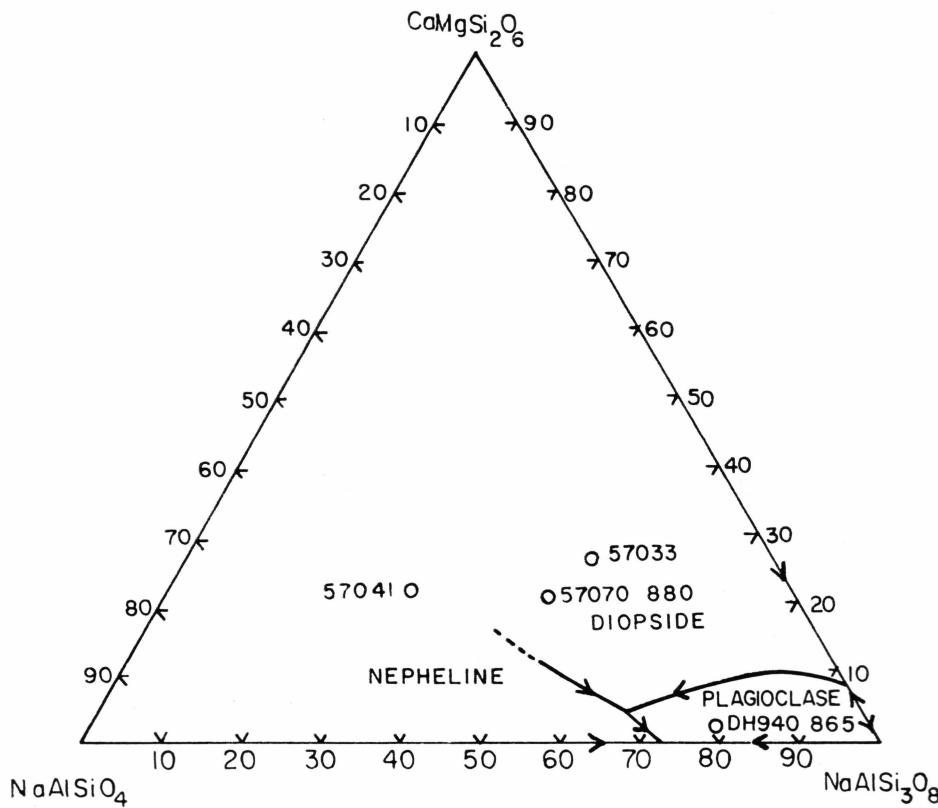


Fig. 13. Samples 57041, 57033, 57070 and DH 940 plotted in the system diopside-nepheline-albite at $\text{PH}_2\text{O} = 1000$ bars.

Comparison of rock melting temperatures with those of the synthetic liquidus, shows that sample 57041 is in excellent agreement. Synthetic liquidus temperatures have been extrapolated from the data of SCHAIRER and YODER (1960). For composition 57041 the corresponding synthetic liquidus is approximately 1150°C , the rock melting temperature 1195°C . For sample 57033 there is a much larger discrepancy of approximately 55°C , with the synthetic liquidus being higher. The phonolite sample (DH 940) has a liquidus temperature approximately 30°C higher than the corresponding synthetic liquidus. Comparison of the primary phases in the melted rocks to those of the synthetic systems shows that 57070 has feldspar as the primary phase on melting, while pyroxene is the primary phase for its composition when plotted on the synthetic system (Fig. 12). Sample 57033 also has feldspar, closely followed by clinopyroxene, as the primary phase. When plotted on the synthetic system this rock is in the pyroxene primary phase field. Sample 57041 has sodalite as the primary phase whereas it

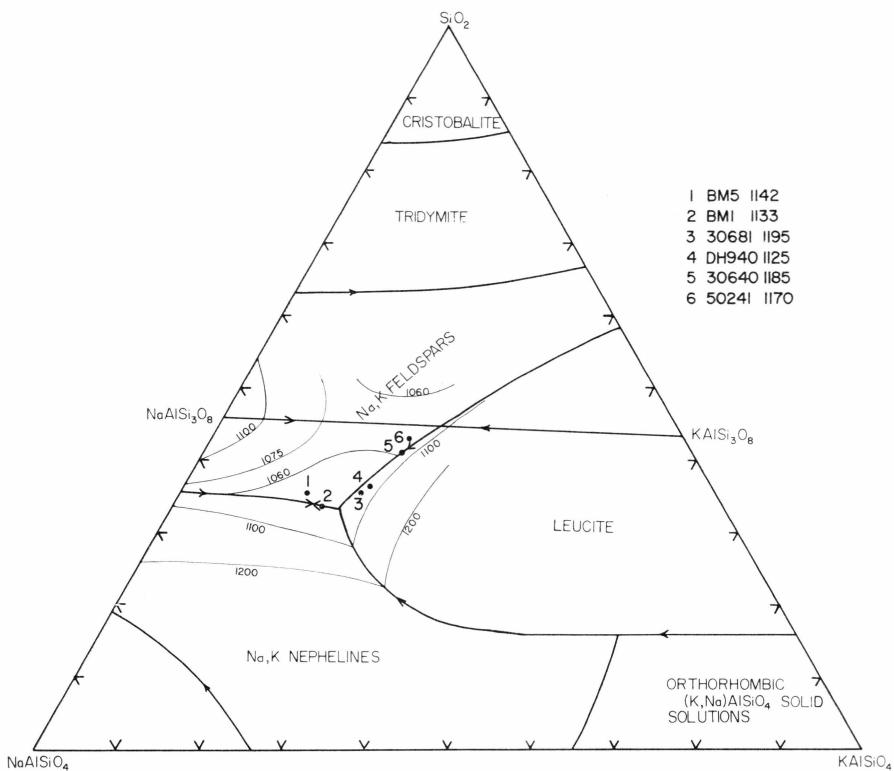


Fig. 14. Plot of selected rocks in the system nepheline-kalsilite-silica at 1 atmosphere.

plots on the nepheline field in the synthetic system. Feldspar as the primary phase in DH 940 is in agreement with its plotted position in the synthetic system.

On Fig. 13, these samples have been plotted on the same system at 1000 bars PH_2O using the data of EDGAR (1964a). Comparisons of liquidus temperatures can be made only for samples 57070 and DH 940. In the former the liquidus temperature at 1000 bars PH_2O is about 60° C lower than the corresponding synthetic liquidus temperature. Similarly for DH 940 the liquidus temperature is about 45° C lower than the corresponding synthetic liquidus.

Agreement between rock melting temperatures and synthetic liquidus temperatures for rocks plotted on the undersaturated part of the nepheline-kalsilite-silica system (SCHAIRER, 1950) is much poorer. As shown in Fig. 14 the compositions of the nepheline syenites from Tugtutôq, Greenland, lying between the feldspar join and the undersaturated minima on this system, have temperatures considerably higher than those of the corresponding synthetic compositions. The litchfieldites from Blue Mountain, Ontario, with compositions very similar to that of the minima

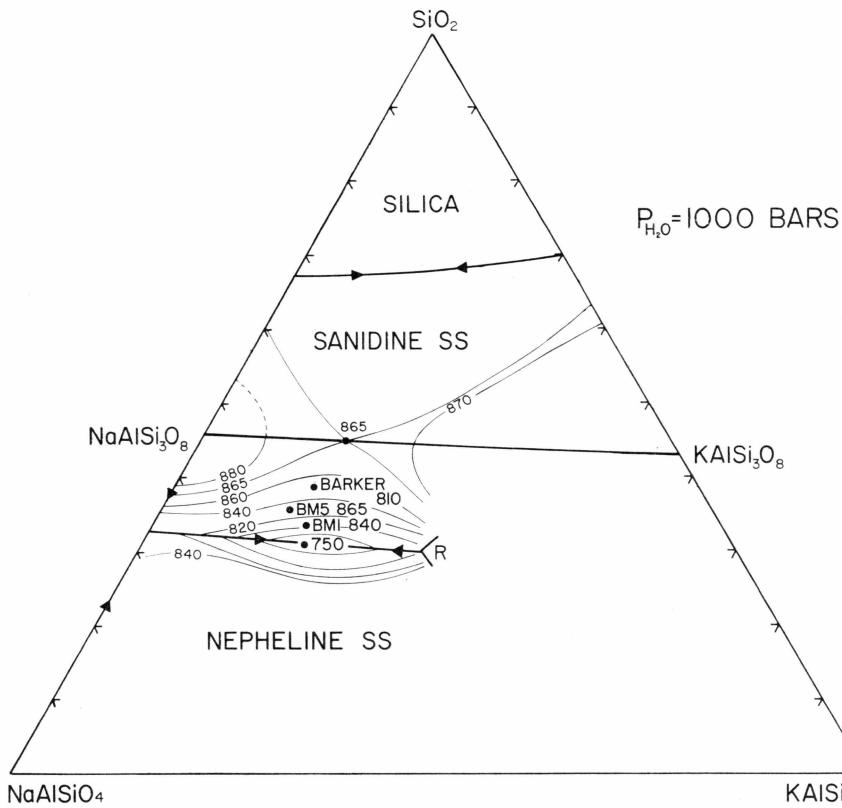


Fig. 15. Plot of samples BM 1, BM 5 and litchfieldite investigated by BARKER (1965) in the system nepheline-kalsilite-silica at $P_{H_2O} = 1000$ bars.

on the synthetic system show correspondingly higher melting temperatures than would be predicted from isotherms in this system. However, the observed melting temperatures of both the Tugtutôq and Blue Mountain rocks are consistently higher than the liquidus temperatures for the corresponding synthetic compositions.

Comparison of the melting temperatures of the Ontario litchfieldites at approximately 1000 bars P_{H_2O} with the synthetic system nepheline-kalsilite-orthoclase-albite at this pressure (HAMILTON and MACKENZIE, 1965) shows that the temperature discrepancies have been considerably reduced to approximately 40° C with the rock temperature being higher (Fig. 15). The litchfieldite used by BARKER (1965) has also been plotted. The similarity in composition of this rock to the Ontario sample might have been expected to produce better agreement in melting temperatures. The reason for this discrepancy cannot be explained at present.

Comparison of rock melting temperatures with corresponding compositions of synthetic systems shows that there are a number of incon-

sistencies, and indicates the dangers of using synthetic systems to estimate crystallization temperatures. Generally there is better agreement between the rocks melted hydrothermally and the corresponding synthetic systems, probably caused by the catalytic action of water reducing kinetic effects. Additional components, such as mafics and volatiles other than water, not present in the synthetic system may also account for these temperature differences. In order to estimate the effect of mafics on liquidus temperatures, melting experiments were made on the Blue Mountain litchfieldites in which the mafics (biotite, magnetite, aegirine-augite and hastingsite) were removed, and in which up to 30 weight percent aegirine was added. Results of these experiments (Table X) show

Table X. *Experiments on Ontario Litchfieldites after Removal of Mafics and with Added Aegirine.*

| | BM 1 | | | BM 5 | | |
|------------------------------|-------------|--------------|------------------------|-------------|--------------|------------------------|
| | Temp. (° C) | Time (hours) | Products ¹⁾ | Temp. (° C) | Time (hours) | Products ¹⁾ |
| a) Mafics Removed. | | | | | | |
| | 1270 | 24 | Gl. | 1246 | 24 | Gl. |
| | 1246 | 24 | Gl., Ne. | 1222 | 22 | Gl., Ne. |
| b) With 10 % added aegirine. | | | | | | |
| | 1138 | 21 | Gl. | 1138 | 21 | Gl. |
| | 1125 | 21 | Gl., Ne. | 1125 | 21 | Gl., Ne. |
| c) With 20 % added aegirine. | | | | | | |
| | 1120 | 24 | Gl. | 1115 | 24 | Gl. |
| | 1106 | 22 | Gl., Ne. | 1106 | 22 | Gl., Ne. |
| d) With 30 % added aegirine. | | | | | | |
| | 1106 | 24 | Gl. | 1106 | 22 | Gl. |
| | 1094 | 24 | Gl., Ne. | 1095 | 22 | Gl., Ne. |

¹⁾ Abbreviations are the same as Table IV.

that removal of the 1-2 modal percent of mafic constituents increases liquidus temperatures substantially. Removal of mafics enhances the chemical similarity between the rock and the synthetic system. The large increase in temperature suggests that minor constituent in the rock should not be neglected when comparing rock and synthetic systems, especially if temperature inferences are made.

The addition of up to 30 percent aegirine lowers liquidus temperatures of these rocks by approximately 30° C, with decreased temperatures approaching a limiting value in the range 20 to 30 percent added aegirine; optics of the added aegirine (from Mt. St. Hilaire, Quebec) suggest that this mineral is nearly pure aegirine. However, since pyroxenes in alkaline rocks usually contain diopside, hedenbergite and augite molecules in

addition to aegirine, these results must be interpreted with caution. Similarly the removal of the mafics which consist largely of iron minerals in these samples may be producing the high increases in liquidus temperatures since it is known from studies of synthetic systems that the addition of iron to silicates will generally lower their liquidus temperatures. It might have been expected that much smaller temperature increases might have resulted had the removed mafic minerals been rich in calcium and magnesium.

PETROLOGICAL IMPLICATIONS

There are a number of petrological implications which can be made from this study.

a) Comparison of Observed Liquidus Temperatures and Extrusion Temperatures

Available data on extrusion temperatures of undersaturated alkaline rocks are given in Table XI. As stressed by GUTENBERG (1951) such temperatures must be regarded as only approximate due to difficulties in their measurement. Liquidus temperatures found in the present study are in fairly good agreement with the observed temperatures.

Tabel XI. *Observed Temperatures of Undersaturated Alkaline Lavas.*

| Locality | Temp. (° C) | Type | Reference |
|-----------------|-------------|-------------------------|---------------------------|
| Nyiragongo | 980 | Nephelinite | SAHAMAMA and MEYER (1958) |
| Nyamuragira | 1095 | Leucite basalt | VERHOOGEN (1948) |
| Vesuvius (1904) | 1100 | Leucite tephrite | GUTENBERG (1951) |
| Vesuvius (1929) | 1150 | Leucite tephrite (?) | RITTMAN (1962) |
| Vesuvius (1913) | 1200 | Leucite tephrite | PERRET (1924) |

WASHINGTON (1924, p. 144) has noted that the leucite tephrites of the central Vesuvian cone have been uniform in mineral and chemical composition since 1631. However the phenocrysts of these lavas are very variable and are composed of leucite, leucite and minor augite, augite with minor leucite, or olivine and augite. Rare plagioclase is present as phenocrysts. DAWSON (1962) has shown that phonolites from the Oldoinyo Lengai volcano have various combinations of feldspar, nepheline and pyroxene occurring as phenocrysts. These observations and the experimental data suggest that the major phases begin to crystallize together within a narrow temperature range early in the cooling history of the lava.

b) Chemical Trends

The small number of comagmatic rocks used in the present study do not warrant any detailed implications regarding the chemical trends of these rocks. In plotting these trends (Fig. 2), the inherent bias of the classical oxide variation diagrams has been avoided. This problem has been discussed in a number of papers by CHAYES (e.g. 1960, 1962) and need not be repeated here. Only three comagmatic rock series containing three or more rocks were used in this study. These are the ijolitic rocks from Kenya (K series), the nepheline syenites from Tugtutôq, Greenland (50241, 30640 and 30681) and the agpaitic rocks from Ilímaussaq, Greenland (57041, 57033 and 57070).

The Kenyan rocks show the most pronounced chemical variation when plotted against their liquidus temperatures. This variation can be explained by considering the mineralogy of the individual samples. Increasing SiO_2 and Al_2O_3 content with decreasing temperature is reflected by the much larger proportions of nepheline, feldspar, wollastonite and melanite in the lower melting phonolitic nephelinite (K 18) and ijolite (K 15) in comparison to the higher melting melteigite (K 14) and melanephelinite (K 5). Increasing TiO_2 with increasing temperature, may be caused by the tendency for titanium-bearing minerals (as rutile, ilmenite etc.) to become separated during the early stage of crystallization (RANKAMA and SAHAMA, 1950). The iron enrichment trend (Fig. 2d) is similar to the SiO_2 and Al_2O_3 trends. The high melting rocks (K 5 and K 14) contain abundant magnetite, olivine, and aegirine-diopside whereas samples K 2, K 15 and K 18 have less mafic minerals with no olivine and less diopsidic pyroxene. This produces lower MgO and hence the iron enrichment ratio $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO})$ increases.

In their melting experiments on basalts, TILLEY, YODER and SCHAIKER (1965) have plotted iron-enrichment ratios against liquidus temperatures and suggest that this parameter characterizes progressive differentiation. The similar trend in the Kenyan ijolites may indicate that iron-enrichment has been important in their genesis. However, differentiation cannot entirely explain the production of alkaline rocks, particularly ijolites (BAILEY and SCHAIKER, 1963).

The nepheline syenites from Tugtutôq represent cumulative rocks (UPTON, 1964) and as such their compositions represent only a restricted portion of the liquid from which they have crystallized, and thus the data of Fig. 2 shows only a small part of their crystallization trends. The variations in SiO_2 , TiO_2 , and iron-enrichment ratio may suggest that the trends in these rocks are opposite to those of the Kenyan ijolites.

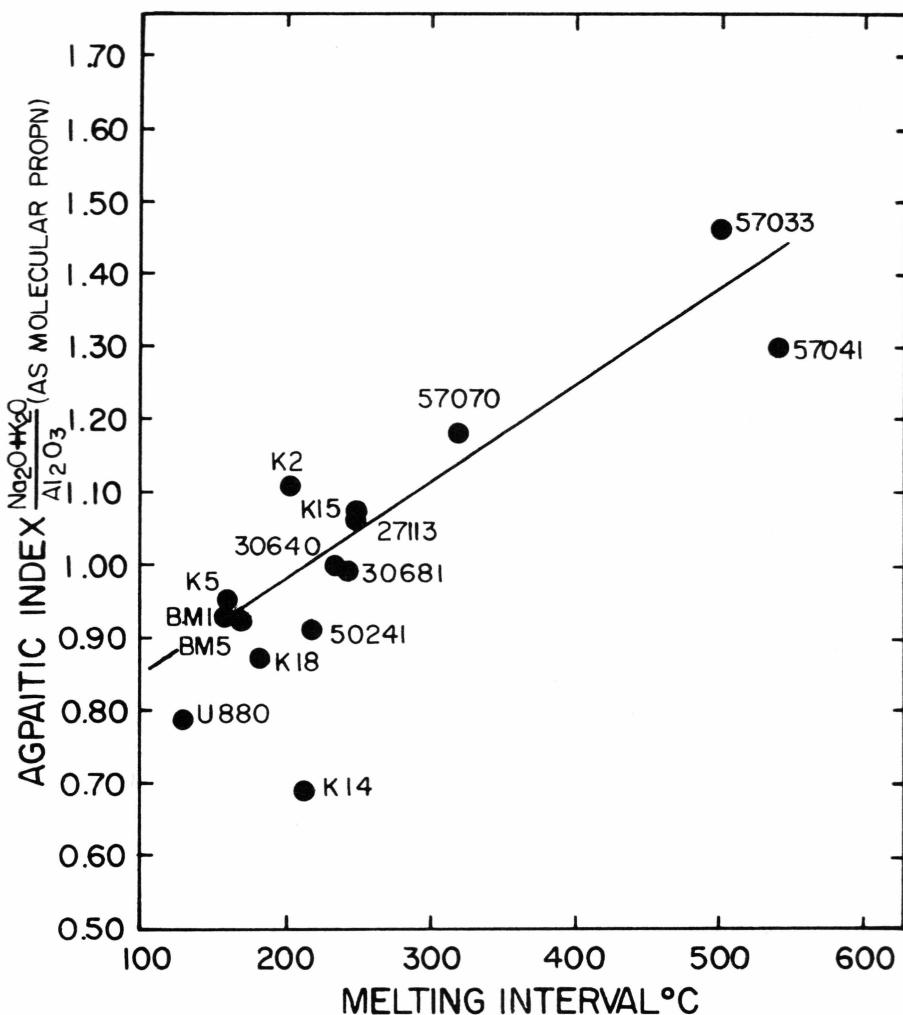


Fig. 16. Plot of melting interval against agpaitic index for selected alkaline rocks.

As has been noted throughout this paper, the agpaitic rocks from Ilímaussaq appear to have different physical characteristics from the other non-agpaitic rocks. Fig. 2 shows that the liquidus temperatures of these rocks are apparently independent of composition. (Attempts to relate liquidus temperatures to other chemical parameters showed similar results). The principal difference between the Ilímaussaq rocks and those from the other localities is in their extremely long melting interval. In Fig. 16, the melting intervals of these rocks have been plotted against their agpaitic index and shows that increasing agpaitic index (indicating increased alkali content) prolongs this interval. Most writers agree that agpaitic rocks are also enriched in volatiles (e.g. SØRENSEN, 1960) and

it is known that volatiles will preferentially transport alkalies (e.g. SMYTH, 1927; KENNEDY, 1955). The combination of high alkali and high volatile contents of these rocks may also considerably prolong their melting intervals as suggested by the results of Fig. 16.

c) Nepheline-Feldspar Composition

The dependence of nepheline and feldspar compositions on temperature is discussed by TILLEY (1954, 1958) who shows that in phonolites and nepheline syenites, representing high temperature rocks, the nepheline composition varies with the bulk rock composition, and that the feldspar is anorthoclase. These are termed hypersolvus nepheline syenites. In contrast, the chemically equivalent, low temperature assemblages, including metasomatic nepheline syenites, contain nepheline of composition close to the theoretical Morozewicz composition (Fig. 10) and albitic feldspar with or without microcline. These are termed subsolvus nepheline syenites and the Morozewicz composition ($Ne_{75}Ks_{21}Q_4$) represents the composition toward which nephelines adjust in response to falling temperature.

The compositions of nephelines from the unheated rocks fall into two groups (Fig. 10). The first group (BM 1, BM 5, 57033 and K 2) plot very close to the Morozewicz composition and have $Na/Na + K$ ratios of 0.76 to 0.79. With the exception of K 2, these rocks have characteristics of the low temperature assemblage defined by TILLEY. Sample K 2 (nepheline syenite) has felsic minerals characteristic of high temperature rocks but the strong zoning in the nepheline makes its composition difficult to determine by X-ray methods. The second group (50241, DH 940, 27113, K 18, and 57041) contain nephelines with larger $Na/Na + K$ ratios (0.82–0.90), which plot away from the Morozewicz composition. In these rocks there is only one coexisting feldspar of the intermediate or high temperature type.

The subsolvus nepheline syenites (group 1 of this study) represent slow cooling and extensive subsolvus crystallization (TILLEY, 1958) with adjustment of nepheline composition toward the ideal 3:1 Na:K ratio. For the Blue Mountain litchfieldites it cannot be determined whether the nepheline compositions have been produced by slow cooling or by metasomatic processes. The banded structure of some of these rocks suggests that some post-consolidation metasomatism has taken place. However, the similarity in the tie-lines of the Blue Mountain rocks when compared to those of other known magmatic rocks (TILLEY, 1952) and their melting behaviour suggests a magmatic origin. This is in accordance with the beliefs of HEWITT (1960) and other writers.

The nepheline of the lujavrite from Ilímaussaq has a composition close to the Morozewicz composition. SØRENSEN (1962) cites evidence to

suggest that this may be caused by crystal-liquid processes rather than adjustment of the composition due to subsolvus recrystallization. He states (p. 148) that "lujavrites possess a very pronounced igneous habit" and that magmatic origin is indicated by the development of an intrusion breccia. In the same paper SØRENSEN states (p. 179) "albite and microcline have formed in mutual equilibrium" and that the feldspars indicate that consolidation of this rock took place around 400° C. The results of melting experiments certainly support this conclusion, and may suggest that the albite and microcline originated as discrete phases rather than representing the products of unmixing of a homogeneous feldspar.

The second group are hypersolvus nepheline syenites crystallized at high temperatures with little or no subsolvus recrystallization. In these rocks the variable nepheline composition reflects crystallization at higher temperatures in which there is freer occupation of alkali sites in the nepheline structure (TILLEY, 1954).

In an attempt to determine the magnitude of compositional changes in the nepheline and feldspar on cooling, several determinations of the nepheline and feldspar were made for the Blue Mountain litchfieldite (BM 1) at temperatures up to 975° C (Table VIII, Fig. 11). At temperatures above 900° C the nepheline has an approximate Na/Na + K ratio of 0.85 whereas in the unheated rock this ratio is 0.76.

There are both sodium and potassium-rich feldspars in this rock before heating, the former as subhedral grains of albite and as antiperthitic intergrowths, the latter as microperthites and perthites. Modal analysis indicates a 2:1 ratio of albite to microcline. On heating to temperatures above 900° C, the composition of the two feldspars are Ab_{91} and Ab_{66} respectively, giving a bulk feldspar composition (based on the 2:1 ratio) of approximately Ab_{83} . Below 600° C the bulk compositions of the feldspar is difficult to estimate as the $\bar{2}01$ reflections of the sodium-rich feldspars overlap. However, the relative peak intensities of both the sodic and potassic phases do not change at the lower temperatures and it is possible to estimate the bulk feldspar composition as Ab_{91} , assuming the same proportions of albite and microcline at these temperatures, and that there has been no alkali exchange between the feldspar phases. If these assumptions are valid, there is a net increase of approximately 8 percent albite with decreasing temperature.

The changes in the nepheline and feldspar compositions in this sample are in agreement with TILLEY's (1958) concept of the temperature dependence of the Na/K ratio in coexisting nephelines and feldspar. With decreasing temperature, nepheline is enriched in potassium and feldspar in sodium.

d) Comparison of Melting Temperatures and Sequences of Crystallization with Field Observations

In order to test the applicability of melting experiments in elucidating magmatic processes, the data of the present study may be compared with the melting temperatures and mineral paragenesis deduced from field and petrographic studies of the same rocks. In many cases information in the literature is either completely lacking or, particularly in the case of melting temperatures, covers such a wide range as to be almost meaningless for the present purposes.

The most complete data are available for the Ilímaussaq rocks studied by SØRENSEN (1958, 1962) who suggests (1962, p. 145) that the lujavrite crystallized later than the naujaite (57041) and kakortokite. No sample of the latter was available but liquidus temperatures of the lujavrite are lower than the naujaite under both atmospheric and hydrothermal conditions. In the same paper (p. 188), SØRENSEN shows that the consolidation of the lujavrite took place around 400° C. The experimental consolidation temperatures are slightly higher than this but certainly within the same range. Comparison of the experimentally determined mineral paragenesis and the sequence deduced by SØRENSEN indicates some discrepancies for the lujavrite but complete agreement for the naujaite. For the lujavrite (SØRENSEN 1962, p. 148) suggests nepheline, sodalite, feldspar, eudialyte, arfvedsonite in contrast to the experimentally determined sequence of feldspar, pyroxene, nepheline and amphibole. For the naujaite SØRENSEN (1958, p. 12) gives sodalite, nepheline, feldspar pyroxene and amphibole in agreement with the sequence determined from the melting experiments.

UPTON (1964, p. 51) has estimated that the nepheline syenites of the Tugtutôq have crystallized at temperatures greater than 750° C with final consolidation at approximately 400° C. No estimate of the depth of crystallization of these dike rocks is given and no melting experiments under pressure have been done. However the range of melting temperature under atmospheric conditions is about 225° C, considerably less than that postulated by UPTON (1964).

Based on comparison with the nepheline-kalsilite-silica system, HEIER (1965, p. 45) has estimated liquidus temperatures of the Blue Mountain litchfieldites as 1050° C at atmospheric pressure and 800° C at 1000 bars PH_2O . Both values are lower than the experimentally determined values, although the estimated temperature at 1000 bars PH_2O is in fair agreement with the 850° C of the present work. These discrepancies may either reflect the inadvisability of estimating liquidus temperatures from synthetic systems or the fact that estimates of liquidus temperatures in these rocks are probably quite variable due to the different

ratios of nepheline to feldspar, and in the type and quantity of mafic minerals present in different parts of the body. KEITH (1939, p. 1820) suggests that feldspar crystallized before nepheline, which is in agreement with the experimentally determined sequence at 1000 bars PH_2O .

The only data available for the foyaite from Grønnedal-Íka is from EMELEUS (1964, p. 16) who shows that alkali feldspar and nepheline crystallization was followed by the mafic minerals. This is in accordance with the sequence found in the melting experiments under oxidizing conditions at one atmosphere.

PULFREY (1950, p. 446) gives liquidus temperatures for the Kenyan melteigites and wollastonitic ijolite as less than 1249°C and greater than 500°C at very low water vapour pressures. The liquidus temperatures of the present study are in fair agreement with PULFREY's upper limits. The crystallization sequences suggested by PULFREY (p. 445-446) are also in good agreement with the sequences found in the melting experiments although PULFREY suggests two generations of pyroxene in the nepheline syenite and ijolitic rocks. This was not observed in the melting experiments.

e) Comparison of Textural Relations and Melting Behaviour

Textural relations in igneous rocks are commonly used to determine crystallization sequences. In some cases such relations may be subject to misinterpretation because the textures may have been produced by a variety of processes.

Most petrographers believe that the phenocrysts of volcanic rocks form during an early period of intratelluric crystallization (JOHANNSEN, 1931). For the volcanic rocks studied, the liquidus phase corresponds to the major phenocryst. In rocks with more than one type of phenocryst, the phenocrysts are melted within $40\text{--}60^\circ\text{C}$ of one another.

In the intrusive rocks, with longer and more complicated crystallization histories, the comparison is not so well defined. The Blue Mountain litchfieldites have textures indicating more or less simultaneous crystallization of the major minerals nepheline and feldspar. These minerals crystallize within a $20\text{--}30^\circ\text{C}$ range below the liquidus temperature. The majority of the plutonic rocks have a hypidiomorphic granular texture, representing earlier crystallization of the idiomorphic constituents with respect to the allotriomorphic constituents (WILLIAMS, TURNER, and GILBERT, 1958). Samples 27113, 50261, and 57041 are cumulative rocks. The first of these has idiomorphic nepheline and feldspar; 50241 has idiomorphic feldspar. On melting, both rocks have feldspar as the primary phase, with intercumulate constituents crystallizing $70\text{--}80^\circ\text{C}$ below

the liquids. In sample 57041, sodalite and nepheline are idiomorphic. Sodalite is the primary phase with nepheline appearing as secondary phase at 75° C lower. The major intercumulate constituent, pyroxene, crystallizes 180° C below the liquidus. In sample K 2, feldspar and nepheline occur as zoned phenocrysts with nepheline as the primary phase and feldspar crystallizing 25° C below the liquidus. In thin section, the strong zoning of these crystals indicates disequilibrium crystallization.

CONCLUSIONS

Provided the limitations listed previously are realized, melting experiments of alkaline rocks are valuable in determining their genesis, particularly when comagmatic rocks are used. The most important conclusions from this study are the much longer melting interval in the agpaitic rocks; the significant differences, in some cases, between liquidus temperatures of the rocks studied and temperatures obtained from pertinent synthetic systems; the importance of oxygen fugacities and volatile pressures in the genesis of these rocks; and the pronounced effect of minor amounts of mafic minerals on the liquidus temperatures of these rocks.

Future investigations, already begun in this laboratory, should be concentrated on melting experiments under water and other geologically important volatile pressures using comagmatic rocks. Experiments based on natural starting materials represent only the final stage of a complex geological process and as such it is difficult to evaluate all of the possible changes occurring during crystallization. This might be overcome by preparing synthetic chemical equivalents of a rock series and investigating their melting relationships under a variety of physical conditions. Work is also being undertaken to determine variations in coexisting nepheline and feldspar compositions in the heated rocks.

REFERENCES

BAILEY, D. K., 1963: The stability relations of acmite. Ann. Rept., Carnegie Inst. Washington, Yearbook No. 62, pp. 131-133.

— and SCHAIRER, J. F., 1963: Crystallization of the rock-forming silicates in the system $\text{Na}_2\text{O}\text{-}\text{Al}_2\text{O}_3\text{-}\text{Fe}_2\text{O}_3\text{-}\text{SiO}_2$ at 1 atmosphere. Ann. Rept., Carnegie Inst. Washington, Yearbook No. 62, pp. 124-131.

— 1966: The system $\text{Na}_2\text{O}\text{-}\text{Al}_2\text{O}_3\text{-}\text{Fe}_2\text{O}_3\text{-}\text{SiO}_2$ at 1 atmosphere and the petrogenesis of alkaline rocks. Journ. Petrol., V. 7, pp. 114-170.

BARKER, D. S., 1965: Alkalic rocks at Litchfield, Maine: Journ. Petrol., V. 6, pp. 1-27.

CHAYES, F., 1960: On correlation between variables of constant sum. Journ. Geophys. Res., V. 65, pp. 4185-4193.

— 1962: Numerical correlation and petrographic variation. Journ. Geol., V. 70, pp. 440-452.

DAWSON, J. B., 1962: The geology of Oldoinyo Lengai. Bull. Volcanologique, V. 24, pp. 349-387.

DAY, A. L. and ALLEN, B. T., 1905: The isomorphism and thermal properties of the feldspars: Carnegie Inst. Washington Publ. 31, 95 p.

EDGAR, A. D., 1964 a: Phase equilibrium relations in the system $\text{CaMgSi}_2\text{O}_6$ (diopside)- NaAlSiO_4 (nepheline) — $\text{NaAlSi}_3\text{O}_8$ (albite) — H_2O at 1,000 kg/cm² water vapour pressure. Amer. Min., V. 49, pp. 573-585.

— 1964 b: Phase equilibrium relations in the system nepheline-albite-water at 1,000 Kg/cm². Journ. Geol., V. 72, pp. 448-460.

— and NOLAN, J., 1966: Phase relations in the system $\text{NaAlSi}_3\text{O}_8$ (albite) — NaAlSiO_4 (nepheline) — $\text{NaFeSi}_2\text{O}_6$ (acmite) — $\text{CaMgSi}_2\text{O}_6$ (diopside) — H_2O and its importance in the genesis of alkaline undersaturated rocks. Indian Mineralogist, Special I. M. A. paper, pp. 176-181.

EMELUS, C. H., 1964: The Grønnedal-Íka alkaline complex, South Greenland. Medd. Grønland, Bd. 172, 75 p.

ERNST, W. G., 1962: Synthesis, stability relations and occurrence of riebeckite and riebeckite-arfvedsonite solid solutions. Journ. Geol., V. 70, pp. 689-736.

FAUST, G. T., 1936: The fusion relations of iron-orthoclase, with a discussion of the evidence for the existence of an iron-orthoclase molecule in feldspars. Amer. Min., V. 21, pp. 735-763.

FERGUSON, J., 1964: Geology of the Ilimaussaq alkaline intrusion, South Greenland. Medd. Grønland, Bd. 172, 4, 82 p.

FERSMAN, A. E., 1929: Geochemische Migration der Elemente. I. Abhandl. prakt. Geol. Bergwirtschaftslehre, V. 18, pp. 1-73.

— 1939: Geokhimiya (Geochemistry) V 4., Goskhimizdat, L.

FYFE, W. S., 1960: Hydrothermal synthesis and determination of equilibrium between minerals in the subliquidus region. Journ. Geol., V. 68, pp. 553-566.

GERASIMOVSKII, V. I., 1956: Geochemistry and mineralogy of nepheline syenite intrusions. *Geochemistry*, no. 5, pp. 494-510.

GORANSON, R. W., 1931: The solubility of water in granite magmas. *Am. Journ. Sci.*, V. 22, pp. 481-502.

— 1932: Some notes on the melting of granite. *Am. Journ. Sci.*, V. 23, pp. 227-236.

GREEN, D. H. and RINGWOOD, A. E., 1966: The genesis of basaltic magmas, in *Petrology of the Upper Mantle*. — High pressure experimental investigations into the nature of the Mohorovicic Discontinuity. Publication of the Australian National University, Canberra.

GREIG, J. W. and BARTH, T. F. W., 1938: The system $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ (nephelite, carnegieite) — $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ (albite). *Am. Journ. Sci.*, V. 35A, pp. 93-142.

GUTENBERG, B., Ed., 1951: *Internal Constitution of the Earth*, 2nd ed., Dover, N.Y., 439 p.

HAMILTON, D. L., BURNHAM, C. WAYNE, and OSBORN, E. F., 1964: The solubility of water and effects of oxygen fugacity and water content on crystallization in mafic magmas. *Journ. Petrol.*, V. 5, pp. 21-39.

— and MACKENZIE, W. S., 1960: Nepheline solid solution in the system $\text{NaAlSiO}_4 \cdot \text{KAlSiO}_4 \cdot \text{SiO}_2$. *Journ. Petrol.*, V. 1, pp. 56-72.

— — 1965: Phase equilibrium studies in the system NaAlSiO_4 (nepheline) — KAlSiO_4 (kalsilite)- $\text{SiO}_2 \cdot \text{H}_2\text{O}$. *Mag.*, V. 34, pp. 214-231.

HARKIN, D. A., 1960: The Rungwe volcanics. *Geol. Surv. Tanganyika*, Mem. 2.

HEIER, K. S., 1965: A geochemical comparison of the Blue Mountain (Ontario, Canada) and Stjernöy (Finnmark, North Norway) nepheline syenites. *Norsk. Geol. Tidskr.*, V. 45, pp. 41-52.

HEWITT, D. F., 1960: Nepheline syenite deposits of Southern Ontario. *Ont. Dept. Mines Rept.*, V. 69, 188 p.

JAHNS, R. H. and BURNHAM, C. W., 1957: Preliminary results from experimental melting and recrystallization of Harding, New Mexico, pegmatite. (Abstract). *Geol. Soc. Am., Bull.*, V. 68, p. 1751.

JOHANSEN, A., 1931: *A Descriptive Petrography of the Igneous Rocks*. V. 1, Univ. Chicago Press, Chicago, 318 p.

KEITH, M. L., 1939: Petrology of the alkaline intrusive at Blue Mountain, Ontario. *Geol. Soc. Am., Bull.*, V. 50, pp. 1795-1826.

KENNEDY, G. C., 1948: Equilibrium between volatiles and iron oxides in igneous rock. *Am. Journ. Sci.*, V. 246, pp. 529-549.

— 1955: Some aspects of the role of water in rock melts. *Geol. Soc. Am. Spec. Paper* 62, pp. 489-504.

KING, B. C. and SUTHERLAND, D. S., 1960: The alkaline rocks of eastern and southern Africa. *Sci. Progress*, V. 48, pp. 298-321, 504-524, 709-720.

MC CALL, G. J. H., 1958: Geology of the Gwasi area. *Rept., Geol. Surv. Kenya*, V. 45, 88 p.

MUAN, A., 1962: The miscibility gap in the system Ag-Fe-Pd at 1000°, 1100°, and 1200° C. *Am. Inst. Mech. Eng., Trans.*, V. 224, pp. 1080-1081.

NOLAN, J., 1966: Melting relations in the system $\text{NaAlSi}_3\text{O}_8 \cdot \text{NaAlSiO}_4 \cdot \text{NaFeSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ and their bearing on the genesis of alkaline undersaturated rocks. *Quart. Journ. Geol. Soc.*, V. 122, pp. 119-157.

ORVILLE, P. M., 1963: Alkali ion exchange between vapor and feldspar phases. *Am. Journ. Sci.*, V. 261, pp. 201-237.

PERRET, F. A., 1924: The Vesuvius eruption of 1906. *Carnegie Inst. Washington, Publ.* 339, 134 p.

PIOTROWSKI, J. M., EDGAR, A. D., and FLEET, M. E. L., 1965: Preliminary investigations of the petrology and melting relations of the Blue Mountain, Ontario litchfeldites. (Abstract) *Can. Min.*, V. 8, p. 401.

PULFREY, W., 1950: Ijolitic rocks near Homa Bay, Western Kenya. *Quart. Journ. Geol. Soc.*, V. 105, pp. 425-459.

— 1954: Alkaline syenites at Ruri, South Nyanza, Kenya. *Geol. Mag.*, V. 91, pp. 209-219.

RANKAMA, K. and SAHAMA, T. G., 1950: *Geochemistry*. Univ. Chicago Press, Chicago, 912 p.

RITTMAN, A., 1962: *Volcanoes and their Activity*. Interscience Publ., New York, 305 p.

SAHAMA, T. G. and MEYER, A., 1958: A study of the volcano Nyiragongo. *Progress Rept., Exploration du Parc National Albert: Mission d'études vulcanologiques*. Fasc. 2, 15.

SCHAIRER, J. F., 1950: The alkali feldspar join in the system $\text{NaAlSiO}_4\text{-KAlSiO}_4\text{-SiO}_2$. *Journ. Geol.*, V. 58, pp. 512-517.

— and BOWEN, N. L., 1935: Preliminary report on equilibrium relations between feldspathoids, alkali feldspars, and silica. *Am. Geophys. Union, Trans.*, 16th Ann. Meeting, pp. 325-328.

— and YODER, H. S., 1960: The nature of residual liquids from crystallization, with data on the system nepheline-diopside-silica. *Am. Journ. Sci.*, V. 258-A, pp. 273-283.

SMYTH, C. H., 1927: The genesis of alkaline rocks. *Am. Phil. Soc., Proc.*, V. 66, pp. 535-580.

SØRENSEN, H., 1958: The Ilímaussaq batholith. A review and discussion. *Medd. Grønland*, Bd. 162, 3, 48 p.

— 1960: On the agpaitic rocks. *XXI Int. Geol. Congr.*, Copenhagen, pt. 13, pp. 319-327.

— 1962: On the occurrence of Steenstrupine in the Ilímaussaq massif, Southwest Greenland. *Medd. Grønland*, Bd. 167, 1, 251 p.

TILLEY, C. E., 1952: Nepheline parageneses. *Sir Douglas Mawson Ann. Vol.*, pp. 167-177.

— 1954: Nepheline-alkali feldspar parageneses. *Am. Journ. Sci.*, V. 252, pp. 65-75.

— 1958: Problems of alkali rock genesis, *Quart. Journ. Geol. Soc.*, V. 113, pp. 323-360.

— YODER, H. S. and SCHAIRER, J. F., 1965: Melting relations of volcanic tholeiite and alkali rock series. *Ann. Rept., Carnegie Inst. Washington, Yearbook No. 64*, pp. 69-82.

TURNER, F. J. and VERHOOGEN, J., 1960: *Igneous and Metamorphic Petrology*. McGRAW-HILL, New York, 694 p.

TUTTLE, O. F., 1949: Two pressure vessels for silicate-water studies. *Geol. Soc. Am., Bull.*, V. 60, pp. 1727-1729.

— and BOWEN, N. L., 1958: Origin of granite in the light of experimental studies in the system $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$. *Geol. Soc. Amer., Mem.* 74, 153 p.

UPTON, B. G. J., 1964: The geology of Tugtutôq and neighbouring islands, South Greenland. Part IV. The nepheline syenites of the Hviddal composite dyke. *Medd. Grønland*, Bd. 169, 3, pp. 49-80.

USSING, N. V., 1912: Geology of the country around Julianehaab, Greenland. *Medd. Grønland*, Bd. 38, 376 p.

VERHOOGEN, J., 1948: Les éruptions 1938-1940 du volcan Ny amuragira — Exploration du Parc National Albert. Mission J. VERHOOGEN (1938 and 1940), Fase 1.

WASHINGTON, H. S., 1924: The Vesuvius eruption of 1906. Carnegie Inst. Washington, Publ. 339, 134 p.

WILKINSON, J. F. G., 1965: Some feldspars, nephelines and analcimes from the Square Top Intrusion, Nundle, N.S.W. Journ. Petrol., V. 6, pp. 420-444.

WILLIAMS, H., TURNER, F. J., and GILBERT, C. M., 1958: Petrography: An Introduction to the Study of Rocks in Thin Sections. W. H. Freeman and Co., San Francisco, 406 p.

YODER, H. S. and TILLEY, C. E., 1962: Origin of basalt magmas: An experimental study of natural and synthetic rock systems. Journ. Petrol., V. 3, pp. 342-532.