EXPERIMENTAL STUDY OF THE SYSTEM DIOPSIDE – ALBITE – NEPHELINE
AT P(H₂O) = P(TOTAL) = 2 AND 10 KBAR AND AT P(TOTAL) = 28 KBAR

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ABSTRACT

Bulk compositions of many nephelinites, melanephelinites, urtites, phonolites and tephrites plot in the system diopside – albite – nepheline. A study of the system under various pressures and temperatures both in the presence and absence of H₂O thus has relevance in the genesis of these rock types. Sixty-five experiments were conducted on 20 starting compositions at 28 kbar under dry conditions. The primary phase volumes of nepheline, clinopyroxene and albite were encountered. The four-phase assemblage Cpx + Pl + Qtz + L occurs at 1200 ± 5°C toward the albite-rich side of the subsystem, whereas in the nepheline-rich portion, the three-phase assemblage of Cpx + Ne + L is obtained at 1249 ± 5°C. The clinopyroxene is a solid solution in the series CaMgSi₂O₆ (diopside) – NaAlSi₂O₆ (jadeite) at 28 kbar. This confirms the observation of Bell & Davis (1969), who suggested complete solid-solution between the two phases at this pressure and above. A nephelinitic or a melanephelinitic magma on further crystallization yields a phonolitic liquid. The same system was also studied at P(H₂O) = P(Total) = 10 and 2 kbar. Eighteen experiments were done at 10 kbar, and the “isobaric invariant” point was observed at Di₄ Ab₄₆₆ Ne₄₉₄ and 835 ± 5°C, whereas this point lies at Di₅ Ab₆₆ Ne₂₉ and 88₅ ± 5°C at P(H₂O) = P(Total) = 2 kbar. The invariant point at 10 kbar is a reaction point, where the equilibrium assemblage comprises Cpx + Ne + Ab + L + V. The reaction point at 2 kbar corresponds to the composition of many nepheline-bearing mafic to felsic rocks. The present data at 10 and 2 kbar [P(H₂O) = P(Total)] indicate that a phonolitic liquid can be obtained by the following schemes of fractionation: i) melanephelinite → nephelinite → phonolite, and ii) “trachyte” → phonolite.

Keywords: diopside, nepheline, albite, phase relations, upper mantle condition, experimental petrology.

SOMMAIRE

La composition chimique de plusieurs néphélinites, mélanéphélinites, urtites, phonolites et tephrites est assez proche du système diopside – albite – néphéline. Une étude de ce système sous conditions variées de pression et de température, avec ou sans H₂O, a donc une certaine importance pour comprendre la genèse de cette suite de roches. Nous avons effectué soixante-cinq expériences sur 20 mélanges à sec à 28 kbar. Les volumes primaires de népheline, clinopyroxène et albite ont été croisés. L’assemblage à quatre phases Cpx + Pl + Qtz + L apparaît à 1200 ± 5°C vers le côté du pôle albite du sous-système, tandis que dans la portion du système se rapprochant du pôle néphéline, nous obtenons l’assemblage à trois phases Cpx + Ne + Ab + L à 1249 ± 5°C. Le clinopyroxène est une solution solide de la série CaMgSi₂O₆ (diopside) – NaAlSi₂O₆ (jadéite) à 28 kbar. Ce résultat confirme l’observation de Bell et Davis (1969), qui proposaient une solution solide complète entre les deux phases à cette pression et au-delà. Un magma néphélinitique ou bien mélanéphélinitique sujet à une cristallisation progressive mènerait à un liquide phonolitique. Nous avons étudié le même système aux conditions P(H₂O) = P(Total) = 10 et 2 kbar. Dix-huit expériences ont été effectuées à 10 kbar, et le point “invariant isobarique” a été défini à Di₄ Ab₄₆₆ Ne₄₉₄ et 835 ± 5°C, tandis que le point correspondant à P(H₂O) = P(Total) = 2 kbar se trouve à Di₅ Ab₆₆ Ne₂₉ et 88₅ ± 5°C. Le point invariant à 10 kbar représente une réaction impliquant l’assemblage Cpx + Ne + Ab + L + V à l’équilibre. Ce point à 2 kbar correspond à la composition de plusieurs roches néphélinitiques maﬁques et felsiques. D’après les données acquises à 10 et à 2 kbar [P(H₂O) = P(Total)], un liquide phonolitique peut résulter des schémas suivants de fractionnement: i) melanéphélinite → néphélinite → phonolite, et ii) “trachyte” → phonolite.

Mots-clés: diopside, néphéline, albite, relations de phases, conditions du manteau supérieur, pétrologie expérimentale.

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INTRODUCTION

The system diopside – albite – nepheline is one of the most important subsystems of the simplified basalt tetrahedron, diopside – nepheline – forsterite – silica, of Yoder & Tilley (1962). Bulk compositions of many nephelinites, melanephelinites, urtites, phonolites and "tephrites" also plot near this plane. Study of this subsystem at variable pressures and temperatures with or without H2O thus has relevance in the genesis of these rock types. Furthermore, the join diopside–jadeite constitutes a thermal barrier at high pressure, and controls the course of crystallization of liquid forming melanephelinite – nepheline – phonolite or tholeiitic rock series (Yoder & Tilley 1962).

Omphacite is one of the two important essential minerals of eclogite (Kushiro 1969, Holland 1983). The bulk composition of omphacite lies on the join diopside–jadeite, which is a part of the plane diopside – albite – nepheline at a pressure typical of the upper mantle. We thus studied the system at 28 kbar.

Many rocks belonging to the nephelinite series contain amphibole (White et al. 1972, Woolley & Jones 1987, Downes 1987). White et al. (1972), therefore, concluded that under suitable P(H2O) conditions, rocks of these series should be converted to amphibolites. We planned another series of experiments to evaluate the effects of H2O in the system at P(H2O) = P(Total) = 2 and 10 kbar.

REVIEW OF WORK ON THE SYSTEM DIOPSIDE – ALBITE – NEPHELINE

The system diopside – albite – nepheline consists of the following bounding joins: 1) nepheline–albite, 2) diopside–nepheline, and 3) diopside–albite. A phase-equilibrium study of the join nepheline–albite was made by Bowen & Schairer (1935) and Schairer (1950). Bell & Roseboom (1969) studied the system nepheline–SiO2 up to 40 kbar and variable temperatures. They presented phase relations on the join diopside–jadeite at variable temperatures at 30 and 40 kbars. At 30 kbar, they showed that it is divided into two portions with two eutectic points. The eutectic point on the nepheline-rich side is present at Ab50Ne50 and the one in the albite-rich portion occurs at Ab70Ne30. The subsolidus assemblage (nepheline+c jadeite) appears slightly below 1285°C in the nepheline-rich side, whereas in the albite-rich portion, the subsolidus assemblage of jadeite+c and albite+c occurs at 1200°C. Robertson et al. (1957) suggested that all the phases in this nepheline–albite subsystem are solid solutions.

The phase-equilibrium study at atmospheric pressure on the join diopside–albite was made first by Bowen (1915), and later by Schairer & Yoder (1960). The same join was studied at high pressure by Kushiro (1965, 1969). His investigation on five compositions (Di40Ab20), (Di35Ab25), (Di40Ab30), (Di35Ab35), and (Di35Ab75) (wt%) at 1350, 1250, 1150 and 1050°C at pressures between 10 and 35 kbar yielded two different assemblages: 1) omphacite + plagioclase + quartz, and 2) omphacite + quartz. He established the P–T coordinates of the breakdown of albite to form jadeite + quartz, and studied the incorporation of the jadeite component in the clinopyroxene structure.

Bowen (1928), and later Schairer et al. (1962) studied the join diopside–nepheline at one atmosphere pressure. They showed that the join cuts the primary phase volumes of carnegieite+c, nepheline+c, forsterite+c, and diopside+c. The assemblage nepheline+c + forsterite+c + liquid appears at 1193 ± 3°C, and melilite coprecipitates with it at 1170 ± 20°C. The five-phase assemblage of nepheline+c + forsterite+c + melilite + diopside+c + liquid appears at 1135 ± 10°C, and forsterite+c reacts out at 1100 ± 15°C. The composition of residual liquids formed under atmospheric pressure in the system nepheline–diopside was studied by Yoder & Kushiro (1972).

The experimental study of the join nepheline–diopside under variable pressures (up to 28 kbar) by Singh et al. (2000) established the presence of a pseudoeutectic point at Ne70Di30 and 1420°C. Melilite and forsterite+c are completely absent in all their runs at 28 kbar. On the basis of eleven runs performed by them at 25, 20 and 15 kbar and 1000°C, they concluded that the complete disappearance of melilite and forsterite+c takes place at 17.5 ± 2.5 kbar.

EXPERIMENTAL TECHNIQUES

A hydrothermal unit (Model HR–IB–2) manufactured by M/S Leco Corporation, Tem–Pres Division, State College, Pennsylvania 16823, U.S.A., was used to conduct experiments at 2 kbar [(P(H2O) = P(Total))] at the National Centre of Experimental Mineralogy and Petrology, Allahabad. Most experiments at 10 and 28 kbar were performed using a piston–cylinder apparatus (Boyd & England 1960) at the same centre. Several experiments on the join diopside–jadeite were conducted at the National Physical Laboratory, New Delhi, using a 200 tonne cubic-press apparatus designed by Hall (1966).

Pure NaCl and NaCl–Pyrex assemblies were used in the case of runs with piston–cylinder apparatus to the highest temperatures. Measurement of temperatures was made with Pt–Pt90Rh10 thermocouples and are considered to be accurate to ±5°C, without taking into account the effect of pressure on e.m.f. Pressure was calibrated at 1000°C against the reactions fayalite + quartz ⇔ orthosilicate (1.41 GPa; Bohlen et al. 1980) and quartz ⇔ coesite (3.07 GPa; Bose & Ganguly 1995). Pressure measurements are considered to be accurate to ±0.05 GPa.

In the case of experiments with the cubic press, the pressure calibration was carried out with respect to high-
pressure phase transformation of Bi (I-II) at 25.4 kbar, Yb (fcc-bcc) at 39 kbar, and Ba (I-II) at 55 kbar (all at room temperature). The reaction cell used for experimental study is made of pyrophyllite in the form of a cube (16 mm). Pressure was applied with tungsten carbide anvils (12.5 mm). In this case, high-temperature calibration experiments also were performed on the following phase transitions: quartz–coesite (3.2 GPa at 1250°C; Bose & Ganguly 1995), and fayalite–γ-FeSiO₃ (0.5 GPa at 1000°C; Yagi et al. 1987).

Synthetic natrosilite (Na₂O.2SiO₃) and reagent-grade CaCO₃, MgO, Al₂O₃ and pure quartz (99.9% SiO₂) were used as sources of Na₂O, CaO, MgO, Al₂O₃ and silica, respectively. For the preparation of Na₂O.2SiO₃, the method of Schairer & Bowen (1956) was used. Schairer’s (1950) method of preparation of glasses and crystallization of starting materials was used. All glasses were crystallized at 1 atm at 800°C for 7 days. All high-pressure runs were conducted on these crystallized starting materials.

Electron-microprobe analyses (accelerating voltage 15 kV, and sample current 20 nA) were made of clinopyroxene (Tables 1, 2), nepheline and plagioclase (Table 3) and glass. A beam of approximately 3 μm in diameter was used. All analyses were done with a JEOL JSM–5300 electron microprobe analyzer at the University of Texas at Dallas. The run products obtained from high-pressure experiments were crushed for optical and X-ray-diffraction studies with CuKα radiation. The phases identified in this study are clinopyroxene, nepheline and plagioclase. The solubility of the various components in these phases at different pressures is discussed below.

The criteria chosen to ascertain equilibrium are based on the following principles: i) homogeneous distribution of phases in the glasses and uniform occurrence of phases in case of a subsolidus run, ii) absence of corroded or zoned crystals, iii) agreement of data at same temperatures for runs of nearby compositions, iv) consistency of experimental results for similar compositions under isobaric-isothermal conditions for varying lengths of time, and v) application of phase-equilibria rules to check for equilibrium assemblage (Boettcher & Wyllie 1969). Quench phases could be easily identified by the development of a feathery texture.

### TABLE 1. COMPOSITION OF CLINOPYROXENE CRYSTALLIZED IN THE SYSTEM DIOPSIDE – ALBITE – NEPHELINE

<table>
<thead>
<tr>
<th>Starting Composition</th>
<th>Temperature (°C)</th>
<th>Na₂O</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>Na₂O</td>
<td>MgO</td>
<td>Al₂O₃</td>
<td>SiO₂</td>
<td></td>
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<td></td>
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<td></td>
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</table>

### TABLE 2. COMPOSITION OF CLINOPYROXENE IN EQUILIBRIUM WITH LIQUID AT VARIABLE TEMPERATURES FROM VARIOUS STARTING MATERIALS

<table>
<thead>
<tr>
<th>a (D₂O-d₂O)</th>
<th>b (D₂O-d₂O)</th>
<th>c (D₂O-d₂O)</th>
<th>d (D₂O-d₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1560°C</td>
<td>1440°C</td>
<td>1400°C</td>
<td>1365°C</td>
</tr>
<tr>
<td>L Cpx L</td>
<td>Cpx L Cpx L</td>
<td>Cpx L Cpx L</td>
<td>Cpx L Cpx L</td>
</tr>
</tbody>
</table>

Compositions a, b, c, and d are plotted in Figure 1. The letters a, b, c and d refer to initial compositions; a: D₂O-d₂O, b: D₂O-d₂O, c: D₂O-d₂O, d: D₂O-d₂O. The temperature of crystallization of the pyroxene is recorded in Table 1. L, (glass), Cpx: clinopyroxene.

### TABLE 3. COMPOSITION OF NEPHELINE AND PLAGIOCLASE IN THE RUN PRODUCTS

<table>
<thead>
<tr>
<th>Na₂O wt%</th>
<th>Al₂O₃ wt%</th>
<th>SiO₂ wt%</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.179</td>
<td>0.049</td>
<td>0.001</td>
<td>1.185</td>
</tr>
</tbody>
</table>

1. Nepheline crystallized from the mixture D₂O-D₂O-Na₂O at 70°C = P (Total) = 2 kbar and 90°C. Nepheline contains 14.3 wt% albite component in solid solution.
2. Nepheline crystallized from the mixture D₂O-D₂O-Na₂O at 70°C = P (Total) = 2 kbar and 92°C. Nepheline contains 14.1 wt% albite component in solid solution.
3. Nepheline crystallized from the mixture D₂O-D₂O-Na₂O at 28 kbar and 1015°C. Nepheline contains 0.25 wt% albite component in solid solution. Duration: 10 hours.
4. Nepheline crystallized from the mixture D₂O-D₂O-Na₂O at 28 kbar and 1015°C. Nepheline contains 0.63 wt% albite component in solid solution. Duration: 30 hours.
5. Nepheline crystallized from the mixture D₂O-D₂O-Na₂O at 28 kbar and 1200°C. Nepheline contains 5 wt% albite component in solid solution.
6. Plagioclase crystallized from the mixture D₂O-D₂O-Na₂O at 10 kbar and 875°C. Plagioclase contains 1 wt% anorthite component.
7. Plagioclase crystallized from the mixture D₂O-D₂O-Na₂O at 28 kbar and 835°C. Plagioclase contains 9 wt% anorthite component.
8. Plagioclase crystallized from the mixture D₂O-D₂O-Na₂O at 28 kbar and 1200°C. Plagioclase contains 0.27 wt% anorthite component.
RESULTS AND DISCUSSION

The system diopside – albite – nepheline at 28 kbar

Twenty compositions were prepared to study the system diopside – albite – nepheline. Altogether, sixty-five experiments were done under variable temperatures at 28 kbar to determine the phase-equilibrium relations. Results of experiments are summarized in Figure 1 and Table 4. The melting point of diopside (1720°C) and that of albite (1320°C) at 28 kbar were taken from Boettcher et al. (1982). The liquidus data for jadeite and compositions along the join diopside–jadeite at this pressure are obtained from Bell & Davis (1969).

The present study (Fig. 1) shows that the join has primary phase-fields for nepheline, albite, and clinopyroxene (omphacite). Reference to the study of Singh et al. (1999) on the join diopside–nepheline indicates that at 28 kbar, the pseudoeutectic occurs at Ne70Di30 and 1420°C. The experimental studies of Windom & Boettcher (1981) and Gupta et al. (1987) show that the nepheline–albite join cuts the primary phase-volumes of nepheline, clinopyroxene, and albite. Thus the field of clinopyroxene, present over a large portion of the diagram, also extends to the nepheline–albite join. Be-

<table>
<thead>
<tr>
<th>Composition</th>
<th>Duration</th>
<th>T (°C)</th>
<th>Assemblage</th>
<th>Composition</th>
<th>Duration</th>
<th>T (°C)</th>
<th>Assemblage</th>
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<tr>
<td>Di₉₈Ab₂₈Ne₄₀</td>
<td>12</td>
<td>1443</td>
<td>all Gl</td>
<td>Di₉₈Ab₂₈Ne₄₀</td>
<td>16</td>
<td>1504</td>
<td>all Gl</td>
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<tr>
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<td></td>
<td></td>
<td>trace Cpx + Gl</td>
<td>(1.513)</td>
<td></td>
<td></td>
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<tr>
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<td>20</td>
<td>1349</td>
<td>trace Cpx + Gl</td>
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<td>all Gl</td>
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<tr>
<td></td>
<td>23</td>
<td>1249</td>
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<td>1353</td>
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<tr>
<td></td>
<td>30</td>
<td>1002</td>
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<td>20</td>
<td>1200</td>
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<td>minor Cpx + Gl</td>
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<td>1354</td>
<td>trace Cpx + Gl</td>
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</tr>
<tr>
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<td>23</td>
<td>1249</td>
<td>minor to moderate Cpx + moderate Ne + minor Ab + Gl</td>
<td>15</td>
<td>1455</td>
<td>all Gl</td>
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<tr>
<td></td>
<td>30</td>
<td>1003</td>
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<td>minor Cpx + trace Ne + Gl</td>
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<td>30</td>
<td>1101</td>
<td>major Cpx + minor Ne + Gl</td>
<td>(1.543)</td>
<td>28</td>
<td>1530</td>
<td>Cpx + Gl</td>
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<tr>
<td>Di₉₈Ab₂₈Ne₄₀</td>
<td>10</td>
<td>1452</td>
<td>all Gl</td>
<td>Di₉₈Ab₂₈Ne₄₀</td>
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<tr>
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<tr>
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<td>trace Cpx + Gl</td>
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<td>(1.508)</td>
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<td>15</td>
<td>1351</td>
<td>trace Cpx + Gl</td>
<td>28</td>
<td>1390</td>
<td>rare Cpx + trace Ab (?) + Gl</td>
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<td></td>
<td>21</td>
<td>1200</td>
<td>major Pl + minor Cpx + minor Qtz + Gl</td>
<td>20</td>
<td>1365</td>
<td>minor Ab + Gl</td>
<td></td>
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<tr>
<td></td>
<td>25</td>
<td>1050</td>
<td>major Pl + minor Cpx + moderate Qtz</td>
<td>20</td>
<td>1355</td>
<td>minor Cpx + minor Ab (?) + rare Gl</td>
<td></td>
</tr>
<tr>
<td>Di₉₈Ab₂₈Ne₄₀</td>
<td>11</td>
<td>1452</td>
<td>trace Cpx + Gl</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1.535)</td>
<td></td>
<td></td>
<td>trace Cpx + Gl</td>
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</tbody>
</table>

Terms such as “trace”, “minor”, “major”, and “rare” refer to amounts of crystals in the run products. The index of refraction of the glass is reported in parentheses in the first column. All glasses were crystallized at 1 atm. and 800°C for seven days. All runs were conducted on those crystallized starting materials. The bulk composition of the starting mixtures (column 1) is reported in weight %. The duration of the experiments is reported in hours.

TABLE 4. EXPERIMENTAL RESULTS IN THE SYSTEM DIOPSIDE – NEPHELINE – ALBITE AT 28 KBAR AND VARIOUS TEMPERATURES.
cause jadeitic clinopyroxene has an incongruent melting relation with liquid, and the field of albite ss is extended along the join, the diopside–albite–nepheline plane does not have a four-phase point, and the composition of the liquid coexisting with Cpx + Ne ss + Ab ss does not lie in this plane. This observation is consistent with the conclusion of Windom & Boettcher (1981) and Gupta et al. (1987). Bell & Davis (1969) also demonstrated the incongruent melting behavior of albite to a pressure slightly above 28 kbar. On the basis of liquidus data related to compositions Di 5 Ab 55 Ne 40 , Di 11 Ab 57 Ne 32 , Di 16 Ab 70 Ne 14 and Di 5 Ab 75 Ne 20 , the albite ss–clinopyroxene phase boundary can be extended to the composition Di 8 Ab 92 , which correspond to the pseudo-eutectic point along the join diopside–albite. The liquidus temperatures for the diopside–nepheline join were obtained from Singh et al. (2000). If the isotherms are plotted with reference to the liquidus data obtained in the present study, they match well with those of the early investigators, as mentioned above. The liquidus isotherms show a gradual slope along the diopside–jadeite join (except for a gentle hump showing a thermal maximum near the jadeite end).

The data in Table 4 indicate that subsolidus assemblages for bulk compositions Di 30 Ab 19 Ne 51 , Di 21 Ab 44 Ne 35 , Di 10 Ab 45 Ne 45 , Di 30 Ab 40 Ne 30 and Di 10 Ab 30 Ne 60 , lying in the nepheline-rich portion of the diopside–albite–nepheline system, consist of Cpx + Ne ss + Ab ss. The mixtures Di 29 Ab 59 Ne 12 , Di 16 Ab 70 Ne 14 , Di 40 Ab 50 Ne 10 and Di 5 Ab 75 Ne 20 , with compositions in the albite-rich portion of the system, consist of the subsolidus assemblage of Cpx + Ab ss + Qtz. The compositions Di 11 Ab 57 Ne 32 , Di 20 Ab 52 Ne 28 , Di 49 Ab 33 Ne 18 and Di 80 Ab 13 Ne 7 , lying on the diopside–jadeite join, yielded

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**Fig. 1.** Liquidus phase relations in the system diopside–albite–nepheline at 28 kbar and variable temperatures (present study). Solid circles indicate starting materials crystallized from homogeneous glasses. Open circles (a1, b1, c1, and d1, etc.) represent compositional plot of glasses (determined by EPMA from run product) in equilibrium with different clinopyroxenes, compositions of which are shown in Table 2.)
only clinopyroxene. In the case of composition Di$_{20}$Ab$_{52}$Ne$_{28}$, however, in addition to clinopyroxene, a small amount of plagioclase also was noted.

Clinopyroxene crystallizing from compositions Di$_{35}$Ab$_{7}$Ne$_{58}$ at 1249°C, Di$_{49}$Ab$_{33}$Ne$_{18}$ at 1249°C and Di$_{80}$Ab$_{13}$Ne$_{7}$ at 1200°C contain 32, 28 and 11 mole % diopside and 55, 37 and 88 mole % of jadeite, respectively (Table 1), which shows that other pyroxene components include CaAlSi$_2$O$_6$ (Ca-Tschermaks component), MgAlSi$_2$O$_6$ (Mg-Tschermaks component), Ca$_{0.5}$Al$_{1.5}$Si$_2$O$_6$ and Mg$_{0.5}$Al$_{1.5}$Si$_2$O$_6$. Table 1 also includes compositions of pyroxenes crystallized from three other mixtures at different temperatures.

In contrast, clinopyroxenes crystallizing from compositions lying on the diopside–jadeite join at 1203 ± 5°C can be expressed in terms of CaMgSi$_2$O$_6$ and NaAlSi$_2$O$_6$ only (Table 2). The proportion of the jadeite component in these compositions, however, conforms to the reaction relation nepheline + albite ↔ 2 jadeite. As the nepheline + albite content in the starting composition increases, the jadeite content also increases. The proportion of the jadeite component, MgAlSi$_2$O$_6$ (Mg-Tschermaks component), Ca$_{0.5}$Al$_{1.5}$Si$_2$O$_6$ and Mg$_{0.5}$Al$_{1.5}$Si$_2$O$_6$. Table 1 also includes compositions of pyroxenes crystallized from three other mixtures at different temperatures.

![Fig. 2. A plot of 2θ versus interplanar spacings for clinopyroxenes crystallizing from compositions lying on the join diopside–jadeite at 28 kbar and 1203°C.](image)

Course of crystallization of liquid in the plane diopside – albite – nepheline at 28 kbar

It can be noted from Table 3 (anal. 8) that albite crystallizing from the composition Di$_{16}$Ab$_{50}$Ne$_{34}$ at 1200°C contains 9 wt.% of CaAl$_2$Si$_2$O$_6$ and nepheline incorporates 5 wt.% albite in solid solution (anal. 5). Hence, the composition of liquids does not strictly lie on the plane diopside – albite – nepheline. If the minor amount of anorthite in plagioclase (9 wt.%) is ignored, however, then the course of crystallization of liquid in this plane can be described as follows. From a liquid of composition "a" (Di$_{16}$Jd$_{50}$), an omphacite pyroxene (Di$_{56}$Jd$_{44}$, Table 2, Fig. 1) crystallizes first, then the liquid composition should move along the join diopside–jadeite toward the univariant curve A–B, but at "a1" (Di$_{36}$Jd$_{64$, Fig. 1), crystallization ceases as the solidus is reached at 1564°C. The composition of "a1" has been determined on the basis of analyses of liquid formed at the above-mentioned temperature. From a melt of composition "b" (Di$_{20}$Jd$_{80}$, Fig. 1), an omphacite (Di$_{39}$Jd$_{61$, Table 2) crystallizes at 1440°C. The final composition of the liquid (Di$_{13}$Jd$_{87}$) is depicted by "b1". Likewise, from a liquid of composition "c" (Di$_{13}$Jd$_{87}$, Fig. 1), an omphacite (Di$_{50}$Jd$_{50}$, Table 2) precipitates at 1400°C, but the liquid (Di$_{28}$Jd$_{72}$) freezes out at 1390°C, when the composition of the melt reaches point "c1" (Fig. 1).

From a liquid of composition "d" (Jd$_{97}$Di$_{3}$, Table 2), a plagioclase (Ab$_{91}$An$_{9}$) crystallizes first at 1365°C, but is joined by a pyroxene (Jd$_{8}$Di$_{6$, Table 2). The solidus is reached at 1360°C, when the melt’s composition reaches point “d1”. The composition of liquids in equilibrium with the pyroxenes at different temperatures at 28 kbar is plotted in Figure 3, along with the diagram of Bell & Davis (1969). The study confirms the observation that the diopside–jadeite phase diagram has a loop-like structure similar to that of the forsterite–fayalite and anorthite–albite systems (Fig. 3).

A liquid of composition “x” (Di$_{30}$Ne$_{10}$Ab$_{60}$), lying toward the SiO$_2$-rich side of the plane diopside–albite–nepheline (Fig. 1), should yield a pyroxene (Di$_{12}$Jd$_{88}$) at 1450°C. Plagioclase and quartz coprecipitate, however, along with pyroxene at 1330°C. A liquid of composition “y” (Di$_{80}$Ne$_{10}$Ab$_{10}$, Fig. 1) yields a pyroxene of composition Di$_{60}$Jd$_{40}$ at 1470°C. If the temperature is lowered to 1400°C, nepheline appears as an additional phase.
In eclogite, exsolution of jadeite in clinopyroxene is noted (Smyth 1980). Robinson (1982) suggested that the presence of Na–Al pyroxene in tholeiitic gabbro and in many common rocks is a result of the breakdown of plagioclase. Curtis & Gittins (1979) have observed that in strongly silica-undersaturated metamorphic rocks of the Red Wine Complex, Labrador, the breakdown of nepheline plus sodic plagioclase stabilizes jadeite and omphacite, coexisting in equilibrium.

The albite content of nepheline crystallized from the composition Di$_{29}$Ab$_{59}$Ne$_{12}$ and 1015°C at 28 kbar is only 0.25–0.36 wt.% (Table 3, anal. 3, 4), compared to 20 wt.% albite in the same phase at 1 kbar (Edgar 1964). The anorthite content of albite in the same system at 28 kbar is only 0.27 ± 0.01 wt.% at 1248°C (Table 3, anal. 9).

Study of the system diopside – albite – nepheline at $P(H_2O) = P(\text{Total}) = 2$ kbar

Ten experiments were made on eight compositions at $P(H_2O) = P(\text{Total}) = 2$ kbar to locate the reaction point in the system diopside – albite – nepheline. The experimental findings are summarized in Table 5 and Figure 4. Our study clearly demonstrates that this plane cuts the

![Figure 3](image1.png)

**Fig. 3.** Phase relations in the join jadeite–diopside at 30 kbar and variable temperatures (bold lines, Bell & Roseboom 1969). The diagram shown by dotted lines is established in the present study at 28 kbar and different temperatures. The points a, b, c and d represent composition of initial liquids (also see Fig. 1) in equilibrium with omphacite of compositions $X_1$, $X_2$, $X_3$ and $X_4$, respectively. The points $a_1$, $b_1$, $c_1$ and $d_1$ (also see Fig. 1) represent compositions of the final liquids.

![Figure 4](image2.png)

**Fig. 4.** Phase relations in the system diopside – albite – nepheline at different temperatures and pressures [$P(H_2O) = P(\text{Total})$].

a) Phase relations in the system diopside – albite – nepheline at 1 atmosphere pressure and different temperatures (after Schairer & Yoder 1960). b) Phase relations in the join diopside – albite – nepheline at 1 kbar [$P(H_2O) = P(\text{Total})$] and at variable temperatures (after Edgar 1964). c) Phase relations in the join diopside – albite – nepheline at 2 kbar [$P(H_2O) = P(\text{Total})$] and various temperatures (this study).
primary-phase-volumes of clinopyroxene, plagioclase and nepheline, cf. Fig. 4 with Fig. 4a of Schairer & Yoder (1960) and Fig. 4b of Edgar (1964)]. The phase assemblage at variable temperatures exhibits a very flat liquidus surface. Table 3 (anal. 1, 2) shows that about 14.1 to 14.3 wt.% of albite goes into the nepheline structure at 1200°C. Edgar (1964) showed that 10 to 20% anorthite is incorporated in the albite structure. The X-ray-diffraction peaks 002, 310 and 211 of clinopyroxene crystallizing from the mixture Di3Ab62Ne35 at 836°C occur, respectively, at 35.41°, 30.45° and 29.80°2/H9258CuK1/H9251. The same reflections for pure diopside are observed at 35.38°, 30.42° and 29.78°, suggesting that the diopside appearing at 836°C and 2 kbar [P(H2O) = P(Total)] is a solid solution. We assume that it contains Ca- and Mg-Tschermaks components. At 2 kbar, the amount of anorthite going into the structure of albite is 1.41 wt.% (anal. 7, Table 3). The reaction point (Di3Ab34.1Ne60.5) at which clinopyroxene, plagioclase, nepheline and liquid are in equilibrium is shifted toward the nepheline-rich side as compared to Edgar’s study (1964) of the diopside – nepheline – albite system at P(H2O) = P(Total) = 1 kbar. The nepheline–albite “isobaric eutectic” composition changes from Ne27Ab73 at 1250°C and 10 kbar [P(H2O) = P(Total)] 1 kbar. The system diopside – albite – nepheline at P(H2O) = P(Total) = 10 kbar

The liquidus temperatures for nepheline and diopside at 10 kbar [P(H2O) = P(Total)] are taken from Boettcher & Wyllie (1969) and Yoder (1965), respectively. Diopside melts congruently at 1265°C, and nepheline melts to a liquid of its own composition at 692°C. The present experimental results are summarized in Table 6 and Figure 5. This diagram is a projection from the H2O apex onto the anhydrous diopside – albite – nepheline plane and shows the field boundaries, which limit the primary phases. The liquidus surface at 10 kbar [P(H2O) = P(Total)] cuts the primary volumes of nepheline, clinopyroxene and plagioclase. The plagioclase crystallizing from bulk composition Di11Ab57Ne32 at 1250°C contains about 1 wt.% An (anal. 6, Table 3) in its structure. This system can be treated as being ternary if one ignores the small amount of calcium entering the albite structure. The X-ray-diffraction studies of pyroxenes crystallizing from the bulk composition Di11Ab57Ne32 at 675°C and 10 kbar [P(H2O) = P(Total)]
show 002, 310 and 221 reflections at 35.395°, 30.518° and 29.985° 20 CuKα. The same reflections for pure diopside are observed at 35.38°, 30.42° and 29.78° 20 CuKα. This observation suggests that the diopside depart from the end-member composition.

The phase diagram demonstrates the expansion of the pyroxene phase-volume at the albite-rich end as well as at the nepheline-rich side. Figure 3 shows that in contrast to the field of pyroxene obtained at atmospheric pressure (Schairer & Yoder 1960; Fig. 4a), it is further enlarged at 1 (Edgar 1964; Fig. 4b) and 10 kbar (Fig. 5). At 10 kbar, the clinopyroxene field increases at the expense of albite and nepheline. This finding illustrates the fact that a silica-undersaturated liquid of composition Di 5 Ab 70 Ne 14 lying on the nepheline ss  + albite ss  + L univariant line at point “n”. At the reaction point, nepheline will co-precipitate in addition to clinopyroxene and plagioclase in the liquid. Likewise, if a liquid of composition Di5Ab0.5Ne35 lying on the nepheline, albite + L univariant curve crystallizes, nepheline and clino- pyroxene will precipitate simultaneously; once the liq-uid reaches the reaction point, plagioclase also will appear as the third phase. With a decrease in temperature, clinopyroxene fractionates out, and the liquid moves toward a phonolite minimum. According to Morse (1980), the nepheline–albite eutectic corresponds to simplified phonolitic compositions and hence, the liquidus for a hydrous phonolitic magma at a depth of 33 km = 10 kbar can be taken to be 635 ± 5°C (Fig. 5). The assemblage corresponding to the reaction point can be ideally treated as a tephritic composition.

**Petrological importance of the system diopside – albite – nepheline studied under 28 kbar and variable temperatures**

Along the join diopside–nepheline studied under atmospheric pressure, forsterite

The results of previous investigators at various pressures and temperatures are given in Table 7. Boetcher & Wyllie (1969) presented a schematic diagram for the univariant curve Ne + Ab + V = L based on topological considerations. Their study shows that the gradient of temperature is very steep: from 1 to 2 kbar: 65°C per kbar, between 2 to 5 kbar: 35°C per kbar, in the range of 5 to 6 kbar: 27°C per kbar and it becomes nearly vertical between 6 and 10 kbar with a constant slope of 3.6°C per kbar (Fig. 6). Hence, for a phonolitic composition, the liquidus temperature in a hydrous regime will decrease with an increase in pressure. The “isobaric eutectic” compositions also should change considerably.
The normative compositions of liquids in the dry systems (Table 8) at 28 kbar correspond to simplified phonotephritic, tephriphonolitic and phonolitic compositions (Le Bas et al. 1986).

Petrogenetic implication of the diopside – albite – nepheline system at $P(H_2O) = P(\text{Total}) = 2$ and 10 kbar

Our experimental study of the system diopside – albite – nepheline – H$_2$O at 2 and 10 kbar was conducted to test whether the modal and normative compositions of nepheline-bearing trachytes, phonolites, tephrites, tephriphonolites and nephelinites have any relationship with the invariant point determined under variable P–T conditions. If the bulk compositions of these rocks are plotted in terms of clinopyroxene – feldspathoid – sodium-rich alkali feldspar, one finds that the maximum cluster occurs in and around the 10 kbar invariant point. Edgar (1964) plotted the normative compositions of 120 plutonic rocks containing 80% or more normative alkali pyroxene, nepheline and alkali feldspar (Fig. 7). Points R$_1$ and R$_2$ correspond to the reaction points, where nepheline$_{ss}$, albite$_{ss}$ and clinopyroxene are in equilibrium. The curves marked A–R$_1$ and A–R$_2$ correspond to the phase boundaries of clinopyroxene and albite$_{ss}$ at 1 and 2 kbar, respectively. Both the 1 and 2 kbar reaction points lie in the shaded area, where the bulk compositions of many syenites plot. The 1 and 2 kbar reaction points, however, do not lie in the maximum density area, presumably because in the experimental system K and Fe are missing.

Figure 8 shows a plot of bulk composition of many phonolites, nephelinites, urtites and trachytes from all over the world on the 10 kbar isobaric diagram. We note that the majority of bulk compositions of phonolites (shown as triangles within the field marked “C”) occur around the 10 kbar reaction point, and some plot along the line Y–R$_3$ or Z–R$_3$ corresponding to the clinopyroxene–nepheline$_{ss}$ or clinopyroxene–albite$_{ss}$ phase.
boundaries. In Figure 8, the squares denote trachyte (marked by area “B”). The bulk compositions of trachyte plot along diopside–albite join and in the vicinity of the pseudoeutectic obtained at 10 kbar. The bulk composition of nephelinites plot in the area marked “A”, close to the diopside–nepheline join, near the diopside end and containing as much as 25% normative albite. Compositions of pyroxene-poor nepheline-rich urtites plot in the area marked “D”. On the basis of phase-equilibrium relations, we expect that nephelinitic rocks should crystallize first. Then the liquid should move along a path joining the nephelinitic composition and clinopyroxene and then proceed to the line Y–R<sub>3</sub>. Later, with further crystallization, the liquid composition moves toward the reaction point “R<sub>3</sub>”, and a phonolitic magma is derived. Thus, a phonolite is obtained either from a nephelinitic or a trachytic magma. Some of these phonolites contain xenoliths of lherzolites [Jos Plateau, Nigeria (Nixon 1987); Klinghardt, Namibia (Lock & Marsh 1981); Auckland Island, New Zealand (Nixon 1987)]. That their bulk compositions plot around 10 kbar reaction point is consistent with the genesis of many phonolitic rocks at depth.

Figure 8 indicates that a phonolitic magma can be derived from either a trachytic magma (note the plot of bulk compositions along the line Z–R<sub>3</sub>) or a nephelinitic magma. Wright (1963) and Saggerson & Williams (1964) suggested that nephelinites or melanephelinites are parental to phonolites. Nash et al. (1969) pointed out the association of nephelinitic and phonolitic rocks, but in their case study of Mount Suswa, Kenya, they considered an alkaline trachytic liquid as the parental magma for the phonolites. In general, they believed that the magmas of Mount Suswa could have been generated by partial or total fusion of silica-undersaturated syenitic plutonic parent, because xenoliths of syenite are observed in the lavas of Mount Suswa. In the present study, we observed that the five-phase point (clino-

**TABLE 8. Compositions of four representative liquids (quenched to glass) in the system diopside – nepheline – albite**

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<th>Composition</th>
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<th>MgO</th>
<th>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</th>
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<tr>
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<td>SM 15.23 1.30 0.93 25.05 57.50 100.01</td>
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GL: glass compositions from runs at 28 kbar and 1450 ± 5°C; note that the glass is observed in the run products. Each composition of GL is the average result of two analyses. The bulk composition of the starting material (SM) in terms of the three components is given in the first column in wt %.
pyroxene + nepheline$_{ss}$ + albite$_{ss}$ + L + V) obtained at 2 kbar [P(H$_2$O) = P(Total)] plots in the “nepheline syenite” field. Alkali feldspar is a solid solution of NaAlSi$_2$O$_6$ and KAlSi$_3$O$_8$, and in absence of the latter component, compositions of many trachytes should not lie in the diopside – nepheline – albite plane. The “nepheline syenites” or “trachytes” discussed here refer to simplified varieties. In the 10 kbar [P(H$_2$O) = P(Total)] isobaric section, the phonolite compositions cluster around the reaction point.

Our experimental study of the system diopside – albite – nepheline indicates that from a liquid of composition “X” (Fig. 8), a melanephelinite can crystalize first, when the liquid composition reaches the univariant curve defined by nepheline + clinopyroxene + liquid (Y–R$_3$). Because the bulk composition (D$_{Di}$Ab$_{2}$Ne$_{28}$) is relatively closer to the diopside end-member, the proportion of diopside in the univariant assemblage should be greater than that of nepheline, and the univariant assemblage should be similar to a “simplified melanephelinite” rock. In the course of crystallization, if diopside is fractionated out, then the assemblage should be similar to a nephelinite. As the liquid composition reaches the invariant point “R$_1$”, the assemblage should correspond to diopside + nepheline + sodic feldspar + liquid + vapor. In the absence of significant amounts of anorthite, the invariant assemblage cannot be strictly referred to as tephrite. The addition of 15–20% modal KAlSi$_3$O$_8$ should not significantly change the course of crystallization of the liquid. If a small amount of anorthite is added to the system, the univariant assemblage (Z–R$_3$) will correspond to a liquid typical of highly fractionated alkali basalt series, i.e., a liquid similar to a mugearitic composition. Although the temperature and composition of the invariant point should change, the topology of the phase diagram is expected to be similar.

Role of H$_2$O in the system diopside – albite – nepheline under variable pressures

In comparison to the reaction point R, determined by Schairer & Yoder (1960) in the system diopside – albite – nepheline, the analogous point R$_1$ established at P(H$_2$O) = P(Total) = 1 kbar moves toward the albite-rich side (Edgar 1964). In our study, however, that at 2 and 10 kbar, as the solubility of H$_2$O in the liquid increases, the “isobaric invariant points” (R$_2$ and R$_3$) shift systematically toward nepheline. This shift may be due to dissolution of larger amount of nepheline in the fluid phase, compared to albite at higher P(H$_2$O) = P(Total). The shift in composition of the reaction point in the system diopside – albite – nepheline is given in Table 7. Yoder (1958) studied the systems albite–H$_2$O and nepheline–H$_2$O. He observed an important drop in the temperature of melting of nepheline relative to albite with increasing H$_2$O pressure. These observations confirm that dissolution of nepheline is indeed greater than that of albite in the fluid. A shift in the isobaric “invariant point” (R$_1$, Fig. 4b) of Edgar (1964) toward albite, therefore, does not seem to be in agreement with our observation and that of Yoder. The system diopside – albite – nepheline, therefore, needs to be restudied at P(H$_2$O) = P(Total) = 1 kbar.

Kushiro (1969) studied the system forsterite – diopside – SiO$_2$ at one atmosphere and under P(H$_2$O) = P(Total) = 20 kbar. Compared to its position determined at one atmospheric pressure, the eutectic point he established at P(H$_2$O) = P(Total) = 20 kbar is located closer to the SiO$_2$-rich end. The studies of Tuttle & Bowen (1958), Luth et al. (1964) and Luth (1976) on the albite – orthoclase – SiO$_2$ system at variable pressures up to 10 kbar, however, show that with increasing pressure (in presence of excess H$_2$O), the minimum or eutectic point moves away from the SiO$_2$-rich side. When anorthite is added as a component to the albite – orthoclase – SiO$_2$ system (von Platen 1965), the minimum points under P(H$_2$O) = P(Total) = 2 kbar shift away from the albite end toward the K-feldspar – quartz join. The above description suggests that the role of H$_2$O in shifting the minimum or eutectic points toward silica-saturated or undersaturated side is rather complex.

Taylor & MacKenzie (1975) studied the role of H$_2$O in the nepheline–albite system and observed that the “isobaric eutectic” gradually shifts toward the nepheline-rich side away from the SiO$_2$ end as pressure is increased from 1 atmosphere to 1 to 2 kbar. In our case, the system diopside – albite–nepheline at P(H$_2$O) = P(Total) = 1, 2 and 10 kbar, the “isobaric eutectic” along the nepheline–albite join also shifts toward the nepheline end.

As the above discussion clearly demonstrates, the genesis of phonolites can be expressed in terms of a simple model system clinopyroxene – alkali feldspar – nepheline. The present experimental study at 10 and 28 kbar (with or without H$_2$O), therefore, helps one to understand the genesis of phonolites and related rocks, in cases where extensive crystal fractionation is believed to have taken place. According to Lippard (1973), trace-element data indicate that phonolites owe their origin to fractionation under subcrustal conditions. The phonolites also plot near the reaction point or in the vicinity of the diopside–albite or diopside–nepheline phase boundaries.

Figure 9 (LeBas 1987) shows a generalized trend from melanephelinite through nepheline to phonolite, as observed in case of the rocks from eastern Uganda (Tyler & King 1967) and western Kenya (Le Bas 1977). The present study supports the trend established by Le Bas (1987). Barker et al. (1987) studied the nepheline-bearing rocks from the alkali igneous provinces of Kenya and northern Tanzania, both of which are associated with the African Rift Valley. The spatial distribution of melanephelinite, nephelineite, nepheline-bearing phonolite, trachyte and alkali basalt from the Kenyan alkali petrographic province can be predicted from the phase relations presented here. If 15–20%
alkali feldspar is added, then from a trachytic magma, a phonolitic liquid can be obtained. Downes (1987) also observed the presence of tephritic, phonolitic, and nephelinitic rocks in close proximity in the Massif Central region of France.

Strong (1972) carried out a detailed petrological study of the alkaline rocks of the Island of Moheli, western Indian Ocean, where alkali basalt and melanephelinite occur with small amounts of nephelinite, trachyte, and phonolite. From the isotopic signatures, Strong (1972) suggested an apparent differentiation from alkali basalt through melanephelinite and trachyte to phonolite. The present study does not suggest such a fractionation scheme. Rather, two trends are possible: 1) melanephelinite → nephelinite → phonolite, and 2) alkali basalt → trachyte → phonolite.

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