Hydrothermal melting behavior of $\text{KAlSi}_3\text{O}_8$ as microcline and sanidine

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ABSTRACT

The hydrothermal melting of $\text{KAlSi}_3\text{O}_8$ has been investigated from 1–28 kbar, using microcline and sanidine as starting materials. Both polymorphs melted at the same $P$-$T$ conditions, and no metastable melting was observed; unlike albite, the inversion temperature from ordered to disordered structures is well below the $P$-$T$ region of melting; thus sanidine cannot melt in the field of microcline, and microcline invariably inverts to sanidine before melting. The melting curve is drawn through points at 950 °C at 2 kbar, 900 °C at 4 kbar, 820 °C at 10 kbar, 800 °C at 12 kbar, 780 °C at 15 kbar, 765 °C at 18 kbar, and 700 °C at 28 kbar. A flattening of the $dP/dT$ slope at higher pressures, although present, is less pronounced and occurs at higher pressures (>20 kbar) than that for albite (>14 kbar), and the effect of pressure on $\text{H}_2\text{O}$ solubility in the melt is less than for albite. The melting of $\text{KAlSi}_3\text{O}_8$ was reversed by two-step reversal experiments that consisted of melting microcline, followed by crystallization of sanidine from the quenched melt. Above 15 kbar coherent glass was not produced by quenching, but a granular incoherent brownish isotropic substance (GIBIS) was observed in the quench product. Abundant quenched vapor precipitate, not readily distinguished from quenched melt, was also observed in experiments above 15 kbar. Vapor solubility of potassium feldspar components is greater than that of albite components at these pressures, and the univariant nature of the melting curve may be lost at $P_{\text{H}_2\text{O}} > 15$ kbar because of incongruent solubility in the vapor phase. The lack of metastable melting of microcline suggests that disordering, as in the case of albite, always precedes melting. No incongruent melting to leucite was observed in experiments as low as 1.8 kbar, suggesting that metastability may have played a role in earlier low-pressure experimentation of others, and a field of leucite + liquid must exist only at lower $\text{H}_2\text{O}$ pressures than previously thought.

INTRODUCTION

Experimental studies on alkali feldspars have furthered our understanding of a broad range of mineralogic and geologic phenomena. Much work has been done on hydrothermal melting, but it has been for the most part concentrated in albite. The rather few studies on $\text{KAlSi}_3\text{O}_8$ have been at low pressures or on a portion of a more complex system (e.g., Goranson, 1938; Shaw, 1963; Lambert et al., 1969; Bohlen et al., 1983). The earliest work on the system $\text{KAlSi}_3\text{O}_8$-$\text{H}_2\text{O}$ was that of Goranson (1938), which was restricted to a pressure range from 0.5 to 3.7 kbar. Goranson’s data indicated that the incongruent melting of potassium feldspar to leucite and liquid was eliminated at $\text{H}_2\text{O}$ pressures greater than 2.6 kbar. The only investigation of the hydrous melting of $\text{KAlSi}_3\text{O}_8$ over a sizeable range of $P_{\text{H}_2\text{O}}$ is that of Lambert et al. (1969), but this study used the composition $\text{Or}_{10}\text{Ab}_9$, not pure $\text{KAlSi}_3\text{O}_8$. In the present study, we present $P$-$T$ data for the melting of pure $\text{KAlSi}_3\text{O}_8$ from 1–28 kbar $P_{\text{H}_2\text{O}}$.

Some aspects of hydrous albite melting may be suggestive of alkali feldspar melting in general and warrant further examination of $\text{KAlSi}_3\text{O}_8$. The melting behavior of ordered vs. disordered albite was reported by Goldsmith and Jenkins (1985b). It was found that the melting temperature of low albite exceeds that of high albite by 75 °C at pressures near 15 kbar. All investigations to date have used disordered sanidine as starting material, not ordered microcline. In the albite system, $\text{H}_2\text{O}$-saturated melts quenched from pressures greater than 14 kbar do not quench to a coherent glass as in lower-pressure experiments, but rather to a granular, unconsolidated powder. This texture is suggestive of a highly hydrated and depolymerized melt, perhaps tending toward a critical state. In addition to presenting melting temperatures for $\text{KAlSi}_3\text{O}_8$ over a large range of pressures, this work also uses both microcline and sanidine as starting material and touches on the physical characteristics of high-pressure $\text{KAlSi}_3\text{O}_8$ melts.

EXPERIMENTAL METHODS

The experimental apparatus and techniques (piston-cylinder apparatus and internally heated Ar pressure vessels) are essentially the same as those described by Goldsmith and Jenkins (1985a, 1985b). $\text{NaCl}$ pressure cells were used in the piston-cylinder experiments, with the charges sealed in Pt capsules. Enough $\text{H}_2\text{O}$ was loaded into each capsule with the solid sample to ensure that the...
melt formed would be vapor-saturated. Exceptions were experiments MC-189a and MC-189b at 1 kbar, which were H2O-unsaturated to avoid bursting of the capsule. Temperatures in piston-cylinder experiments were controlled and measured with chromel-alumel thermocouples, situated above and perpendicular to the horizontally oriented capsules. Temperatures are considered accurate to within 10°C. The lower-pressure experiments (<10 kbar) were made in the gas apparatus, with the capsule placed between two chromel-alumel thermocouples. The temperature difference between the two thermocouples did not exceed 3°C. Temperature accuracy in these experiments is considered to be better than ±2°C. Ar pressure was measured with a bourdon-type gauge and independently checked against a manganin cell. Both the gauge and the manganin cell were checked against a 100,000-psi Heise gauge, calibrated by the manufacturer. Pressure was read and controlled to a conservatively estimated ±50 bars. Experiments were conducted with NaCl furnace assemblies using the piston-out technique, and no pressure correction was applied.

Analytical technique

At the completion of each experiment the capsule was opened, dried at 110°C, and analyzed with the petrographic microscope and by X-ray powder diffraction. Selected experimental products were also examined with a JEOL scanning electron microscope (SEM). Best estimates by eye of relative proportions of crystals and amorphous material were made where pertinent, and whenever possible the estimate was also based on the intensities of the X-ray diffraction pattern relative to scans of crystalline sanidine.

Starting materials

Nine samples of potassium feldspar were used for the experiments: four triclinic microcline feldspar samples, four monoclinic sanidine samples, and one orthoclase sample. All were essentially pure KAISi4O10, as follows: Microcline A: K-exchanged Amelia albite, Hovis 71104 (Hovis, 1986). Microcline B: K-exchanged Amelia albite (Rutherford Mine, USNM C5390), using 400 mg in 13 g KCl, 850°C, 23.5 h. Reexchanged in 8 g KCl for 9 h. Microcline C: Essentially Na-free microcline, Jeffrey Mine, Ontario, large mica. Microcline D: Microcline perthite from Deponiestollen, Palagudra, Tessin, Switzerland, K-exchanged at 850°C. Sanidine A: Crystallized from KAISi4O10 gel, 800°C, P1/2 = 1 kbar, 46 h. Sanidine B: Crystallized from K2CO3, Al2O3, SiO2, 750°C, P1/2 = 1 kbar, 4 d. Sanidine C: Amelia albite (USNM C5390), converted to high albite at 1150°C, 55 kbar, 15 h, K-exchanged at 850°C, 24 h. Sanidine D: K-exchanged Amelia albite, heat-treated at 1077°C, 57 d, then K-exchanged (supplied by H. T. Haselton). Orthoclase: K-exchanged orthoclase from Betroka, Madagascar, Hovis 7053 (Hovis, 1974).

The four microcline feldspar samples all had values of triclinicity or obliquity equivalent to maximally observed Al/Si order, i.e., Δ ~ 1.0, where Δ = (d(1131) − d(1311)) × 12.5 (Goldsmith and Laves, 1954).

Experimental results

Table 1 contains the data on the hydrothermal melting of KAISi4O10 and the behavior of the starting materials. Because interpretations of what appears to be complex behavior are not always straightforward or obvious, discussion of the textures observed is in order.

Identification of quenched phases

At pressures greater than 15 kbar, melts do not quench to a coherent glass, but to a fine-grained (granular) brownish isotropic substance, which is soft and pulverulent, not crunchy in the mortar and pestle. Similar behavior of NaAlSi3O8 was noted in the references given above and in Goldsmith and Jenkins (1985b). The characteristics of this amorphous substance are in part also dependent on temperature and the degree of H2O saturation, but these factors have only been examined in this study with several exploratory experiments. Some experiments, noted in Table 1, show tiny sparkles under the microscope, reminiscent of a starry night sky. The birefringent substance is probably mica. In some experiments the basal peaks of a mica are present (weakly) on diffraction scans. It is not known if some or all of the mica is formed during the quench, although larger crystals might be expected if mica were a liquidus phase. It is our impression that the sparkles are more apparent when sanidine rather than microcline is the starting material.

In Table 1 the isotropic material of the higher pressure experiments is identified as GIBIS (granular isotropic brownish incoherent substance). Boettcher and Wyllie (1968) investigated the hydrothermal melting of granite to 32 kbar and noted that at pressures greater than 15 kbar a (presumed) vapor-phase deposit was abundant and formed brown aggregates of isotropic or slightly birefringent material. Mica was also present. Difficulty in unequivocal identification of this material leads to uncertainty not only in the precise location of the melting curve at higher pressures, but also about its character. Hydrothermal melting curves of many phases are considered to be univariant, but if the substance is incongruently soluble in the vapor, melting will not be univariant, and a detectable melting interval or region will be present. Tuttle and Bowen (1958) reported that albite melts over a temperature range of 10°C or more and ascribed the melting interval to several possibilities, one of which was that the liquid or the vapor had compositions off the binary join albite-H2O. Goldsmith and Jenkins (1985b) noted similar melting behavior and pointed out that there is no compelling argument for congruent solubility of multicomponent phases.

Solubility considerations, textures, and the nature of the melting curve

The data of Table 1 are plotted in Figure 1. The melting curve of KAISi4O10 is depressed less with increased P1/2.
TABLE 1. Hydrothermal melting data

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Starting material</th>
<th>T (°C)</th>
<th>P (kbar)</th>
<th>Time (h)</th>
<th>Results</th>
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<td></td>
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<td></td>
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<td>675</td>
<td>28</td>
<td>6.5</td>
<td>xls (~1/3) in GIBIS</td>
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<td>5</td>
<td>rare xls in GIBIS with sparkles**</td>
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</tr>
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<tr>
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<td>22</td>
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<td>xls, some GIBIS</td>
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<td>725</td>
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<td>23</td>
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<td>23</td>
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<td>185a</td>
<td>microcline B</td>
<td>815</td>
<td>12</td>
<td>23</td>
<td>all glass, but incoherent powder + some quench globules</td>
</tr>
<tr>
<td>b</td>
<td>microcline B</td>
<td>815</td>
<td>12</td>
<td>23</td>
<td>unopened—used for B</td>
</tr>
<tr>
<td>186a</td>
<td>capsule 185b</td>
<td>790</td>
<td>12</td>
<td>72</td>
<td>large euhedral xls + quench globules</td>
</tr>
<tr>
<td>b</td>
<td>microcline B</td>
<td>790</td>
<td>12</td>
<td>72</td>
<td>all strs, angular starting material + quench globules</td>
</tr>
<tr>
<td>135a</td>
<td>microcline A</td>
<td>850</td>
<td>11</td>
<td>4.7</td>
<td>all glass (bubbly) + quench globules</td>
</tr>
<tr>
<td>b</td>
<td>microcline D</td>
<td>850</td>
<td>11</td>
<td>4.7</td>
<td>all glass (bubbly) + quench globules</td>
</tr>
</tbody>
</table>
than is that for NaAlSiO₄, indicating that the effect of pressure on the solubility of H₂O is less in KAlSi₃O₈ melt than in NaAlSiO₄ melt. Although solubility data for H₂O in melts are meager, as they also are for solubilities in supercritical fluid, the data available indicate that H₂O solubility in the albite melt indeed in greater than that of KAlSi₃O₈ (Goranson, 1938; Oxtoby and Hamilton, 1978).

This fact, however, does not imply that the solubility of K-containing components in the vapor is clearly indicated in the work on the hydrous melting of granite by Boettcher and Wyllie (1968). A granite with 29 modal % orthoclase was reacted with 300% H₂O at 600 °C and 20 kbar. No orthoclase remained after experiments of only 6 h, and all K₂O (4.6% in the rock) had been transferred to the vapor, producing a solution with about 10.8 g K₂O/100 g H₂O, in addition to the other dissolved components. Ryabchikov and Boettcher (1980) presented data for the solubility of K in aqueous vapor in equilibrium with assemblages, including phlogopite with one or more of forsterite, orthopyroxene, and spinel at 1100 °C. The results in grams of K₂O per 100 g H₂O were 4 at 11 kbar, 7 at 20 kbar, and 25 at 32 kbar. They estimated that total dissolved solute amounted to about 25% at 20 kbar and 50% at 30 kbar.

The high solubility of potassic compositions in the vapor is also indicated in the current study, based upon the amount of noncrystalline material observed in experiments quenched from above, as well as from well below, the liquidus. We have been unable to distinguish material quenched from the vapor at pressures greater than 15 kbar from melts quenched from above the liquidus. As a

![Fig. 1](image-url)  
Fig. 1. The liquidus curve for H₂O-saturated melts in the system KAlSi₃O₈-H₂O. As discussed in the text, no field containing leucite was observed. The distinction in the symbols in the lower-pressure and high-pressure regions is also discussed in the text.
consequence, we cannot define a solidus curve at the higher pressures. The brownish aggregates of isotropic or slightly birefringent matter described by Boettcher and Wyllie (1968) from experiments quenched at greater than 15 kbar and interpreted as a vapor-phase deposit are probably this same ambiguous material. Figure 2 shows SEM photographs of two experiments at or near the melting curve of Figure 1 and one at considerably lower temperature. The melting curve drawn in Figure 1 is our best estimate of the liquidus curve, above which feldspar is not stable in the presence of H$_2$O. The single point at 5 kbar for the melting of KAlSi$_3$O$_8$ determined by Yoder et al. (1957) falls on the curve of Figure 1. The liquidus curve shows a less-pronounced flattening of the $dP/dT$ slope at higher pressures than does that of albite (Goldsmith and Jenkins, 1985b), but the reversed curvature and inflection point are present, as in the case of albite. The more pronounced reverse bend in the albite melting curves was discussed in the above reference, and it was suggested that the flattening of the solidi might indicate an approach to maxima on the three-phase curves, as observed in K$_2$Si$_2$O$_5$ (Morey and Fenner, 1917).

This approach to critical behavior could be complicated by incongruent solubility relations; a rather large multiphase region (melting band) could separate the liquidus from the solidus curve. Much of the higher-pressure region of Figure 1 indicated by shaded symbols (sanidine + GIBIS + vapor) can be considered to represent this multiphase region, and an approach to a maximum may well exist on a solidus curve (as yet undetermined).

No measure has been made of the H$_2$O content of either NaAlSi$_3$O$_8$ or KAlSi$_3$O$_8$ melts at the high pressures...
from which the incoherent melt phases are quenched, and
it would be difficult to do so. Determination of this as
well as the high-pressure solubility in the vapors awaits
the development of apparatus in which these phases can
be isolated and directly analyzed. It is most unlikely that
ambient conditions of the experiments can be maintained
in a quenched liquid. The melts are certainly highly depol-


ermized (Burnham, 1975; Goldsmith and Jenkins, 1985b), and the textures observed probably represent those
resulting after H₂O is exsolved from a melt too
tenuous to form a coherent glass upon quenching.

Reversals

Reversals of melting equilibria are usually not attempt-
ed. The presumption is generally made that under the
conditions that produce melting, equilibrium is readily
attained. As a precautionary measure, two-stage reversal
experiments were made at 790 °C and 900 °C (experi-
ments MC-186 and 184). In addition, what amounted to
a single-stage reversal was made in experiment MC-183.
In the two-stage reversals, the sample in one of two cap-

tules was observed to have melted to glass. The other
(unopened) capsule was brought again to a lower tem-
perature (MC-186a) or a lower pressure (MC-184a). In
both experiments the glass produced large crystals, many

euhedral, along with relict spheres of what was once melt,
now recrystallized. In experiment MC-183, the pressure
in the gas vessel inadvertently dropped (because of leak-
age) from 4.0 to 3.5 kbar. The experiment (183a) con-
tained glass and large euhedral crystals, almost certainly
produced by the decreased pressure. These experiments
clearly indicate the equilibrium nature of the lower-pres-
sure portion of the liquidus curve.

No reversals were made at pressures greater than 15
kbar. The difficulty in elucidating the nature of the phases
in the region where GIBIS is present would cloud reversal
criteria.

Conversion of Microcline to Sanidine—
No Metastable Melting

Significantly different melting curves were obtained
when low and high albite were used as starting materials
in an earlier study (Goldsmith and Jenkins, 1985b). At
temperatures below ~760 °C, the melting curve for high-

albite starting material deviates increasingly from that of
the low-albite starting material. At this temperature and
above (at ~18 kbar) albite is largely disordered, with a
Δ2θ(131) value of 1.85 and greater (Goldsmith and Jen-
kins, 1985a). At 15 kbar, high albite melts at 600 °C,
whereas the melting curve for low albite is at 675 °C; at
12 kbar the two curves are only about 20° apart. On the
other hand, no metastable melting of low albite was
observed; a single melting curve was produced by both low
and high albite starting materials. It was apparent that at
temperatures >760 °C the hydrothermal conversion of
low albite to high albite is rapid enough that the melting
of high albite determined the liquidus, even if residual
low albite remains. The absence of a detectable metasta-
ble extension of the low-albite melting curve beneath the
high-albite curve may be because disordering is a neces-
sary precursor to melting. The melting of low albite may
require that the enthalpy of disordering be added to that
of melting, resulting in either a two-stage process or one
requiring superheating.

Unlike albite, both microcline and sanidine produce a
single hydrothermal melting curve. No metastable melt-
ing of either polymorph is observed. There is no melting
of the high-temperature (disordered) form at tempera-
tures below the inversion temperature because, unlike in
the case of albite, this temperature or temperature range
is well below that of any hydrothermal melting. Although
the triclinic-monoclinic inversion temperature is not
known, it is presumed to be in the range 450–500 °C
(Goldsmith and Laves, 1954; Hovis, 1974; Senderov and
Yas’kin, 1975; Bambauer et al., 1989), and any presumed
crossover of melting curves at the inversion temperature
would occur in a P-T region far below that of melting of
either polymorph. As in albite, the low-temperature (or-
dered) form does not melt as such. The temperature is
high enough and the conversion to the stable (disordered)
sanidine rapid enough that disordering precedes melting.
It is possible that rapid superheating of dry microcline
would produce melting before disordering, but no sign of
metastable hydrothermal melting of the ordered poly-
morphs has been seen for either NaAlSi₃O₈ or KAlSi₃O₈.
In all of the experiments in Table 1 in which microcline
was used as the starting material, conversion to mono-
clinic potassium feldspar took place before melting was
observed. Structural state variation (degree of Al/Si or-
der, to be considered) in the monoclinic form had no
apparent effect on the melting relations.

In conjunction with disordering prior to melting, it was
observed that when capsules of both microcline and san-
idine were held at conditions close to the liquidus curve,
recrystallization took place in the microcline starting ma-
terial, but not in the sanidine. This is well shown in ex-
periments MC-189a and MC-189b, at 1 kbar and 970 °C.
Under these conditions, disordering takes place by a solu-
tion-reprecipitation process, or regrowth of the feldspar.
The crystals of sanidine, the stable phase, retain their
original form during the process.

Structural State

In conjunction with the melting experiments, some
preliminary experimental data are at hand on the equi-
librium state of Al-Si order as a function of temperature
in monoclinic potassium feldspar (Goldsmith, 1988a). The
rate of Al-Si interchange is extremely slow in the range
of several kilobars in which most hydrothermal experi-
mentation takes place; reversals of degree of order have
not been feasible and structural state-temperature rela-
tions of KAlSi₃O₈ are not known. Because of the prelim-
inary nature of the data, the information is not included
in Table 1, but observable reversal of the degree of order
is seen in experiments of several days at 15–25 kbar, in
hydrothermal experiments and in experiments containing
carbonate flux but lacking H$_2$O (as in Goldsmith and Jenkins, 1985a). Longer times are necessary to establish equilibrium, but it is apparent that the degree of order is variable and reversible with temperature over at least this interval. The state of order is determined by a simple X-ray powder diffraction technique (three-line spacings) developed by Hovis (1989), using feldspars ranging from monoclinic adularia to high sanidine.

Microcline is converted to monoclinic KAlSi$_3$O$_8$ at high pressures by a nucleation and growth (two-phase) process, with little or no change in the triclinic geometry (triclinic or obliquity) during conversion. The unobserved phase change to triclinic geometry takes place well below 600°C. These results are similar to those observed in anhydrous conversion at high pressures (Goldsmith, 1988b); it is suggested that the triclinic-monoclinic transformation may be a first-order phase change.

**THE LEUCITE PROBLEM**

Leucite was not observed in any of the experimental products, although no special effort was made to locate a field of leucite along the lower pressure and higher temperature portion of the liquidus curve. Goranson (1938) showed a field of leucite + liquid + vapor that appears at pressures below 2.6 kbar at 950°C and enlarges at lower pressures and higher temperatures. In this study only sanidine, and no leucite, was observed in an experiment at 1 kbar and 970°C, and only glass was observed at 1.8 kbar and 975°C. It is possible that Goranson’s reported temperatures and pressures differ somewhat from ours, but our data indicate that Goranson’s value of 2.6 kbar for the maximum pressure stability of leucite is too high.

The diagram of Bowen and Tuttle (1950) of the system KAlSi$_3$O$_8$-NaAlSi$_3$O$_8$ at pressures of 1 bar (dry) and at $P_{H_2O}$ of 1000 kg/cm$^2$ and at 2000 kg/cm$^2$ (essentially 1 and 2 kbar) are widely known. In the dry system a liquidus curve delimiting the field of leucite + liquid is shown from the data of Schairer and Bowen (1935) and Schairer (1950). A smaller field with leucite is shown at 1000 kg/cm$^2$, and the field is almost nonexistent at 2000 kg/cm$^2$. The data of Bowen and Tuttle showed only five leucite-containing experiments at three different compositions, all at 1000 kg/cm$^2$ and all between 980°C and 1000°C. At 2000 kg/cm$^2$, no compositions containing less than 20% NaAlSi$_3$O$_8$ were used, and no leucite was observed. No liquidus-determining experiments were made at either pressure. Only two experiments were made with pure KAlSi$_3$O$_8$. At 1000 kg/cm$^2$, a 4-h experiment at 1000°C yielded glass + leucite, and at 980°C all feldspar. Neither result disagrees with our data, as plotted in Figure 1. The leucite-containing fields shown by Bowen and Tuttle (1950) were for the most part based on the published data of Goranson (1938). Bowen and Tuttle’s (1950) principal concern, however, was with the solvus, not the liquidus or solidus curves.

Goranson’s original data are of interest. His tables of experiments list pressure and temperature, but not the duration of the experiments. The only comment made as to length of the experiments was: “For a particular run pressure and then temperature are raised to the desired amounts and held at these values for a length of time sufficient for attainment of equilibrium. Although these silicates are very sluggish in crystallizing from an anhydrous melt they crystallize very readily from hydrous solutions, in fact relatively large crystals have been grown in half an hour” (Goranson, 1938, p. 73). Goranson gave no indication whatsoever of the time he felt was required to establish equilibrium, and in 1938 reversing of equilibria was not done. Goranson’s experiments used glasses as the starting material, and Goranson, as most who followed him, perhaps felt than in hydrothermal experiments the promotion of a reaction implied equilibrium. More recently, experimenters have realized that melting equilibria can be quite sluggish, as shown by Peterson and Newton (1989b). It is quite possible that the field containing leucite shown by Goranson is at least in part metastable.

In the dry system, Schairer and Bowen (1935) and Schairer (1950) have shown that the field of leucite produced by incongruent melting of potassium feldspar on the join KAlSi$_3$O$_8$-NaAlSi$_3$O$_8$ is very large, extending to 51% albite along the join. As mentioned by Goranson (1938), the sluggishness of the feldspar-containing systems is well known, and the system K$_2$O-Al$_2$O$_3$-SiO$_2$ at the composition of KAlSi$_3$O$_8$ may well be the most sluggish and intractable, even at the melting temperature, of any system known. Schairer (1950) said: “All alkali-feldspar compositions and particularly those with more than 50 per cent of potash feldspar give viscous melts that are difficult to crystallize dry, and in these crystalline or partly crystalline melts equilibrium between crystals and liquid is attained very slowly. It was possible to determine liquidus temperatures within narrow temperature limits by observing temperatures at which a small amount of tiny crystals grew in the melt and above which they were dissolving. On the other hand, it was not possible to determine the beginning of melting, since none of these alkali-feldspar compositions could be completely crystallized dry and since, even if crystallized hydrothermally, no accurate value for beginning of melting can be obtained because the crystals must be heated above their temperature of beginning of melting for a week or several weeks before observable melting (glass under the microscope) can be recognized.”

The elimination at H$_2$O pressures of several kilobars or less of the field of leucite + liquid that was outlined by Schairer (1950) at 1 atm is impressive. It might be produced by the lowering of the hydrothermal melting point of KAlSi$_3$O$_8$ to a temperature below that of the metastable congruent melting point of KAlSi$_3$O$_8$. Schairer (1950) showed the incongruent melting point to be at 1150 ± 20°C, and a metastable congruent melting point at 1 bar could be at a lower temperature. Although extrapolation of the liquidus of Figure 1 to 1 bar is uncertain because of the flatness of the curve, it would appear
to be below 1150 °C. Goranson (1938) extrapolated the curve orthoclase + vapor to ~1110 °C at $P_{\text{H}_2\text{O}} = 1$ bar. If the quaternary point for orthoclase, leucite, liquid, and vapor shown by Goranson at 2.6 kbar and 950 °C could be dropped to 1 bar, the field of leucite + liquid would disappear at ~1110 °C, and KAISi$_3$O$_8$ would melt congruently at all pressures of H$_2$O. Thus hydrous congruent melting might produce the realization of the metastable congruent melting point. If equilibrium reactions prove to be sluggish at low H$_2$O pressures, metastability might be a factor, and the true disappearance of leucite might be below 1 kbar. Although this study has not been aimed at this problem, it would appear that investigation of possible metastable behavior in this system, both dry and hydrothermally at low pressures, should be considered.

**Melt Behavior**

The possibility exists that a tenuous, alkali-rich, near-critical fluid could be formed at pressures corresponding to the lowermost crust. The inability to quench melted KAISi$_3$O$_8$ to glass in the higher-pressure experiments is indicative of a fluid with much lower viscosity than other silicate melts. Because of its greater mobility, a fluid of this nature may greatly enhance heat transfer and element distribution, as well as alkali metasomatism in the lower crust. In the KMASH-CO$_2$ system, Peterson and Newton (1989a) found that volatile, alkali-rich melts were not quenchable to glass at temperatures as low as 700 °C at pressures in the range 6–10 kbar. The presence of these ultraviolet-rich liquids (or fluids rich in alkalis and silica) at moderate $P$-$T$ conditions in feldspathic and granite-analogue systems is just beginning to be recognized. Further examination is needed to evaluate their petrologic potential.

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**REFERENCES CITED**


