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REVISION 2

The System Fayalite-Albite-Anorthite and the Syenite Problem

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ABSTRACT

The presence in a magma of fayalite, the iron end-member of the olivine binary series, affects the feldspars at pressure by lowering the temperatures at which they crystallize from the magma. Starting with estimates from published literature it becomes obvious that at pressure, fayalite becomes important because the pressure effects on the melting temperatures are very different: large for albite, and small for anorthite. In this experimental study, a powder of fayalite composition was combined with six finely ground natural feldspars from Ab to An_{97} to make six bulk compositions. Using graphite crucibles in piston-cylinder apparatus at a pressure of 5 kbar, a cotectic in the ternary system was found to run from 1,141°C at An(Fa) to 1,124°C at Ab(Fa), with fayalite contents from 68 to 17 weight percent, respectively. The results can be used to show that ternary feldspars saturated with fayalite and Fe monoclinic pyroxene will crystallize at a 5-kbar multiphase eutectic 1010°C, 56°C below a calculated azeotropic point on the Ab-Or join. The results are used to compare the end points of two very different layered intrusions, Skaergaard and Kiglapait, and to illuminate the nature and origins of syenite and trachyte, which are leucocratic rocks unsaturated with mafic minerals. Because fayalite-saturated melts are responsive to pressure unequally on the feldspar end members, olivine of intermediate composition will have a damped but potentially significant effect on feldspar fractionation in the lower crust of the Earth, possibly affecting the origin of anorthosite and syenite.

Keywords: Fayalite, olivine, feldspar, fractionation, melting experiments, syenite origin

INTRODUCTION

This study was undertaken to quantify an early estimate about the low temperature of the fayalite-saturated cotectic in the system Fa-An-Ab. The original estimate of this thermal effect was developed by the senior author in ~1988 from published studies of the systems Fa-An and Fa-Ab. Because the fayalite-saturatred composition also occurs in some syenites, we considered that rock type and its genesis to be a logical target for comparison.

The fayalite component of olivine in crystallizing melts can have a profound effect on the fractionation of plagioclase at pressure because it affects albite and anorthite very differently. The pressure effect is large for albite and small for anorthite, which makes the plagioclase binary loop and the cotectic curve flatter in temperature (Lindsley, 1968). Because of this behavior, the fractionating power of plagioclase is affected by the presence of fayalite, and in principle by the presence of olivine in general. This contribution was designed to quantify the influence of olivine composition on plagioclase fractionation. This was done by finding the cotectic trace in the system Fa-An-Ab at 5 kbar. The results are applied to natural rocks both known and conjectured.

METHOD OF WORKING

The purpose of this exercise was to locate the cotectic in the system Fa-An-Ab at 5 kbar pressure and to determine its temperature profile. The method adopted was to work in piston-cylinder apparatus because of our satisfactory experience with this technology (e.g., Morse et al., 2004). We chose to make up the bulk compositions using a mixture of feldspar end members and natural plagioclase in compositions spaced so that observed melting would bracket equilibrium values for the fayalite-plagioclase cotectic. We chose three hours as a nominal run-time in the expectation that at the high temperatures of these experiments, melting would occur if melt is stable.

This work has been done by making up a set of six bulk compositions, holding them, three at a time in graphite, at 5 kbar in a piston-cylinder apparatus at a chosen temperature, quenching them, mounting in epoxy, and interpreting them in reflected light. This procedure suffices to show the existence of melt and crystalline phases (if any). It does not afford the time required for determination of equilibrium crystal compositions, which in our experience requires experimental durations of ~24 hr at 5 kbar in graphite (Morse et al., 2004), nor need it do so to define a cotectic. The criterion of relevance is not reversal but reproducibility.

In our experiments, there are examples of glass only (quenched melt) above the liquidus, no

glass (below the solidus), glass plus feldspar only (on the plagiclase side of the ternary cotectic composition), glass plus fayalite only (on the olivine side of the ternary cotectic composition), and glass plus fayalite plus plagioclase at co-saturation. In our set of 36 experiments (Table S1[1]) 24 were deemed successful. There are 10 at three-phase cotectic equilibrium and the rest at zero or one solid phase. Three bulk compositions were found to be sub-solidus, without melt, while other bulk compositions in the same crucible were partly melted. A result having melt plus one crystalline phase represents one leg of a three-phase triangle; melt plus two crystalline phases makes a complete three-phase, invariant triangle. Experimental results at An_{15} and An_{66} have been studied with SEM and microprobe to characterize examples of crystal and melt compositions.

STARTING MATERIALS AND COMPOSITIONS

The starting materials for this experimental endeavor were synthetic fayalite and six natural feldspar compositions described in Table 1. The synthetic fayalite was confirmed pure by X-ray diffraction. Of the feldspars, one was an endmember (Amelia albite, Ab, from the Amelia Court House leucogranite, VA), two were blends of endmembers, and three were natural samples from the Kiglapait layered intrusion (e.g., Morse, 2015b). The endmember An was a natural sample from an amphibolite in the Kiglapait contact zone (KI 2072, An_{97}). Plagioclase compositions were made for An_{15} and An_{30} by physically adding powdered sample KI 2072 to Amelia albite as described below. To these feldspars, variable amounts of fayalite were added. The resulting list of intended bulk compositions is given in Table 1.

This project was begun by estimating the 1-atm ternary cotectic from the studies of Bowen and Schairer (1936) for the binary Fa-Ab, and Schairer (1942) for the binary Fa-An. The results were interpreted as a straight-line cotectic from Fa_{64} on the Fa-An sideline to Fa_{16} on the Fa-Ab sideline. The temperature difference on this cotectic was estimated from the 1-atm temperatures on the sidelines to be 1,110 - 1,050 = 60°C. Adjustments to 5 kbar were made from literature data (e.g., Morse, 1994) assuming pressure corrections of 11.6°C/kbar for Fa-Ab and ~4°C/kbar for Fa-An, yielding an estimate for the Fa-saturated span An to Ab of only 20°C. These preliminary values have been superseded by reference to a corrected value for 1-atm melting of albite at 1,100°C (Lange, 2003) and a reconsideration of the pressure effect, discussed below.

[1]Deposit item AM-16-00000, Table S1. Deposit items are free to all readers and found on the MSA web site, via the specific issue's Table of Contents (go to http://www.minsocam.org/MSA/AmMin/TOC/)

Mixtures for the experiments were made by weighing, combining, and grinding the components under acetone in a mullite mortar, typically for ~5 minutes. For each of the starting feldspars, fayalite was added to make a bulk composition bracket over a range of fayalite amounts and a range of temperatures. Electron probe compositions of the starting materials are listed in Table 2. The calculated bulk compositions of all the experiments are listed in Table 3 by the name of the plagioclase given in column 4. The initial composition brackets in % Fa were mostly small, e.g., 4% Fa for An_{15} and An_{30}, but 18% Fa for An_{48}, only one value (60% Fa) for An_{66}, and a bracket of 3% Fa for An_{97}.

After grinding, the mixed bulk composition powders were dried overnight at 120°C, placed in small glass vials, and stored in a desiccator.

EXPERIMENTAL

Melting experiments were made at 5 kbar pressure in a Rockland Research 19mm piston-cylinder apparatus at the Five College Experimental Petrology Laboratory at Smith College. The ~ 7mg samples were packed, three per run, into 1.5 mm diameter holes drilled to a depth of 2.5 mm in an 8 mm long graphite rod. This crucible was covered with a <1-mm graphite lid and placed inside a fired pyrophyllite cup with lid. This in turn was placed within a graphite furnace containing MgO spacers below and above the crucible. The furnace was surrounded by a Pyrex tube, then placed into a salt sleeve with a lead foil sheath, then placed in the tungsten carbide core of the cylinder. It was topped by a brass base plug placed inside a pyrophyllite sleeve. An alumina thermocouple sheath with Type D W-Re thermocouple wires crossed over at the tip was fed through the base plug and upper spacer to rest on the top of the fired pyrophyllite cap.

In conventional protocol, samples were pressurized hydraulically to about 120% of the working pressure (because pressure drops with heating) and then heated with a run-up in stages with a programed controller. The pressure was corrected in the 'hot piston-in' routine near and at the chosen run temperature, which was controlled to ~ 1°C and ± 100 bar, generally for three hours, then quenched to 300°C in 20 seconds by turning off the power to the furnace. The retrieved samples in their graphite cylinder were then embedded in epoxy and held in vacuum overnight. The cured 1-inch disks were ground by hand on silicon carbide sheets until the sample showed. The disk was then polished in a succession of diamond grits to 1-micron in a Struers automatic polisher.

The experimental data and visual interpretations are summarized in Supplemental Table S1. Most of the experiments were quenched at three hours. A few early experiments were kept at

temperature for 6 to 8.5 hours, but only one composition at 7.7 hr (run 3.3 in Table 2) was used in the final array. Of special note is the observation of small blebs of metallic iron in six experiments, signifying reduction in the graphite capsule. These amounted to less than 1% and were found in only two experiments (6.1 and 6.3) that were listed but not definitive in the final results. Some euhedral plagioclase crystals have swallowtail cores. In Run 8.3, fayalite spinifex clusters were observed amongst big euhedral olivines. In run 9.1 plagioclase rims were seen on olivine. Our experience and that of other workers suggests that graphite-saturated equilibria at pressure tends to maintain the oxygen fugacity to values lower than FMQ; in the present case with these bulk compositions the f_{O_2} is clearly lower than the wüstite-magnetite (WM) buffer.

Because of the steep temperature gradients in piston-cylinder apparatus (see Watson et al., 2002), our reported temperatures are believed to be precise only to +/- 5°C.

TEST OF THE EXPERIMENTAL DESIGN

Our method of working reflects our experience that melting is rapid in this system at temperatures above 1000°C and that the presence of melt speeds the approach to equilibrium. We tested this approach with more detailed analyses of two samples, as shown in the SEM/BEI images and chemical studies of Figure 1 and Table 4, which will best work in unison. In Fig. 1A of nominal composition An_{15} we observe a pale gray background of melt accompanied by dark plagioclase in many subhedral forms, and white, more rounded, grains of fayalite. The plagioclase contacts against melt have a characteristic bright BEI outline that arises from the mafic rejected solute pushed away by crystal growth. Careful examination will reveal that several dark crystals in the NW and SE corners have calcic cores that are of a lighter gray intensity.

In Fig. 1B of plagioclase composition An_{66} we find no bright BEI outlines and only anhedral to rarely subhedral plagioclase; the sample is annealed but unmelted.

Electron microprobe studies of these two experimental samples are shown in Table 4. It is clear from the analyses that the olivine compositions are essentially the same (columns 1,7 and 11), even though they do not meet the test of good stoichiometry. The plagioclase composition in FAA 4.1 is $An_{15.7}$, near the nominal bulk composition of An_{15}. The normative glass (melt) composition is $An_{17.7}$. We find that both crystal phases are present, so the bulk composition straddles the cotectic at this temperature. We find that some of the plagioclase is zoned but near the expected composition. At these high temperatures we find that the physical mixture (Table 1) of finely ground Ab and An_{97} has, within three hours, yielded crystals and melts that are, as far as we know, essentially on composition. We conclude that reaction rates are sufficiently fast

at the experimental conditions for our experiments to approach equilibrium closely and to constrain the location of the desired cotectic, possibly within the measurement limits of +/- 5°C. The experimental liquid and plagioclase compositions are close and therefore the three-phase triangle for the An15 composition is very narrow.

Concerns about the possibility that feldspar might not nucleate can be dispelled by looking at Fig. 1B, where several compositions on and near the cotectic have actually nucleated. It is also our experience that we have never yet encountered failure of feldspar to nucleate at pressure, very likely due to the high surface energy of the finely ground samples.

RESULTS FOR THE COTECTIC LIQUIDUS

A summary of the pertinent experimental results is shown in Table 5, ordered by the plagioclase composition. Details of this table, ordered by experiment number, are furnished in Supplementary Table S1. Compositional brackets on the cotectic can be inferred from the relative amounts of plagioclase and olivine. From the nominal temperature and the fraction of glass observed optically, the best-fit cotectic temperature is shown in the right-hand column. The results of the 5-kbar, fayalite-saturated melting experiments are shown in the ternary plot of Fig. 2. The six bulk feldspar compositions are pure Ab and the five compositions listed along the Ab-An base line. The ternary cotectic is drawn through the space between nearest olivine and plagioclase saturation pairs. It is straight at higher temperatures above $An_{15,}$ then curved to meet the Fa-Ab cotectic. The amount of fayalite is expressed in weight percent, as measured in the mixtures. The melting points of the three corner compositions are given in degrees C at 5 kbar. The entire cotectic range of plagioclase compositions is reached in 17 degrees.

Of course, this result is relatively meaningless at the high-temperature end because fayalite is not ordinarily found in An-rich rocks. However, as fractionation proceeds, the relevance of the diagram increases. The pair Fa + Ab is an end member almost never found, and cannot occur in the presence of any CaO-bearing phase (Bowen, 1945); in particular, calcic pyroxene. Instead, crystallization of Fa-saturated liquids more likely involves oligoclase and alkali feldspars.

The thermal profile of the cotectic in Fig. 2 is shown in Fig. 3. The steepening of the cotectic temperature toward Fa-Ab is chiefly a reflection of the large effect of pressure on temperature for albite as compared to anorthite. This effect is combined with the systematic increase in feldspar relative to olivine.

EFFECT OF FAYALITE ON TERNARY FELDSPARS

Melting of albite, sanidine, and anorthite

As usual the terminology is simplified by using Ab, Or, and An as the compositional end members, but describing the Or component as sanidine when melting is to be considered.

At 1-atm albite melts at 1100°C (Lange, 2003) and the pressure effect in her figure 3, 0 to 10 kbar, is given by T°C = 0.36(P^2) +18.15(P) +1,100, for which $R^2 = 1$. At 5 kbar, then, the melting point is 1,182°C and the mean difference is 16.6°C/kbar.

At 1-atm sanidine melts incongruently to leucite + melt but metastably by itself at 1,200°C. Its metastable melting behavior is given by Waldbaum and Thompson (1969) in a curve satisfied by the polynomial T°C = 0.307(P^2) +18.61(P) +1,200, $R^2 = 1$. The mean pressure effect is 17°C/kbar and the 5 kbar melting point is 1,285°C. Note the interesting similarity of the coefficients for Ab and Or and the mean pressure effect.

The 1-atm system Ab-Or is an azeotrope with an azeotropic point at $X_{Or} = 0.331$ (Waldbaum and Thompson, 1969) which the authors chose to take as precisely 1/3, a tradition followed here. The temperature at the minimum was taken by these authors as 1,061°C, here corrected to 1,041°C using the Lange correction for Ab. This step for the binary is warranted by the similarities of the Ab and Or coefficients mentioned above. The 5-kbar azeotropic melting point is 1124°C, and here the stable phase is sanidine, well away from the more K-rich breakdown to Lc + L.

The ternary feldspar system is completed by addition of An, which melts at 1,553°C at 1-atm and 1,563°C at 5 kbar (Goldsmith, 1980).

Melting of fayalite

The metastable melting of fayalite by itself, bypassing the 1-atm incongruent breakdown to Fe plus liquid, is taken to occur at 1,205°C. A high-pressure Simon equation for the melting curve based on Lindsley (1966) was given by Morse (1994) in Fig. 18.24. This relationship is more conveniently represented using temperature as the dependent variable in the polynomial T°C = -0.0592(P^2) + 7.788(P) +1205, which yields 1,243°C at 5 kbar; again, the value of $R^2 = 1$.

AN APPLICATION OF FAYALITE-SATURATED TERNARY FELDSPAR

Fayalite-saturated feldspar at 5 kbar

Albite melts at 1,182°C; the sideline Fa-Ab cotectic is at 1,124°C and the difference is 58°C. The azeotropic point at X_{Or} = 1/3 melts at 1,124°C, forming a fortuitous isotherm with Fa-saturated albite. Because of the similar pressure effects on Ab and Or, and for lack of any evidence to the contrary, we assume that the Fa effect is the same at the azeotropic point as at the Ab-Fa sideline, and therefore that a Fa-saturated alkali feldspar would melt at 1,124-58 = 1,066°C.

A result calculated specifically for the terminal ferrosyenite of the Kiglapait intrusion is shown in Fig. 4. The diagram shows a 5-kbar section from An to the alkali feldspar azeotropic point AP at X_{Or} = 1/3 on the binary Ab-Or. The temperatures 1,141 and 1,010°C are experimental from this contribution (Fig. 2) and from Morse and Brady (in review), respectively. The temperature of the AP point, 1,066°C, is described above as calculated from the Ab-Or join and then reduced to account for the fayalite saturation. The thermal minimum is represented as an azeotrope lying at 11% ternary An and therefore projecting from Or to An_{16} on the Ab-An sideline. The bulk composition at this terminal point includes components and indeed crystals of ferrohedenbergite, a CaAl-bearing pyroxene, that requires the feldspar to be calcic relative to pure Ab (Bowen, 1945).

We now have three interesting fayalite-saturated thermal points at 5 kbar: the azeotropic point, the experimental, pyroxene-saturated ternary minimum (Fig. 4) at ~An_{16} as projected from Or (and so lying on the An_{11} line), and An. The experimental temperature of the natural ternary feldspar eutectic is 56°C below that of the Ab-Or azeotrope.

VARIABLE OLIVINE COMPOSITIONS

A derivative ternary diagram can be constructed to show liquids with variable Mg-Fe olivine compositions with plagioclase, as in Fig. 5. The results are guided in part by the 5-kbar experimental studies of troctolites in the Kiglapait intrusion (Morse et al., 2004). Paths are shown for the approximate trends of the Skaergaard and Kiglapait liquids. The locations of average trachyte (TR) and syenite (SY) are taken from Fig. 5, to be discussed. These locations appear to be anomalous in terms of their high Mg ratio and low An content, and are unlikely to have been produced by any simple trajectory of magmatic fractionation. Decompression (see arrow "-*P*") would move the field boundaries and the sample compositions somewhat closer to the feldspar join. Note that both these compositions are much richer in total (i.e., ternary) feldspar than in plagioclase alone, shown here. One conclusion from this system is that the effect of Mg on the feldspar-richness of syenites and trachytes is not large.

THE SYENITE PROBLEM

Because this contribution is mainly about the terminal crystallization of rocks that can be described as syenites, it is pertinent to expand the discussion to a very old problem of that rock type. A glance at Fig. 6 will quickly show the problem. In this paper and others on the Kiglapait intrusion we tacitly assume that prolonged fractional crystallization leads to rocks called syenite (or ferrosyenite) that are mutually saturated with olivine and calcic pyroxene as well as feldspars, whereas nearly 100 percent of what are called syenites and trachytes in the rest of the world are felsic and far from saturation with mafics.

There is perhaps a general agreement that syenites are fundamentally rocks of alkali feldspars, a few mafic phases, and no quartz. But the contrast in color index means that when we say "syenite" we may not understand each other. Indeed, the difference between the Gardar rocks and the evolved rocks of layered intrusions is stark. More troublesome yet is the origin of the most abundant syenites: How do they get to be so felsic? In this they become cousins of anorthosite: felsic leftovers of once-cotectic magmas that have left their mafics behind. They have enough traces of mafics to know that there is considerable variety among them, so it isn't just one magma type that generates these separate magmas that intrude overlying crust.

Is there somewhere lurking among our outcrops a mid-crustal mafic residue of parental syenite? If not, can it be in the basal crust or uppermost mantle, undetected?

One word of caution: the Kiglapait troctolitic magma gives a residue of mafic-saturated syenite about the size of a teacup: ~0.15 % (i.e. ~ 5 km^3) of the total magma (Morse, 2015b). Real leucosyenites have had a very different history (e.g., an alkalic magma) to make sizeable intrusions (e.g., Upton, 2013).

The fayalite component of magma has a profound effect on the phase equilibria of residual magma. But it operates only at mutual saturation with mafics, leaving the real syenite problem unresolved.

FURTHER CONSIDERATION OF THE PRESSURE EFFECT

It is significant that Fig. 2 presents the effect of fayalite on plagioclase composition at 5 kbar. At atmospheric pressure the estimated difference between the melting temperatures of fayalite-saturated albite and anorthite is ~60°C. The pressure effect is about 16.6°C/kbar for Fa-saturated albite and only 1.6°C for anorthite. At ~6.3 kbar, therefore, the fayalite-saturated

temperatures are essentially the same for all values of X_{An}. This result requires that the liquidus and solidus are jointly reduced to a straight line, with loop width zero. That is why the above estimates of plausible loop widths are chosen to be small.[2]

At higher pressures, the fayalite-saturated plagioclase loop is reversed! The next question must then be, is this effect anywhere relevant within the Earth? The answer must be, perhaps surprisingly, yes.

Fayalite presumably does not occur with calcic plagioclase, but a significant fraction of it does occur in olivine coexisting with plagioclase in troctolites or olivine gabbros. In a sense, then, all natural olivine at pressure must have some partial effect to narrow the effective plagioclase loop and therefore to reduce the effect of plagioclase fractionation. In more evolved bulk compositions the fayalite effect can reduce zoning and thereby supplement adcumulus growth.

At depth in the Kiglapait intrusion the presence of olivine must have some small effect on the fractionation of plagioclase in addition to the more important effect of the augite component of the liquid that affects the activity of silica and therefore, preferentially, of albite (Morse, 2014). But our consideration must go deeper. At the base of the crust, what does fractionation do to the origin of anorthosite? Or syenite, for that matter. There is a potential here for the generation of plagioclase at nearly constant composition while mafics sink and feldspar becomes concentrated in the lower crust.

IMPLICATIONS

The effect of iron-rich olivine to limit the variability of plagioclase composition is shown to be considerable at modest pressure. The ususal assumption of a relatively fat Ab-An loop that drives substantial plagioclase fractionation must be modified if Fe-rich olivine is present in the local magmatic system. This effect ramifies to assumptions about plagioclase fractionation efficiency at moderate pressures, including both cumulus feldspar crystals and their interstitial

[2]We have not attempted to determine tielines or three-phase triangles in this exercise but these can be estimated as follows. For Fo70 olivine and coexisting plagioclase the value of K_D in linear partitioning (Morse et al., 2004) is 0.52, rising with pressure as the loop width diminishes (e.g., Morse, 2015a). The partition coefficient K_D is inversely proportional to loop width (idem) and has the expected value of 1.0 for Fa-An-Ab at 6.3 kbar, shown here. At the experimental pressure used here, 5 kbar, if the value of K_D is 0.8, the mid-range loop width is 5.6% An; if K_D is 0.9, the width is 2.6%. Either value would be time-consuming to determine experimentally.

trapped liquids, if any. It applies especially to any modeling of feldspar-rich, olivine-bearing magmatic systems at lower crustal depths, including the possibility that feldspar crystals may grow, accumulate, and fractionate at constant composition. If then separated from their mafic minerals they might ascend to form felsic rocks ranging from anorthosites to syenites.

HISTORY OF THIS STUDY (by Morse)

I have in my files an entertaining letter from Hatten S. Yoder Jr. dated at the Geophysical Laboratory on January 27, 1989, including a page of 12 ternary diagrams, all with the base at Ab - An, and each with a different apical phase, in order: Diopside, Wollastonite, Enstatite, Sphene, Silica, Nepheline, Leucite, Sanidine, Fayalite, Forsterite, Åkermanite, and Spinel. Cotectics and peritectics where needed are drawn with neat curves from known or inferred sideline temperatures. It is suggested that such drawings would be good lab exercises for students. In particular, this sentence is found at the end of paragraph 1:

"Take special note of the one for fayalite - within 58°C you can run from anorthite to albite!"

My response on 26 Feb 1989 mentioned re-emergence of his letter from my desk stratigraphy and continued in paragraph three with a discussion of our small differences for Fa-An-Ab, where I got 36.5% An at the sideline compared to his 27%. [cf.31% An in Fig. 2: together we bracketed it!]. I refer to my drawings "which I happened to have in my file awaiting your beck and call." We agreed that the temperature range was small, but had not yet considered the pressure effect, in which the steep pressure dependence of Ab-melting tends to overtake the lesser pressure effect of An-melting. My response ended with the fervent desire to have somebody study "my favorite system, Fa-An-Ab-Or." The advent of the piston-cylinder apparatus with graphite crucibles finally made this quest feasible.

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at ---------- online. (Table S1)

REFERENCES

Bowen, N. L. (1945). Phase equilibria bearing on the origin and differentiation of alkaline rocks. American Journal of Science 243A, 75-89.

Bowen, N. L., and Schairer, J. F. (1936). The system, albite-fayalite. Proceedings of the National Academy of Sciences 22, 345-350.

Bryan, W. B., Thompson, G. , Frey, F. A. , and Dickey J. S. (1976). Inferred geologic settings and differentiation in basalts from the Deep-Sea Drilling Project. Journal of Geophysical Research 81(23), 4285-4304.

Fuhrman, M. L., Frost, B. R., and Lindsley, D. H. (1988). Crystallization conditions of the Sybille Monzosyenite, Laramie Anorthosite Complex, Wyoming. Journal of Petrology 29, 699-729.

Goldsmith, J. R. (1980). Melting and breakdown reactions of anorthite at high temperatures and pressures. American Mineralogist 65, 272-284.

Grove, T. L., Kinzler, R. J., and Bryan, W. B. (1992). Fractionation of mid-ocean ridge basalt (MORB). American Geophysical Union Monograph (eds. J.P. Morgan, D.K. Blackman, J.M. Sinton), 71, 281-310. (Table 1 #7)

Lange, R. A. (2003). The fusion curve of albite revisited and the compressibility of $NaAlSi_3O_8$ liquid with pressure. American Mineralogist 88, 109-120.

Le Maitre, R. W. (1976). The chemical variability of some common igneous rocks. Journal of Petrology 17, 589-598 plus 39 figures.

Lindsley, D. H. (1966). Pressure-temperature relations in the system FeO-SiO_2. Carnegie Institution of Washington Yearbook 65, 244-247.

Lindsley, D. H. (1968). Melting relations of plagioclase at high pressure. In Isachsen, Y. W., ed., Origin of anorthosite and related rocks, New York State Museum and Science Service Memoir 18, 39-46.

McBirney, A. R. , and Naslund, H. R. (1990). The differentiation of the Skaergaard intrusion: A discussion of Hunter and Sparks (Contrib Mineral Petrol 95:451-461). Contributions to Mineralogy and Petrology 104, 235-240.

Morse, S. A. (1981). Kiglapait geochemistry IV: The major elements. Geochimica et

Cosmochimica Acta 45, 461- 479.

Morse, S. A. (1994). Basalts and Phase Diagrams. Corrected and reprinted by Krieger, Melbourne, FL, 493 pp.

Morse, S. A. (2014). Plagioclase fractionation in troctolitic magma. Journal of Petrology 55, 2403-2418.

Morse, S. A. (2015a). Linear partitioning in binary solutions: A review with a novel partitioning array. American Mineralogist 100: 1021-1032.

Morse, S. A. (2015b). Kiglapait Intrusion, Labrador. In Charlier et al. (eds), Layered Intrusions Springer-Dordrecht, 589-648.

Morse, S. A. (Sub judice) Kiglapait Mineralogy V: The feldspars. In revision at American Mineralogist.

Morse, S. A. , and Brady, J. B. (In revision). Thermal history of the Kiglapait Upper Zone. In revision for Journal of Petrology.

Morse, S. A. & Ross, Malcolm (2004). Kiglapait mineralogy IV: The augite series. American Mineralogist 89, 1380-1395.

Morse, S. A., Brady, J. B., and Sporleder, B. A. (2004) Experimental petrology of the Kiglapait intrusion: Cotectic trace for the Lower Zone at 5kb in graphite. Journal of Petrology 45, 2225-2259.

Schairer, J. F. (1942). The system CaO-FeO-Al_2O_3-SiO_2. I. Results of quenching experiments on five joins. American Ceramic Society Journal 25, 241-274.

Schairer, J. F., and Yoder, H. S. (1967). The system Albite-Anorthite-Forsterite at 1 Atmosphere. Yearbook Carnegie Institution of Washington 65, 204-209.

Upton, B. G. J. (2013) Tectono-magmatic evolution of the younger Gardar southern rift, South Greenland. Geological Survey of Denmark and Greenland Bulletin 29, 124 pp.

Upton, B. G. J., Martin, A. R., and Stephenson, D. (1990). Evolution of the Tugtutôq Central Complex, South Greenland: A high-level, rift-axial, late-Gardar centre. Journal of Volcanology and Geothermal Research 43, 195-214. (Table 2)

Wager, L. R., and Brown, G. M. (1967). Layered igneous rocks. San Francisco: Freeman (1968, Edinburgh: Oliver & Boyd): 588 pp.

Waldbaum, D. R., and Thompson, J. B., Jr. (1969). Mixing properties of sanidine crystalline solutions. I. Phase diagrams from equations of state. American Mineralogist 54, 1274-1298.

Watson, E. B., Wark, D. A., Price, J. D., and Van Orman, J. A. (2002). Mapping the thermal structure of solid-media pressure assemblies. Contributions to Mineralogy & Petrology 142, 640-652.

Watt, S. W. (1966). Chemical analyses from the Gardar Igneous Province, South Greenland. Rapport Grønlands Geologiske Undersøgelse 6: 92 pp.

CAPTIONS

Figure 1. SEM/BEI images of two experimental results, for FAA 4.1 (A) and FAA 11.3 (B). Melt is plentiful in (A) and the subhedral plagioclase grains have bright BEI outlines. Zoning can be seen in both plagioclase and glass. In (B) no melt is present, nor any bright BEI outlines. The measured plagioclase composition (Table 2) is equal to the input bulk composition (Table 1).

Figure 2. The system Fayalite - Plagioclase at 5 kbar. The cotectic boundary between fayalite and plagioclase is located as shown in weight percent fayalite, since these were the quantities weighed in to make the bulk compositions. The endmember components are pure fayalite and natural feldspars. Compositions An_{48} and An_{66} are analyzed plagioclase feldspars from the Kiglapait Intrusion, Labrador (Morse, in review). A mixture of the two plagioclase end members An_0 and An_{97} was used to create the compositions An_{15} and An_{30}. All starting materials were finely ground crystalline mixtures whose bulk compositions are indicated along the Ab-An sideline. All but one of the experiments were held at temperature and pressure for 3 hours. Those in the plagioclase field were typically poor in crystals and rich in glass, whereas those in the olivine field typically contained tens of percent olivine. The total temperature range from fayalite-saturated pure An to pure Ab is estimated at 17°C.

Figure 3. Temperatures along the cotectic trace of Figure 1. The fayalite contents in Wt. % are given at each determined point. The sample at An_{48} appears to have an abnormally low temperature and can be raised by 5°C within experimental error.

Figure 4. A calculated 5-kbar *T-X* phase diagram to show the thermal effect of saturating the feldspars with fayalite. The anorthite temperature is taken directly from the ternary diagram (Figure 1) and is not of petrologic interest. The implied azeotropic minimum at 1,010°C is the 5-kbar endpoint of the Kiglapait fractionation history reported in Morse and Brady (in review) representing the terminal reaction liquid = feldspar (cryptoperthite) + olivine + ferrohedenbergite + apatite + ilmenite. The temperature plotted at Ab is that of the fayalite - saturated binary minimum at $X_{Or} = 1/3$ on the Ab-Or sideline, calculated as described in the text. The final liquid owes its An-rich composition to the presence of the Ca-Al-Fe pyroxene known from experiment

484 to have lost Al to feldspar during cooling (Morse and Ross, 2004). The temperature drop of 56℃
485 recalls Bowen's (1945) "plagioclase effect" in which it is understood that no pure albite can
486 crystallize from a magma containing Ca. Abbreviation: Ap, Azeotropic point.
487
488 **Figure 5**. The system Olivine - Plagioclase at 5 kbar, in oxygen units, contoured in X_{Mg}. The
489 heavy line nearest the OL corner is the cotectic for the system Fa-Ab-An, converted from Figure
490 2. The lowermost cotectic line is that for the system Fo-An-Ab (Schairer & Yoder, 1967),
491 recalculated to 5 kb, and the intervening lines of variable X_{Mg} are interpolated. The arrows
492 shown for the Kiglapait (KI) and Skaergaard (SKD) Intrusions are net LIQUIDUS paths between
493 the endpoints, taken from Morse et al. (2004) and Morse (1981) in the first case, and from
494 McBirney & Naslund (1990) and Wager & Brown (1968) in the second case. The fractionation
495 paths of the layered intrusions are taken as guides to magma evolution in general in this
496 composition space. The notation "-*P*" with arrow signifies decompression. The vertical line at
497 An_{50} is simply a guide to the eye.
498
499 **Figure 6**. (A) Ternary plot of olivine + hypersthene (OLHY), feldspar (FSP), and augite (AUG)
500 referred to a weight ferrous ratio $FeO/(FeO+Fe_2O_3) = 0.9$. The solid line is the experimental
501 cotectic trace of liquid + Ol + Pl for the Lower Zone of the Kiglapait intrusion (Morse et al.,
502 2004), from an initial composition at 5.2% AUG to saturation with augite at 24.5% AUG. The
503 cross marked IBZ is the average of three rock compositions from the Kiglapait Inner Border
504 Zone. The solid circles (KI SY) are the compositions of the six uppermost syenites in the
505 intrusion (Morse, 1981); the red dot is the average of the two uppermost samples. MORB
506 compositions are plotted to illustrate their near-saturation with augite; the upper symbol is a glass
507 from Grove et al. (1992); the lower symbol is the average of 155 Atlantic glasses from Bryan et
508 al. (1976). Compositions of average syenite and trachyte are from Le Maitre (1976). The
509 Gardar SY is an average of 8 Kûngnât syenites from Watt (1966). The symbol SYB refers to the
510 Sybille monzosyenite, Wyoming, from Table 2 of Fuhrman et al. (1988). The arrow labeled
511 MELTS shows the calculated result of feldspar fractionation from a saddle syenite composition
512 in Tugtutôq Central Complex of South Greenland (Upton et al. 1990, Table 2). The end of the
513 arrowhead denotes the premature appearance of olivine in the calculation. (B) Compositions of
514 syenite and trachyte in terms of feldspar end members An and Or, plotted against Mg number;
515 abbreviations as in (A).

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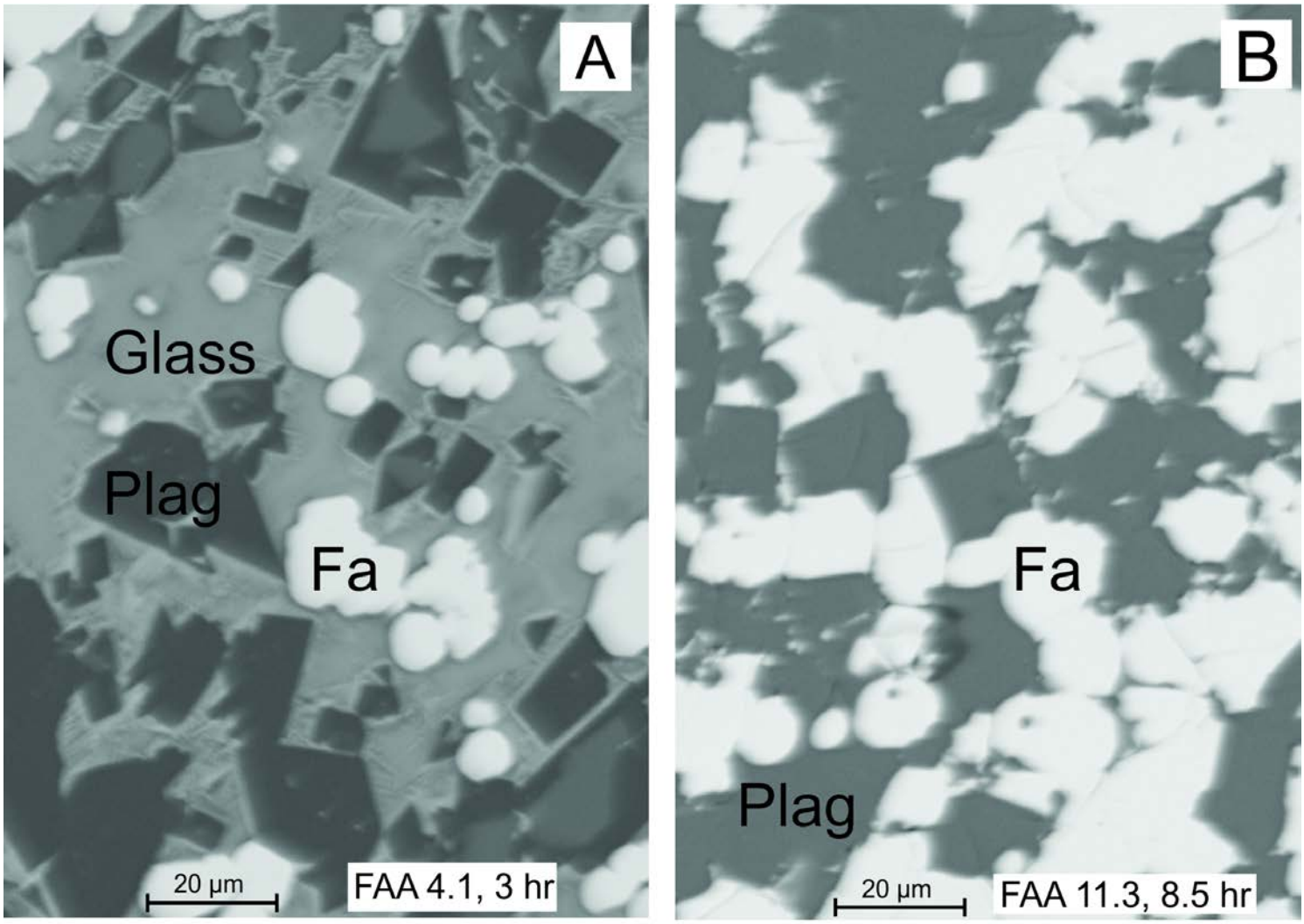

FAA SEM 1

Morse-Brady Fig. 1

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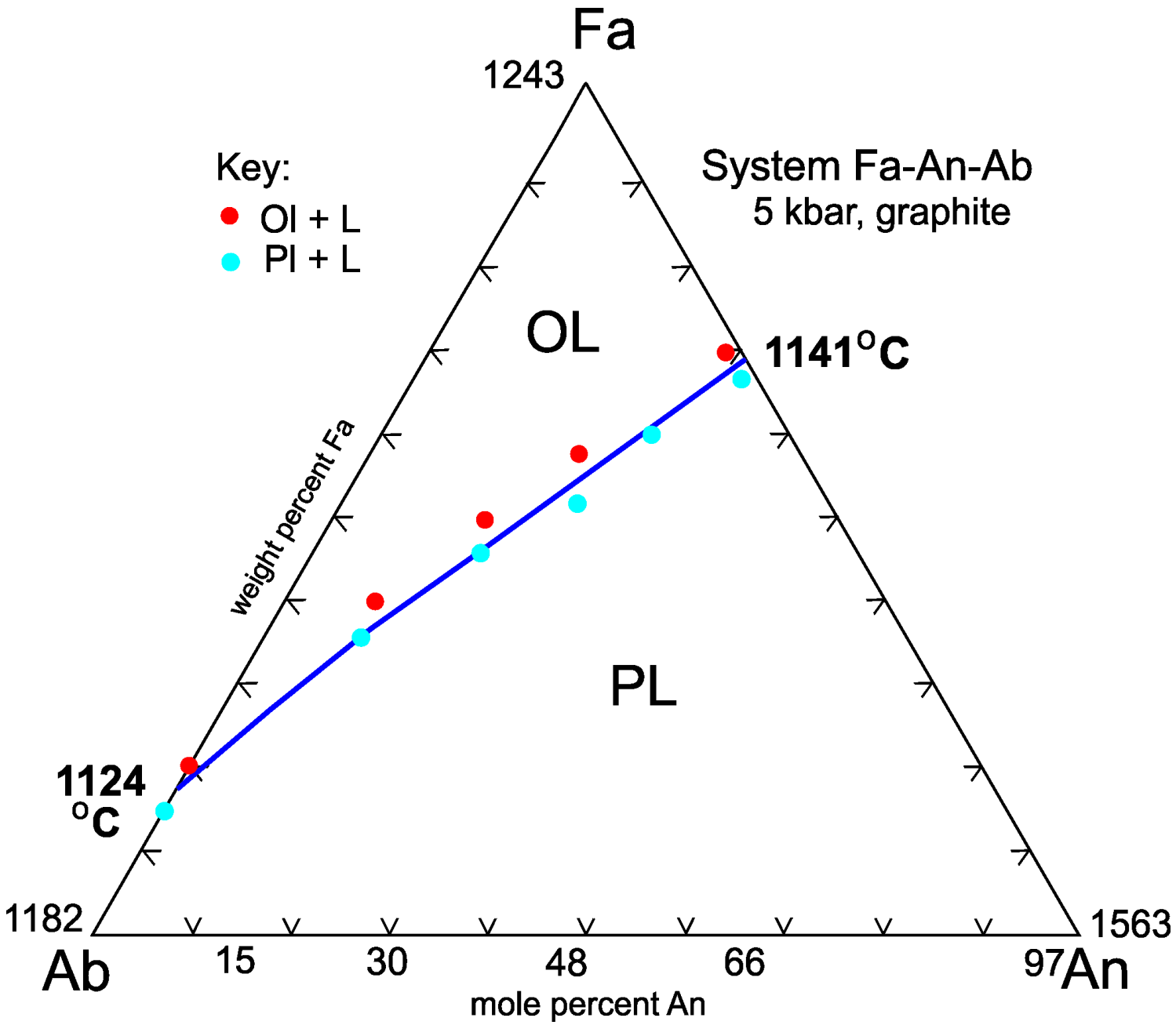

Morse-Brady Fig. 2
"Color online"

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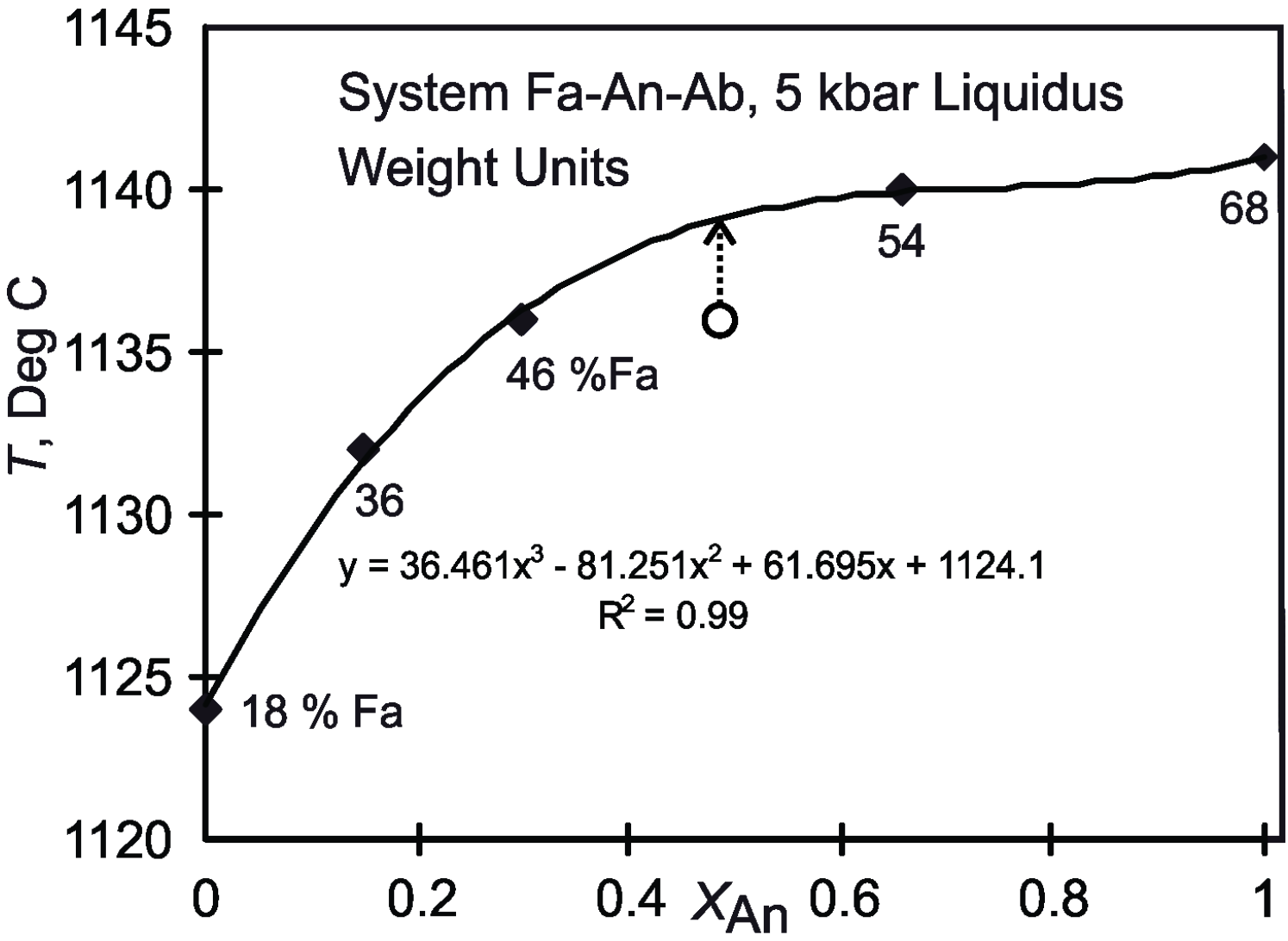

FaAnAb 09 15

Morse-Brady Fig. 3

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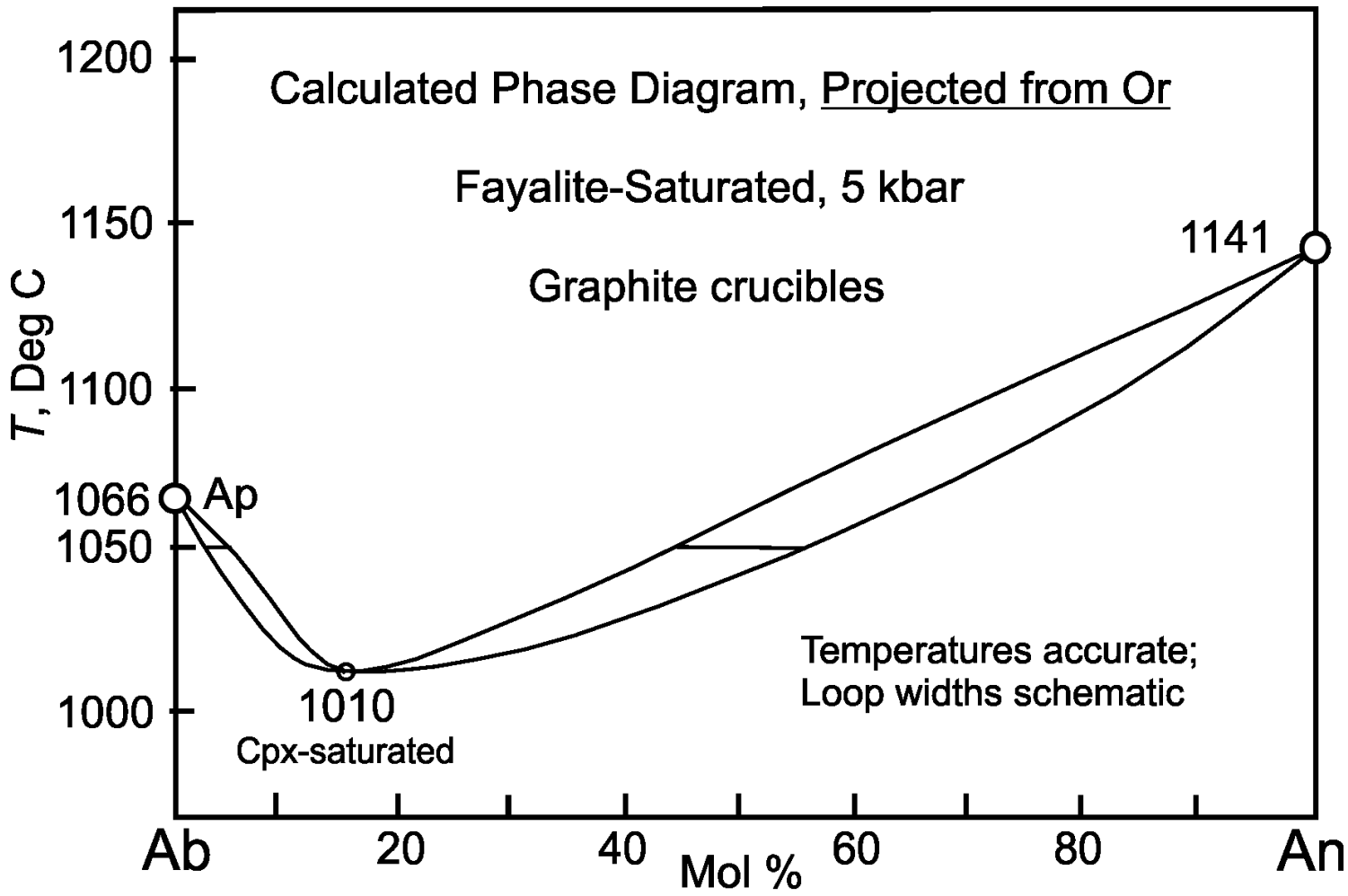

Conc Ph Diag 3
9 Feb 16

Morse-Brady Fig. 4

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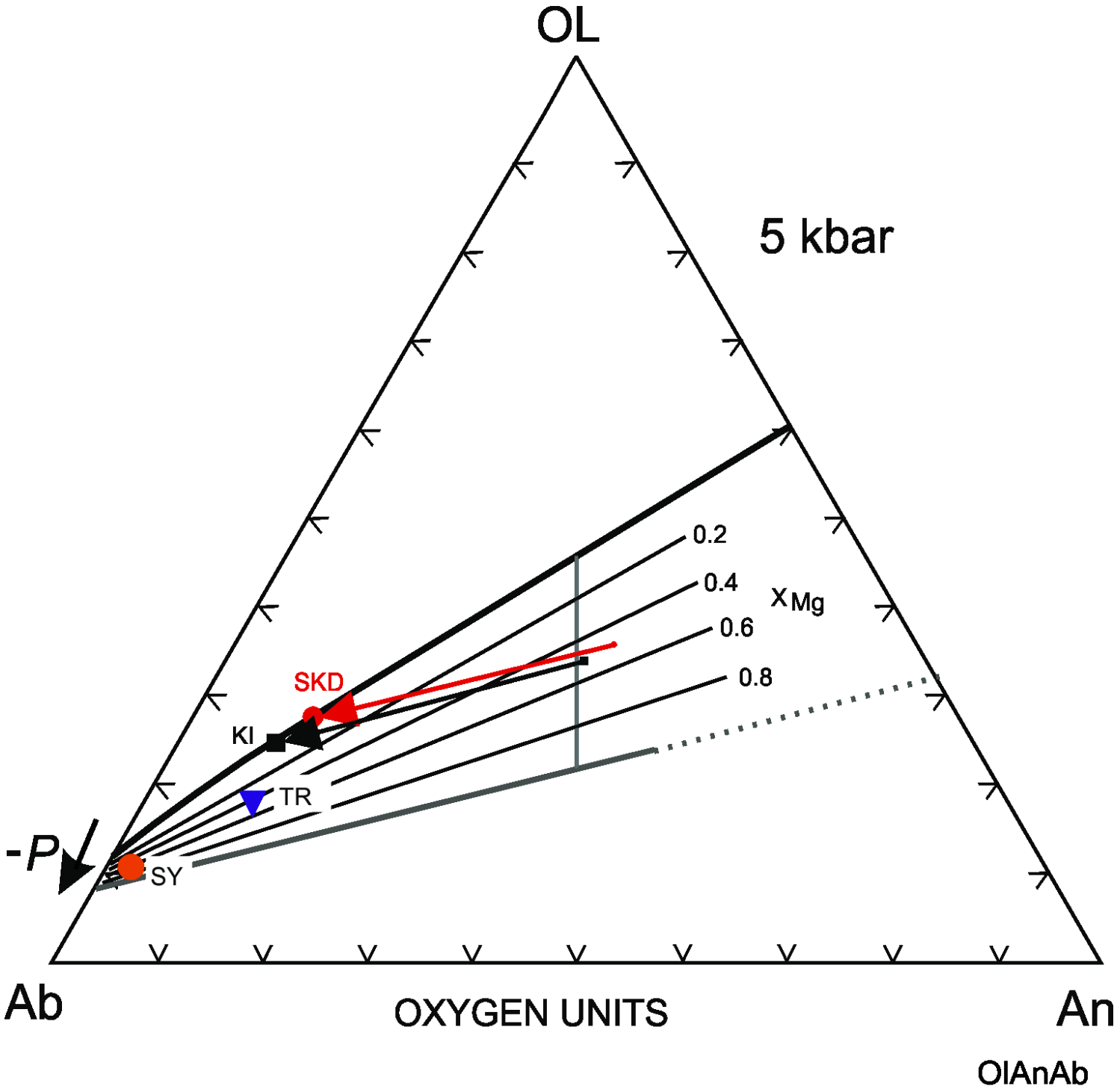

Morse-Brady Fig. 5
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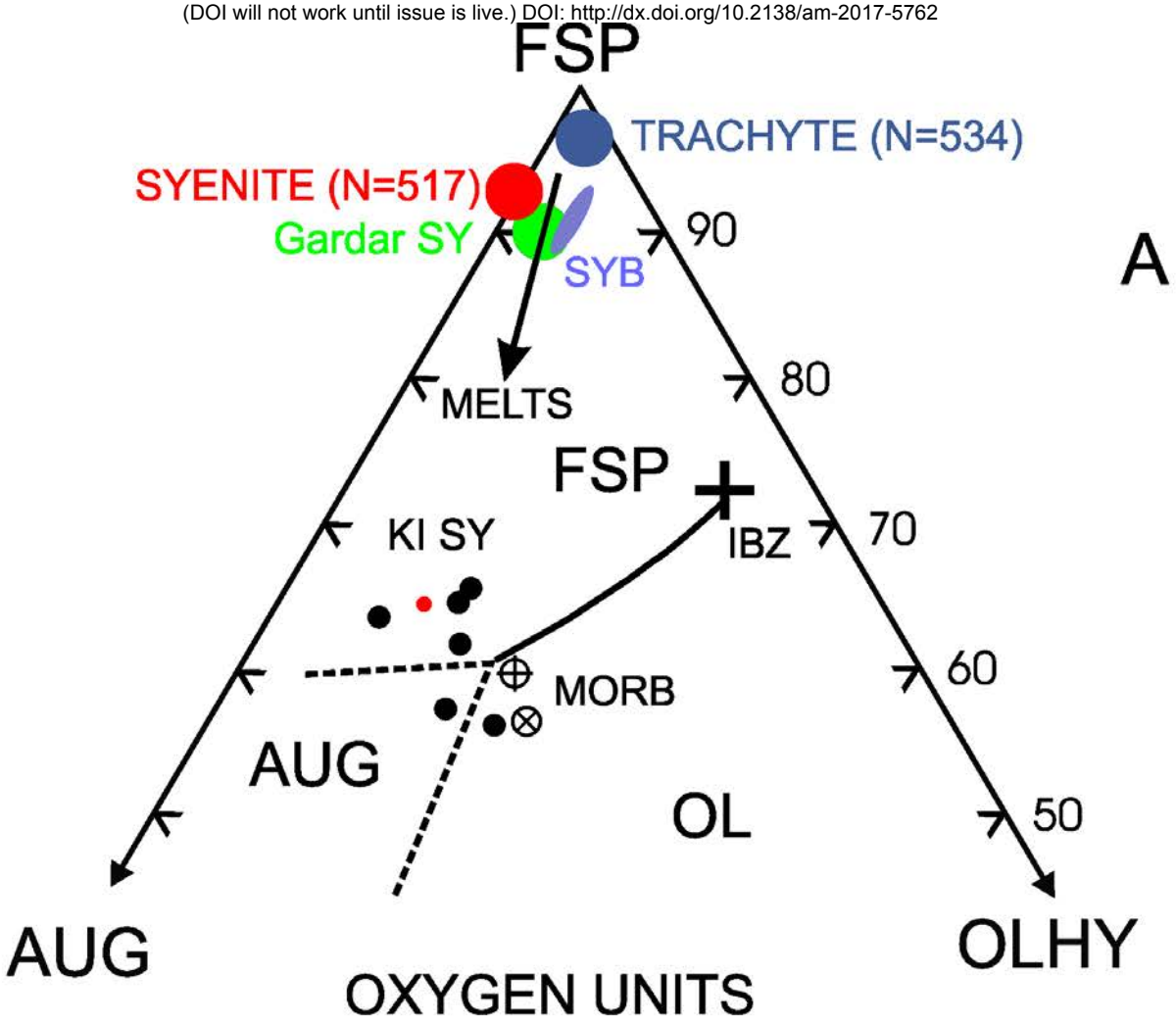

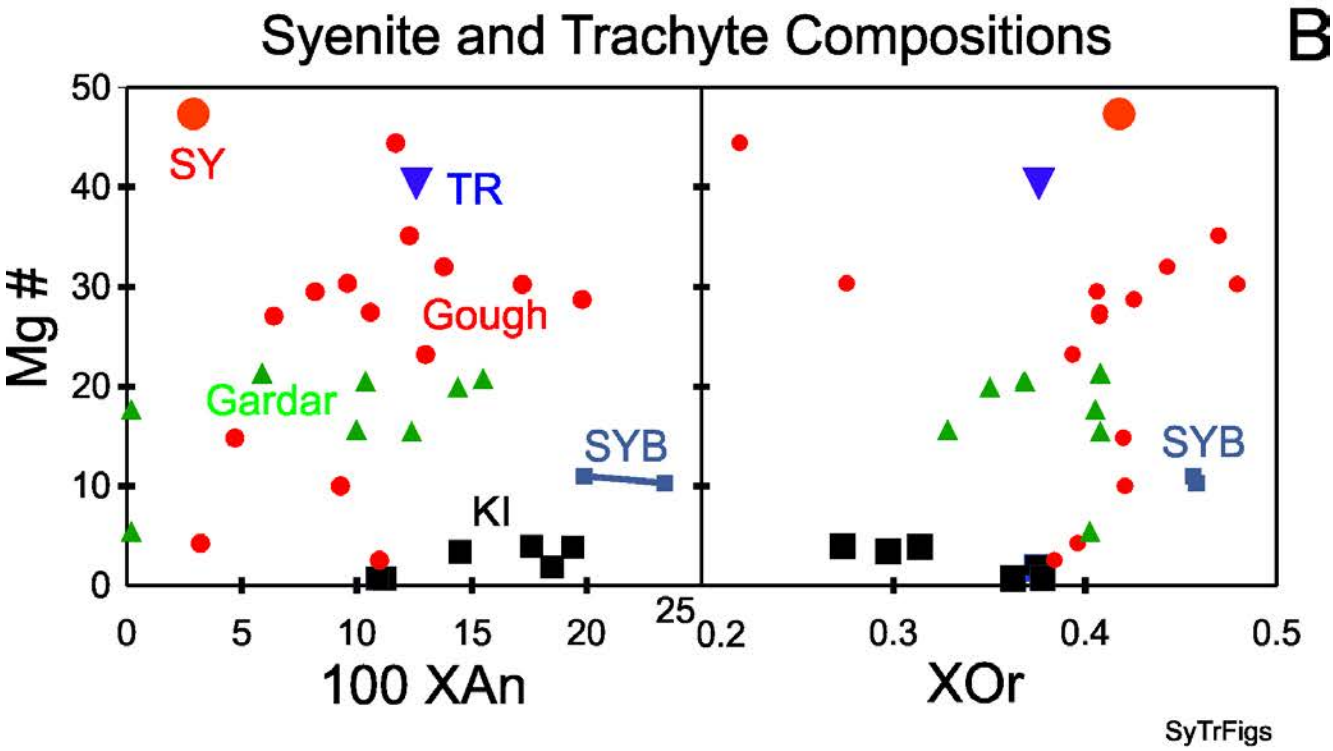

Morse-Brady Fig. 6
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Table 1. System Fa-An-Ab

Measured starting compositions, from oxygen norms.

Starting Material:						
	Amelia	An+Ab	An+Ab	KI 3369	KI 3645	KI 2072
Composition Target	An 0	An 15	An 30	An 48	An 66	An 97
Expected An	0.47	15	30	48.3	66.1	97
Probe result	0.47	14.8	30	48.5	66.2	97
	Crystal	Glass	Glass	Crystal	Crystal	Crystal

Table 2. Electron microprobe compositions of starting materials

		(Normalized to 100)					
Sample:	Fayalite	Amelia	An 15*	An 30*	An 48.3	An 66.1	KI 2072
SiO2	29.48	68.24	64.27	60.26	56.04	41.51	41.1
TiO2	0	0	0	0	0.08	0.08	0
Al2O3	0	19.48	22.03	24.8	27.86	30.71	37.1
Fe2O3	0	0	0	0	0.09	0.25	0
FeO	70.52	0	0.05	0.09	0.25	0.15	0.28
MgO	0	0	0	0	0.06	0.14	0
CaO	0	0.10	3.25	6.44	9.6	13.21	21.3
Na2O	0	12.03	10.17	8.3	5.67	3.74	0.35
K2O	0	0.15	0.13	0.1	0.34	0.21	0
Total	100	100	100	100	100	100	100
An, Mol %	0	0.5	15	30	48.3	66.1	97.0

Samples with * are mixtures of Amelia albite and An 97

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Table 3. Bulk Compositions of experiments

BC	%	%	Plag		Ternary		
#	Fa	Plag	Name	XAn	An	Ab	Or
Amelia		100	Am	0.005	0.0047	0.9872	0.0081
KI 3369pl		100	An48	0.483	0.474	0.506	0.020
KI 3645pl		100	An66	0.661	0.653	0.335	0.012
KI 2072pl		100	An97	0.970	0.970	0.030	0
An15		100	An15	0.146	0.146	0.854	0.007
An30		100	An30	0.291	0.291	0.709	0.006
BC1	15	85	Am	0.005	0.004	0.846	not calc
BC2	25	75	Am	0.005	0.004	0.746	--do--
BC3	40	60	An48	0.483	0.290	0.310	–etc--
BC3a	36	64	Am	0.005	0.003	0.637	
BC3b	55	45	An48	0.483	0.217	0.233	
BC4	36	64	An15	0.015	0.010	0.630	
BC4a	36	64	An15	0.015	0.010	0.630	
BC5	46	54	An30	0.03	0.016	0.524	
BC5a	46	54	An30	0.03	0.016	0.524	
BC6	58	42	An48	0.483	0.203	0.217	
BC7	60	40	An66	0.661	0.264	0.136	
BC8	67	33	An97	0.97	0.320	0.010	
BC9	70	30	An97	0.97	0.291	0.009	
BC10	40	60	An15	0.146	0.088	0.512	
BC11	50	50	An30	0.291	0.146	0.355	
BC12	20	80	Am	0.005	0.004	0.796	
BC13	53	47	An48	0.483	0.227	0.243	
BC14	17	83	Am	0.005	0.004	0.826	
BC15	10	90	Am	0.005	0.005	0.896	

 # Experiments An 15, 2; An30, 2; An 48, 4; An 66, 1; An 97, 2

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Table 4: Two electron probe results in the system Fa-An-Ab

	Exper # FAA 4.1						Exper # FAA 11.3				
	OLIVINE	SD	PLAGIO-CLASE	SD	GLASS	SD	OLIVINE	SD	PLAGIO-CLASE	SD	OL(4) - OL(11)
SiO2	31.03	0.41	63.34	0.36	52.31	0.26	30.94	0.30	50.01	1.10	0.09
TiO2	0.01	0.01	0	0	0.00	0.00	0.00	0.00	0.03	0.02	0.01
Al2O3	0.12	0.20	22.42	0.49	14.70	0.34	0.12	0.13	30.76	0.91	0.00
FeO	68.52	0.58	1.57	0.84	25.53	0.66	68.40	0.64	1.70	0.86	0.12
MgO	0.13	0.02	nd		0.02	0.01	0.13	0.01	nd		0.00
CaO	0.20	0.05	3.31	0.34	2.12	0.33	0.40	0.04	13.54	0.94	-0.20
Na2O	nd		9.81	0.13	5.36	0.33	nd		3.81	0.49	
K2O	nd		0.05	0.01	0.03	0.01	nd		0.15	0.04	
Sum	100.00*	0.37	100.5		100.20		100.00**		100.00***		
N	12		8		12		12		12		
					P2O5 0.04						
	Fo 0.03		**An 15.7**		**An 17.7**				**An 66.2**		

(*) normalized from 101.00
(**) normalized from 100.89
(***) normalized from 99.13
Note: Mn in olivine = 0.00

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Table 5. System Fayalite-Albite-Anorthite, 5 kbar

Comp	% Fa	Run	*T* deg C	% OL	% PL	% Glass		Interpreted Result
An 0	15	1.1	1120	0	10	90		
	25	2.1	1125	0	1	99		**LIQUIDUS 1124**
	25	9.1	1125	25	1	74		
	20	10.1	1125	25	10	65		
An 15	36	4.1	1120	30	20	50		**LIQUIDUS 1132**
	36	6.1	1130	2	0	98		
	36	10.2	1125	40	10	65		
	40	9.2	1125	40	0	60		
An 30	46	4.2	1120	35	25	40		**LIQUIDUS 1134**
	46	7.1	1135	0	0	100		
	50	9.3	1125	50	0	50		
	46	10.3	1125	45	25	30		
	46	11.1	1128	45	10	45	T?	
	46	12.2	1133	40	30	30		
An 48	40	1.3	1120	0	50	50		**LIQUIDUS 1136?**
	40	3.3	1122	0	40	60		
	58	6.3	1130	1	0	98		
	58	7.2	1135	0	0	100		
	53	11.2	1128	60	40	0		
	53	12.3	1133	50	50	0		
An66	60	8.1	1140	0	0	100		**LIQUIDUS 1138?**
	60	11.3	1128	70	30	0		
An 97	67	8.2	1140	0	4	96	T>1140	**FaAn 1141**
	70	8.3	1140	30	5	45		