

Beginning of melting in the granite system $Qz - Or - Ab - An - H_2O$

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Abstract. The beginning of melting in the system $Qz - Or - Ab - An - H_2O$ was experimentally reversed in the pressure range $P_{H_2O} = 2-15$ kbar using starting materials made up of mixtures of quartz and synthetic feldspars. With increasing pressure the melting temperature decreases from $690^\circ C$ at 2 kbar to $630^\circ C$ at 17 kbar in the An-free alkalifeldspar granite system $Qz - Or - Ab - H_2O$. In the granite system $Qz - Or - Ab - An - H_2O$ the increase of the solidus temperature with increasing An-content is only very small. In comparison to the alkalifeldspar granite system the solidus temperature increases by $3^\circ C$ ($7^\circ C$) if albite is replaced by plagioclase An 20 (An 40). The difference between the solidus temperatures of the alkalifeldspar granite system and of quartz - anorthite - sanidine assemblages (system $Qz - Or - An - H_2O$) is approximately $50^\circ C$.

With increasing water pressures plagioclase and plagioclase-alkalifeldspar assemblages become unstable and are replaced by zoisite + kyanite + quartz and zoisite + muscovite-paragonite_{ss} + quartz, respectively. The pressure stability limits of these assemblages are found to lie between 6 and 16 kbar at $600^\circ C$. At high water pressures (10–18 kbar) zoisite - muscovite - quartz assemblages are stable up to 700 and $720^\circ C$. The solidus curve of this assemblage is $10-20^\circ C$ above the beginning of melting of sanidine - zoisite - muscovite - quartz mixtures.

The amount of water necessary to produce sufficient amounts of melt to change a metamorphic rock into a magmatic looking one is only small. In case of layered migmatites it is shown that 1% of water (or even less) is sufficient to transform portions of a gneiss into (magmatic looking) leucosomes. High grade metamorphic rocks were probably relatively dry, and anatexitic magmas of granitic or granodioritic composition are usually not saturated with water.

cur by partial melting within deeper parts of the continental crust.

Tuttle and Bowen mention that average granites contain less than 10% of normative constituents other than Ab, Or, and Qz. They therefore conclude that the equilibrium relations determined in this system will yield information directly applicable to the granite problem.

According to Winkler (1979) it is absolutely necessary to consider the anorthite component present in the plagioclase of gneisses and granites when dealing with problems of gneiss anatexis. Winkler emphasizes that small contents of An-component have a pronounced effect on the solidus temperatures and on the composition of cotectic melts.

Winkler and v. Platen (1958, 1960, 1961) investigated the beginning of melting and the development of melt compositions in gneisses and crystalline schists during high grade metamorphism. The solidus temperatures increase dramatically (according to Winkler, 1979, see also v. Platen 1965) with increasing An-content of the involved plagioclases. The close relationship between plagioclase composition, solidus temperatures, and melt composition is one important finding in the papers of Winkler (1966, 1979) explaining the formation of migmatites and subsequent melts of granitic composition. The problem to explain the plagioclase compositions of migmatite layers by the results of hitherto known melting experiments is discussed by Mehnert (1971) and more recently by Mehnert and Büsch (1982).

Experimentally determined solidus conditions are used to map out metamorphic temperatures. But it will be shown that only under special and ideal circumstances (e.g. eutectic rock composition and surplus of water) can temperatures and pressures of a solidus determined in the laboratory be related unequivocally to field observations. The knowledge of solidus temperatures and pressures are the most important parameters needed to evaluate partial melting as a rock forming process.

There are clear-cut solidus data for the system $Qz - Or - Ab - H_2O$ (Tuttle and Bowen 1958; Luth et al. 1964; Huang and Wyllie 1975) but not for the more pertinent system $Qz - Or - Ab - An - H_2O$. The solidus temperatures given by Johannes (1980a) for $P_{H_2O} = 5$ Kbar do not correspond very well with the 2 kbar data of Winkler and v. Platen (1958, 1960, 1961) and v. Platen (1965). The construction of a complete set of solidus curves for different plagioclase (and alkalifeldspar) compositions seems to be necessary and overdue and is presented in this paper.

Introduction

One of the most exciting contributions in the field of experimental petrology is that of Tuttle and Bowen (1958) dealing with the origin of granite in the light of experimental studies in the system $NaAlSi_3O_8 - KAlSi_3O_8 - SiO_2 - H_2O$. Tuttle and Bowen showed that melts of alkalifeldspar granite composition can be formed at high water pressures below $700^\circ C$. It was immediately obvious that the generation of migmatites and magmas of granitic composition could oc-

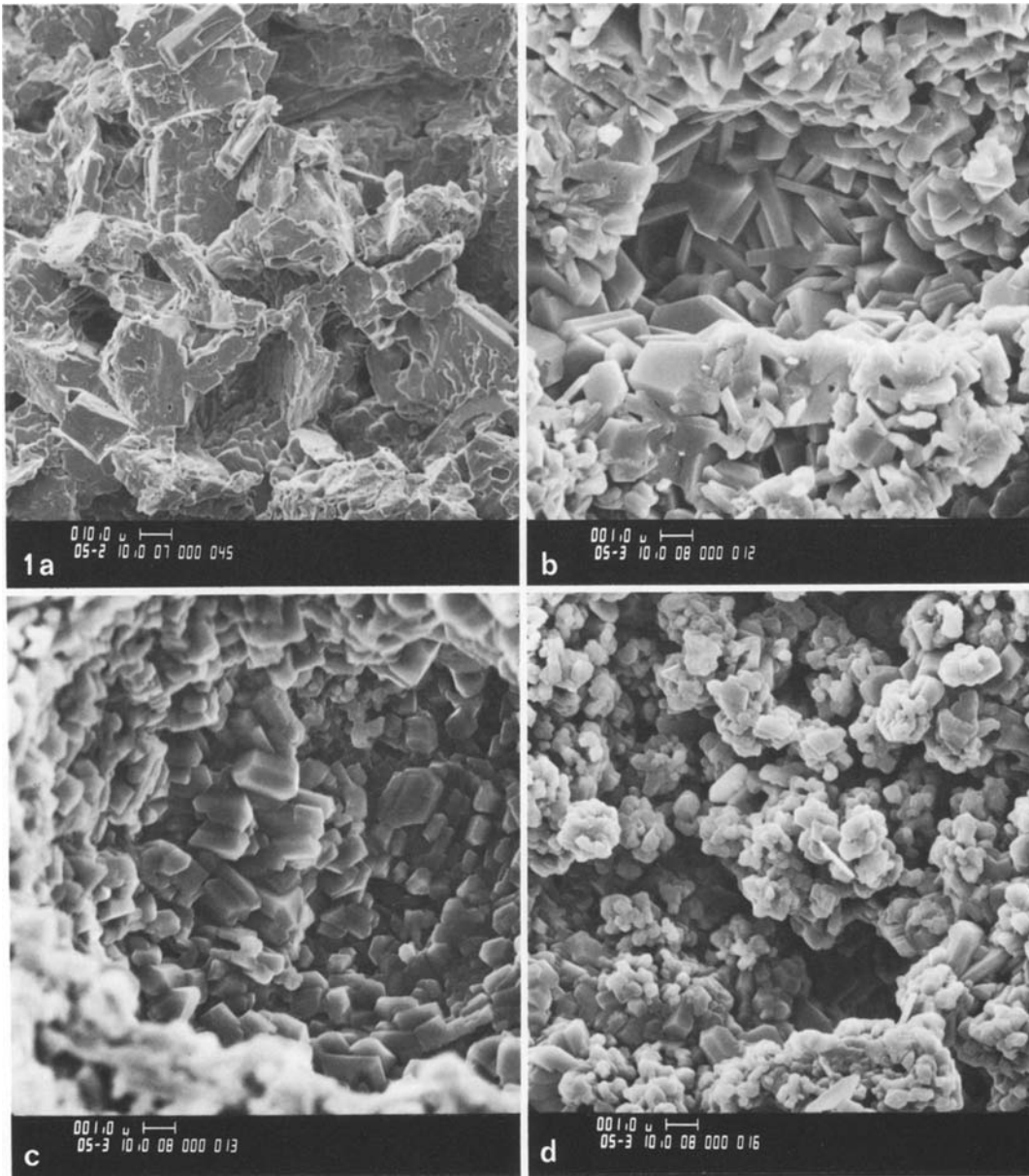


Fig. 1 a–d. SEM photographs of products and starting materials **a** alkali feldspar Or65 **b** plagioclase An00 **c** plagioclase An30 **d** plagioclase An100

Experimental methods

Hydrothermal apparatus

All runs up to 7 kbar (also those needed to prepare crystalline starting materials from glasses or gels) were performed in cold-seal pressure vessels of Tuttle type (Tuttle 1948). The pressure was measured by strain gauges manufactured in our machine shop and calibrated at the Physikalisch-Technische Bundesanstalt, Braunschweig. The accuracy of these instruments is better than ± 20 bar. Each pressure vessel used in the experiments was equipped with a strain gauge instrument in order that the run pressures could be controlled and recorded continuously. The pressures quoted are accurate to within ± 100 bar.

Piston-Cylinder apparatus

High pressure runs ($P \geq 7$ kbar) were performed in a piston-cylinder apparatus similar to that described by Johannes (1973). All the parts surrounding the samples consisted (except the thermocou-

ple and the graphite heater) of bone-dry rock salt. In all high pressure runs the instroke technique was used. The nominal pressure was kept constant within a range of 0.2 kbar just above the given nominal (=sample) pressure. The pressure accuracy of the piston-cylinder runs is believed to be better than ± 0.5 kbar.

Temperature measurement

The temperatures of both hydrothermal and piston-cylinder runs were measured with NiCr-Ni thermocouples and given in $^{\circ}\text{C}$. These are believed to have an absolute accuracy of $\pm 1\%$.

Run time

The run times of all melting experiments for determining the solidus temperature were 16 to 24 h. The run times of reversals were 3 to 4 weeks. At low temperatures (around 400°C) run durations up to six months were needed in order to achieve relatively narrow brackets.

Quenching procedure

In case of the melting experiments, the runs were quenched by reducing the pressure abruptly to one or two kbar (at least one) and subsequently reducing the temperatures to below 500° C within a few seconds. In the case of reversal experiments, the starting mixture was partly melted at temperatures between the solidus and the (estimated) liquidus curve at run pressure within 24 h. Thereafter the sample was brought down to run temperature while the run pressure was kept constant. The final quench was performed as described above.

Investigation of run products

The run products were X-rayed and optically investigated. The An-content of the plagioclases of the run products was determined with the help of the K-exchange method (Viswanathan 1972, see also Johannes 1978). The K-exchange was performed at 830° C in a KCl-melt for 1 h. The incoming of the first small amount of melt could not only be detected indirectly by the disappearance of quartz in the run products but also directly by observing small particles of glass with help of the scanning electron microscope.

Starting materials

Synthetic plagioclases, alkali feldspars, 2 M₁-muscovite, orthorhombic zoisite, natural quartz (from Göschenen, Switzerland), and natural kyanite (Brunsville, North Carolina) were used to prepare the starting mixtures. The experimental details for the synthesis of muscovite and zoisite, in addition to scanning electron microscope photographs and crystallographic data for these minerals are given by Chatterjee and Johannes (1974) (for muscovite) and by Storre et al. (1982) (for zoisite).

The feldspars were synthesized from gels at 800° C and P_f = 2 kbar in 6–8 day runs. They are almost completely disordered (see Table 1 and 2). The average grain size of the synthetic plagioclases is around 1 µm and that of the alkali feldspars up to 10 µm (Fig. 1).

Starting mixtures

In order to have a near equilibrium composition in the starting mixtures for the melting experiments, plagioclases and alkali feldspars of appropriate compositions were chosen; these are given in Table 3.

All starting mixtures (for melting experiments with feldspars) contained equal quantities of plagioclase and alkali feldspar (or of an Ab-rich plus Or-rich alkali feldspar). The amount of quartz was 6 wt%. The slight quartz admixture allows detection of small amounts of melt by X-rays (Johannes 1978).

The feldspar compositions used in the starting mixtures do not exactly correspond with the ternary feldspars stable at the given run conditions. In order to approach more precisely the stable mineral compositions both feldspars were prepared from gels of the appropriate ternary composition. These gels were crystallised at 700° C and P_{H₂O} = 2 kbar in 8 day runs. The composition of the ternary feldspars was checked by measuring the position of the (201) X-ray peak of the unexchanged and that of the KCl-exchanged feldspars (Viswanathan 1972, Orville 1963, Johannes 1979).

In both types of starting mixtures the beginning of melting could be observed at the same temperature. In this paper only the data of runs with binary feldspars are presented because the determination of synthetic ternary feldspar compositions is complicated and not yet totally convincing.

Experimental results

Solidus temperatures of the alkali feldspar system Qz–Or–Ab–H₂O

The solidus temperatures determined with mixtures of 2 alkali feldspars plus quartz (for composition of starting

Table 1. Plagioclases crystallized from gels at 800° C, P_{H₂O} = 2 kbar in 6–8 days

| Composition in mol% An | 2 θ 131 – 2 θ 13̄1 | 2 θ 241 – 2 θ 24̄1 (CuK α radiation) |
|---------------------------|--------------------|---|
| 0 | 1.84 | 0.38 |
| 20 | 1.85 | 0.32 |
| 40 | 1.91 | 0.28 |
| 50 | 1.92 | 0.19 |
| 70 | 2.07 | 0.02 |
| 80 | 2.10 | –0.08 |
| 100 | 2.25 | –0.35 |

Table 2. Alkali feldspars crystallised from gels at 800° C, P_{H₂O} = 2 kbar in 6–8 days

The occupancy of the t₁-sites with Al is calculated according to the equation

$$2 t_1 = 8.369 + 0.6773 \times 2 \theta (060) - 0.7068 \times 2 \theta (204)$$

Cu K α radiation (H. Kroll pers. comm.)

| Or | 2 t ₁ |
|-----|------------------|
| 20 | 0.57 |
| 60 | 0.58 |
| 70 | 0.60 |
| 80 | 0.58 |
| 100 | 0.60 |

Table 3. Alkalifeldspar-plagioclase pairs combined in starting mixtures for melting experiments with plagioclases of intermediate compositions (and with pure An)

An20Ab80 + Or70Ab30
An40Ab60 + Or80Ab20
An50Ab50 + Or85Ab15
An70Ab30 + Or90Ab10
An80Ab20 + Or90Ab10
An100 + Or100

Alkalifeldspar pairs combined in starting mixtures for melting experiments in the system Qz–Ab–Or–H₂O

Or05Ab95 + Or85Ab15 (for 15 kbar)
Or05Ab95 + Or75Ab25 (for 10 kbar)
Or10Ab90 + Or65Ab35 (for 5 and 7 kbar)
Or20Ab80 + Or60Ab40 (for 3 kbar)

For the 2 kbar runs an alkali feldspar of Or30Ab70 composition was used

minerals and mixtures see Tables 1–3) are presented in Fig. 2. For comparison the data of Tuttle and Bowen (1958), and Luth et al. (1964) are also given.

The difference between the previous and the new data is ±5° C, and thus well within the margin of error. The systematic differences shown in Fig. 2 are probably due to differences in the temperature calibrations and not to different chemical compositions or structural states of the feldspar starting materials. In Fig. 7 only the new data of this paper are shown in order to have a precise internal comparison with the curves for mixtures including plagioclases of intermediate composition.

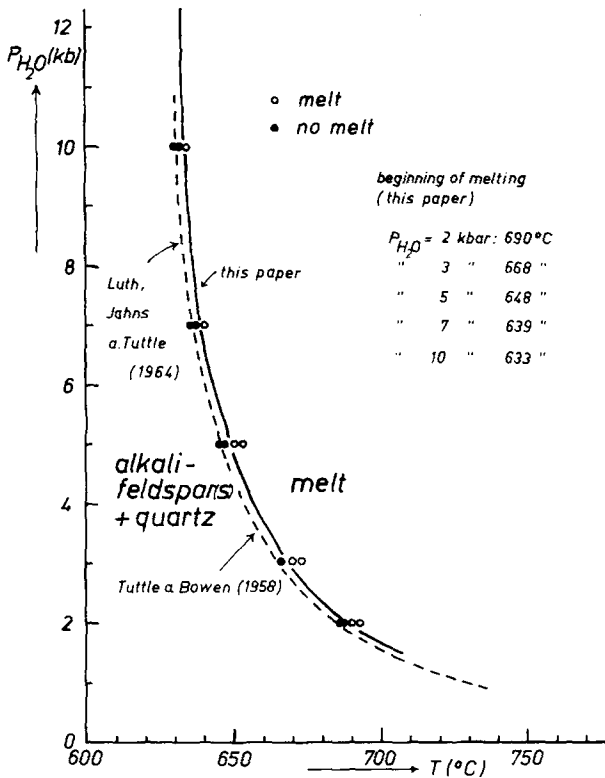


Fig. 2. Solidus boundary curve of the system $Qz-Or-Ab-H_2O$. For comparison the data of Tuttle and Bowen (1958) and Luth, Jahns and Tuttle (1964) are also shown

Solidus temperatures of the system $Qz-Or-An-H_2O$

The solidus curve of the system $Qz-Or-An-H_2O$ was given by Johannes (1980a) and later confirmed by Schliestedt and Johannes (1984). New data about melting reactions occurring at higher pressures and including zoisite and muscovite are also given by Schliestedt and Johannes (1984).

Solidus temperatures in the granite system $Qz-Or-Ab-An-H_2O$

The low pressure ($P \leq 5$ kbar) data points in Fig. 7 are from the isobaric T-X sections shown in Figs. 3-5. At higher pressures additional runs were accomplished with mixtures containing a pure anorthite, albite, or a plagioclase rich in albite.

The solidus temperatures at 2 kbar

Solidus temperatures and the projection of the liquidus boundary curve for cotectic compositions are shown in Fig. 3. In addition to my own results the data of previous investigations are given. The solidus temperatures presented by Winkler and v. Platen (1961) were determined with 4 metagraywackes of different composition, but all containing quartz, alkali feldspar, plagioclase, biotite, cordierite, opaques, and some also sillimanite. The data of Winkler and v. Platen are also given in table 18-6 of Winkler's book (1979), with some corrections applied.

Besides solidus temperatures and compositions of cotectic melts, the composition of plagioclases coexistent with

Ab-rich melts are also determined by Winkler and v. Platen (for experimental details and determination of plagioclases in synthetic magmas see Winkler and v. Platen). The data of Winkler (1979) and Winkler and v. Platen (1961) indicate a considerable increase of the solidus temperature with increasing An content of the plagioclases. This observation is very different from the data given in the present paper (Figs. 3 and 7).

The beginning of melting in the system $Qz-Or-Ab-H_2O$ as determined by Tuttle and Bowen (1958) and the eutectic temperature of the system $Qz-Or-An-H_2O$ (Winkler and Lindemann 1972) are also indicated in Fig. 3. The liquidus temperatures of cotectic compositions (shown as a liquidus boundary curve projected on to the Ab-An join) are estimated. Because of "metastable" melting of mixtures with plagioclases of intermediate composition the stable liquidus boundary curve cannot be determined (Johannes 1978, 1980a). Complete melting occurs below stable melting conditions. It is estimated that the stable liquidus temperatures are 0-10° C (0° at the ends and 10° at the middle of the Ab-An join) above the temperature where complete melting of a cotectic mixture is observed experimentally.

The solidus temperatures at 3 and 5 kbar

The data bracketing the solidus temperatures for mixtures with An0, An20, An40, An50, An70, An80, and An100 at $P_{H_2O} = 3$ and 5 kbar are presented in Figs. 4 and 5.

Reversal experiments were performed with the starting mixture An50 + Or85 + quartz at $P_{H_2O} = 5$ kbar and with the mixture An70 + Or90 + quartz at $P_{H_2O} = 3$ kbar. Initially partial melts were produced a few degrees above the solidus. Afterwards the temperature was lowered to the values shown in Figs. 4 and 5. This temperature was kept constant for 3 weeks.

The bracket between melting and crystallisation of quartz (+ alkali feldspar and plagioclase) is 10° C at 3 kbar and 8° C at 5 kbar. Run times shorter than three weeks were not chosen. It may be possible to achieve narrower brackets by applying run times of much longer duration. Melting of feldspar-quartz mixtures is much faster than crystallisation of partial melts and it is believed that the stable solidus temperatures are just below the temperatures indicating the first incoming of partial melts.

Reversibility of a hydrothermal experiment is a necessary condition but not sufficient to establish equilibrium. A further argument for equilibrium is the fact that the given solidus is connecting the eutectic points of the systems $Qz-Or-An-H_2O$ and $Qz-Or-Ab-H_2O$. The eutectic temperature of these two quarternary subsystems determined in the present paper agree well with those of Luth et al. (1964) and of Winkler and Ghose (1974).

Subsolidus reactins I: 2 zoisite + 1 muscovite + 2 quartz = 4 anorthite + 1 sanidine + H₂O,
II: 2 zoisite + 1 kyanite + 1 quartz = 4 anorthite + H₂O, and
III: plag₂ + zoisite + kyanite + quartz = plag₁ + H₂O

At high water pressures plagioclases and plagioclase-alkali feldspar assemblages are replaced by zoisite + quartz and by zoisite + muscovite + quartz. The assemblage K-feldspar + anorthite is the first assemblage to become unstable with increasing water pressure at a constant temperature. The data of reaction I ($An + Or + H_2O = Zo + Ms + Qz$) are

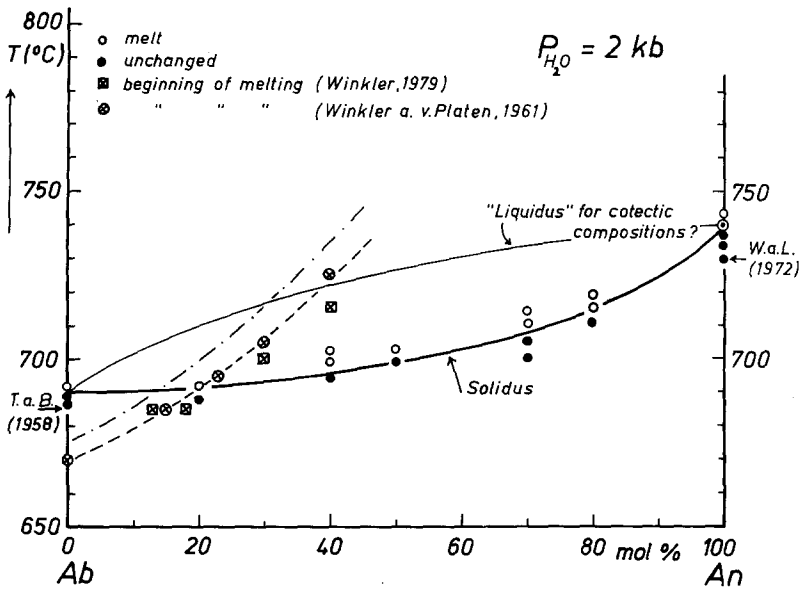


Fig. 3. $T-X_{An}$ diagram showing the composition of plagioclases coexisting with a cotectic melt in the system $Qz-Or-Ab-An-H_2O$ at $P_{H_2O}=2$ kbar. The An molefraction of the liquidus boundary curve is a projection from the Qz and Or apexes of the $Qz-Ab-An-Or$ tetrahedron. For comparison data of Winkler (1979) and Winkler and v. Platen (1961) are also given. Dashed-dotted curve: composition of plagioclases coexisting with cotectic melts as determined by Winkler and v. Platen (1961, p 59). T.a.B.: Tuttle and Bowen (1958), W.a.L.: Winkler and Lindemann (1972)

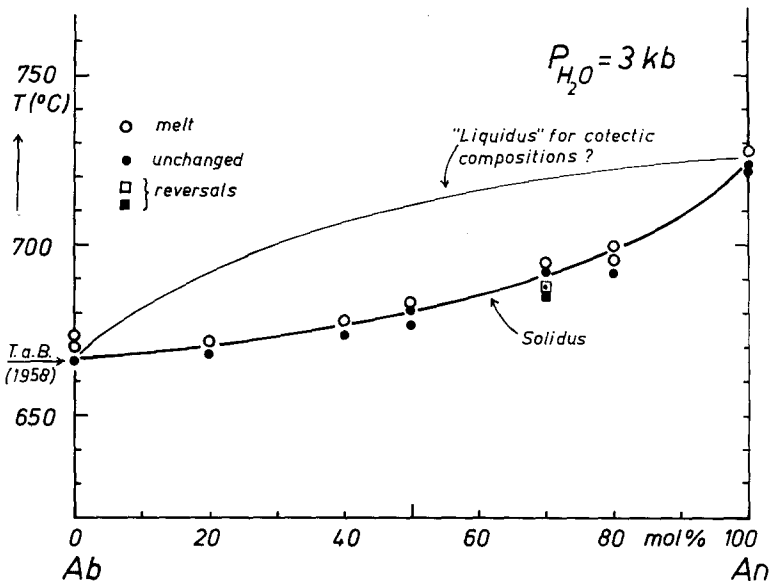


Fig. 4. $T-X_{An}$ diagram showing the composition of plagioclases coexisting with a cotectic melt in the system $Qz-Or-Ab-An-H_2O$ at $P_{H_2O}=3$ kbar. The An molefraction of the liquidus boundary curve is a projection from the Qz and Or apexes of the $Qz-Ab-An-Or$ tetrahedron

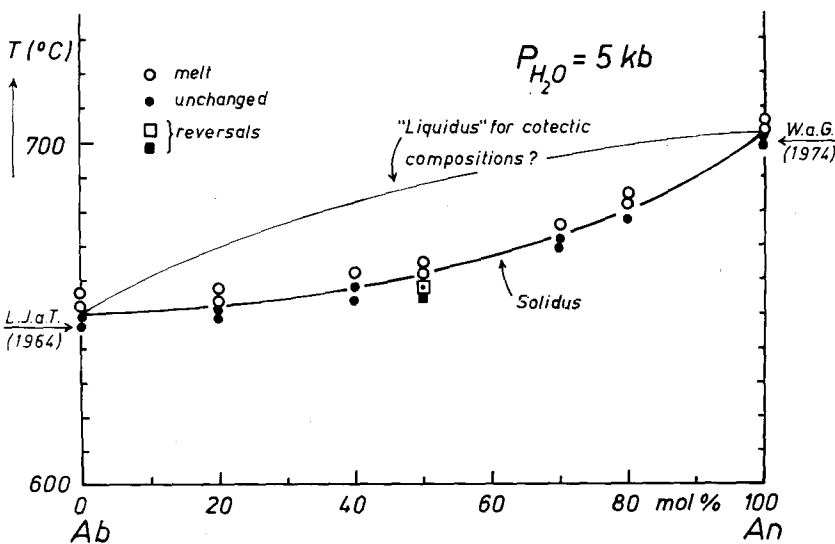
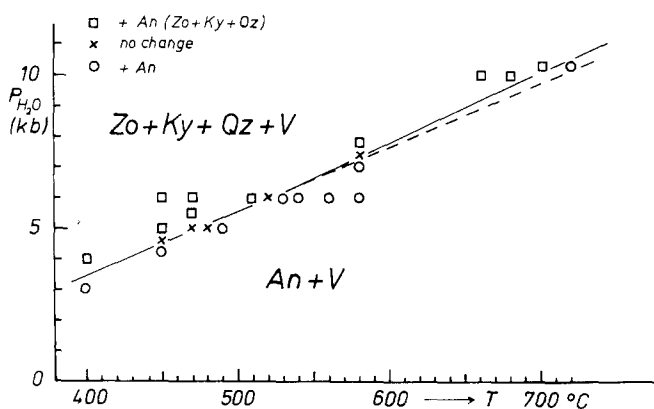


Fig. 5. $T-X_{An}$ diagram showing the composition of plagioclases coexisting with a cotectic melt in the system $Qz-Or-Ab-An-H_2O$ at $P_{H_2O}=5$ kbar. The An molefraction of the liquidus boundary curve is a projection from the Qz and Or apexes of the $Qz-Ab-An-Or$ tetrahedron. L.J.a.T.: Luth, Jahns and Tuttle (1964), W.a.G.: Winkler and Ghose (1974)

Table 4. Data for reaction $Zo + Ky + Qz = An + V$

| run # | T (°C) | P (kbar) | time (d) | result |
|-------|--------|----------|----------|-------------|
| 24 | 400 | 3.0 | 82 | + An |
| 1 | 400 | 4.0 | 90 | no An |
| 13 | 450 | 4.2 | 35 | + little An |
| 11 | 450 | 4.6 | 35 | unchanged |
| 2 | 450 | 5.0 | 60 | no An |
| 72 | 450 | 6.0 | 28 | no An |
| 4 | 470 | 5.0 | 60 | unchanged |
| 3 | 470 | 5.5 | 67 | no An |
| 73 | 470 | 6.0 | 28 | no An |
| 44 | 480 | 5.0 | 104 | unchanged |
| 51 | 490 | 5.0 | 112 | + An |
| 9 | 510 | 6.0 | 90 | no An |
| 5 | 520 | 6.0 | 46 | unchanged |
| 20 | 530 | 6.0 | 50 | + An |
| 17 | 540 | 6.0 | 68 | + An |
| 7 | 560 | 6.0 | 32 | + An |
| 8 | 580 | 6.0 | 32 | + much An |
| 21 | 580 | 7.0 | 7 | + little An |
| 22 | 580 | 7.4 | 7 | unchanged |
| 28 | 580 | 7.8 | 13 | less An |
| 25 | 660 | 10.0 | 50 | no An |
| 29 | 680 | 10.0 | 30 | less An |
| 23 | 700 | 10.3 | 8 | less An |
| 47 | 700 | 10.3 | 8 | less An |
| 46 | 720 | 10.3 | 14 | + An |
| 48 | 720 | 10.3 | 18 | + An |

**Fig. 6.** Experimental data and P-T curve for the reaction zoisite + kyanite + quartz = anorthite + H_2O . V: vapour. Dashed curve: data of Goldsmith (1981)

given by Johannes (1980). For the equilibrium constant the following equation was derived:

$$\log K_I = -11,193 T^{-1} + 22.60 - 0.2828 T^{-1}(P-1).$$

Data for reaction II ($An + H_2O = Zo + Ky + Qz$) are given in Table 4. According to these data the equation for the equilibrium constant is:

$$\log K_{II} = 6,586 T^{-1} + 14.40 - 0.3373 T^{-1}(P-1).$$

The results are almost identical with those recently published by Goldsmith (1981). There is only a small difference of 0.3 kbar at 700° C. The equilibrium curve for reaction II is shown (together with the results of Goldsmith) in Fig. 6.

The anorthite used in the subsolidus reaction is synthesized from a glass at 800° C and $P_{H_2O} = 2$ kbar. The sanidine was made from a gel at 700° C and $P_{H_2O} = 4$ kbar. For fur-

ther experimental details and unit-cell data of these minerals see Johannes (1980b).

The stability boundaries for plagioclases with intermediate compositions were determined by Goldsmith (1982). According to Goldsmith at high pressure (8–10 kbar) all plagioclase compositions from An40 to An100 break down along the same P-T curve as pure anorthite. This finding agrees well with my observations that zoisite (and muscovite) comes in, in the run products of the melting experiments with plagioclase – alkali feldspar – quartz mixtures at $P_{H_2O} = 9$ and 10 kbar when the An content of the plagioclase is greater than 30 mol%.

In Figure 7 boundary curve III (plag An20 = zoisite + kyanite + quartz) is taken from Goldsmith (1982). The position of the boundary IV (plag An20 + Or-Ab_{ss} = Zo + Ms-Pa_{ss} + Qz) is estimated (curve IV must be located below curve III, the distance between III and IV should be similar to that between I and II). It is shown (Goldsmith 1982) that the assemblage Plag An40 + Or-Ab_{ss} breaks down along the same P-T curve as pure anorthite + sanidine.

Beginning of melting at high pressures in rocks of granitic composition

The assemblage Ab-rich and Or-rich alkali feldspars + quartz is stable up to 17 kbar. At higher pressures the beginning of melting is indicated by the reaction VI sanidine + jadeite + quartz + $H_2O =$ melt (Huang and Wyllie 1975).

At pressures above approximately 8 kbar and at temperatures above the solidus for the alkali feldspar granite composition $Qz - Ab - Or(-H_2O)$ the beginning of melting is initiated, as a first approximation, by the breakdown of $Zo + Ms - Pa_{ss} + Or - Ab_{ss} + Qz$ assemblages. Phase relationships between the solid solution series involved may become rather complicated (Chatterjee and Froese 1975) and the only meaning of the almost vertical dashed curves in Fig. 7 is to indicate that the solidus temperatures are increasing with decreasing Na- and increasing Ca-content of the system.

In the Na-free system $K_2O - CaO - Al_2O_3 - SiO_2 - H_2O$ at high pressure the beginning of melting is indicated by the reaction VII $Or + Zo + Ms + Qz + H_2O =$ melt (Fig. 7). With increasing temperature the next (Or-missing) reaction is VIII, $Zo + Ms + Qz + H_2O =$ melt + Ky (for experimental results of reactions VII and VIII see Schliestedt and Johannes 1984).

Comparison of solidus temperatures of systems with plagioclase (Ab + An)

So far solidus temperatures are known for the systems Ab-An (Bowen 1913), Ab-An- H_2O (Yoder 1957; Johannes 1978), $Qz - Ab - An - H_2O$ (Johannes 1978), $Qz - Or - Ab - An - H_2O$ (Johannes 1980a). The 5 kbar data of the water containing systems and the 1 atm data of Bowen are presented in Fig. 8.

The comparison in Fig. 8 shows how much the melting temperatures are decreased by the influence of high water pressures and by adding Qz and finally $Qz + Or$ to the plagioclase system Ab-An. The temperature decrease is greater on the An-side than on the Ab-side. This makes the solidus curve relatively flat in the granite system $Qz - Or - Ab - An - H_2O$. In rocks of granitic composition the solidus temperatures seems to be almost independent of the composition of plagioclases up to An40.

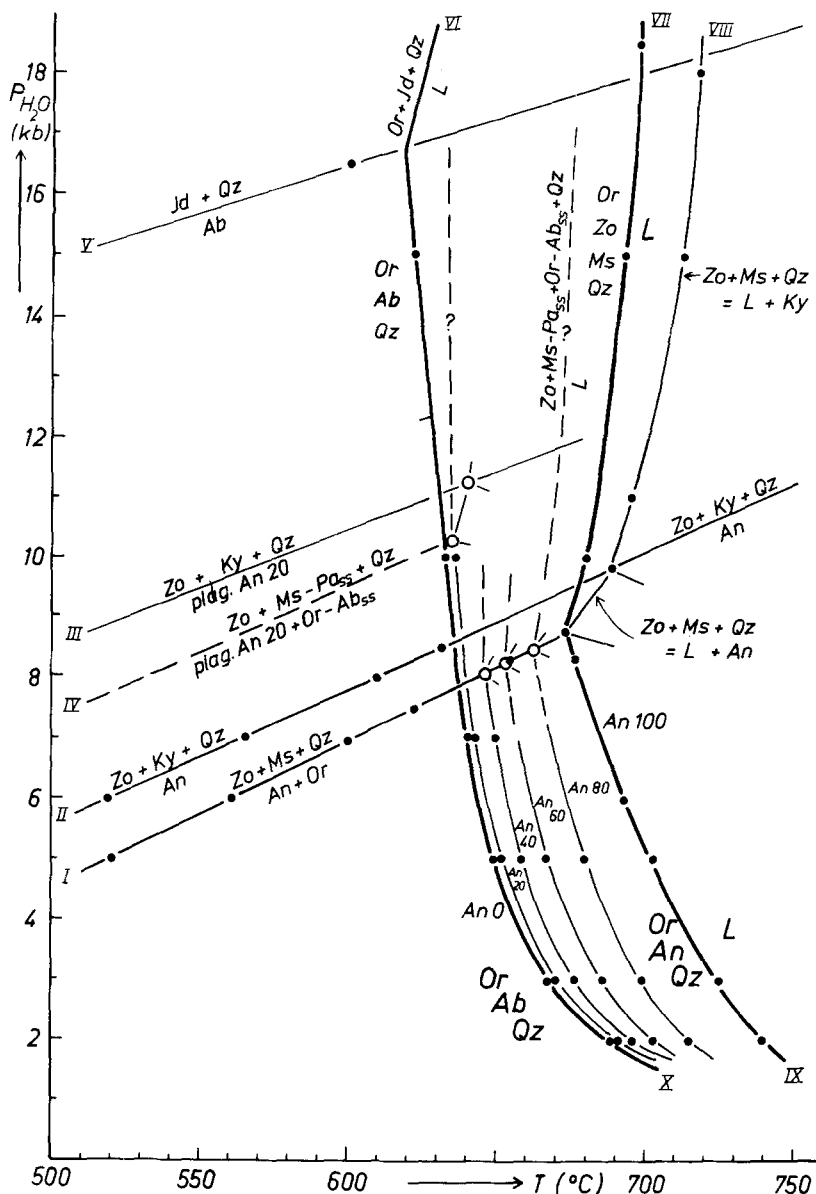


Fig. 7. Melting and subsolidus reactions in the system $\text{Na}_2\text{O}-\text{K}_2\text{O}-\text{CaO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$. Data sources: I: Johannes (1980b), II: this paper, III: Goldsmith (1982), IV: estimated (see text), V and VI: Huang and Wyllie (1975), VII and VIII: Schliestedt and Johannes (1984), IX: Johannes (1980), X: this paper. For details see text

Discussion

Plagioclase composition, solidus temperatures, and anatexis

In general it is taken for granted that the beginning of melting of rocks with granitic or granodioritic composition very much depends on the composition of the plagioclases present in the rocks. According to Winkler (1979) different metagraywakes having qualitatively very similar mineralogical compositions showed appreciable different solidus temperatures (685–715°C at $P_{\text{H}_2\text{O}}=2$ kbar) because of the different plagioclase compositions (An13–40) of the investigated gneisses. As a consequence of the different solidus temperatures, it has been concluded that the melting behaviour of the gneisses would be different (Winkler 1979 p. 326f.). The experimental findings of Winkler do not agree with the data presented in Figs. 3–5, 7, and 8.

If there are paragneiss layers with plagioclases of very different composition (e.g. An10 and An40) the difference

in solidus temperature is smaller than 10°C under typical crustal pressures (Fig. 7). Usually the plagioclase compositions within a gneiss or between adjacent gneiss layers is not very different. (In case of the Arvika gneiss, the supposed parent rock of the Arvika migmatite (Johannes and Gupta 1982), the An-content of the plagioclases present in the gneiss layers is only $\pm 3\%$ while the An of the migmatite plagioclases varies within $\pm 5\%$). The relatively small differences in the composition of gneiss and migmatite plagioclases and especially the small increase of the solidus temperatures with increasing An content do not support the idea that plagioclases could be an important factor controlling partial melting and formation of migmatites.

Beginning of melting, a reasonable isograd?

Of course any reaction observed in the field can be used to map isograds. Incoming of migmatites is considered to mark solidus temperatures or temperatures a few degrees

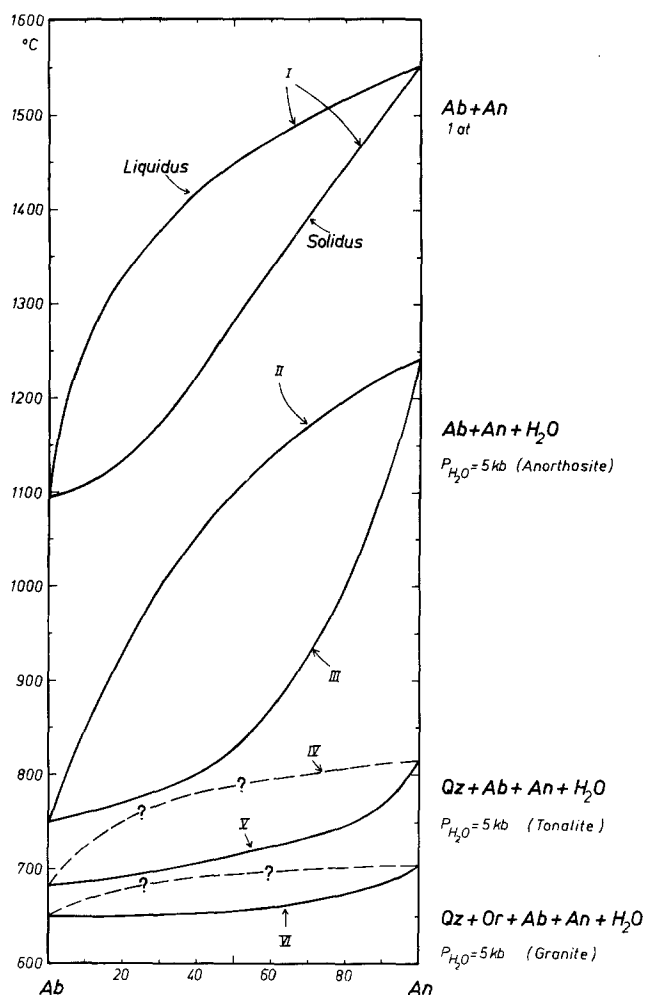


Fig. 8. $T-X_{An}$ diagram showing the composition of plagioclases coexisting with minimum melts of various systems. The An mole fractions of the liquidus boundary curves are projections onto the Ab–An join (compare Figs. 3–5). Data sources: I: Bowen (1913), Yoder, Stewart and Smith (1957), III: Johannes (1978), IV: Yoder (1968), V: Johannes (1978), VI Johannes (1980). For details see text

above the solidus. At a first glance the data given in Fig. 2 may suggest for normal crystalline schists and gneisses having quartz, alkali feldspars and Ab-rich plagioclases a “beginning of melting” isograd which is almost independent of rock composition. Such a simple P-T isograd would require a surplus of water and a fluid phase with H_2O as the only volatile component.

If the water pressure is smaller than the rock pressure the solidus temperatures of granites and granodiorites is (at a given depth) higher than the data given in Fig. 7. For review of undersaturated melting at crustal conditions and upper mantle pressures see Wyllie (1977, 1979).

If an additional “volatile” soluble in granitic melts (like P_2O_5 , B_2O_3 , HF, LiOH) is added to the system the solidus temperatures can be reduced considerably. Wyllie and Tuttle (1964) showed that the addition of 5% of a second volatile to H_2O (starting mixture: 50 wt% granite + 50 wt% fluid) lowered the beginning of melting of a granite 20° C by the addition of P_2O_5 , 60° C for HF and 90° C for LiOH. V. Platen (1965) found a lowering of solidus temperatures by 5–20° C in melting experiments with granite of various compositions when 0.5 m HCl-solutions were used instead

of pure H_2O . In case of 0.5 m HF the solidus was lowered by 35° C ($P_f=2$ kbar).

Recently Manning (1981) investigated the effect of fluorine on liquidus phase relationships in the system Qz–Ab–Or– H_2O at 1 kbar. He observed a decrease of the minimum liquidus temperature by 100° C for a granite system with 4% fluorine. In exploratory experiments he detected two alkali feldspars, quartz, melt, and vapor at temperatures as low as 550° C. This means a decrease of the solidus temperature of almost 200° C at $P_f=1$ kbar. Pichavant (1981) studied the effect of boron on a water saturated haplogranite at 1 kbar vapour pressure. He found that the solidus temperature of the Qz–Or–Ab composition is lowered by 60° C when 5 wt% B_2O_3 and by 130° C when 17 wt% B_2O_3 is added to water.

These data suggest that there is no simple unique solidus temperature for rocks of granitic or granodioritic composition. If the water pressure is smaller than the rock pressure or if the fluid phase contains besides H_2O additional components soluble in granitic melts the solidus temperatures of granites can only be estimated. There is a range of several hundred °C for possible solidus temperatures depending on whether the H_2O is diluted by an inert component (like CO_2) or by a volatile component soluble in granitic melts (like B and F).

On the other hand the ability to map the “beginning of melting” isograds and to estimate P-T conditions in partially molten high grade metamorphic rocks is much better than it looks at a first glance. As long as the content of fluorine, borine or chlorine remains low the amount of the first melt remains also low and such melts may not be detectable. In gneisses and crystalline schists the volatile components may be concentrated in specific minerals (like tourmaline or apatite) or in fluid inclusions. Provided that such minerals are stable up to relatively high temperatures (like tourmaline) and provided that the additional component is preferentially concentrated in the solid phases the amounts of low temperature melts may be small and so remain petrogenetically without any importance.

In the field the beginning of melting is indicated by the incoming of migmatites. “Migmatite” means that a certain volume of a gneiss or schist (20% of volume?) is no longer metamorphic but now plutonic in appearance. According to the viscosity data of van der Molen and Paterson (1979) the amount of melt in the plutonic parts of a migmatite may be as low as 30–40 vol%. If this is accepted as the minimum amount of melt in leucosomes the total proportion of melt present in a migmatite can be as low as 6 or 8 vol%.

In many high grade metamorphic rocks there will be enough water to produce 6–8% of water saturated or almost water saturated melt. In such rocks the incoming of migmatites indicate temperatures (for given pressures) 0–20° C above the data given in Figs. 3–5 and in Fig. 7. (0° C for alkali feldspar – quartz rocks with eutectic mineralogy, and 20° C for cotectic compositions with intermediate plagioclases). These are minimum temperatures. If the partial melts are considerably water-undersaturated the incoming of migmatites indicates higher temperatures than those given in this paper.

On the water content of high grade metamorphic rocks

Metasomatism, partial melting, crystal growth, rock deformation, etc., depend very much on the amount of water

present in rocks and magmas. The significance of water in the genesis of rocks and ore deposits is well established but the quantity of water taking part in rock forming processes is usually not known. Hydrothermal experiments with excess water are usually not representative of natural processes and define only limiting conditions. According to the calculations of Walther and Orville (1982) "Regionally metamorphosed rocks will have a discrete fluid phase only when devolatilization reactions are actually taking place. At other times only an absorbed surface monolayer of volatiles on the minerals will be present".

For review of melting and subsolidus reactions at water saturated and undersaturated conditions see Maaløe and Wyllie (1975), Huang and Wyllie (1975), and Wyllie (1977 and 1979). In the light of the present study and using information on the composition of migmatites the last part of this paper will focus on the possible water content of high grade metamorphic rocks.

The amount of melt necessary to transform a gneiss layer or a portion of a schist into leucosome material (the plutonic looking part) of a migmatite may be (as shown above) as low as 6–8 vol%. The water content of H₂O saturated melts at $P_{H_2O} = 5$ kbar is approximately 10% (Tuttle and Bowen 1958). This means that very little water is needed (1 wt% or even less) in order to form a migmatite via water saturated partial melts.

The proportion of leucosome material present in migmatites is obviously controlled by the amount of water available for melting if there are no appreciable amounts of additional components preferentially concentrated in low temperature melts. The mineralogical (and chemical) composition of the leucosomes (the plutonic portions) and mesosomes (the metamorphic parts) of many migmatites are very similar (Johannes and Gupta 1982; Gupta and Johannes 1982; Johannes 1983). According to these petrologic observations and to the experimental data shown in Figs. 3–5 and Fig. 7 the different layers of a migmatite (or its parent rock) have practically the same solidus temperatures. Besides similar solidus temperatures the various layers of a migmatite (or its parent rock) should display very similar cotectic melting (until a certain amount of melt is reached) if there is excess water and an even distribution of this water. For some not yet known reason the supply of (the relatively small amounts of) water causing partial melting is concentrated in the leucosomes. (The very first melts formed in the leucosomes may act here as a sink for water.)

In migmatite areas the proportion of leucosomes increases with increasing temperature. But such an increase of the plutonic portions is not continuous and the amount of leucosome may be different and even lower in areas of higher metamorphic grade. In many occurrences differences in the degree of melting cannot be related to differences in the bulk rock compositions but may be due to different amounts of water present or transported into different portions of the high grade metamorphic rocks. In the light of the experimental data discussed here migmatites and nonmigmatized high grade metamorphic rocks tell us that the proportion of water can be (and probably very often is) low (1 wt% or less?) in partially melted rocks and even lower in many high grade gneisses and crystalline schists. Consequently it must be supposed that anatectic magmas of granitic and granodioritic composition are usually not saturated with water.

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References

- Bambauer HU, Corlett M, Eberhard E, Viswanathan K (1967) Diagrams for the determination of plagioclases using X-ray powder methods. *Schweiz Mineral Petrogr Mitt* 47:333–349
- Bowen NL (1913) The melting phenomena of plagioclase feldspars. *Am J Sci* 35:577–599
- Chatterjee ND, Johannes W (1974) Thermal stability and standard thermodynamic properties of synthetic 2 M₁-muscovite, KAl₂AlSi₃O₁₀(OH)₂. *Contrib Mineral Petrol* 48:89–114
- Chatterjee ND, Froese E (1975) A thermodynamic study of the pseudobinary join muscovite-paragonite in the system KAlSi₃O₈-NaAlSi₃O₈-Al₂O₃-SiO₂-H₂O. *Am Min* 60:985–993
- Goldsmith JR (1981) The join CaAl₂Si₂O₈-H₂O (anorthite-water) at elevated pressures and temperatures. *Am Min* 66:1183–1188
- Goldsmith JR (1982) Plagioclase stability at elevated temperatures and water pressures. *Am Min* 67:653–675
- Gupta LN, Johannes W (1982) Petrogenesis of a stromatic migmatite (Nelaug, Southern Norway). *J Petrol* 23:548–567
- Huang WL, Wyllie PJ (1975) Melting reactions in the system NaAlSi₃O₈-KAlSi₃O₈-SiO₂ to 35 kilobars, dry and with excess water. *J Geol* 83:737–748
- Johannes W (1973) Eine vereinfachte Piston-Zylinder-Apparatur hoher Genauigkeit. *Neues Jahrb Mineral Monatsh* 1973:337–351
- Johannes W (1978) Melting of plagioclase in the system Ab–An–H₂O and Qz–Ab–An–H₂O at $P_{H_2O} = 5$ kbar, an equilibrium problem. *Contrib Mineral Petrol* 66:295–303
- Johannes W (1979) Ternary feldspars: Kinetics and possible equilibria at 800° C. *Contrib Mineral Petrol* 68:221–230
- Johannes W (1980a) Metastable melting in the granite system Oz–Or–Ab–An–H₂O. *Contrib Mineral Petrol* 74:29–34
- Johannes W (1980b) Melting and subsolidus reactions in the system K₂O–CaO–Al₂O₃–SiO₂–H₂O. *Contrib Mineral Petrol* 74:29–34
- Johannes W (1983) On the origin of stromatic (layered) migmatites. In: Atherton MP and Gribble CD (eds) *Migmatites, Melting and Metamorphism*. Orpington: Shiva Publishing Ltd.
- Johannes W, Gupta L (1982) Origin and evolution of a migmatite. *Contrib Mineral Petrol* 79:14–23
- Luth WC, Jahns RH, Tuttle OF (1964) The granite system at pressure of 4 to 10 kbar. *J Geophys Res* 69:759–773
- Maaløe S, Wyllie PJ (1975) Water content of a granite magma deduced from the sequence of crystallisation determined experimentally with waterundersaturated conditions. *Contrib Mineral Petrol* 52:175–191
- Manning DAC (1981) The effect of fluorine on liquidus phase relationships in the system Qz–Ab–Or with excess water at 1 kbar. *Contrib Mineral Petrol* 76:206–216
- Mehnert KR (1971) *Migmatites and the origin of granitic rocks*. Amsterdam: Elsevier
- Mehnert KR, Büsch W (1982) The initial stage of migmatite formation. *N Jb Miner Abh* 145:211–238
- Molen van der I, Paterson MS (1979) Experimental deformation of partially melted granite. *Contrib Mineral Petrol* 70:299–318
- Orville PM (1963) Alkali ion exchange between vapor and alkali feldspar. *Am J Sci* 261:201–237
- Pichavant M (1981) An experimental study of the effect of boron on a watersaturated haplogranite at 1 kbar vapour pressure. *Contrib Mineral Petrol* 76:430–439
- Platen v H (1965) Kristallisation granitischer Schmelzen. *Beitr Mineral Petrol* 11:334–381

- Schliestedt M, Johannes W (1984) Melting and subsolidus reactions in the system $K_2O-CaO-Al_2O_3-SiO_2-H_2O$: corrections and additional experimental data. in prep. for *Contrib Mineral Petrol*
- Storre B, Johannes W, Nitsch K-H (1982) The stability of zoisite in H_2O-CO_2 mixtures. *Neues Jahrb Miner Monatsh* 1982:395-406
- Tuttle OF (1948) A new hydrothermal quenching apparatus. *Am J Sci* 246:628-635
- Tuttle OF, Bowen NL (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8-KAlSi_3O_8-SiO_2-H_2O$. *Geol Soc Am Mem* 74:153 pp
- Viswanathan K (1972) Kationenaustausch an Plagioklasen. *Contrib Mineral Petrol* 37:277-290
- Walther JV, Orville PM (1982) Volatile production and transport in regional metamorphism. *Contrib Mineral Petrol* 79:252-257
- Winkler HGF, v. Platen H (1958) Experimentelle Gesteinsmetamorphose II. Bildung von anatektischen granitischen Schmelzen bei der Metamorphose von NaCl-führenden kalkfreien Tonen. *Geochim Cosmochim Acta* 15:91-112
- Winkler HGF, v Platen H (1960) Experimentelle Gesteinsmetamorphose III. Anatektische Ultrametamorphose kalkhaltiger Tone. *Geochim Cosmochim Acta* 18:294-316
- Winkler HGF, v Platen H (1961) Experimentelle Gesteinsmetamorphose IV. Bildung anatektischer Schmelzen aus metamorphisierten Grauwacken. *Geochim Cosmochim Acta* 24:48-69
- Winkler HGF (1966) Der Prozeß der Anatexis: Seine Bedeutung und die Genese der Migmatite. *Tscherm Min Pet Mitt* XI:266-287
- Winkler HGF (1979) Petrogenesis of metamorphic rocks. Berlin Heidelberg New York: Springer 348 pp
- Winkler HGF, Ghose NC (1974) Further data on the eutectics in the system $Qz-Or-An-H_2O$. *Neues Jahrb Mineral Monatsh* 1973:481-484
- Winkler HGF, Lindemann W (1972) The system $Qz-Or-An-H_2O$ within the granitic system $Qz-Or-Ab-An-H_2O$. Application to granitic magma formation. *Neues Jahrb Mineral Monatsh* 1972:49-61
- Wyllie PJ, Tuttle OF (1964) Experimental investigation of silicate systems containing two volatile components. Part III The effects of SO_3 , P_2O_5 , HCl , and Li_2O , in addition to H_2O , on the melting temperatures of albite and granite. *Am J Sci* 262:930-939
- Wyllie PJ (1977) Crustal anatexis: an experimental review. *Tectonophysics* 43, 41-71
- Wyllie PJ (1979) Magmas and volatile components. *Am Min* 64:469-500
- Yoder HS (1968) Albite-anorthite-quartz-water at 5 kb. *Carnegie Inst Wash Year Book* 66:477-478
- Yoder HS, Stewart DB, Smith JR (1957) Feldspars. *Carnegie Inst Wash Year Book* 56:206-214

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