

Kinetics of lamellar coarsening in cryptoperthites

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Abstract

The coarsening of the coherent lamellar microstructure in a high sanidine-high albite cryptoperthite of Or_{36} bulk composition was determined experimentally between 560° and 470°C. The lamellar spacing (λ) was measured by transmission electron microscopy. It increases as a function of the isothermal annealing time (t) and is expressed by $\lambda = \lambda_0 + kt^{1/3}$, where k is a rate constant and λ_0 is the initial lamellar spacing. The maximum temperature for the development of this microstructure is about 570°C, and the lowest temperature practical for experimental study is about 470°C where the lamellae coarsen only 60Å/year. Annealing times were for ≤ 548 days and the experiments were done dry at one atmosphere. An experiment at 560°C and a water pressure of 2 kbar yielded a similar result to the dry experiments. The kinetic data are summarized by k (Å/day^{1/3}) = $1.78 \times 10^8 \exp(-25000/RT)$ where R is the gas constant and T is the absolute temperature. These data predict an increase in the lamellar spacing of 5500Å for exsolution starting at 560°C and a linear cooling rate of 0.01 degree/year. The potential application of these kinetic data to cryptoperthites in volcanic and shallow intrusive rocks is considered; one of the most important factors is the size of the initial lamellar spacing in natural samples.

Introduction

One of the principal goals of the study of exsolution microstructures has been to use this information to interpret the thermal history of the rocks in which they occur. Previous studies have concentrated on how a particular microstructure develops. The potential applications of microstructural relations combined with certain kinetic data are outlined in a number of recent papers (McConnell, 1975; Yund, 1975a; Nord *et al.*, 1975; Champness and Lorimer, 1976; Willaime *et al.*, 1976). We report here the results of an experimental study of the change in the microstructure of alkali feldspar cryptoperthites as a function of annealing time. We believe these data can be used to interpret a portion of the subsolidus cooling history of cryptoperthites.

The term cryptoperthite will be used here for any exsolved alkali feldspar in which the lamellae cannot be resolved with the optical microscope (Laves and Soldatos, 1963). The lamellae in most cryptoperthites are coherent, which involves a continuity of the tetrahedral structure across the lamellar interface (*i.e.*, no interface dislocations). Although the lattice is continuous, there is a difference in the K/Na ratio of the

lamellae, which creates an elastic strain in both phases. Thus the cell parameters of coherent phases are not the same as those for noncoherent or strain-free phases, and this results in what was originally referred to as 'anomalous' feldspars (Wright and Stewart, 1968).

In a system of coherent phases the elastic strain contributes an additional energy term which is opposite in sign to the change in the Gibbs or volume free-energy accompanying exsolution (Robin, 1974a and b; Yund, 1975b). As long as coherency is maintained, the phases (lamellae) will not reach the equilibrium compositions of the strain-free solvus. The compositions of the coherent phases lie within the strain-free solvus and are given by the coherent solvus (curve b in Fig. 1). Coherency is not necessarily a transitory state even on a geological time scale, as shown by the occurrence of coherent cryptoperthites in volcanic and shallow intrusive bodies.

Coherent lamellae can only form by exsolution in the solid state. Their mechanism of formation can be either by nucleation and growth beneath the coherent solvus or spinodal decomposition and coarsening beneath the coherent spinodal. These mechanisms are

discussed in detail in several of the articles referred to above. Figure 1 shows Sipling and Yund's (1976) data for the coherent solvus and an estimate of the position of the coherent spinodal. The coherent solvus and spinodal calculated by Robin (1974b) are similar in general character but differ somewhat in position, due to approximations and uncertainties involved in the calculation.

Slow annealing of an exsolved sample may produce modifications in the initial microstructure. One of the first major changes is an increase in the lamellar spacing. This process, which is known as coarsening, occurs while the lamellae are still coherent. This coarsening was first demonstrated for the ordered alkali-feldspar series (maximum microcline-low albite) at 700° and 600°C (Yund *et al.*, 1974). We report here a detailed experimental study of the kinetics of lamellar coarsening in the disordered alkali feldspars (high sanidine-high albite) and outline the application of these data for determining the subsolidus cooling rates for cryptoperthites.

Experimental procedures

The preparation of a homogeneous alkali feldspar for the coarsening experiments was identical to that described by Sipling and Yund (1976). Briefly it consisted of annealing crushed fragments ($\sim 150 \mu\text{m}$) of a natural adularia crystal at 1100°C, and then exchanging the alkali ions in molten chlorides to produce a homogeneous phase whose composition was Or_{35} as determined by electron microprobe analysis. Examination of this material by transmission electron microscopy (TEM), single-crystal precession photographs, and least-squares cell refinement of powder X-ray diffraction demonstrated that the material was homogeneous and belonged to the high sanidine-high albite series.

Portions of the above material were annealed isothermally in unsealed platinum tubes in air at 470°, 500°, 530°, and 560°C for 1 to 548 days. Chromel-Alumel thermocouples were calibrated against the melting point of NaCl (800.5°C) and National Bureau of Standards zinc of known melting point (419.5°C). The maximum temperature variation during these annealing experiments was $\pm 3^\circ\text{C}$. Samples were quenched in air, portions were removed, and the remainder was annealed for a longer time. One experiment was done at 2 kbar water pressure in a standard cold-seal pressure vessel.

Samples were prepared for TEM examination by crushing fragments between glass slides, carbon-coating the slides, floating the carbon film with thin frag-

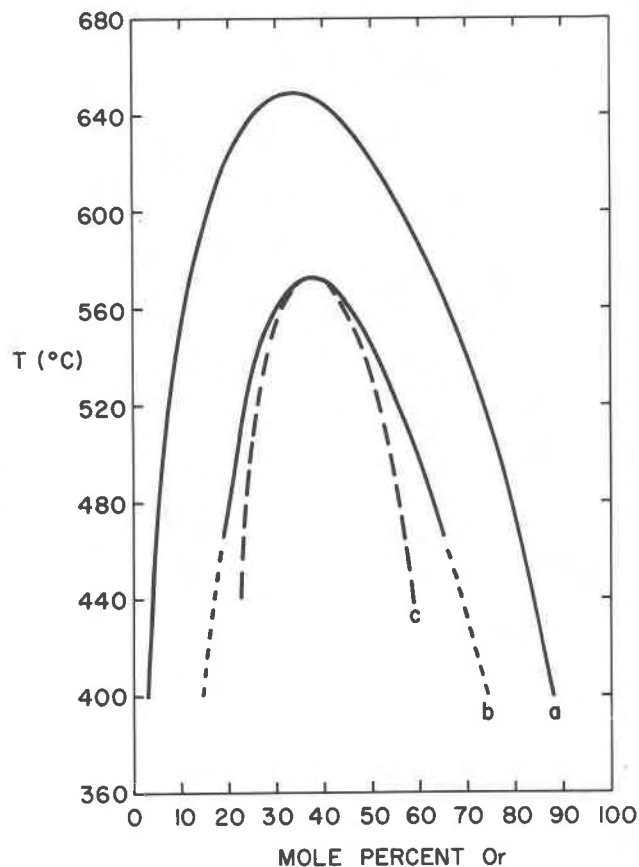


Fig. 1. Summary of the relations for the high sanidine-high albite series at one atmosphere. Curve (a) is the strain-free or equilibrium solvus (Thompson and Waldbaum, 1969). Curves (b) and (c) are the coherent solvus and coherent spinodal, respectively (Sipling and Yund, 1976).

ments of sample adhering to it off on water, and collecting pieces of the carbon film on 200-mesh electron microscope grids. These grids were examined using a model JEM-7A transmission electron microscope operating at 100 kV. The specimen stage could be tilted 8° and rotated 360°.

The procedure for determining the magnification of the electron micrograph images was as follows. At the beginning of each session on the electron microscope, two photographs of a carbon replica of a diffraction grating (2160 lines/mm) were taken at the lowest and highest magnification to be used. These were normally at $\times 12,000$ and approximately $\times 35,000$ on the same magnification range. This procedure was repeated at the end of the session, and if any difference was observed between the lens current and the magnification on the plates between the beginning and end of a session, a linear interpolation

was used to estimate the magnification at an intermediate time. Normally any difference was small compared to other possible errors.

Electron micrograph images and diffraction patterns were used to determine that the lamellar interface was parallel to (801). This agrees to within a few degrees with orientations reported previously (e.g., Owen and McConnell, 1974). This information was used to correct the apparent lamellar spacing for fragments which were photographed with their lamellar interface inclined to the plate. The orientation of a fragment was determined from its diffraction pattern, and its true lamellar spacing was calculated from the apparent spacing and its orientation. Whenever possible, several measurements of the lamellar spacing were made on a plate and the mean value used. Only data from fragments whose lamellar interface was within approximately $\pm 30^\circ$ of normal to the plate were used. The reproducibility of this method is indicated by the results presented below.

Experimental results

The experimental data for the change in the lamellar spacing as a function of isothermal annealing time are listed in Table 1. Each value for the lamellar spacing is the mean of at least two and in a majority of instances four or more measurements on different fragments, as indicated in the table. One standard deviation of these measurements is indicated by the numbers in parentheses.

The data for 470°C are not as extensive as those for the higher temperatures (Table 1). After annealing at 470°C for 8 days, the contrast in the electron micrographs between the lamellae is very slight and the lamellar spacing could not be measured. There are no data for the longer annealing times at this temperature because the furnace controller failed and the sample was accidentally heated to over 1000°C. This occurred after a total annealing time of over 300 days and the experiment was not repeated.

The relation between the annealing time and the lamellar spacing for each temperature is shown in Figure 2. The line for each temperature was fitted by least-squares. The lamellar spacing (λ) is proportional to the cube root of the annealing time (t) at each temperature and is expressed by the relation:

$$\lambda = \lambda_0 + kt^{1/3} \quad (1)$$

where λ_0 is the spacing at zero time and k is a rate constant for each temperature.

The above $t^{1/3}$ relation has been observed for coarsening of precipitates under a wide range of conditions. This dependence of the spacing on $t^{1/3}$ was

reported for exsolution lamellae in a maximum microcline-low albite (Yund *et al.*, 1974); for lamellar precipitates in $\text{SnO}_2\text{-TiO}_2$ (Park *et al.*, 1976); and for nonlamellar precipitates in a Ni-Al alloy (Ardell and Nicholson, 1966) and in a Cu-Ni-Fe alloy (Butler and Thomas, 1970). This relation is also predicted by coarsening theory for spheres in a fluid matrix (Lifshitz and Slyozov, 1961; Wagner, 1961) and for widely spaced coherent particles (Langer, 1971).

This coarsening behavior should not be confused with the development of a preferred initial wavelength during the early stage of spinodal decomposition. The preferred wavelength is not proportional to $t^{1/3}$ for alloys (Butler, 1971; Cornie *et al.*, 1973). Even though it has been argued that alkali feldspars exsolve by a spinodal mechanism (Owen and McConnell, 1974; Yund *et al.*, 1974), the changes in the lamellar spacing observed in our study are part of the late-stage coarsening. This coarsening is independent of the mechanism by which the coherent lamellar microstructure initially forms. Comparison with the experimental data for the determination of the coherent solvus (Sipling and Yund, 1976) indicates that the lamellae in the present experiments attain steady-state compositions before most of the coarsening occurs.

The lamellar microstructures for samples annealed for 343 days at 530°C and for 166 days at 470°C are shown by the electron micrographs in Figure 3a and b. Although the principal characteristic of this microstructure is a lamellar intergrowth, it is not perfectly regular and the lamellae bifurcate and terminate as shown in the micrographs. Coarsening would be impossible in a perfectly regular microstructure, and the small but important differences in the width of lamellae influence the selection of the lamellae which will grow and those which will shrink. The lamellae remain coherent throughout the course of these experiments as indicated by electron diffraction patterns. The driving force for this coarsening is a reduction of the interfacial area, but the rate controlling factor is the diffusivity of the alkali ions. Thus the regular decrease in the coarsening rate with decreasing temperature, as shown by the progressively lower slopes of the lines on Figure 2, is qualitatively correct.

The natural log of the rate constant, k , should vary as a function of $1/T$ as expressed by the Arrhenius relation. This is shown in Figure 4. The data define a straight line within experimental uncertainty and the equation of this line is:

$$k(\text{A/day}^{1/3}) = (1.78 \pm 2.20) \times 10^8 \exp\left[\frac{-25,000 \pm 1200}{RT}\right] \quad (2)$$

Table 1. Experimental coarsening data

| Annealing Temperature (°C) | Annealing Time (days) | Number of Measurements | Lamellar Spacing (Å) |
|----------------------------|-----------------------|------------------------|----------------------|
| 560 | 8 | 5 | 171 (12) |
| " | 27 | 2 | 212 (34) |
| " | 64 | 2 | 247 (8) |
| " | 166 | 3 | 309 (9) |
| " | 343 | 2 | 399 (18) |
| " | 548 | 5 | 462 (26) |
| 530 | 8 | 6 | 129 (9) |
| " | 27 | 2 | 165 (24) |
| " | 64 | 5 | 191 (21) |
| " | 166 | 3 | 242 (20) |
| " | 343 | 4 | 267 (16) |
| " | 548 | 2 | 314 (8) |
| 500 | 8 | 3 | 110 (7) |
| " | 27 | 6 | 126 (5) |
| " | 64 | 5 | 146 (15) |
| " | 166 | 3 | 149 (9) |
| " | 343 | 5 | 176 (12) |
| " | 548 | 5 | 208 (18) |
| 470 | 27 | 5 | 95 (6) |
| " | 64 | 7 | 108 (4) |
| " | 166 | 6 | 117 (6) |

* Numbers in parentheses are one standard deviation.

where R is the gas constant and T is °K. The uncertainties are one standard deviation and are based on the uncertainties of the least-squares fits to the data in Figure 2. The linearity of the data on Figure 4 permits the coarsening data to be extrapolated to at least 400°C without major error. At this temperature the rate constant is approximately one, and coarsening is not significant except at very slow cooling rates. This is discussed in the last section.

The activation energy for coarsening is related to the activation energy for interdiffusion of the alkali ions in feldspar. This diffusion would be expected to vary slightly with the compositions of the lamellae, which are themselves temperature-dependent. The compositions of the coexisting coherent phases are $Or_{30.0}$ and $Or_{19.5}$ at 560°C and $Or_{45.9}$ and $Or_{64.6}$ at 470°C (Sipling and Yund, 1976). Thus it appears that any variation in the interdiffusion coefficients between these pairs of compositions is less than the experimental error for the coarsening data, which define a straight line with a constant activation energy as shown on Figure 4.

The rate constant, k , is proportional to $D^{1/3}$ in Wagner's (1961) formulation for coarsening. Ardell and Nicholson (1966) and Butler and Thomas (1970) have approximately confirmed this relation for alloys of Al-Ni and Cu-Ni-Fe, respectively. It is not certain whether the coarsening rate for coherent lamellar

precipitates has the same dependence on the diffusion coefficient. Assuming that it does, the experimental data for cryptoperthites yield an activation energy for diffusion of 75 kcal/mole.

Unfortunately there are no data for the interdiffusion of potassium and sodium ions in alkali feldspars. An estimate of diffusion rates can be made from a relation given by Manning (1968, p. 21) and discussed by Brady (1975), who points out that this relation has not been verified experimentally. We will assume that the solid solution is ideal, that alkali diffusion is isotropic (see Petrović, 1974), and that self-diffusion coefficients are linear between the end-members. Using the end-member self-diffusion coefficients from Foland (1974) and Kasper (1974), we estimate that the activation energy for interdiffusion in Or_{20} is approximately 60 kcal/mole. Although this is 20 percent lower than the activation energy obtained from the coarsening data, the difference is not surprising considering the approximations noted above. However, the difference is sufficiently large that we cannot positively conclude that the rate constant is proportional to the cube root of the interdiffusion coefficient.

The only other lamellar coarsening data for alkali feldspars are those for the ordered maximum microcline-low albite series (Yund *et al.*, 1974). These data were for 600° and 700°C, and the rate constants at these temperatures are about half of that predicted by extrapolation of the data in Figure 4. This difference may be accounted for by the lack of absolute calibration of the electron micrographs by Yund *et al.* (1974), although there may be a real difference in the absolute rates for the ordered and disordered series. The activation energy for coarsening for each of the two series is the same within experimental error, indicating that this energy is independent of ordering.

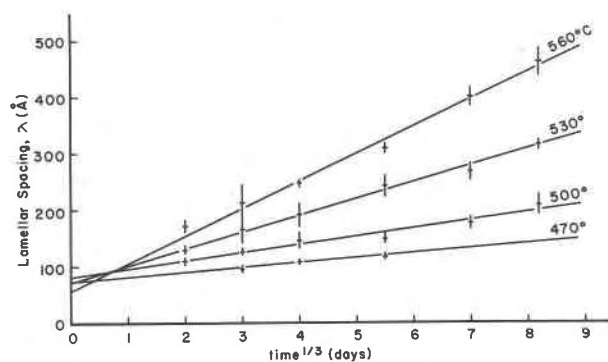


Fig. 2. Change in the lamellar spacing for samples annealed isothermally at the four temperatures shown. Lines are least-squares fits to the data. See equation (1) in the text.

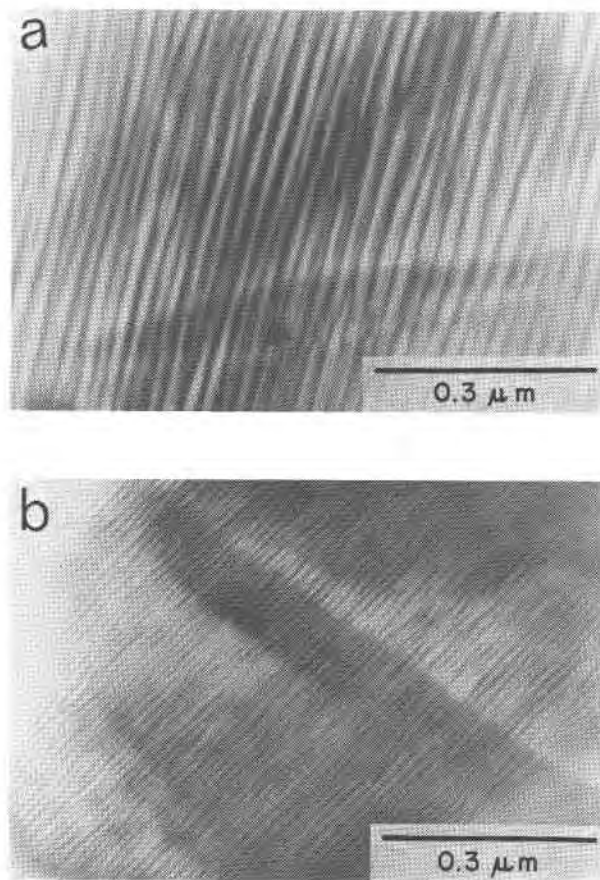


Fig. 3. Electron micrograph of (010) sections for two samples; (a) was annealed at 530°C for 343 days and (b) was annealed at 470°C for 166 days.

Cryptoperthites commence to exsolve while they are still highly disordered, and hence refinement of the data for the maximum microcline-low albite series does not appear to be warranted. However, if that series had not been studied first, the lower temperature and hence slow coarsening for the disordered series would probably have precluded recognition of cryptoperthite coarsening or the time-dependence of the coarsening.

Two experiments were done in addition to those listed in Table 1. The purpose of one of these was to determine whether pressure or the presence of water has any effect on the coarsening rate. A portion of the same starting material was sealed in a platinum tube with 38 percent water by weight, and this was heated at 2 kbar and 530°C for 27 days. Measurement of three fragments gave a mean lamellar spacing of 158Å. This agrees very well with the dry experimental data (Table 1), and indicates that the kinetics of the

coarsening are not affected by water pressure. This is consistent with the available diffusion data, which also indicate that alkali ion diffusion in feldspar is not affected by water pressure (Lin and Yund, 1972; Petrović, 1974).

The other experiment was designed to determine the effect of slow cooling on the value of the initial lamellar spacing, λ_0 . A sample was cooled from 580° to 560°C over a period of 26 days. The furnace temperature was lowered in approximately equal increments each day. The lamellar spacing in this sample was observed to be 205Å. If we estimate that the sample commenced to exsolve at 570°C, the approximate temperature of the coherent solvus and spinodal, it would have developed a final lamellar spacing of 200Å if λ_0 was 75Å. Thus this slow cooling did not generate a significantly different initial spacing than in the isothermal experiments. The significance of this observation is discussed in the next section.

Discussion

The application of the coarsening data to natural cryptoperthites is considered in this section. In order to make this application several parameters must be determined or estimated. These include the initial temperature of coherent exsolution for a particular bulk composition, the initial lamellar spacing, the extrapolation of the coarsening data to lower temperature, and the dependence of temperature on time for the rock mass. Each of these factors is discussed below.

Coherent lamellae can only form by exsolution, and the maximum temperature at which this can occur is determined by the bulk composition of the sample and the temperature of the coherent solvus for that composition. However, Owen and McConnell (1974) and Yund *et al.* (1974) have argued that the mechanism of exsolution for alkali feldspars is probably spinodal decomposition. This would limit the start of exsolution to the coherent spinodal for a particular bulk composition. Fortunately, for compositions between about Or₂₀ and Or₅₅, the temperature difference between the coherent solvus and coherent spinodal for monoclinic alkali feldspars is probably less than 10°C, as shown on Figure 1. Thus for cryptoperthites whose bulk compositions lie within this interval, the initial temperature at which coherent exsolution commences is similar regardless of which mechanism is operative. The uncertainty in the position of the coherent solvus appears to be on the order of $\pm 10^\circ\text{C}$ between Or₂₀ and Or₆₅ (Sipling

and Yund, 1976). The available data suggest that the coherent spinodal may be closer to the coherent solvus on the sodic limb than it is on the potassic limb (Fig. 1).

The spacing of the initial lamellae is a difficult parameter to assess. If the exsolution occurs by a spinodal mechanism, theory predicts that the initial spacing or wavelength will be infinite at the coherent spinodal and much smaller at a temperature only a few degrees below the coherent spinodal (Cahn, 1968). Natural cryptoperthites cool slowly through this critical region, and hence it is important to determine the initial spacing before coarsening occurs. This initial wavelength cannot be predicted for feldspars, and we must turn to experimental observations to resolve this question.

For the coherent exsolution of maximum microcline-low albite, Yund *et al.* (1974) report that the initial wavelength was 65Å at 600° and about 200Å at 700°C. The latter temperature is probably within a few degrees of the coherent solvus for ordered feldspars (Yund, 1974). The data in Figure 2 do not demonstrate an increase in λ_0 with higher annealing temperatures. (Within the experimental uncertainties, λ_0 is the same for all temperatures.) The highest temperature is within about 10°C of the coherent spinodal but did not result in a larger λ_0 . The question remains whether a natural cryptoperthite cooling slowly through this critical temperature interval would develop a longer initial wavelength.

In order to test the effect of slow cooling, a sample was cooled from 580° to 560°C at slightly less than one degree per day, as described in the previous section. The resulting lamellar spacing is not larger than what would have been produced by coarsening of a 75 ± 10 Å initial spacing which is characteristic of the isothermal experiments (Fig. 2).

It is possible that still slower cooling in a volcanic or shallow plutonic rock might result in a larger value of λ_0 . Probably the best way to test this is to examine natural cryptoperthites near the contact of a volcanic unit which have cooled more slowly than is possible in laboratory experiments. If the amount of coarsening in these samples can be predicted from heat-flow calculations, the initial wavelength can be estimated.

If cryptoperthite exsolution occurs by coherent homogeneous nucleation, the initial lamellar spacing might also be dependent on the temperature or supersaturation of the original phase. However, the experimental data show no effect of this beyond the experimental error of approximately ± 20 Å in the 90° temperature interval studied, and argue against any

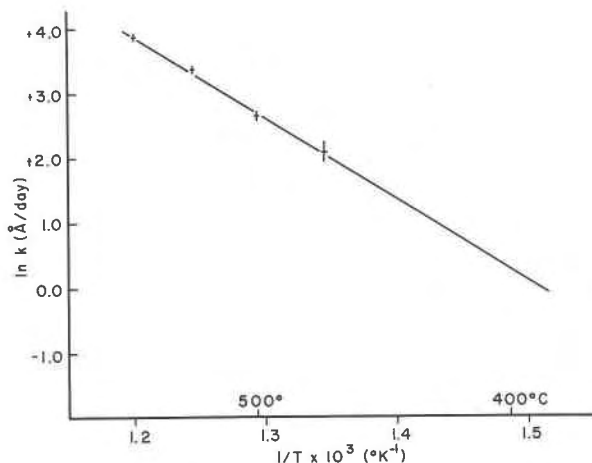


Fig. 4. An Arrhenius plot of the rate constant, k , from equation (1) for the four isothermal annealing temperatures. The line shown is the least-squares fit and corresponds to equation (2) in the text.

significant increase in the initial lamellar spacing in the first 10° interval.

Thus it appears reasonable to use the experimental value of 75Å for λ_0 unless additional observations demonstrate that this is incorrect. Even if the true value for this parameter is several times larger, the resultant error would be small for a natural cryptoperthite with a lamellar spacing of several thousand angstroms.

The experimental error in the coarsening data and their extrapolation to lower temperatures is another possible source of error. It is impractical to do laboratory experiments below 470°C because at this temperature the coarsening is only 60Å/year. Fortunately little extrapolation of the present data is required for application to cryptoperthites in volcanic rocks and even shallow intrusives into cold country rock. Extrapolation of the data in Figure 4 indicates an isothermal coarsening rate of only 97Å/10⁸ years at 400° and 37Å/10⁸ years at 300°C. Thus, depending on the geologic situation, an extrapolation of less than 100°C may be required. The internal consistency of the data justify this extrapolation.

The reproducibility of the experimental results is indicated by the assigned uncertainty. The accuracy depends on the magnification calibration. The carbon replica of the diffraction grating is reported to be accurate to within ± 0.3 percent. This is smaller than the error of our measurements. The other important

factor is the temperatures of the furnaces. Careful calibration as described in an earlier section results in an uncertainty of $\pm 3^\circ\text{C}$. This uncertainty is included in equation (2). The magnification and temperature are the principal sources of systematic errors in the data, and hence we believe the accuracy of the results is essentially equal to the reported uncertainty.

Other considerations which may be important are the effects of pressure or water on the coarsening kinetics. We have shown that the coarsening rate is the same for 2 kbar water pressure as it is for one atmosphere dry. The effect of an increase of several kbar in the pressure is not expected to significantly modify the diffusion rates (Foland, 1974, and others). If water had any effect it would probably be to alter the coarsening mechanism via a dissolution and re-precipitation process which would result in loss of coherency. Thus it appears that the water pressure is not a significant parameter for application of the coarsening data. Total pressure raises the strain-free solvus approximately $16^\circ\text{C}/\text{kbar}$ (Smith and Parsons, 1974) and would probably cause a similar displacement of the coherent solvus/spinodal. However, cryptoperthites are restricted to volcanic or shallow-level intrusives, and a pressure correction is not significant in most instances.

Other factors which might be significant include tetrahedral ordering and twinning, especially of the sodic phase. A careful study of natural cryptoperthites will be necessary to evaluate the applicability of the coarsening data and the extent to which other factors interfere. For compositionally-zoned samples it will be important to correlate the lamellar spacing with the bulk composition, including the An content, and other parameters in that portion of the grain.

The procedure for applying the coarsening data to natural cryptoperthites consists of determining the bulk composition (K/Na ratio) from electron microprobe or X-ray analysis, and using the data in Figure 1 to determine the temperature at which exsolution commenced for that composition. The lamellar spacing of the cryptoperthite is evaluated by TEM. The thermal history can then be estimated for an assumed dependence of temperature on time. Assuming that this relation is linear, the lamellar spacings in a cryptoperthite of composition Or_{33} for various cooling rates are shown in Table 2. For these calculations it was assumed that the exsolution commenced at 560°C , which is near the maximum temperature (Fig. 1). A lower temperature for the start of exsolution will decrease the final lamellar spacing.

As shown in Table 2, most of the coarsening occurs above 400°C , even when the cooling rate is only $1^\circ\text{C}/$

Table 2. Predicted lamellar spacings for exsolution starting at 560°C^*

| Cooling Rate $^\circ\text{C}/\text{year}$ | Temperature has reached ($^\circ\text{C}$) | Lamellar Spacing (\AA) |
|--|---|--------------------------------------|
| 1 | 500 | 1098 |
| 1 | 450 | 1159 |
| 1 | 400 | 1172 |
| 0.1 | 500 | 2497 |
| 0.1 | 450 | 2525 |
| 0.1 | 400 | 2532 |
| 0.01 | 400 | 5440 |
| 0.001 | 400 | 11721 |
| 0.0001 | 400 | 25252 |
| 0.0001 | 300 | 25320 |
| 0.0001 | 200 | 25322 |

* Values do not include initial spacing, λ_0

10,000 years. (The large lamellar spacing for this cooling rate is only a hypothetical example, because coherency would probably be lost before the lamellae reached this size.) Thus the temperature interval within which coarsening of the coherent lamellae occurs is only $100\text{--}200^\circ\text{C}$, and over such a narrow temperature interval the assumption of linear cooling is a good approximation for many geologic situations. However, other relations between temperature and time can be assumed or estimated from heat-flow calculations.

The values for the lamellar spacing in Table 2 appear reasonable, based on the limited observations for natural cryptoperthites. However, in order to evaluate this method, a variety of geologic situations needs to be selected and the cryptoperthites carefully characterized as a function of distance from the margin of the body, *etc.* It is desirable to do this for situations where heat-flow calculations can be used to provide control on the thermal history. Work of this nature is currently in progress.

If the kinetic data are shown to be applicable to cryptoperthites, it would be interesting to extrapolate the data even further to include noncoherent, lamellar perthites. However, this requires a major new assumption that noncoherent perthites form initially as coherent cryptoperthites and lose coherency during very slow cooling in their later history. This requires that the feldspar cool through the temperature interval between the equilibrium or strain-free solvus and the coherent solvus/spinodal (Fig. 1) without exsolving by heterogeneous nucleation. It is tempting to suggest that the regularity of the lamellar microstructure observed in some perthites is unlikely to develop as a result of heterogeneous nucleation.

However, this assumption must be justified by careful analysis of noncryptoperthitic lamellar perthites from geologic environments where the thermal history can be estimated by independent means and compared to that predicted by extrapolation of the kinetic data for cryptoperthites. In order to extrapolate the present data to noncoherent perthites it would be necessary to assume there was no change in the coarsening rate after coherency is lost.

We conclude that the coarsening data reported here offer promise for interpreting the thermal histories of coherent cryptoperthites and should be tested as outlined above. It should also be possible to evaluate whether coarser noncoherent lamellar perthites have undergone a cryptoperthite stage by using the coarsening data to determine whether reasonable thermal histories are indicated. This will require careful analysis of perthites from numerous geologic settings to test basic assumptions which are not directly amenable to experimental study.

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