Microstructure and thermal history of cryptoperthites in a dike from Big Bend, Texas

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Abstract

The lamellar spacings of cryptoperthite phenocrysts sampled across a 5m-wide rhyolite dike have been determined by transmission electron microscopy. The cryptoperthites have a lamellar exsolution microstructure, and the average spacing of the lamellae varies in a regular manner with position in the dike. Near the margins the average spacing is larger (500–630Å) than at the center (460–470Å). The observed spacings are essentially in agreement with the predicted values based on experimental coarsening data and reasonable values for the parameters of heat flow calculations. The larger spacings near the dike margins can be accounted for if the combined initial temperature for the dike and country rock is between 950°–1100°C, and if the latent heat of fusion is between 70–120 cal/gm-deg C. These results limit the initial lamellar spacing to < 300Å, and they are consistent with the available experimental value of 80Å.

Introduction

The spacing of the coherent lamellae in alkali feldspar cryptoperthites from different geologic environments is known to vary over an order of magnitude or more. In previous transmission electron microscope (TEM) studies these variations have been attributed to differences in thermal history (Lorimer and Champness, 1973; Brown and Willaime, 1974). Experimental kinetic data for the lamellar coarsening of cryptoperthites have been published recently (Yund and Davidson, 1978), and these data afford a method for quantitatively estimating the thermal history of natural cryptoperthites.

We have carried out a systematic TEM study of cryptoperthites in a rhyolite dike to see if their lamellar spacings record their thermal histories. The possible cooling histories of the samples have been constrained by constructing theoretical cooling models for the dike. In a companion study, Yund and Chapple have used a similar method to study cryptoperthites in two lava flows. We selected a dike because its cooling history could be suitably modeled using heat flow calculations, and because it provided a controlled field setting.

Geologic setting and sample description

The dike studied is located within the Tertiary rocks of Big Bend National Park, Texas. It is one of several northwest-trending rhyolite dikes which intrude volcanic and sedimentary units west of Ward Mountain in the central region of the park. These dikes are described briefly by Maxwell *et al.* (1967).

Although partially covered by alluvium, the dike can be traced for a distance of 0.8 km. A sample traverse was made where the Castolon access road exposes fresh rock in a roadcut, which is approximately midway between the ends of the dike. Eight hand-specimens were collected at measured intervals. At this locality the dike is 5.2 m wide, dips almost vertically, and has sharp contacts. Along strike the width is estimated to vary by no more than 1.5 m, and 5.2 m is a reasonable average for the dike's width. Field observations indicated little contact metamorphism of the country rock (basalt).

The rhyolite is composed of 5–10% quartz and sanidine cryptoperthite phenocrysts in a groundmass which is cryptocrystalline at the margins to microcrystalline at the center of the dike. The cryptoperthite phenocrysts are 1–3 mm in size and occur as separate, euhedral crystals or in glomerocrysts with quartz.

The rock is best classified as a comendite because the groundmass contains minor amounts of a Na-rich

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ferromagnesian phase, either riebeckite or aegirine augite, and the feldspar phenocrysts are Or_{40}–Or_{43} in composition (see below).

Phenocryst composition and microstructure

Selected sanidine phenocrysts from the margin and center of the dike were analyzed by conventional electron microprobe methods. Pure albite and microcline standards were used, and corrections were made by the procedure of Bence and Albee (1968). One phenocryst from the dike margin had a bulk composition of $Or_{40.2}$ and two phenocrysts from the center of the dike had similar compositions of $Or_{42.6}$ and $Or_{43.1}$. The samples contained no detectable CaO, and probe traverses indicated they were unzoned.

Based on these results we have adopted bulk compositions between $Or_{40.2}$ and $Or_{43.1}$ as representative of the range of compositional variation of these cryptoperthites. However, because only a few crystals were analyzed we recognize that some of the crystals studied in TEM may have compositions slightly outside this range.

The cryptoperthite phenocrysts were prepared for TEM study and examined in the manner described in the accompanying paper by Yund and Chapple. All the phenocrysts show essentially the same coherent exsolution microstructure in TEM. The microstructure as observed in a foil oriented normal to [001] is shown in Figure 1. The lamellae are evenly spaced, straight and continuous for 1–2 μm, and all observations are consistent with an orientation on ($\bar{8}$01). Albite twins were observed in the Na-rich phase in all samples.

The only aspect of the microstructure which varies from phenocryst to phenocryst is the average spacing of the coherent lamellae. This parameter was determined by photographing and measuring 8–12 different thinned areas in each grain. Usually 3–4 places were measured on each photograph and the results for all the areas averaged to obtain a value representing the mean spacing of the microstructure for a grain. The reported error is one standard deviation. At the beginning and end of each session on the TEM, photographs of a carbon replica of a diffraction grating were taken in order to accurately determine the magnification.

It was necessary to correct lamellar spacing values determined for crystals photographed with their lamellar interface inclined to the plane of the photograph. The orientation of each image was determined from its diffraction pattern, and this was used to cor-
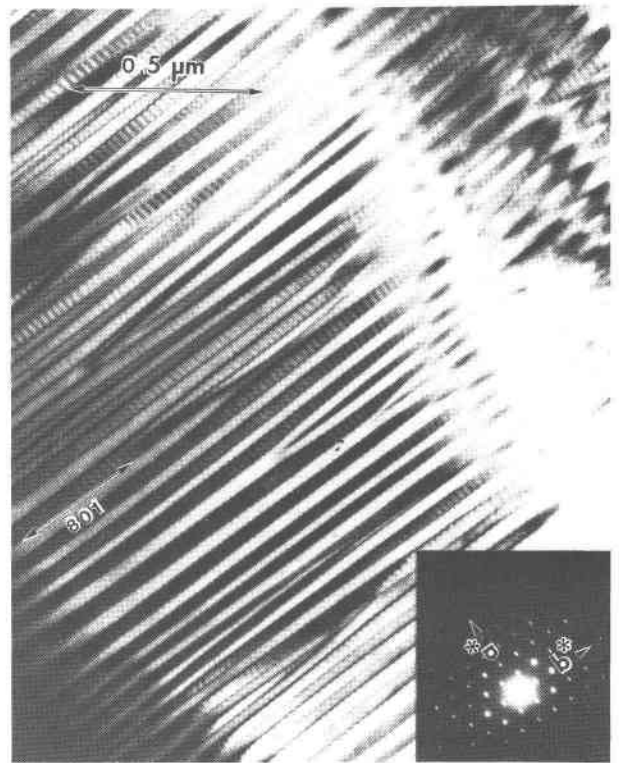

Fig. 1. Bright-field electron micrograph showing the exsolution microstructure of a cryptoperthite phenocryst in the sample 0.5 m from the margin of the dike.

rect measured lamellar spacings when necessary. Only measurements of lamellae oriented within ±15° of normal to the plane of the photograph are reported.

In Figure 2 the lamellar spacing values for phenocrysts in the eight samples are plotted as a function of their position in the dike. The dashed and solid lines are the calculated spacings and are discussed below. The mean lamellar spacings of cryptoperthites from the same hand specimen do not, except for one sample, vary by more than 30Å. One of the contact samples shows greater variation than this and contains a phenocryst with a lamellar spacing 100Å larger than the two other grains in the sample.

The principal feature of the observed spacings is the somewhat larger value for cryptoperthites in samples from the margins of the dike as compared to samples from the center. Within 0.5–1.0 meters of the margins the spacings increase from approximately 460Å to approximately 540Å. Cryptoperthites from the interior portion of the dike have similar lamellar spacings near 460Å.
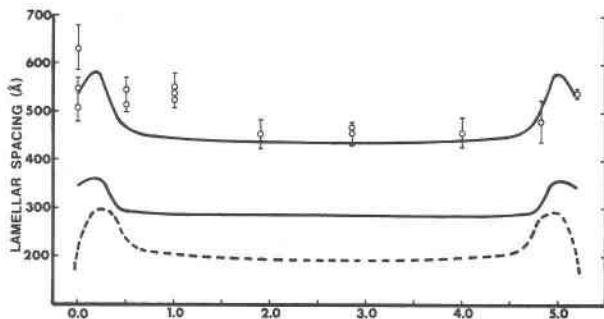
Fig. 2. Comparison of observed and calculated lamellar spacings across the dike whose margins are at 0.0 and 5.2 m. The observed spacings are shown by circles and vertical bars; the calculated spacings are represented by smooth curves which assume an initial spacing of 80Å. The lower dashed curve shows the results for the heat flow case which is illustrated in Fig. 3. The solid curves are for an initial magma temperature of 1000° instead of 900°C (dashed curve). The upper solid curve is for a coarsening activation energy of 24,100 cal/mole instead of 25,000 cal/mole (other curves).

Application of coarsening data and cooling models

A principal objective was to see if the magnitude and distribution of the cryptoperthite lamellar spacings could be correlated with calculated values obtained by combining the experimental coarsening data with theoretical cooling models. The kinetic data and heat flow models used in the calculations will be described before comparing the observed and calculated lamellar spacings.

Coarsening kinetics

The rate of the late-stage lamellar coarsening in a cryptoperthite at a given temperature is given by the experimentally determined relation (Yund and Davidson, 1978):

$$k(\text{Å/day}^{1/3}) = (1.78 \pm 2.20) \times 10^8$$

$$\exp{[(-25,000 \pm 1,200)/RT]} \qquad (1)$$

where k is the rate constant, R is the gas constant and T is temperature in °K. The value 25,000 corresponds to the activation energy for coarsening in units of calories/mole.

The final lamellar spacing attained after a given episode of cooling will depend on the initial spacing which developed during exsolution as well as on the subsequent coarsening. As discussed by Yund and Davidson (1978), the initial spacing should in turn be affected by the degree of undercooling below the coherent solvus/spinodal, and larger initial spacings are to be expected in more slowly cooled samples. They reported that for a sample cooled at about 1°C/day the initial spacing was approximately 80Å.

This value was also obtained for samples which were isothermally annealed between 560°–470°C.

As will be seen below, the cooling paths calculated for the sample positions in the dike predict gradual cooling at average rates of 1°–2°C/day, or rapid cooling (40°–50°C/day) followed by a period during which the positions remain at temperatures between 520°–550°C for 130–150 days. Consequently, an initial spacing of 80Å is consistent with our cooling models, since they predict cooling conditions which are similar to the experimental ones. Because the cooling models allow us to evaluate the coarsening of these cryptoperthites, we have been able to place limits on the initial spacing independent of the experimental value.

The importance of the exsolution temperature as defined by the coherent solvus/spinodal in controlling the total coarsening is discussed in the companion article by Yund and Chapple. The compositional range of our samples ($Or_{40.1}$–$Or_{43.1}$) corresponds to a 3° variation in the exsolution temperature. For most of the coarsening calculations we assume an initial exsolution temperature of 572°C for all samples. Although 3°C is less than the uncertainty in the absolute temperature of the coherent solvus/spinodal, our calculations show that even this small difference between samples could change their final lamellar spacings by 10–20Å and thus measurably affect the lamellar spacing distribution.

Cooling models

Theoretical cooling curves for positions in the dike were calculated by considering that the dike cooled as a 5.2m-wide infinite slab. This idealization is consistent with the dike's observed geometry. The calculations considered the following factors: latent heat of fusion, the thermal diffusivity of the dike and country rock, the initial temperature and solidification temperature of the magma, and the initial temperature of the country rock. The cooling history was calculated analytically during solidification (Jaeger, 1957) and using finite differences after solidification (Smith, 1965, p. 17–20).

Geological and theoretical considerations led us to believe that preheating of the country rock by flowing magma, viscous heating caused by internal friction within the magma, and convective circulation of meteoric water probably were not major factors in the cooling of this particular dike. The considerations are as follows.

(1) The cryptocrystalline texture of the rhyolite at the dike margins suggests very rapid solidification relative to the interior, where the groundmass is micro-

crystalline. There is also no evidence of extensive contact metamorphism. These observations suggest that preheating was minimal.

(2) Although viscous heating has been postulated to explain superheating of magma in some volcanic terrains (Lionel Wilson, personal communication, 1978; Fujii and Uyeda, 1974), this can only be an important factor in dikes greater than 10 m wide (Fedotov, 1976; Fujii and Uyeda, 1974).

(3) Application of boundary layer theory (Parmentier, 1978; Parmentier and Schedl, in preparation) suggests that the dike is too narrow to have cooled by convective circulation of meteoric water. The boundary layer of hot, flowing steam for geologically reasonable permeabilities is at least an order of magnitude wider than the dike. The dike is too narrow to have produced this much steam.

The results of the cooling calculations for one set of input parameters are shown in Figure 3. The cooling curves are for points at the center, and at or near the margins of the dike. The horizontal lines define an initial exsolution temperature of 572°C and the temperature (400°C) below which equation (1) predicts negligible coarsening.

For this heat flow case, points in the dike within 0.5 m of the contacts are cooled almost immediately to temperatures between 570°–540°C and remain at a nearly constant temperature for 0.4 years. Points within 2 m of the center cool more rapidly from 572° to 400°C, but all at essentially the same rate. Thus, according to this model samples at the margins spend a longer time at temperatures just below the coherent solvus and should be expected to coarsen more than samples from the interior.

Calculated lamellar spacings

From the theoretical cooling curves and the coarsening data, lamellar spacing values were calculated for positions in the dike spaced 0.22 m apart. This was done for a number of cooling models. The values for the activation energy of coarsening and initial lamellar spacing were also varied to see how this changed the magnitude and distribution of the calculated spacings. For initial spacings larger than 80Å the coarsening must be calculated over a time interval increased by the time required for the crystal to coarsen the amount of the initial spacing at 572°C. This is necessary because the coarsening rate depends on the lamellae size as well as the temperature. An increase in the initial spacing decreases the total coarsening but still produces a net increase in the final spacing.

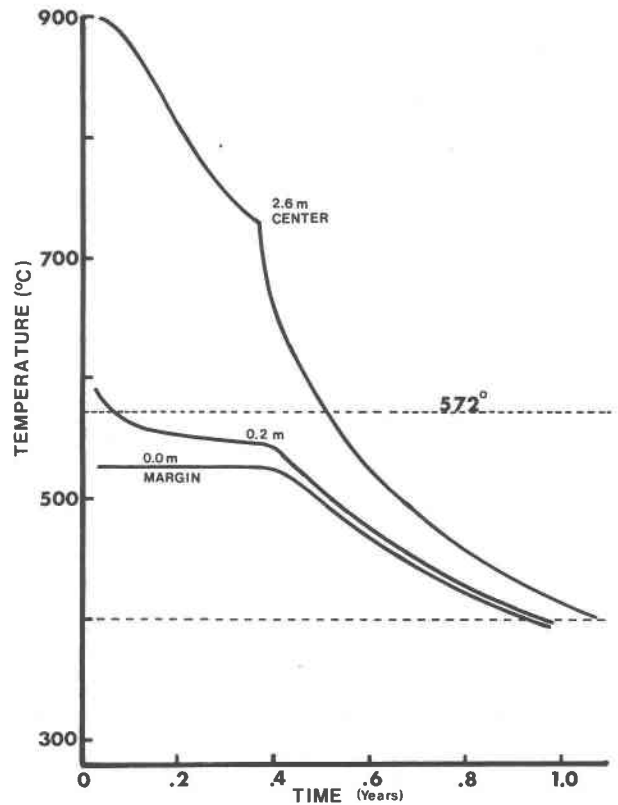The predicted lamellar spacings for two different

Fig. 3. Cooling curves for positions adjacent to the margin and center of the dike. The curves are based on an infinite slab heat flow model which assumes an initial magma temperature of 900°C, a solidus temperature of 750°C, a country rock temperature of 50°C, and a latent heat of fusion of 80 cal/gm-deg C.

sets of heat flow parameters are summarized in Figure 2. For ease of comparison with the observed values, the calculated spacings are represented by smooth curves. The lower dashed curve shows the results obtained from the heat flow case illustrated in Figure 3, combined with an initial spacing of 80Å at all positions, and an activation energy of 25,000 cal/mole. As mentioned previously, 80Å is the initial spacing most consistent with the assumed cooling model and the experimental results of Yund and Davidson (1978). The model predicts no variation in the spacings across the central 4 m of the dike and an abrupt increase in spacing adjacent to the margins. However, within 0.2 m of the margins the predicted spacing decreases abruptly by 150Å. This is not consistent with the observed spacings (see Fig. 2). The agreement at the margins of the dike can be improved by assuming a higher initial magma temperature (1000° instead of 900°C) in the heat flow calculations. The lower solid curve on Figure 2 shows better agreement with the pattern of observed spacings. The distribution has been modified because the

increased magma temperature has displaced the isothermal portion of the contact cooling curve to a higher temperature, increasing the total coarsening at the margins in relation to the center.

Larger spacings at the margin were obtained only for those heat flow cases in which the combined country rock and magma temperature was between 950°–1100°C (for a latent heat of fusion of 70–120 cal/gm-deg C). If the combined temperature exceeds 1100°C the isothermal portions of the contact cooling curves are raised above the coherent solvus, and within the temperature interval 572°–400°C the cooling paths become essentially the same at every position. A flat distribution of lamellar spacings results. Likewise, if the combined temperature is less than 950°C (*e.g.*, the heat flow case in Fig. 3), the spacing is predicted to be smaller at the contact than in the center, although just in from the contact the spacing is larger.

The agreement between the calculated and observed spacings can be further improved by assuming a slightly lower value (24,100 cal/mole) for the activation energy of coarsening (upper solid curve, Fig. 2). This value is within the experimental error (equation 1) reported by Yund and Davidson (1978). The distribution obtained from the lower activation energy agrees in its essential features with the observed spacings. It predicts spacings at the contacts of approximately 540Å, a slight increase in from the margin, and then an abrupt decrease to spacings near 440Å towards the center of the dike.

Discussion

Reasonable agreement between the observed and calculated lamellar spacings was obtained by using an initial spacing of 80Å and allowing for relatively minor variation in the activation energy of coarsening. This suggests that the initial spacings of the cryptoperthites in this dike need not have differed from the values expected on the basis of the experimental data. Furthermore, our calculations show that the predicted spacings do not change significantly as the initial spacing is increased, until the initial spacing exceeds about 250Å. At this point, the predicted distribution begins to deviate from the observed data. Thus the initial spacing appears to have been less than 300Å, and is consistent with the experimental value of 80Å. The remaining differences between the observed and calculated spacings may be attributed to any of the causes summarized by Yund and Chapple. As cited earlier, some of the deviation can

be explained by variations in composition from one crystal to another.

In conclusion, the overall agreement between the predicted and observed spacings is good. This indicates that the lamellar spacings of these cryptoperthites do record their thermal history, and that this history can be quantitatively evaluated. An interesting aspect of the analysis of this dike is that, within our assumed constraints on the possible cooling models (*e.g.*, no pre-heating, no viscous heating), only a relatively small range of heat flow parameters need be used to explain the observed mineralogical relations. Thus, our approach of combining heat flow models with considerations of mineralogical kinetics has permitted us to place reliable constraints on the thermal history of this rock unit.

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