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Thermal histories of two lava flows estimated from cryptoperthite lamellar spacings

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Abstract

The spacings of coherent cryptoperthite lamellae in phenocrysts of two rhyolitic lava flows from Big Bend, Texas have been determined by transmission electron microscopy. The lamellar spacings (660–2140Å) along a section through the lower and upper flows vary systematically, and this pattern of variation is in agreement with that predicted by heat flow calculations and reheating of the lower flow by the upper flow. The values of the observed lamellar spacings can be approximately explained by using the published experimental data for the coarsening of cryptoperthite lamellae and the estimated thermal history from heat flow calculations. The calculated spacings are very sensitive to the initial temperature of exsolution, and hence to the factors which affect this temperature.

Introduction

A knowledge of the kinetics of microstructural changes in minerals provides the potential for estimating at least a portion of the thermal history of a rock unit. Experimental data for the coarsening of the coherent lamellar microstructure in cryptoperthites have been previously published (Yund and Davidson, 1978). In this study we have selected a relatively simple geologic situation (lava flows) to determine whether the lamellar microstructure of natural cryptoperthites records information about their thermal history, and how applicable the experimental data are for estimating this history. The independent control for this study is provided by heat flow calculations of the cooling history for the flows. In an accompanying paper, Christoffersen and Schedl have used the coarsening data and heat flow calculations to evaluate the thermal history of a dike.

Geologic setting

The lava flows selected for this study are located in Big Bend National Park, Texas. They are the lower and upper flows on Burro Mesa (Cerro Castellan and Tule Mountain Quadrangles), which were first mapped and named the Burro Mesa Riebeckite Rhyolite by Maxwell *et al.* (1967). A more comprehensive study of these flows was made by Becker (1967a,b), who mapped Burro Mesa in detail and reported petrographic data and mineral and whole-rock chemistry for both flows. Becker reports that the rhyolite is mildly peralkaline and is a comendite. The blue amphibole is actually fluor-arfvedsonite instead of riebeckite. The features of these flows which are important for the present study are summarized below. Most of this information is taken from Becker (1976b), and her study should be consulted for detail.

The lower flow is sparsely porphyritic (alkali feldspar and quartz) and commonly flow-banded. Becker reports probe analyses of the feldspar phenocrysts which range from Or_{33} to Or_{38}. The flow is from 0 to 80 m thick (about 50 m where we sampled it), and it overlies the Wasp Springs Formation, which is a well-bedded yellow tuff. The basal two meters of the flow are locally brecciated and several discontinuous breccia zones occur within it. Becker interprets these to be due to autobrecciation within a single flow unit.

The upper flow is similar but more porphyritic, and it does not have flow-banding. The feldspar composition range is $Or_{41\text{-}45}$. Erosion has removed the top of the upper flow; it has a thickness of 150 m 0.3 km northeast of where the samples were collected.

The main sample collection traverse started at the base of the lower flow at a normally dry waterfall called the Pouroff, and continued up through Javelina Wash to about 60 m above the base of the upper flow. It is impossible in this area to collect samples higher in the section without moving large distances horizontally. The two flows in this area are separated by about 2 m of a tuff breccia, 1 m of a densely welded tuff, and 3–5 m of an unwelded tuff. The

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length of the hiatus between the two flows is not known, but Becker suggests there may have been some erosion, because of the variable thickness (1–25 m) of the welded tuff in this area.

A few samples were collected from a second traverse in the dry wash and box canyon about 0.5 km northwest of the above area. These were not studied in detail and are only briefly discussed.

These flows are two of the youngest volcanic units in Big Bend Park, about 30 m.y. old (Maxwell *et al.*, 1967), and have probably not been buried or subjected to later thermal events. There is, however, a major normal fault on the eastern margin of Burro Mesa, and the southern half of the mesa has been folded into a gentle syncline.

Measurement of lamellar spacing

In both the lower and upper flows, the feldspar phenocrysts occur as euhedral crystals 1–3 mm in length. They belong to the sanidine–high albite series, as indicated by single-crystal X-ray and electron diffraction. Exsolution lamellae were not visible in most samples with the optical microscope, but all phenocrysts were observed to be exsolved by transmission electron microscopy (TEM). Two phenocrysts, either (001) or (010) sections, were selected from each thin section and foils prepared by ion milling. Bright-field images were taken from 4 to 8 areas around each thinned hole. The larger number of images was recorded if there appeared to be a variation in the lamellar spacing. A carbon replica of a diffraction grating (2160 lines/mm) was also photographed during each session on the electron microscope to ensure an accurate determination of the magnification. A typical micrograph is shown in Figure 1.

Electron micrographs and diffraction patterns showed that the lamellar interface was essentially parallel to ($\bar{8}$01). The orientation of each image was determined from its associated diffraction pattern, and the apparent lamellar spacing was corrected for the orientation of the foil. Measurements were not made unless the lamellae were within 20° of normal to the photograph.

The range in the lamellar spacing within the area of a photograph was normally considerably less than the variation between areas. The lamellar spacings reported in Table 1 are the mean and one standard deviation for the 8–16 areas in the two phenocrysts of each sample. Only one phenocryst was thinned for the sample 20 m above the base of the upper flow, hence we do not report a standard deviation for this sample.

Heat flow calculations

The following idealizations were made in order to calculate the thermal history of the flow. The flow is

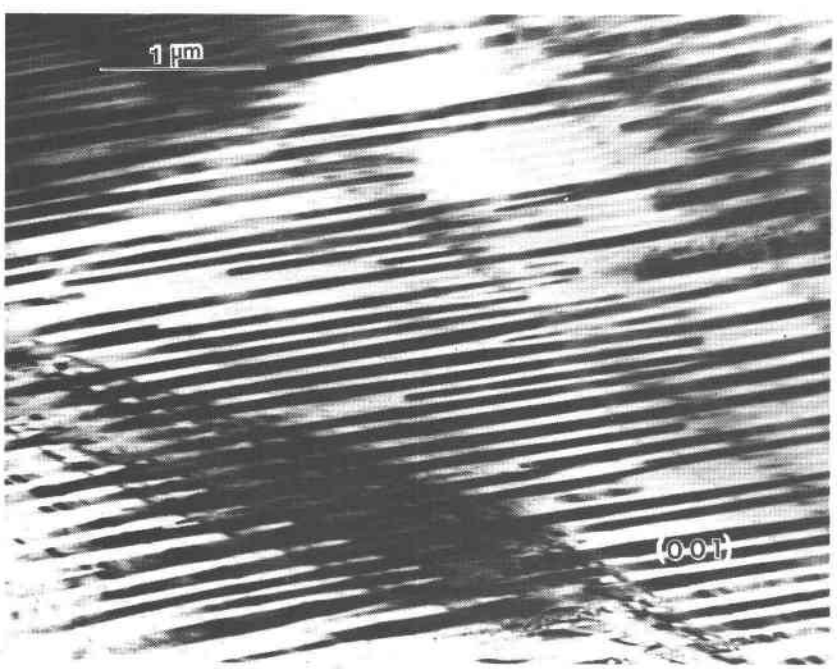

Fig. 1. Bright-field electron micrograph of a (001) foil showing a typical lamellar microstructure in the sample 28 m above the base of the lower flow.

tabular with heat loss only from the top and bottom; it was extruded instantaneously at a temperature of 800°C, which is the fixed solidus temperature. Input parameters are a latent heat of crystallization of 100 cal/g, a thermal conductivity of 0.007 cal/cm sec deg, and a specific heat of 0.2 cal/deg cm^3, all of which are reasonable values for a rhyolitic flow. For simplicity, the thermal properties of the country rock are taken to be the same as those of the flow.

Because of the assumption of a constant solidus temperature, the early history of the flow can be separated into two problems, each of which has an analytical solution. The upper portion of the flow will crystallize and cool according to the solution for a fluid half-space whose surface is held at 0°C (Carslaw and Jaeger, 1959, p. 285–286), while the lower portion follows the solution for a fluid half-space in contact with a solid half-space initially at 0°C (Carslaw and Jaeger, 1959, p. 288). Because in both solutions the fluid portion remains fixed at the solidus temperature, the two solutions can be linked as long as uncrystallized magma remains. The level and time at which the last magma crystallizes can be found from the rates of advance of the fluid–solid interfaces.

After the last magma crystallizes, the problem becomes that of a half-space with a given initial temperature distribution whose surface is held at zero. The solution was obtained by numerical integration of equation 1, p. 59 of Carslaw and Jaeger (1959).

The results of the calculation are summarized in Figure 2, which shows cooling curves for various heights above the base of the flow. The break in the curves at about 10 years corresponds to the disappearance of the last melt, which occurs about 19.7 m above the base of the flow. The steeper slope of the curves after this time occurs because latent heat is no longer being liberated. The horizontal lines indicate the temperature interval of interest for coarsening of cryptoperthite lamellae and will be discussed in the following section. The cooling curves for equivalent positions in a flow of different thickness scale as the square of the thickness; *i.e.*, for a flow 3 times as thick, the time axis in Figure 2 is multiplied by 9.

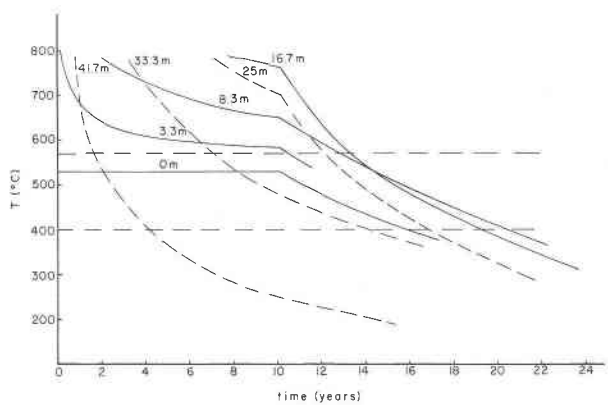

Fig. 2. Calculated heat flow curves for a 50m-thick flow. The curves show the height above the base of the flow. The last liquid occurs at approximately 19.7 m. The curves for the three uppermost levels are shown dashed for clarity. The two horizontal dashed lines indicate the temperature interval of interest for lamellar coarsening.

Interpretation of the lamellar spacings

Calculation of the spacings

The cryptoperthite lamellae in these phenocrysts are coherent and hence must have developed either at the coherent solvus by homogeneous nucleation or at the coherent spinodal by a spinodal mechanism (*e.g.*, Champness and Lorimer, 1976; Yund, 1975). The coherent solvus and spinodal curves are tangential at their crest, $Or_{37.4}$ at 573°C (Sipling and Yund, 1976), and the bulk compositions of these cryptoperthites, Or_{33-38} for the lower flow and Or_{41-45} for the upper flow, are situated on either side of the crest of these curves. Thus the maximum exsolution temperature would be the same within about 5°C regardless of which mechanism was operative. Furthermore, the maximum exsolution temperature for compositions in the interval from Or_{33} to Or_{45} is nearly the same, and to a first approximation this can be taken as 570°C.

The rate of coherent cryptoperthite lamellae coarsening is given by the following equations (Yund and Davidson, 1978):

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

and

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

where λ is the lamellar spacing, λ_0 is the initial spacing, k is the rate constant for a given temperature (T), t is time in days, and R is the gas constant. The experimental value for λ_0 is 60 to 80Å for 470° to 560°C, and the latter temperature is only about 10° below the crest of the coherent solvus. These relations together with the cooling curves shown in Figure 2 were used to calculate the lamellar spacings at the levels in the two flows corresponding to the samples. These spacings are shown in Table 1, and the general pattern of the results will be considered be-

Table 1. Comparison of observed and predicted lamellar spacings

	Height above Base (m)	Observed Spacing (Å)	Predicted Spacing (Å) from Coarsening Data and Heat Flow Calc.			
			50 m thick			150 m thick
			570-470°C λ_o = 100 Å	570-400°C λ_o = 100 Å	570-400°C λ_o = 500 Å	570-400°C λ_o = 100 Å
UPPER FLOW	60	660 ± 30				770
	40	1230 ± 90				1065
	20	1200				1065
	4	1960 ± 170				1160
	1	2100 ± 80				1045
	48	1450 ± 150		Reheating by upper flow		
	38	1220 ± 110		" " " "		
LOWER FLOW	28	1060 ± 90	490	535	605	1010
	23	1390 ± 100	515	565	625	1065
	18	1300 ± 130	515	565	625	1065
	1.7	2140 ± 240	875	895	910	1750
	1.0	1870 ± 140	690	705	805	1340
	0.25	1870 ± 190	550	555	735	1045

fore discussing the differences in the actual values of the observed and predicted spacings.

From the base of the lower flow upwards, the observed spacing first increases and then decreases. This feature is predicted by the cooling curves near the base of the flow. The initial temperature at the base of the flow was probably about 520°C, hence exsolution commenced immediately and coarsening continued for a long time. Above about 2 m from the base, the temperature did not get below 570°C for many years, and when it did the cooling rate to 400°C was relatively rapid, hence there was less coarsening. Samples slightly above the base, but below 2 m, remained at a temperature only slightly below 570°C for a relatively long time. This allowed them to coarsen more than samples nearer the base. The coarsening rate is very sensitive to the length of time spent just below 570°C. Thus the observed reversal in the lamellar spacing near the base of the flow is correctly predicted by the heat flow calculations and coarsening data.

The absence of a similar reversal in the upper flow is not too surprising. It may have been missed by the wide sampling interval, or it may be absent because the base of the flow was above 570°C. This could be due to either a different initial temperature of the flow, or possibly to a still hot lower flow or tuff beneath it.

In a single flow unit the lamellar spacing should decrease continously from a few meters above the base towards the top. This pattern is observed in the upper flow, but not in the lower flow. (The minor reversal between 20 and 40 m in the upper flow is probably not real and is well within the uncertainty of the measured mean spacings.) The second reversal in the lower flow between 28 and 38 m is believed to be due to reheating by the upper flow. Given the uncertainties discussed below, we have not attempted to model this with heat flow calculations, although we believe this could be done within the wide constraints provided by the known geologic relations.

Uncertainties in the calculated spacings

Although the pattern of the lamellar spacings in both flows appears to be accounted for, the calculated spacings are mostly smaller than the corresponding observed values. There are several factors which may account for this difference. These include (1) the uncertainty in the experimental coarsening data and/or their application to a geologic situation in which other variables may have been important, (2) lack of geologic control on the original thickness of the flows and the temperature of the lower flow or tuffs when the upper one was laid down, and (3) the values of the parameters in the heat flow calculation as well as the applicability of this idealized model to

a viscous rhyolitic lava. These uncertainties are considered below.

Experimental coarsening data. These data were determined over the temperature interval from 560° to 470°C. For the cooling rates of these flows, most of the coarsening would occur above 470°C, and it would essentially cease by 400°C. This is shown by the calculations for coarsening in the lower flow for the temperature intervals from 570° to 470°C and from 570°C to 400°C which are given in Table 1. Thus little extrapolation, if any, of the experimental data is required and this is not a significant source of error. Furthermore, even if one uses the maximum and minimum values, respectively, for the pre-exponential factor and for the activation energy permitted by the uncertainties in equation (2), this would increase the predicted lamellar spacing by only about 6–7 percent. In addition, there is no experimental evidence for a change in the coarsening rate with time, as has been observed for some alloys (Saunderson *et al.*, 1978).

Another possible source of error is the initial lamellar spacing. We have rounded the experimental value of 80Å to 100Å for most of these calculations. As discussed by Yund and Davidson (1978), a slow cooling rate might result in a somewhat larger initial spacing. The best argument that the initial value was not significantly larger is provided by the companion study of Christoffersen and Schedl of the cryptoperthites in a dike. To explain the observed lamellar spacing in the dike, the initial spacing has to be less than 300Å.

The parameter λ_0 in equation (1) is not an adjustable constant which can be arbitrarily changed, but the effect of a large value for the initial spacing can be taken into account. This is done by adding to the calculated final spacing the coarsening which would occur during the time it would have taken for the lamellae to coarsen from 100Å to the chosen initial spacing. Assuming an arbitrary initial spacing of 500Å instead of 100Å, the final spacings for the lower flow are increased by a minimum of 50Å and a maximum of 200Å (Table 1). This is because the coarsening rate decreases rapidly with increasing lamellar size. The net effect is that a larger initial spacing reduces the range in the maximum and minimum spacings for the flow, and cannot account for the observed spacings and their range of values.

The effect of water must also be considered. The experimental data were mostly determined at atmospheric pressure and hence a low partial pressure of water. However, one experiment was done at 530°C and 2 kbar water pressure, and the lamellar spacing was consistent with the 1 atm results. Thus the presence of water in the flows would not appear to result in faster coarsening rates. Note also that because these lamellae are coherent, the interface is not similar to a normal grain boundary. Hence water and other volatiles would not have had a high diffusivity path along the interfaces. Neither was there any evidence for an increase in the lamellar spacing along cracks in the phenocrysts. Nevertheless, water is known to increase the rate for volume diffusion of oxygen (Yund and Anderson, 1974) and for Al/Si interchange (Tullis and Yund, 1979) in feldspars; hence it would be desirable to further evaluate the effect of volatiles for lamellar coarsening in cryptoperthites. Although we cannot completely rule out the possibility of water or other volatiles affecting these kinetics, neither is there any direct evidence that the experimental data are not directly applicable to these rocks.

Compositional differences will also affect the lamellar spacings by changing the initial exsolution temperature. As noted previously, the bulk Or/Ab ratio of these phenocrysts changes only slightly and is near the crest of the coherent solvus/spinodal. Thus this compositional variability is not a major uncertainty in the calculated lamellar spacings.

A more important compositional factor is probably the higher Ca content of some phenocrysts compared to the essentially Ca-free material used by Sipling and Yund (1976) to determine the coherent solvus/spinodal. The few samples collected just north of the main traverse have a larger range in the lamellar spacing for individual phenocrysts, and we have tentatively correlated this variation with their chemistry. Most of the phenocrysts from these flows which Becker (1976b) analyzed had only 0.1 to 0.3 mole percent An, although two phenocrysts were as high as 0.5 and 0.6 percent An. The effect of Ca and other impurities on the strain-free and coherent phase relations of the alkali feldspars is not known. Nevertheless, less than one mole percent An might raise the solvus/spinodal a few tens of degrees. This is very important, because the final lamellar spacing is very sensitive to the maximum temperature of exsolution. For example, raising this temperature only 30°C (from 570° to 600°C) would increase the predicted lamellar spacings shown in Table 1 by 30–50 percent. This would account for most of the difference between the observed and predicted spacings. Clearly there is a need for information about the effect of Ca on the phase relations of the alkali feldspars in order

to make quantitative predictions of the coarsening in many cryptoperthites.

Geologic control. The lack of knowledge about the geologic history of these flows is also a major source of uncertainty. The top of the upper flow is eroded, but it is 150 m thick just 0.3 km northeast of the sample area, hence we have used that thickness for the upper flow. The lamellae near the base of both flows are coarser than the calculations predict. A possible explanation for the upper flow would be that the tuffs or lower flow had not completely cooled when it was extruded. However, in order to make the lamellae in the basal portion of the lower flow coarser to match the observed values, the lower flow would have to have been either originally thicker, or underlain by a substantial heat source. Thus although these flows have a relatively simple geologic history, the field situation does not provide sufficient control to evaluate the applicability of the experimental coarsening data in greater detail.

Uncertainties in the heat flow calculations. The calculated thermal history depends on the parameters chosen and on the idealizations made. The most important parameter governing lamellar growth is the solidus temperature. The temperature of the base of the flow falls immediately to a value about 2/3 of the solidus temperature and remains fixed at this value until the last magma crystallizes. Thus the basal temperature changed by 2/3 ΔT for a change in solidus of ΔT. Because lamellar growth is particularly sensitive to temperature variations in this range, the choice of the proper solidus temperature is a critical one. Variations in the other parameters will have a lesser effect.

Of the idealizations made, two are most likely to be important. The assumption of a fixed solidus temperature is crucial for the method of solution, but probably does not change the qualitative nature of the temperature history. However, the assumption that the flow is emplaced before any heat is lost is probably an important oversimplification, particularly near the locally brecciated base of the flow.

By using more complex numerical calculation schemes and adjusting the solidus temperature, it would have been possible to achieve a much closer correspondence between observed and predicted lamellar spacing. However, because it is not clear which of the causes just discussed is responsible for the lack of correspondence, such a close fit would be illusory, and we have therefore not attempted it.

Conclusions

In conclusion, the lamellar spacings of these cryptoperthites do appear to record their thermal history, and the variation of the spacings along a section through the flows is consistent with the geologic relations and heat flow calculations. Furthermore, the observed values of the lamellar spacings can be approximately explained from the experimental coarsening data and the results of heat flow calculations. The lack of closer correspondence between the observed and calculated spacings may arise from several factors, but the most important ones appear to be the lack of geologic control, the uncertainty in the solidus temperature, and the effect of Ca on the coherent solvus/spinodal.

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