

## Simultaneous crystallization of feldspar intergrowths from the melt: a discussion

S. A. MORSE<sup>1</sup>

*Department of Geology and Geography  
University of Massachusetts, Amherst, Massachusetts 01003*

AND GARY E. LOFGREN

*Geology Branch, SN6, NASA Johnson Space Center  
Houston, Texas 77058*

Lofgren and Gooley (1977) have presented a thought-provoking case for simultaneous growth of "perthite-like" intergrowths from the melt. However, some of the discussion needs clarification, particularly in regard to the thermal location of the runs with respect to the ternary feldspar solvus, and the zoning arguments used to refute exsolution.

### Initial conditions

It should be made clear that all runs were held at 1000°C for 24 hours before the cooling experiments. Duplicate 24-hour runs at that temperature revealed only homogeneous glass ( $\pm$  vapor) when quenched. Therefore we have no doubt that all the feldspars observed nucleated and grew during the cooling experiments.

### Solvus position

The question at hand is whether these intergrowths formed by exsolution from a metastable homogeneous feldspar, or formed by simultaneous growth from the melt. The simultaneous growth hypothesis is favored by the probability that all or nearly all of these runs were held *within* the ternary feldspar solvus, rather than above it as implied by the discussion on p. 222–223 of the paper. The Ab–Or solvus as discussed by Lofgren and Gooley has no relevance here. The effect of An in their ternary feldspar starting materials is to increase the consolute

temperature drastically. Unfortunately, we have no complete  $T$ – $P$ – $X$  maps of the ternary solvus. The single point determined for a natural mesoperthite by Morse (1969) at 0.5 kbar is not in close accord with the more comprehensive synthetic studies at 0.5 and 1.0 kbar by Seck (1971). Nevertheless, we can calculate useful if approximate estimates of temperature. Assuming a value for  $dT_c/dP$  of 15°C/kbar, we can deduce solvus limb temperatures at 5 kbar ranging from about 920°C for composition F-1 (the only value below 1000°C) to more than 1200°C for composition F-11. The estimated limb for F-1 lies above the H<sub>2</sub>O-excess liquidus temperature found by Yoder *et al.* (1957), and above the inferred nucleation temperature of 800–850°C for capsule 510 (p. 221 of Lofgren and Gooley). The other solvus limbs manifestly lie above the 1000°C starting point (in the liquid field) of the cooling experiments. Inasmuch as the solvus position remains roughly fixed under the approximately isobaric conditions of the runs, and is cut by the solidus for hydrous melts, there can be little doubt that the main nucleation events took place within the stable solvus. This does not exclude the possibility, of course, that single-phase plagioclase cores nucleated *metastably* before sanidine overgrowth began, but it does assure us that the two-feldspar intergrowths were formed under conditions where two feldspars were stable.

In view of this analysis, the rejection of cotectic crystallization on p. 223 *ff* of the paper is incorrect. The textures themselves abundantly prove that the second phase nucleated, and this could not happen

<sup>1</sup> Temporary address: Mineralogisk-Geologisk Museum, Sarsgt. 1, Oslo 5, Norway

unless the liquid had reached (and probably overreached) the sanidine field boundary or its metastable extension at least locally. Whether the "bulk liquid" (p. 225) is at or near the field boundary is immaterial because it is the local boundary-layer liquid that counts.

#### Further argument for simultaneous growth

One line of evidence for simultaneous growth was inadequately emphasized in the original paper. In many of the experimentally grown crystals (Fig. 2, p. 220; Fig. 3, p. 221) the sanidine overgrowths have areas of lamellar intergrowth and areas free of lamellar intergrowth. It is most likely that the sanidine sectors (Fig. 2, p. 220) free of intergrowths grew at the same time as the sectors defined by the lamellar intergrowths. The sanidine in both sectors has the same composition (Fig. 11b, p. 226), yet in the lamellar intergrowth sector there are about equal proportions of  $An_{25-15}Or_{15}$  plagioclase and  $Or_{70-60}An_{2-4}$  sanidine. For the intergrowth to have formed by exsolution, the original composition of the unexsolved feldspar would have had to have been significantly different from the hypersolvus feldspar in the adjacent sectors. Furthermore, this hypersolvus composition would have to have exsolved a sanidine of the same composition, and normally zoned in the same manner, as the sanidine in the intergrowth-free sector. Sector zoning has been observed in feldspar, but compositional differences between the sectors sufficient to produce the intergrowths would have to be more dramatic than has been reported. Even if the sector zoning argument were adequate to explain the above case, it would not explain the relationship between the intergrowth-free area and the areas defined by lamellar intergrowths in zone 3 of the crystal shown in Figure 3 (p. 221), where the same spatial-distribution, composition argument outlined above can be applied.

These arguments strengthen the case for simultaneous growth. Taken together with the subsolvus nature of the cooling experiments, they seem to us quite persuasive. The boundary layer-supersaturation mechanism suggested in the original paper appears to be an adequate hypothesis for the observed textures. Despite this, the case against exsolution is not as strong as suggested in the original paper, as we now show.

#### Zoning and exsolution

One argument by Lofgren and Gooley (p. 223) was based on zoning. It was argued that since the alkali-

ion distributions have not been equilibrated by diffusion during the runs, one should not expect exsolution, said to involve the stronger Al-O and Si-O bonds. This line of argument is weak, because the structures observed are to a close approximation alkali feldspars in which Na,K migration will dominate the exsolution process, requiring little tetrahedral Al,Si rearrangement. This might seem to strengthen the argument that zoning precludes exsolution, but cation exchange and exsolution are very different phenomena, driven by very different potentials. If one considers hypersolvus  $G-X$  diagrams, for example, one can conclude that a single feldspar composition, homogeneous in Na/K, might be only slightly minimized relative to a mechanical mixture of two different zone compositions. Local equilibrium would also lessen the tendency for diffusive alkali exchange. By contrast, the  $G-X$  diagram for temperatures well within a solvus would suggest that a mixture of nodal compositions would be strongly minimized in  $G$  relative to a homogeneous single phase. The tendency to decompose or exsolve may, at least conceptually, be far stronger than the tendency for cation exchange; behold the double  $G-X$  curvature in the former case as compared to the single curvature in the latter case. See Yund (1975) for a discussion of the barriers (or lack of them) relevant to exsolution.

Another argument against exsolution was based on lamellae compositions, but these are in any case far from "equilibrium" compositions in the experimental runs. If the lamellae grew by spinodal decomposition, they would be expected to have compositions closer together than the equilibrium compositions. If they arose by nucleation and growth, one would expect the "equilibrium" (binodal) composition, but what is that? In this case it is actually the spectrum of compositions produced by sliding or stepping down the solvus; the lamellae themselves should be (and may really be) zoned, and the individual composition distribution in a single lamella should bear some resemblance to a fractional crystallization product. In either spinodal decomposition or nucleation and growth, the expected lamellae compositions for these experiments are surely closer together than the equilibrium compositions for a given single-step temperature within the range of the run.

One may therefore conclude that neither the presence of zoning gradients nor the compositions of lamellae preclude an origin of the intergrowths by exsolution. Further, it is difficult to see how lamellae composition could be used to differentiate simultaneous growth from exsolution in natural rocks. That

would best be done by evaluating the overall textural evidence for strong supersaturation, and by observation of such compositional disparities in adjacent areas as cited in the section above.

### Conclusions

In summary, simultaneous growth appears a reasonable hypothesis, strengthened by the subsolvus location of the runs and by marked disparities in bulk composition (but not sanidine composition) between adjacent sectors or zones. Exsolution is not precluded by the existence of zoning gradients or by the compositions of lamellae, as far as we know. Epitaxial growth of lamellae from a supersaturated melt is a process energetically and conceptually indistinct from metastable nucleation of a single phase followed quickly by exsolution. Given the positive evidence for simultaneous growth, the role of exsolution is in any event minor, and perhaps moot.

The first author owes the second a deep apology

for not reading a preprint carefully more than a year ago, when these problems could have been aired before publication.

### References

- Lofgren, G. E. and R. Gooley (1977) Simultaneous crystallization of feldspar intergrowths from the melt. *Am. Mineral.*, 62, 217-228.
- Morse, S. A. (1969) Ternary feldspars. *Carnegie Inst. Wash. Year Book* 67, 124-126.
- Seck, H. A. (1971) Koexistierende Alkalifeldspäte und Plagioklase im System  $\text{NaAlSi}_3\text{O}_8$ - $\text{KAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$ - $\text{H}_2\text{O}$  bei Temperaturen von 650°C bis 900°C. *Neues Jahrb. Mineral. Abh.* 115, 315-345.
- Yoder, H. S. Jr., D. B. Stewart and J. R. Smith (1957) Ternary feldspars. *Carnegie Inst. Wash. Year Book* 56, 206-214.
- Yund, R. A. (1975) Microstructure, kinetics, and mechanisms of alkali feldspar exsolution. In P. H. Ribbe, Ed., *Feldspar Mineralogy*, Mineral. Soc. Am. Short Course Notes 2.

*Manuscript received, October 31, 1977; accepted for publication, November 16, 1977.*