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The role of magmatic reaction, diffusion, and annealing in the evolution of coronitic microstructure in troctolitic gabbro from Risör, Norway: a discussion

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ABSTRACT. The data of Joesten (1986) are re-interpreted. The petrography of the coronas is not consistent with magmatic origin. Both microstructural types described by Joesten (1986), here re-named 'columnar' and 'tabular', formed by solid-state replacement of plagioclase and of adjacent olivine or ilmenite. Tabular microstructures are not annealed, but result from overgrowth or epitaxy of amphibole and pyroxene on pre-existing grains. Since the diffusion-controlled models of Joesten (1986) can account for major aspects of the coronas, it seems possible that a slightly modified, less simplified theory might explain them fully. Open-system behaviour must be admitted, with some constraints provided by symplectites. It may also be necessary to develop the theory in more than one dimension, and to allow for departures from local equilibrium at layer boundaries.

KEYWORDS: coronitic microstructure, gabbro, Risör, Norway.

JOESTEN (1986) presents valuable data, but I do not accept his interpretation. In his introduction, he straightforwardly declares his 'advocative' approach, which stresses features consistent with magmatic origin, and seeks to overthrow the widely accepted metamorphic interpretation of such coronas (e.g. Mongkoltip and Ashworth, 1983). I propose to show that Joesten's interpretation is untenable, and that all features of the Risör coronas are consistent with metamorphic origin. Beyond that, it will be shown that if solid-state origin is accepted, then details of Joesten's data may help to explain discrepancies between the natural coronas and his model computations, based on the theory of steady-state diffusion control (SSDC).

Magmatic origin versus solid-state replacement. The coronas occur around grains of magmatic olivine and ilmenite, where these are adjacent to magmatic plagioclase. A series of layers consistently separates the plagioclase from olivine (fig. 1) or from ilmenite. According to Joesten (1986), the layers originated by reaction with, and crystallization from, a melt, not by reaction between the solid plagioclase and olivine (or ilmenite). He disregards their constant association with the particular primary, magmatic phases. His descriptions and figures demonstrate that a corona of rather uniform width is developed along a given olivine/plagioclase or ilmenite/plagioclase boundary. This geometry could not arise if crystallization of interstitial melt (laterally adjacent to the corona) was a major source of corona material. Nor is it reasonable to suggest that a layer of melt, around olivine or ilmenite, crystallized the corona minerals which then by chance came into contact, consistently, with plagioclase. Orthopyroxene layers around olivine not adjacent to plagioclase, and amphibole-spinel symplectite around plagioclase not adjacent to olivine, are presumably of similar origin to the corona layers and can be interpreted if the coronas are understood. This is not to deny that some orthopyroxene in the Risör specimen may be magmatic, particularly where it does not form a simple layer.

In his magmatic interpretation, Joesten (1986) does not accept plagioclase as a reactant in corona formation: 'The apparent cross-cutting of plagioclase by coronas on olivine . . . does not necessarily imply consumption of plagioclase by the reaction.' This statement is irrelevant because he has already deduced that the 'columnar impingement' effect seen in some of the coronas (columnar microstructure of my fig. 1) implies replacement, not only of olivine (by orthopyroxene) but also of plagioclase (by amphibole–spinel symplectite). Whether or not it is part of a corona, amphibole-spinel symplectite is consistently in contact with plagioclase; very rare exceptions (e.g. Joesten, 1986, fig. 6) are easily explained by the plagioclase having

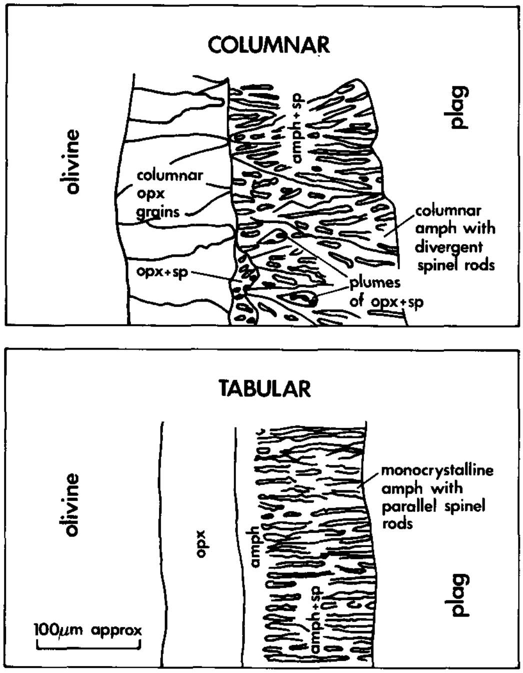

FIG. 1. Summary diagrams of the two microstructures described, in coronas between olivine and plagioclase, by Joesten (1986). The descriptive terms 'columnar' and 'tabular' (based on grain shapes) are proposed in place of the erroneous genetic terms, 'primary' and 'annealed' respectively, of Joesten (1986). The layer widths are drawn approximately to scale, for typical measurements by Joesten (1986, Table VI), but the width of spinel rods in the symplectites is exaggerated. Mineral abbreviations: amph = amphibole, opx = orthopyroxene, plag = plagioclase, sp = spinel.

been entirely replaced (within the plane of the thin section).

Despite assertions to the contrary (e.g. in his abstract), Joesten's (1986) corona amphiboles have distinctive compositions. Relative to the magmatic amphibole, that in coronas around olivine has strikingly lower Ti, and that around ilmenite has higher Ti (Joesten, 1986, Tables I, II, and IV). That magmatic orthopyroxene is compositionally indistinguishable from corona orthopyroxene is not surprising, since the major variable (Mg/Fe, at or near exchange equilibrium with olivine) is rather insensitive to temperature (Medaris, 1969), and moreover, the magmatic minerals may have undergone Mg–Fe exchange during cooling. Joesten (1986) interestingly points out the pargasitic nature of the amphiboles, i.e. high Na content in the *A*-site. Indeed, this is unusual for metamorphic amphiboles (Robinson *et al.*, 1982, pp. 19–20), and suggests either disequilibrium or very high metamorphic grade. Disequilibrium amphibole compositions, including some pargasitic ones, are documented by Mongkoltip and Ashworth (1986, especially fig. 14), in partly amphibolitized rocks: however, corona reactions that consistently produce pargasitic amphibole may truly reflect high-temperature conditions, at an 'early retrograde' stage, only just below the solidus. Otten (1984) discusses the subsolidus origin of such amphiboles, at high temperatures (~ 1000 °C if the Ti content of amphibole coexisting with ilmenite can be trusted as a geothermometer). Indeed, it is quite conceivable that some coronas (of the general kind under discussion) originate while there is still interstitial melt in the rocks; they are not crystallization products of this melt (which would produce intercumulus associations, not coronas), but the melt may interact diffusively with the growing corona in an open system (see below). My essential point is that coronas of this kind are derived from pre-existing solid minerals. Thus I shall call them *solid-state replacement* products (rather than 'metamorphic' or 'subsolidus', which could be taken as denying any possibility of nearby existence of melt).

Joesten's (1986) further arguments for magmatic origin are based on conflicts between the observations and his SSDC theoretical model, discussed below. Whether or not the data can be reconciled with diffusion control, arguments about mechanism cannot detract from the consistent petrographic evidence for solid-state replacement.

Annealing versus monocrystalline growth. A very useful contribution by Joesten (1986) is to distinguish two varieties of microstructure in the coronas (fig. 1). Along a 'columnar' layer, many adjacent grains of orthopyroxene or amphibole differ only slightly in orientation of the lattice, i.e. have 'low-angle' grain boundaries (Joesten, 1986). Other salient observations (Joesten, 1986) are: that one corona often contains both types of microstructure; that transitional types exist (notably with columnar orthopyroxene but tabular amphibole); and that all olivine grains that have tabular coronas are also partly rimmed by pre-corona, magmatic amphibole in optical continuity with the tabular amphibole.

A crucial observation is that, in both types, the spinel rods in amphibole are approximately perpendicular to the amphibole/plagioclase interface. Thus, in a columnar amphibole grain the rods fan out; in the tabular case they form an approximately parallel array (fig. 1). Joesten's (1986) interpretation is that columnar amphibole becomes tabular on annealing, by coalescence of grains through migration of their low-angle boundaries, and that during this process the spinel rods 'rotate into parallel'. But the rods would not rotate in this way: material between them would not be redistributed so as to cause any rotation. They would retain their pre-existing orientations while the amphibole boundary swept past them, just as exsolution lamellae in pigeonite preserve their old (001) orientation after the pigeonite has inverted to an orthopyroxene (with a completely new lattice orientation) whose boundary may have swept through several pigeonite grains (e.g. Bonnichsen, 1969, fig. 11). If amphibole had coarsened, it is possible that the shape (rather than orientation) of spinel would have begun to adjust to a lower-energy configuration: rods might coarsen and lose some of their elongation, as in metamorphically annealed myrmekite (Ashworth, 1986). There is little sign of this in Joesten's (1986) 'annealed' microstructure (e.g. his fig. 9).

Also, if one of several columnar grains is to absorb its neighbours during annealing, there is no reason why this favoured grain should invariably be in exact optical continuity with nearby magmatic amphibole. Joesten (1986) calls the magmatic grain a 'template for annealing'. The more sensible interpretation is that it was a template for *growth.* The monocrystalline (tabular) amphibole grew as a monocrystal, without any nucleation event, as an outgrowth from the magmatic grain. Initially, it must have spread as a thin layer along the olivine/plagioclase contact. Then it grew into the plagioclase. This explains the attitude of the spinel rods, which record the growth direction of the host amphibole in both tabular and columnar microstructures. The columnar amphibole occurs where this mineral nucleated afresh, instead of overgrowing a magmatic grain.

This interpretation accounts for the other relevant observations. Monocrystalline orthopyroxene layers are either continuous with earlier (magmatic) orthopyroxene or nucleated epitaxially on the amphibole. Occurrences of a columnar orthopyroxene layer with a tabular amphibole one may reflect difficulty of epitaxy of the orthopyroxene on the clinoamphibole. The tabular microstructure is favoured where the magmatic amphibole is fortuitously oriented favourably for fast growth and diffusion in the corona-forming reaction. Thus, the abrupt changes of microstructure at corners of olivine (Joesten, 1986, fig. 12) can be attributed to changes from favourable to unfavourable growth direction for the tabular microstructure. Other lateral transitions from tabular to columnar may be changes from unfavourable to favourable sites for heterogeneous nucleation on the initial olivine/plagioclase interface, or may represent increasing distance from the nearest magmatic amphibole.

The above interpretation invalidates the idea of a time-sequence from columnar to tabular microstructure, for which Joesten (1986) presents no acceptable evidence.

Coronas and diffusion control. Joesten (1986) applies the SSDC theory that has been successful in modelling other layered, solid-state 'reaction bands' (Joesten, 1977). Given only the compositions of the minerals, the theory predicts the possible, diffusionally stable sequences of layers. For the tabular coronas around olivine, it successfully predicts the observed layer sequence, but not the bulk compositions of coronas (e.g. the relative widths of layers). It is worth remarking that this discrepancy might have gone unnoticed if Joesten had measured only the mineral compositions (as being the only input required for the computations), as did the previous SSDC modeller of similar coronas (Nishiyama, 1983), making it difficult to assess the significance of his results. The very detailed observations of Joesten (1986) are thus an excellent complement to his theoretical work. For the columnar coronas, the model fails to predict one layer (the orthopyroxene–spinel symplectite). This leads Joesten (1986) to reject a solid-state origin categorically: 'If the mineral assemblage layer sequence of an observed corona is not stable, then that corona cannot have been produced by *any* solid-state process' (my italics). The word 'any' seems too strong here; also Joesten's (1986) model embodies simplifications which make it questionable whether diffusional instability has been proved.

A major part of the discrepancy between model and observations can be attributed to open-system behaviour of the coronas. The model assumes a system that is closed except to H_2O. In the latter part of his section on Interpretation of Critical Compositional Relations, Joesten (1986) rightly emphasizes the impossibility of explaining the coronas by such closed-system reaction between the primary minerals. This does not mean that coronas around olivine did not form by reaction between olivine and plagioclase; it means that the reaction also involved transfer of material to and from the corona's environment (see also Mongkoltip and Ashworth, 1983). Joesten (1986) himself stresses the difficulty of writing a closed reaction, even on a whole-rock scale, particularly for Fe, Mg, Ti, and K. Thus, the closed-system constraint in the model is unnatural and unjustifiable. From the outset of the modelling it is evident that not all the observations can be accounted for, because immediately after presenting his model reaction (his equation 1), Joesten (1986) points out that the observed layer-width ratios violate it. It is noteworthy that, despite this fundamental flaw, the

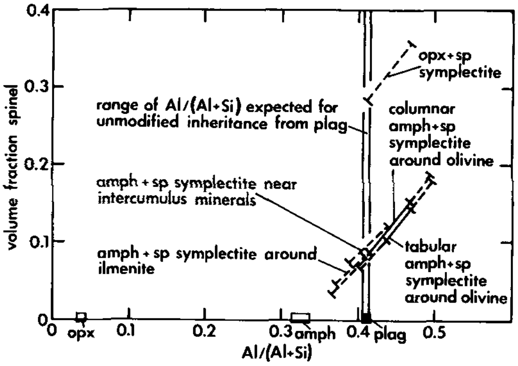

FIG. 2. Diagram to illustrate the similarity between Al/(Al + Si) in symplectites and in adjacent plagioclase, from the data of Joesten (1986). His range of estimated volume fraction of spinel in each type of symplectite is plotted against the Al/(Al + Si) range calculated from that volume-fraction range combined with his analyses. Dashed lines represent overall ranges, including all uncertainties quoted by Joesten (1986) for the volume fraction of spinel: solid lines for amph + sp symplectites around olivine represent his preferred ranges. The Al/(Al + Si) ranges of individual silicate minerals, occurring in or adjacent to the symplectites, are shown for comparison. Mineral abbreviations are the same as in fig. 1.

theory does generate the observed sequence of tabular layers. This suggests that minor modification of the SSDC theory, to allow an open system, might produce a completely successful model for the tabular coronas.

The open-system behaviour requires transport along grain boundaries of the rock, presumably by grain-boundary diffusion rather than through a free aqueous phase, since the assemblages are not H_2O-saturated (Mongkoltip and Ashworth, 1983). This is diffusion in a different direction from that modelled by Joesten (1986), whose theory is one-dimensional (or radially symmetric, as he expresses it). Diffusion in a 'tangential' direction, within a layer boundary of the growing corona, deserves at least a mention where symplectites are produced (cf. Mongkoltip and Ashworth, 1983, fig. 2). The symplectites may provide evidence that some elements were relatively slow-diffusing. Mongkoltip and Ashworth (1983) show that Al/(Al + Si) in some symplectites is so close to that of reactant plagioclase as to indicate that Al and Si contents were inherited almost unmodified from the plagioclase, and that within the symplectite-forming interface these elements moved only short distances to produce the quasi-periodic symplectic intergrowth. Joesten's (1986) data support the same interpretation. If allowance is made for inevitable uncertainties in estimating the volume fraction of spinel in a symplectite, the results for Al/(Al + Si) cluster closely around the value for reactant plagioclase (fig. 2), and it is difficult to imagine what else might constrain them to this part of the diagram. Joesten (1986) himself points out (but makes no use of) the fact that Al/(Al + Si) in orthopyroxene–spinel symplectite is indistinguishable from that in the associated amphibole-spinel symplectite. That is an important observation, strongly indicating that both symplectites are derived ultimately from plagioclase (cf. the comparison of amphibole–spinel and amphibole-anorthite symplectites by Mongkoltip and Ashworth, 1983). Of course, Al and Si are not absolutely fixed in the symplectites: for example, a little Al gets into Joesten's (1986) non-symplectic orthopyroxene. However, the above interpretation does offer a simplifying approximation that may be useful in open-system SSDC models of such coronas: it may be reasonable to hold Al and Si constant within the model corona-forming system. Incidentally, since the symplectite is derived from plagioclase, much the greater part of the corona around ilmenite in fig. 3 of Joesten (1986) is derived from the plagioclase, and only a small volume of ilmenite has been consumed: this lessens (but admittedly does not eliminate) the difficulty of accounting for Fe and Ti from the reactant ilmenite. Clearly, there is a need for integrated studies of all the reactions within a rock. Van Lamoen (1979) has attempted this, but makes a questionable assumption by fixing Si but not Al. In the future, judicious study of symplectites may perhaps provide sufficient, realistic constraints for fairly complete modelling, including an assessment of bulk metasomatic changes or diffusive interactions with any residual melt. It may then become clear whether the processes are consistent with diffusion-controlled kinetics.

In contrast to the tabular coronas, the columnar coronas with an orthopyroxene–spinel layer are apparently unstable in Joesten's (1986) model. However, they are otherwise very similar to the tabular coronas for which the SSDC model so nearly succeeds, suggesting that the theory needs further modification rather than total rejection. The discontinuous nature of the orthopyroxene–spinel 'layer' (fig. 1) does seem inconsistent with the usual criteria for recognizing a diffusion-controlled layer structure ('strong spatial organization, with well-defined mineral zones . . . arranged in an orderly sequence': Fisher, 1977, p. 383). However, the criteria apply strictly to the one-dimensional case only. If 'tangential' diffusion (along lateral gradients of chemical potential) is allowed, lateral changes in layer sequence seem permissible. One wonders whether such gradients for H_2O (a component not modelled at all by Joesten, 1986) could be relevant. The spread of an anhydrous assemblage (orthopyroxene–spinel) into the plagioclase-derived volume suggests a local shortage of water. (Admittedly, the time dimension may also be involved here: it is difficult to tell whether the two symplectites grew simultaneously or sequentially). It would be interesting to know whether the orthopyroxene-spinel layer could be stable in a hydrous model computed at low μ_{H_2O}. If not, then further scrutiny of the theory is called for. In the corona context, the most obviously suspect of the fundamental assumptions is that of local equilibrium at all layer boundaries. Mongkoltip and Ashworth (1983) commented on the improbability of equilibrium between relict, igneous plagioclase, and adjacent corona products, notably (in their rocks) anorthite. Perhaps the SSDC theory should be modified accordingly. On the other hand, Joesten (1986) cites detailed textural features of the columnar coronas which he judges to be inconsistent with diffusion control (section on Interpretation of Critical Microstructures, points 1, 2, 6, and 7). If this is correct, some different kinetic control should be sought for this solid-state replacement process, irrespective of whether the products are diffusionally stable.

An interesting aspect of this study is that the layer sequence appears to be related to *mechanism of reaction*. The orthopyroxene–spinel symplectite is generally associated with the columnar microstructure (though Joesten, 1986, does mention some orthopyroxene–spinel plumes in tabular amphibole–spinel symplectite). Thus, development of the orthopyroxene–spinel 'layer' seems to be favoured by nucleation of the other layers on the olivine/plagioclase boundary. If diffusion is relevant, then it should be borne in mind that the columnar microstructure provides an additional pathway (the low-angle grain boundaries). This could enhance reaction rates, which would be consistent with the generally wider layers in columnar than in tabular microstructures (Joesten, 1986, Table VI). If water-deficiency is relevant, then one may speculate that the faster-growing columnar coronas might tend to exhaust the local supply of H_2O.

Conclusions. My conclusions from Joesten's (1986) data are:

1. The coronas in the Risör specimen formed by solid-state replacement of plagioclase and of adjacent olivine or ilmenite.

2. The two microstructural types of layering, here called 'columnar' and 'tabular', arise from different mechanisms of reaction. Tabular amphibole and orthopyroxene overgrow, or are epitaxial on, magmatic grains. In the columnar microstructure, these minerals have heterogeneously nucleated at the olivine/plagioclase contact.

3. The success of the SSDC model in generating the tabular layer sequence, while failing to simulate more detailed aspects such as the (variable) layer-width ratios, suggests that SSDC theory can account for the processes in this microstructure but should be modified to allow for an open system. Compositions of symplectites replacing plagioclase suggest approximate closure to Al and Si.

4. For the columnar microstructure, further modifications to the SSDC theory (e.g. variable water deficiency, departures from local equilibrium) might be tried, in the hope of modelling the slightly different layer sequence.

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