

Reply

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INTRODUCTION

THE two observations that are the basis for the metamorphic hypothesis for the origin for coronas are that (1) coronas occur only in gabbroic rocks in high-grade metamorphic terrains and that (2) in these rocks, grains of olivine and ilmenite are everywhere separated from plagioclase by the mineral assemblage layers of the corona structure. With the experimental demonstration that the troctolitic assemblage forsterite + anorthite reacts to form diopside + enstatite + spinel at pressures in excess of about 8 kbar (Kushiro and Yoder, 1966), a plausible mechanism became available for production of coronas either by prograde metamorphism or by reaction on cooling of synmetamorphic intrusions. The pyroxene-spinel assemblage is also produced by reaction of forsterite and liquid at high pressure (Presnall *et al.*, 1979), however. Thus, although the geologic association of coronitic gabbros with amphibolite-facies and granulite-facies metamorphism is consistent with an origin by metamorphic reaction, the same experimental results demonstrate that coronas may just as well be the result of magmatic crystallization at pressures above the stability range of the olivine-plagioclase cotectic.

Although there are no features of coronitic rocks, apart from these, that suggest a solid-state or metamorphic origin, essentially all of the authors of the twenty or so papers dealing with the genesis of coronas published over the past twenty years unquestioningly accept their metamorphic origin (see bibliography in Mongkoltip and Ashworth, 1983). The author of the paper under discussion approached the study of the coronitic rocks from Risör with the same perspective. However, coronitic microstructures are unusually well developed and well preserved in these rocks, and the inescapable conclusion of that study was that coronitic microstructures cannot have been produced by solid-state reaction between olivine and plagioclase.

The main conclusions of the original paper (Joesten, 1986) are that: (1) coronas identified as possessing primary 'as-grown' microstructure are the result of sequential crystallization of a spinel-saturated basaltic magma at pressures above the stability field of the plagioclase-olivine cotectic; (2) coronas possessing the tabular microstructure are the annealed equivalent of the primary coronas; and (3) irreversible thermodynamic calculations show that the mineral assemblage layer sequence of the primary coronas is diffusionally unstable along the chemical potential gradients established by buffering at layer contacts, and thus should spontaneously transform to a stable sequence; the mineral assemblage layer sequence of the annealed coronas is diffusionally stable.

Ashworth (1986) rejects these conclusions and counters that (1) coronas are the product of solid-state reaction between olivine and plagioclase, (2) microstructural types identified as primary and annealed in fact formed simultaneously due to differences in nucleation behaviour, and (3) oversimplifications in the model preclude prediction of a stability field for the mineral assemblage layer sequence of primary coronas. He further argues that the near identity in the ratio $Al/(Al + Si)$ of plagioclase and spinel-bearing symplectite means that growth of corona layers involved limited transport of Al and Si.

At least our differences are clear-cut! For the purpose of continuity in this exchange, I accept Ashworth's substitution of the descriptive terms, 'columnar' and 'tabular' for the interpretative terms, 'primary' and 'annealed' used in reference to the two microstructural types of coronas (compare fig. 1, Ashworth, 1986, and figs. 5 and 9, Joesten, 1986).

Textural and compositional observations that demand a magmatic rather than a metamorphic origin for the primary or columnar corona microstructure and which lead to the identification of the tabular corona microstructure as the annealed equivalent of the columnar microstructure are extensively documented in the original paper (Joesten, 1986). Having had the benefit of Ashworth's comments for the revision of the original manuscript, many of the textural and compositional issues raised in his discussion (Ashworth, 1986) have been specifically addressed. There is little more that can be said. The reader either accepts those observations and finds their interpretation persuasive or does not. Rather than repeat those observations here, the reader is urged to review the material enumerated in the sections entitled, 'Interpretation of critical microstructures of primary coronas' and 'Interpretation of critical compositional relations in coronas' as well as the descriptive and interpretative sections on annealing.

The model for magmatic reaction, diffusion and annealing proposed by Joesten (1986) involves the sequential formation of the successive mineral assemblage layers of the columnar corona, outward from the olivine core, and the sequential evolution of the tabular microstructure from that of the columnar corona. The solid-state reaction model supported by Ashworth (1986), on the other hand, requires the simultaneous growth of all mineral assemblage layers on a given corona and argues for simultaneous growth of both columnar and tabular corona microstructures. Rather than develop the discussion of the genesis of corona microstructures in the context of metamorphic or magmatic processes, it will be useful to rephrase the question of corona genesis in terms of a sequential versus simultaneous origin for the layers comprising individual columnar coronas and a sequential

versus simultaneous relation between columnar and tabular corona microstructures.

Sequential versus simultaneous origin of mineral assemblage layers in columnar coronas

The following textural relations in columnar coronas are consistent with the sequential development of mineral assemblage layers but are incompatible with their simultaneous origin:

(1) Columnar impingement orthopyroxene, characteristic of the primary corona microstructure, separates grains of cumulus olivine, forms a rim separating olivine and intercumulus amphibole and is epitaxially intergrown with intercumulus amphibole. Because the orthopyroxene layer with the columnar impingement microstructure separates phases of magmatic origin, it cannot be the product of reaction between olivine and plagioclase, whereas this relation is to be expected were it the product of magmatic crystallization. Most importantly, it shows that columnar impingement orthopyroxene layer formed prior to formation of orthopyroxene-spinel and amphibole-spinel symplectite.

(2) Olivine occurs only in contact with orthopyroxene, but orthopyroxene in primary coronas is found in contact with orthopyroxene + spinel, amphibole + spinel, and plagioclase, while it occurs in contact with clinopyroxene and with amphibole in the intercumulus association. There is thus ample textural evidence that olivine was rimmed by orthopyroxene before coming into contact with any other phase. There is no direct textural evidence that olivine was in contact with plagioclase at any time. In addition, the apparent stable coexistence of orthopyroxene and plagioclase rules out an incompatibility between these two phases as the reaction initiating metamorphic corona growth.

(3) The contact of the orthopyroxene + spinel layer with the amphibole + spinel layer is irregular and the layer is locally missing, leaving orthopyroxene in contact with amphibole-spinel symplectite. The irregular, discontinuous nature of the orthopyroxene + spinel layer implies dissolution along its contact with the amphibole + spinel layer, while the unidirectional nature of the columnar impingement microstructure of amphibole-spinel symplectite implies that it grew outward from its contact with the orthopyroxene + spinel layer. These relations are consistent with partial dissolution of the orthopyroxene + spinel layer, followed by growth of the amphibole-spinel symplectite at the expense of surrounding melt. They are inconsistent with simultaneous growth of the orthopyroxene + spinel and amphibole + spinel layers. Note that the columnar impingement microstructure of the amphibole-spinel layer provides information on the direction of layer growth but provides no information on the identity of the material into which the colonies were growing.

(4) Amphibole-spinel symplectite with the columnar microstructure occurs with orthopyroxene, orthopyroxene + spinel, ilmenite or spinel along its inner contact. Although ilmenite shows evidence of dissolution, the unidirectional nature of the amphibole-spinel symplectite colonies show that they grew outward from their contact with ilmenite. Further, if ilmenite were a

contributing participant in reaction with plagioclase, then the phase composition, phase proportion and/or microstructure of the amphibole + spinel layer should record some sort of changes where it crosses the boundary between ilmenite and spinel grains in the oxide corona core. No such changes are observed.

Clearly, the mineral assemblage layer sequence of the columnar coronas formed by sequential growth on the olivine core and at no time were olivine and plagioclase in contact. Combining these results with the fact that the convex-inward, cusped shape of the olivine-orthopyroxene layer contact and the doubling of the columnar orthopyroxene layer along narrow cusped terminations of olivine grains (fig. 6, left, Joesten, 1986) are incompatible with diffusion-controlled growth of the orthopyroxene layer, it becomes quite clear that the mineral assemblage layer sequence and microstructure of the columnar coronas cannot have formed as a result of solid-state reaction and diffusion-controlled element redistribution between olivine and plagioclase.

Sequential versus simultaneous relation between columnar and tabular corona microstructures

Coronas with the tabular microstructure are interpreted as the annealed equivalents of coronas with the columnar microstructure by analogy with alloy and ceramic systems in which unstable low-angle grain boundaries are eliminated by heat treatment. This interpretation is supported by the existence of transitional microstructures that clearly show that coronas with the tabular microstructure evolved from coronas with the columnar microstructure. These features include: (1) the persistence of the columnar impingement microstructure of the orthopyroxene layer in coronas in which the amphibole of the amphibole + spinel and amphibole layers is monocrystalline; (2) the progressive elimination of orthopyroxene grain boundaries resulting in fuzzy or indistinct grain contacts; and (3) the preservation of columnar impingement amphibole-spinel symplectite and isolated plumes of orthopyroxene + spinel in the outer part of the monocrystalline amphibole + spinel layer (figs. 6 and 10, Joesten, 1986). The sequence of steps on annealing is thus (1) breakdown of the orthopyroxene + spinel layer, (2) formation of the monocrystalline amphibole layer, (3) elimination of amphibole-amphibole grain boundaries and rotation of spinel rods into parallel in the amphibole-spinel layer, (4) elimination of orthopyroxene-orthopyroxene grain boundaries and breakdown of plumose colonies of orthopyroxene + spinel.

The diffusional instability of the mineral assemblage layer sequence of the columnar coronas in the model system, provides the rationale for the spontaneous transformation of the unstable columnar microstructure to that of the tabular coronas with a stable mineral assemblage layer sequence. Thus, on annealing, the energetically unfavourable microstructure with low-angle amphibole-amphibole and orthopyroxene-orthopyroxene grain boundaries is converted to a stable microstructure with monocrystalline layers, while the diffusional unstable mineral assemblage layer sequence $P:A+S:S:E:F$ is converted to the stable mineral assemblage layer sequence $P:A+S:E:F$.

A clear example of both the sequential relationship between columnar and tabular microstructures and role of the lattice orientation of intercumulus amphibole in determination of the orientation of amphibole in the annealed corona is illustrated in fig. 6 of Joesten (1986). Olivine of the right-hand corona is rimmed by columnar impingement orthopyroxene. Along its right-hand side, the columnar layer of amphibole-spinel symplectite passes along its length into the tabular microstructure with development of a monomineralic layer of amphibole separating orthopyroxene and amphibole-spinel symplectite. A large grain of intercumulus amphibole, with a margin of symplectitic spinel, is in contact with the corona. The contact between intercumulus amphibole and the amphibole-spinel layer of the corona follows the outer surface of individual amphibole-spinel colonies in the columnar part of the corona but is planar where the corona layers have the tabular microstructure. Thus, intercumulus amphibole crystallized contemporaneously with or after growth of the amphibole-spinel symplectite colonies. The orientation of the monocrystalline amphibole in the tabular part of the corona is the same as that of the intercumulus amphibole. Thus, unless the common orientation of tabular amphibole of the corona and intercumulus amphibole is purely coincidental, annealing took place after the corona layers came into contact with the intercumulus amphibole. Ashworth (1986) dismisses these relations as being the result of consumption of plagioclase within the plane of the thin section. Note, however, that were the juxtaposition of amphibole-spinel symplectite on the corona with intercumulus amphibole due to the consumption of plagioclase that previously separated them, the corona layers should thicken along their length where plagioclase remains, and amphibole-spinel symplectite colonies should fan or curve toward the remaining plagioclase. These features are not observed.

Ashworth (1986) points out the difficulty of converting the fanning arrangement of spinel rods in the columnar microstructure to the parallel arrangement characteristic of the tabular microstructure by a mechanism involving the rotation of the structure of the amphibole of individual colonies to a common orientation. The problem is readily solved, however, if the conical space that results from spreading apart of spinel rods along the inner margin of the two-phase layer can be filled by amphibole.

The product of the initial breakdown reaction at the orthopyroxene + spinel/amphibole + spinel layer contact consumes orthopyroxene and spinel and produces amphibole (Reaction [9], Joesten, 1986). Breakdown of an orthopyroxene + spinel layer 15 μm thick (Joesten, 1986, Table VI), produces a volume of amphibole equivalent to a layer 26 μm thick per millimetre of layer contact. As the typical thickness of the monomineralic amphibole layer is 18 μm , there is an excess of amphibole which must be precipitated with spinel in the tabular symplectite. The role of the excess amphibole in producing the parallel alignment of spinel rods may involve either the passive infilling of space left on rotation of spinel rods into parallel or its precipitation may act as a wedge to force the spinel rods apart. Preservation of columnar impingement amphibole-spinel symplectite in the outer part of the tabular amphibole + spinel layer along the top margin of

the right-hand corona in fig. 6 of Joesten (1986) suggests that the transformation of the columnar to the tabular microstructure of the amphibole + spinel layer may propagate outward from the amphibole layer.

Modelling of diffusion-controlled growth of coronas

An attempt was made in Joesten (1986) to simulate the diffusion-controlled growth of coronas in a model system analogous to the natural system in the Risør sample by solution of a system of mass balance, conservation and flux ratio equations that link the stoichiometry of reactions at mineral assemblage layer contacts with the fluxes of components that diffuse down their chemical potential gradients through the layers. Because modelling was restricted to radially symmetric diffusion, it did not allow for mass transfer into or out of the corona and did not explicitly include the behaviour of water. Ashworth (1986) is not willing to accept the primary results of the model calculations, but holds out the hope that were these factors to be properly taken into account, a solid-state origin for both corona microstructures might be supported by the model. Indeed, he states that the prospect of generating columnar or primary coronas was doomed from the start because these factors were not built into the model.

As was emphasized in the original paper and reiterated above, the textural relations in the orthopyroxene + spinel and amphibole + spinel layers of coronas with the columnar microstructure preclude the simultaneous growth of all layers. Thus, growth of the columnar coronas by solid-state reaction between olivine and plagioclase is precluded on textural grounds. The fact that the model failed to predict a stability field for the analogue of the columnar coronas is thus most reassuring!

Diffusional stability and annealing. The significance of the model calculations is the confirmation that the mineral assemblage layer sequence of the columnar corona microstructure cannot be produced by relaxation of the chemical potential gradients established by the juxtaposition of olivine and plagioclase but that the mineral assemblage layer sequence of the tabular coronas is diffusional stable. The calculations shed no light on how the mineral assemblage layer sequence of the columnar coronas may have formed. They merely show that because the mineral assemblage layer sequence of the columnar coronas is diffusional unstable along the chemical potential gradients established across it by buffering at layer contacts, it must ultimately transform to a stable mineral assemblage layer sequence. Thus, the instability of the columnar microstructure provides the driving force for the spontaneous transformation to the diffusional stable mineral assemblage layer sequence of the tabular coronas.

Diffusion in amphibole-spinel symplectite. Well-organized two-phase lamellar microstructures like the amphibole-spinel symplectite, can be produced by three processes: (1) eutectic crystallization from the melt; (2) eutectoid breakdown of a single solid phase to two solids with structures unrelated to the host phase; and (3) discontinuous precipitation or exsolution of a solute phase from a solid solution host. Modelling of corona growth involves nothing more than solution of a set of mass

balance relations at mineral assemblage layer contacts under the constraints on diffusive fluxes imposed by conservation of mass and the Gibbs–Duhem relations for the phases involved. Thus, model calculations deal only with the stoichiometry of layer contact reactions. They are not capable of prediction of the microstructure of individual layers.

Mongkoltip and Ashworth (1983) argue that the symplectic intergrowth of amphibole and spinel in coronas essentially identical to those from Risör is the result of the eutectoid-like breakdown of plagioclase in which the diffusive transport of $\text{AlO}_{3/2}$ and SiO_2 is limited to the scale of the half-spacing of spinel rods in the symplectite, while MgO and FeO are transported to the advancing interface from elsewhere in the rock. In their model, the rate of motion of the advancing plagioclase: amphibole + spinel interface is controlled by grain-boundary diffusion of $\text{AlO}_{3/2}$ and SiO_2 along the layer contact, perpendicular to the direction of interface motion. Note however, that the chemical potential gradients within a growing symplectite layer on a corona are in fact quite different from those in a symplectite formed by eutectoid reaction. The product symplectite in a eutectoid reaction is enveloped by the host phase and has a bulk composition identical to it. Thus the chemical potential gradients that control its growth are established by local equilibrium between phases of the symplectite and the host phase and necessarily act on the scale of the half-spacing of the lamellar intergrowth. In addition, chemical potential differences buffered by assemblages of different variance but sharing phases in common, are necessarily smaller than potential differences between assemblages with singular phases (Joesten, 1977, pp. 665–6). Thus, while periodic variation in the chemical potentials buffered by the phases in the symplectite in contact with plagioclase may be present in the growing corona, potential differences of equal or greater magnitude are established across the layers of the growing structure. Indeed, the existence of chemical potential gradients across a symplectite layer or the transport of material into or away from a growing symplectite from elsewhere in the structure (Mongkoltip and Ashworth, 1983, fig. 2c–f) will probably render the periodic variation in the chemical potentials along the advancing interface ineffective as a driving force for component redistribution. Thus the assumption of radially symmetric diffusion for the growth of coronas in the model system of Joesten (1986) is justified.

Relative fluxes of $\text{AlO}_{3/2}$ and SiO_2 in the growth of symplectite. Mongkoltip and Ashworth (1983) present a detailed analysis of the compositional and microstructural relations in coronas from the Newer Gabbros of NE Scotland from which they conclude that the symplectic microstructures are the result of the slow diffusion of $\text{AlO}_{3/2}$ and SiO_2 relative to other components and that the ratio $\text{Al}/(\text{Al} + \text{Si})$ of symplectite is inherited, essentially unchanged, from plagioclase consumed in the corona-forming reaction. Ashworth (1986, fig. 2) demonstrates that a similar relation exists in the Risör coronas. Although Mongkoltip and Ashworth (1983) and Ashworth (1986) demonstrate a correlation between $\text{Al}/(\text{Al} + \text{Si})$ of coexisting symplectite and plagioclase and the existence of lamellar, two-phase microstructure, no causal relationship between ‘immobility’ of $\text{AlO}_{3/2}$ and

SiO_2 and formation of the symplectite microstructure has been shown.

The magnitude of the fluxes of $\text{AlO}_{3/2}$ and SiO_2 across corona layer contacts relative to those of other components in corona growth may be determined by solution of a system of mass balance equations at each layer contact. Such a system of mass balance equations is necessarily underdetermined. There are two strategies for obtaining a solution.

One may solve the full system of mass balance equations for all layer contacts simultaneously by including the constraints of local equilibrium and by linking diffusive fluxes and the stoichiometric coefficients of the layer contact reactions through a system of conservation and flux ratio equations as is done in the steady-state diffusion-control model described by Joesten (1977 and 1986).

Alternatively, one may arbitrarily choose a reference frame by fixing the volume change (volume-fixed frame) or by setting the flux of a given component to zero at the layer contact (component-fixed frame) and obtain an independent solution for each layer contact (see section on ‘Mass transfer in the annealing process’ in Joesten, 1986). One always obtains a balance for a single layer contact irrespective of the reference frame chosen, so that the fact that a balance is obtained for an Al- or Si-fixed frame provides no support for the assumption that the actual fluxes of these components were zero during growth of the layered structure. Note that one cannot arbitrarily specify the fluxes of two or more components.

Both strategies were used to model exchanges in the tabular coronas in the original paper (Joesten, 1986, Table VIII) and both can be used to test the hypothesis that $\text{AlO}_{3/2}$ and SiO_2 were essentially ‘immobile’ in the growth of Risör coronas.

The hypothesis that the ratio $\text{Al}/(\text{Al} + \text{Si})$ of the amphibole–spinel symplectite is inherited from plagioclase can be simulated in the model calculations for diffusion-controlled corona growth by setting the fluxes of $\text{AlO}_{3/2}$ and SiO_2 equal to zero. Because the ratios of the chemical potential gradients within the corona layers are fixed by the Gibbs–Duhem equations for the phases, the condition of zero flux of $\text{AlO}_{3/2}$ and SiO_2 is obtained by setting $L_{\text{AlAl}} = L_{\text{SiSi}} < L_{\text{MgMg}}$. The effect of corona growth thus dominated by the flux of MgO is modelled by setting $L_{\text{AlAl}}/L_{\text{SiSi}} = 1.0$ and $L_{\text{MgMg}}/L_{\text{SiSi}} > 10$. It can be seen on fig. 11 of the original paper (Joesten, 1986) that the resulting corona would have the mineral assemblage layer sequence P : A + S : S : E : F. Thus the layer sequence of the columnar coronas in the model system is not stabilized by restricted diffusion of Al and Si.

Results of mass balance calculations for each of the four layer contacts of the tabular coronas as computed with equation (1) of Joesten (1986) are shown on Gressens’s (1967) composition–volume diagrams in fig. 1 A–D. The lines represent the variation of the stoichiometric coefficients of individual transported components in the layer contact reaction as a function of the ratio of volume of product assemblage formed to the volume of reactant assemblage consumed. Results are normalized to 100 cm^3 of product assemblage. Where the value of Δm_i is positive, component i is consumed in the layer contact reaction while a negative value means that component i is evolved.

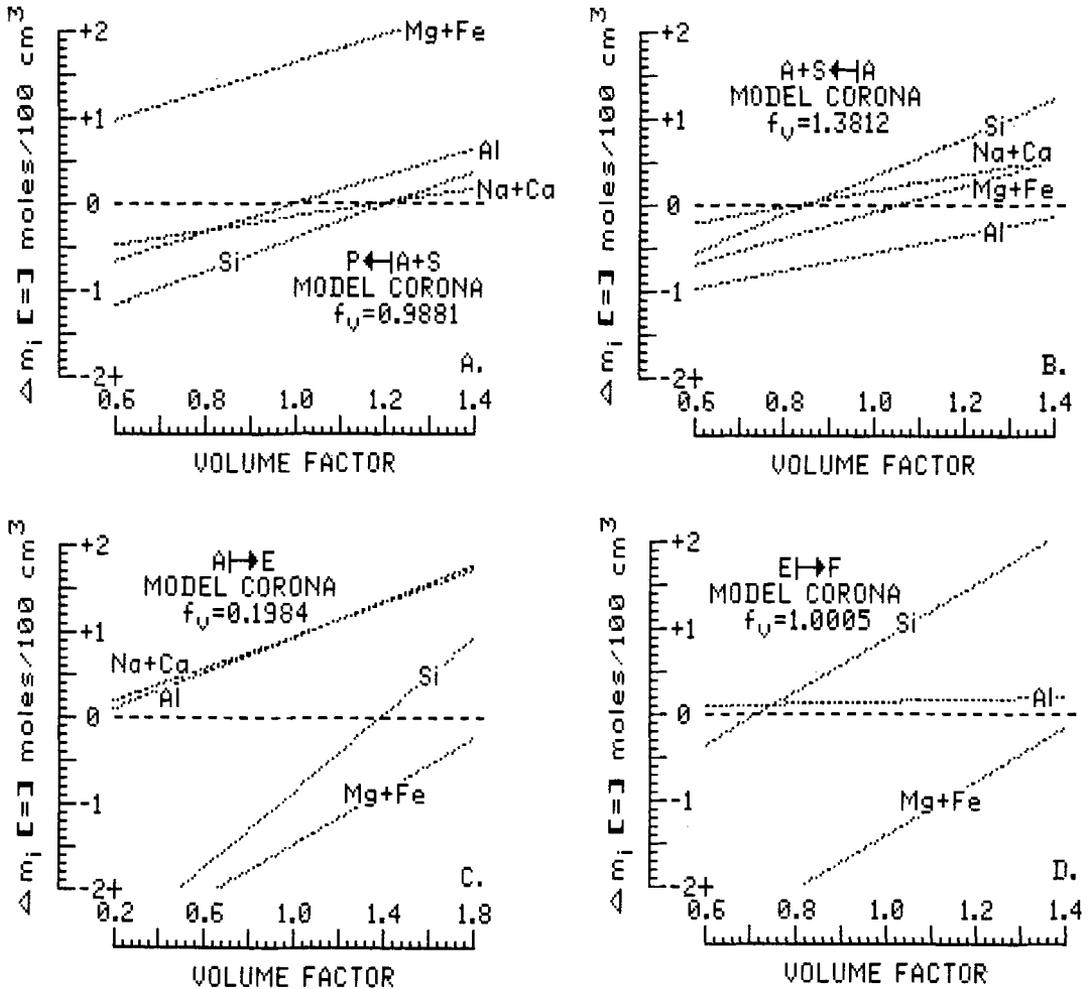


FIG. 1. Variation in stoichiometric coefficients of layer contact reactions for tabular corona using data from Tables III and V in Joesten (1986) using method of Gresens (1967). Component i is consumed in reaction for $\Delta m_i > 0$, and evolved for $\Delta m_i < 0$ for motion of layer contact as shown. Mass transfer scaled to 100 cm³ of product layer formed. (A) Plagioclase/amphibole-spinel symplectite, (B) amphibole-spinel/amphibole, (C) amphibole/orthopyroxene, and (D) orthopyroxene/olivine layer contacts.

Note that the sign convention is the opposite of the results listed in Table VIII of Joesten (1986).

The value of Gresens's diagram is that it allows the simultaneous comparison of mass transfer on a wide range of reference frames. The drawback of this approach, involving the arbitrary specification of reference frame, is that the fluxes or stoichiometric coefficients of exchanged components are not constrained to be those consistent with local equilibrium, so that a solution so obtained may be inconsistent with diffusion-controlled mass transfer.

It is clear from fig. 1A-D that the fluxes of Al and Si cannot simultaneously be zero at any of the layer contacts. Calculations using the extremes of symplectite composition allowed by the uncertainty in the measured volume

fraction spinel in the symplectite show no overlap for $AlO_{3/2}$ and SiO_2 where they cross the $\Delta m_i = 0$ line. Note, however, that for the volume factors that correspond to the solution for the tabular corona in the model system (Joesten, 1986, reactions 5-8 and Table VIII), the flux of Al is nearly zero at all layer contacts, while fluxes of Si are large. Thus, analysis of mass balance using the phase composition from the Risør tabular coronas do not support the assertions that the ratio $Al/(Al+Si)$ of symplectite is inherited unchanged from reactant plagioclase and that the fluxes of $AlO_{3/2}$ and SiO_2 were essentially zero during corona growth. Although results are presented only for tabular coronas, substantially similar results are obtained for columnar coronas.

Corona growth in an open system. The overall stoichiometry of a corona in the model system $\text{NaCa}_2\text{O}_{5/2}\text{-MgO-AlO}_{3/5}\text{-SiO}_2\text{-HO}_{1/2}$ formed by reaction between forsterite and plagioclase (AN_{67}) with no transfer of material into or out of the structure, is given by the reaction [1] in Joesten (1986) and consists of enstatite, pargasite, and spinel in the proportion 7:1:1. Mongkoltip and Ashworth (1983) argue that some of the MgO needed for corona growth is transported to the contact between plagioclase and amphibole-spinel symplectite from elsewhere in the structure. For each mole of MgO added from outside the system, one mole less forsterite is consumed in reaction [1] and one mole less enstatite is formed. Thus, if $\text{MgO} + \text{FeO}$ were added to Risør coronas from outside, the proportion orthopyroxene:amphibole:spinel should be less than the 7:1:1 given by the stoichiometry of reaction [1]. This is in fact what is observed by Joesten (1986, Table VI). Note, however, that addition of $\text{MgO} + \text{FeO}$ from the matrix cannot change the ratio of amphibole to spinel, which is unity in the model system but greater than unity in columnar coronas and less than unity in tabular coronas (Joesten, 1986, Table VI).

Calculations in the model system of Joesten (1986) are based on the assumption that all material involved in the growth of the corona layers is derived from the breakdown of forsterite and plagioclase. This is achieved by setting the flux of each component across the plagioclase and forsterite layer contacts equal to zero. As a result, the overall stoichiometry of the corona reactions (reactions [5]–[8] of Joesten (1986)) sum to that of reaction [1]. Van Lamoen (1979) and Mongkoltip and Ashworth (1983) argue that material is transported into growing coronas from elsewhere in the rock. The closed system assumption can be relaxed and a solution to the system of equations for the model corona obtained by setting the flux of MgO to an arbitrary non-zero value at the plagioclase contact and including this value in the appropriate conservation equation.

The effect of variation in the flux of MgO across the P:A+S layer contact in the model system is the same as that of varying the ratio $L_{\text{MgMg}}/L_{\text{SiSi}}$. Boundaries of the six corona fields are shifted parallel to the $L_{\text{MgMg}}/L_{\text{SiSi}}$ axis on the *L*-ratio diagram (fig. 11, Joesten, 1986), but no new corona types are stabilized. The effect of adding MgO from outside the corona is to diminish the flux of MgO through the A+S layer needed for reaction with plagioclase and thus produce a given reaction stoichiometry at lower values of $L_{\text{MgMg}}/L_{\text{SiSi}}$. The net result of transport of MgO into the corona from the matrix is to restrict the stability range of the annealed corona layer sequence on the *L*-ratio diagram. The mineral assemblage layer sequence of the columnar coronas is not stabilized in the open system.

Effect of H_2O on corona stability. The model calculations of Joesten (1986) do not explicitly take H_2O and $(\text{OH})^-$ into account and are thus equivalent to treating

the system either as anhydrous or assuming that the flux of $\text{HO}_{1/2}$ is much less than that of SiO_2 . Inclusion of $\text{HO}_{1/2}$ as a component and inclusion of $(\text{OH})^-$ in the formula of amphibole expands the stability fields of coronas with a monomineralic layer of amphibole in contact with enstatite. Increasing the ratio $L_{\text{HO}_{1/2}2\text{HO}_{1/2}}/L_{\text{SiSi}}$ from a value of 0.1 causes the proportion of amphibole formed at A+S:E to increase relative to its value in the anhydrous system. The result is equivalent to a shifting of the curves for $V^{\text{P:A+S}}_{\text{Ss}}$ and $V^{\text{A:S}}_{\text{Ss}}$ parallel to the $L_{\text{AlAl}}/L_{\text{SiSi}}$ axis on fig. 11B and C of Joesten (1986). Thus, the stability field of the model annealed coronas with the layer sequence P:A+S:A:E:F increases to higher values of $L_{\text{AlAl}}/L_{\text{SiSi}}$ as the flux of $\text{HO}_{1/2}$ is increased relative to that of SiO_2 . No new corona types are stabilized in the hydrous system, however.

Conclusion

Evidence has been reviewed which demonstrates that the layers comprising coronas with the columnar microstructure formed sequentially, from the core outward, and that the microstructure and mineral assemblage layer sequence of the tabular coronas evolved from those of the columnar coronas. It has been further shown that relaxation of the simplifying assumptions in the model presented in the original paper does not lead to stability of the mineral assemblage layer sequence of the columnar coronas.

The consistent spatial association of corona layers separating olivine or ilmenite and plagioclase remains the strongest evidence in support of a metamorphic origin by reaction between solid phases and is perhaps the most difficult feature to reconcile with a magmatic origin. It should be clear from the foregoing, however, that there are too many textural relations in the coronas from Risør that are inconsistent with a solid-state origin for the metamorphic hypothesis to remain viable.

ADDITIONAL REFERENCES

- Ashworth, J. R. (1986) The role of magmatic reaction, diffusion and annealing in the evolution of coronitic microstructure in troctolitic gabbro from Risør, Norway: a discussion. *Mineral. Mag.* **50**, 469–73.
- Gresens, R. L. (1967) Composition–volume relationships of metasomatism. *Chem. Geol.* **2**, 47–65.
- Kushiro, I., and Yoder, H. S., Jr. (1966) Anorthite–forsterite and anorthite–enstatite reactions and their bearing on the basalt–eclogite transformation. *J. Petrol.* **5**, 195–218.
- Preshall, D. C., Dixon, J. R., O'Donnell, T. H., and Dixon, S. A. (1979) Generation of mid-ocean ridge tholeiites. *Ibid.* **20**, 3–36.

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