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Mixing of supernatant and interstitial fluids in the Rhum layered intrusion

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ABSTRACT. An alternative explanation for the occurrence of chrome-spinel layers in the Eastern Layered Series of the Rhum intrusion is suggested by extreme concentrations of chrome-spinel in small-scale structures in the layer at the unit 7-8 boundary (Brown, 1956). These take the form of downward pointing cones several centimetres across and deep, and lined or wholly filled with chrome-spinel; lamination in the underlying allivalite exhibits quaquaversal dips around these cones. By comparing these structures to fluid escape structures in clastic sediments, it is proposed that spinel is the product of mixing and reaction of upward moving interstitial liquid and more primitive liquid newly emplaced in the chamber. Further evidence for the presence of a second liquid during spinel crystallization is provided by spherical silicate inclusions within spinel grains. Complex zoning in feldspars in the underlying allivalite suggests that the newly emplaced primitive liquid was able to penetrate the crystal mush on the intrusion floor.

CHROMITE often occurs concentrated in layers of great areal extent in ultrabasic-gabbroic plutons (Irvine, 1975). Interpretations placed on the origin of these layers range from local physical sorting of crystals to abrupt changes in pressure or oxygen fugacity during an intrusion's cooling history. Several recent interpretations hinge on Irvine's proposition (1975, 1977) that mixing of two liquids fractionating along the olivine-chromite cotectic in the system forsterite-diopside-anorthite-quartz-picrochromite will push the resultant liquid composition into the chromite primary phase field. The more and less fractionated liquids have been ascribed to mixing of magma in the chamber with acid liquid derived by melting of roof rock (Irvine, 1975), mixing of parental and evolved magmas during chamber replenishment (Murck and Campbell, 1982), and double-diffusive mixing in a stratified magma chamber (Irvine, 1981).

This paper describes features associated with chrome-spinel layers in the Rhum layered intrusion and it is proposed that chrome-spinel was precipitated at the mush-magma interface in response to mixing of liquid expelled from the porous cumulate pile with magma newly emplaced in the chamber.

Chromite in the Rhum intrusion—stratigraphic setting and previous research. The ultrabasic portions of the Rhum intrusion consist of structurally complex, cyclic layered units with associated breccia zones. The cyclic units are of eucrite, feldspathic peridotite, or peridotite in the Western Layered Series (Wadsworth, 1961), whereas they are of peridotite (olivine-chrome-spinel cumulates) succeeded by allivalite (plagioclase-olivine-chrome-spinel cumulates) and pyroxenic allivalite (plagioclase-olivine-clinopyroxene-chrome-spinel cumulates) in the Eastern Layered Series (Brown, 1956). The major cycles have been interpreted as cumulates formed in a replenished magma chamber (Brown, 1956; Wadsworth, 1961; Dunham and Wadsworth, 1978). In the Eastern Layered Series these replenishments are reflected in abrupt transitions from allivalite to peridotite.

The presence of chrome-spinel layers was noted by Harker (1908). Subsequently Brown (1956) stressed their occurrence at the contacts of allivalite with overlying peridotite and Wadsworth (1961) noted their presence within and between peridotitic and harrisitic cumulates. Both Brown and Wadsworth ascribed them to preferential settling of chromite grains.

The first detailed work on the chemistry of Rhum chrome-spinels was carried out by Henderson and Suddaby (1971) who proposed that chrome-spinel layers at the bases of cyclic units were a consequence of the position of chromite on the liquidus of the Rhum parent magma, early-formed chromite being concentrated by settling into layers. They also recognized that post-cumulus reaction of chromite with olivine, plagioclase, and intercumulus liquid had taken place to give a larger volume of a more aluminous chrome-spinel. This work was extended by Henderson (1975) and Henderson and Wood (1981) who recognized two post-cumulus reaction trends, an Fe-enrichment trend and an Al-enrichment trend, the position of any particular spinel on either trend being determined by the modal composition of the enclosing cumulates and the amount of trapped intercumulus liquid. Henderson and Wood sampled chrome-spinel layers from within the unit 7 peridotite.

As an alternative origin for chrome-spinel layers at the base of cyclic units, Huppert and Sparks (1980) proposed that picritic liquid newly emplaced in the magma chamber, hybridized with a little evolved liquid already present in the chamber, was able to melt the allivalite floor with chrome-spinel being a product of the reaction of floor melt and hybrid liquid.

Structures associated with, or defined by chrome-spinel concentrations. Structural complexities associated with chrome-spinel layers in the Eastern Layered Series are well-exposed at the contacts of units 11 and 12, the 'type' example of Brown (1956), on the northern and eastern flanks of Hallival, and units 7 and 8 on the eastern flank of Coire Dubh (grid reference 13917973). Sketches of structural features are presented in fig. 1 and features considered pertinent to the genesis of chrome-spinel layers described below.

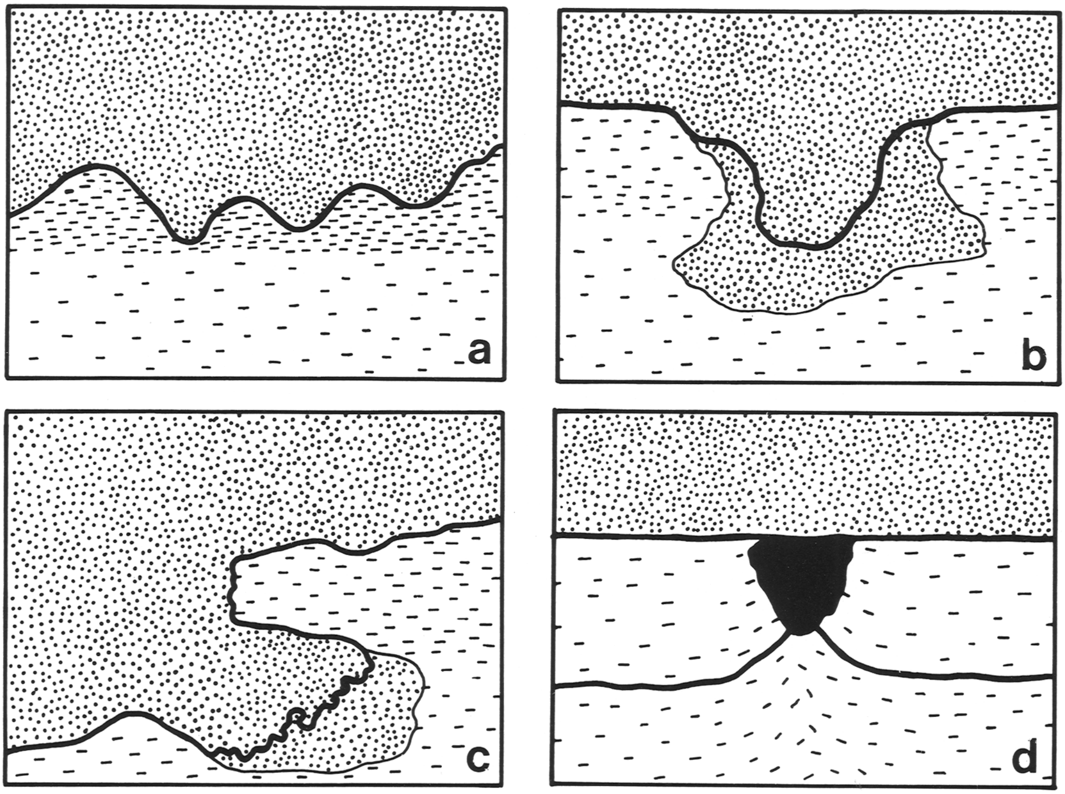


FIG. 1. Schematic diagrams of small-scale structures associated with chrome-spinel layers at unit junctions. Peridotite indicated by stippled ornament and chrome-spinel layers by heavy black line or shading (fig. 1*c*). The dashed ornament indicates the orientation of the feldspar lamination and its density is proportional to the modal proportion of feldspar. Vertical and horizontal scales are equal. (*a*) Undulatory contact between peridotite and allivalite with intervening chrome-spinel layer. In three dimensions these structures take the form of circular depressions in the allivalite. The lamination in the allivalite is cut by the undulatory contact. Note also that the lower ratio contact of the top allivalite layer is unaffected by the irregularities at its upper contact. Horizontal dimension 30 cm. (*b*) Embayment structure with transgressive chrome-spinel layer. These structures are roughly equidimensional in plan. The structure illustrated increases in its horizontal dimension where a less feldspathic variety of allivalite is encountered by peridotite. Horizontal dimension 30 cm. (*c*) Margin of horizontally extensive embayment structure illustrating the development of a chrome-spinel layer on the underside of a protrusion of allivalite into peridotite and the transgressive nature of some chrome-spinel layers. Only the two-dimensional form of these structures can be seen. Horizontal dimension 50 cm. (*d*) Cone structure in unit 7 allivalite. Three chrome-spinel layers are developed at this locality, though only two are illustrated, one within each silicate lithology and one at their junction. That at the junction forms a number of cone structures, and in at least one case the underlying chrome-spinel layer is deflected upwards with the feldspar lamination into the cone. Horizontal dimension 8 cm.

1. Peridotite may cut across the layering and feldspar lamination in allivalite, without associated deformation of either. This occurs on all scales from thin section to outcrop. The form of these transgressions ranges from regular undulations (fig. 1*a*), through larger irregular embayment structures (fig. 1*b*) to horizontally extensive embayments, up to 1 m deep and several metres across, which may be analogous to the pothole structures of the Bushveld complex (fig. 1*c*). These embayments often increase in their horizontal dimension where different textural or modal varieties of allivalite are encountered (fig. 1*b*, *c*). Where an olivine lamination is developed at an undulatory contact, it is invariably oriented parallel to that contact.

2. Chrome-spinel layers may line the margins of these embayments in allivalite, or may locally transgress into peridotite (fig. 1*b*, *c*). They have not been noted transgressing into allivalite.

3. Within embayments chrome-spinel layers may be developed on the underside of allivalite 'overhangs' (fig. 1*c*). Where this is observed the layer is often thicker on the top surface of the allivalite protrusion.

The structures described above are usually but not always found associated with chrome-spinel layers. They may be found in isolation, regularly spaced, or extend continuously along several metres of outcrop. The structures in (4) are defined by chrome-spinel layers.

4. Extreme concentrations of chrome-spinel are developed in small (1–3 cm in diameter and depth), irregularly shaped, downward-pointing cone structures, generally 2–20 cm apart, which may have peridotite cores. Sections cut perpendicular to the plane of the layering indicate that these cones are developed at culminations in the lamination in the underlying allivalite (fig. 1*d* and fig. 2). Below these cone structures the feldspar is generally randomly or vertically oriented.

Petrography. Chrome-spinel occurs in a variety of textural and silicate environments. Within layers at unit junctions, spinels are small (average 0.2 mm in diameter) and range from euhedral through sub-spherical to complex amoeboid shapes. On the scale of a thin section, individual layers show large variations in thickness and may even be locally absent. Chain texture is poorly developed. Textural evidence for post-cumulus reaction is common in the form of chrome-spinel grains located within embayments in olivine crystals. Rare inclusions of silicates can be identified in transmitted light, some are in optical continuity with the silicate phase enclosing the spinel, indicating a cylindrical embayment in the spinel, while others are discrete silicate inclusions. Optical examination with transmitted light reveals the presence of brown amphibole, pyroxene, olivine, and plagioclase. Similar, though larger, inclusions are to be found within cumulus olivine crystals in the overlying peridotites. Poikilitic phases in the cones are much larger than in the adjacent chrome-spinel layers.

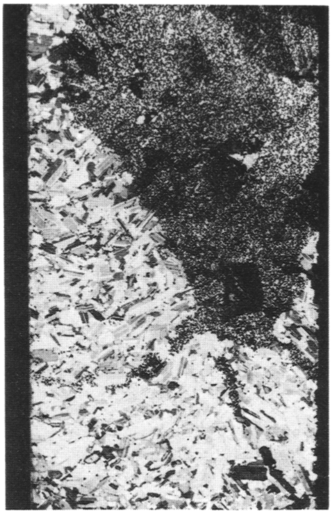
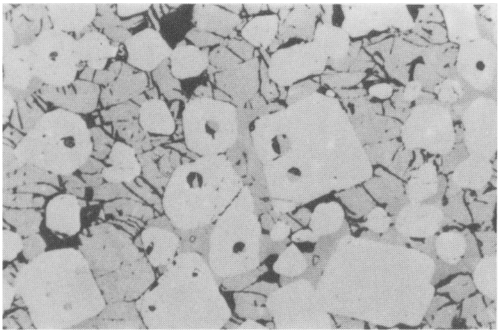
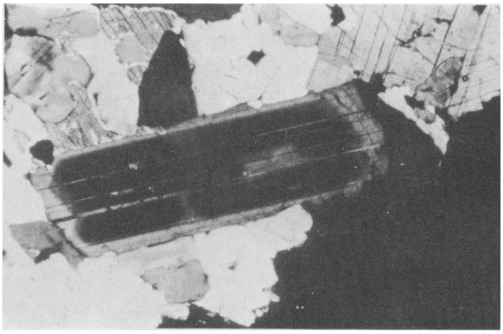


FIG. 2. Photomicrograph of section of cone structure illustrating orientation of feldspar lamination (field of view = 34 x 19 mm, partially crossed polars).

Examination under reflected light reveals granular textures with 120° triple junctions between chrome-spinel grains, patchily developed within the cone structures. Exsolved ilmenite platelets are common in the 7–8 boundary samples though rare in the 11–12 boundary samples. It further reveals that the inclusions noted above are abundant and that some are occupied partially or wholly by sulphide; sulphide is more abundant as interstitial blebs within chrome-spinel layers or silicate cumulate. These inclusions are small (10–100 μm), spherical and most commonly situated singly and centrally within their host (fig. 3). Some spinels contain more than one inclusion and a very few contain a large number, up to eighteen having been counted in one grain. Spinels within the cone structures are especially rich in inclusions, whereas inclusions are very rare within disseminated spinels in allivalite. The compositions of a number of inclusions within chrome-spinel have been determined by electron microprobe using standard wavelength dispersive spectrometry (WDS). The small size of these inclusions renders it difficult to obtain analyses of pure phases; nevertheless enstatite, pargasitic hornblende, mica (a titatian natronphlogopite slightly deficient in 2^+ cations), olivine, plagioclase, augite, and chalcopyrite have been





FIGS. 3 and 4. FIG. 3 (*left*). Silicate and sulphide inclusions within chrome-spinels. Sample from layer at unit 7–8 junction (field of view = 1.28 × 0.86 mm, reflected light). FIG. 4 (*right*). Reverse zoned and embayed feldspar crystal from unit 7 allivalite (field of view = 2.64 × 1.72 mm, crossed polars).

positively identified. Representative analyses of the first three named phases are presented in Table I.

The underlying allivalites exhibit a range in the amount of poikilitic material and the extent of feldspar zoning. The poikilitic mineral is commonly olivine, a textural relationship peculiar to the top of the allivalite portions of units (Harker, 1908). Complex zoning patterns within cumulus plagioclase of unit 11 have been noted previously (Henderson and Suddaby, 1971), and are common within the unit 7 allivalite. Optical examination reveals two principal styles of zoning. In the more common type, feldspars have a uniform core composition and a normally zoned rim (cf. Brown, 1956). In the other type, a small, sodic core is mantled by a more calcic zone which is in turn mantled by a normally zoned rim; the calcic zone is often embayed (figs. 4 and 5). In both types zoning outwards to the rim may be discontinuous or continuous. More rarely the reverse zoned type show two discontinuous reversals followed by normal zoning to the rim. The compositional changes have been measured by electron microprobe using standard WDS methods. One or more points were selected in each optically defined zone. Percentage anorthite values of the zones in three typical crystals are presented in fig. 5. Patchy zoning and fine-scale, oscillatory zoning may also be found. Complex zoning has been traced downwards to a depth of 2 m in the unit 7 allivalite.

TABLE I. *Analyses of silicate inclusions within chrome-spinels at the unit 7–8 boundary*

Wt. %	Opx.	Opx.	Amph.	Amph.	Mica	Mica
SiO_2	56.02	54.67	43.42	44.50	38.95	38.67
TiO_2	0.18	0.10	3.49	2.48	8.17	4.57
Al_2O_3	1.31	2.16	12.00	10.99	15.14	16.39
Cr_2O_3	0.91	2.76	n.d.	2.46	—	—
Fe_2O_3	0.78	0.69	0.78	0.61	—	—
FeO	6.33	5.44	4.44	3.44	3.30	2.83
MnO	0.22	0.18	0.09	0.10	0.04	n.d.
MgO	33.63	32.42	17.18	16.71	21.31	22.47
CaO	0.29	0.72	9.95	9.75	0.12	0.02
Na_2O	0.06	0.24	3.79	4.99	6.74	4.54
K_2O	—	—	0.06	n.d.	0.61	3.23
F_2O	—	—	0.07	n.d.	0.02	0.08
Total	99.73	99.39	95.27	96.03	94.40	92.80
Atoms						
Si^{4+}	1.948	1.914	6.319	6.440	5.403	5.467
Ti^{4+}	0.005	0.003	0.382	0.270	0.852	0.486
Al^{3+}	0.054	0.089	2.058	1.875	2.475	2.731
Cr^{3+}	0.025	0.076	—	0.281	—	—
Fe^{3+}	0.020	0.018	0.086	0.066	—	—
Fe^{2+}	0.184	0.159	0.541	0.417	0.383	0.335
Mn^{2+}	0.006	0.005	0.011	0.012	0.005	n.d.
Mg^{2+}	1.743	1.692	3.727	3.605	4.407	4.735
Ca^{2+}	0.011	0.027	1.551	1.512	0.018	0.003
Na^+	0.004	0.016	1.069	1.400	1.813	1.244
K^+	—	—	0.011	—	0.108	0.582
F^-	—	—	0.023	—	0.006	0.025
O^{2-}	6.000	6.000	23.000	23.000	22.000	22.000

All analyses made using an accelerating potential of 20 kV and a probe current (as measured in a Faraday cage) of 30 nanoamps, 4 × 10 second counts made on peak and 2 × 10 second counts on background.

Origin of structures and chrome-spinel layers at unit junctions. Truncation of lamination in allivalites and the presence of irregularly shaped embayments within allivalites (fig. 1*a–c*) indicates removal of allivalite cumulate before chrome-spinel accumulation and not slumping or loading within a crystal mush. Removal of allivalite could take place by resorption, mechanical erosion, or replacement. The lack of fragments of allivalite or of cumulus feldspar crystals within peridotite suggests that resorption, perhaps aided by mechanical loosening, was the dominant erosive process and thus, in part, confirms the predictions of Huppert and Sparks

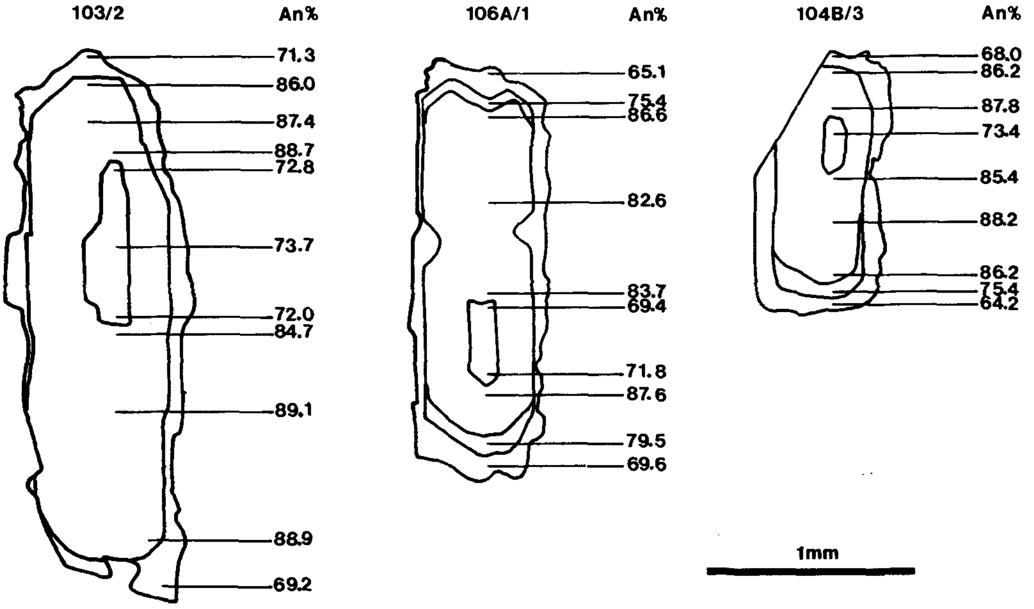


FIG. 5. Sketches of three feldspar crystals from unit 7 allivalite showing optically defined zones and An mol. % values determined by electron microprobe.

(1980). The transgressive nature of some chrome-spinel layers (figs. 1*b* and *c*) suggests that either limited replacement of allivalite by peridotite has taken place after chromite crystallization (see Robins, 1982, for a description of replacement structures elsewhere in the intrusion), or that some olivine accumulation occurred before chrome-spinel layers formation on the floors and at the corners of the embayment structures. The presence of chrome-spinel layers on the underside of protrusions of allivalite (fig. 1*c*) indicates conclusively that crystal settling was not important in the formation of such layers. Thus chromite must have crystallized *in situ* on an uneven floor of allivalite, with the possibility of minor olivine accumulation in irregularities on that floor.

An alternative to previous models of chromite concentration is suggested by the cone structures at the unit 7-8 boundary. Their ubiquitous occurrence at culminations in the allivalite lamination cannot be fortuitous and rules out an origin by slumping, loading or auto-intrusion. Similar upward deflections of a pre-existing lamination have been recorded in the Bushveld complex and ascribed to fluid escape (Lee, 1980), the analogy being with water-escape structures in clastic sediments (see Lowe, 1975, for review). If this interpretation is correct, then thick chrome-spinel accumulations are coincident with paths of relatively rapid fluid escape from the permeable crystal mush.

Petrographic descriptions of Brown (1956), Henderson and Suddaby (1971), Dunham and Wadsworth (1978), and Maaloe (1978) indicate that chrome-spinel is present, if somewhat sporadically, throughout the Eastern Layered Series stratigraphy. Thus magmas parental to peridotite must have been in equilibrium with olivine and chrome-spinel and those interstitial in allivalite in equilibrium with olivine, plagioclase, clinopyroxene and chrome spinel. These relations can be illustrated in the system Fo-Di-An-Pc-Qtz, e.g. path 1 in Irvine (1977, figs. 51-4) which models the evolution of a Rhum cyclic unit. It is thus apparent that mixing of interstitial liquid from allivalite (in equilibrium with Fo, An, Di, and Pc) with overlying picritic liquid (in equilibrium with Fo and Pc) must precipitate chromite alone, due to the curvature of the cotectic fractionation path away from the picrochromite apex of the phase diagram (see also Irvine, 1981). Cr concentrations must have been kept high in the neighbourhood of growing spinels by vigorous magma convection (Huppert and Sparks, 1980).

The inclusions within the spinels may be interpreted as further evidence for the presence of a relatively evolved liquid. Their morphology, their occurrence within olivine as well as spinel, and their morphological similarity to sulphide (immiscible liquid) inclusions suggest that they crystallized from liquid trapped within growing crystals and are not products of reaction of spinel with trapped or supernatant liquid. Morphologically similar silicate inclusions in Muskox chromite grains have also been interpreted as crystallized droplets of trapped liquid (Irvine, 1975, 1981). Their compositions and similarity to interstitial phases present throughout the intrusion suggests that this liquid was residual and was relatively hydrous, siliceous and alkali rich by comparison with the intrusion's parental picritic magma. They are not considered to represent an immiscible phase themselves, but droplets of residual liquid from the underlying cumulates which may not have been readily miscible with the supernatant magma. Any liquid-liquid interface which may have existed would have been a convenient site for heterogeneous nucleation of chrome-spinel.

Discussion. The upward expulsion of liquid from a cumulate pile is not a new concept. Previous studies have emphasized the role of compaction in driving fluid upwards (e.g. Irvine, 1980; Donaldson, 1982). However, compaction must be less effective in feldspar cumulates due to the small or even negative density contrast of feldspar with interstitial liquid. Consideration of the likely density contrast between dense picritic supernatant liquid and less dense interstitial liquid in the allivalite suggests that the driving force for fluid expulsion may have been convective overturn. The envisaged process is analogous to that described by Musgrave and Reeburgh (1982) in which a convective flow was set up between cold (dense), winter, bottom water in an Alaskan lake and warm (less dense) pore water in the lake-bottom sediments. A similar fluid flow was invoked by Morse (1981) to explain apparently anomalous Rb and K concentrations in Kiglapait cumulates; in this case the driving force was assumed to be the density increase associated with Fe enrichment. Dispersed sulphides in the footwall anorthosite of the Merensky reef in the Bushveld intrusion are considered to represent the downward percolation of a sulphide-rich fluid (Vermaak, 1976). Evidence for the migration of relatively hot, basic liquid into the allivalite mush may be provided by the common reversed zoning (figs. 4 and 5), irregular core shapes of allivalite feldspars and common poikilitic form of olivine towards the top of allivalites. Elsewhere in the Rhum intrusion the process offers an alternative explanation of the cryptic reversal that exists at the top of unit 10 (Dunham and Wadsworth, 1978) by the metasomatizing action of the downward filtering liquid, and offers a source of high-temperature components for adcumulus growth.

The proposed explanation of chromitite formation has only been applied to chrome-spinel layers at allivalite-peridotite contacts. It is clear, however, that the mechanism could account for the formation of any chromite layer where the appropriate conditions of relatively slow silicate sedimentation and mixing of expressed and overlying liquids occurs which are far enough apart on the fractionation path to allow crystallization of a significant amount of chromite. Thus all three chrome-spinel layers at the 7–8 junction may have formed in this way, perhaps during minor replenishment and mixing before the major replenishment which gave rise to the unit 8 peridotite. It is abundantly clear, however, that not all chrome-spinel layers in the Rhum intrusion could have originated in this way; particularly problematical are the chromitites intimately associated with harrisite layers in the Western Layered Series.

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