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FORMATION OF THE EASTERN LAYERED SERIES OF THE RHUM COMPLEX, NORTHWEST SCOTLAND

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Abstract

The Eastern Layered Series of the Rhum Complex in Scotland consists of inwardly dipping, coupled peridotite–troctolite cyclic units in which peridotite is overlain by rhythmically layered trotolite. Troctolites are impersistent in strike sections, and thin down-dip, whereas the peridotites thicken. Layering is developed to within two meters of the outwardly dipping bounding surface of the intrusion. The contact is an intrusive rather than a tectonic one, and thus the complex is preserved *in situ*. Transitions between units are abrupt, whereas transitions within units from peridotite to troctolite may be abrupt or gradational through a zone of interleaving of the two rock types. Mineral compositions indicate that the troctolites crystallized from more evolved magmas than the peridotites, and isotopic evidence shows the troctolites to be more contaminated with crustal components. These features are combined in a model in which contemporaneous crystallization of peridotite and troctolite layers occurred from stratified picritic and basaltic magmas, respectively. Major cycles developed in response to vertical movements of the zones of peridotite and troctolite crystallization.

Keywords: Rhum Complex, Eastern Layered Series, peridotite, troctolite, mineral compositions, isotopic data, solidification scheme, Scotland.

Sommaire

La série stratifiée du secteur oriental du complexe du Rhum (Ecosse) se compose d'unités cycliques constituées de couples péridotite - troctolite à pendage centripète; dans chaque cas, la troctolite, à stratification rythmique, recouvre la péridotite. Les horizons troctolitiques sont limités en étendue latérale, et s'amincissent en profondeur, tandis que les horizons péridotitiques s'épaississent. On observe une stratification jusqu'à deux mètres du contact du massif, à pendage vers l'extérieur. C'est un contact intrusif plutôt que tectonique, ce qui indique que le massif a cristallisé *in situ*. Les transitions entre unités sont franches, tandis qu'au sein d'une unité, le passage de péridotite à troctolite peut être soit franc, soit graduel, par alternance des deux lithologies. Les compositions des phases minérales montrent que les troctolites ont cristallisé à partir de magmas plus évolués que les péridotites; les données isotopiques prouvent que les troctolites ont subi une plus forte contamination crustale. On explique ces caractéristiques par un modèle de cristallisation simultanée des niveaux péridotitique et troctolitique à partir de magmas stratifiés, de composition respectivement picritique et basaltique. Les cycles principaux se seraient développés à la suite de mouvements verticaux des zones de cristallisation de péridotite et de troctolite.

(Traduit par la Rédaction)

Mots-clés: complexe du Rhum, Ecosse, série stratifiée orientale, péridotite, troctolite, compositions minérales, données isotopiques, schéma de cristallisation.

Introduction

Whereas some intrusions show uninterrupted cryptic variation throughout their exposed stratigraphic thicknesses (*e.g.*, Skaergaard and Kiglapait), in others the large-scale, cyclic layering is widely thought to result from periodic replenishment of magma in a chamber. This view, first advanced by Brown (1956) in his seminal paper on the Eastern Layered Series (ELS) of the Rhum ultrabasic complex, Scotland, subsequently has been proposed for many other intrusions (*e.g.*, Stillwater, Muskox, Fongen–Hyllingen, and mid-ocean ridge chambers).

Although the open-system character of the Rhum chamber is no longer in doubt, it is uncertain how the magma differentiated to give cyclic units, varying upward from peridotite to troctolite to gabbro. In this paper we briefly review the geology of the ELS and the crystallization schemes that have been proposed, and show that none of these adequately accounts for all that is known about the ELS. An alternative solidification scheme is outlined in which cyclic units form due to a combination of i) crystallization from a zoned magma along a sloping floor, and ii) variations in the input rate of a more or less continuously replenishing magma.

The Layered Complex

The Rhum ultrabasic complex has been subdivided into three separate layered series: the Eastern

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Layered Series (ELS), Western Layered Series (WLS), and Central Series (CS) (Brown 1956, Wadsworth 1961, McClurg 1982, Volker 1983). The ELS is dominated by cyclic units composed upwards of peridotite, troctolite, and gabbro (the last two being *allivalite* of Harker 1908), whereas the WLS consists largely of peridotite. Age relations of the WLS and ELS are uncertain; although the WLS is structurally lower, it is separated from the ELS by the younger CS. The Central Series also consists predominantly of peridotite, with subordinate troctolite and gabbro; much of the series is separated from the older two series by bands of intrusion breccia (McClurg 1982, Volker 1983).

The Eastern Layered Series

The ELS is bounded by acid volcanic rocks of the Northern Marginal Complex (NMC) and Southern Mountains Complex (SMC), and in the east by Proterozoic Torridonian sandstone and shale. The ELS is separated from all of these by a narrow zone of variable width (generally less than 30 m), consisting of partly melted country rock, intrusion breccia and hybrid rocks. At several places, the eastern contact of the ELS is coincident with the earlier Tertiary structure known as the Main Ring Fault (MRF) (Emeleus *et al.* 1985).

Extensive roof-like relationships occur between the ELS and the country rocks. In the north the contact dips gently to the north-northeast. In the southeast, at Beinn nan Stac, Tertiary felsite and Torridonian sandstone and shale overlie peridotite and troctolite of the ELS, the contact between them dipping approximately 30° to the east (Fig. 1). Here the cyclic units continue, without modification, to within 2 m of the contact where they are separated from the country rocks by a zone of intrusion breccia and hybrid rocks. In the south, near Dibidil, the ELS extends underneath the SMC; hybrid rocks occupy the sub-horizontal contact. These observations indicate that the ELS developed *in situ* and is not a fault-emplaced portion of a larger body, as advocated by Brown (1956).

Lithostratigraphy and Small-Scale Structures

The presence at the base of some ELS cycles of a thin seam of chromite and of cumulus clinopyroxene in the upper portions of the troctolites led Brown (1956) to propose a genetic subdivision of the ELS into 15 units, based on an analogy with phase relations in the system Fo–Di–An. Each unit was considered to be mainly continuous over the mapped portion of the ELS. Brown's stratigraphy has been adopted by many later investigators and though, as shown below, major departures from this simple picture occur, it is still useful for stratigraphic nomenclature. It has been suggested recently that the fine-grained gabbro sheets in the lower part of the ELS, mapped and interpreted as intrusive by Brown, ought also to be considered an integral part of the stratigraphy (Faithfull 1985). The bases of the peridotites are sharp and, as mentioned, in several cases are marked by development of thin chrome-spinel seams.

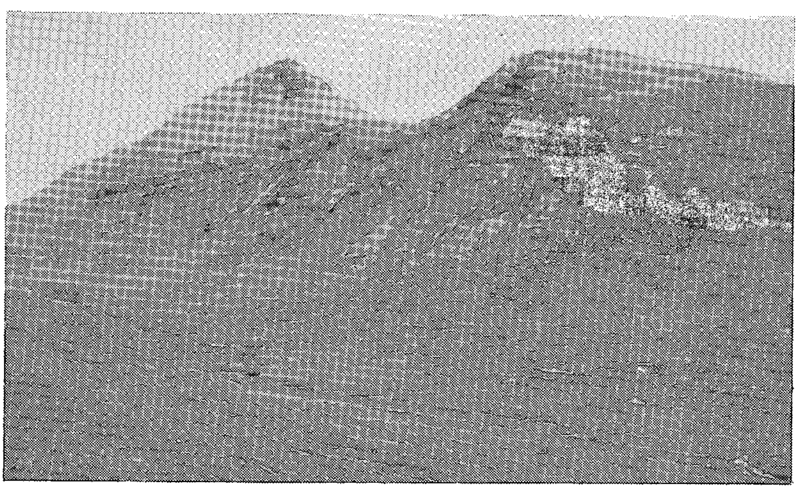

FIG. 1. The ELS as seen looking northward across Glen Dibidil toward the mountains of Beinn nan Stac (right) and Askival (left). The contact between the country rocks to the east (Tertiary felsite and Torridonian sandstone) and the ELS follows the shadow below the crags of Beinn nan Stac. The ribbing in the ELS consists of allivalite layers that dip and thin to the northwest. (Photo courtesy of R.M. Forster).

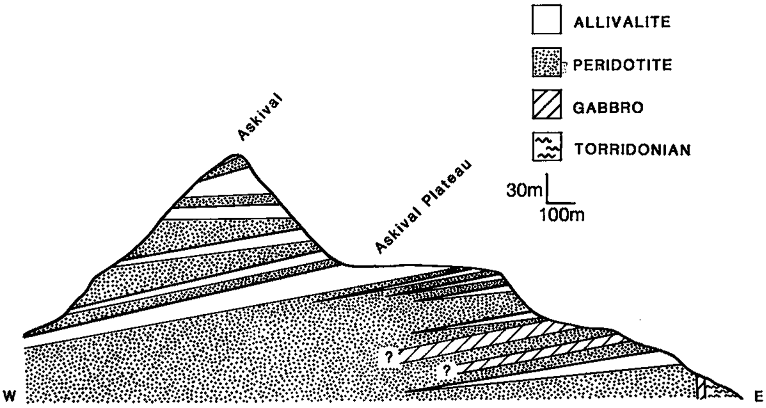

FIG. 2. Cross-section of the ELS, constructed from the map of Emeleus (1980), showing (a) thinning of allivalite and thickening of peridotite down-dip, and (b) the gentler dips of the intra-unit contacts (indicated by the thin lines) as compared with the inter-unit contacts (indicated by the thick lines). As the area on the western slopes of Askival has not been surveyed accurately, the section must be regarded as semi-schematic.

Chrome-spinel seams also occur toward the top of some peridotite horizons (*e.g.*, Unit 7 in Coire Dubh), and at the bases of thin peridotites developed in those parts of each cycle dominated by troctolite (*e.g.*, Unit 14, Hallival).

The upward transition of massive peridotite to allivalite is either abrupt, or is gradational over an interval of about a meter in which the rock types interleave (Brown 1956, Dunham & Wadsworth 1978, Faithfull 1985). Lamination, rhythmic layering and phase layering are almost ubiquitous features of the troctolites. Structures such as erosion-and-fill, "slump" folds, and load structures are present. The upper portions of many allivalites are marked by the appearance of cumulus clinopyroxene, and in places these gabbroic rocks make up the bulk of the allivalitic part of the Unit (*e.g.*, Unit 8). Most troctolites contain cm- to m-thick peridotites whose textures are indistinguishable in hand specimen or thin section from the peridotite portions of Brown's units. Unit 14 on Hallival provides a particularly spectacular example of this, with more than 15 thin peridotite layers (see Butcher *et al.* 1985).

Layering in the allivalites dips from 5–20° concentrically towards the center of the intrusion. Examination of a) recently published maps (Emeleus 1980, Butcher *et al.* 1985, Faithfull 1985), b) the field relations in Glen Dibidil and Coire Dubh, and c) a comparison of the stratigraphy of the eastern and western flanks of Hallival and Askival, confirms Harker's (1908) observation that the allivalite portions of the units thin down-dip (Fig. 2), though strike variations in thickness also occur. Dips do not increase appreciably inward or upward in the section, therefore allivalite thinning is compensated for by an equivalent thickening of the peridotite portions of the units.

As noted earlier, peridotites are structureless, though in places layers of different textural characteristics can be recognized (*e.g.*, Maaløe 1978, Butcher 1985). Upward transitions from peridotite to troctolite are characterized by "finger structures", vertical protrusions of peridotite into troctolite (Butcher *et al.* 1985). These are generally filled with peridotite similar to that of the underlying layer, though locally may be pyroxene-enriched (as in the "upward-growing pyroxene structures": Brown 1956). Fingers cut across layers, laminae, and lamination without significant deformation. In places, fingers coalesce and troctolite is embayed by massive peridotite.

Upward transitions from troctolite to peridotite are commonly marked by chrome-spinel laminae, 2 to 3 mm thick. Associated with these, though also present in outcrops lacking chrome-spinel seams, are structures in which peridotite embays troctolite, cutting across both layering and lamination. Embayments vary from simple, dimple-shaped structures to complex, horizontally extensive embayments with marginal 'overhangs' of troctolite (Young 1984).

TEXTURES AND MINERAL COMPOSITIONS

In peridotites the texture generally consists of equant, or less commonly, of elongate touching olivine crystals of euhedral or somewhat rounded habit, mostly 1 to 2 mm in diameter. Euhedral chrome-spinel grains (0.1 to 0.2 mm) are enclosed in, or

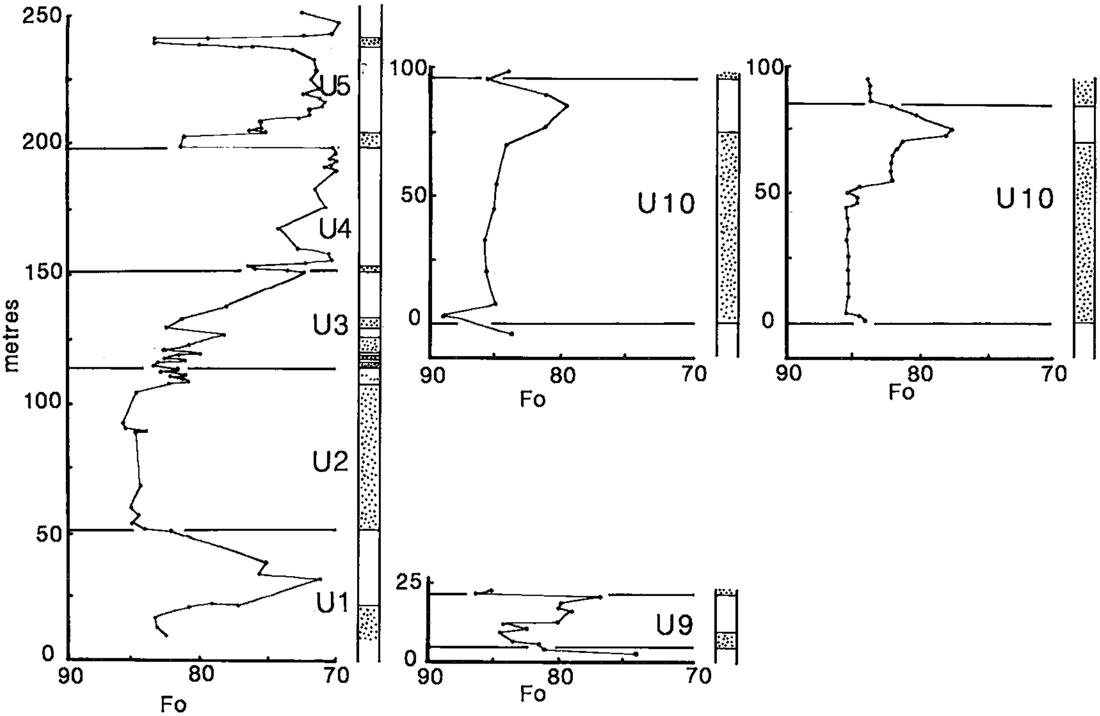

FIG. 3. Olivine compositions in measured profiles through units of the ELS. The data are from Faithfull (1985), Dunham & Wadsorth (1978), Tait (1985), and Palacz (1984). A lithological section is drawn beside each; the stippled sections represent peridotite, the unornamented sections allivalite. Several data points in the more densely sampled parts of units 1–5 have been omitted for the sake of clarity. All the profiles have several features in common: (i) in general olivine in the peridotite is more magnesian than that in the allivalite; this generality includes olivine in thin peridotite layers set in troctolite; (ii) the most magnesian olivine in any one unit is found at or just above the base, and conversely, the most iron-rich olivine is either at or just below the top; (iii) there is a relatively abrupt change in olivine compositions across peridotite/troctolite boundaries.

cluster around olivine. Poikilitic or intergranular plagioclase ± clinopyroxene crystals occupy the interstices of the rock.

The overlying troctolites, olivine gabbros and gabbros tend to have a trachytoid texture of euhedral to subhedral, tabular crystals of plagioclase, up to 2 × 1.5 mm. Most olivine and augite crystals have a similar size and partly wrap around the plagioclase crystals; the largest pyroxene grains poikilitically enclose plagioclase. Chrome spinel is generally absent from these rocks. Modal olivine content is 70 ± 10 vol.% in the peridotites and 10–50% in the allivalites.

Olivine is the only cumulus mineral present throughout the ELS. Published data on cryptic variation are scant and are collated in Figure 3. All profiles show certain similarities; the olivine in the peridotites is generally more magnesian, by some 5% Fo, than that in the allivalites. The change in olivine composition between units is not abrupt; rather, the most forsteritic compositions tend to be found some distance above the base of each peridotite layer, and the most evolved are found just below the top of the allivalites. Subsidiary peridotite layers within the allivalite portions of units exhibit small cryptic reversals (Faithfull 1985).

ISOTOPE GEOCHEMISTRY

Palacz (1985) has presented a $^{87}Sr/^{86}Sr$ profile from units 8 to 14 of the ELS that reveals a complex pattern of variation, both within and between units. Significant variations in $^{87}Sr/^{86}Sr$ occur at several unit contacts, with the ratio increasing abruptly in the underlying 3 m of troctolite, and then falling sharply at the base of the overlying peridotite. Both the study of Palacz (1985) and a more detailed examination of unit 14 by Renner & Palacz (1988) demonstrate that abrupt changes in $^{87}Sr/^{87}Sr$ values also occur within units and are not always coincident with lithological contacts.

A detailed Nd and Sr isotopic investigation of unit 10 by Palacz & Tait (1985) has revealed a more regular pattern of variation than seems to be the case for other units. The lowermost 30 m of unit 10 has a fairly constant $^{87}Sr/^{86}Sr$ value of 0.7037–0.7038, which increases gradually in the upper 35 m of the peridotite layer to around 0.7051. There is a sharp increase in $^{87}Sr/^{86}Sr$ at the peridotite–troctolite boundary, above which values continue to rise to a maximum of 0.7064, 3 m below the upper contact, beyond which the ratio again decreases rapidly. The $^{143}Nd/^{144}Nd$ ratios show a similar pattern of variation, as do Nd and Sr whole-rock contents and the Fo content of olivine.

Palacz & Tait (1985) suggested that the basal peridotite of unit 10 crystallized from a primitive, uncontaminated magma, and the allivalite from an evolved contaminated magma. The increase in $^{87}Sr/^{86}Sr$ and decrease in $^{143}Nd/^{144}Nd$ at the top of the peridotite, and the reverse variation at the top of the allivalite, are interpreted as the result of downward migration of variably contaminated liquids into the cumulate pile. Palacz (1985) proposed that the major source of crustal contamination was amphibolite-facies Lewisian gneiss. New Pb and Sr isotope analyses of the various country-rock units to the ELS by one of us (RCG) suggests that crustal contamination occurred *in situ* by wallrock assimilation.

Evolution of Ideas on ELS Formation

Harker (1908) believed that the peridotites and allivalites of Rhum represent successive intrusions of heterogeneous magmas of appropriate compositions. Tomkeieff (1945) amended Harker's scheme when he proposed that the layering developed during the injection of a single pulse of heterogeneous magma, with the different components streaking out to form the layering.

It was Wager & Brown (1951) who first suggested that the ultrabasic rocks were part of a layered complex; this concept was further developed by Brown (1956), who recorded features in the ELS resembling those of the Skaergaard intrusion. Unlike at Skaergaard, he found no marginal border rocks and therefore postulated that the Rhum Complex is an uplifted, fault-bounded portion of a larger body. In his interpretation (see Fig. 4) each cyclic unit of the ELS represents the solid differentiate of separate

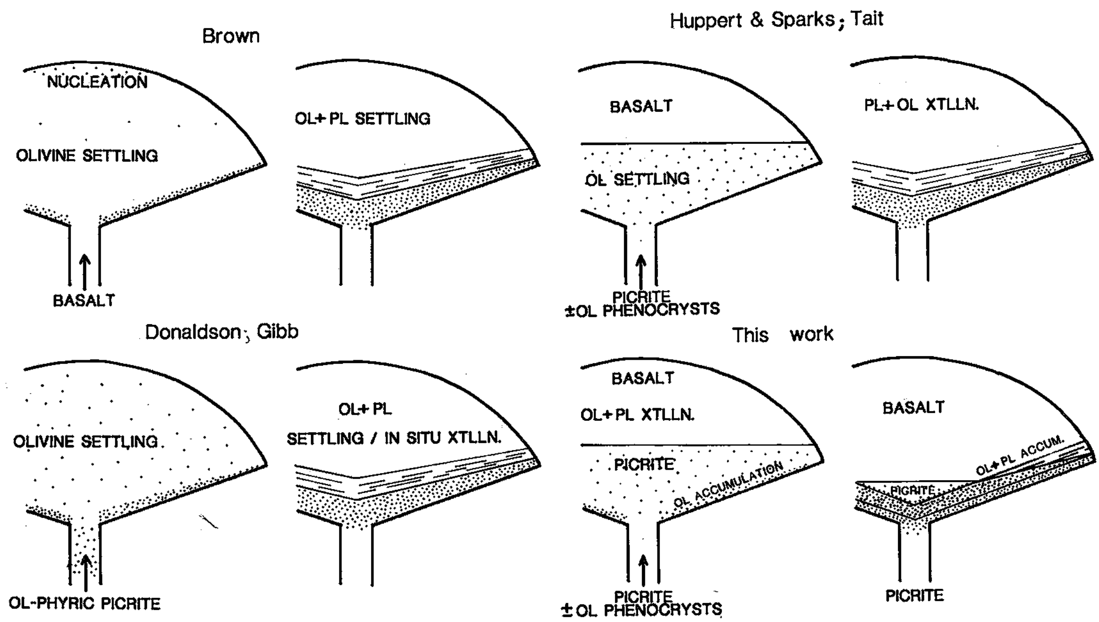

FIG. 4. Schematic representations of recent hypotheses on ELS formation. (a) Replenishment by basaltic liquid followed by fractional crystallization (Brown 1956). (b) Replenishment by olivine-phyric picrite, the olivine being dumped to form a massive peridotite layer. Subsequent cumulates form by fractionation of basalt (Donaldson 1975, Gibb 1976). (c) Injection of picritic magma which ponds at the base of the chamber. Olivine is held in suspension until convection slows, then is dumped to form a massive peridotite layer. Subsequent cumulates form by fractionation of basalt (Huppert & Sparks 1980, Tait 1985). (d) Injection of picritic magma which ponds at the base of the chamber. Olivine crystallization and plagioclase + olivine crystallization go on simultaneously within the picritic and basaltic layers, respectively. As the volume of picrite diminishes, a wedge of troctolite builds out across a lower peridotite layer (this study).

injections of basic magma. Residual liquid from each magma pulse was considered to be displaced through a volcanic vent by each replenishing magma batch.

Interpretations of recent geochemical investigations have not greatly altered Brown's scheme of events; all confirm the correlation of one cyclic unit with one pulse of replenishing liquid (*e.g.*, Dunham & Wadsworth 1978, Palacz 1984, Tait 1985, Faithful 1985). By contrast, the nature and composition of the replenishing magma have been controversial. Brown (1956) and subsequently Dunham & Wadsworth (1978), thought it to have been basaltic, with a transitional to tholeiitic composition. Donaldson (1975) and Gibb (1976) challenged this with the contention that the magma was a picrite, emplaced as a mixture of olivines in a melt fraction that was "eucritic" (Fig. 4), a local term implying an olivine basalt capable of crystallizing bytownite rather than labradorite. However, the discovery on Rhum of aphyric minor intrusions with MgO contents of up to 21% (Forster 1980, McClurg 1982) showed that a picritic liquid was available at the time the Rhum Complex was forming. This has led most investigators to regard the ELS parent magma as being an ultrabasic liquid, perhaps with some suspended crystals of olivine and spinel (*e.g.*, Huppert & Sparks 1980, Faithful 1985, Butcher *et al.* 1985, Tait 1985; contrast Kitchen 1985).

Sparks *et al.* (1980) and Huppert & Sparks (1980) argued that dense, replenishing picritic magma would pond at the base of the chamber under the resident, less dense basaltic liquid, until, by fractionation, it evolved to the same density as the basalt (Fig. 4). Peridotites were viewed as the products of fractional crystallization of the picritic liquid. Owing to initial turbulence in the picrite magma, early-formed olivine remained in suspension, then, as the two magmas reached equal density they mixed, convection slowed, and the olivine settled onto the chamber floor. The resulting single, basalt layer then crystallized troctolite followed by gabbro, until a further replenishment by picritic liquid repeated the cycle.

Most recently, the possibility that some, or all, of the peridotite is intrusive into allivalite (*cf.* Harker 1908) has been re-introduced (Morse *et al.* 1987, Renner & Palacz 1988, Bedard *et al.* 1988), the evidence being locally cross-cutting relationships between the two lithologies.

Another Interpretation

Recognition that the ELS is preserved *in situ* and is only partly unroofed has an important bearing on the evaluation of petrogenetic models. In particular it greatly restricts the volume of magma available at any time in the chamber from which the cumulates could have formed. During solidification of the upper layered units the chamber was probably only a few tens to a few hundreds of meters thick; certainly the chamber was much thinner than the values calculated by Tait (1985) on thermal grounds. The peridotites are, however, characterized by a lack of cryptic variation, suggesting that they did not form from the small magma volumes available in a thin chamber, or in sills. The constraints of thinness and constant composition can be satisfied if the thick peridotites are built up during relatively constant introduction of magma to the chamber.

The contact relations further indicate that the magmas parental to peridotite and allivalite portions of the ELS shared a common margin which, together with the large-scale regularity of the stratigraphy, is consistent with Brown's interpretation of the ELS as having been formed by superposition.

The mechanism responsible for the stratigraphic thickness variations is more obscure. Assuming that these are a primary (cumulus) feature, we propose a model of cyclic unit formation which involves contemporaneous crystallization of peridotite and allivalite cumulates from a compositionally stratified magma along a sloping floor. Crucial to this proposition is the realization that the Rhum magma probably did not have a density minimum on its fractionation path (Tait 1985). Therefore, a stable compositional stratification would have existed for the greater part of the lifetime of the chamber (*cf.* Huppert & Sparks 1980).

Consider an inwardly dipping cumulate floor overlain by compositionally stratified magma. Picritic magma replenishes the chamber, space being created by eruption (Brown 1956), it ponds at the base and crystallizes olivine (Fig. 4) (see Huppert & Sparks 1980, Huppert *et al.* 1982). The olivine may nucleate and grow within the picritic magma and remain suspended in the turbulently convecting liquid, or crystallize *in situ* on the chamber floor. Continuing influxes of magma allow more olivine to accumulate. However, slight variations in replenishing magma composition, temperature, phenocryst content, and input rate may lead to the development of textural and compositional layering in the peridotite. This could take place by olivine nucleation and growth at different degrees of supersaturation. Crystallization may be occurring within the overlying, more evolved liquid, driven by heat loss to the hydrothermal cooling system; however, any crystals falling into the lower layer by two-phase convection (Morse 1986) will react (olivine) or be resorbed (plagioclase and clinopyroxene). If, however, replenishment stops or slows sufficiently, the relative volume of evolved, plagioclase-saturated magma must increase and ultimately impinge on, and move down and across the chamber floor (Fig. 5). Note that this is not the same as the movement of any double-diffusive interface in the liquid column, which conceivably could move in the opposite sense.

Thus we envisage a situation being reached in which peridotite cumulates formed from the lower part of the liquid column while allivalite cumulates formed from the upper part. This situation would also hold if the initial replenishment never covered the whole chamber floor. Similar concepts have been applied to interpretations of the cumulates of the Muskox (Irvine 1981), Stillwater (Irvine *et al.* 1983) and Fongen–Hyllingen (Wilson & Larsen 1985) intrusions.

As the zones of olivine and of olivine and plagioclase crystallization move downward and across the floor, peridotite and troctolite cumulates form concurrently (Fig. 5). Any rhythmic layering produced at the mush–magma interface will be developed parallel to the chamber floor; by contrast, the junction between the lower and upper portions of resulting cyclic units will grow outward in the cumulate pile at a shallower angle. This contact is diachronous and results in peridotite thickening, and allivalite thinning, down-dip. Angular discordance between phase layering and rhythmic layering is a feature of some other layered intrusions and has been reproduced experimentally by cooling compositionally zoned solutions along sloping boundaries (Sparks *et al.* 1984).

Relatively abrupt, minor, vertical movements of the liquid column could be expected to arise by stoping, dyke emplacement, eruption, or minor replenishments, causing the zones of peridotite and troctolite crystallization to move back and forth across the floor. Consequently, the junction between peridotite and overlying troctolite cumulates will not be abrupt; rather, the two rock types will interleave (Fig 6).

The cyclic stratigraphy in the ELS is viewed here as a response to changes in magma throughput instead of major and abrupt changes in the composition of the magma occupying the chamber. Peridotite formation predominantly occurred when the rate of replenishment of olivine components was equal to or greater than the rate at which they were removed by crystallization. Troctolite accumulation occurred when the converse situation held.

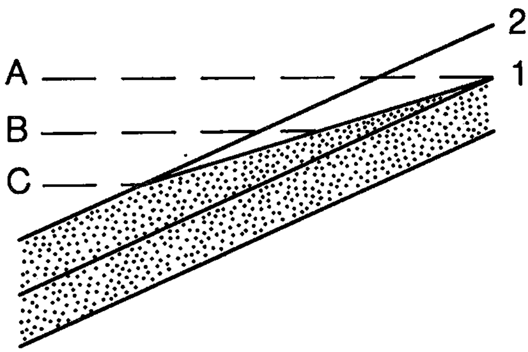

FIG. 5. Accumulation of a hypothetical slab of cumulate on a dipping chamber floor. In this Figure and those that follow a stippled ornament represents olivine cumulate whereas an unornamented area represents plagioclase cumulate. Numbers 1 and 2 refer to successive positions of the floor, letters A to C to successive positions of the transition between peridotite and allivalite accumulation, represented here as a line for clarity; this transition itself may be a thick zone. As crystal accumulation continues, the position of the transition moves down and across the floor, resulting in a wedge of allivalitic cumulates building out across underlying peridotite cumulate.

As previously mentioned, our interpretation assumes a cumulus origin for the down-dip thinning of allivalite layers. This assumption is open to doubt, however, because local development of finger structures testifies to the replacement of allivalite by peridotite from below (Butcher *et al.* 1985), and irregularities on the upper surfaces of some allivalites indicate that resorbtion has also occurred from above (Young 1984), *i.e.*, it is conceivable that down-dip thinning in allivalites was produced by resorbtion, a process which may have been more efficient toward the center of the chamber.

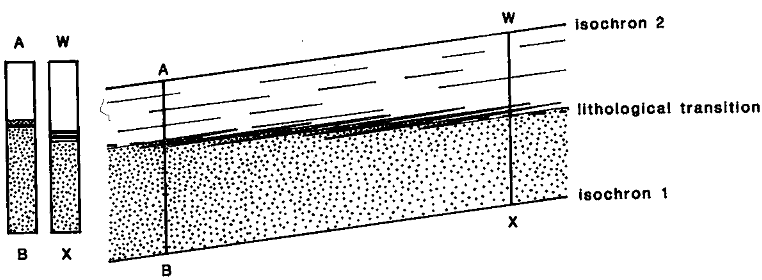

FIG. 6. An enlarged part of Figure 5 showing the interleaving of cumulate types in the transition zone, formed during minor oscillations in the position of the liquid column relative to the floor. Cross-sections AB and WX illustrate the differences in stratigraphy that can be produced by such a scheme during one time interval.

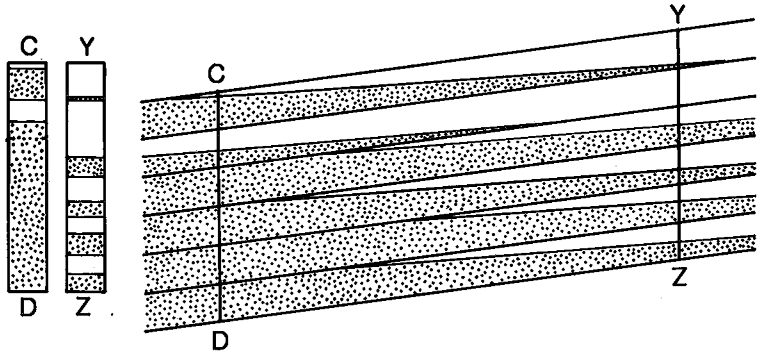

FIG. 7. Six cyclic units, each built up as in Figures 5 and 6 but repeated as a result of increases in the rate of chamber replenishment having pushed the position of the liquid/liquid interface back up and across the floor; the additional heat supplied slowed or even stopped crystallization, resulting in a relatively abrupt transition from allivalite to overlying peridotite. Cross-sections CD and YZ illustrate the variations in stratigraphy produced during equivalent times.

Unfortunately, the setting in which peridotite formed (Young & Donaldson 1985) on the chamber floor, or within the crystal pile, cannot be established unequivocally on textural or compositional grounds. Isotopic data are also subject to a wide range of interpretations due partly to problems in identifying the source of contaminating components, to the extent of cumulus crystal overgrowth, and to infiltration of intercumulus material. Further uncertainty is added by the possibility that more than one magma type fed the ELS chamber and by the recognition of apparently intrusive peridotites, which could be genuinely intrusive, or auto-intrusive in the manner of sandstone sills. These uncertainties will only be removed by more careful examination of critical field relations.

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