

Cryptic variation in the Rhum layered intrusion

A. C. DUNHAM AND W. J. WADSWORTH

Department of Geology, University of Manchester

SUMMARY. Electron-microprobe analyses of cumulus olivine, chromite, pyroxene, and plagioclase from layered peridotites and allivalites of the Eastern and Western Layered Series of Rhum demonstrate the presence of cryptic variation. Olivine varies from $Fe_{0.88-0.78}$ within individual units, and there are corresponding changes in the $Mg/(Mg + Fe^{2+})$ ratios in the pyroxenes and chromites. Plagioclase changes are not so dramatic, but the An-content broadly follows the $Mg/(Mg + Fe^{2+})$ ratio in the other minerals. The most Fe- (and Na-) rich phases do not occur at the top of lithological units, but some way below. The composition trend above them is reversed. The data are interpreted as the result of periodic infilling of a magma chamber, the new magma mixing with the remains of the previous pulse. Each pulse was followed by a period when fractional crystallization produced the layered rocks. New data on Ni in the olivines suggests that the ratio of the volume of initial magma to volume of layered rocks was about four to one, the initial magma being allied to the high-calcium low-alkali tholeiitic basalts of Skye.

THE Isle of Rhum has long been noted for its layered ultrabasic rocks, which form a roughly cylindrical mass (7 km in diameter) emplaced within Lewisian and Torridonian country rock during Tertiary igneous activity. These ultrabasic rocks consist of a sub-horizontal alternation of olivine-rich (peridotite) and plagioclase-rich (allivalite) layers, which were originally thought to represent a succession of sill-like injections of peridotite and allivalite magma (Harker, 1908), but are now interpreted as a cumulate sequence dominated by a large-scale alternation of olivine (-chrome-spinel) cumulates and olivine-plagioclase (-clinopyroxene) cumulates (Wager and Brown, 1968). Each peridotite layer and the overlying allivalite layer are thought to be the complementary products of a single major episode of crystal accumulation, and are referred to as *cyclic units* (or units, in brief). Two distinct stratigraphic successions have been identified. In eastern Rhum, fifteen units are represented in a 750 m sequence forming the twin peaks of Hallival and Askival (Brown, 1956). These are termed the Eastern Layered Series (ELS). Individual units (numbered

1-15 from the lowest upwards) vary between 15 m and 150 m in thickness, and the peridotite member is generally considerably thicker than the allivalite. In south-west Rhum the succession reaches a thickness of approximately 1400 m, but comprises fewer cyclic units (Wadsworth, 1961). Three complete units (B, C, D) have been recognized, and these are underlain by cumulates believed to represent the top of another unit (A). Together they form the Western Layered Series (WLS), with the individual units between 300 m and 500 m in thickness. Peridotite is even more dominant than in eastern Rhum. The relationship between the ELS and WLS is not at all clear. There is a region of considerable structural complexity between the two, and this has not yet been investigated in detail.

The cyclic pattern of peridotite and allivalite accumulation has been interpreted by Brown (1956) and Wadsworth (1961) in terms of repeated pulses of basaltic magma, depositing their early formed crystallization products in a high-level magma chamber before continuing to the surface to be erupted as lavas. On this basis, each unit represents the sequential precipitation of olivine (with minor chrome-spinel) to give the peridotite, followed by olivine + plagioclase, and then olivine + plagioclase + clinopyroxene, to give the allivalite. This reflection of the over-all crystallization sequence in the stratigraphic succession of cumulates is generally referred to as *phase layering*. This is not to be confused with the smaller (centimetre) scale variation in cumulate mineralogy and texture, termed *rhythmic layering*, which is typically superimposed on the phase layering, and is conventionally interpreted in terms of sedimentational sorting operating within the magma, although other factors such as supercooling and discontinuous nucleation are probably involved as well. The progressive fractionation of the magma is also generally expressed in a more subtle but continuous variation in the cumulate succession. This is termed *cryptic layering*, which describes the gradual changes in mineral composition with stratigraphic position, in response to the changing magma

composition. It is thus complementary to the phase layering.

The Rhum layered intrusion displays obvious phase layering, but is particularly distinctive in that the same pattern of phase layering is repeatedly developed. However, until now, there has been little or no evidence of a symplathetic cryptic variation, and this apparent anomaly has been difficult to explain in terms of a basalt fractionation model (Gibb, 1976).

Brown (1956) found no appreciable cryptic variation within the ELS units, but Wadsworth (1961) detected slight iron enrichment of the olivines from base to top of units B and D of the WLS, as well as a reverse trend in the thin Transition Series (between Unit A and Unit B), which was believed to be the result of mixing a fresh pulse of magma with the differentiated residual magma from the previous unit. Wadsworth suggested that although the phase-layering pattern was the same in both the ELS and WLS, the occurrence of slight cryptic layering in the WLS was related to the greater thickness of the individual units in south-west Rhum. He also noted that the olivines at the base of the WLS units (B and D at least) appeared to be slightly more magnesian than those of the ELS, and on this basis proposed that the WLS represented batches of slightly more primitive magma than the ELS, and that the WLS may therefore have been stratigraphically lower than the ELS in the original Rhum succession.

However, these earlier results were based primarily on optical data ($2V_{\alpha}$ and β), supplemented by a very limited number of chemical analyses of separated minerals. The present account is based on an electron microprobe study of the principal minerals in Unit B of the WLS, in order to establish the validity (or otherwise) of the optical data, but it was extended to Unit 10 (Brown's type unit) in the ELS when it became apparent that the cryptic variation in Unit B was more dramatic than expected.

Unit B (WLS)

Not only are the cyclic units of south-west Rhum relatively thick, but they do not form a simple topographic succession as in eastern Rhum. For this reason the WLS was originally mapped (Wadsworth, 1961) as a series of lithologically contrasted formations (mostly peridotite or allivalite), which were subsequently grouped together as major units. The lithological divisions forming Unit B and the immediately adjacent units are shown in Table I.

The Harris Bay Series, which is presumed to represent the topmost part of Unit A, consists of plagioclase-pyroxene-olivine cumulates, which are

texturally unlike any of the other allivalites, and originally appeared to be the most differentiated members of the Rhum succession. They are separated from the peridotites at the base of Unit B (Ard Mheall Series) by the Transition Series, which has intermediate lithological characteristics, and displays reverse cryptic layering.

TABLE I

Units	Lithological divisions	Thickness
Unit C	Lower Ruinsival Series (LRS)	
Unit B	Dornabac Series (DS) (120 m) (Zone of igneous breccia) Ard Mheall Series (AMS) (380 m) Transition Series (TS)	500 m
Unit A	Harris Bay Series (HBS)	

The junction between the peridotite member of Unit B (Ard Mheall Series) and the allivalite member (Dornabac Series) is complicated by a zone of breccia, consisting of peridotite blocks in an olivine-plagioclase cumulate matrix, and believed to represent a period of structural disturbance and disruption during the deposition of Unit B. The incoming of significant quantities of cumulus plagioclase occurs at about this level. Cumulus clinopyroxene only appears in the upper part of the Dornabac Series. The top of Unit B is marked by a relatively sharp contact between the Dornabac Series allivalites and the overlying peridotites in the Lower Ruinsival Series, but a detailed investigation revealed a very thin layer (0.5 m) of olivine-plagioclase cumulates, which might be regarded as a lithological transition zone between the two units, and possibly comparable with the Transition Series between Units A and B.

Perhaps the most distinctive feature of the Harris Bay Series, Transition Series, and Ard Mheall Series is the occurrence of harrisitic layers, interspersed among the normal cumulates. These contain exceptionally large and complex olivines, some of which show evidence of having grown upwards from the top of the cumulate pile, and have been interpreted as representing crystallization during periods of non-deposition (Wadsworth, 1961) probably under conditions of considerable supercooling (Donaldson, 1977a). In so far as these harrisitic layers may represent special conditions of formation they have been excluded from the study of cryptic layering, although a preliminary study of the harrisitic olivines suggests that they do not differ significantly in composition from the cumulus olivines in adjacent layers.

Unit 10 (ELS)

Unit 10 was selected as the type unit of the ELS, because it is relatively thick (80–90 m) and exceptionally well-exposed. A detailed description is presented by Brown (1956). The lower two-thirds of Unit 10 are olivine (-chrome-spinel) cumulates, with very occasional thin harrisitic layers. Abundant cumulus plagioclase appears relatively abruptly in the sequence (at approximately 70 m from the base of Unit 10) so that peridotite passes upwards into allivalite over a thickness of only 1–2 m. Definite cumulus clinopyroxene is present only in the topmost 12 m of the unit. Unlike Unit B of the WLS there is no evidence of a lithological transition either at the top or bottom of Unit 10.

Cryptic layering

Olivine is the only cumulus phase that is consistently present throughout the Rhum cyclic units, and is therefore the best indicator of cryptic variation. Cumulus olivines from 30 rocks (17 from the WLS and 13 from ELS) have been analysed (see Tables II and III) and their forsterite contents plotted against stratigraphic height (fig. 1). The main conclusions to be drawn from the olivine data are:

The apparent range of compositions represented within each rock is extremely small, and is believed to be within the limits of analytical error (see Tables II and III for standard deviations, also Dunham and Wilkinson, in press). There is no trace of zoning, even within the large and morphologically complex harrisitic olivines. Thirty-two analyses from different parts of a single crystal (9663 H in Table II) of this type gave results between $FO_{85.4}$ and $FO_{86.2}$ (average $FO_{85.9}$).

Within the units investigated the over-all range in composition is between FO_{78} and FO_{88} . In general there is progressive Fe-enrichment with increasing stratigraphic height throughout a considerable part of Unit B and Unit 10, although in the former the most magnesian olivines occur approximately one-third of the way up the succession (see further discussion of this point below).

The variation in olivine composition is most dramatic in the upper parts of each unit. The Fe-enrichment trend is significantly more pronounced after the appearance of cumulus plagioclase, with the upward change from FO_{85} to FO_{78} (Unit B) and FO_{83} to FO_{79} (Unit 10) taking place over approximately 20% of the unit thickness in each case. However, the most Fe-rich olivines do not occur at the lithological top of each unit, but between 5% (Unit B) and 10% (Unit 10) of the over-all thickness below the top. Above this level there is a significant

reversal in the olivine composition trend, with sharp but progressive Mg-enrichment in the topmost 5–10% of the unit, until the most magnesian olivines of the succeeding unit are reached at, or just above, the lithological change from allivalite to peridotite (except at the base of Unit B). A minor reversal also occurs 15–20 m above the base of Unit 10 (between samples 713 and 714).

The junction between Units A and B appears to be exceptional in terms of this reversal. Not only is there a 50 m thickness of lithologically intermediate cumulates between the two, but reverse cryptic variation, especially at the base of this Transition Series, was identified by means of optical determinations on olivine and plagioclase (Wadsworth, 1961). This variation is clearly substantiated by the microprobe analyses and in particular the olivine data indicate that the reversal is much more protracted than previously recognized, with the occurrence of progressively more magnesian olivines from the top of Transition Series (FO_{84}) to approximately 250 m above the base of the Ard Mheall Series ($FO_{88.5}$).

Of the analysed minor elements, Ni and Ca show a positive correlation with Mg. The range of NiO contents is closely comparable to that described by Irvine (1975) for the Muskox intrusion, while the CaO contents straddle the limit suggested by Simkin and Smith (1970) for distinguishing between plutonic and volcanic (or hypabyssal) olivine, indicating that the activity of Ca in the magma is as important as the depth of crystallization in determining the Ca content of the olivines.

Chrome-spinel. With the exception of the pyroxene-allivalites (Harris Bay Series) at the top of Unit A, cumulus chrome-spinel is generally restricted to the peridotite member of each unit, where it is typically disseminated among the cumulus olivines, but is locally concentrated into distinct layers up to 1 cm thick. Some of the disseminated chrome-spinels are contained within the olivine crystals, while others lie between the olivines, or in marginal embayments of the olivines, often forming small clusters, and enclosed by intercumulus plagioclase or pyroxene. Layers rich in cumulus chrome-spinel are quite common within the Ard Mheall Series of Unit B (WLS), and they are also encountered immediately beneath the peridotites of certain units in the ELS (notably at the base of Units 8 and 12), where Henderson and Suddaby (1971) and Henderson (1975) have shown that there is considerable compositional variation among the chrome-spinel grains within individual layers. This variation was attributed to postcumulus reaction processes involving the spinels, the adjacent silicates (especially plagioclase), and the interstitial magma.

TABLE II. Averaged olivine analyses from the Western Layered Series (mainly Unit B)

	9605	9618	9621	9622	9640*	9646*	9663	9663 H	R48	R49	R51	DA	9692	9698	DB	LR3	LR6
SiO ₂	39.34	39.35	39.49	39.57	38.87	39.28	40.67	39.82	40.69	41.05	40.53	39.85	39.41	38.40	40.56	40.73	40.79
FeO	20.25	19.16	18.43	17.16	19.49	15.35	12.64	13.47	10.96	11.56	11.77	14.39	18.46	19.91	13.33	11.91	12.43
MnO	0.34	0.30	0.38	0.27	0.21	0.25	0.21	0.27	0.26	0.30	n.f.	0.23	0.29	0.28	0.23	0.26	0.22
MgO	40.42	40.87	41.94	42.62	42.08	45.25	45.97	46.01	47.17	47.39	46.95	45.20	41.83	41.10	46.43	47.11	46.81
CaO	n.f.	0.04	0.05	0.05	0.03	0.12	0.20	0.18	0.18	0.18	0.15	n.f.	0.02	0.05	n.f.	n.f.	n.f.
NiO	0.32	0.21	0.25	0.28	n.f.	n.f.	0.40	0.35	0.35	0.34	n.f.	0.31	0.33	0.17	n.f.	0.31	0.37
Total	100.67	99.93	100.54	99.95	100.68	100.25	100.09	100.10	99.61	100.82	99.40	99.98	100.34	99.91	100.55	100.32	100.62
	Standard deviations																
SiO ₂	0.21	0.26	0.63	0.12	0.51	0.06	0.11	0.25	0.28	0.37	0.22	0.31	0.21	0.17	0.53	0.28	0.22
FeO	0.14	0.19	0.12	0.29	0.08	0.01	0.54	0.23	0.30	0.22	0.25	0.23	0.30	0.33	0.53	0.28	0.40
MgO	0.18	0.13	0.30	0.33	0.26	0.06	0.10	0.32	0.21	0.16	0.30	0.38	0.40	0.14	0.54	0.21	0.37
No. of analyses	5	4	4	4	3	3	3	32	17	6	5	3	5	3	4	8	7
	Number of cations on the basis of 4 oxygens																
Si	1.006	1.008	1.003	1.004	0.991	0.987	1.009	0.996	1.007	1.006	1.006	0.999	1.003	0.990	1.003	1.006	1.005
Fe	0.433	0.411	0.391	0.364	0.416	0.322	0.262	0.282	0.227	0.237	0.244	0.302	0.393	0.429	0.276	0.246	0.256
Mn	0.007	0.006	0.008	0.006	0.005	0.005	0.004	0.006	0.005	0.006	—	0.005	0.006	0.006	0.005	0.005	0.005
Mg	1.541	1.561	1.588	1.613	1.598	1.694	1.701	1.717	1.741	1.732	1.738	1.689	1.587	1.580	1.712	1.735	1.720
Ca	—	0.001	0.001	0.001	0.001	0.003	0.005	0.005	0.005	0.005	0.004	—	0.001	0.001	—	—	—
Ni	0.007	0.004	0.005	0.006	—	—	0.008	0.007	0.007	0.007	—	0.006	0.007	0.004	—	0.006	0.007
Fe	78.1	79.1	80.2	81.6	79.3	84.0	86.6	85.9	88.5	88.0	87.7	84.9	80.2	78.6	86.1	87.6	87.0
s.d.	0.16	0.17	0.15	0.25	0.20	0.00	0.50	0.23	0.26	0.21	0.26	0.24	0.40	0.21	0.62	0.24	0.27

* Wavelength spectrometer analyses. s.d. = Standard deviation. n.f. = Not found.

TABLE III. Averaged olivine analyses from the Eastern Layered Series (mainly Unit 10)

	711	712	713	714	715	716	717	718	719	720	721	722	723
SiO ₂	39.74	40.66	39.91	39.99	40.27	39.96	39.76	39.51	39.33	38.88	39.62	40.47	39.77
FeO	15.03	11.56	14.62	13.69	13.52	14.63	14.92	15.69	18.28	19.36	17.43	14.28	15.21
MnO	0.27	0.22	0.24	n.f.	0.22	0.26	0.22	0.27	0.25	0.28	0.33	0.32	n.f.
MgO	44.79	47.83	45.29	45.53	45.63	45.17	44.77	43.94	42.43	41.40	43.03	45.11	44.78
CaO	n.f.	0.10	n.f.	0.14	0.12	n.f.	n.f.	0.13	0.09	0.09	0.08	n.f.	n.f.
NiO	n.f.	0.29	0.33	0.32	0.30	0.33	n.f.	0.31	0.20	0.17	0.23	n.f.	n.f.
Total	99.83	100.66	100.39	99.67	100.06	100.35	99.67	99.85	100.58	100.18	100.72	100.18	99.76
Standard deviations													
SiO ₂	0.20	0.42	0.18	0.11	0.26	0.38	0.03	0.26	0.25	0.18	0.19	0.24	0.30
FeO	0.32	0.12	0.28	0.26	0.20	0.21	0.15	0.44	0.17	0.20	0.28	0.29	0.34
MgO	0.24	0.52	0.32	0.52	0.14	0.24	0.17	0.38	0.18	0.23	0.31	0.26	0.08
No. of analyses	4	5	4	3	5	7	3	5	4	7	4	11	3
Number of cations on the basis of 4 oxygens													
Si	0.999	0.999	0.998	1.002	1.004	0.999	1.001	0.999	0.998	0.996	1.000	1.009	1.000
Fe	0.316	0.238	0.306	0.287	0.282	0.306	0.314	0.332	0.388	0.415	0.368	0.298	0.320
Mn	0.006	0.005	0.005	—	0.005	0.006	0.005	0.006	0.005	0.006	0.007	0.007	—
Mg	1.679	1.752	1.687	1.700	1.696	1.684	1.680	1.656	1.605	1.581	1.619	1.677	1.679
Ca	—	0.003	—	0.004	0.003	—	—	0.003	0.002	0.002	0.002	—	—
Ni	—	0.006	0.007	0.006	0.006	0.007	—	0.006	0.004	0.004	0.005	—	—
Fo	84.2	88.1	84.7	85.6	85.7	84.6	84.2	83.1	80.2	79.0	81.5	84.9	84.0
s.d.	0.29	0.23	0.21	0.20	0.15	0.21	0.12	0.36	0.05	0.38	0.13	0.30	0.30

n.f. = Not found. s.d. = Standard deviation.

In order to minimize the effect of such reactions on any genuine cryptic variation in the chrome-spinel compositions, only grains that were apparently contained within the original cumulus olivines (with no intervening plagioclase or pyroxene rim) were investigated in detail. Analyses of such chrome-spinels in 10 rocks from Unit B and adjacent units in the WLS and from 7 rocks in Unit 10 and from the base of Unit 11 in the ELS (Tables IV and V) show that the apparent compositional variation between grains is small compared with the variation between intra-olivine chromites from rocks at different stratigraphic levels. There is no evidence of zoning. The cryptic variation closely parallels the olivine trend, at least in the peridotites. (Unfortunately the scarcity of cumulus chrome-spinel in the allivalites of Unit B and Unit 10 precludes any comparison in the region where the olivine compositions change most dramatically.) Mg/(Mg + Fe²⁺) of the chrome-spinels shows the normal tendency towards progressive iron enrichment in the upper part of the peridotites, as well as evidence of the composition reversal at the junctions between units (fig. 1). It is also interesting to note that the minor reversal indicated by the cumulus olivines 15–20 m above the base of Unit 10 is confirmed by the chrome-spinels (and by the

intercumulus pyroxene and plagioclase). In terms of the trivalent cations, there is progressive enrichment of Fe³⁺ relative to Cr as Mg/(Mg + Fe²⁺) decreases. The Al/Cr ratio is remarkably constant, except in the most basic cumulates of Unit B, where the chrome-spinels are relatively aluminous.

R49, from the middle of Unit B, appears to be exceptional in containing two distinct generations of chrome-spinel within the olivines, in terms of both size and composition (fig. 1). Of these, the larger grains (200–400 μm) are assumed to be approximately contemporary to the olivines. The smaller grains (< 75 μm), which are significantly more iron-rich, may represent an earlier crystallization episode from a more evolved magma, such as that available during the transition from Unit A to Unit B. It seems possible that these small chrome-spinel crystals may not have settled with their contemporary phases, but were accidentally incorporated in olivines of a later generation.

A preliminary comparison of the cumulus chrome-spinels from within and between the cumulus olivines indicates that there are considerable compositional differences between the two. In general, the chrome-spinels enclosed by intercumulus material are richer in Al than those from within the olivines. This effect is most marked when

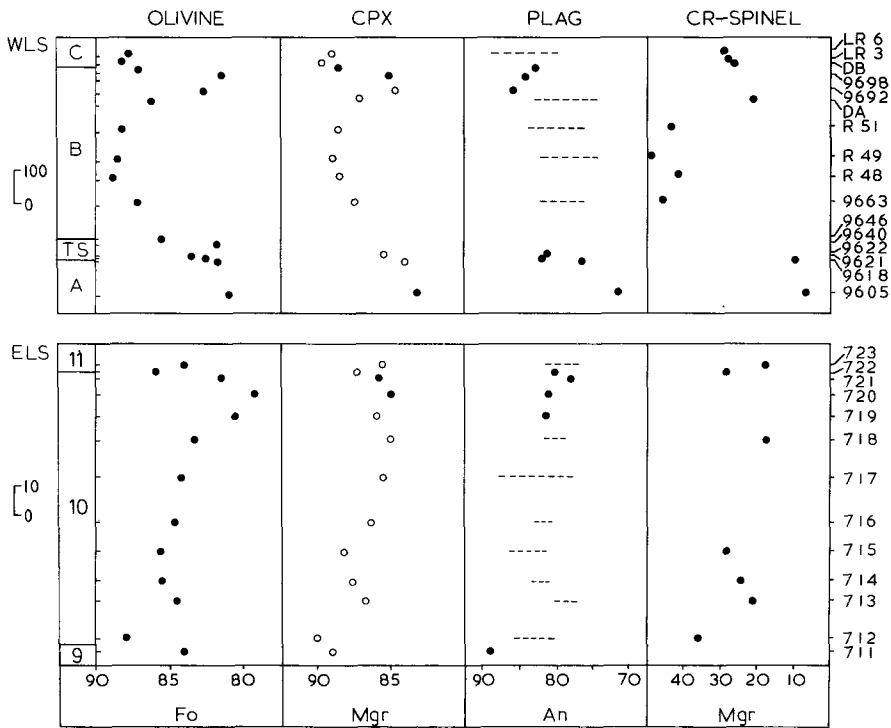


FIG. 1. Cryptic variation shown by olivine, clinopyroxene, plagioclase, and chrome-spinel in Unit B (WLS) and Unit 10 (ELS) and parts of adjacent units. Filled circles represent averaged analyses of cumulus crystals; open circles represent averaged analyses of intercumulus pyroxene (excluding obvious marginal zoning); dashed lines indicate the apparent range of intercumulus plagioclase compositions (again excluding obvious marginal zoning.) Mgr = $100 \text{ Mg}/(\text{Mg} + \text{Fe})$. Vertical scale in metres.

plagioclase is the host. These results confirm the conclusions of Henderson and Suddaby (1971) that postcumulus reaction processes may significantly modify the original chrome-spinel compositions.

Although cumulus *pyroxene* is restricted in occurrence to the uppermost 5–10% of the stratigraphic thickness of each unit, it is present as an intercumulus phase throughout the layered succession. In view of the fact that most of the rocks investigated have been described as adcumulates, it might be anticipated that the intercumulus minerals would faithfully reflect any changes in the bulk magma composition, and that in particular, the cumulus olivine trend would be mirrored by the intercumulus pyroxenes. This is clearly shown to be the case for both Unit B and Unit 10 (fig. 1), although the extent of the composition variation, in terms of $100 \text{ Mg}/(\text{Mg} + \text{Fe})$, is more limited than in the olivines, and there are minor discrepancies between the two trends (e.g. 719, 9692). The validity of using intercumulus material in this way is confirmed by the fact that where cumulus py-

roxenes occur they appear to be part of the same trend.

The pyroxenes are all diopside or diopsidic augites (see Table VI for representative analyses). As with the olivines the recorded range of composition within individual rocks is generally within the limits of analytical error (Dunham and Wilkinson, in press). Slight normal zoning has been detected at the extreme margins of some grains, but such variations have been excluded, as far as possible, from the data presented here.

Plagioclase. A preliminary reconnaissance of plagioclase compositions in Unit B and Unit 10 gives more equivocal results. Where cumulus plagioclase is present, in the upper parts of the units, there is some evidence of Na-enrichment parallel to the Fe-enrichment of the olivines and pyroxenes, but the range of compositions is relatively limited, and the most evolved compositions appear to occur slightly higher in the succession than with the other minerals. This may be the result of slower crystal settling by plagioclase, because of

TABLE IV. *Averaged analyses of intra-olivine chromites from the Western Layered Series*

	9605	9618	9663	R48	R49 (< 75 mμ)	R49 (> 200 mμ)	R51	DA	DC	LR3	LR6
Al ₂ O ₃	4.11	6.85	20.02	16.50	11.89	20.27	14.86	8.35	10.15	10.88	11.77
Cr ₂ O ₃	11.47	16.21	31.84	36.00	35.05	35.27	33.89	31.72	31.40	31.87	28.54
Fe ₂ O ₃	42.71	37.03	15.80	13.75	18.47	13.70	15.24	23.35	24.04	23.33	26.77
TiO ₂	5.32	4.01	1.23	2.04	2.08	0.73	2.73	2.79	2.36	1.74	1.21
SiO ₂	0.25	n.a.	n.f.	n.f.	n.f.	n.f.	0.43	0.23	n.f.	n.f.	n.f.
MgO	1.39	1.96	9.61	9.00	6.70	10.63	8.89	4.39	5.30	5.61	5.79
MnO	0.45	0.86	n.f.	n.f.	n.f.	n.f.	0.49	n.f.	1.30	0.63	0.51
FeO	34.62	32.04	21.32	22.30	25.26	19.47	22.88	29.05	26.30	25.71	25.07
NiO	0.31	0.30	n.f.	0.31	n.f.	n.f.	n.f.	0.32	n.f.	n.f.	0.38
Total	100.63	99.26	99.82	99.90	99.45	100.07	99.41	100.20	100.85	99.14	100.04
No. of analyses	6	2	8	7	3	5	2	5	3	1	3
Number of cations per 32 oxygens											
Al	1.42	2.34	5.99	5.07	3.81	6.05	4.61	2.75	3.26	3.52	3.79
Cr	2.65	3.72	6.39	7.42	7.53	7.06	7.05	7.01	6.77	6.92	6.16
Fe ³⁺	9.40	8.09	3.02	2.70	3.78	2.61	3.02	4.91	4.94	4.82	5.50
Ti	1.17	0.88	0.23	0.40	0.42	0.14	0.54	0.59	0.48	0.36	0.25
Si	0.07	—	—	—	—	—	0.11	0.06	—	—	—
Mg	0.61	0.85	3.64	3.50	2.71	4.01	3.49	1.83	2.16	2.30	2.35
Mn	0.14	0.27	—	—	—	—	0.14	—	0.39	0.19	0.15
Fe ²⁺	8.47	7.78	4.73	4.86	5.74	4.12	5.04	6.79	6.00	5.90	5.72
Ni	0.07	0.07	—	0.06	—	—	—	0.07	—	—	0.08
Percentage proportions of principal trivalent cations											
Al ³⁺	10.5	16.7	39.0	33.3	25.2	38.5	31.3	18.7	21.8	23.1	24.4
Cr ³⁺	19.7	26.3	41.7	48.9	49.7	44.9	48.1	47.8	45.2	45.3	39.9
Fe ³⁺	69.8	57.0	21.4	17.8	25.1	16.6	20.7	33.5	33.0	31.6	35.7
% Mg*	6.7	9.8	45.8	41.8	32.2	49.3	43.3	21.2	26.4	28.0	29.1
s.d.	1.20	—	3.04	3.36	4.90	2.21	—	1.31	1.00	—	2.55

* 100 Mg/(Mg + Fe²⁺).

n.a. = Not analysed.

n.f. = Not found.

s.d. = Standard deviation.

its lower density. There is also evidence, at least in Unit 10, of a reversal to more calcic compositions just below the top of the unit, while the reversal at the top of Unit A in the WLS is clearly demonstrated.

The intercumulus plagioclase compositions in individual samples are surprisingly variable, especially for rocks previously described as adcumulates. Even when obvious marginal zoning is discounted, there is often a range of more than 5% An from crystal to crystal, or within individual crystals. In part this may be due to some intercumulus crystals being sectioned entirely within their zoned margins, but it is unlikely that this would account for the variation recorded in rocks like 717, from Unit 10. The whole of the determined composition range is recorded in fig. 1, excluding only undoubted marginal zones, which would extend the range to considerably more sodic values in most rocks. In the lower part of Unit 10 there is a recognizable similarity to the intercumulus pyroxene trend (and to the cumulus olivine trend), but elsewhere this is

less apparent. In Unit B the intercumulus plagioclase compositions bear no relation to the variation shown by olivine and pyroxene. In this case it is possible that insufficient crystals have been analysed to reflect the true composition of the plagioclase in equilibrium with the contemporary magma, because of the markedly poikilitic habit typically developed by the intercumulus feldspars. In any case it is clear that the concept of these rocks as extreme adcumulates may require some modification. Another point to note is the unusually calcic composition of the cumulus plagioclase at the top of Unit 9 (ELS). Representative analyses of cumulus plagioclase are shown in Table VII.

Conclusions. From the data presented, it is clear that there is significant cryptic variation within the Rhum layered intrusion, and that the pattern of this variation is closely related to the cyclic repetition of lithological units. This is taken to support the contention of Brown (1956) and Wadsworth (1961) that each unit corresponds to a separate batch of magma, and that the upward succession of phase

TABLE V. Averaged analyses of intra-olivine chromites from Unit 10 (ELS)

	712	713	714	715	718	722	723
Al ₂ O ₃	13.95	8.90	11.18	11.50	8.95	9.27	8.04
Cr ₂ O ₃	38.13	30.82	33.69	34.34	31.05	31.72	29.47
Fe ₂ O ₃	13.09	23.26	18.53	18.25	23.85	21.59	27.13
TiO ₂	2.41	2.88	2.85	2.70	2.40	3.55	2.26
SiO ₂	n.f.	0.20	n.f.	n.f.	n.f.	0.21	n.f.
MgO	7.58	4.40	5.13	5.94	3.64	5.93	3.47
MnO	0.55	n.f.	n.f.	n.f.	n.f.	0.56	n.f.
FeO	24.14	29.04	28.24	27.04	29.98	26.97	29.77
Total	99.85	99.50	99.62	99.77	99.87	99.80	100.14
No. of analyses	5	3	5	5	5	2	5
Number of cations per 32 oxygens							
Al	4.37	2.94	3.63	3.70	2.97	3.01	2.68
Cr	8.01	6.83	7.33	7.41	6.90	6.92	6.58
Fe ³⁺	2.62	4.91	3.84	3.75	5.05	4.48	5.77
Ti	0.48	0.61	0.59	0.55	0.51	0.74	0.48
Si	—	0.06	—	—	—	0.06	—
Mg	3.00	1.84	2.11	2.42	1.53	2.44	1.46
Mn	0.12	—	—	—	—	0.13	—
Fe ²⁺	5.36	6.81	6.50	6.17	7.05	6.22	7.03
Percentage proportions of principal trivalent cations							
Al ³⁺	29.2	20.0	24.5	24.9	19.9	20.9	17.8
Cr ³⁺	53.4	46.5	49.6	49.9	46.3	48.0	43.8
Fe ³⁺	17.4	33.5	25.9	25.2	33.8	31.1	38.4
% Mg*	35.9	21.3	24.4	28.1	17.8	28.1	17.2
s.d.	2.5	0.8	2.2	1.8	3.1	—	1.4

* 100 Mg/(Mg+Fe²⁺). n.f. = Not found.
s.d. = Standard deviation.

and cryptic layering within each unit is the result of progressive *in situ* fractionation of that magma. On the other hand it appears to conflict with the hypothesis developed by Gibb (1976), that each influx of magma was already carrying most of its olivine in suspension when it arrived in the Rhum depositional chamber, since it is unlikely that crystal settling under these conditions would lead to any systematic variation in olivine composition with stratigraphic height. Gibb also argued that it was unlikely that repeated batches of magma would have precisely the same initial composition, or that they would be replenished at exactly the same stage of fractionation each time, especially in view of the variation in thickness from unit to unit. Although there appears to be no fundamental objection to repeated accessions of rather uniform basaltic magma, it is now apparent that the olivine compositions at the base of four units (10, 11, B, C) are not quite the same, and that the compositions of the olivine-plagioclase-pyroxene assemblage precipitating towards the tops of the units investi-

TABLE VI. Averaged analyses of selected cumulus pyroxenes (WLS)

	9698	DB
SiO ₂	51.46	51.78
TiO ₂	0.50	0.30
Al ₂ O ₃	3.17	3.12
Cr ₂ O ₃	0.61	0.68
FeO	5.48	4.14
MnO	n.f.	n.f.
MgO	15.63	16.63
CaO	23.09	23.00
Na ₂ O	n.f.	n.f.
Total	99.94	99.65
No. of analyses	3	3
Cations per 6 oxygens		
Si	1.899	1.903
Al	0.101	0.097
Al	0.037	0.038
Ti	0.014	0.008
Cr	0.018	0.020
Mg	0.860	0.911
Fe	0.169	0.127
Mn	—	—
Ca	0.913	0.906
Na	—	—
Wo	47.0	46.6
En	44.3	46.8
Fs	8.7	6.5
100 Mg/(Mg+Fe)	83.6	87.8

n.f. = Not found.

gated are by no means identical in each case, although it is clear that replenishment always occurred soon after pyroxene became a cumulus phase. This rather constant end-point of the Rhum cycle is not easy to explain, although it is not unusual for magmatic events culminating in volcanic activity to develop a very regular cyclic pattern, as the delicate balance between magma influx, storage, and removal must be largely controlled by the nature of the threshold conditions necessary for eruption to be initiated. This might equally well apply to the mechanism of repeated cauldron subsidence postulated for Rhum by Dunham (1970). Certainly the wide range of thickness from unit to unit can readily be interpreted on this basis, in terms of differing amounts of subsidence.

In many ways the aspect of the cryptic variation that is most difficult to explain is the reversal in the

trend, as progressively higher-temperature members of the respective solid-solution series appear over the topmost few metres of a unit. In the case of the Unit A/Unit B junction, this trend persists well into Unit B, as shown by the cumulus olivine compositions. One possibility (C. H. Emeleus, personal communication) is that this part of the cryptic variation pattern is not a primary stratigraphic feature, but is concerned with the post-cumulus (diagenetic) crystallization. On this basis it could be argued that a new influx of relatively undifferentiated magma might exert a chemical influence on the intercumulus liquid in the upper few metres of relatively unconsolidated allivalite at the top of the underlying unit, such that the cumulus phases re-equilibrated with the hotter, less evolved magma. Against this is the fact that the thickness of crystal mush implied is rather greater than indicated by other criteria (Brown, 1956), and also that there is no evidence of recrystallization or zoning (at least among the olivines) such as might be expected locally if this process had operated.

It seems more likely that the cryptic variation is a primary stratigraphic feature, and that the reversals represent periods of mixing between the residual magma of one episode and the fresh magma of the succeeding episode, as suggested by Wadsworth (1961) to account for the Transition Series in the WLS. On this basis it is suggested that some degree of mixing took place, although generally on a more limited scale than at the Unit A/Unit B junction,

with every major influx of magma. It seems likely that there would be a period of progressive dilution of the more fractionated magma as successive pulses of the fresh magma came into contact with it, and that this would be reflected by changes in the cumulus (and adcumulus) mineral compositions as successive crystal crops nucleated from progressively warmer and more basic liquids, until the new magma became dominant. Presumably the phase layering is also reversed, but this is difficult to study in detail, because pyroxene is not sufficiently persistent as a cumulus phase in the rhythmically layered allivalites to establish whether or not it disappears from the cumulus crystallization sequence just before plagioclase (corresponding to its appearance *after* plagioclase in the normal fractionation sequence seen in the main part of the units).

The relatively minor reversal in the cumulus olivine and chrome-spinel compositions (confirmed also by the intercumulus pyroxene and plagioclase) recorded in the lower part of Unit 10, may indicate that magma replenishment sometimes occurred at an earlier stage in the cycle, when its effects would be far less dramatic. A more detailed study of Unit 10 (and other units) is now in progress, in order to determine whether there are other minor departures from the main trend.

The established fractionation pattern, together with the composition of the minerals concerned, is entirely consistent with the hypothesis that the Rhum cumulates were precipitated from basaltic magma. It is certainly not necessary to invoke ultrabasic, picritic, or eucritic magmas (Donaldson, 1975; Gibb, 1976) although the precise compositions indicated by these terms are not clear, especially as they generally seem to imply a bulk composition of magma with crystals in suspension. However, it is probable that much of the current dispute about parental magmas of the Rhum (and Skye) cumulates is semantic. There is an increasing amount of evidence to suggest that the most likely composition is close to that of the low alkali, high calcium, olivine-tholeiite lavas and minor intrusions of Skye (Esson, Dunham, and Thompson, 1975; Donaldson, 1977*b*), which are broadly similar to the high-lime magmas described by Drever (1966) and the 'eucritic' magmas mentioned by Gibb (1976). There seems to be no compelling reason to describe these as anything but basaltic, although certain distinctive aspects of their chemistry may justify the use of a suitable prefix.

The new data on the variation of Ni in cumulus olivine within individual units is relevant to the problem of what proportion of the original magma is represented by the Rhum Layered Series. Dunham (1970) suggested that the magma chamber may have been disc-shaped, with an average height

TABLE VII. *Averaged analyses of selected cumulus plagioclase (WLS)*

	9692	DB
SiO ₂	47.58	47.71
Al ₂ O ₃	33.17	33.05
FeO	0.32	0.27
CaO	17.19	16.91
Na ₂ O	1.56	2.02
Total	99.82	99.96
No. of analyses	4	4
Cations per 8 oxygens		
Si	2.188	2.192
Al	1.798	1.790
Fe	0.011	0.009
Ca	0.847	0.832
Na	0.139	0.180
An	85.9	82.2

of 0.5 km, to produce a 100–200 m thickness of cumulates. Henderson and Gijbels (1976) have disputed this estimate on the grounds that there is very little variation in the Ni-content of olivines collected from the base and top of certain units, and that the application of the Rayleigh fractionation law (Rayleigh, 1896) implies that each unit represents only a few per cent by mass of the parent magma. It is now clear that the range of Ni contents in olivines from Unit B and Unit 10 is substantial (0.17–0.40 wt. %), but because of the reversals in the cryptic layering pattern, this cannot be established merely by sampling the top and bottom of a unit.

The new data suggest that Ni_{max}/Ni_{min} for Unit B was about 2.5. Allowing for the fact that the distribution coefficient of Ni between melt and olivine is strongly dependent on the melt composition (Irvine, 1975) and may vary between about 6 and 16, then the amount of olivine precipitated was probably of the order of 20% by mass of the liquid, not the 2–12% suggested by Henderson and Gijbels (1976). In addition, the magma had also precipitated chrome-spinel, pyroxene, and plagioclase, and on the basis of modal data from both Eastern and Western Layered Series, the proportion of cumulates to parent magma may have been between 25 and 30% by mass.

Acknowledgements. We are grateful to the Nature Conservancy for permission to work on Rhum, and for assistance in the field; to the Institute of Geological Sciences for financial support; to F. C. F. Wilkinson for guidance and advice on the analytical procedures; and to I. Nicholson for preparing fig. 1.

REFERENCES

- Brown (G. M.), 1956. *Phil. Trans. R. Soc., B*, **240**, 1–53.
 Donaldson (C. H.), 1975. *J. Geol.* **83**, 33–45.
 ——— 1977a. *Miner. Mag.* **41**, 323–36.
 ——— 1977b. *J. Petrol.* **18**, 595–620.
 Drever (H. I.), 1966. *Ibid.* **7**, 414–20.
 Dunham (A. C.), 1970. *Geol. J. Special Issue*, **2**, 23–32.
 ——— and Wilkinson (F. C. F.). *X-ray Spectrometry*. In press.
 Esson (J.), Dunham (A. C.), and Thompson (R. N.), 1975. *J. Petrol.* **16**, 488–97.
 Gibb (F. G. F.), 1976. *J. Geol. Soc.* **132**, 209–22.
 Harker (A.), 1908. *Mem. Geol. Surv. Scotland*.
 Henderson (P.), 1975. *Geochim. Cosmochim. Acta*, **39**, 1035–44.
 ——— and Suddaby (P.), 1971. *Contrib. Mineral. Petrol.* **33**, 21–31.
 ——— and Gijbels (R.), 1976. *Scott. J. Geol.* **12**, 325–33.
 Irvine (T. N.), 1975. *Geochim. Cosmochim. Acta*, **39**, 991–1020.
 Rayleigh (J. W. S.), 1896. *Phil. Mag.* **42**, 77–107.
 Simkin (T.) and Smith (J. V.), 1970. *J. Geol.* **78**, 304–25.
 Wadsworth (W. J.), 1961. *Phil. Trans. R. Soc. B*, **244**, 21–64.
 Wager (L. R.) and Brown (G. M.), 1968. *Layered Igneous Rocks*, Oliver and Boyd, Edinburgh.

[Manuscript received 6 December 1976,
 revised 17 April 1978]

Analytical methods. Most analyses were made using a Cambridge Instrument Company Geoscan fitted with a Link Systems model 290-2KX energy-dispersive spectrometer. The remainder were made using conventional wavelength-dispersive spectrometry on a Geoscan II. Analyses were made using 15 kV, a specimen current of around 3 nA on cobalt metal, and an input rate to the pulse processor of around 300 cps. The accuracy and precision of this ED system has been investigated recently by Dunham and Wilkinson (in press).

The chromites have been recalculated to give values for Fe_2O_3 and FeO, making the assumption that the minerals are stoichiometric. Thus $Al + Cr + Fe^{3+} + Ti \pm Si = 2(Fe^{2+} + Mn + Mg + Ni)$. The analytical totals following this calculation all lay between 99 and 101%.