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Cryptic variation in the Kapalagulu layered intrusion, western Tanzania

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ABSTRACT. The Kapalagulu intrusion displays the following sequence of cumulus phase layering in a stratigraphic sequence of 1400 m: *Basal Zone* (BZ) olivine $\pm$ chromite $\rightarrow$ *Intermediate Zone* (IZ) olivine + plag + opx $\rightarrow$ olivine + plag + opx + cpx $\rightarrow$ *Main Zone* (MZ) plag + opx + cpx $\rightarrow$ plag + cpx + Fe/Ti oxide + apatite. The corresponding cryptic variation is *olivine* Fo_{83-77} (limited to BZ and IZ), *orthopyroxene* En_{82-56}, *clinopyroxene* $Ca_{46}Mg_{45}Fe_9$ to $Ca_{43}Mg_{37}Fe_{21}$ and *plagioclase* An_{88-80}. Reversals of the cryptic variation occur at the base of MZ (minor reversal) and in the middle of MZ (major reversal), and are attributed to the influx of relatively primitive magma. The major reversal indicates that progressive mixing of fresh and residual magmas occurred. Because of the major reversal, inverted pigeonite appears twice in the layered sequence, but at different compositions (En_{65} and En_{56}). Unlike the cumulus olivine and pyroxene, cumulus plagioclase exhibits a wide range of composition (5-10% An) in individual rocks and even in single crystals.

THE Kapalagulu intrusion is situated in western Tanzania, close to the eastern shore of Lake Tanganyika, 100 km south of Kigoma. It has a narrow outcrop, approximately 15 km long and up to 2 km wide, trending NW-SE, and tapering towards the NW. The intrusion occurs at the junction of two Precambrian formations, namely the Ubendian, consisting of gneisses and amphibolites, believed to be > 1800 Ma in age, and the Itiaso Group, comprising slightly metamorphosed sandstones and shales. These are now generally regarded as belonging to the Karagwe-Ankolean system, and are probably 1200-1300 Ma old (Cahen and Snelling, 1966). Both main contacts of the Kapalagulu intrusion, with the Ubendian gneisses to the SW, and the Itiaso Group to the NE, are apparently tectonic (Wadsworth, 1963), and for this reason the age of the original magmatic event is obscure, although the emplacement of the body in its present situation is clearly post-Itiaso. The only direct information about the crystallization date is a K/Ar determination on interstitial biotite from the Basal Zone of the intrusion, which indicated an age of 1230 ± 50 Ma (Cahen and Snelling, 1966). This suggests that Wadsworth's (1963) tentatively proposed genetic connection between the Kapalagulu intrusion and basaltic activity associated with the Bukoban system, now dated at approximately 800 Ma (Piper, 1975), is almost certainly no longer tenable.

The principal petrological features of the Kapalagulu intrusion have previously been described by van Zyl (1959) and by Wadsworth (1963). In addition to its steep margins the intrusion displays a number of internal features which strike parallel to the main contacts (NW-SE) and are generally near-vertical in attitude. These include the main lithological variations (peridotite-troctolite-gabbro) as well as the small-scale rhythmic layering, locally well-developed in the troctolites and gabbros. Both van Zyl (1959) and Wadsworth (1963) interpret this arrangement to be the result of tectonic disturbance of an initially sub-horizontal layered intrusion. On this basis the original stratigraphic succession is now displayed in horizontal traverses across the intrusion from SW to NE.

Van Zyl (1959) divided the stratigraphic succession into three principal units, namely the Basal Zone (BZ), Intermediate Zone (IZ), and Main Zone (MZ). This system was followed by Wadsworth (1963), although he further divided the Main Zone

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into five subzones (MZ a–e). The overall thickness is approximately 1400 m, although this must be regarded as a minimum since there is now no evidence of original floor or roof facies, and comparison with other layered intrusions suggests that a substantial portion of the upper part of the original body may have been removed during final tectonic emplacement. The BZ is assumed to represent material from close to the floor of the original intrusion, but even here some of the succession may be missing. From the detailed mapping of the intrusion (Wadsworth, 1963) it is clear that the tectonic contacts are slightly transgressive to the cumulate stratigraphy, so that the most complete succession is found in the south-eastern part of the outcrop and successive units are progressively cut out towards the NW, especially near the extreme north-western end. (The precise nature of the south-eastern termination of the intrusion is obscured by drift deposits.)

Phase layering. The Kapalagulu cumulate stratigraphy has been described in detail by Wadsworth (1963). The principal mineralogical features are summarized below, together with an indication of the approximate thickness of the various zones and subzones:

Main Zone.	(e) Plagioclase–cpx(–opx)–magnetite cumulates	(200 m)
	(d) Plagioclase–opx–cpx cumulates	(380 m)
	(c) Plagioclase–opx–cpx cumulates	(160 m)
	(b) Plagioclase cumulates	(100 m)
	(a) Plagioclase–opx–cpx cumulates	(160 m)
Intermediate Zone.	Olivine–plagioclase–opx(–cpx) cumulates	(270 m)
Basal Zone.	Olivine(–chromite) cumulates	(130 m)

In terms of the phase layering (fig. 1) BZ consists of cumulus olivine, with local concentrations of cumulus chromite, and one layer in which sulphide globules (pyrrhotine associated with pentlandite) appear to represent an immiscible sulphide liquid. Olivine is joined by cumulus plagioclase and orthopyroxene at the base of IZ, and by cumulus augite at a higher (and not clearly marked) level in IZ.

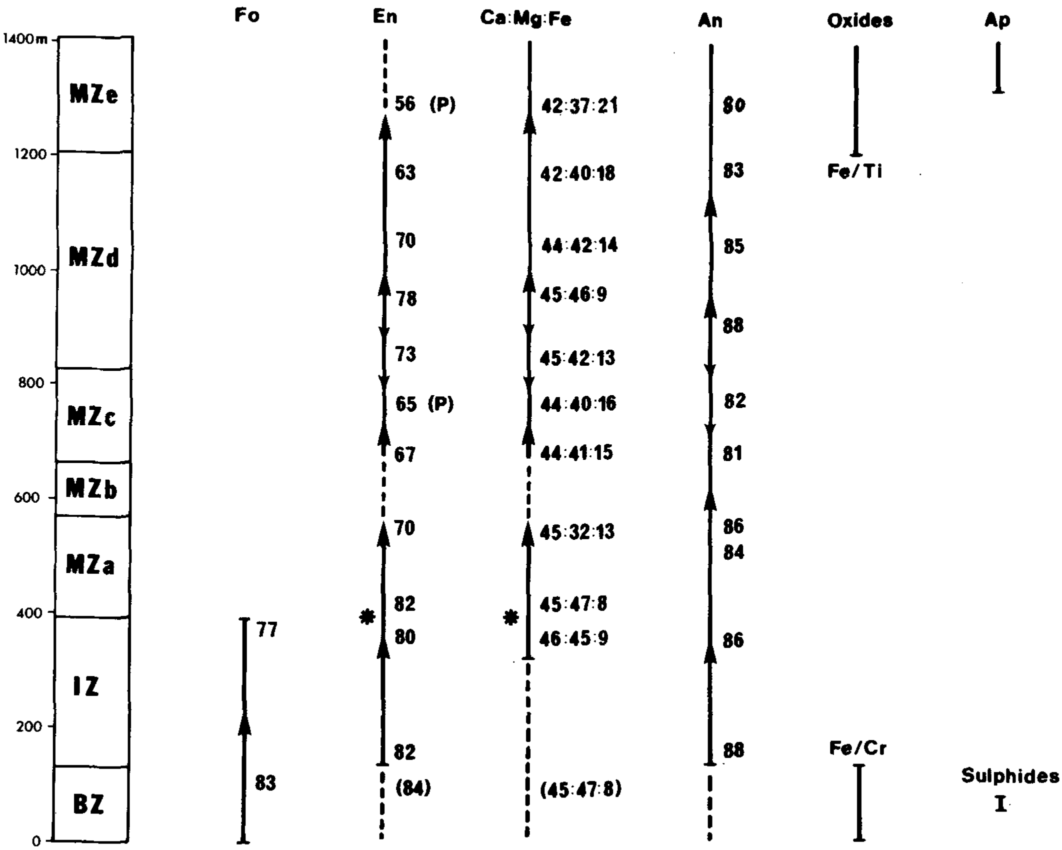

FIG. 1. Summary of phase and cryptic layering of the Kapalagulu intrusion. Full lines indicate cumulus material, dashed lines intercumulus; large arrows show direction of normal progressive fractionation, small arrows indicate reversals of this direction; asterisks mark minor breaks in the cryptic variation; (P) refers to inverted pigeonite; Ap is apatite.

The base of MZ is marked by the disappearance of cumulus olivine, while MZb contains only cumulus plagioclase. Cumulus pyroxenes (both opx and cpx) reappear in MZc, and continue into MZe, although cumulus orthopyroxene does not persist to the top of the succession. The distinction between MZc and MZd is mainly concerned with the precise mineral compositions (see section on cryptic variation) and cannot be made in the field. The base of MZe is marked by the appearance of cumulus magnetite, while cumulus apatite also occurs in the upper part of this subzone. A particularly interesting feature of the orthopyroxenes in MZ is the textural evidence of original cumulus pigeonite (now inverted to orthopyroxene) at two levels in the succession, one at the top of MZc and the other in MZe. Most of the Kapalagulu rocks are adcumulates, but intercumulus quartz is commonly present in MZ, and in MZd and MZe it is associated in micrographic intergrowth with alkali feldspar, and reaches 10% by volume in certain layers. Despite the lack of much obvious marginal zoning to the cumulus minerals, these rocks must be regarded as mesocumulates. The upper parts of MZ are also characterized by the local occurrence of gabbro-pegmatite segregation veins, containing even more abundant quartz and alkali feldspar (up to 30% by volume), as well as relatively high concentrations of apatite and Fe–Ti oxides.

Rhythmic layering. Rhythmic layering occurs locally within the main framework of phase layering outlined above, and consists of small-scale variations (centimetre to metre scale generally) in the cumulus mineralogy or texture. Thus, in some cases the variation is simply a matter of modal proportions, with all the appropriate cumulus phases present; in other cases certain potential minerals are missing from particular layers, although such minerals are generally present as intercumulus material, and occur as cumulus phases in nearby layers. These types of small-scale layering have been characterized by Jackson (1971) as producing ratio contacts and phase contacts, respectively, between adjacent layers, but it is important to distinguish between phase contacts of this type, and the more significant feature of large-scale phase layering, which is clearly related to the overall progressive fractionation of the magma. Small-scale (rhythmic) layering was originally explained in terms of crystal sorting, involving cumulus grains of different density, size, and shape (e.g. Wager and Deer, 1939), but it is now clear that this is an inadequate mechanism in many cases. It is generally more acceptable to invoke minor departures from equilibrium crystallization such as preferential nucleation (van Zyl, 1959; Wager, 1959) or discontinuous nucleation (Wadsworth, 1961; Goode, 1976) to account for this type of feature, although it must be realized that if crystal settling is the principal process involved in cumulate formation, then some degree of crystal sorting may be superimposed on any non-equilibrium nucleation effects.

In addition to the small-scale lithological variations, the rhythmic layering in the Kapalagulu intrusion includes examples of cross-bedding (MZc), graded layers (IZ). igneous lamination of cumulus plagioclase (IZ and MZc), and possible slump structures (IZ).

Cryptic layering. Previous studies of the variation in mineral composition within the Kapalagulu layered succession have been based entirely on optical data. Van Zyl (1959) noted certain trends, such as slight Na enrichment of plagioclase and Fe enrichment of orthopyroxene with increasing stratigraphic height, as well as a possible reversal of olivine cryptic variation within BZ. Wadsworth (1963) made a more detailed investigation based largely on 2V determination of orthopyroxene throughout the sequence, with supplementary data from cumulus olivine and plagioclase at selected levels in the sequence. His principal conclusions are summarized as follows:

1. Although there is an overall cumulus orthopyroxene composition variation from En_{85} (BZ) to approximately En_{70} (MZd), this is not simply progressive from bottom to top of the succession but involves a major reversal at the base of MZd. There is also a hint of minor reversal near the base of MZa.
2. This pattern of cryptic variation is supported by the plagioclase determinations, although the overall composition range is relatively limited (An_{87} to An_{79}).
3. Cumulus olivine, which is restricted to BZ and IZ, shows slight Fe enrichment over this range (Fo_{85} to Fo_{82}).
4. The appearance of inverted pigeonite at two distinct levels in the layered sequence occurs at quite different compositions, in terms of Mg/Fe ratio. The lower occurrence (MZc), where the composition is approximately En_{75}, is considerably more magnesian than the upper one (MZe), although in this case the precise composition was in doubt, because of discrepancies between the results from different optical determinative methods.

The purpose of the present study has been to make more precise determinations of the mineral compositions, using the electron microprobe, in order to establish the pattern of cryptic variation more accurately. By this method it has also been possible to investigate the clinopyroxenes, which typically coexist with orthopyroxene throughout

TABLE I. *Representative olivine analyses*

	250	237	26
SiO_2	39.36	39.11	38.66
FeO	15.63	17.95	20.73
MnO	0.25	0.33	0.35
MgO	44.49	42.36	40.46
Total	99.73	99.75	100.20
Number of cations per 4 oxygens			
Si	0.994	0.999	0.996
Fe	0.330	0.383	0.447
Mn	0.005	0.007	0.008
Mg	1.675	1.612	1.554
Fo	83.5	80.8	77.7

much of the Kapalagulu sequence, but were not amenable to earlier optical determination. The new data have been obtained from the same samples as used in the earlier work (Wadsworth, 1963). It should be emphasized that these samples were not all collected from a single traverse, but that a 'type' succession has been constructed, using material from four stream sections. This was necessary because of lack of sufficient exposure in any one traverse, and because of local alteration of the cumulates. However, the possibility that lateral variations might confuse the overall picture has been eliminated by comparing the results from lithologically or texturally distinct horizons which can be clearly recognized in more than one traverse. These show no evidence of lateral changes in mineral composition.

In all the crystals analysed, whether cumulus or intercumulus, obvious marginal areas were avoided, so that the extra complication of intercumulus zoning can be largely discounted.

Olivine. Cumulus olivine has been analysed from BZ, and from the lower and upper parts of IZ (see Table I for representative analyses). Despite the limited number of samples there is evidence of Fe enrichment upwards from Fo_{83} to Fo_{77}. In addition, olivine compositions have been determined from BZ drill core (provided by the Geological Survey of Tanzania). Despite the problem of relating the precise position of this material to the 'type' succession, the results again indicate slight Fe enrichment upwards, and there is no evidence of the reversal noted by van Zyl (1959) in the vicinity of the horizon at which sulphides are concentrated.

Table II. Representative orthopyroxene analyses

	250	237	26	30	334	128	163	59	61	62	65	65a	66	67	68	269
SiO_2	54.89	55.25	54.31	55.74	54.33	53.11	53.16	52.24	53.36	54.41	54.70	53.97	53.71	53.01	52.15	51.82
TiO_2	n.f.	0.17	0.37	0.24	n.f.	0.30	0.30	0.37	0.11	0.23	n.f.	0.22	0.21	0.25	0.32	0.31
Al_2O_3	1.63	1.60	1.36	0.52	0.71	1.08	0.75	0.78	1.17	0.84	1.57	0.81	1.26	1.26	1.30	0.56
Cr_2O_3	0.65	0.48	0.35	0.38	0.22	n.f.	n.f.	n.f.	0.41	0.25	0.38	0.28	n.f.	n.f.	n.f.	n.f.
FeO	10.14	11.32	13.05	11.60	16.05	18.17	20.48	22.02	17.39	15.03	14.03	18.16	18.59	20.56	22.45	25.87
MnO	0.35	n.f.	0.23	n.f.	0.24	0.37	0.33	0.54	0.32	0.25	0.40	0.32	0.50	0.64	0.46	0.34
MgO	30.30	29.62	28.38	29.80	27.04	24.56	23.29	22.39	25.28	26.89	27.67	24.68	23.74	21.91	21.31	18.52
CaO	1.78	1.70	1.73	1.74	1.83	2.27	1.47	1.49	1.55	1.67	1.79	1.71	1.92	2.07	2.14	1.93
Total	99.74	100.14	99.78	100.02	100.62	99.86	99.78	99.83	100.16	99.57	100.54	100.15	99.93	99.70	100.13	99.35
Cations per 6 Oxygens																
Si	1.945	1.955	1.948	1.977	1.965	1.953	1.972	1.956	1.947	1.972	1.955	1.973	1.972	1.973	1.952	1.984
Ti	-	0.005	0.010	0.006	-	0.008	0.008	0.010	0.003	0.006	-	0.006	0.006	0.007	0.009	0.009
Al	0.068	0.067	0.058	0.022	0.030	0.047	0.033	0.035	0.050	0.036	0.066	0.035	0.055	0.055	0.057	0.025
Cr	0.018	0.013	0.010	0.011	0.006	-	-	-	0.012	0.007	0.011	0.008	-	-	-	-
Fe	0.301	0.335	0.392	0.344	0.484	0.559	0.635	0.689	0.530	0.455	0.419	0.555	0.571	0.640	0.703	0.828
Mn	0.011	-	0.007	-	0.007	0.011	0.010	0.017	0.010	0.008	0.012	0.010	0.016	0.020	0.015	0.011
Mg	1.601	1.562	1.518	1.575	1.453	1.347	1.287	1.250	1.406	1.452	1.474	1.345	1.300	1.215	1.189	1.057
Ca	0.068	0.064	0.066	0.066	0.071	0.089	0.058	0.060	0.061	0.065	0.069	0.067	0.075	0.082	0.086	0.079
Ca	3.4	3.3	3.3	3.3	3.5	4.5	2.9	3.0	3.1	3.3	3.5	3.4	3.9	4.2	4.4	4.0
Mg	81.3	79.6	76.8	79.4	72.4	67.5	65.0	62.5	70.4	73.6	75.1	68.4	66.8	62.7	60.1	53.8
Fe	15.3	17.1	19.8	17.3	24.1	28.0	32.1	34.5	26.5	23.1	21.4	28.2	29.3	33.1	35.5	42.2
$100 \times \frac{Mg}{Mg + Fe}$	84.2	82.3	79.5	82.1	75.0	70.7	67.0	64.5	72.6	76.1	77.9	70.8	69.5	65.5	62.8	56.1

n.f. not found

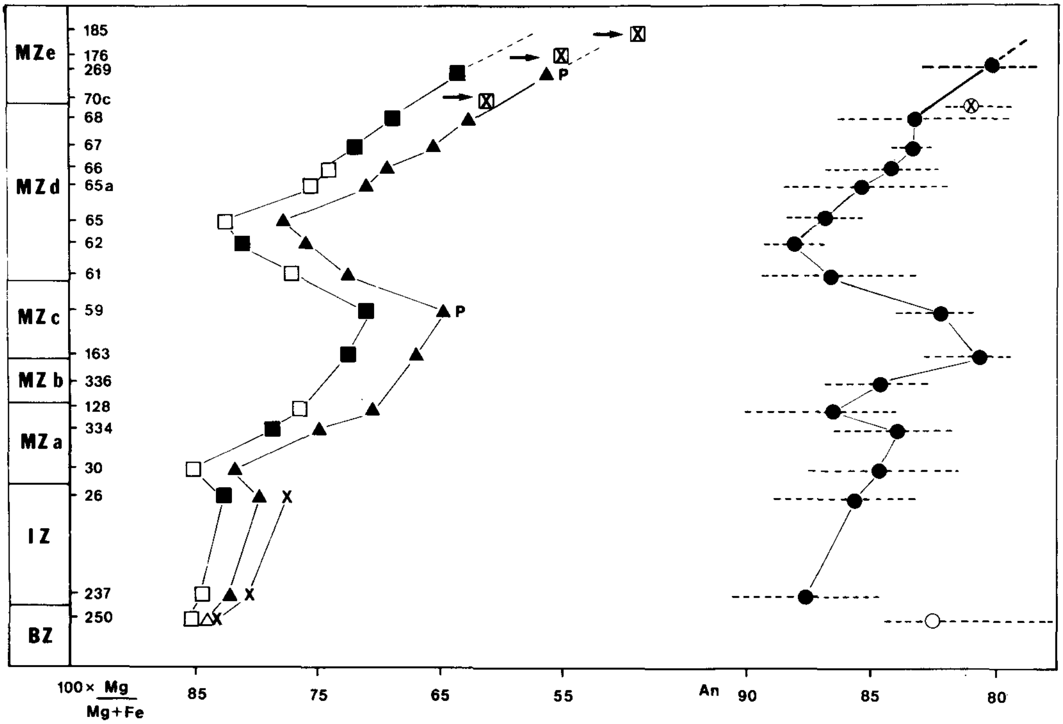

FIG. 2. Kapalagulu cryptic variation in terms of 100 × Mg/(Mg + Fe) for olivine (×), orthopyroxene (triangles), and clinopyroxenes (squares), and An content for plagioclases (circles). Filled symbols (and ×) indicate cumulus occurrences and open symbols are intercumulus; horizontal dashed lines indicate the range of plagioclase 'core' compositions recorded for each rock sample. Open symbols containing × are from the pegmatitic segregation veins, and the arrows emphasize their residual nature compared with their host cumulates. P refers to inverted pigeonite. Location of analysed samples shown on stratigraphic column.

Orthopyroxene. As in the earlier study (Wadsworth, 1963), orthopyroxene is the most sensitive indicator of the cryptic variation pattern. Not only is cumulus orthopyroxene abundant throughout the succession (except in BZ, MZb, and the upper part of MZe), but the precision of the method is such that quite small changes of composition ($< 1\%$ En) are probably significant. Representative orthopyroxene analyses are given in Table II, and the composition trend against stratigraphic position is shown in fig. 2 (together with information from the other main silicate minerals).

The overall composition range is from En_{84} (intercumulus opx in BZ) to En_{56} (cumulus opx from the lower part of MZe). It is likely that this would be extended further if it had been possible to analyse intercumulus orthopyroxene from higher levels in MZe, but unfortunately this material is too heavily altered. The electron microprobe data also confirmed the earlier optical evidence of a major reversal in the pattern of cryptic variation at the top of MZc and in the lower part of MZd. The most Fe-rich composition achieved in the first stage of normal fractionation (BZ to MZc) is En_{65}, and this is followed upwards by a progressive reversal to En_{78}, over a thickness of approximately 200 m. From this level in MZd to the top of the succession the variation reverts to normal, and the composition range is from En_{78} to En_{56} (at least). In addition, there is also clear evidence for the minor reversal at the base of MZa (En_{80} to En_{82}) hinted at by the optical results (Wadsworth, 1963). Further, there is confirmation of the significantly different compositions of the inverted pigeonite which appears at the two levels in MZ. Its first appearance, at the culmination of the first stage of normal fractionation (in MZc), is at a composition of En_{65}, but its reappearance towards the top of the succession (MZe) is not achieved until a considerably higher degree of Fe-enrichment has been developed, at a composition of En_{56}. All the Kapalagulu orthopyroxenes contain exsolution lamellae of Ca-rich pyroxene, but the analyses quoted in Table II represent the host material

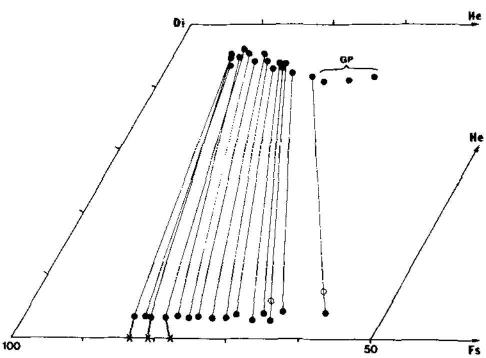

FIG. 3. Compositions of Kapalagulu pyroxenes (circles) and olivines (×) with tie lines between coexisting phases. GP refers to cpx in the late-stage gabbro-pegmatites of MZe (where fresh opx is absent), and the open circles indicate the approximate bulk composition of the inverted pigeonites (from XRF analyses of separated minerals). All the other opx analyses represent the host crystal composition (exsolution lamellae avoided).

only. Approximate bulk compositions of the two inverted pigeonites are shown in fig. 3.

Clinopyroxene. Although clinopyroxene is less consistently present as a cumulus phase than orthopyroxene, at least in the samples studied, it provides very convincing confirmation of the cryptic variation trend already established (figs. 1 and 2). Of particular significance is that it does not appear to matter whether the clinopyroxene is of cumulus or intercumulus habit, suggesting that many of these rocks are true heteradcumulates (Wager *et al.*, 1960), with the intercumulus pyroxene having the same composition as might be expected if it had been present as cumulus crystals. Similar results have been obtained for clinopyroxene in the Rhum layered intrusion (Dunham and Wadsworth, 1978). Representative clinopyroxene analyses are presented in Table III.

The overall range in composition of clinopyroxene in the Kapalagulu cumulates is from $Ca_{45}Mg_{47}Fe_8$ (BZ) to $Ca_{42}MG_{37}Fe_{21}$ (MZe), and this is extended to $Ca_{42}Mg_{29}Fe_{29}$ in residual gabbro pegmatites from the upper part of MZe. The exact parallelism of the orthopyroxene and clinopyroxene trends is shown in terms of Mg/Fe ratio in fig. 2. This applies not only to the main features of progressive fractionation, interrupted by the reversal at the MZc/MZd junction, but also to the minor reversal at the base of MZa. The composition of coexisting Ca-poor and Ca-rich pyroxenes are also shown in fig. 3, together with those of clinopyroxene from gabbro-pegmatites at various levels in MZe (see fig. 1), for which there are no corresponding orthopyroxene data (too altered to be analysed).

Plagioclase. Cumulus plagioclase is present throughout IZ and MZ although in the highest subzone (MZe) it is often completely replaced by secondary minerals. The original optical data (Wadsworth 1963) suggested that although the overall composition range was surprisingly limited (An_{87}–An_{79}), the plagioclase composition trend broadly followed the orthopyroxene pattern, with evidence of a reversal at the base of MZd. The electron microprobe analyses generally confirm

Table III Representative clinopyroxene analyses

	250	237	26	30	334	128	163	59	61	62	65	65a	66	67	68	269	70c	176	185
SiO_2	52.73	51.57	52.00	51.92	52.04	51.14	52.24	51.29	51.25	52.29	52.56	52.36	51.90	51.86	51.21	51.22	50.91	51.07	50.56
TiO_2	0.45	0.39	0.29	0.81	0.28	0.19	0.48	0.63	0.86	0.26	0.49	0.78	0.75	0.61	0.53	0.60	0.68	0.63	0.62
Al_2O_3	2.69	2.57	1.94	1.88	2.11	2.14	1.89	1.66	1.70	1.55	1.95	1.51	1.93	1.79	1.76	1.45	1.39	1.34	1.29
Cr_2O_3	1.16	1.33	0.88	0.50	0.72	0.55	n.f.	n.f	0.81	0.43	0.49	0.35	n.f.	0.36	0.33	0.21	n.f.	n.f.	n.f.
FeO	5.00	5.47	5.84	5.25	7.31	7.75	9.64	10.16	7.73	6.46	5.96	8.57	9.04	9.92	11.15	13.00	14.18	16.19	18.18
MnO	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	0.28	0.35	n.f.	0.32	n.f.	0.24	0.38	0.24	0.45	0.30	0.34	0.26	0.24
MgO	16.42	16.71	15.56	16.91	15.70	14.94	14.57	14.02	14.76	15.92	15.73	14.69	14.94	14.29	13.87	13.06	12.57	11.38	9.91
CaO	21.81	21.18	22.90	22.07	21.96	22.12	21.73	21.36	22.12	22.63	21.99	21.92	20.80	20.95	20.39	20.18	19.68	19.59	20.04
Total	100.26	99.22	99.41	99.34	100.12	98.83	100.83	99.47	99.23	99.86	99.17	100.42	99.74	100.02	99.69	100.02	99.76	100.48	100.84
Number of cations per 6 oxygens																			
Si	1.926	1.904	1.932	1.920	1.925	1.924	1.937	1.935	1.923	1.938	1.948	1.942	1.937	1.939	1.933	1.940	1.942	1.950	1.945
Ti	0.012	0.011	0.008	0.023	0.008	0.005	0.013	0.018	0.024	0.007	0.014	0.022	0.021	0.017	0.015	0.017	0.019	0.018	0.018
Al	0.116	0.112	0.085	0.082	0.092	0.095	0.082	0.074	0.075	0.068	0.085	0.066	0.085	0.079	0.078	0.065	0.063	0.060	0.059
Cr	0.034	0.039	0.026	0.015	0.021	0.016	-	-	0.024	0.013	0.014	0.010	-	0.011	0.010	0.006	-	-	-
Fe	0.153	0.169	0.181	0.162	0.226	0.244	0.299	0.321	0.243	0.200	0.185	0.266	0.282	0.310	0.352	0.412	0.453	0.517	0.585
Mn	-	-	-	-	-	-	0.009	0.011	-	0.010	-	0.008	0.012	0.008	0.014	0.010	0.011	0.008	0.008
Mg	0.894	0.920	0.861	0.932	0.865	0.838	0.805	0.788	0.826	0.879	0.869	0.812	0.831	0.796	0.780	0.738	0.715	0.647	0.568
Ca	0.853	0.838	0.911	0.874	0.870	0.892	0.863	0.863	0.889	0.899	0.873	0.871	0.832	0.839	0.825	0.819	0.805	0.802	0.826
Ca	44.9	43.5	46.6	44.4	44.4	45.2	43.9	43.8	45.4	45.4	45.3	44.7	42.8	43.1	42.2	41.6	40.8	40.8	41.8
Mg	47.1	47.7	44.1	47.4	44.1	42.5	40.9	40.0	42.2	44.4	45.1	41.7	42.7	40.9	39.9	37.5	36.2	32.9	28.7
Fe	8.0	8.8	9.3	8.2	11.5	12.4	15.2	16.3	12.4	10.1	9.6	13.6	14.5	15.9	18.0	20.9	23.0	26.3	29.6
$\frac{100Mg}{Mg+Fe}$	85.4	84.5	82.6	85.2	79.3	77.4	72.9	71.1	77.3	81.5	82.4	75.3	74.7	72.0	68.9	64.2	61.2	55.6	49.3

n.f. not found

these conclusions, but in detail they raise a number of complications. The most striking feature of the new data is the wide range of compositions recorded from the cumulus plagioclase within each rock, and often within single crystals. This range may be as great as the overall cryptic variation throughout the layered sequence (fig. 2) and is generally of the order of 5% An. This local variation is unrelated to marginal zoning, since all the analyses were made on apparent cores of cumulus crystals, and although some apparently discrete crystals may in fact represent sections restricted to the outer parts of cumulus grains (so that the apparent core is really part of the zoned margin), statistically this would be a rare feature, whereas the compositional variation recorded is the rule rather than the exception. Further, the variation appears to be extremely patchy within individual crystals and is not generally matched by any obvious variation in extinction angle. Similar results have been obtained from cumulus plagioclase in parts of the Critical Zone and Main Zone of the Bushveld Complex (unpublished data), where the range of compositions recorded from a single rock (or crystal) is generally of the order of 8-10% An. However, there is evidence from the Bushveld data to suggest that the mean value of 10-15 determinations is reasonably significant in terms of the pattern of cryptic variation, and it is on this basis that the Kapalagulu plagioclase composition trend is defined in fig. 2. The overall range is from An_{88} (base of IZ) to An_{80} (top of MZd), and there is reasonably clear evidence of the two main stages of progressive fractionation, with an intervening reversal (An_{81-82} to An_{88}) in MZc and the lower part of MZd, although the plagioclase trend appears to be slightly displaced by comparison with the pyroxene trends. In addition, there is a hint of a minor reversal in plagioclase composition at the top of MZa, rather than between IZ and MZa, as indicated by the pyroxenes, but in view of the uncertainty about the precise meaning of the range of plagioclase compositions within individual rocks, it would be unwise at this stage to regard these minor discrepancies as significant in terms of the cryptic layering. For the same reason, it was decided not to tabulate representative (or average) plagioclase analyses. All that needs to be said is that the stoichiometry of the individual microprobe analyses was consistently good, and that the small-scale chemical variations recorded are believed to be real, whatever their explanation.

Opaque minerals. The opaque minerals, with their rather limited stratigraphic range as cumulus phases in the Kapalagulu intrusion, have not been studied in the same detail as the silicates. Minor cumulus chromite is generally present in BZ, and it is locally concentrated into thin seams. Chrome-spinels appear to be particularly susceptible to postcumulus modifications in composition (Henderson, 1975), but on the assumption that chromite grains enclosed within cumulus olivine are likely to be the best indicators of original composition (Dunham and Wadsworth, 1978) preliminary data from the BZ drill core indicate a slight upward increase in Fe^{2+}/Mg and Fe^{3+}/Cr, over a stratigraphic thickness of approximately 50 m.

Fe-bearing oxides reappear as cumulus phases in MZe, where they are also relatively abundant in the pegmatitic segregation veins. The dominant mineral is Ti-magnetite, but this is typically associated with ilmenite in the form of composite grains. Ilmenite occasionally forms discrete grains as well. So far there is no evidence of cryptic variation of the Fe-Ti oxides in MZe.

Comparison with other layered intrusions. Each layered intrusion has its own distinctive fractionation sequence, involving both phase layering and cryptic layering. This is largely dependent on the initial magma composition and the prevailing *PT* conditions, but it may also be influenced by other factors, such as the periodic development of open-system conditions, allowing access of fresh magma (with the possibility of mixing batches of more and less evolved liquids) and a means of escape for residual fractions.

In the case of the Kapalagulu intrusion the fundamental crystallization sequence: olivine (+minor chromite) $\rightarrow$ olivine + plag + opx $\rightarrow$ olivine + plag + opx + cpx $\rightarrow$ plag + opx + cpx, does not appear to be precisely matched elsewhere, although it is not dissimilar to the Bushveld and Stillwater patterns, except that they are characterized by the earlier appearance of cumulus orthopyroxene (Wager and Brown, 1968). More significant is the surprisingly narrow range of cumulus plagioclase compositions at Kapalagulu (An_{88}-An_{80}) compared with the degree of Fe enrichment displayed by the ferromagnesian minerals (e.g. En_{84}-En_{56}). This is emphasized by comparison with the Bushveld Complex. Both intrusions have early cumulus minerals of broadly similar composition (Wager and Brown, 1968), but the cumulus assemblage at the base of Kapalagulu MZe (En_{56}, An_{80}) is in marked contrast to the equivalent (in terms of Fe enrichment) material in the Bushveld Main Zone (top of subzone B, Von Gruenewaldt, 1973), where orthopyroxene (En_{56}) coexists with much more sodic plagioclase (An_{56}). Most other layered intrusions follow the Bushveld pattern in this respect.

In other characteristics the Kapalagulu and Bushveld layered sequences show remarkable similarities, despite the great difference in size and stratigraphic thickness. In both cases the upper part of the succession is marked by the appearance of cumulus Fe–Ti oxides and apatite (although cumulus olivine does not reappear at Kapalagulu). Even more interesting is the occurrence of a major composition reversal at a comparable stage in both intrusions, and the effect this has on the pattern of cryptic variation in general, and the orthopyroxene–pigeonite transition in particular. In both cases the reversal took place soon after pigeonite became established as a cumulus phase for the first time, and resulted in normal orthopyroxene temporarily reappearing in the succession, until the second main phase of progressive fractionation reached sufficiently Fe-rich compositions for pigeonite to be the stable form of Ca-poor pyroxene again. The precise compositions at which these changes occurred are not the same in each intrusion. In the Bushveld Complex the orthopyroxene–pigeonite transition is rather protracted, and occurs at approximately the same composition (En_{65}) both times, as shown by Von Gruenewaldt (1973), while at Kapalagulu the change is relatively abrupt, and as already described is achieved at En_{65} in MZc, but is not repeated until a considerably higher degree of Fe enrichment has been reached (En_{56}) in MZe.

The nature of the principal reversal in the two intrusions also shows interesting similarities, although, not surprisingly, the actual composition changes are different. At Kapalagulu the reversal is from $En_{65}(An_{82})$ to $En_{78}(An_{88})$, taking place gradually over a stratigraphic thickness of 200 m. The Bushveld reversal (Von Gruenewaldt, 1973) is from $En_{56}(An_{56})$ to approximately $En_{70}(An_{70})$, and although the record is less continuous there is evidence that it is also gradational over a similar thickness.

Discussion. Reversals and repetitions of phase layering and associated cryptic variation patterns are now well established in many layered intrusions. In certain cases these repetitions are particularly numerous and regular, as, for example, in the Stillwater (Jackson, 1961), Jimberlana (Campbell, 1977), Muskox (Irvine, 1980), and Rhum (Dunham and Wadsworth, 1978) intrusions, and the pattern has been described as macrorhythmic or cyclic. In other cases the breaks in the normal fractionation sequence are more sporadic in occurrence and variable in effect, and the Kapalagulu intrusion clearly falls in this category. Two main types of mechanism have been proposed to explain these features. Firstly, there are the internally controlled processes, such as periodic convective overturn of the magma, or intermittent changes in water pressure or oxygen fugacity (Jackson, 1970). These have often been invoked to explain the more regularly repeated (cyclic) patterns. Secondly, there are the processes which involve interruption of the normal crystallization sequence by intervention from outside the magma chamber. The most obvious of these is the addition of new magma to the system. This has the attraction of great flexibility, in that it could happen at any stage during crystal accumulation, that the effects might be dramatic or trivial depending on the relative compositions of fresh and residual magmas, and that there would be the possibility of intermediate compositions (magmas and cumulates) resulting from the mixing of the two. Such a mechanism is particularly applicable to intrusions where there are occasional major breaks in the sequence as, for example, in the Bushveld Main Zone (Von Gruenewaldt, 1973), but it has also been proposed to explain the more regular cyclic variations, such as those at Jimberlana (Campbell, 1977) and Muskox (Irvine, 1980). The development of open-system conditions, at least periodically, also has the advantage of providing a convenient outlet for residual magmas as, for example, in the case of the Rhum intrusion, where only the early formed cumulates appear to have been deposited (Brown, 1956).

In his earlier account of the Kapalagulu sequence, Wadsworth (1963) proposed what is essentially an internal process to explain the main reversal in the mineral composition trend, although it did involve the escape of volatile material from the magma chamber at one particular stage. The basis for this interpretation was the apparent connection between the cryptic variation pattern, as indicated by the detailed study of orthopyroxene 2V (Wadsworth, 1963, fig. 4), and the occurrence of a substantial thickness of plagioclase cumulates (MZb) within a sequence typically comprising plagioclase–2 pyroxene cumulates. The optical evidence indicated that the most Fe-rich orthopyroxene in the first stage of progressive fractionation occurs immediately below MZb, following a rapid change of composition relative to stratigraphic height, to be succeeded by a much more gradual reversion to Mg-rich material (MZc–MZd) after the plagioclase cumulates had been deposited. This asymmetry of the orthopyroxene cryptic variation curve, and its relationship to the anorthosite subzone, were explained in terms of a sudden loss of volatiles from the magma chamber, as the deposition of MZa was completed, resulting in a temporary change from cotectic crystallization of plagioclase and pyroxene to precipitation of plagioclase alone, together with a concomitant shift in composition towards more sodic plagioclase, and (when it reappeared as a cumulus phase) more Fe-rich orthopyroxene. The more gradual return to relatively calcic and magnesian compositions, respectively, was attributed to the progressive increase in water pressure once the magma chamber had been sealed again, until, having returned to its former state soon after the commencement of MZd, the trend towards progressive fractionation was resumed.

It is now clear that this hypothesis is untenable, since the new mineralogical data show no connection between the plagioclase cumulates of MZb and the reversal of cryptic variation, and there is no evidence of the type of asymmetry inferred in the earlier study. As a result, it is assumed that the plagioclase cumulates of MZb represent a temporary non-equilibrium departure from cotectic crystallization conditions, and the major compositional reversal is now attributed to an influx of new, and relatively primitive, magma during the deposition of MZc. The gradational nature of the reversal is believed to reflect progressive mixing of the primitive and residual magmas, until the new material dominated the bulk composition, and may indicate that the accession of fresh magma took place by a number of increments over a period of time represented by a thickness of 200 m of cumulates, rather than in one major influx. A similar explanation for gradational reversals in the Rhum intrusion has been put forward by Dunham and Wadsworth (1978). A further point in favour of the magma replenishment hypothesis is that it can also be invoked to account for the much smaller reversal at the base of MZa. In this connection it is interesting to note that cumulus olivine is absent from MZa, despite the fact that the pyroxene compositions are more magnesian than at the top of IZ where olivine was still being precipitated. This suggests that the fresh magma being added at this stage was not of precisely the same composition as the original magma. In the case of the major reversal (MZc–MZd), the absence of cumulus olivine is less surprising, since the pyroxenes here do not reach quite such magnesian compositions. However, the fact that pigeonite reappears at a different composition after this reversal suggests that this batch of fresh magma was not identical to its precursors, although it was precipitating the same cumulus phases.

Although a cumulate succession provides an excellent way of monitoring the crystallization history of a layered intrusion, it does not indicate the precise chemical composition of the parent magma, and, in the absence of chilled margins or closely related minor intrusions, as at Kapalagulu, it is difficult to make more than a very general estimate of the magma type. From a study of the initial cumulus mineral assemblage (and overall cryptic variation pattern) at Kapalagulu, compared with other layered intrusions where there is more reliable evidence of parental magma composition, it is reasonably clear that the Kapalagulu magma was basaltic, with tholeiitic affinities. However, it should also be noted that recent evidence from the Bushveld Complex (Von Gruenewaldt, 1979; Cawthorn *et al.*, 1981) suggests that magma unusually rich in Mg and Si was responsible for the earlier cumulates at least, although it may have become progressively diluted by more normal basaltic magma later. The persistently calcic nature of the Kapalagulu plagioclase has already been noted, and it may also be significant that the composition of the earliest cumulus crystals (An_{88}) is slightly more Ca-rich than in otherwise comparable sequences. Together, these facts suggest an initial magma of relatively high Ca content. The occurrence of intercumulus quartz quite low in the succession (MZa), and the abundance of micropegmatite higher, in MZ, especially in the segregation veins of MZe, also testify to the tholeiitic nature of the magma, but the implication (Wadsworth, 1963) that the quartz-dolerite dykes cutting the Kapalagulu intrusion provide independent evidence of this is now shown to be incorrect, in view of the radiometric dating evidence.

This type of study re-emphasizes the importance of detailed investigations of cryptic variation in layered intrusions. So far, the available evidence from intrusions such as Rhum, Bushveld, and Kapalagulu suggests that the cumulus minerals provide evidence of original depositional compositions, and that the variations have primary stratigraphic significance. This is in marked contrast to the evidence from the Muskox intrusion which has led Irvine (1980) to suggest that cumulates may be highly susceptible to late-stage chemical modification as the result of upward migration of intercumulus fluids.

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APPENDIX

Analytical methods. The mineral analyses were made using a Cambridge Instrument Company Geoscan fitted with a Link System model 290-2KX energy-dispersive spectrometer (using 15 kW, a specimen current of around 3 nA on cobalt metal) and ZAF-4/FLS quantitative analysis software system. At least five spots were analysed for each mineral (except plagioclase), generally from the apparent cores of five different crystals, but sometimes fewer in the case of large poikilitic pyroxenes. For plagioclase, at least ten (and often fifteen or more) spots were analysed in each rock investigated. For olivines and orthopyroxenes the apparent composition range in each rock was generally less than 0.7% (Fo and En respectively), and for clinopyroxenes less than 1% [Mg/(Mg+Fe)].