

IX. THE MODIFIED DIFFERENTIATION INDEX AND THE MODIFIED CRYSTALLIZATION INDEX AS PARAMETERS OF DIFFERENTIATION IN LAYERED INTRUSIONS

1. Introduction

Several parameters have been proposed by various writers to illustrate differences in chemical composition between various rock types or suites of rocks. Some of these, such as the solidification index (Kuno, *et al.* 1957), modified Larsen index (Nockolds and Allen, 1953, p. 116), iron and albite ratios (Wagner, 1956), etc. are atomic or oxide proportions calculated directly from the chemical analyses, whereas others, notably the differentiation index (Thornton and Tuttle, 1960) and the crystallization index (Poldervaart and Parker, 1964) are combinations of various normative minerals calculated from the chemical analyses. All these indices were proposed to serve as parameters of igneous differentiation, and were plotted against different oxides to illustrate variation trends by which suites of rocks are characterized. The differentiation index (DI) and crystallization index (CI) have the advantage that they are parameters of igneous differentiation, based on theoretical petrological principles, and are therefore used in this study to illustrate the fractional crystallization of the Bushveld magma. However, when these parameters are used on layered intrusions such as the Bushveld Complex, some complications arise which can be overcome to some extent by making a few modifications. Consequently, a modified differentiation index (MDI) and a modified crystallization index (MCI) are proposed to illustrate the differentiation trends in layered intrusions.

2. The Modified differentiation index (MDI)

The DI was proposed by Thornton and Tuttle (1960, p. 664) and is based on petrogeny's residua system, namely, $\text{SiO}_2 - \text{NaAlSiO}_4 - \text{KAlSiO}_4$, i. e. the goal towards which all magmas will move on fractional crystallization.

$$\text{DI} = \sum \text{Qz} + \text{Or} + \text{Ab} + \text{Ne} + \text{Lc. (given as normative minerals).}$$

The DI is therefore an indication of the degree of fractionation of a magma, which is reflected by the amount of normative quartz, orthoclase, albite, nepheline and leucite present in the analysed rock. It is obvious that granite, syenite or foyaite will have a very high DI, whereas a pyroxenite or dunite will have a very low DI.

In Fig. 65 the DI of a number of analysed rocks from the Bushveld is plotted against the height in the intrusion. From this figure it is obvious that

the DI as defined by Thornton and Tuttle cannot be used to illustrate the differentiation trend of the Bushveld magma. This is in part due to the variation of rock types caused by variations in the proportions of minerals. Anorthosite has, for example, a much higher DI than an over- or underlying gabbroic rock because of the larger amount of normative albite present in the anorthosite, whereas iron enrichment in the pyroxenes of the gabbroic rocks is not taken into account. This failure to bring out the pronounced iron enrichment which is shown by some basaltic rock series such as the Skaergaard and Bushveld Intrusions is the main criticism against the DI (Poldervaart and Parker, 1964, p. 282 and 1965, p. 279). Diagrammatically this may be seen in Fig. 65 where the DI for anorthosite falls well on the right of the diagram, whereas the DI for pyroxenite falls on the left and in themselves show differentiation trends separate from the more "normal" gabbroic rocks.

For the above reason, it is suggested that the DI should be modified in such a way that the iron enrichment in the minerals is also taken into account. For layered mafic intrusions like the Bushveld Complex, the modified differentiation index (MDI) can therefore be defined as being the sum of the normative quartz, orthoclase, albite, ferroan diopside ($\text{CaFeSi}_2\text{O}_6$), ferrosilite and fayalite, as well as nepheline and leucite which may be present in small amounts in the norm.

$$\text{MDI} = \sum (\text{Qz} + \text{Or} + \text{Ab} + \text{Di}' + \text{Fs} + \text{Fa} + \text{Ne} + \text{Lc})$$

where $\text{Di}' = 1,88052 \text{ Fs (Di)}$ (Fs of normative diopside) (See Table XV).

But before the MDI of rocks against height in the intrusion is plotted, another factor which will influence the MDI (or DI) must be taken into account, namely, the various amounts of oxidic ore minerals present in the rock types. Consider, for instance, a magnetite-bearing anorthosite, which, for the sake of simplicity, consists of 50 per cent normative magnetite and 50 per cent normative plagioclase which is composed of 24 per cent normative Ab and 26 per cent normative An. The MDI of this rock will be 24. A rock type directly above or below this magnetite-bearing anorthosite is, for argument's sake, a magnetite-free troctolite which consists of 50 per cent normative olivine (26 per cent Mg_2SiO_4 and 24 per cent Fe_2SiO_4) and 50 per cent normative plagioclase (24 per cent Ab and 26 per cent An). The MDI of this rock will be 48. A magnetite-free anorthosite at the same level in the intrusion will also have an MDI of 48 (48 per cent normative Ab and 52 per cent normative An). The difference in MDI between the first two rock types is considerable although these rocks may occupy nearly the

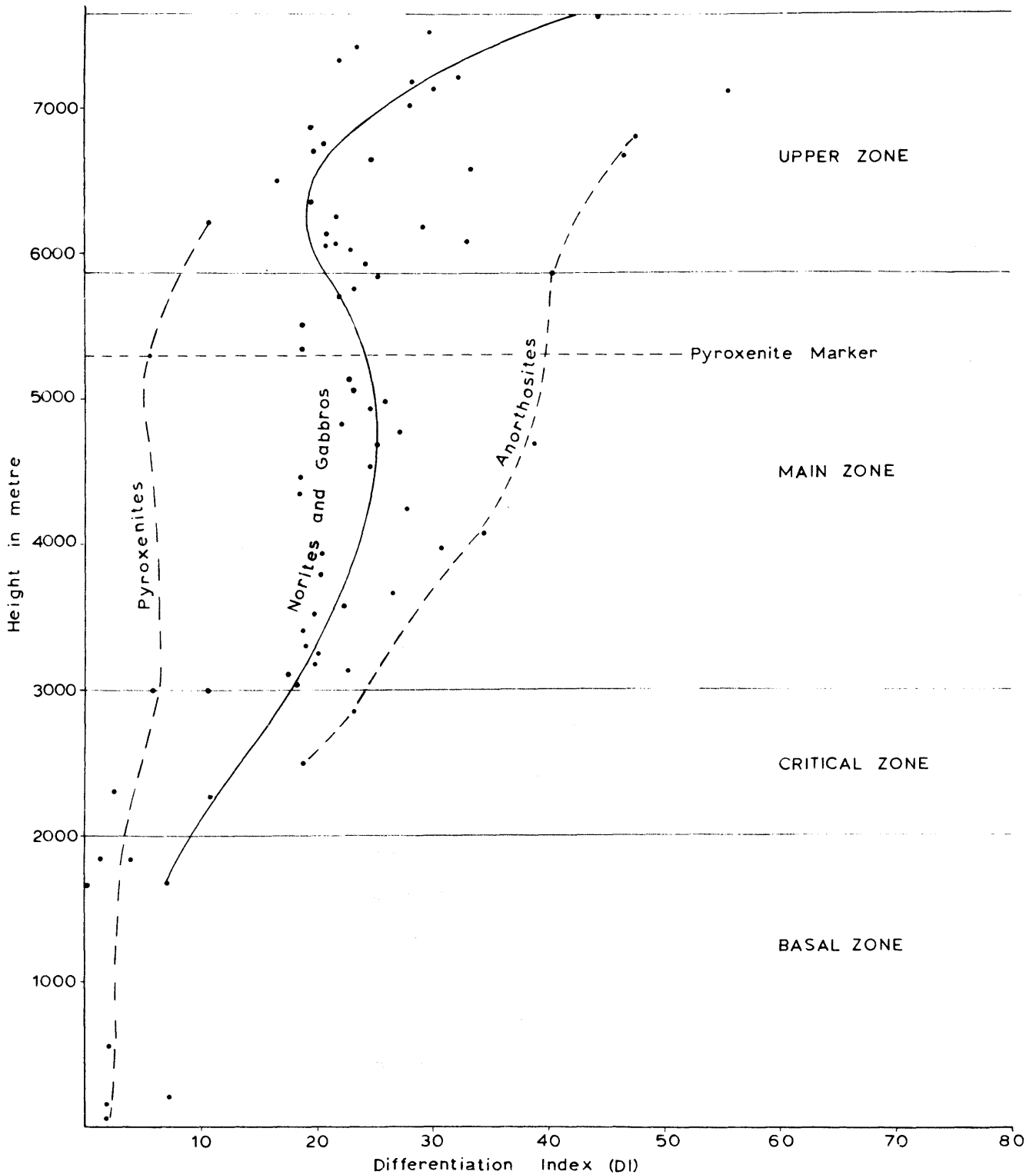


FIG. 65. PLOT OF THE DIFFERENTIATION INDEX OF ROCKS FROM THE BUSHVELD COMPLEX

same height in the intrusion. It follows that all the "inactive" minerals like magnetite, ilmenite, apatite and chromite, (i. e. those normative minerals which do not change in composition with differentiation and which may be present in varying amounts, especially in the Upper, Critical and Basal Zones of the Bushveld Complex) must be subtracted from the norm, the remaining norm must be recalculated to a percentage and the MDI calculated from this recalculated norm. In this way, the magnetite-bearing anorthosite, the troctolite and the magnetite-free anorthosite, which are used as examples above, will all have MDI's of 48. An example of the MDI calculation from the chemical analysis is given in Table XV.

In Fig. 66, a plot of the MDI against height in the intrusion, a fairly good trend in the differentiation is observed. Although the scatter of points is still considerable, the MDI of anorthosites and pyroxenites now fall within the trend of the gabbroic and noritic rocks. The influx of fresh magma at the level of the Pyroxenite Marker of the Main Zone is also clearly indicated.

3. The modified crystallization index (MCI)

The crystallization index was proposed by Poldervaart and Parker (1964, p. 281) and is based on the argument that the great diversity of rock types produced during the late stages of crystallization evolved from very similar source-magmas. The CI is therefore a parameter of differentiation which is based on the onset of magmatic crystallization, i. e. the system $\text{CaAl}_2\text{Si}_2\text{O}_8 - \text{CaMgSi}_2\text{O}_6 - \text{Mg}_2\text{SiO}_4$. According to Poldervaart and Parker, the CI "measures the progression of partial magmas or igneous rocks from the primitive system anorthite - diopside - forsterite".

$$\text{CI} = \text{normative An} + \text{Di}' + \text{Fo}' + \text{Sp}' \text{ where}$$

Di' = magnesian diopside ($\text{CaMgSi}_2\text{O}_6$) calculated from normative diopside.

Fo' = normative forsterite plus normative enstatite converted to forsterite.

Sp' = magnesian spinel (MgAl_2O_4) calculated from normative corundum in ultramafic rocks.

Rocks which consist of anorthite, magnesian diopside or forsterite have a CI of 100, whereas rocks which consist of quartz, alkali feldspars or feldspathoids have a CI of 0. Poldervaart and Parker stress that the CI is more useful in indicating trends of differentiation in basaltic magmas, especially where there is a gradual enrichment of iron owing to fractional crystallization. This they illustrated (1965, p. 281, Fig. 2) with the aid of calculated compositions of successive

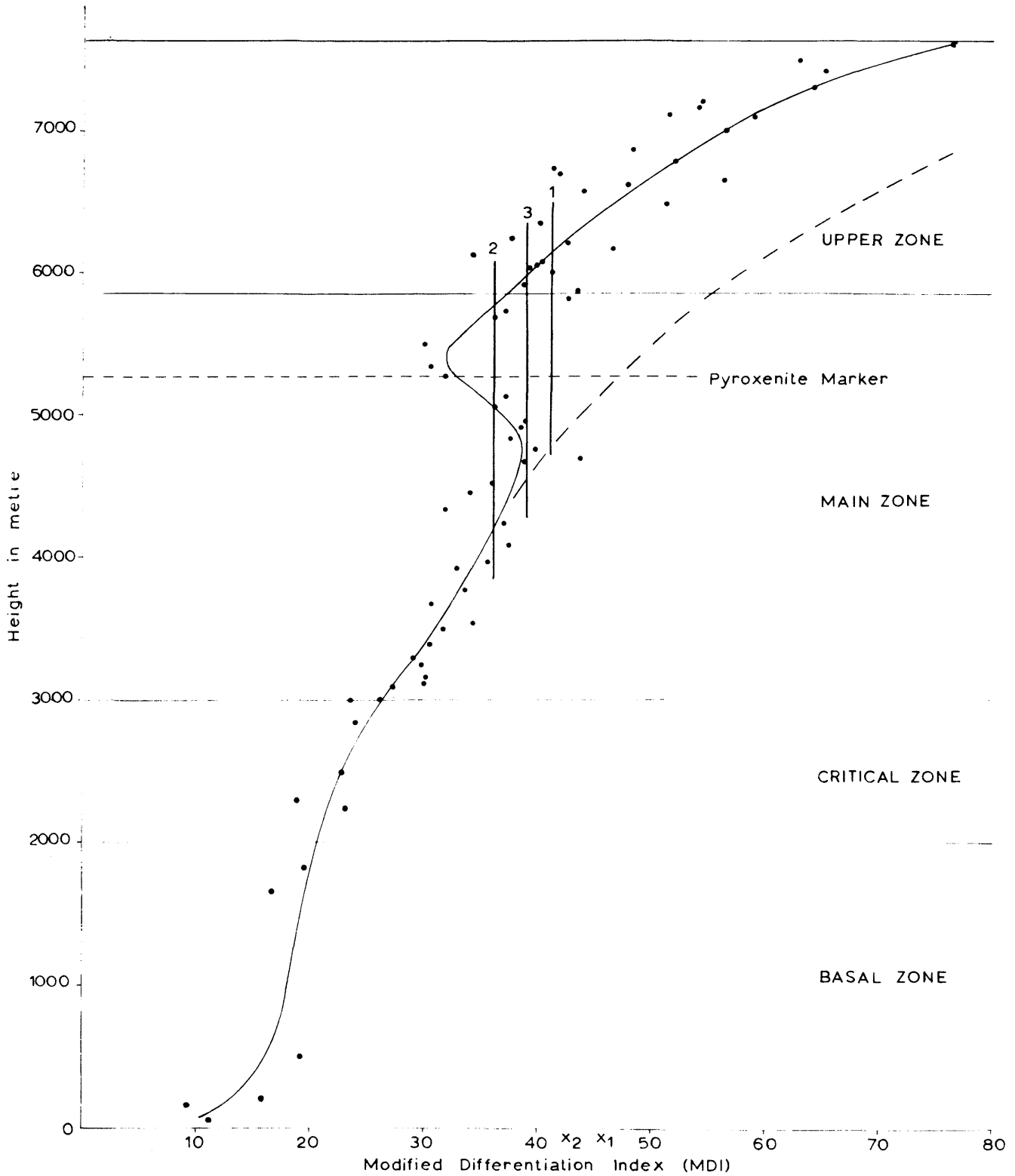


FIG. 66. PLOT OF THE MODIFIED DIFFERENTIATION INDEX OF ROCKS FROM THE BUSHVELD COMPLEX

Skaergaard liquids (Wager 1960, p. 386) which will necessarily give a linear trend as shown. If, however, analyses of rocks are used for the CI calculations and these values plotted against height in the intrusion, as was done with the available analyses of Bushveld rocks (Fig. 67) a sharp reversal in the differentiation trend is observed in the lower zones of the Complex. This may be explained as follows:

A dunite which consists of forsterite has a CI of 100 and an anorthosite which consists of anorthite also has a CI of 100. Dunite and anorthosite are however rock types which do not occur together in layered intrusions. The association pyroxenite and anorthosite is however common, for instance in the Critical Zone of the Bushveld Complex. It follows that an anorthosite with CI 100 may be found in association with a pyroxenite of CI 70. The anorthosites of the top of the Critical Zone and the harzburgites of the Basal Zone have therefore higher CI's than the pyroxenites which occur between these two (Fig. 67). This discrepancy may be overcome if the CI is modified so that the calculations are based on the orthopyroxene content of the norm, in such a way that the CI for both the pyroxenite (enstatite only) and the anorthosite (anorthite only) is 100. Consequently, the CI for a dunite (forsterite only) must be more than 100, namely, 142,68. This figure, based on the amount of SiO_2 necessary to convert all the olivine to orthopyroxene is obtained by multiplying the amount of normative forsterite by

$$\frac{\text{mol. weight } 2\text{MgSiO}_3}{\text{mol. weight } \text{Mg}_2\text{SiO}_4} = 1,4268$$

The maximum value of the CI is therefore 142,68. Recalculation of the CI obtained by this method to 100 is achieved by multiplying by the factor 0,70084. A dunite will now have a MCI of 100, a pyroxenite (enstatite only) will have a MCI of 70,08 and an anorthosite (anorthite only) will also have a MCI of 70,08.

Although Poldervaart and Parker's argument that the "ideal parameter of magmatic differentiation should represent the phases of petrogeny's primitive system" (1964, p. 285) is correct, it must also be borne in mind that the onset of fractional crystallization of a basaltic magma in intrusions such as the Bushveld Complex is not at the ternary eutectic in this system, as implied by Poldervaart and Parker, but usually commences in the olivine field whereupon the

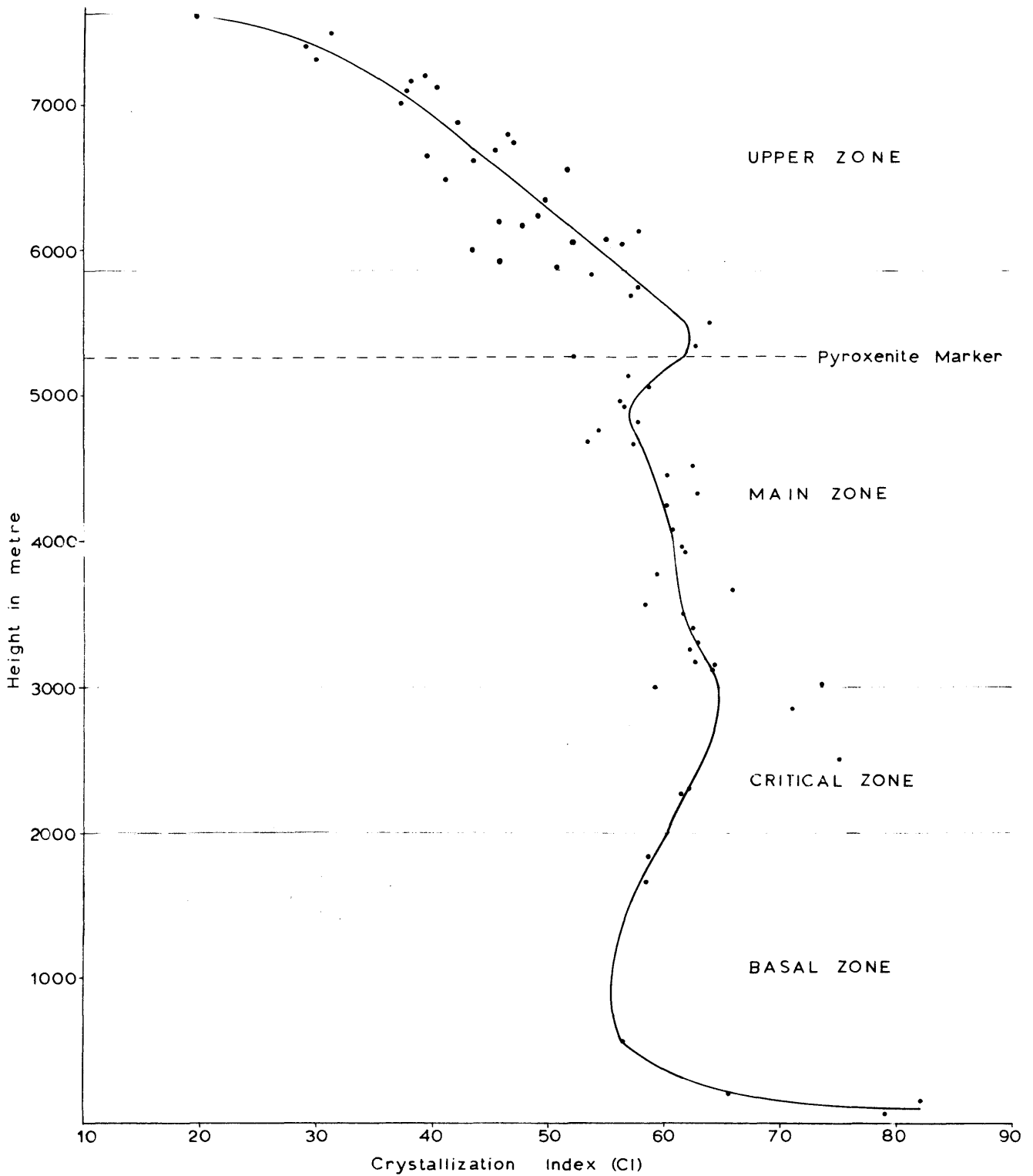


FIG. 67. PLOT OF THE CRYSTALLIZATION INDEX OF ROCKS FROM THE BUSHVELD COMPLEX

TABLE XV EXAMPLE OF MDI AND MCI CALCULATIONS FROM THE CHEMICAL ANALYSIS

Analysis	C. I. P. W.	Norm	Recalculated norm	MDI	MCI	
SiO ₂	48,00	Or	7,39	8,49		
TiO ₂	2,26	Ab	27,04	31,05		
Al ₂ O ₃	13,00	An	17,54	20,14	20,14	
Fe ₂ O ₃	3,03	Di {	Wo	4,25	5,19	
FeO	16,20		En	1,10	1,27	Di' 2,74**
MnO	0,26		Fs	3,69	4,23	Di' 7,95*
MgO	2,88	Hy {	En	5,63	6,46	6,46
CaO	7,14		Fs	18,84	21,64	21,64
Na ₂ O	3,18	Ol {	Fo	0,28	0,32	Fo' 0,46***
K ₂ O	1,23		Fa	1,05	1,21	1,21
P ₂ O ₅	1,06	Mt	4,41			
H ₂ O	2,05	Il	4,35			
	100,29	Ap	2,55	Total	70,34	29,80
		H ₂ O	2,05			x 0,7008
			100,44			= 20,89

$$* \quad 4,23 \times \frac{\text{mol. wt. CaFeSi}_2\text{O}_6}{\text{mol. wt. FeSiO}_3} = 4,23 \times \frac{248,04}{131,90} = 4,23 \times 1,88052 = 7,95$$

$$** \quad 1,27 \times \frac{\text{mol. wt. CaMgSi}_2\text{O}_6}{\text{mol. wt. MgSiO}_3} = 1,27 \times \frac{216,52}{100,38} = 1,27 \times 2,15700 = 2,74$$

$$*** \quad 0,32 \times \frac{\text{mol. wt. 2MgSiO}_3}{\text{mol. wt. Mg}_2\text{SiO}_4} = 0,32 \times \frac{200,76}{140,70} = 0,32 \times 1,4268 = 0,46$$

liquid proceeds towards the ternary eutectic. Pyroxene and plagioclase usually crystallize after olivine, and rocks consisting of magnesian diopside and anorthite should therefore have a lower CI than rocks which consist essentially of olivine.

When the MCI as outlined above is calculated, it is again advisable to subtract mineral phases such as magnetite, ilmenite, apatite and chromite which may be present in variable amounts in the norm and to recalculate the remaining norm to 100. This is necessary because a pyroxenite which, for instance, contains 25 per cent chromite will have a lower MCI than a chromite-free pyroxenite immediately above or below. In norms which do not contain large amounts of magnetite, ilmenite, apatite or chromite, this correction is not necessary as it will not greatly influence the MDI or MCI.

$$\text{MCI} = (\text{An} + \text{Di}' + \text{En}' + \text{Sp}') \times 0,70084$$

where An = normative anorthite.

Di' = magnesian diopside, $\text{CaMgSi}_2\text{O}_6$, calculated from normative diopside.

En' = normative enstatite of normative hypersthene plus normative forsterite converted to enstatite.

Sp' = magnesian spinel, MgAl_2O_4 , calculated from normative corundum in ultramafic rocks.

An example of the calculation of the MCI is given in Table XV.

In Fig. 68 the MCI of rocks from the Bushveld Complex are plotted against height in the intrusion. If this diagram is compared with Fig. 66 it can be seen that, for the greater part of the intrusion, there is a striking similarity between the observed differentiation trends. This is obvious, because the relationship between the MDI and MCI is to some extent a reciprocal one. The lowest portion of the curve in Fig. 68 flattens out considerably, which is an indication of the relatively few dunitic rocks in the exposed sequence of the Bushveld Intrusion.

4. Binary variation diagrams

The variation diagrams presented in Figs. 69 to 77 are constructed from more than 100 analyses, mostly of rocks from the eastern part of the Bushveld Complex. The majority of the analyses were kindly made available to the author by Dr. D. R. Bowes and Dr. T. G. Molyneux, prior to publication. The rocks for these analyses were collected by Molyneux (1970, Plate III) along traverses across the Main and Upper Zones in the Leolo Mountains and at Magnet Heights

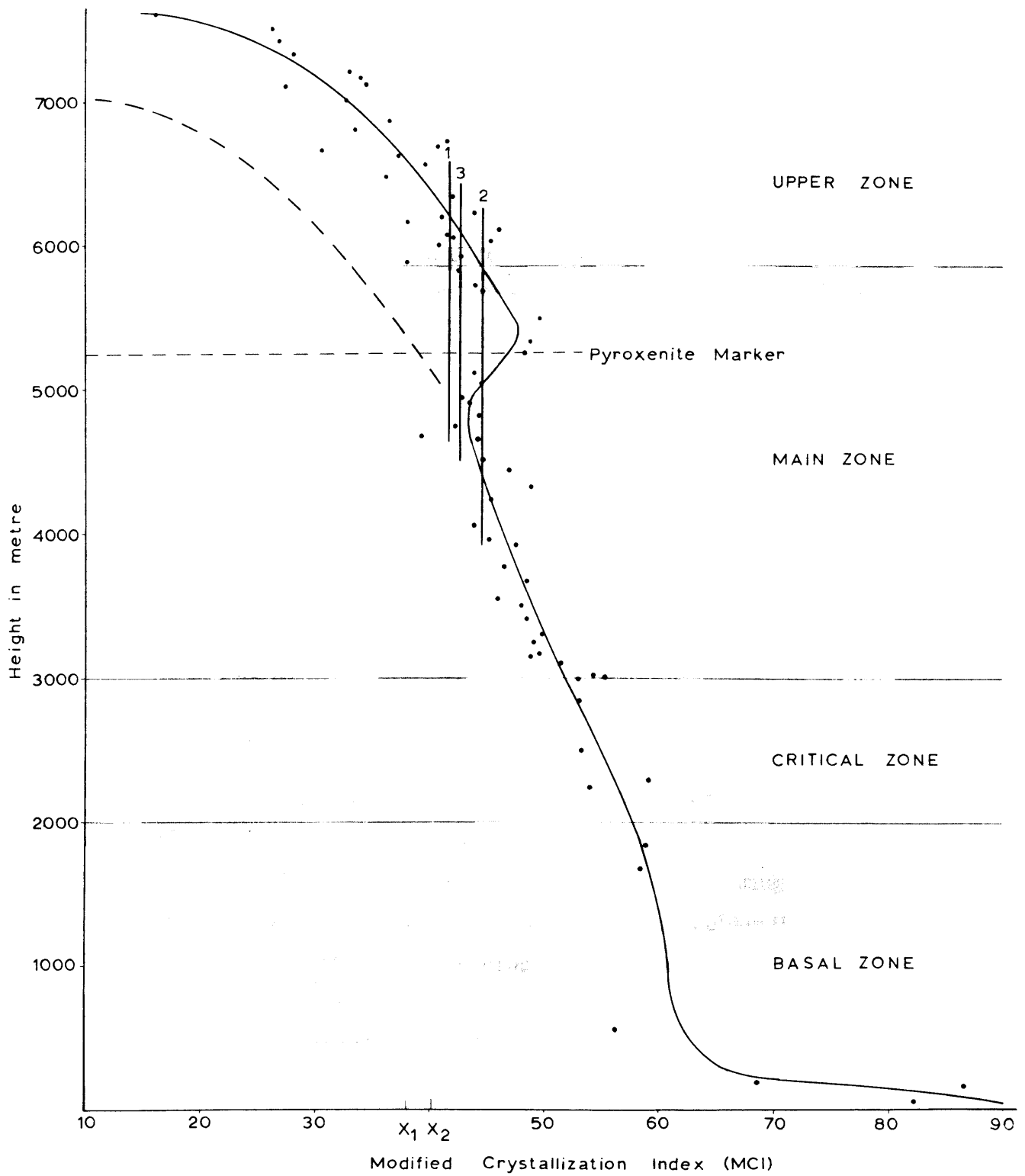


FIG. 68. PLOT OF THE MODIFIED CRYSTALLIZATION INDEX OF ROCKS FROM THE BUSHVELD COMPLEX

respectively, and were analysed by the Department of Geology at the University of Glasgow. Dr. Bowes also kindly supplied the C. I. P. W. norm and the CI of these analyses which were calculated by computer at the University of Glasgow. All the analyses, the C. I. P. W. norms recalculated to 100 (Thornton and Tuttle, 1960, p. 670 and Poldervaart and Parker, 1964, p. 285), CI, DI and the recalculated norms for the MDI and MCI are given in Appendix II, together with a list of the names of the analysed rocks, localities and literature references.

a) Calculated parameters vs. height in the intrusion

For the construction of Figs. 65 to 68 analyses of Molyneux's samples were used for the Main and Upper Zones. The thickness of these two zones is that reported by Molyneux (1970, p. 14) from the area to the north, where the samples were collected, and not the thickness as calculated for these two zones in this study (Folder II). Thicknesses of the lower two zones are rough estimates and the position in the sequence of rocks from these two zones was judged from the description of the localities and are therefore not accurate. Unfortunately, not many analyses of rocks from the Critical and Basal Zones of the eastern part of the Complex are available, and consequently the trends as observed from the few available analyses must be regarded with reservations.

Comparison of Figs. 65, 66, 67 and 68 clearly shows that the MDI and MCI are better parameters to illustrate the differentiation in layered mafic intrusions than the DI and CI, for reasons which are outlined in the sections dealing with the calculation of the MDI and MCI.

The scatter of points in Figs. 66 and 68 is to some extent due to the different degree of fractionation of the coexisting mineral series. Plagioclase usually contains more mol. per cent Ab than the coexisting orthopyroxene contains mol. per cent Fs (Willemse, 1969, p. 8 and Folder III of this study) and consequently, variations in the proportions of coexisting cumulus phases as well as variations in the amount of intercumulus material in the analysed rocks will cause a scatter of points in the diagram.

The MDI and MCI of three available analyses of rocks presumed to be from the chill zone of the Bushveld Complex were also calculated and are shown on Figs. 66 and 68 as vertical lines to indicate where these values intersect the differentiation trend. If the influx of fresh undifferentiated magma at the level of the Pyroxenite Marker of the Main Zone is ignored, and the observed differentiation trend continued (dashed lines Figs. 66 and 68) then the MDI and MCI

of rocks from the chill zone correspond to those of rocks approximately two-thirds up in the Layered Sequence. If the rocks from the chill zone represent the composition of the original magma, then one would expect these to have a MDI or MCI which would correspond to rocks of about half way up in the Layered Sequence, provided that the degree of fractionation of the magma was maintained at a fairly constant rate. Inasmuch as the MDI and MCI may be considered as parameters of fractionation, a constant rate of fractionation would result in a linear variation diagram. The trend, as observed in Figs. 66 and 68 is however, not linear (influence of the addition of fresh magma at the level of the Pyroxenite Marker excluded), but show, owing to a flattening of the curve, an increase in the degree of fractionation during crystallization of the Upper Zone. Consequently, the original magma will have a MDI or MCI which will correspond to that of the rocks in the upper half of the intrusion, as observed in these diagrams. However, the effect of flattening of the curve in the lower portion of the diagram (Basal Zone) will tend to counterbalance the flattening at the top, with the result that the MDI and MCI of the original Bushveld magma would be inclined to correspond to MDI's and MCI's of rocks in the middle of the sequence.

If, on the other hand, the degree of fractionation during crystallization of the Bushveld magma took place at a constant rate, then a steepening of the curve would indicate the presence of cyclic units either due to processes in a single batch of magma, or due to the influx of fresh, undifferentiated magma. Influx of a large volume of fresh magma at the level of the Pyroxenite Marker even resulted in the reversal of the trend in Figs. 66 and 68.

The observed relationship between MDI and MCI of rocks of the Chill Zone and those of the Layered Sequence must, however, be treated with caution as there are several ways in which such a relationship can be explained. These are among others:

- i) That these fine-grained rocks are contaminated by assimilation of country-rocks (J. Willemsse, 1969, p. 7).
- ii) That more acid differentiates (i. e. diorites and granodiorites) existed along the outer, higher levels of the essentially funnel-shaped intrusion, and that the majority of these rocks have since been eroded away.
- iii) There are also some indications that the Bushveld magma extended

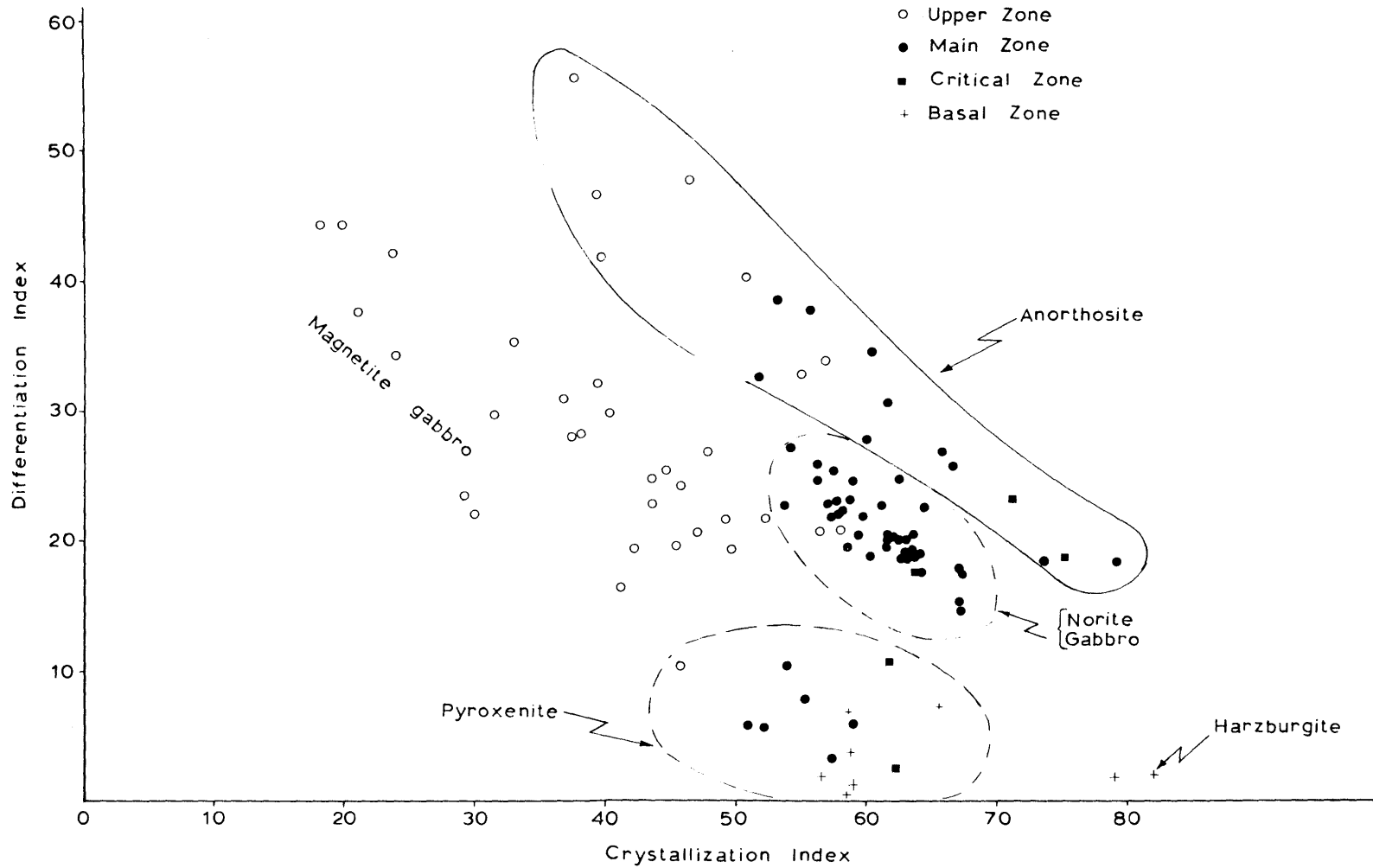


FIG. 69. PLOT OF THE DI VERSUS THE CI FOR ROCKS OF THE BUSHVELD COMPLEX

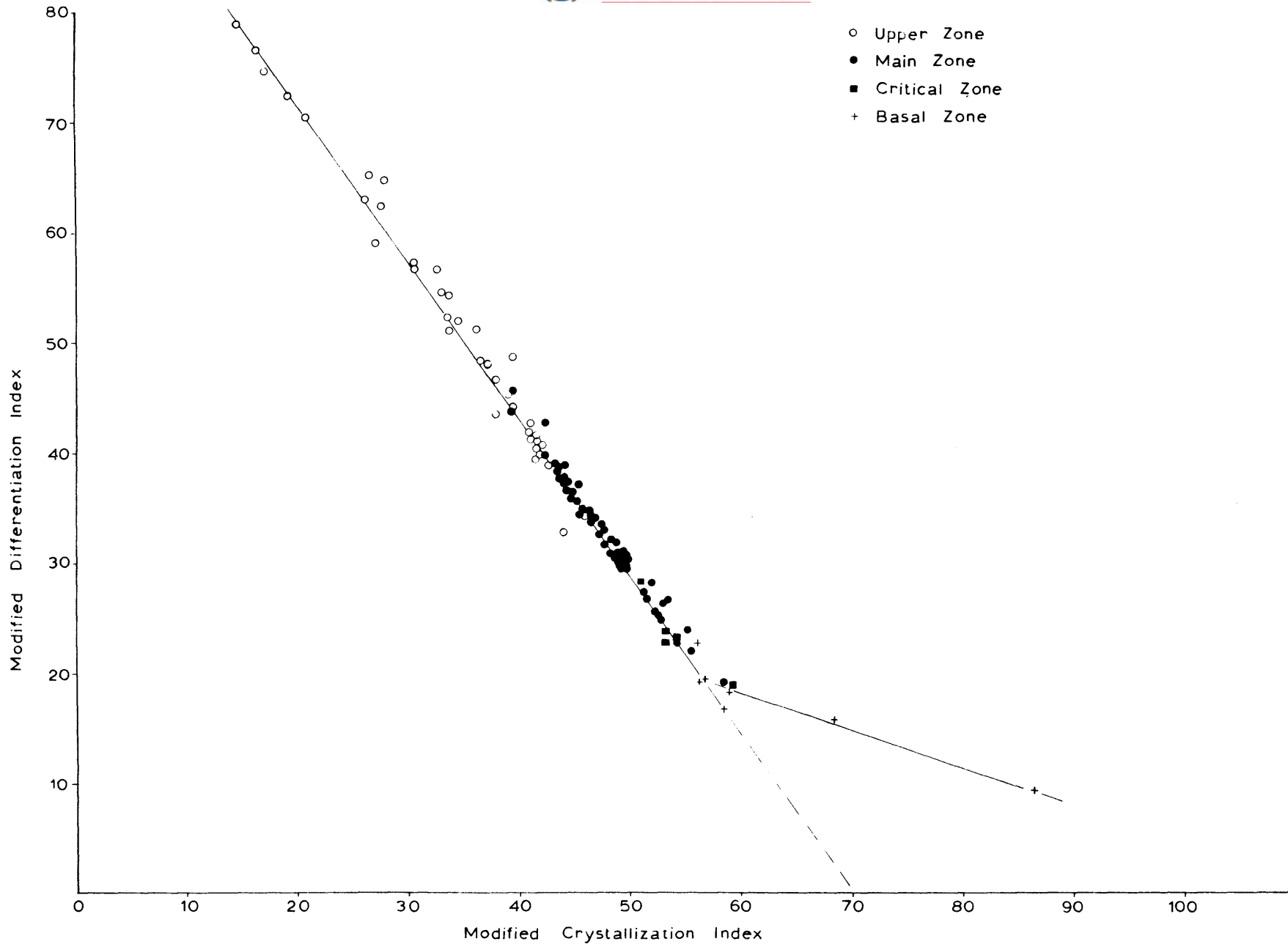


FIG. 70. PLOT OF THE MDI VERSUS THE MCI FOR ROCKS OF THE BUSHVELD COMPLEX

pected because $MCI = (100 - MDI) \times 0,7008$ of rocks which contain no normative forsterite, and consequently all these analyses will fall on the straight line in Fig. 70. Rocks which do contain normative forsterite have, according to the rules of calculation of the MCI, a higher index (see method of calculation of MCI above) with the result that the $MCI \geq (100 - MDI) \times 0,7008$ and will therefore plot to the right of the line. This deviation from the straight line is not pronounced for the olivine-bearing rocks of the Upper Zone, because of the low normative forsterite content, but for rocks of the Basal Zone which contain larger amounts of normative forsterite, the deviation to the right is considerable and thus causes the deflection of the curve at high MCI and low MDI values.

c) DI, CI, MDI and MCI vs. weight per cent oxides

In Figs. 71 to 77 the DI, CI, MDI and MCI of rocks from the Bushveld Complex are plotted against weight per cent of some of the oxides or combinations of oxides. Seeing that layered intrusions consist of crystal cumulates, the composition of the rock is determined by the quantities of settled mineral phases with the result that a specific cumulate may contain a considerably higher or lower percentage of a certain oxide than the magma from which it crystallized. In most of the diagrams (Figs. 71 to 77) separate trends or areas could be delineated for the major rock types, viz. anorthosite, pyroxenite, norite and gabbro, harzburgite and magnetite-bearing rocks of the Upper Zone.

From the spread of the points in these diagrams, 55 units for the DI, 67 units for the CI, 70 units for the MDI and 72 units for the MCI, it seems as though the last three are the most suitable parameters to illustrate differentiation trends in layered intrusions. In variation diagrams involving the CI, it can again be seen that pyroxenites have a lower CI than gabbros and consequently it is not a suitable parameter to illustrate differentiation trends. The MDI and MCI variation diagrams show very similar trends and seem to be the most suitable parameters. For igneous complexes where many dunites, harzburgites and pyroxenites are developed, the MCI would be the most useful, whereas for the Bushveld Complex where relatively few ultramafic rocks are developed, the MDI seems the more useful parameter (Compare also Figs. 66 and 68).

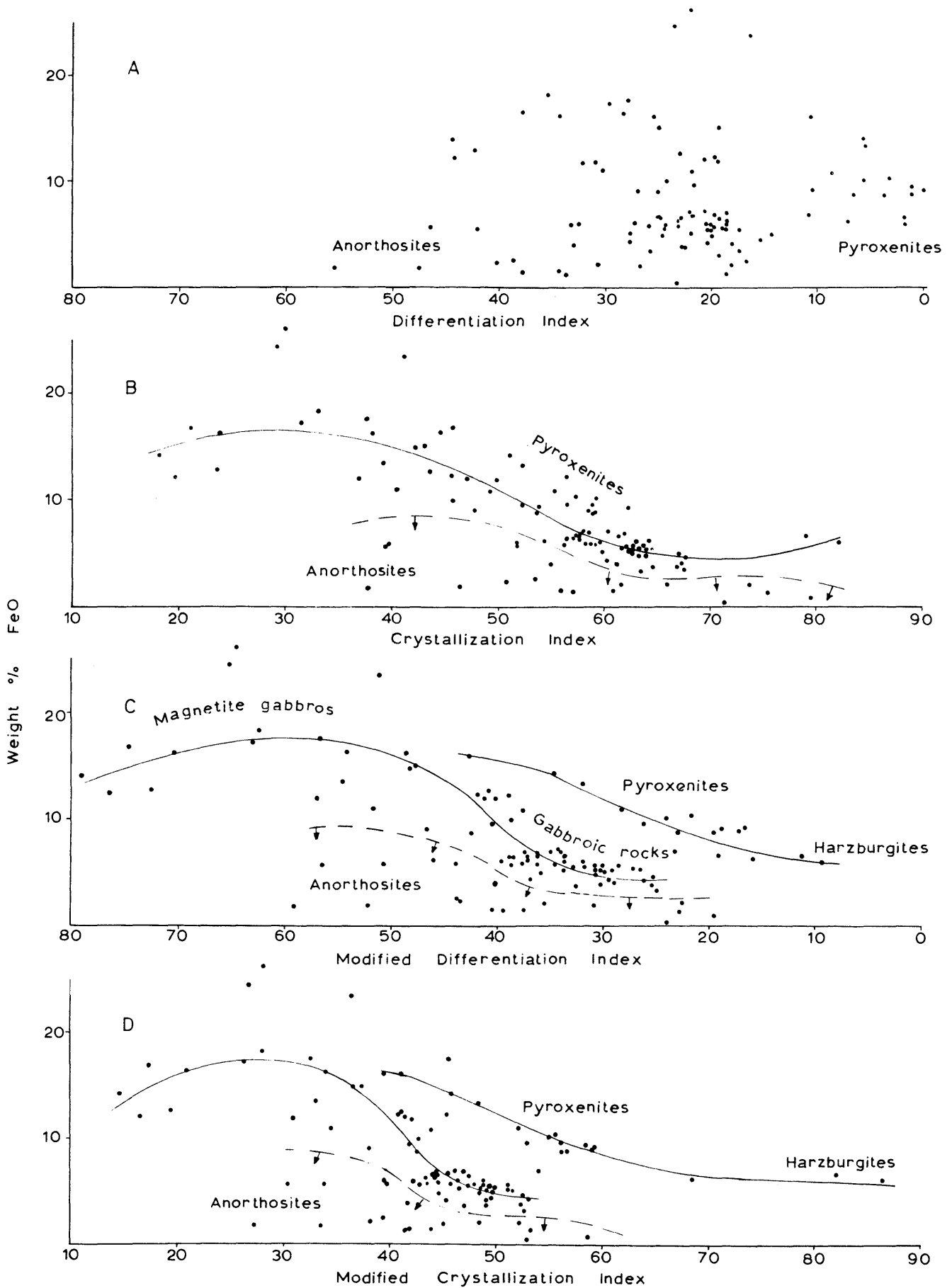


FIG. 71. PLOT OF DI, CI, MDI AND MCI AGAINST WEIGHT % FeO

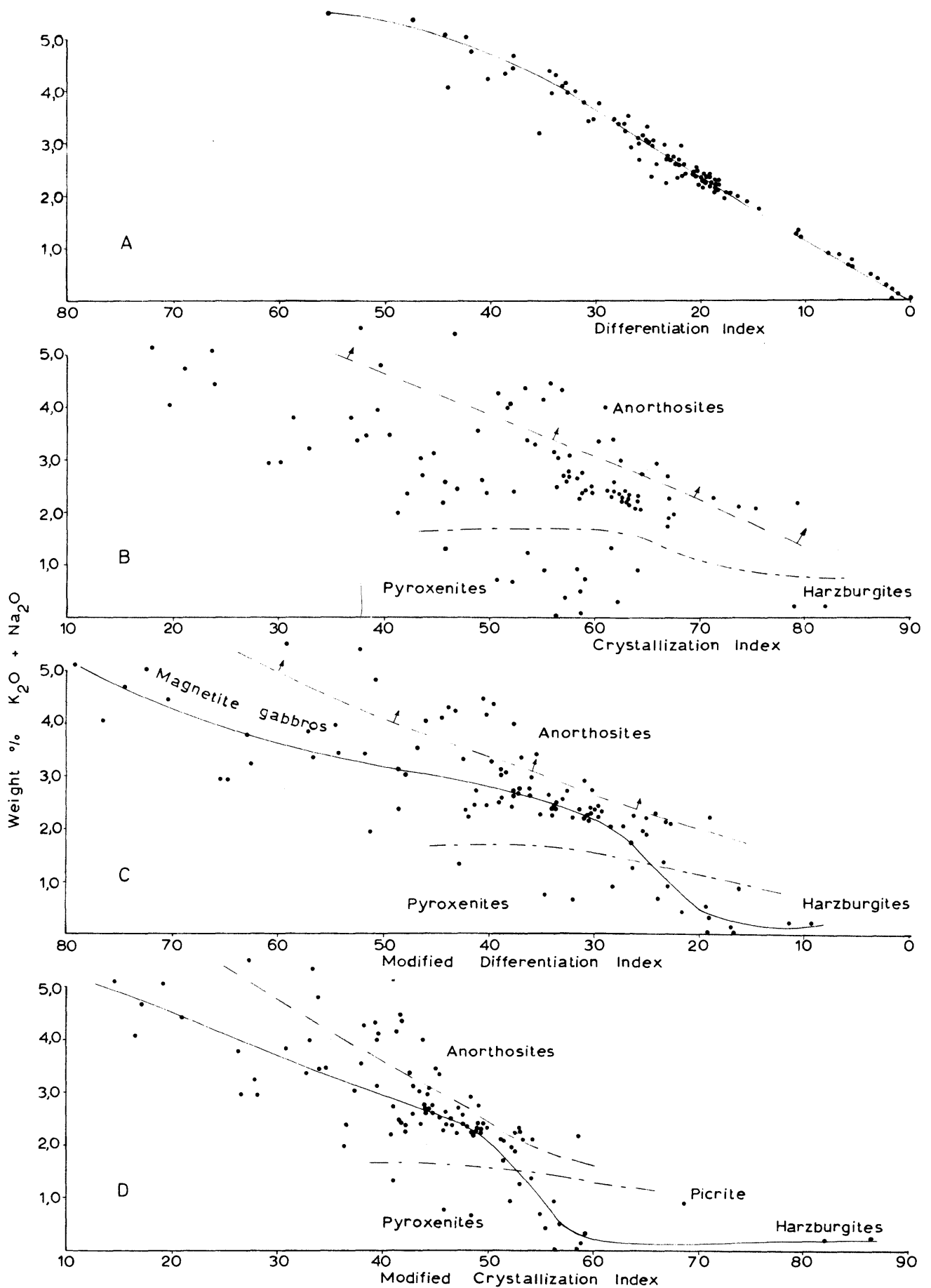


FIG. 72. PLOT OF DI, CI, MDI AND MCI AGAINST WEIGHT % K_2O AND Na_2O

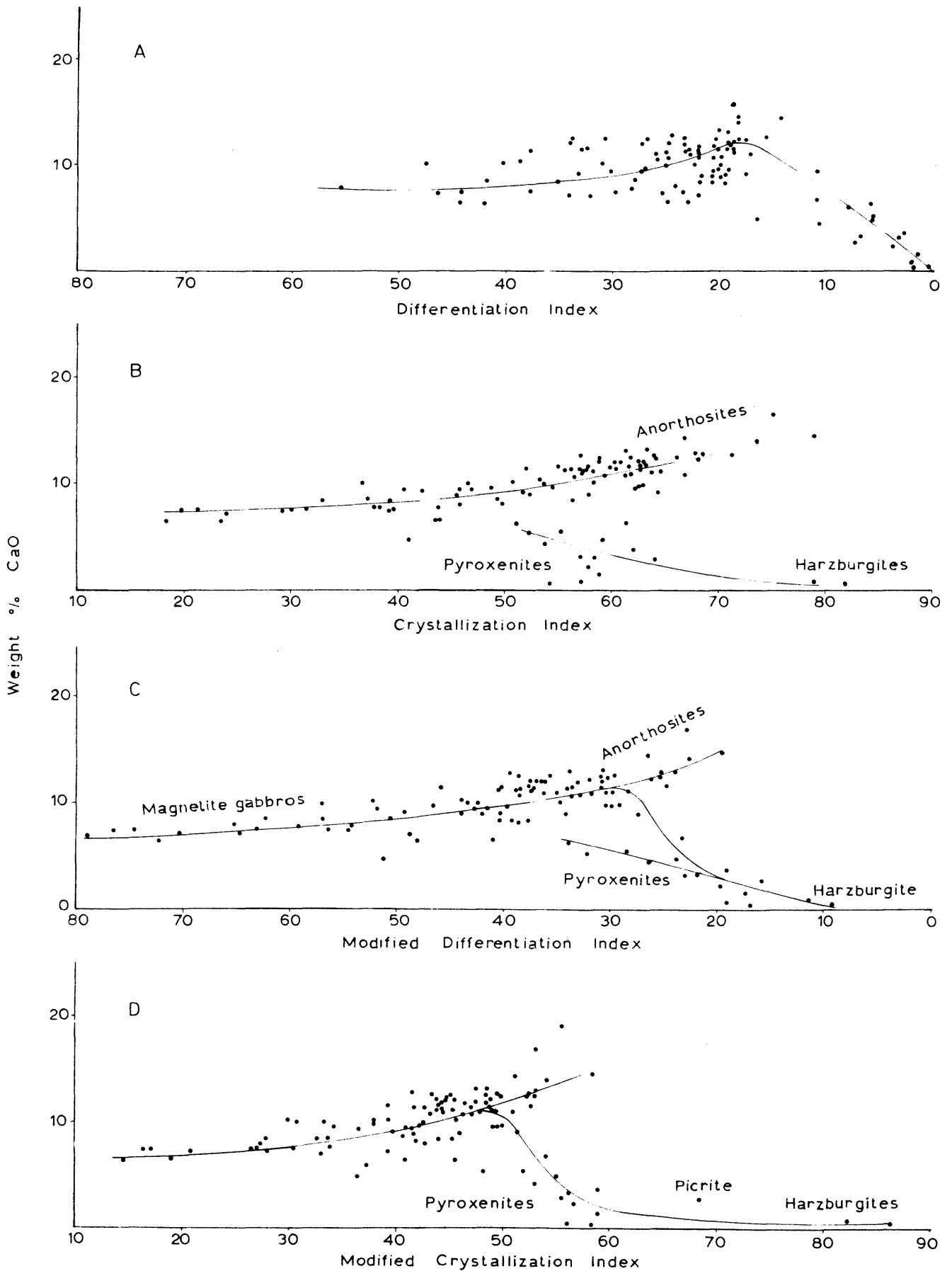


FIG. 73. PLOT OF DI, CI, MDI AND MCI AGAINST WEIGHT % CaO

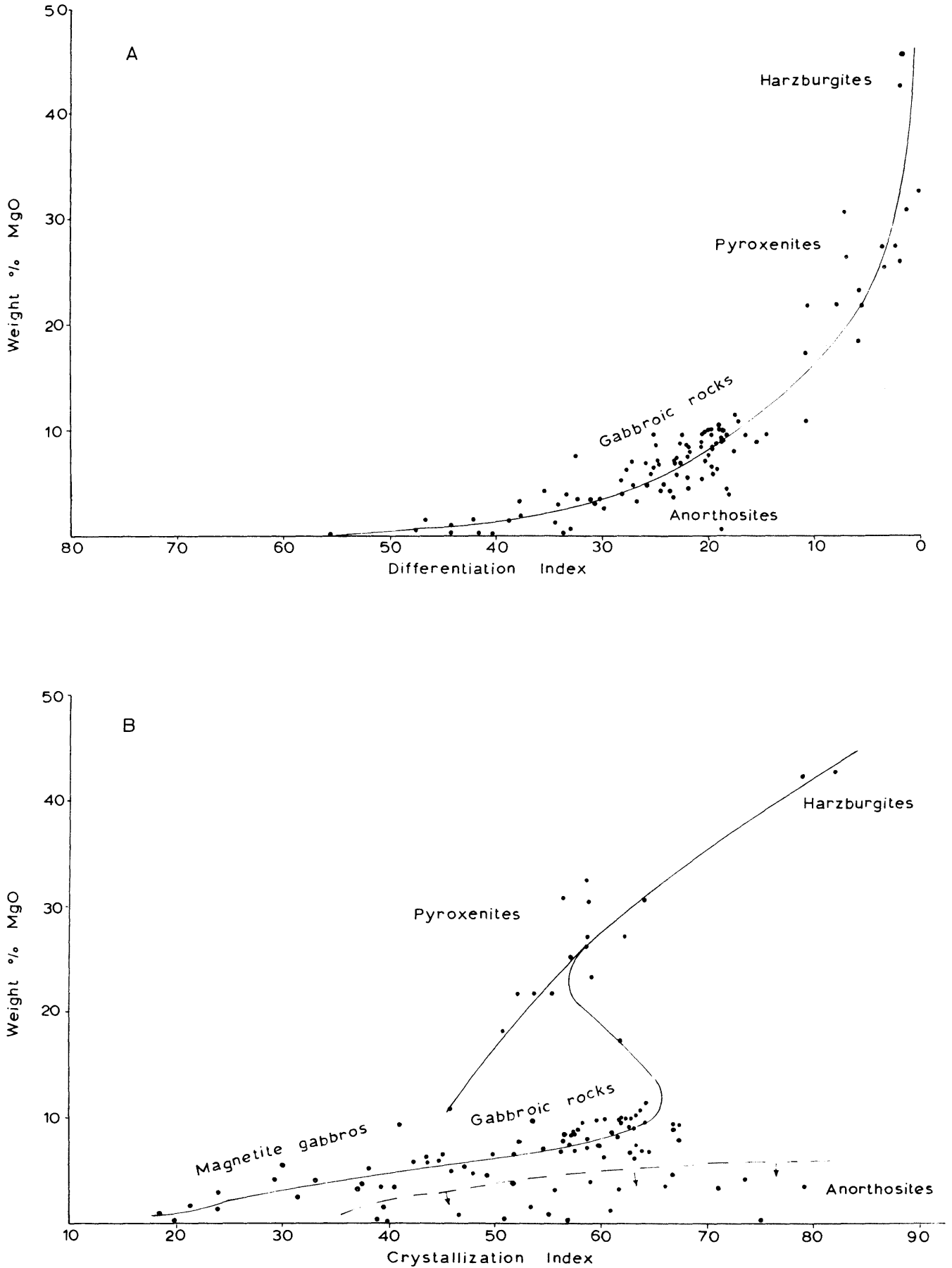


FIG. 74. PLOT OF DI AND CI AGAINST WEIGHT % MgO

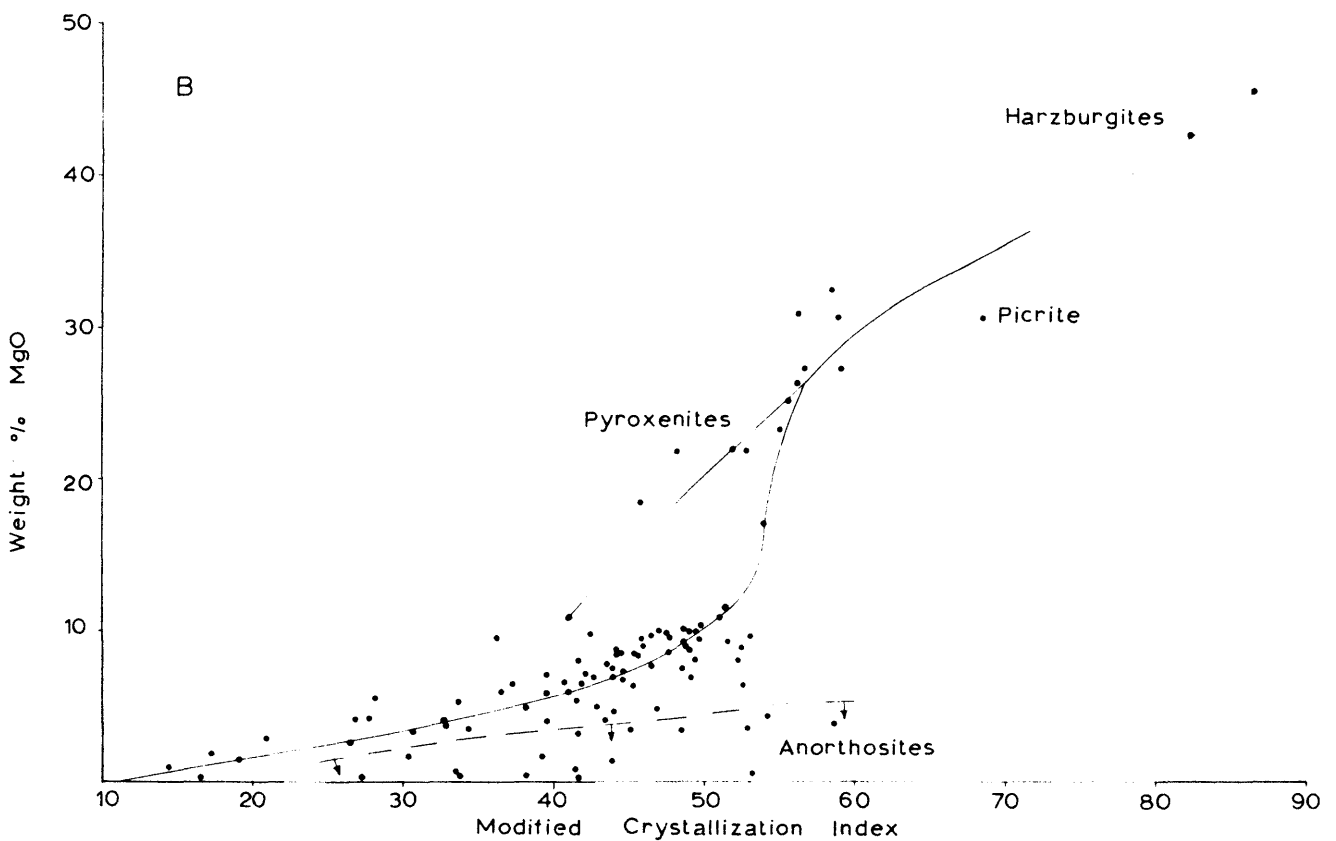
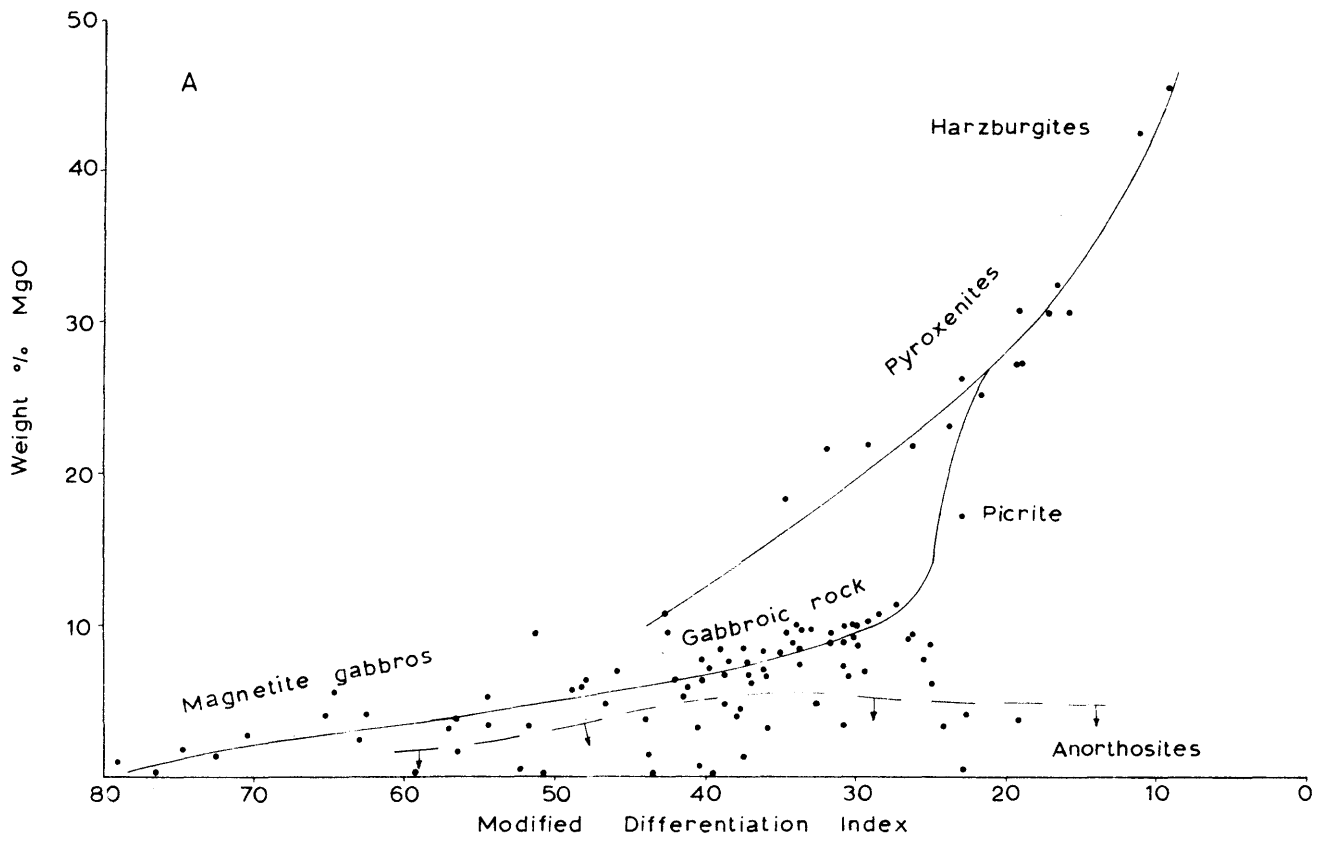


FIG. 75. PLOT OF MDI AND MCI AGAINST WEIGHT % MgO

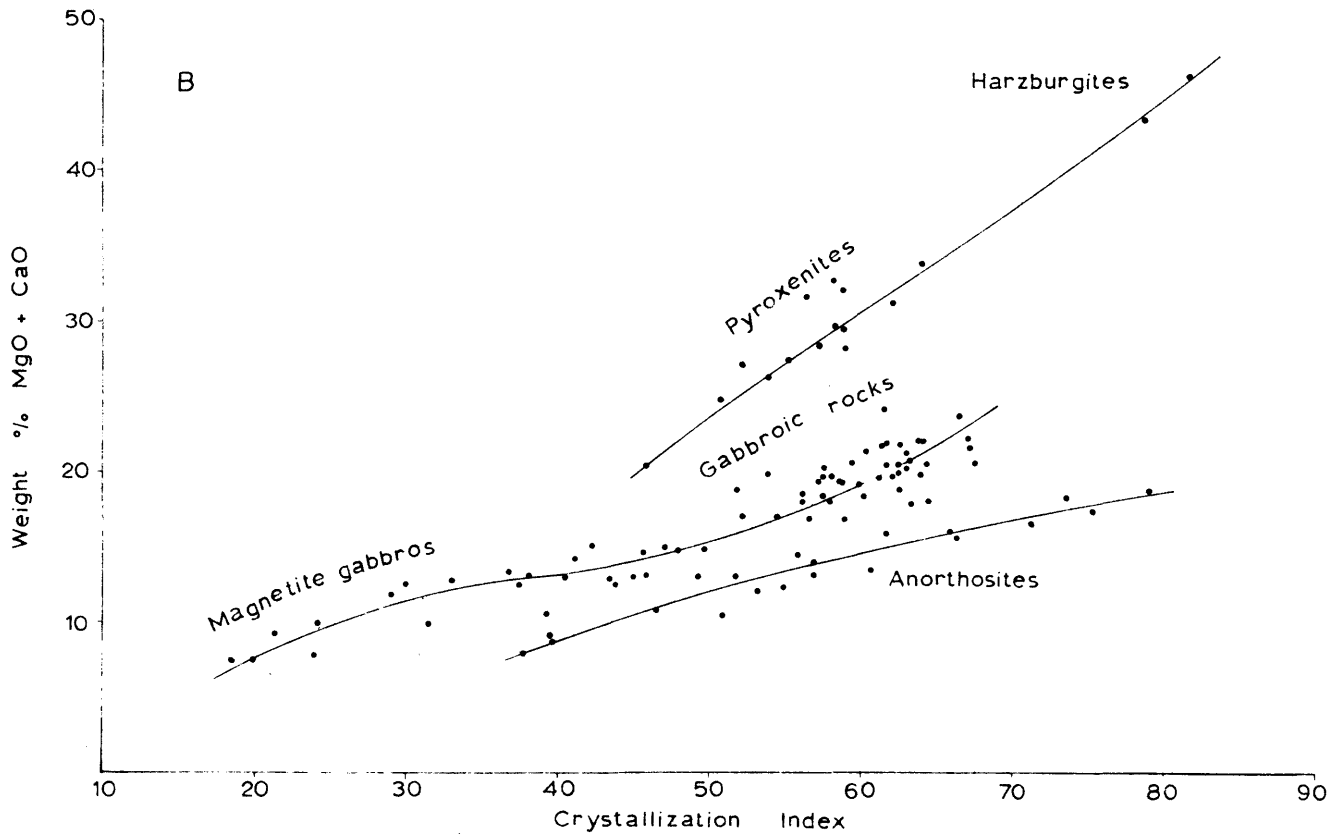
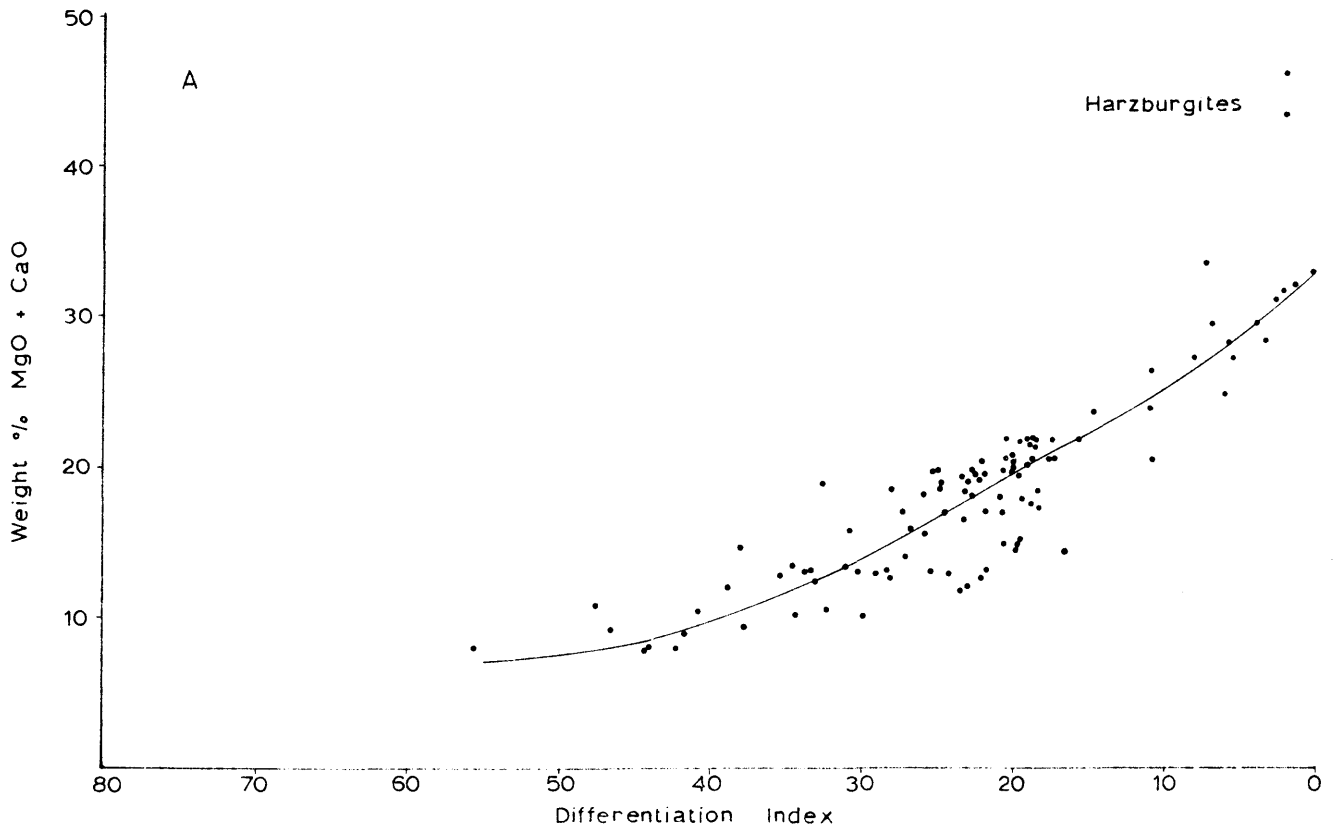


FIG 76. PLOT OF DI AND CI AGAINST WEIGHT % MgO + CaO

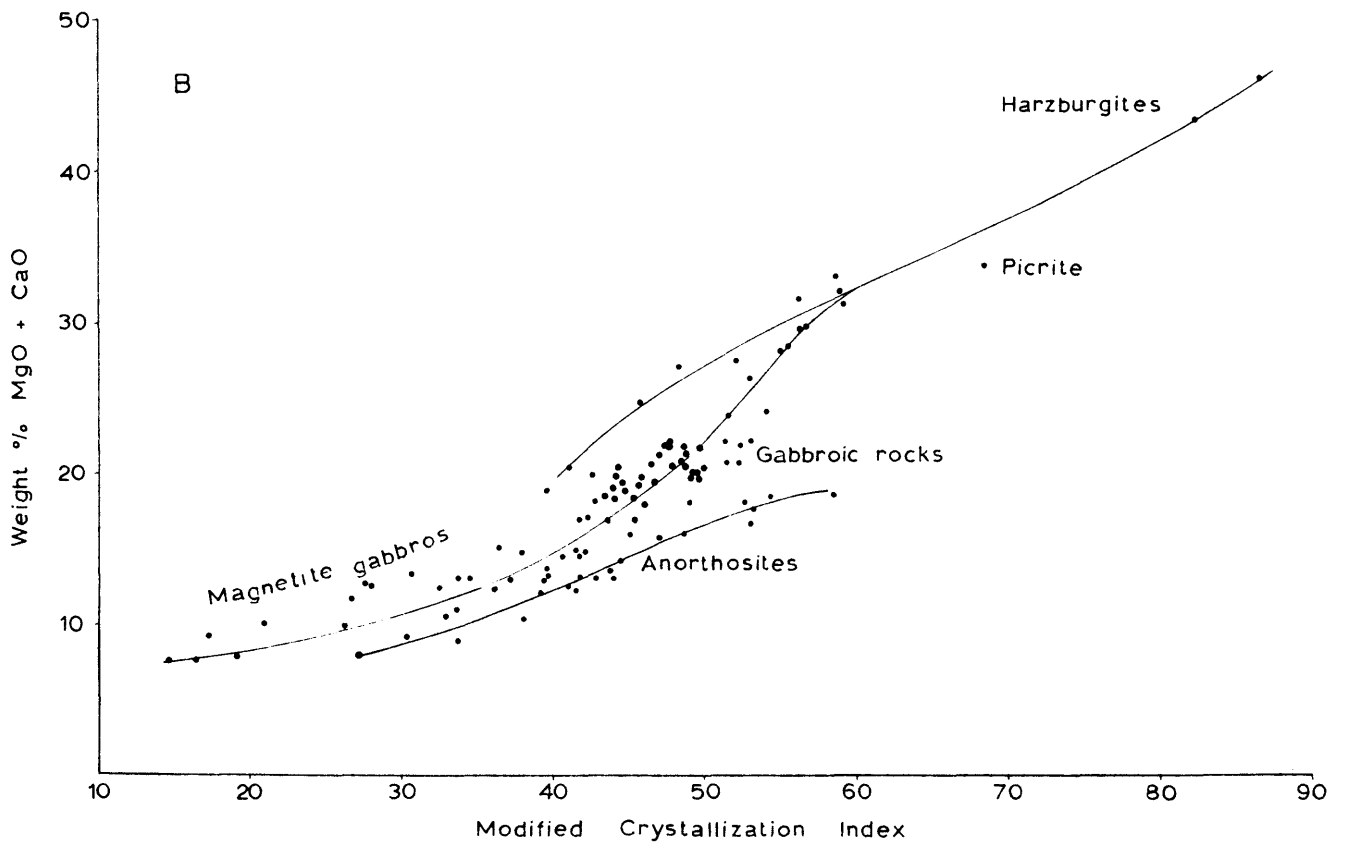
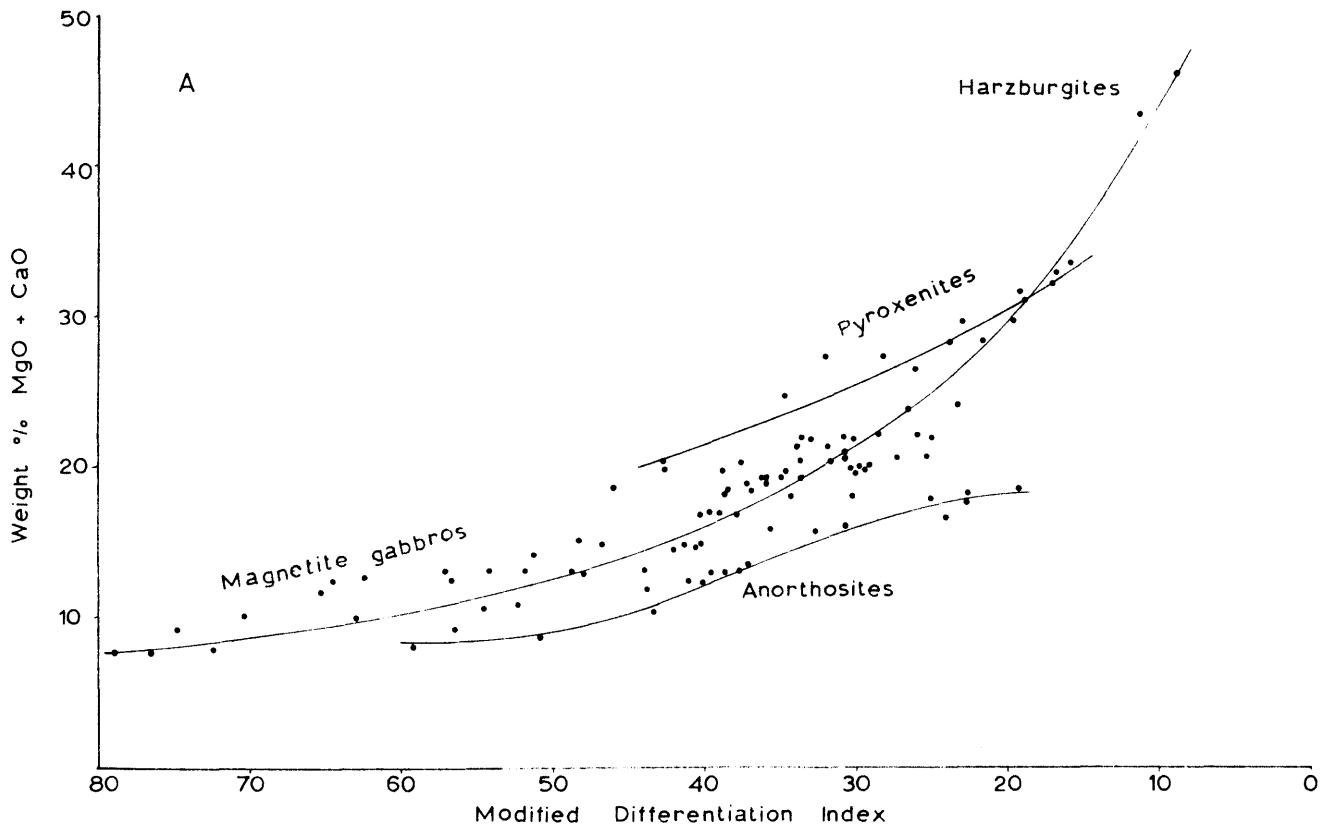


FIG. 77. PLOT OF MDI AND MCI AGAINST WEIGHT % MgO + CaO