

## VIII. THE CAUSE OF THE DIVERSITY OF THE ROCK TYPES IN THE LAYERED SEQUENCE

It is beyond the scope of this treatise to review in detail the various hypotheses according to which the rock types in the Layered Sequence of the Bushveld Complex could have originated, and only those mechanisms which are considered to be separately or jointly responsible for the diversity of rocks will be summarized briefly below.

### 1. Convection currents

Wager and Deer (1939, p. 262-266) found ample evidence to suggest significant movement of the magma during solidification and differentiation of the Skaergaard Intrusion. From this evidence they concluded (p. 267-270) that cooling and partial crystallization of the magma took place at the top and walls of the intrusion. This crystal-laden magma was heavier than the rest and would sink to the bottom to give rise to convective circulation.

This hypothesis was further elaborated upon by Wager and Brown (1968, p. 210-227) and they suggest the existence of two types of currents in the Skaergaard Intrusion, namely, a fast turbulent current and a considerably slower current with a laminar flow. The continuous slow currents gave rise to homogeneous cumulates and were periodically interrupted by high velocity currents which were heavily laden with crystals and which gave rise to gravity-stratified layers. Alternation of gravity-stratified layers and homogeneous cumulates gives rise to the rhythmic layering as observed in the Skaergaard Intrusion.

Hess (1960, p. 148-149) also favours convective overturn as a mechanism whereby rhythmic layering can be produced, but points out that there is no evidence for a regular convection-cell system in the Stillwater and Bushveld Complexes in contrast to the Skaergaard Intrusion.

On the grounds of detailed investigations of the textures in the cumulates of the Ultramafic Zone of the Stillwater Complex, Jackson (1961, p. 83-85) rejected convection currents as being the means by which the rhythmically layered sequence in this zone originated. He postulated a theory of crystallization of a stagnant layer of magma at the bottom of the chamber, and variable depth convection to account for the repetitive stratigraphy in the Ultramafic Zone (p. 96-99) and recently (1970, p. 403-419) expanded his hypothesis to

account for cyclic units in the basal zones of other layered intrusions. He is, however, of the opinion (1961, p. 99) that, as the crystal pile above the Ultramafic Zone in the Stillwater Complex thickened and the magma temperatures decreased, crystallization at the top of the intrusion became increasingly more important and would favour continuous convection.

Whether cyclic units of the type described by Jackson are developed in the upper two zones of the Bushveld Complex, seems, at our present knowledge, doubtful, although a more detailed study especially on the rocks of the Main Zone is necessary before this possibility can be excluded. Jackson (1971, p. 420) maintains that there is a general tendency for the cyclic units to decrease in thickness with height in the layered intrusion, and as mentioned above, he is of the opinion that conditions for continuous convection are favoured as the depth of the magma chamber decreases.

It was concluded from modal analyses that continuous bottom crystallization took place during formation of the relatively homogeneous rocks of the Main Zone. Such conditions would prevail during constant, slow convection, a process by which the homogeneous rocks of the Stillwater Intrusion originated (Wager and Brown, 1968, p. 216-217). It is not implied hereby that crystallization started at the top of the intrusion, but that slow convection resulted in a uniform decrease in the temperature of the magma, i. e. , the adiabatic gradient was maintained for a long period (Jackson, 1961, p. 94, Fig. 91).

## 2. Intermittent injection of magma

Hess (1960, p. 154-156) and Jackson (1961, p. 96) are of the opinion that large layered intrusions were emplaced as one surge of magma and that the layering is accounted for by an internal mechanism which controlled the rate of sedimentation of crystals on the floor.

Lombaard (1934, p. 32) proposed a mechanism of intermittent injection of pre-differentiated magma and settling of crystals from each flow to account for the layering of the Bushveld Complex. On the grounds of intrusive relationships between various rock units of the Layered Sequence in the western part of the Bushveld Complex, Coertze, (1970, p. 18-19) came to a similar conclusion and is of the opinion that differential melting of the mantle may be important in generating successive magmas of different composition.

This mechanism has found little support among students of layered intrusions, mainly because it necessitates an elusive, deep-seated, pre-intrusive

differentiation mechanism (Turner and Verhoogen, 1960, p. 300).

Cooper (1936, p. 44-45) postulated repeated injections of original undifferentiated magma to account for the repetitive stratigraphy in the Bay of Islands Complex. Although such a mechanism is rejected by Hess (1960, p. 154) for the Bushveld Igneous Complex, he is of the opinion that the Merensky Reef indicates a quantitatively small addition of undifferentiated basaltic magma. Wager and Brown (1968, p. 353), on the other hand, consider the alternating cumulates of the lower two zones of the Bushveld Complex to have originated in a way similar to that proposed by Cooper for the Bay of Islands Complex.

To account for the disproportionately large amount of ultramafic rocks compared with the basaltic composition of the chilled margin of the MuskoX Intrusion, Irvine and Smith (1967, p. 48-49) proposed a mechanism of periodic influx of fresh, undifferentiated magma into the chamber, combined with extrusion of the old, partially differentiated magma to the surface as volcanic fissure eruptions. They are of the opinion that each cyclic unit reflects a major renewal of the composition of the magma brought about by a large influx of fresh liquid in place of that which had partially crystallized. The model proposed by Irvine and Smith for the MuskoX Intrusion is essentially the same as that suggested by Brown (1956, p. 44-49) for the cyclic units in the ultramafic complex of Rhum. Although there are no indications of contemporaneous volcanic activity at the surface during crystallization of the Layered Sequence of the Bushveld Complex, periodic injections of undifferentiated magma probably did take place.

Such an influx was postulated by the author (1970, p. 69) at the level of the Pyroxenite Marker in the Main Zone. Owing to the apparent absence of cyclic units or repetitive stratigraphy in the Subzone C of the Main Zone, apart from the reversal at the Pyroxenite Marker, it is possible to calculate the minimum amount of fresh, undifferentiated magma that was added to the magma chamber. When the new influx occurred, the magma of the Bushveld had differentiated to a point where cumulus phases crystallized which are similar in composition to those at the base of Subzone A of the Upper Zone. The differentiated liquid of the old magma (A) and the new influx of fresh magma (B) gave rise to the differentiates of the Upper Zone (C + D) by fractional crystallization.

If A is the thickness of the Layered Sequence below the Pyroxenite Marker, i. e., about 6000m, B is the repetition of the Layered Sequence from the Pyroxenite Marker to the base of Subzone A of the Upper Zone, i. e., about 700m, and

(C + D) is the total thickness of the Upper Zone (2200m) in which C is the result of fractional crystallization of A, and D the result of fractional crystallization of B, then it follows that  $A/B = C/D$  and that B + D is the minimum addition of fresh, undifferentiated magma, which according to this calculation amounts to about 930m of the intrusion or to about 10 per cent of the total volume of the Bushveld magma.

If the Merensky Reef also indicates, as is generally believed, the addition of fresh magma, then there is no reason why intermittent injections of fresh, undifferentiated magma did not take place during crystallization of the Basal and Critical Zones. Such a process cannot be excluded as being responsible for the repetitive stratigraphy in these zones.

It may also be concluded that these intermittent additions were partially responsible for the lateral extension of the magma chamber during crystallization, probably in conjunction with Hess's (1960, p. 154) hypothesis that the initial magma chamber was deeper and of smaller extent and that "either gradually or spasmodically the magma chamber extended itself horizontally and diminished in thickness so that the 'sea' of magma transgressed over its 'shore lines' bringing stratigraphically higher and higher horizons in contact with the floor as it progressed farther from the limits of the original magma 'basin'".

### 3. Effects of pressure and oxygen fugacity

Experimental studies at different oxygen fugacities on silicate systems which are related to basaltic rocks have revealed important information on the differentiation paths with fractional crystallization and the conditions necessary to crystallize certain phases from the magma.

The effect of oxygen pressure on the crystallization and differentiation of basaltic magma was studied by Osborn (1959, and 1962), Roeder and Osborn (1966) and Hamilton and Anderson (1968). They came to the conclusion that under high constant  $pO_2$  conditions, magnetite crystallizes from a basaltic magma, whereas at lower  $pO_2$  crystallization of silicates (olivine) would be favoured and cause enrichment of iron in the liquid.

Ulmer (1969) examined systems which contain spinel and came to similar conclusions, namely, that the oxygen fugacity in the magma is an important control in the precipitation of spinel, and that fluctuations of  $fO_2$  may result in cyclic repetition of layers of chromite and silicates. He found that (p. 129) "spinel crystals would be produced at relatively high oxygen fugacities and silicate

crystals would be produced at comparatively lower oxygen fugacities". Cameron and Desborough (1969, p. 38-39) and Cameron (1970, p. 55) who investigated the chromite of the Bushveld Complex also suggested that cyclic recurrence of chromite as a cumulus phase was controlled by variations in oxygen fugacity.

Crystallization of the Bushveld magma during formation of the Main Zone probably took place at low oxygen pressure resulting in the enrichment of iron in the residual magma. Extreme iron enrichment and a slight rise in  $fO_2$  probably caused titanomagnetite to crystallize together with silicates. Periodic increases in the  $fO_2$  (or  $pO_2$ ) would have enhanced the crystallization of titanomagnetite, the concentration of which to form seams was probably assisted by its faster settling velocity than the other precipitating silicates.

Irvine (1970, Fig. 16 and p. 466) has shown the pronounced effect of total pressure on the liquidus boundaries in a modelled clinopyroxene-plagioclase-olivine-quartz system. He points out that if liquid crystallizing at a pressure of 4, 5 kilobar along the plagioclase-clinopyroxene-orthopyroxene cotectic line is moved to a lower pressure environment it would become isolated in the stability field of plagioclase. He therefore envisaged that the magma, while generally crystallizing near its floor at the relatively high pressures, may, under conditions of convection, also have crystallized periodically near its roof with the result that only plagioclase crystallized, giving rise to anorthosites.

Hess (1961, p. 86) explained the origin of thick sheets of anorthosite in the Stillwater Complex by means of convective overturn. He is of the opinion that pyroxene would settle from a convection current at a faster rate than the plagioclase, causing the magma near the floor to be enriched in the latter. The next convection current would displace the plagioclase-enriched liquid upwards into the central portion of the magma chamber where it would mix with hotter undifferentiated magma which would cause the resorption of the suspended plagioclase crystals. In this way, Hess envisages a mechanism whereby a portion of the magma near the centre of the chamber becomes progressively enriched in the constituents of plagioclase. The composition of this liquid would be in the stability field of plagioclase and plagioclase alone would crystallize to form anorthosite.

Wager and Brown (1968, p. 342) proposed an alternative hypothesis to explain the thick anorthosites in the Stillwater Complex. They suggest that slightly undercooled magma moved downwards during convective overturn and crystallized

both plagioclase and pyroxene near the bottom of the intrusion where pressures were higher. If the velocity of the currents was high enough, only a few plagioclase crystals would settle out, the remainder being carried up by the current (convection-cell) to levels of lower pressure where they may have melted. The magma would become enriched in the plagioclase component and when this magma started to crystallize, only feldspar would settle from it for a long period.

Although no opinion can be expressed as to which of the three hypotheses above would seem most likely for the origin of anorthosite in the Bushveld Complex, it must be pointed out that all three of them rely on a convection mechanism in the magma chamber to produce these monomineralic rocks.