Canadian Mineralogist
Vol. 17, pp. 233-256 (1979)

A REVIEW OF SOME RECENT CONCEPTS OF THE BUSHVELD COMPLEX, WITH PARTICULAR REFERENCE TO SULFIDE MINERALIZATION

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ABSTRACT

With resources of close to 22 x 10^6 t of Ni metal, the layered mafic rocks of the Bushveld Complex can be considered the largest repository of low grade, disseminated Ni-sulfide deposits in the world. These vast resources are contained in several mineralized layers of which the Merensky Reef, the UG2 chromitite layer and the Platreef are the most important. The four mafic to ultramafic compartments which constitute the layered sequence of the Bushveld Complex were emplaced 2095±25 m.y. ago, essentially into a relatively undeformed sedimentary cover of the Kaapvaal craton. The loci of emplacement as well as the present-day configuration of the various intrusions are controlled largely by the structural features of the Kaapvaal craton. Evidence is presented in support of a bimodal character of the magmas that gave rise to the layered sequence of the complex. The initial magma is considered to be ultramafic and to have been followed by several heaves of magma of tholeiitic character. These parental magmas of the complex were apparently poor in sulfur so that incorporation in the magma of S, CO_2 and H_2O liberated during metamorphic reactions resulted in mineralized layers near the floor of the intrusion. The hypotheses to account for sulfide concentration are reviewed. Compaction and ascending intercumulus liquids, which constitute more than 20% of a pile of cumulus crystals, are important processes in the formation of adcumulates and the different types of mafic pegmatites. These liquids must also have had an effect, firstly, on the crystallization of "isolated" batches of magma near the floor of the chamber to give rise to the Merensky Reef type of mineralization and, secondly, in the concentration of platinum-group elements in chromitite layers of the upper critical zone.

SOMMAIRE

Vu ses réserves de 22 x 10^6t de Ni, on peut considérer le complexe stratiforme du Bushveld comme le plus vaste entrepôt de gisements de sulfures de nickel disséminés du monde. Ces ressources se trouvent localisées à plusieurs niveaux minéralisés, dont les bancs Merensky et Platreef et la chromitite UG2 sont les plus importants. Les quatre chambres de roches mafiques à ultramafiques qui constituent le complexe ont été mises en place il y a 2095(25) m.a., presque entièrement dans la couverture sédimentaire peu déformée du craton du Kaapvaal, dont les structures gouvernent l'emplacement ainsi que la forme actuelle des différentes intrusions. Deux magmas ont produit la séquence stratifiée du complexe; le premier, à caractère ultramafique, a été suivi par plusieurs épisodes de magmatisme tholéitique. Ces magmas parentaux, pauvres en soufre, auraient, par incorporation de S, CO_2 et H_2O libérés lors de réactions métamorphiques, donné les horizons minéralisés situés à la base du complexe. On revoit les hypothèses visant à expliquer les concentrations de sulfures; la compaction de cumulats et la migration ascendante de liquides résiduels intercumulus (qui constituaient plus de 20% d'un empilement de cristaux cumulus) sont des processus importants de la formation des adcumulats et des différents types de pegmatites mafiques. Ces mêmes liquides ont aussi influencé (1) la cristallisation des poches isolées de magma près de la base de la chambre, produisant ainsi le type de minéralisation du banc Merensky et (2) la concentration des éléments du groupe du platine dans les niveaux de chromitite de la zone critique supérieure.

(Traduit par la Rédaction)

INTRODUCTION

It is well known that the layered mafic rocks of the Bushveld complex house the world's largest reserves of the platinum-group metals, chromium and vanadium (Willemse 1969, von Gruenewaldt 1977), estimated to be about 86, 83 and 64%, respectively, by van Rensburg & Pretorius (1977). These authors consider the world's reserves of nickel to be approximately 50 x 10^6 t and South Africa's share in these to be 5 x 10^6 t, contained in the Merensky Reef, which is presently being mined at several localities. If, however, the estimated tonnages of nickel metal contained in the UG2 chromitite layer and the Platreef (Table 1) are added to this figure, total nickel resources in the Bushveld Complex amount to a substantial 22 x 10^6 t, making the Bushveld Complex one of the largest repositories of low-grade disseminated nickel sulfide ores in the world. Nowhere in the complex does nickel occur in sufficiently large quantities to be exploited on its own; the contribution of the associated platinum-group metals, Au and Cu make these large disseminated sulfide deposits economically viable.

This review is confined essentially to the latest thoughts and developments concerning the environment and mode of emplacement of the complex, the composition of the magmas that gave rise to the layered mafic rocks of the complex and the magmatic sulfide concentrations contained within them. A basic knowledge of the various lithologies that comprise the Bushveld Complex is assumed. For this information, the reader is referred to the many review-type papers (Wager & Brown 1968, Willemse 1969, Hunter 1976, Vermaak & Lee 1978, Hunter & Hamilton 1978). Although in most of these reviews an attempt was made to cover all aspects and components of the Bushveld Complex, the approach differs from review to review; this is understandable when the large amount of literature on the Bushveld Complex is considered. Well over 800 articles, theses and research reports are listed in two recent bibliographies (Molyneux *et al.* 1976, Knowles 1978).

TABLE 1. PROPORTIONS AND RESOURCES OF PGE + Au, Ni AND Cu IN MINERALIZED LAYERS OF THE BUSHVELD COMPLEX[x]

	MERENSKY REEF	UG2 CHROMITITE LAYER	PLATREEF	TOTAL
PGE + Au				
Proportions[xx]				
Pt	59	41	42	
Pd	25	34	46	
Ru	8	12	4	
Rh	3	9	3	
Ir	1	1.9	0.8	
Os	0.8	1.7	0.6	
Au	3.2	0.4	3.4	
Recovery grade gm/t	5.5	6.0	3.0	
Resources kg x 10^6	18.15	32.50	12.24	62.89
Ni				
Content %	0.18	variable	variable	
Recovery grade kg/t	1.3	0.7	3.6	
Resources t x 10^6	4.3	3.8	14.7	22.80
Cu				
Content %	0.11	low	variable	
Recovery grade kg/t	0.8	-	1.8	
Resources t x 10^6	2.65	-	7.30	9.95

[x]after von Gruenewaldt (1977); [xx]values taken from Cousins & Vermaak (1976).

The Setting and Shape of the Complex

Regional tectonic setting

The assemblage of well-exposed Precambrian rocks on the Kaapvaal craton displays a fairly continuous record of the evolution of the crust from the early Archean, some 3600 m.y. ago, to late Waterberg times, ±1250 m.y. (Hunter 1974a, b). Detailed studies on the many rock units that comprise the Kaapvaal craton have shown that the evolution of the crust during this 2300 m.y. period was dominated by east–northeast and north–northwest structural trends and that these structures are also important controls on the present configuration of the lithologies preserved on the craton. The east–northeast direction is especially well-developed in the eastern part of the Kaapvaal craton and is manifest in the prominent Murchison lineament (Fig. 1), a site of repeated tectonic reactivation from Archean to late Waterberg times, as well as in several other linear east–northeasterly-trending structures (Button 1973, Hunter 1975). The north–northwesterly trend is represented by the so-called Amsterdam lineament and the Kraaipan trend, as well as a broad north–northwesterly-trending arch that is the location of a number of domical basement windows. Termed "Vryburg arch" by Hunter (1975), this consists of a number of positive, dome-like features, the magnitude of which varied at different times during the deposition of the sedimentary successions that overlie the basement. At other times, however, these positive areas also coincided with the axes of maximum deposition of sedimentary basins (Brock & Pretorius 1964).

According to Hunter (1975), the development of the Kaapvaal craton, rigid enough to sustain and preserve ensialic basins, took place about 3000 m.y. ago. On this crust a series of distinct depositional basins developed, the basin axes and northern flanks of which migrated across the craton from southeast to northwest (Anhaeusser 1973, Hunter 1974b). In these basins the sedimentary and volcanic rocks of, in ascending order, the Pongola, Dominium Reef–Witwatersrand, Ventersdorp, Transvaal and Waterberg Supergroups accumulated. Sedimentological studies suggest that, in general, the southern margins of these basins reflect gradual subsidence in contrast to the more active northern flanks, and that transport directions were, except for local deviations, mostly from the northern and northeastern sides of the basins (Brock & Pretorius 1964, de Villiers 1967, Visser 1969, Button 1973, 1975).

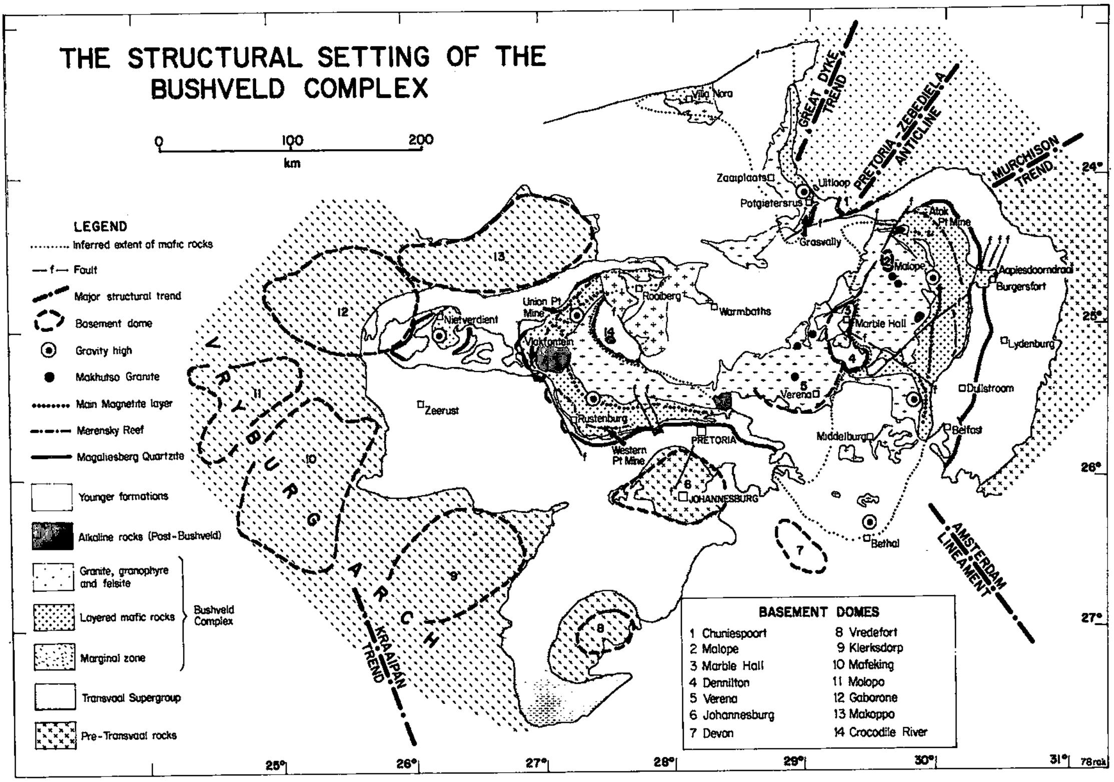

FIG. 1. The structural setting of the Bushveld Complex.

An explanation for the development and the migration of the sedimentary basins with the associated volcanic activity was put forward by Pretorius (1965), who considers the basins to have developed under tensional conditions in an environment where vertical tectonics prevailed. The nature and type of sedimentary and volcanic rocks are considered to reflect the variations in the energy associated with periods of uplift and succeeding quiescence.

Hunter (1974b, 1975) has attempted to relate the evolutionary history of the sedimentary basins in terms of other events that occurred in the Kaapvaal crustal plate subsequent to its stabilization some 3000 m.y. ago. He argued (1974b) that periods of magmatic activity, whether they involved large-scale emplacement of granite or relatively smaller-scale mafic plutonism and volcanism, followed regressive sedimentary patterns of basin infilling. This, as well as other features of the Kaapvaal crustal plate, implies, according to Hunter, a connection between events in the mantle, crust and depositional basins. He developed the concept that both the Usushwana Complex and the Great Dyke were emplaced during periods of inflation caused by subcrustal thermal expansion. During such times the lithosphere would have been in a state of tension and conditions would have prevailed favoring the formation of dykes. In contrast, the Bushveld Complex was intruded at the termination of Transvaal sedimentation, at a time of maximum continental deflation, when compressional conditions resulting from subsidence would have dominated the upper crust. Although regional stress conditions at the termination of Transvaal times favored the formations of sill-like intrusions such as the Bushveld Complex and its associated sheets of diabase in the floor rocks of the complex, this does not offer a suitable explanation for the siting of the complex, which is limited to an area in the northeastern part of a basin that probably extended over the whole Kaapvaal craton.

Earlier contentions (Daly 1928, Hall 1932) that the Bushveld Complex was a lopolith had to be modified when more detailed mapping revealed that the floor contact was in many localities transgressive. Consequently, several overlapping, essentially funnel-shapped intrusions were proposed to account for the form of the complex (Wilson 1956, Wager & Brown 1957, Willemse 1959, 1964). However, when interpretations of gravity data (Cousins 1959, Smith *et al.* 1962) revealed that the mafic rocks do not extend beneath the centre of the complex, the more modern concept developed, according to which the complex consists of a number of essentially separate and only partly overlapping intrusions (Willemse 1969, Hunter 1975, 1976; Vermaak 1976b, Vermaak & Lee 1978, Sharpe & Snyman 1978).

Apart from a small body at Nietverdient, north of Zeerust in the western Transvaal, the intrusions have what Hunter (1975) termed a "cruciform" outline. They outcrop as four lobes: the western lobe, the eastern lobe, a southeastern lobe that is continuous with the eastern lobe but largely concealed by a younger Paleozoic cover, and a nothern lobe. In this definition, the four lobes are arranged approximately symmetrically about two perpendicular axes, each 350 km long, aligned east–northeast and north–northwest (Fig. 1). The east–northeast axis coincides with the depositional axis of the Transvaal basin (Visser 1969, Button 1973) which in turn is oriented parallel and in close proximity to several other linear, east–northeasterly-trending structures, amongst them the Murchison lineament. On the other hand, the north–northwest axis corresponds, according to Hunter (1975), to a structurally controlled depression on the northeastern flank of the Vryburg arch. Although Bushveld rocks are today preserved in this depression there is reason to believe that both the areas of the northern and the southeastern lobes were structural highs during or shortly before the time of emplacement.

Hunter (1975) assumed the Vryburg arch to have originated as a result of the culmination of two or more fold axes of different wavelength and amplitude. Such a broad arch would be flanked by two major synclines, the northeastern one of which would correspond to the basin of sedimentation of the Transvaal Supergroup in the Transvaal whereas the southwestern one would represent the northern Cape depositional basin of the same supergroup. According to Hunter the broad locus of emplacement of the Bushveld Complex is sited within the Transvaal depositional basin close to the interface between dominantly domical structures and essentially linear structures.

Structural relationships

Roberts (1970) has shown that sills in large depositional basins such as the Transvaal basin ideally would be emplaced close to the stratigraphic level occupying the chord position, *i.e.*, a horizontal to near-horizontal surface. From this it follows that any transgressions of a sill of large horizontal dimensions would reflect irregularities in the attitude of the bedding of the intruded sequence. This is diagrammatically illustrated in Figure 2 from which it is seen that a downward transgression into lower stratigraphic levels implies the existence of an upwarp at the time of emplacement, whereas a transgression upward in the sequence implies the existence of a downwarp in the basin, assuming constant thickness of cover.

With the aid of this model, it becomes possible to explain various structural relationships in the Bushveld Complex (von Gruenewaldt & Sharpe *in prep.*); these are too numerous to elaborate upon here. A few of these transgressive features have a bearing on the present-day configuration of the lobes and on the discussion of the tectonic setting as outlined above; they will be briefly discussed here.

Both the northern and southeastern lobes are characterized by pronounced transgressions. In the southeast the layered mafic rocks of the Bushveld transgress, over a distance of 100 km, from a level above the Dullstroom volcanic rocks at the top of the Pretoria Group over the entire group to rest 200 m above the Transvaal dolomite at Bethal (Buchnan 1975). The transgression in the northern lobe is even more pronounced in that the Bushveld rocks transgress from above the Magaliesberg Quartzite Formation into Archean granite over a distance of less than 20 km (van der Merwe 1976). Both these transgressions necessitate the exis-

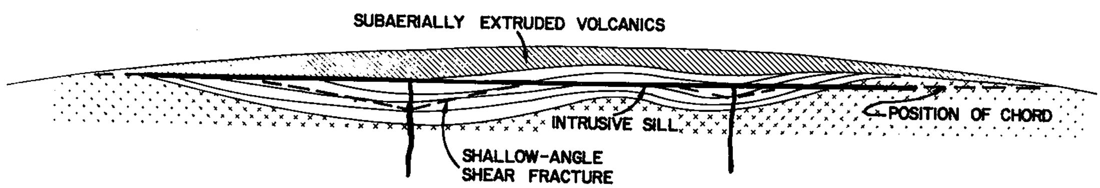

FIG. 2. Relation of stratigraphic succession to a sill of large horizontal dimensions emplaced into a gently warped basin at or close to the position of the chord.

tence of structurally controlled anticlines in the area during emplacement of the complex and *not* synclines as postulated by Hunter (1975). Such anticlines within the Transvaal depositional basin were conceivably caused by compressional stress during subsidence of the basin.

In the western Transvaal, the Bushveld Complex was emplaced semiconcordantly above the Magaliesberg Quartzite Formation, except in an area west of the Pilanesberg where it transgresses these quartzites and rests on underlying shales (Vermaak 1970, Liebenberg 1970). At Nietverdient, the Bushveld was emplaced at a similar level as in the western lobe and it is therefore evident that no anticline existed at the loci of emplacement of this intrusion. The present-day limited extent of this occurrence, with only representatives of the lower half of the critical zone and the lower zone remaining, is the result of subsequent upwarping of the Vryburg arch. Of interest is the extensive metamorphic aureole of the Nietverdient occurrence which affects the Malmani Dolomite up to 60 km south of the intrusion (Hammerbeck 1970, Klop 1978). This vast metamorphic aureole not only indicates that the mafic rocks extended for a considerable distance to the south, but also suggests that these lithologies substantially transgressed their floor because the thickness of the Pretoria succession below the present-day floor contact is of the order of 3000 m in this area (Klop 1978). It is of interest to note that Martini (1976) recognized the presence of a paleoridge in the dolomite at the same position where this transgression is postulated. The evidence thus suggests only limited and localized upwarps along the eastern flank of the Vryburg arch after deposition of the Transvaal sequence but prior to emplacement of the Bushveld Complex.

Several modeled profiles through the eastern Bushveld Complex based on available and new gravimetric data as well as airborne magnetometric data show that the mafic rocks laterally penetrate the dome-like features at Marble Hall and Dennilton situated along the western flank of the eastern lobe. Two sections, based on the gravity models of Hattingh (1977) and of Molyneux & Klinkert (1978), are reproduced here as Figures 3a and 3b. This relationship, together with the pronounced thinning of the Transvaal strata over the Marble Hall dome (de Waal 1970) in proximity of the depositional axis of the Transvaal basin, points to the presence of a relatively inert area during subsidence of the Transvaal basin that underwent doming prior to emplacement of the complex. Further evidence indicates that the western flank of the eastern Bushveld was tectonically active during emplacement of the complex: (1) the absence of the delicate layering typical of the gently dipping portions of the complex along its eastern flank (Hunter 1976), and (2) some deformation features described by Marlow & van der Merwe (1977) from the Malope area.

In an alternative interpretation of his gravity data of the area southeast of the Dennilton dome, Hattingh (1977) postulated the presence of another large, dome-like feature, centred approximately over Verena (Fig. 1). A surface

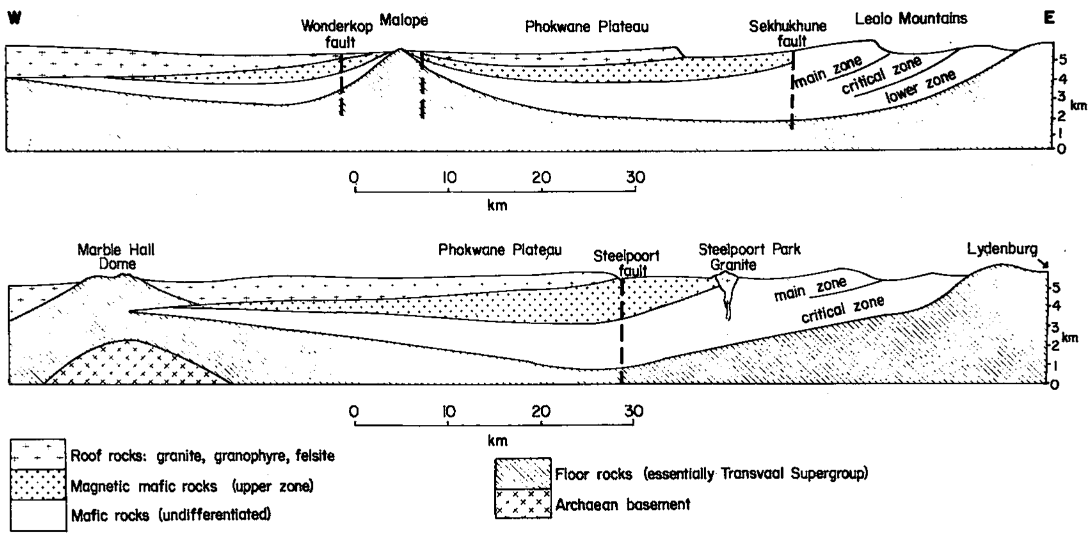

FIG. 3. Idealized sections through the eastern Bushveld based on the geophysical interpretations of Hattingh (1977) and Molyneux & Klinkert (1978).

manifestation of this dome could be the curved nature of the Waterberg basin along the southern flank of this anticline.

The above evidence suggests the existence, beginning in early Transvaal times, of a broad anticlinal warp, termed the Pretoria–Zebediela anticline, along the western flank of the eastern Bushveld. The warp consists of a number of dome-like features, which, from south to north, includes the Halfway House dome, the postulated Verena dome, Dennilton dome, Marble Hall fragment, the Malope dome and the Chuniespoort arch. This north–northeast- to northeast-trending anticline defines the western flank of the eastern Bushveld Complex and is roughly parallel to the three north–northeast-trending gravity highs (Fig. 1) that have been interpreted as a possible dyke-like feeder to the eastern and southeastern sectors of the Bushveld Complex (Cousins 1959). Reactivation of the Pretoria–Zebediela anticline in post-Bushveld times is indicated by the emplacement some 1650 m.y. ago of a number of diapiric granite intrusions, referred to as the Makhutso Granite (de Bruiyn & Rhodes 1975, Marlow 1976), along the eastern flank of the anticline (Fig. 1). These features strongly suggest that the north–northeast grain predominated in the eastern part of the Transvaal basin during emplacement of the Bushveld Complex. This trend parallels the deep abyssal fracture of Cousins (1959) along which the majority of layered intrusions in southern Africa are aligned; it is also widely considered as having influenced the siting of the Bushveld Complex (Hall 1932, Cousins 1959, Vermaak 1976a, Vermaak & Lee 1978).

It is the *subsequent* upwelling along the broad Vryburg arch and the concomitant formation of a syncline along its northeastern flank in conjunction with reactivation along the linear east–northeast Murchison trend that largely controlled the present-day configuration of mafic rocks. This is also borne out by the considerably younger age of 1250–1400 m.y. of the Pilanesberg and related alkaline intrusions (Ferguson 1973); the majority of these were emplaced along the structural monocline on the eastern flank of the Vryburg arch, and contrast with an age of 2095 m.y. for the mafic rocks of the Bushveld Complex (Hamilton 1977).

Emplacement of the mafic rocks

As outlined in the preceding section, the north–northwest and east–northeast aligned lineaments and arches are considered largely responsible for the present-day configuration and the lobate outline of the mafic rocks of the Bushveld Complex. However, it is the deep, magma-tapping fractures and their alignment to which some importance must be attached when considering the tectonic setting of the complex. Based on this argument, the layered sequence of the complex should be seen in terms of seven shallow, cone-like intrusions, the feeders of which are postulated to coincide with the observed gravity highs in the Bushveld (Fig. 1). Of these seven intrusions (i) three are aligned along a north–northeast gravity high in the eastern complex, (ii) two are aligned along a north–northwest gravity high in the western complex, (iii) one is sited northwest of Potgietersrus at the intersection of the Amsterdam lineament, the Pietersburg lineament and possibly also the southern extension of the Great Dyke direction (van der Merwe 1976), and (iv) one is situated at Nietverdient where Biesheuvel (1970) indicated the presence of a feeder close to the position now occupied by the Goudini alkaline complex.

A model for the emplacement of the mafic rocks in the Transvaal sequence is provided by Sharpe & Snyman (1978). They point out that extrusion of some 7 km of subaerial basalt and felsite onto the 7.7 km thick pile of submarine sediments of the Transvaal sequence resulted in the depression of the floor of the basin into a regime of maximal horizontal compression. This induced favorable conditions for the intrusion of a total of 2.5 km of diabase sills, which further assisted in the subsidence of the basin into a regime typical for shear failure. Emplacement of the Bushveld magma into this regime initiated shallow-angle shear fractures that extended upward into the sedimentary rock–diabase sandwich, tending to parallel the chord at its position below the subaerially extruded volcanic rocks. This resulted in a series of shallow cones, the upper and outer reaches of which overlapped in the vicinity of the chord position.

The Bushveld Magma

Earlier concepts

For many years the initial magma that gave rise to the layered sequence of the Bushveld Complex was considered to be essentially basaltic in composition (Hall 1932, Hess 1960, Wager & Brown 1968, Atkins 1969). This assumption was based on the composition of the undifferentiated sills of diabase in the floor of the complex and the fine-grained marginal rocks of the layered sequence. Experimentally determined crystallization sequences from two fine-grained marginal rocks, one corresponding to a high-alumina basalt and the other to an olivine tholeiite, as well as theoretically deduced crystallization sequences from their respective chemical composition, have led Tilley *et al.* (1968) and Irvine (1970a) to doubt the validity of these rocks as a measure of the composition of the parental basalt.

Evidence for an initial high-magnesium magma

In the eastern Bushveld, the Hendriksplaas norite, characterized by numerous highly metamorphosed xenoliths of sedimentary origin, is usually developed along the floor-contact of the layered sequence where it constitutes part of the marginal zone. In the vicinity of Burgersfort, however, this norite, together with some of the underlying quartzite, is separated from the base of the intrusion by several hundred metres of an alternating succession of pyroxenite and harzburgite. This, together with the semidetached nature of the Aapiesdoorndraai peridotite mass and several other separate peridotite bodies in the floor of the intrusion, led Liebenberg (1964) and Willemse (1969) to suggest the presence of a magma of peridotitic composition in early Bushveld times. Subsequently Gijbels *et al.* (1974) proposed, on the basis of a partitioning model for platinum-group elements between magma and cumulus minerals of the lower and critical zones, that the lower zone represents ⅔ crystallization of an early, magnesium-rich magma; this was followed by a second, much larger pulse of magma, which mixed with the remaining ⅓ of the first batch and from which the critical, main and upper zones formed by a process of fractional crystallization. The second magma was, according to the authors, enriched in chromium in order to precipitate chromite in layers shortly after its emplacement. The validity of their deductions was criticized by Cameron (1978), who emphasized that there is no indication of any break, either structural or compositional, between the lower zone and the critical zone in the eastern Bushveld and that it is virtually impossible to obtain pure mineral fractions for analyses at ppb levels because of the numerous tiny inclusions of sulfides and other minerals in the cumulus minerals. The lack of change in composition of cumulus bronzite and olivine throughout the great thickness of cumulates that constitute the lower zone and the lower half of the critical zone led Cameron (1978) to propose that both these zones crystallized from one batch of magma.

From available modal and mineralogical data Cameron calculated the weighted average MgO value for the upper, main, critical and lower zones of the eastern Bushveld Complex to be about 13%. He also determined the average Cr content of the eastern complex to be in excess of 1000 ppm, compared to 170 ppm for average basaltic rocks given by Turekian & Wedepohl (1961); he concluded from these figures that the initial Bushveld magma was probably olivine tholeiitic or picritic in composition, rather than normal tholeiitic basalt.

An evaluation of the bulk composition of the Bushveld magma based solely on a stratigraphic column of present-day exposures must be viewed with some reservations as there seems to be a considerable difference between the proportions of the four layered zones in section and in aerial extent. Interpretation of gravity data of the eastern Bushveld (Hattingh 1977, Molyneux & Klinkert 1978) shows a considerable westward thinning of the mafic rocks from a maximum outcrop position at present (Fig. 3). In both interpretations the distribution of the ultramafic rocks is restricted to such an extent that it is doubtful whether the lower two zones or considerable parts thereof are developed in areas overlain by roof rocks today (Fig. 3). This interpretation is to a large extent substantiated by field relations at Malope (Marlow & van der Merwe 1977) and along the southeastern flank of the Dennilton dome. In both these areas, rocks correlated with the upper part of the critical zone seem to be resting directly on the floor of the intrusion. Furthermore, interpretation of the aeromagnetic data indicate that about ⅓ of the mafic rocks concealed by the Bushveld granite is highly magnetic, *i.e.*, upper-zone type rocks (Molyneux & Klinkert 1978).

It is not only in the eastern lobe where upper- and main-zone type rocks predominate. A similar situation seems to prevail in the Bethal area (Buchanan 1975) where ultramafic rocks have only a very limited thickness except perhaps beneath the upper-zone rocks in the vicinity of the very pronounced gravity high to the northeast of Bethal. In the northern lobe a thick succession of ultramafic rocks seems to be restricted to a relatively small area in the vicinity of Potgietersrus, whereas rocks of the main and upper zones transgress those of the lower two zones to occupy an area several times that of the ultramafic rocks (van der Merwe 1976). Peculiar to this area are the ultramafic satellite bodies of massive bronzitite, some of which contain chromitite layers similar in composition to the LG3 and LG4 layers near the base of the critical zone in the western lobe.

Of considerable interest, however, is the huge body of ultramafic rocks at Grasvally, inasmuch as these are the most magnesian rocks (En_{95}, Fo_{88}) known from the Bushveld Complex. Associated chromitite layers have Cr/Fe ratios similar to those of the Great Dyke (de Villiers 1970). This mass of ultramafic rocks is considered to be upfaulted from lower levels in the cone-shaped intrusion (Barrett *et al.* 1978).

Available evidence therefore suggests that the upper- and main-zone type rocks, which have an average MgO content close to that of typical basalt (Cameron 1978) outweigh the ultramafic rocks of the critical and lower zones by a factor considerably greater than that which is obtained from present-day outcrops in the eastern Bushveld. The bulk composition of the layered mafic rocks should therefore be intermediate between that of olivine tholeiite and normal tholeiitic basalt, probably closer to the latter. Further evidence in support of an early Mg-rich magma is provided from recent mapping by M.R. Sharpe (Sharpe & Snyman 1978), who records the presence of fine-grained marginal rocks adjacent to the lower zone with lithologies similar to that zone. The recognition of such rocks is significant as these may yield some indications of the character of the initial Bushveld magma. Also, in the northeastern Bushveld, several sills of peridotite 10 to 20 m thick occur in sedimentary rocks of the Pretoria Group several hundred metres below the floor contact of the intrusion (Schwellnus *et al.* 1962).

Petrogenesis of the Bushveld magmas: towards a model

From the available evidence it is doubtful whether fractional crystallization of normal tholeiitic basalt produced the relatively large quantity of ultramafic rock types encountered in the layered mafic sequence. The presence of ultramafic bodies at the base of the complex, such as Aapiesdoorndraai, Grasvally, the Uitloop pyroxenites as well as the ultramafic, fine-grained marginal rocks of the lower zone, clearly point towards an early Mg-rich magma. The extensive development of upper-zone and main-zone lithologies, on the other hand, indicate that subsequent influxes of magma were less magnesian, possibly normal tholeiites. It would serve little purpose at this stage to speculate any further on the possible nature and composition of the Bushveld magmas; suffice it to say that an evaluation of the fine-grained marginal rocks of the ultramafic bodies and the lower-zone rocks should yield important information (Sharpe, Lee, research in progress).

The extensive partial melting to produce a MgO-rich magma is considered by Hamilton (1977) to be the result of a sudden release of overload pressure on a shallow-level mantle system at or near solidus temperatures. He bases his assumptions on the model of Richardson *et al.* (in Hamilton 1977) who expressed the opinion that mantle material near solidus temperatures would rise beneath zones of separation in areas of rifting and that the ascent will be accompanied by a rapid increase in temperature and extensive partial melting. They demonstrated that earlier magmas would be MgO-rich (20–30%) followed by magmas with lesser and comparatively uniform MgO values of about 7–8%.

Although the Transvaal basin was in a state of compression during emplacement of the Bushveld Complex, downwarping of the rigid crust below the Transvaal basin may have given rise to tensional conditions in the lower crust–upper mantle regimes and the reactivation of deep north-northeast (Great Dyke) and north-northwest (Usushwana) tensional fractures beneath which the initial high-magnesium magma could have been generated. The early magma rose upward along these tension fractures but spread out laterally along the shallow-angle shear fractures that developed as a result of stress conditions in the Transvaal depositional basin beneath the chord position (Sharpe & Snyman 1978). This resulted in the initial cone-sheet intrusion in which the early high-magnesium magma crystallized to give rise to the rocks of the lower zone and lower part of the critical zone. Gradual addition of magma of more basaltic composition and mixing of these with the partly differentiated earlier magma resulted, firstly, in the very gradual changes in compositional trends of the cumulus minerals with height in the lower parts of the intrusion (Cameron 1970, 1978) and secondly, the simultaneous lateral expansion of the conical magma chambers. Lateral expansion was governed by the position of the chord at the time of emplacement, with the result that the individual cone-sheets could have become interconnected at higher levels at a particular time in the stages of their development.

The last major influx of magma amounting to at least 10% of the volume of the total Bushveld magma is postulated to have taken place immediately prior to crystallization of the pyroxenite marker, *i.e.*, after about ¾ of the main zone had accumulated (von Gruenewaldt 1973) A gradual reversal in the compositional trend of the cumulus minerals is actually noted some distance below this marker, with a fairly pronounced break at the marker itself. The rocks below the marker correspond closely to those at the base of the upper zone and the volume of the influx was therefore calculated purely on the basis of the duplication of lithologies in the main zone plus a proportional contribution to the upper-zone type lithologies. The addition at this level must, however, have been considerably more than the postulated minimum of 10%, firstly, because of the gradual reversal which is observed some distance below the marker and, secondly, because of the dilution effect of the residual magma; a quantitavely much larger influx is necessary to cause the observed reversals than one based on the actual duplications of the resultant lithologies. The influx of undifferentiated magma at this level in the intrusion was recently substantiated by pronounced reversals in Ni and Cr content of rocks from samples collected along several traverses across the pyroxenite marker in the eastern Bushveld (Marais 1977).

Note here that the pronounced lateral transgressions in the Potgietersrus lobe involve not only rocks of the upper zone but the upper parts of the main zone as well (van der Merwe 1976). Similarly, rocks of the upper part of the main zone are also involved in the tongue-like transgressions of the upper zone north of the Pilanesberg in the western Bushveld (Vermaak *pers. comm.*). In both these areas and possibly also the Bethal area, the transgressions may be related to the volumetrically large influx of magma postulated after a large proportion of the main zone had crystallized.

A characteristic feature of the layered mafic rocks is their relatively high initial $^{87}Sr/^{86}Sr$ ratio and the pronounced variation in this ratio in the various zones of the complex (Hamilton 1977). Hamilton interpreted this as indicating successive emplacements of a number of discrete magmas derived from a heterogeneous mantle. Although contamination of the magmas either on their upward movement through the crust or by the felsic roof-rocks of the complex is rejected by Hamilton; it is especially at the roof contact where the existence of an anatectic melt derived from the Rooiberg felsite (Irvine 1970b, von Gruenewaldt 1972) could have caused some contamination of the magma. The strontium-isotope data were recently reassessed by McCarthy & Cawthorn (in press) who consider the observed fluctuations to be due to a combination of two major influxes of magma and the effects of fractional crystallization on this ratio. According to their model the gradually increasing $^{87}Sr/^{86}Sr$ ratio, to a level above the Merensky Reef, indicates fairly undisturbed and continuous fractional crystallization of a first batch of high-magnesium magma, the Merensky Reef having formed after the crystallization of about 90% of the first magma. Emplacement of a second batch of magma with a low initial $^{87}Sr/^{86}Sr$ ratio after crystallization of the Merensky Reef and mixing with the residual magma of the first batch would result in the observed wide fluctuations in preserved initial ratios in the main zone. After homogenization, continued fractional crystallization would produce the gradually increasing ratios in the upper zone.

The relatively high initial $^{87}Sr/^{86}Sr$ ratio of 0.70563 of the early magnesian magma of the Bushveld is considered by Hamilton (1977) to reflect a relatively high Rb/Sr ratio in the source region at the time of melting. Similarly high ratios for the Great Dyke and other rocks of basaltic composition on the Rhodesian and the Kaapvaal cratons would seem to indicate fundamental differences of the initial ratio in the source regions below the cratonic areas on the one hand and for ocean-floor basalt on the other. The high $^{87}Sr/^{86}Sr$ ratio is related to the stabilization of the Kaapvaal craton and the underlying mantle 2600 to 3000 m.y. ago and the subsequent differences in the evolution of the mantle beneath cratonic and oceanic environments (Hamilton 1977, Hunter & Hamilton 1978).

Sulfide Mineralization

Although sulfides occur in minor quantities throughout most of the layered mafic rocks of the complex, above-average concentrations are restricted to a few layers. Of these, three very extensive deposits are of economic importance, *i.e.*, the Merensky Reef, the best known although not necessarily the largest deposit of magmatic sulfides in the Bushveld (Table 1), the UG2 chromitite layer and the Platreef in the Potgietersrus area. Platinum mineralization in all three of these layers has been known since the twenties, and Wagner (1929) in his classical work on the platinum deposits in South Africa not only describes the Merensky Reef and the "Platinum Horizon" of the Potgietersrus area in considerable detail, but also reports briefly on the platinum mineralization in the upper chromitite layers. Since publication of this monumental work, the results of numerous investigations on the Merensky Reef have appeared in print, but very little additional information has become available on the other two layers.

With respect to their position in the sequence, as well as from petrogenetic considerations, the above-average concentrations of sulfides in the complex can be classified into three types: enrichments at or near the basal contact of the intrusion, disseminated stratiform enrichments and enrichments in crosscutting pegmatitic bodies.

Sulfide enrichments near the floor of the intrusion

Sulfide concentrations near the base of the intrusion have been described from several localities (Liebenberg 1970). Their composition seems to depend largely on the lithologies in contact with the floor rocks. They are generally more nickel-rich where the concentrations occur in ultramafic rocks of the lower zone, *e.g.*, at Aapiesdoorndraai and in the western Bushveld, Ni–Cu-rich where the rocks are correlated with those of the critical and main zones as at Potgietersrus (Wagner 1929), and Fe-rich where upper-zone lithologies are involved, e.g., in the Bethal area (Buchanan 1975).

The lower zone. The sulfide concentrations at Aapiesdoorndraai, investigated by Liebenberg (1970), occur as round droplets near the top and the floor contact of the ultramafic body. Troilite and cubanite are common constituents, indicating a S-deficient environment. In contrast, the sulfides in lower-zone rocks of the western Bushveld form local disseminations in layers of feldspathic bronzitite and harzburgite and constitute about two vol. % of the rocks (Liebenberg 1970, Vermaak 1976a). Although Liebenberg considers the mechanism of sulfide precipitation in these rocks to be in accordance with normal crystallization processes, he believed that the S was introduced by a process of sulfurization of the magma. In both the Aapiesdoorndraai area and the western Bushveld, the layered mafic rocks transgress the floor rocks to positions well below the Magaliesberg Quartzite Formation where the intrusion is in direct contact with sulfide-bearing shales and calcareous sediments. Sulfur isotope data presented by Liebenberg (1968) substantiate this hypothesis in that the sulfides are notably different in $\delta^{34}S$ concentrations compared with magmatic sulfur in the sulfides at higher levels of the intrusion.

The Platreef. "Platreef" is a name introduced by the geologists of the Johannesburg Consolidated Investment Co. for the platinum-bearing rocks in the Potgietersrus area (van der Merwe 1976) in order to distinguish this layer from the Merensky Reef with which it was correlated by Wagner (1929) and Liebenberg (1970). Where fully developed, the Platreef consists of two units: a harzburgite unit, pegmatitic in places at the base, overlain by a pyroxenite unit, consisting of a lower pegmatitic pyroxenite layer and an upper porphyritic pyroxenite layer. Cumulus grains of chromite are developed sporadically, whereas plagioclase and clinopyroxene together with sulfides constitute the intercumulus minerals. This reef, which can be traced along strike for more than 60 km, may attain a thickness of 200 m (van der Merwe 1976). It may rest directly on floor-rocks of the complex or it may be developed above a few metres of intervening norite and anorthosite (Wagner 1929, van der Merwe 1976).

From the descriptions by Wagner (1929) the mineralization occurs in three different environments. (i) The main mineralization is developed in the coarse-grained feldspathic bronzitite and in serpentinized rocks near the base of the Platreef. Although Wagner referred to these serpentinized rocks as representing altered, highly metamorphosed dolomite with which the reef is ized harzburgites of the lower part of the reef as if these rocks could also represent serpentin-in contact over part of the area, it would seem in near-surface environments. The sulfides, pentlandite $\simeq$ pyrrhotite > chalcopyrite with graphite a conspicuous accessory constituent, occur as irregular disseminated patches up to 4 cm in diameter (Schneiderhöhn 1929, Liebenberg 1970). According to Wagner and Liebenberg the platinum minerals are predominantly cooperite and sperrylite. (ii) Ni-sulfide mineralization is developed up to 30 m away from the floor contact of the reef where it is underlain by highly metamorphosed dolomitic limestones (silicified dolomite according to Wagner). These deposits, referred to as skarn-type mineralization by Liebenberg (1970), contain irregularly shaped patches of sulfide up to 4 mm across. Sulfides described by Schneiderhöhn (1929) are pentlandite $\simeq$ pyrrhotite > chalcopyrite > cubanite, the main platinum-bearing phases being sperrylite and stibiopalladinite (Wagner 1929). Mineralized and unmineralized xenoliths of calc-silicates, commonly several tens of metres in diameter, occur in the feldspathic bronzitite. (iii) Sulfide deposits are also developed some distance away from the mafic rocks in the floor of the complex, especially in pegmatites and in what Wagner termed crush zones in banded ironstone. These deposits are fairly massive in places, containing up to 5% Cu and 2.5% Ni. Very little is known about the deposits; their high Cu content corresponds to similar deposits in the floor of the Sudbury (Hawley 1962) and Duluth intrusions (Bonnichsen 1972).

A fourth type of mineralization seems restricted to the area south of Potgietersrus. In this type up to 10 modal % sulfides occur evenly disseminated throughout fine-grained norite. Although the position of this layer in the sequence is uncertain because of structural complexities, it is tentatively grouped with the marginal zone of the complex by L. Hulbert (research in progress).

Much more detailed information is required on the various types of mineralization at the base of the mafic sequence at Potgietersrus before they will be understood. The complicated relationships at the floor contact, the development of platiniferous sulfides in the floor rocks and in rafts of floor rocks in the Platreef, all point towards a complicated process of interaction between the Bushveld magma and its floor. Processes such as sulfurization (Liebenberg 1970) or CO_2 and H_2O flushing (de Waal 1977) as controlling factors in sulfide precipitation at the base of the layered sequence seem very attractive models on which to base further investigations. Features such as the pegmatitic nature of the mineralized portion of the reef, the slightly higher Cu/(Cu + Ni) ratios as compared for example with the Merensky Reef (Table 2), the development of abundant graphite, the skarn-type mineralization and still limited sulfur isotope data (Liebenberg 1968), all point towards volatile activity, probably caused by degassing of the dolomite during thermal metamorphism.

The Bethal area. Deep drilling in the Bethal area of the Bushveld Complex has revealed the existence of sulfide-mineralized upper-zone type rocks beneath a cover of Paleozoic sedimentary rocks (Buchanan 1975). The mineralization is confined to coarse-grained, magnetite-bearing pegmatitic gabbros in the lower 120 m of the upper zone. Sulfides are irregularly disseminated throughout and in places occur in fairly massive patches several cm in diameter. The sulfides are essentially pyrrhotite, usually between 85 and 90 modal %, with only subordinate amounts of chalcopyrite and pentlandite. There is, however, a gradual upward increase in the Cu/(Cu + Ni) ratio from about 0.40 at the base to 0.60 at the top of the 120 m thick mineralized zone (Buchanan 1972). The mineralized zone overlies a 50 m thick succession of harzburgite and pyroxenite of the lower zone, which seems to imply a major transgression of the upper-zone magma onto underlying mafic and ultramafic rocks. Furthermore, borehole data presented by

TABLE 2. Cu/(Cu + Ni) AND Pt/(Pt + Pd) RATIOS FOR VARIOUS LAYERS AND PIPES IN THE BUSHVELD COMPLEX

	Pt/(Pt + Pd)	Cu/(Cu + Ni)	Reference
upper zone, below main magnetite layer		0.82	1
upper zone, below lower magnetite layer 2	0.45	0.86	2
Bethal area, top of mineralized zone		0.60	3
bottom of mineralized zone		0.40	3
Merensky Reef, average	0.70	0.38	4,5
Pseudoreef	0.64		4
Platreef, average	0.48	0.44	4,5
UG2 chromitite layer	0.55	(0.22)[x]	4,5
Vlakfontein nickel pipes, centre	0.5	0.07	6
edge	0.29	0.59	6
Onverwacht dunite pipe	0.99		7
Tweefontein (in floor-rocks)		0.65	7

[x]includes Ni in chromite.
References: 1 Liebenberg (1970); 2 von Gruenewaldt (1976); 3 Buchanan (1972); 4 Cousins & Vermaak (1976); 5 von Gruenewaldt (1977); 6 Vermaak (1976a); 7 Wagner (1929).

Buchanan (1975) indicate that the mafic rocks of the complex are in places intrusive into dolomitic limestones of the Transvaal sequence. These relationships, as well as the presence of intercumulus carbonate minerals in the mineralized zones, have prompted de Waal (1977) to suggest that the upper-zone magma transgressed the lower-zone rocks but in places also dolomite and so became contaminated with CO_2 and H_2O.

Notable is the comparatively low Cu/(Cu + Ni) ratio of the sulfides in the Bethal area as compared with mineralized layers at the base of the upper zone in the eastern Bushveld (Table 2). This feature strongly supports the suggestion made earlier that the upper-zone lithologies in the Bethal area reflect a lateral expansion of the magma chamber subsequent to the addition of substantial quantities of undifferentiated magma after about ⅔ crystallization of the main zone. Transgression of this magma across sedimentary rocks, possibly dolomite, during lateral expansion would result in the incorporation of volatiles (CO_2, H_2O, possibly also S) to produce the magnetite and comparatively Ni-rich sulfide-bearing pegmatitic rocks near the base of the succession. This interpretation differs slightly from that of Buchanan (1975, 1979) who suggested that the magma from which the iron-rich upper zone crystallized was injected as a separate igneous event.

Disseminated stratiform enrichments

UG2 chromitite layer. Many of the chromitite layers, especielly those higher in the sequence, contain small quantities of sulfides and associated minerals of the platinum-group (PGM). The highest concentrations occur in the UG2 chromitite layer (Fig. 4; notation after Cousins & Feringa 1964) but published information on the platinum-group-element concentrations and the

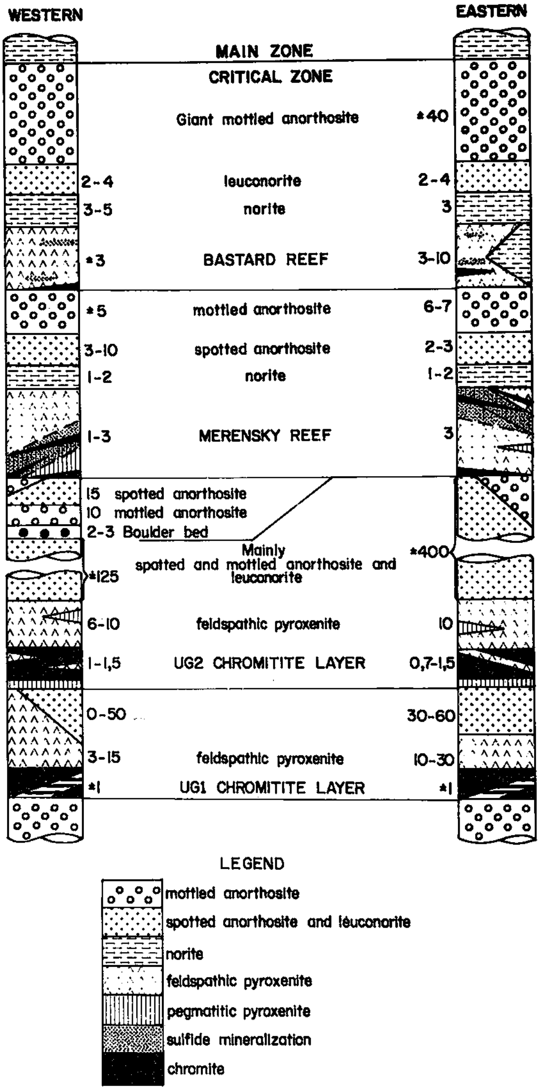

FIG. 4. Generalized columnar sections through the upper critical zone of the eastern and western Bushveld, illustrating amongst others also the pronounced lateral variation in the relative position of the components of the Merensky Reef.

nature of the PGM and other sulfides is limited. Although Wagner (1929) records values from many localities, the highest being 19.0 g/t, it is not always certain whether these represent the UG2 layer or other layers within the upper group. McLaren (1978) has recently published some preliminary results of his investigations of borehole material from the eastern and western parts of the complex. These results point to considerable lateral variations of the PGM, even over short distances. He found the highest PGE concentrations near the bottom and middle of the layer, and noted that Pt/Pd is low near the base but higher in the middle or at the top.

The majority of the PGM, usually more than 80%, occur along grain boundaries or in association with interstitial sulfides; only a very small proportion are enclosed in chromite or in the intercumulus silicates. In drill cores from most of the areas investigated, McLaren found the platinum sulfides laurite, braggite, cooperite and an unnamed mineral with the approximate formula Pt Rh(Ir)CuS to be the most abundant carriers of PGE. However, in the Maandagshoek area of the eastern Bushveld, from where exceptionally high PGE values of about 10 g/t are recorded, the PGE form complex alloys with a variety of other metals, notably Pb, Cu, Fe, Mg, Bi, Te, Sb and Ag. Platinum sulfides are rare, laurite being the most common. Other sulfides are mostly pentlandite, pyrrhotite and chalcopyrite.

As can be seen from Table 1, the Ni and Cu contents of the UG2 layer are considerably lower than those of either the Merensky Reef or the Platreef, which reflects the comparatively sulfide-poor nature of this layer. This feature is repeated in the chromitite stringer of the Merensky Reef [except at Marikana (Newman 1973, Brynard *et al.* 1976)]; it contains the highest platinum values, whereas the bulk of the sulfides occur in the pegmatitic part of the reef.

Available information suggests that the resources of PGE contained in the UG2 layer are almost twice those of the Merensky Reef. The chromite in this layer is of a rather low quality; it has a Cr/Fe ratio of 1.35 and a Cr_2O_3 content of 43.5%, as compared to values of 1.6 and 46.5, respectively, for the LG6 or main chromitite layer. But, should an economical beneficiation process for this low-grade chrome ore become available, this layer could become the most important ore deposit in the Bushveld Complex: 5.5 x 10^9 t are available to a depth of 1200 m (von Gruenewaldt 1977).

The Merensky Reef. Undoubtedly the most peculiar layer in the whole sequence of mafic rocks is the Merensky Reef (Fig. 4). Because of its economic importance, it has been drilled extensively and has been investigated in more detail than other layers of the complex. Vermaak & Hendriks (1976) recently redefined the reef as comprising a mineralized pegmatitic, feldspathic pyroxenite bounded at the top and bottom by thin chromitite stringers. According to earlier definitions the term referred to the associated porphyritic pyroxenite. The present author considers the definition by

Vermaak & Hendriks to be too restrictive, because economic sulfide mineralization is not always confined to the pegmatitic part of the reef and because the richly mineralized chromitite stringers may be developed in the porphyritic pyroxenite (Schwellnus *et al.* 1976, Brynard *et al.* 1976). It is therefore proposed to define the Merensky Reef as the basal, pyroxenitic portion of the Merensky cyclic unit; this includes the porphyritic pyroxenite, the pegmatitic pyroxenite and any chromitite stringers that may be developed (Fig. 4).

It is not within the scope of this paper to describe the reef in detail; schematic sections of the reef are presented (Fig. 4) in which variations of the relative positions of the various components are shown for different parts of the complex. For further detail the interested reader is referred to the excellent contributions of Cousins (1969), Liebenberg (1970), Schwellnus *et al.* (1976), Vermaak & Hendriks (1976) and Brynard *et al.* (1976). For present purposes it is considered advisable to point out certain aspects of the reef that highlight its complex nature, aspects that must be borne in mind when considering its origin. (i) The reef forms the basal pyroxenitic part of a cyclic unit referred to as the Merensky unit (Fig. 4), which, according to Vermaak (1976b), forms the most complete of a series of broadly similar over- and underlying cyclic units; (ii) the cyclic units of the Merensky type usually display an upward basification of the plagioclase (van Zyl 1970, Vermaak 1976b). In the Merensky unit the An content increases by a few mol % from the base to the top, whereas the associated cumulus orthopyroxene displays a normal upward Fe enrichment; (iii) the reef has a sharp footwall contact. Underlying rocks vary from one locality to another, but they are usually either mottled or spotted anorthosite, although porphyritic pyroxenite may constitute the footwall at places in the eastern Bushveld. This has widely been interpreted as indicating a hiatus in the crystallization during which the floor was "eroded" in places prior to deposition of the reef; (iv) the relative position of the chromitite layers, the pegmatitic pyroxenites, the porphyritic pyroxenite and the sulfide mineralization in the sequence within the reef shows considerable lateral variation (Fig. 4); (v) the composition of the chromite within the reef displays, according to Vermaak & Hendriks (1976), an upward increase in the Cr/Fe and Mg/Fe ratios, although this trend is normal (*i.e.*, decreases) in the Merensky Reef at the Western Platinum mine (Brynard *et al.* 1976); (vi) the sulfide content of the mineralized portions of the reef is usually less than 3 vol. %. Mineralization occurs as irregularly shaped patches occupying, together with plagioclase, clinopyroxene, biotite, hornblende and magnetite, the interstitial spaces between the large cumulus orthopyroxene crystals; (vii) although the sulfides, in decreasing order of abundance, are usually pyrrhotite, pentlandite, chalcopyrite and pyrite, this sequence is reversed at the Atok Platinum mine in the northeastern Bushveld where pyrite > chalcopyrite > pentlandite > pyrrhotite (Schwellnus *et al.* 1976). This together with the development of cubanite in certain areas (Liebenberg 1970) indicates lateral fluctuations in the sulfur content of the sulfide liquid that separated from the silicate magma; (viii) considerable variations have been recorded in the abundance of the various PGM along the strike of the reef (Brynard *et al.* 1976). The platinum sulfides cooperite and braggite predominate at the Rustenburg mine; the arsenides and tellurides sperrylite, kotulskite and moncheite considerably outweigh the sulfides at the Western Platinum mine; the Pt–Fe alloys and laurite are very common at the Union mine. Interestingly, the type and relative abundance of the PGM at Atok and Rustenburg are similar even though major sulfide mineralogy of the two areas show pronounced differences. Furthermore, the major mineralization at Atok is in porphyritic pyroxenite and in two associated chromitite stringers near the top of the reef, whereas the mineralization at Rustenburg occurs in pegmatitic pyroxenite and chromitite at the base of the reef; (ix) detailed mineralogical investigations have shown that by far the majority of the platinum-group minerals are developed along the outer edges of the sulfide grains and as separate minerals between interstitial silicates. Only a small proportion (~ 15%) occurs within the sulfides (Vermaak & Hendriks 1976); (x) the highest PGE values are usually found within the chromitite stringers. The only major exceptions are in the Western Platinum mine where high values are commonly found a few cm above this stringer (Newman 1973) and with areas of late-stage deuteric alteration of the reef (Crocket *et al.* 1976); (xi) within the reef, considerable differences in platinum mineralogy are evident: the PGM associated with the silicates differ from those in the chromitite layer. Pt/(Pt + Pd) ratios are usually higher in the chromitite layer than in sulfides associated with the silicates; (xii) the high Pt/(Pt + Pd) ratio and the low Cu/(Cu + Ni) ratio (Table 2) illustrate the high Pt and Ni content of the Merensky Reef compared with many other deposits associated with tholeiitic intrusions (Naldrett & Cabri 1976).

Any "hypothesis for the genesis of the Merensky Reef, whether by differentiation by gravity settling in the mafic portions of the Bushveld Complex as a whole, or whether from a more restricted pulse (heave) of magma, create as many problems as they solve" (Lauder 1970). The validity of this statement was amplified by Vermaak's (1976b) thorough treatise on the reef and its associated rock types. He reviewed the various hypotheses and tested them against the wealth of information amassed by the Johannesburg Consolidated Investment Company over many years of exploratory drilling and laboratory investigations. On the basis of all these data he postulated a crystallization model that accounts for the majority of the features displayed by the Merensky Reef. This hypothesis, also extended to all the cyclic units in the upper part of the critical zone, can briefly be summarized as follows.

Fractional crystallization of the Bushveld magma resulted in an increase of the components of plagioclase until a stage was reached when this mineral was on the liquidus. Anorthosite layers that crystallized from this liquid are characterized by an upward basification of the plagioclase which is ascribed by Vermaak to floating of the plagioclase, the upward movement being arrested by a compositional and/or density and/or temperature inversion. Floating of crystallizing plagioclase resulted in a mat of crystals that gradually thickened owing to underplating of continued plagioclase crystallization. As a result of this process the magma beneath the mat was trapped and isolated from the magma chamber. Simultaneously, the trapped magma was enriched in volatile constituents, and also in sulfur, PGE, Cu and Ni through the upward migration of the intercumulus liquid from the consolidating pile of cumulates below. Cardinal to the subsequent crystallization of the magma below the mat is the degree of impermeability of the anorthosite mat and consequently its efficiency as a trap for the volatile constituents. Removal of the plagioclase caused enrichment of the ferromagnesian constituents which initiated crystallization of chromite to form a thin layer at the base of the unit. When the ferromagnesian minerals started to crystallize, the volatile-enriched magma enhanced rapid growth and crystal aggregation into spherical boulders that sank in the magma, dimpled the early chromitite layer and merged to form the basal pegmatitic pyroxenite. Boulders of this nature are preserved in the so-called "boulder bed" at Rustenburg (Cousins 1969, Figs. 7 and 8) where for some reason the process to form a cyclic unit of the Merensky type was not completed. (It is of interest to note that Lee & Sharpe (1978) called upon a process of spherical agglomeration to account for similar boulders in gabbroic rocks of the main zone, close to the margin of the complex). Extraction of FeO for the chromite and silicates lowered the sulfur-carrying capacity of the magma and resulted in the separation of an immiscible sulfide melt. This melt settled to fill interstitial spaces in the pegmatitic basal layer of the reef, in places even percolating through the reef to become entrapped in interstitial spaces of the footwall anorthosite. Through continued crystallization of chromite and pyroxene, the upper chromitite layer and the porphyritic pyroxenite accumulated, the latter grading upward into norite and anorthosite to complete the cyclic unit.

The immiscible Cu–Ni sulfide liquid acted as a collector not only for the PGE but also for small amounts of Ag, Bi, Te, Sn, Sb and other rare metals to form the multitude of different PGM encountered in the reef. The presence of Cu, Ni and PGE is considered by Vermaak to represent a progressive enrichment of the main body of magma through expulsion of interstitial liquids by a process of post-cumulus growth or filter pressing. He attributes the association of base-metal sulfides and PGM with the chromitite layers in the upper part of the critical zone to a decrease in the FeO content during crystallization of a chromitite layer, a resultant increase in the sulfur fugacity of the crystallizing magma and the separation of an immiscible sulfide melt.

Vermaak's model, based on a wealth of data from underground workings and boreholes in the western lobe of the complex, seems to account for most of the observed features in the reef. His model could be adapted slightly to account for lateral variations in the nature of the Merensky Reef; the absence of the pegmatitic portion of the reef may indicate that conditions for the aggregation of boulders were not met, possibly due to absence of sufficient volatiles in the crystallizing magma. He recognizes that his model does not account satisfactorily for certain aspects, *e.g.*, the mechanisms involved in the precipitation of the second chromitite layer, and whether depletion of FeO during crystallization of the chromitite was sufficient to precipitate sulfides from the entrapped Merensky magma.

Several authors (Hamilton 1977, McCarthy & Cawthorn *in press*) have recently proposed that the Merensky Reef represents a relatively late-stage product of fractional crystallization of an early magnesian magma. This, as well as Vermaak's (1976b) contention that the sulfides in the Merensky Reef originated essentially by a process of filter pressing of intercumulus liquids from underlying cumulates raises the question as to whether such an origin for the reef can be reconciled with the comparatively low Cu/(Cu + Ni) ratio of 0.38 for the sulfides in the reef. A concept of intermittent replenishment of the crystallizing magma seems more attractive to account for the relatively low Cu/(Cu + Ni) ratio. Crystallization of several thousand metres of bronzitites and interlayered harzburgites, dunites and chromitites without periodic replenishment of the magma would have extracted considerable quantities of Ni from the magma, so that a higher Cu/(Cu + Ni) ratio would be expected than that observed for the reef. A further problematical aspect is the enrichment of PGE in certain of the chromitite layers relative to the sulfide concentrations in the silicates. This chromitite, described by Wagner (1929) as behaving in effect "like a sponge" with the PGE, not only characterizes the Merensky Reef and the UG2 chromitite layer, but also xenoliths of chromitite in the Onverwacht pipe (see below) and, to a lesser extent, other chromitite layers in the upper half of the critical zone. This feature is not satisfactorily accounted for merely by precipitation of a sulfide liquid in response to decreasing S solubility of the magma during chromitite crystallization. In such case, the composition of the sulfide precipitated should be similar to the bulk of the sulfides in the silicates, *e.g.*, in the pegmatitic pyroxenite of the Merensky Reef. The grain size of the PGM in the chromitite is usually half or less than that associated with sulfides in the pegmatitic portion of the Merensky Reef. Although this latter feature may be ascribed to the smaller grain size and closer packing of the chromitite (Vermaak 1976b), the presence of fairly large amounts of intercumulus silicates (mostly plagioclase) would militate against such an explanation, especially if it is assumed that the immiscible sulfide liquid formed in response to crystallization of chromite and pyroxenes. Grain sizes of the PGM and associated sulfides in the UG2 chromitite layer vary considerably, but average values presented by McLaren (1978) indicate diameters of the order of 5.0 and 40 μm, respectively.

As noted in many of the chromitite layers in the Bushveld Complex, the chromite commonly shows signs of late-stage reaction and equilibration (Sampson 1932, van Zyl 1970, Schwellnus *et al.* 1976). Therefore, it is suggested that the PGM of the chromitite layers formed at a late stage when deuteric liquids percolated upward through the pile of cumulates. Reaction of these liquids with the chromite and the interstitial silicates of chromitite layers resulted in conditions favorable for the precipitation of discrete PGM. Whether the PGE were transported and introduced by late hydrous solutions (Stumpfl & Tarkian 1976) or were present in the spinel either as minute mineral inclusions (Cousins & Vermaak 1976) or in solid solution (Naldrett & Cabri 1976) is debatable. The exact processes involved are by no means clear at this stage, but the extremely small grain size of the PGM and associated Ni–Cu sulfides and their bulk composition testifies against their precipitation from the overlying magma during crystallization of the chromite.

The upward increase in Pt/Pd ratio described by McLaren (1978) from various localities of the UG2 layer might possibly be ascribed to the preferential collection of Pd in sulfides at the base of the layer during the upward migration of the deuteric fluids. The very low Cu/(Cu + Ni) ratio of the UG2 chromitite layer cannot be evaluated at this stage because the analytical values available represent only bulk samples of the reef. McLaren (1978) records Ni average values of 0.1% or greater. The bulk of this Ni would clearly seem to be bound in the chromite structure when the values are compared with analyses given by de Waal (1975) for purified chromite from the UG2 layer. From the description of the UG2 layer, pentlandite seems to be the most abundant sulfide present, so that the Cu/(Cu + Ni) ratio of the sulfides in the reef is probably also relatively low, a feature that may be related to subsolidus equilibration between sulfides and chromite.

Sulfide enrichments in the upper zone. Concentrations of disseminated sulfides are known from various layers in the upper zone of the complex (von Gruenewaldt 1976). In the lower part of this zone, sulfides are developed at the top of anorthosite layers, directly beneath the thicker of the magnetite layers, where they usually occupy the intercumulus spaces of the plagioclase cumulate. In contrast, the sulfides in the upper half of the zone occur evenly distributed as tiny, spherical, drop-like bodies included in silicates; they usually make up about 0.5 vol. % of the rock. Larger concentrations, both as tiny droplets and as larger, lenticular bodies several cm in diameter, are developed within the thick uppermost magnetite layer.

The composition of the sulfide assemblage in the rocks of the upper zone shows a gradual and systematic variation upward in the succession. In the mineralized anorthosites near the base of the upper zone, the sulfide assemblage contains the highest chalcopyrite content of the layered mafic sequence, in the order of 55 vol. %. Both chalcopyrite and pentlandite gradually decrease in abundance upward in the sequence with a concomitant increase in the pyrrhotite content. Pyrrhotite attains its maximum concentration, between 90 to 95% of the sulfide assemblage, in the droplets of the rocks in the upper half of the zone.

Characteristic of the sulfides of the upper zone is their very high Cu/(Cu + Ni) ratio, unsually about 0.85 or more. A Pt/(Pt + Pd) ratio of 0.45 is recorded by von Gruenewaldt (1976) for the mineralized anorthosite below lower magnetite layer 2, the only value so far available from the upper zone. Little is known about the lateral distribution of the sulfides in the upper zone, mainly because of poor exposure in most of the areas underlain by the rocks of this zone. The above information on the sulfide concentrations in the upper zone pertains to an area of exceptionally good exposure in the eastern Bushveld. It would be unwise at this stage to extrapolate observed trends to the other parts of the complex, as the available evidence suggests that the rock sequences in the upper zone of the Potgietersrus, the western and even the southeastern (Bethal) area of the complex deviate considerably from those in the eastern Bushveld. From this it must be deduced that crystallization histories in the upper parts of the complex differed from one locality to the next and that the nature and composition of sulfide concentrations may differ accordingly. Disseminated Cu–rich sulfide concentrations are known to be associated with certain of the lower magnetite layers in the Potgietersrus area and in the western Bushveld.

The presence of sulfides in the rocks of the upper zone is ascribed by von Gruenewaldt (1976) to a gradual enrichment of sulfur in the crystallizing magma due to processes of fractional crystallization. The pronounced iron enrichment in the Bushveld magma prevented the formation of immiscible sulfide droplets during crystallization of the lower half of the upper zone. Only where the FeO content of the crystallizing magma was sufficiently reduced, as for instance during formation of the thicker magnetite layers, did small quantities of immiscible sulfide liquid separate and settle to the floor where they became concentrated in the intercumulus spaces of the plagioclase cumulates directly below the magnetite layers. During crystallization of the upper half of the upper zone, the magma must have been very close to saturation in sulfur, because crystallization of only small quantities of silicates resulted in the separation of numerous drop-like bodies of sulfide liquid evenly dispersed throughout the cumulates.

Mafic and ultramafic pegmatites

Mafic pegmatite bodies displaying a large variety of mineralogical compositions are widely developed in the layered sequence of the Bushveld Complex (Willemse 1969, von Gruenewaldt 1973). The bodies are usually concentric and pipe-like although diallagite pegmatite commonly forms large, irregularly shaped masses, especially in the critical zone (Cameron & Desborough 1964). Only the hortonolite dunite pipes and the nickeliferous bronzitite pipes carry significant quantities of PGE and nickel, respectively, and these will therefore be described in more detail below. However, small quantities of sulfides are developed in many of the other mafic pegmatites, *e.g.*, in the diallage pegmatite surrounding the magnetite plug at Kennedy's Vale (van Rensburg 1965), the vermiculite-bearing breccia pipes in the upper zone (von Gruenewaldt 1973), and the anorthositic pegmatites in the upper zone. The disseminated sulfides associated with these pegmatites have not yet been investigated.

Nickeliferous bronzitite pipes. More than 200 nickeliferous bronzitite pipes have been located in an area of about 200 km^2 situated to the west of the Pilanesberg in the western Bushveld (Vermaak 1976a). The area is underlain by rocks of the lower zone and of the lower part of the critical zone, *i.e.*, mostly by bronzitite and harzburgite. The bodies are generally pipe-like but they may show extensive mushrooming in the pyroxenite, usually directly below harzburgite layers. Most pipes are overlain by opaline gossans, which are considerably larger in surface diameter and commonly also in volume than the underlying sulfide orebody. Although the largest gossan measures 25 m in diameter, most of the gossan occurrences are considerably smaller and have an average diameter of 7 m (Vermaak 1976a).

Ideally, the nickel pipes consist of massive sulfide surrounded by what Wagner (1929) termed "poikilitic ore", which in turn has fairly sharp contacts with the country rock. Many of the country rocks do, however, contain disseminated sulfide, and Liebenberg (1970) noticed an increase in these disseminations towards the pipes. The mineralogical composition of the ore varies; pyrrhotite always predominates, constituting 70% or more of the sulfides, followed by pentlandite, chalcopyrite and mackinawite (Liebenberg 1970). Although Liebenberg does not describe any pyrite from the nickel pipes, this sulfide seems to predominate in some of the pipes in which nickel values are particularly low (Vermaak 1976a).

The main ore type is the so-called 'poikilitic ore', which commonly constitutes up to 80% of the pipe. It consists mostly of euhedral orthopyroxene crystals set in a matrix of sulfide. In exceptional cases the poikilitic ore contains large, euhedral olivine crystals partly replaced by pyrrhotite and is 'intruded' by a later orthopyroxene poikilitic ore. Detailed descriptions of the mineragraphy of the ore are provided by Liebenberg (1970) and will not be repeated here. Of interest, however, is the zonation in the sulfide pipes: the Cu sulfides increase towards the margins of the pipes. Cu/(Cu + Ni) ratios consequently increase considerably from about 0.07 in the central, massive ore to 0.59 along the edge of the pipes. Similarly the Pt/(Pt + Pd) ratio changes from about 0.5 in the centre to 0.3 or less near the edge (Vermaak 1976a).

Other minerals observed by Liebenberg (1970) and Vermaak (1976a) are chromite within the peripheral ores, and graphite, biotite, chlorite and talc around the outer circumference of the pipes. Contacts of the pipes with their country rocks are usually gradational over less than 3 cm with a fine-grained variety of the poikilitic ore developed along the contact.

Both olivine and orthopyroxene in the poikilitic ore are enriched by 10 to 15% of the Fe-rich end-member compared to the country rock. This feature is in keeping with the majority of the transgressive pegmatite bodies; all are considerably enriched in iron.

Three diverging hypotheses have in recent years been advanced for the origin of the nickel pipes. All three, however, have two aspects in common, *i.e.*, that the siting of the pipes is structurally controlled and that the sulfur is partly derived from an external source. Liebenberg (1970) considered the pipes to have originated by segregation of sulfide-enriched intercumulus liquids under conditions of tectonism and that these liquids migrated into zones of weakness to form the orebodies. The sulfur is considered to be essentially of sedimentary origin, and Liebenberg therefore related the interstitial sulfides and consequently also the nickel pipes to the downward transgression of the Bushveld magma into sulfur-bearing argillaceous rocks in the area to the west of the Pilanesberg.

Detailed mapping in the western Bushveld led Vermaak (1970, 1976a) to recognize areas of intense basification (serpentinized harzburgite) of bronzitites along fault and fracture zones with which the nickel pipes are associated. He postulated that the basification of the bronzitite layers developed as a result of tectonic overpressure. The metals required for the Ni pipes are considered to have been liberated from the silicates during basification, whereas sulfur was introduced into the fracture zones from the underlying sediments by circulating waters that reacted with the metals to form sulfides. These in turn were remobilized and concentrated in favorable structures along the fault zones during renewed overpressure. Most of the fracturing and faulting is related by Vermaak (1976a) to emplacement of the Pilanesberg alkaline complex, with the result that formation of the nickel pipes is considered to postdate the complex.

Temperatures during emplacement of the nickel pipes must have been high, probably in excess of those attained in the area of maximum pipe development during intrusion of the Pilanesberg. This deduction is made from various features described by Liebenberg (1970), amongst others the replacement of niccolite by maucherite and the development of orthopyroxene and olivine in the poikilitic ore, all of which indicate temperatures well in excess of 800°C.

De Waal (1977) recently suggested a process whereby release along fractures of carbon dioxide and water from metamorphic reactions in the floor of the complex could be held responsible for the nickel pipes at Vlakfontein. Where the CO_2–H_2O fluids entered the magma, precipitation of sulfides and spinel took place if the magma was driven to saturation with respect to these two minerals. The emergence of these fluids into the magma will, according to de Waal (1977) be focused at points along the fault and fracture zones. In the immediate vicinity of these CO_2–H_2O "fountains", $f(O_2)$ in the magma was raised and precipitation of sulfide liquid resulted, a process that was augmented by sulfur in the fluid. New magma, from which the metals of the sulfides were extracted to form the pipe-like bodies as the pile of cumulates grew, was supplied by slow convection of the magma in the chamber. The zones of basification are considered by de Waal to represent areas where near-consolidated bronzite cumulates reacted with the carbon dioxide–water fluids to form harzburgite according to the reaction: pyroxenite + vapor → harzburgite + melt.

Hortonolite dunite pipes. Numerous bodies of dunitic and pyroxenitic pegmatites occur in rocks of the critical zone in the eastern and western Bushveld (Wagner 1929, Cameron & Desborough 1964, Willemse 1969). They are either lenticular flat bodies parallel to the stratification, irregular in outline, or pipe-like. It is these pipe-like pegmatitic dunite bodies that have become well-known in the geological literature for their remarkably high platinum content (up to 2000 g/t). Only the Onverwacht, Mooihoek and Driekop pipes contained sufficiently high platinum values to warrant exploitation.

Both the Mooihoek and Onverwacht pipes consist of a circular, carrot-shaped core of coarse-grained hortonolite dunite (Fo_{50}), the main platinum-bearer, surrounded by medium-grained dunite (Fo_{80}). At Mooihoek an outer shell of coarse, pegmatitic diallagite and feldspathic pyroxenite is developed (Wagner 1929). The country rocks of the Onverwacht pipe are the pyroxenites below and above the main chromitite layer. Prior to mining, huge rafts of the chromitite were preserved in a relatively undisturbed position in the pipe, and these rafts "acted like sponges so far as platinum was concerned" (Wagner 1929, p. 68). In contrast, the country rock of the Mooihoek pipe is anorthositic norite, and the pipe is therefore situated at a slightly higher stratigraphic level.

The Driekop pipe differs from the previous two in that the pipe is not zoned and the central, platinum-bearing portion consists of hyalosiderite–chrysolite (Fo_{71-84}) composition. Although Wagner (1929) described the platinum-bearing dunite to be enriched in iron compared to the barren dunite and to consist of a large number of irregular and composite bodies in the more magnesian dunite, Heckroodt (1959) could establish no relationship between the platinum content of the ore and the composition of the olivine. The pipe is located in norite of the critical zone at a stratigraphic position considerably higher than the Onverwacht and Mooihoek pipes. Exploitation of the pipe continued until 1961, in contrast to the other two pipes at which mining operations ceased soon after their discovery in the early twenties. Consequently a considerable amount of information on the PGM of the Driehoek pipe is available, as was recently summarized by Tarkian & Stumpfl (1975). These authors found that the PGM in the Driekop pipe are iron-bearing platinum (50%), sperrylite and geversite (30%), minerals of the hollingworthite–irarsite group (15%) and a variety of sulfides and antimonides (5%). They point out that the mineral association differs distinctly from the sulfide- and telluride-bearing assemblages of the Merensky Reef.

From detailed field and microscopic observations, Cameron & Desborough (1964) presented convincing evidence that the olivine dunite surrounding the hortonolite dunite at the Onverwacht pipe owes its origin to replacement of bronzite in the original chromite-bearing pyroxenite by olivine. Although the investigations of these authors were not conclusive regarding the origin of the central hortonolite dunite, they drew analogies with similar rocks in other irregularly shaped dunite pegmatites and concluded that the dunite also formed during the replacement process. They were of the opinion that water-rich, high-temperature fluids were the agents for pegmatite formation and, although they could not specify the time of formation and the source of such fluids, they pointed out that all the constituents required in the replacement reaction are available in the rocks of the critical zone through which the fluids must have passed. On the basis of their investigations of the PGM of the Driekop pipe, Stumpfl (1974) and Tarkian & Stumpfl (1975) supported the conclusions reached by Cameron & Desborough (1964) and considered that the PGE were introduced by and deposited from fluid phases during the late stages of formation of the dunite pipes.

Discussion

Various authors (*e.g.*, Willemse 1969, Liebenberg 1970, Vermaak 1976a) have commented on the S-poor nature of the Bushveld magma. A shallow upper-mantle origin in a S-deficient zone as postulated by Naldrett & Cabri (1976) seems therefore indicated. From the available evidence at present, an early immiscible sulfide melt that could have separated from the Bushveld magma to form a massive deposit near the floor is therefore not to be expected. Wherever large concentrations of sulfides are developed near the base of the complex, as in the Potgietersrus area, the western Bushveld and the Bethal area, evidence is at hand that the Bushveld magma assimilated sedimentary sulfur and other gases such as would promote separation of an early sulfide liquid.

Concentrations of sulfides at higher levels in the intrusion must be related to a combination of processes, such as periodic replenishment of undifferentiated magma to maintain a relatively low Cu/(Cu + Ni) ratio in the magma at least up to the level of the Merensky Reef, enrichment of the magma in sulfur by normal processes of fractional crystallization and expulsion of the intercumulus liquids from the accumulating pile of crystals as a result of compaction. These highly fractionated liquids, which ascended through the pile of cumulates, possibly augmented by CO_2 and H_2O-rich fluids from degassing metamorphosed sediments, may be of considerable importance in consideration of the origin of the large variety of mafic pegmatites developed in the complex.

The initial porosity of the settled crystals in the accumulating mush is estimated as being between 20 and 50% by various authors (Hess 1960, Jackson 1961, Wager & Brown 1968), with the result that the mechanism of enlargement of cumulus crystals to form adcumulates or monomineralic rocks without pore material is difficult to explain. Quantitative information on the amount of intercumulus liquid present directly after settling of pyroxene and plagioclase in cumulates of the main zone can be obtained from point counts of the so-called "black norite" developed to the west of Belfast (Fig. 1). Numerous tiny needles of magnetite and ilmenite in the plagioclase impart the dark color to the rock. In several of the specimens investigated the needles are restricted to the central, evidently cumulus parts of the plagioclase grains, whereas the adcumulus overgrowths are free of needles (Fig. 5a). Point counts of these sections showed that the overgrowths on the plagioclase make up between 10 and 15% of the rock. If this figure is extrapolated to other cumulus minerals, especially pyroxene, it can be shown that adcumulus overgrowths constitute more than 20 vol. % of gabbroic cumulates in the main zone.

Preferred explanations for the mechanism of enlargement of cumulus crystals in adcumulates were pointed out by Cameron (1969): firstly, settled crystals continued to grow after shallow burial by diffusion of the required constituents into the crystal mush down a slight temperature gradient; secondly, enlargement of crystals occurred while still in contact with the supernatant magma; thirdly, a combination of both processes could have occurred. The first of these processes can be ruled out as G.B. Hess (1972) concluded from thermal considerations that crystallization of the pore material occurs only long after deposition and that ionic diffusion between crystallizing pore material and the bulk of the magma is not possible.

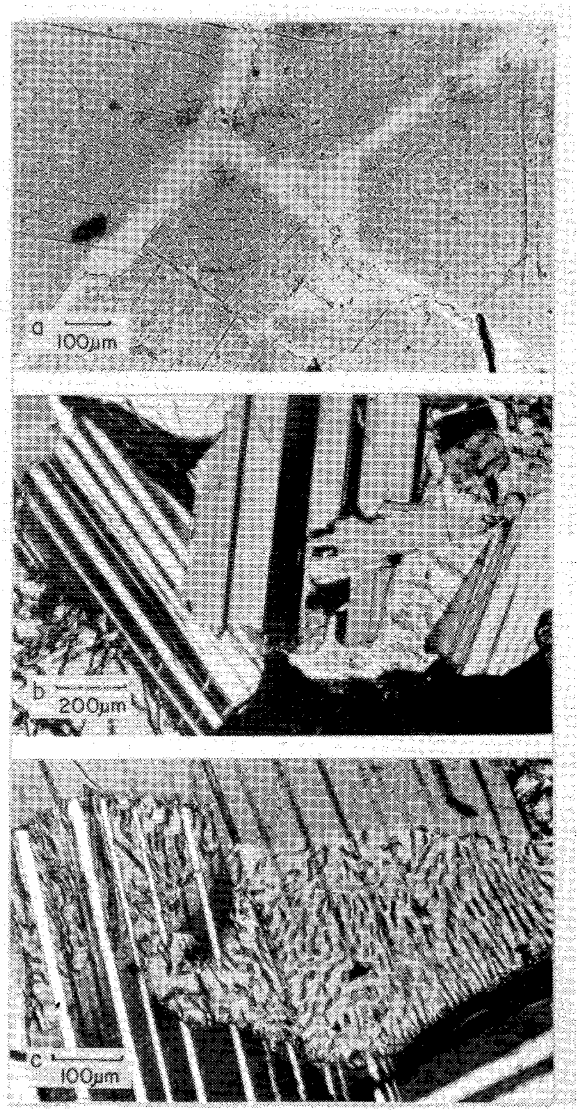

FIG. 5. Features of plagioclase crystals in the main zone. (a) Fine magnetite-ilmenite dusting of the cumulus portions of plagioclase crystals; (b) Interpenetrating crystals of plagioclase; (c) Development of myrmekite in interpenetrating plagioclase crystals.

Another mechanism whereby the amount of intercumulus liquid can be reduced is compaction of the crystal mush prior to cementation "if this were attended by re-solution of crystals at points of contact and redeposition in interstices" (Cameron 1969). However, Cameron states that owing to lack of evidence, this process has found little favor with students of magmatic sediments. Interestingly in this regard, Cameron (1975) concluded that minimal post-cumulus overgrowth has taken place in chromitites and bronzitites of the Bushveld Complex and consequently, minimal amounts of post-cumulus equilibration. This was interpreted by Flynn *et al.* (1978) as being indicative that intercumulus liquids were in close equilibrium with the cumulus crystals, situations which would prevail under conditions of crystallization close to the magmatic solidus.

In plagioclase-bearing cumulates, however, compaction of the crystal mush is considered to be one of the most important processes whereby large quantities of intercumulus liquid were pressed out of the pore spaces into the overlying magma. This is evident from several textural features displayed by the plagioclase crystals (von Gruenewaldt 1971), such as interpenetration, myrmekite textures, bent crystals and reverse zoning (Figs. 5b, c). An especially important mechanism whereby adcumulus growth can take place seems to be the process of re-solution, causing interpenetration and the redeposition of this material in the interstices. The ascending intercumulus liquids could have become concentrated in places to form transgressive pipe-like or sill-like mafic pegmatites. It is envisaged that where their movement to higher levels was hampered by layers where adcumulus enlargement of crystals effectively sealed the intercumulus spaces, these liquids spread out laterally, reconstituting the cumulates to form the irregularly shaped pegmatites commonly displaying gradational as well as sharp contacts with the country rocks, as described by Cameron & Desborough (1964). Such layers in which substantial secondary enlargement of crystals took place at an early stage could have formed at the top of the mush during periods of intense convection near the mush–liquid interface.

Conflicting views prevail concerning the association of PGE with chromitite. Cousins & Vermaak (1976) have expressed doubt whether any of the PGE can be accommodated in spinels at high temperatures as has been suggested amongst others by Naldrett & Cabri (1976). Evidence presented by Cousins & Vermaak (1976), Vermaak & Hendriks (1976) and McLaren (1978) suggests that all the PGE in chromitite of the Bushveld can be accounted for in discrete PGM. Data presented by McLaren (1978) for the UG2 chromitite layer show furthermore that the proportion of PGM contained as inclusions in chromite grains is, on the average, only about 4% of the total PGM. Although most authors agree that PGE have an affinity for chrome spinel at high temperature, be it in solid solution or as minute inclusions, the abnormally high concentrations in the iron-rich UG2 and Merensky Reef chromitite as compared with chromitite layers lower in the sequence remains problematical. Of interest in this regard is that where Cr/Fe in the Steelpoort Chromitite layer was reduced by equilibration with late liquids during formation of the Onverwacht pipe, the chromitite rafts acted as collectors for the PGM. It is uncertain where the PGE in the hortonolite dunite pipes were derived from. Their concentration in the central portion of the pipes as a result of the reaction replacement of the surrounding pyroxenites in which they are present on a ppb level (Gijbels *et al.* 1974) seems a distinct possibility. The enrichment of the chromitite rafts in the Onverwacht pipe suggests that a related process involving late liquids could have resulted in the enrichment of the iron-rich upper chromitite layers, including the thin chromitite layers in the Merensky Reef.

CONCLUSIONS

(1) The broad loci of emplacement of the Bushveld Complex is in the Transvaal basin at the intersection of several prominent structural directions on the Kaapvaal craton.
(2) The present-day configuration of the complex is controlled by a series of dome- and basin-like features, the presence of which has characterized the Kaapvaal craton since earliest times; these developed in response to interfering north–northwest – east–northeast oriented anticlinal and synclinal warps.
(3) Emplacement of an early, magnesian magma was into low-angle conical shear fractures that developed in the Transvaal sequence in response to depression of the basin below the chord position after subaerial extrusion of the Rooiberg felsite and emplacement of numerous diabase sills. Subsequent replenishments of magma resulted in the lateral extension and interconnection of the initial magma chambers, to form the large sheeted nature of the upper two

zones of the complex. Postulated centres of intrusions are aligned along deep seated north–northwest and north–northeast tension fractures.
(4) Petrographic and field evidence suggests the existence of an early, high-magnesium magma, followed by emplacement of normal tholeiite.
(5) Concentrations of sulfides near the floor of the intrusion have been interpreted by various authors as being the result of degassing of the floor rocks during metamorphic reaction and the addition of S, CO_2 and H_2O to the crystallizing magma.
(6) Several cyclic units characterize the upper part of the critical zone. The Merensky unit is the most complete and laterally the most constant; it contains the largest sulfide concentrations. The features of the reef suggest a hiatus in the crystallization immediately prior to its formation, followed by crystallization from an isolated batch of magma near the floor of the chamber and enrichment of sulfur prior or during crystallization.
(7) Concentrations of PGE in the iron-rich chromitite layers in the upper part of the critical zone and in the Onverwacht pipe seem to be related to late solutions that percolated upward through the pile of semiconsolidated cumulates.
(8) Concentrations of sulfides in the upper zone are ascribed firstly, to sulfur enrichment in the magma as a result of normal fractional crystallization, and secondly, to the crystallization of magnetite and ferromagnesian silicates.
(9) Mobilization of intercumulus liquids by compaction and their ascent to higher levels is considered important in the formation of the mafic pegmatites in the complex.

Acknowledgements

The author thanks Drs. T.N. Irvine, N.J Page and M.R. Sharpe for their constructive criticism of the manuscript.

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Received September 1978, revised manuscript accepted January 1979.