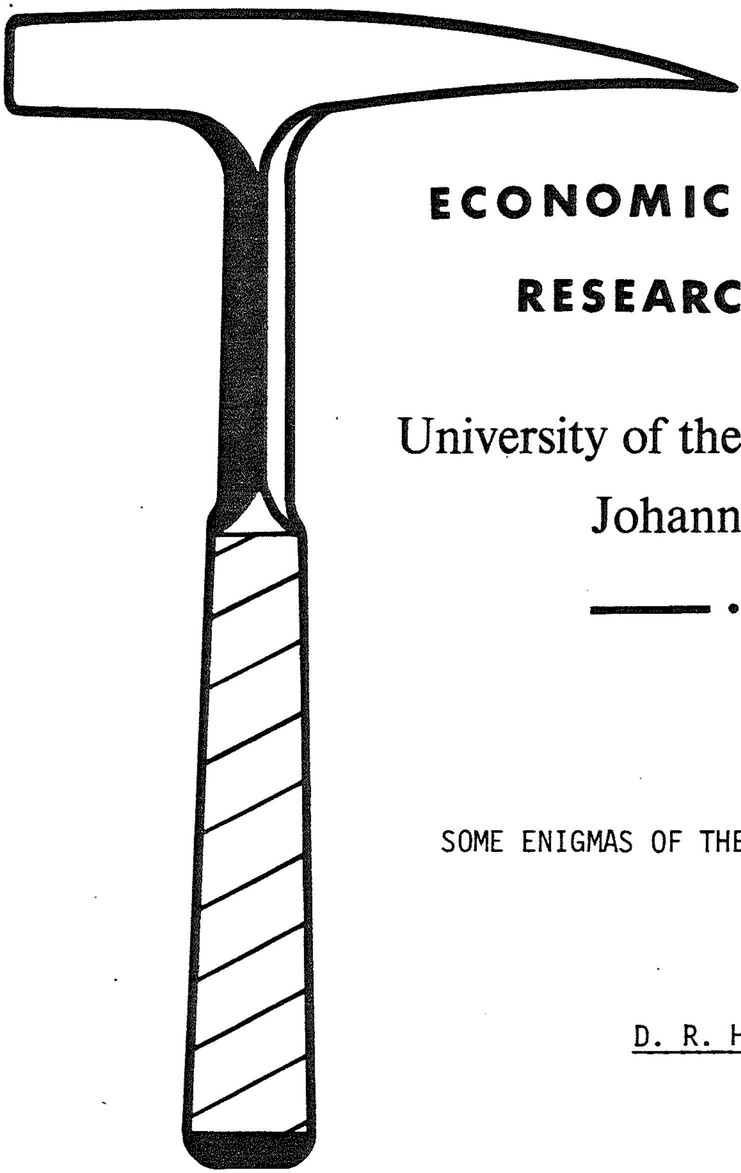

ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
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SOME ENIGMAS OF THE BUSHVELD COMPLEX

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INFORMATION CIRCULAR No. 92

UNIVERSITY OF THE WITWATERSRAND

JOHANNESBURG

SOME ENIGMAS OF THE BUSHVELD COMPLEX

by

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ABSTRACT

The largest known, layered complex has been studied for nearly 100 years but, despite this, the problems concerning its regional setting, the genesis of certain of the constituent rock-types, their age relationships, level of emplacement, the origin of their layered nature, and the morphology of the complex, are unresolved. Problems also exist in regard to the mineralization, particularly with respect to that associated with the acid phase of the complex and to allegedly hydrothermal deposits in the enclosing sedimentary rocks. The opposing views on these problems are reviewed and an attempt is made to reconcile them.

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SOME ENIGMAS OF THE BUSHVELD COMPLEX

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INTRODUCTION

Despite nearly one hundred years of intensive geological study, the Bushveld Complex still presents a number of, as yet, unresolved problems, that concern, in particular, the genesis of the constituent rock-types, their age relationships, the level of emplacement of certain of the mafic rocks, and the origin of their layered nature, the morphology of the complex, and its regional setting.

The Bushveld Complex is a major world source of platinum group metals, chrome, and vanadiferous iron ores. Production of tin and fluorite is significant in the South African economy. Within the metamorphic aureole of the complex are mineable deposits of industrial minerals, while the Bushveld norite is itself prized for its qualities as a monumental and building stone. It is, therefore, of considerable importance to the mineral industry, both nationally and internationally, that the geologic problems of the complex should be resolved. This paper attempts to identify and review some of these problems without presuming to solve any or all of them.

COMPONENTS OF THE COMPLEX

Hall (1932) regarded the Bushveld Complex as the main expression of a major petrogenetic cycle that affected wide areas of the Transvaal and Cape Provinces of the Republic of South Africa, as well as parts of the adjacent countries of Rhodesia and Botswana. Similarities in petrographic characters led to the inclusion (Hall, 1932; Willemse, 1969) of the following as related intrusives within this broad cycle (Figure 1) :

1. Great Dyke of Rhodesia,
2. Losberg layered intrusive,
3. Trompsburg layered intrusive,
4. Kaffirskraal pyroxenite,
5. Vogelstruisfontein pipe-like mass of mafic rocks,
6. Koringkoppies chromiferous pyroxenite,
7. Uitloop layered pyroxenite, and
8. Modipe gabbro and associated granite along the Crocodile River.

Recent isotopic age measurements (Daviès et al, 1970) indicate that the Great Dyke and the Trompsburg Complex were emplaced at 2.541 ± 0.030 b.y. and 1.372 ± 0.142 b.y. respectively, compared to the age of 1.954 ± 0.030 b.y. for the Bushveld Complex. The uncertainty of the age of 1.881 ± 0.282 b.y. determined for the Losberg Complex suggests that it could be of Bushveld age. Mapping along the Crocodile River has shown that the Modipe gabbro and its associated granite pre-date the Transvaal Supergroup and, therefore, are older than the Bushveld Complex. Exclusion of those intrusives that have ages significantly older or younger than the Bushveld Complex restricts the distribution of possibly related intrusives to the northern portion of the Transvaal Province, but still results in the recognition of an intrusive event of a magnitude greatly in excess of any other known, layered mafic complexes ; only the Dufek intrusion in Antarctica may approach this size.

The events leading up to and constituting the emplacement of the complex have been summarized (Willemse, 1964; Hall, 1932) as follows :

1. Deposition of the Transvaal Supergroup including contemporaneous volcanicity, heralding the magmatic event, at three stratigraphic levels (i.e. Ongeluk, Machadodorp and Dullstroom),

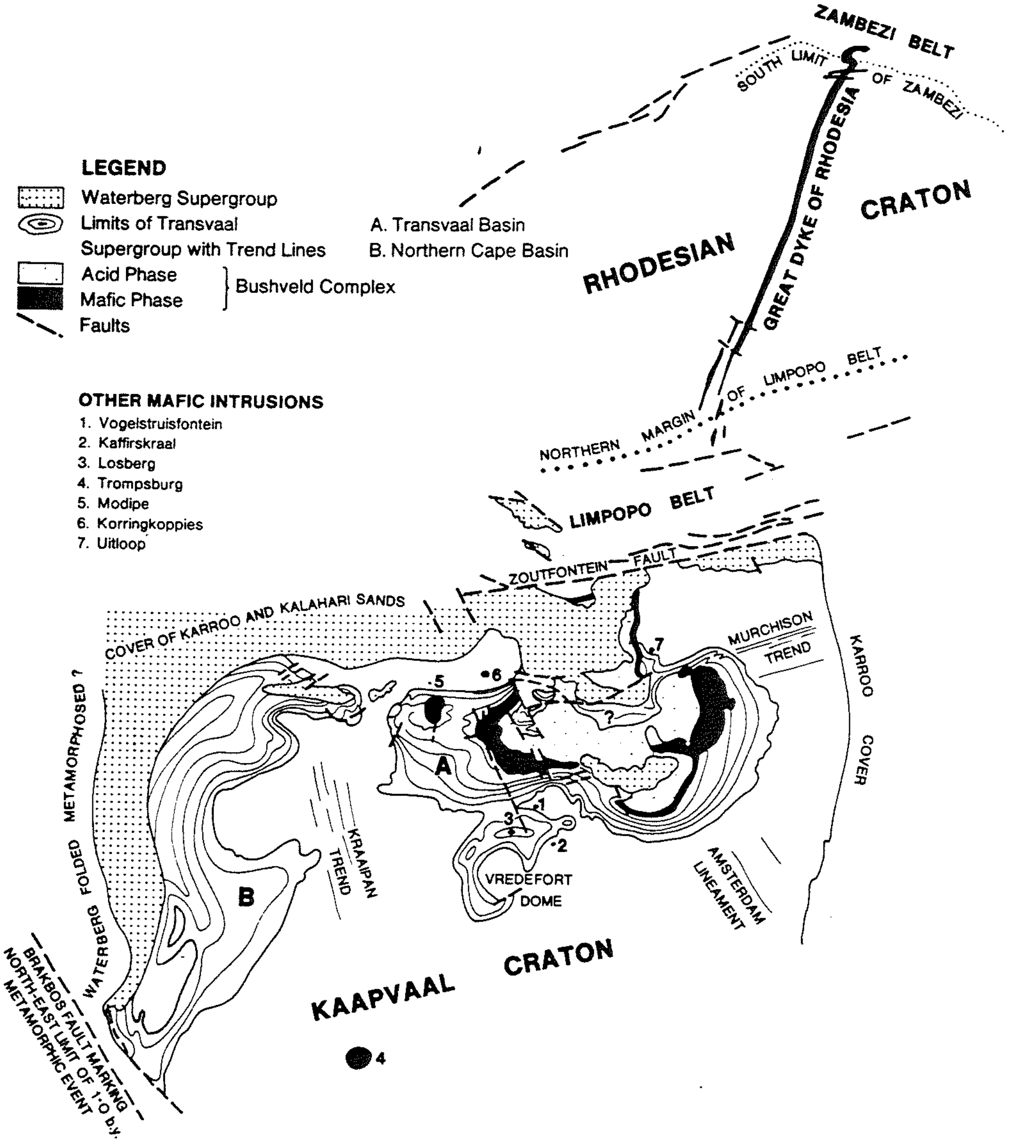

Figure 1 : The Bushveld Complex and locations of various mafic intrusions that have been regarded as members of the Bushveld intrusive episode, in the broad regional setting.

2. Sill phase of diabase sheets injected into the Pretoria Group of the Transvaal Supergroup,

3. Epicrustal phase represented by the Rooiberg felsites, granophyre, and interbedded sedimentary rocks,

4. Main plutonic phase which produced the layered sequence of ultramafic and mafic rocks,

5. Late plutonic phase represented by the Bushveld granites.

Objections (Truter, 1955) to the inclusion of the volcanics in this scheme were based on the eccentric distribution of these rocks with respect to the main mass of the Bushveld Complex. It was suggested (Willemse, 1969) that the presence of volcanic rocks in the northern Cape Province might be related to the Trompsburg layered intrusion, which at that time was regarded as a possible time-equivalent of the Bushveld Complex. This proposal does not appear to be valid in the light of the latest geochronologic data.

It was believed that the Dullstroom lavas had a restricted geographic distribution in proximity to the Bushveld Complex, and, on this basis, it was considered that only this unit had a genetic connection with the complex (Willemse, 1969). However, proposals (de Villiers, 1967) to include the Hartley Hill volcanics, formerly part of the post-Transvaal, Matsap Group, in the Transvaal Supergroup, implies that stratigraphic equivalents of the Dullstroom lavas extend into the northern Cape basin of the Transvaal Supergroup. If this re-classification is substantiated, volcanism at all stratigraphic levels in the Transvaal Supergroup has a consistent eccentric distribution with respect to the Bushveld Complex.

The petrographic similarity between the mafic rocks of the complex and the olivine-orthopyroxene-bearing sills, in conjunction with their increasing abundance close to the complex was taken as evidence for a genetic connection between them (Hall, 1932). The sills were subsequently shown (Lombaard, 1934; Willemse, 1959) to be divisible into two groups, namely, the noritic, orthopyroxene-bearing Maruleng, and the hornblende-bearing, Lydenburg types, the former lying closer to the complex. In Willemse's opinion, the Lydenburg type sills owed their mineral paragenesis to metamorphism during which hornblende was formed at the expense of clinopyroxene.

The concept of a genetic connection is rejected by Cousins (1962) and Truter (1962), the former believing that many of the sills are, in fact, lava flows because of the lack of thermal alteration in the overlying sediments, of the presence of amygdales towards the top of the sills, their apparently consistent stratigraphic position and the absence of related dykes. Truter (1962) argued that the mafic sheets are prolific in areas remote from the Bushveld Complex. He cites the apparent and imperceptible merging of a discordant sill with Ongeluk lavas in the type area for these rocks in the northern Cape Province as indicative of a close relationship between certain periods of sill emplacement and volcanism in the Transvaal Supergroup. The recognition in the eastern Transvaal of pillow structures (Button, 1973) in rocks that had been previously mapped as an intrusive sill partially vindicates Cousins's (1962) contention. However, the discordant nature of other mafic bodies is evidence for the existence of sills.

Frick (1973) identified the two varieties of sill as diorites and dolerites, retaining the use of the term diabase only in the English sense (Howell, 1957). The presence of dioritic fragments in Machadodorp pyroclastics and of other diorite sills that intrude stratigraphically higher beds indicates at least two periods of dioritic sill emplacement. Dolerite sills cross-cut both the Dullstroom volcanics and diorite sills (Frick, 1973), demonstrating a further period of sill emplacement. Thicker dolerite sills are layered into an olivine-orthopyroxene cumulate, an orthopyroxene cumulate, a plagioclase cumulate, and granophyre. A variety of diabases including uralite-, saussurite-, and quartz-bearing types can be recognized (Frick, 1973), the presence of clinopyroxene and uralite being taken as evidence of metamorphism, in the hornblende hornfels grade, of dolerite rather than diorite.

The calc-alkaline character of the Dullstroom lavas and the diorites contrasts with the tholeiitic nature of the dolerites and mafic rocks of the Bushveld Complex (Frick, 1973) but does not necessarily disapprove a genetic connection between them. It does, however, cast doubt on Cousins's (1962) proposal that the dolerites are a metamorphic response, similar reservations having been expressed by Vermaak (1970) on petrologic grounds.

Resolution of the relationships of the sills to the Bushveld Complex is of considerable importance in elucidating the morphology of the complex. In the western Transvaal, Liebenberg (1970) and Vermaak (1970) have reported differences in times of emplacement and petrology between sills and the Bushveld magma, whereas Coertze (1970) recognized no sharp contact between his quartz norite subunit (i.e. the sills of Vermaak and Liebenberg) and his marginal norite subunit (i.e. the base of the Bushveld layered sequence of Vermaak and Liebenberg). Acceptance of Coertze's view implies that there is a western extension of the Bushveld Complex from the Pilanesberg alkaline intrusive to the small basin of Bushveld mafic rocks north of Zeerust (see Figure 2); a view that is in accord with previously published maps of the complex (Hall, 1932; Willemse, 1964, 1969). Gravimetric data (Biesheuvel, 1970) suggests a distinct break in the continuity of the complex between the basin north of Zeerust and the Pilanesberg area, that lends support to the views expressed by Liebenberg (1970) and Vermaak (1970). Recognition of this revised configuration results in the main mass of the Bushveld Complex, together with its subsurface extension beneath the Karroo cover in the south-eastern Transvaal, having the form of four lobes arranged like a cross, with the north-northwest and east-northeast axes being approximately equal in length.

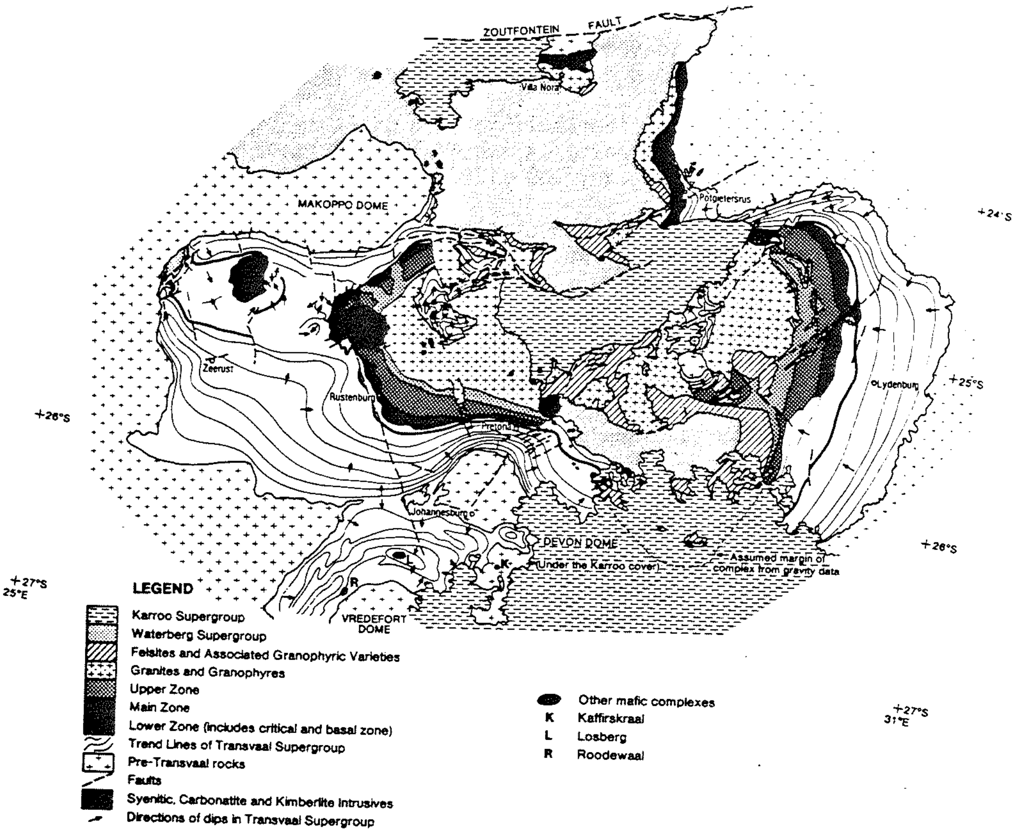

Figure 2 : Simplified geologic map of the Bushveld Complex.

The lack of agreement in regard to the first manifestations of the Bushveld magmatic event is repeated when the third, or Willemse's (1964) Epicrustal Phase is considered. The thick (± 4 km) pile of felsites with their associated granophyres and interbedded sediments was regarded originally as the basal Rooiberg Group of the Waterberg Supergroup, until it was recognized that, whereas the Rooiberg Group is intruded by the Bushveld granite, the stratigraphically higher units in this supergroup rest with a sedimentary contact on the same granites. As a consequence, it was concluded that the felsites represent, either the effusive roof of the Bushveld granite, or the terminal period of volcanism in the Transvaal depositional basin.

Willemse (1964) drew attention to the confinement of the felsites within the overall basin structure of the Bushveld Complex, implying a close relationship between the complex and the volcanics. The genetic connection between the felsites and the granite is borne out by the available geochemical data (Hunter, 1973a), from which it appears that the felsites could represent the explosively extruded, unfractionated product of partial melting in the crust, induced by the rise of mafic magma while the granites are derived from more complete melting of the crust by which stage fractional crystallization began to operate. However, there are other opinions concerning age relationships between felsites and mafic phase that are not in accord with this interpretation.

REGIONAL SETTING

Seven hypotheses have been proposed to account for the siting of the complex, namely :

1. a response to the central collapse of a vast geanticlinal structure produced by tangential forces in a cratonic environment (Daly, 1928),

2. alignment along a major lineament, that is most prominently marked by the Great Dyke of Rhodesia, trending slightly east of north (Hall, 1932; Brock, 1956, 1957; Cousins, 1959),

3. a response in the cratonic environment to deformation, particularly transcurrent movement on a continental scale, in the adjacent Limpopo mobile belt (Crockett, 1969),

4. emplacement of mafic magma along an east-northeast axis as a result of tension produced by tangential forces directed north-south in an orogenic environment (Truter, 1955; Visser, 1957),

5. emplacement in an orogenic environment, deformed by vertical movement, in which the supracrustal rocks are melted and, thereafter, injected as "magmas" of compositions appropriate to the original sedimentary rocks (Sandberg, 1926),

6. *in situ* replacement of the Pretoria Group sedimentary rocks (van Biljon, 1949), or

7. the product of meteorite impact (Dietz, 1963; Hamilton, 1970).

If the last hypothesis has substance, it follows that there were no pre-existing tectonic or structural controls that influenced the siting of the complex.

In discussing the impactite hypothesis to explain the origin of the Vredefort dome and Bushveld Complex, Cousins (1970) drew attention to the coincidence of sites of postulated meteorite impact with specific positions within the centres of the Witwatersrand and Transvaal sedimentary basins. Whereas shatter cones in the encircling sedimentary rocks of the Vredefort dome have been interpreted as being compatible only with an impact hypothesis (Hargraves, 1961; Manton, 1965), no evidence of shock-metamorphic effects has yet been found in rocks associated with the Bushveld Complex (Hamilton, 1970; French and Hargraves, 1971).

The remaining hypotheses require consideration of the tectonic controls that operated to permit the large-scale invasion of mafic and salic magmas into the upper parts of the crust, or, in the case of a metasomatic origin, the egress of the transforming solutions. Tangential forces are essential requirements in two of the hypotheses, but it must be noted that Brock and Pretorius (1964) have emphasized the role of vertical movements to explain the sedimentological and deformational history of the Witwatersrand basin, and a similar environment is apparent from the sequences in subsequent sedimentary basins (see, for example, Crockett, 1969). If tangential forces had been operative prior to and during the emplacement of the Bushveld Complex, it would be reasonable to expect to find more evidence in the deformational style.

Sandberg's (1926) postulate requires that the vertical movements were of a magnitude sufficient to depress the deeper parts of the Transvaal basin into the zone of melting. Even if this situation had been obtained, it is difficult to visualize the production of pyroxenitic and noritic magmas as a result of the partial or total melting of dolomite.

The alignment of the Great Dyke, Bushveld Complex, Vredefort Dome, Trompsburg Complex and various smaller occurrences of mafic rocks led to the hypothesis that mafic magma was injected into the crust via a deep-seated mega-fracture. The wide range of isotopic ages determined for some of these intrusives implies that this lineament was repeatedly reactivated. If the extent of the transcurrent, consistently dextral, movement within the Limpopo belt (Mason, 1969) is confirmed, it is difficult to explain the present-day alignment of these intrusions unless all movement pre-dated the first emplacement of mafic magma. It is now known that the Limpopo belt has undergone a long history involving metamorphism to granulite grade that pre-dates the intrusion of the Great Dyke (Robertson, 1968), but the age relationship between the Great Dyke and the transcurrent faulting is not known.

Crockett (1969) has suggested that the cause of basin formation on the Kaapvaal craton is linked with intermittent ductile flow of mantle material away from the foci of subsidence. The outbreaks of mafic andesitic volcanicity that preceded the Bushveld Complex are considered to be the products of the periodic heating and melting of the base of the steadily sinking crust. He postulates that the significantly different nature of the Bushveld magmas, which display a differentiation into basalt and granite, may be indicative of a more sudden collapse of the Transvaal basin which would leave little time for magmatic mixing so that tholeiitic magmas were injected, while the granite represents mobilization of sialic crustal material.

On a broad regional scale, the following facts require consideration :

1. the location of the Bushveld Complex adjacent to the broad, northwesterly trending basement arch that includes the Makoppo, Johannesburg, Devon and other domes,

2. the apparent confinement of the Rooiberg felsites to a northwesterly trending zone, coincident with the complex,

3. the location of the post-Bushveld alkaline intrusives at or close to the northeasterly flank of the arch,

4. the northwesterly aligned isostatic gravity positive feature under the western Bushveld,

5. the coincidence of the location of the Bushveld Complex with the interface between the northwesterly trending arch with the east-northeasterly trending linear features of the basement (i.e. Uitloop and Sabie platforms, the Chuniespoort arch) to the east.

The strong influence of a controlling, northwesterly aligned grain on the emplacement of the Bushveld Complex is emphasized further by the location along a similar and parallel trend of the Goudini outcrop of Bushveld rocks north of Zeerust, the Losberg layered complex, and the Vredefort dome with its associated gravity positive (Maree, 1944) that is interpreted to indicate the presence of mafic rocks within the domical structure.

That a north-northeasterly or northeasterly direction is present in the eastern Transvaal is indicated by :

1. the alignment of the isostatic gravity positive under the eastern Bushveld,

2. the elongation of the Magnet Heights, Steelpoort Park, and the Wonderfontein granite masses intrusive into the layered sequence in the eastern Transvaal,

3. the trend of the post-Transvaal dyke swarm.

Hall (1932) drew attention to the fact that the centre of the complex lies at the intersection of the east-northeasterly trending Murchison lineament and a projection of the Great Dyke trend. It was then believed that the complex had the form of a simple lopolith, but the gravity data do not confirm this interpretation and hence the point of intersection does not coincide with a focus of emplacement.

Deviations in the dominant trends observed in the eastern and western Bushveld areas may be due to a heterogeneous stress distribution at the time of emplacement. It is, however, important to note the directions of folding and faulting observed in the complex are repeated from the earliest Precambrian through to the Mesozoic.

AGE RELATIONSHIPS

Although narrow dykes and larger stocks of granite (e.g. Magnet Heights, Steelpoort Park) cut the mafic phase, Daly (1928) postulated that the main mass of the Bushveld granite together with its associated felsites and granophyre pre-dated the mafic phase. Strauss (1954) was unequivocal in regarding all the Bushveld granite as younger than the Main Plutonic Phase on the grounds that the granite at Magnet Heights corresponds to the earliest granitic phase post-dating the mafic rocks north of Potgietersrus. De Waal (1972) has interpreted the granitic rocks in the same area as the products of re-crystallization and metamorphism of felsite and porphyry consequent upon the intrusion of the mafic rocks of the complex. While the younger age of the granite, whatever its genesis, is now evidently accepted, there is a major divergence of opinion concerning the age relationships of the felsitic portion of the acid phase of the complex. Von Gruenewaldt (1968, 1972) concluded from his study of contact relationships in the eastern Transvaal that intrusion of the mafic magma into the felsites caused metamorphism involving re-crystallization and subsequently partial melting, the products of which gave rise to micrograinophyric sheet-like intrusions within the felsite pile. Continued addition of partial melt products thickened the sheets and gradually destroyed the metamorphosed felsite (i.e. the so-called leptites). As fractional crystallization of the mafic magma proceeded, the residual dioritic magma became enriched in volatiles, the upward migration of which caused additional melting of the leptites and hybridization to give rise to granodioritic liquids. The granodiorite so formed solidified as veins and pockets with sharp and gradational contacts with the leptites. Von Gruenewaldt (1972) concluded that the granodiorite remained liquid after the solidification of the diorites, and that some portions of the melt injected downwards into the diorites as thin dyke-like projections. The chemistry of the granophyres is in accord with their derivation by partial melting of the leptites at about 2 kb pressure which would be appropriate to the lithostatic pressure at the base of the felsite pile.

Despite this argument, broad structural relationships between the mafic phase and the felsites are not satisfactorily explained in the view of some students of the complex (e.g. Cousins, 1973), and emphasize the problems of interpreting contacts between felsitic and mafic rocks where field relationships show both the acid and mafic rocks to have apparently intrusive relationships with each other.

The felsites have a present distribution that is strongly aligned northwestwards within the overall lobate shape of the complex, that extends along its northwest axis beyond the presently exposed limits of the Transvaal Supergroup. Remnants of the roof of the mafic phase are preserved at several places (e.g. west of Pretoria, north of Magnet Heights, and north of Potgietersrus) consisting of upper members of the Transvaal Supergroup that are metamorphosed and structurally deformed. These relationships suggest that the Transvaal Supergroup was deformed before the eruption of the felsites, but at Rooiberg there is an apparently conformable sequence from uppermost Transvaal rocks to felsites, none of which is highly metamorphosed or strongly deformed. It has been suggested that these sediments are the products of sedimentation, preceding the volcanic event, derived from the erosion of Transvaal rocks deformed in the roof of the mafic phase.

ORIGIN OF THE ROCK TYPES

A magmatic origin for the mafic rocks of the complex has been generally accepted, although Sandberg (1926) and van Biljon (1949, 1963) postulated origins by melting of the Transvaal Supergroup and by transformation *in situ*, respectively. Despite van Biljon's vigorous defence of his hypothesis, the results of experimental petrology together with the increasing knowledge of the geochemistry of the complex makes acceptance of this concept difficult. However, a metasomatic origin for some or all of the varieties in the acid phase has been more widely proposed (de Waal, 1972; Coetzee, 1970; Iannello, 1970; Söhnge, 1963; Strauss, 1947).

Daly (1928) suggested that the layered sequence of felsite-granophyre-granite resulted from different rates of crystallization of an enormous lava field, derived by a process of differentiation by gravity in, and assimilation of wall-rocks by, a mafic magma. The proposal (Menge, 1963) that the felsites were ignimbrites is rejected by Coetzee (1970) because of the presence of flow-banding, flow-top phenomena, local amygdaloidal characteristics, and of undistorted volcanic bombs. Coetzee (1970) considered that the criteria cited by Menge (1963) in support of an ignimbrite origin were not unequivocal. Extrusion as a tuff-lava is not accepted because of the restricted development of pyroclastic features in many of the thick, massive and homogeneous piles of felsite (Coetzee, 1970). Beds and lenses of agglomerate, tuffs, and sediments are interlayered in felsite successions that also include quartzite xenoliths that range in size from masses several tens of meters in diameter to smaller bodies less than a meter across. It is the presence of these xenoliths with their sharp or gradational contacts with the enclosing felsites together with the absence of xenoliths of any other composition, which prompted Coetzee (1970) to suggest tentatively that some of the felsites are fused and mobilized Transvaal sedimentary rocks.

Hypotheses have been advanced that the layered structure discernible in the granophyres and granites of the complex may have been inherited from originally bedded sedimentary formations (Söhnge, 1963), or from sheeted porphyry intrusives related to the felsites and emplaced at their interface with underlying sedimentary rocks (de Waal, 1972). According to the former hypothesis, cross-cutting contacts of the granites may represent sharply defined fronts of recrystallization and, possibly, of melting. The tin ore-bodies in the granite north of Potgietersrus are regarded as the granitized equivalents of tin deposits found in sediments at Rooiberg. The proposal that the granites represent granite porphyry and quartz porphyry sheets recrystallized and metamorphosed by the emplacement of the mafic phase of the complex is based on the decrease in grain size of the granites away from the mafic rocks, the parallelism in the granite of isograds of pyroxene, hornblende-sphene, and biotite with the contact of the mafic rocks, and the discordance of the isograds to the felsite cover. The formation of porphyry sheets is believed to be due to the choking of the extrusive vents with the result that later heaves of felsitic magma were forced to spread as intrusive sheets. Only the stock of stanniferous Bobbejaankop granite is regarded in this hypothesis as the crystallization product of the magma, formed by palingenesis of unspecified siliceous rocks.

The origin of the granitic rocks has been discussed (Davies et al, 1970) on the basis of their isotope geochemistry. The R_0 value of 0.7153 ± 0.0088 derived for the granite is unusually high, but there is an overlap of the R_0 values of the mafic and acid rocks, although at the 68 per cent confidence level they are significantly different. It is concluded that the Sr isotope data are inconclusive and do not resolve the genetic relationship between acid and mafic magma, but that the most probable origin for the acid rocks lies in the remelting of crustal rocks at depth.

Granophyric rocks associated with the complex have been the subject of considerable speculation. Prior to the recognition that granophyres are developed in a number of different environments, they were taken to be the lower portions of felsite flows that solidified under their own roof (Hall, 1932; Lombaard, 1932). Where granophyre is intrusive into felsite, it was concluded that the granophyre intruded its own roof or that it was related to an overlying flow. However, granophyre is absent at the base of thick flows within the felsite pile (von Gruenewaldt, 1968), and is found with the following field relationships, for which a variety of origins has been proposed :

1. at the contact of mafic rocks with felsite. Origin : partial to complete melting of felsite as a consequence of the intrusion of Bushveld mafic magma (von Gruenewaldt, 1968, 1972).

2. at the contact of Bushveld granites and overlying felsites or sediments. Origin : direct crystallization from magma (Lombaard, 1932; Strauss, 1954; Steyn, 1962); metasomatic reaction (Strauss, 1947, 1954; Iannello, 1971); or metamorphic effect of intrusion of mafic phase (de Waal, 1972).

3. at the base of the Bushveld granite in association with discontinuous lenses of meta-sediments that occupy the interface between the acid and mafic magmas (pseudo-granophyre of Strauss and Truter, 1944). Origin : metamorphism and partial melting as a result of the intrusion of either the granitic or mafic phases (Strauss and Truter, 1944; Kuschke, 1950).

4. within the Bushveld granites adjacent either to cross-cutting plugs of younger granite or intrusive mafic dykes and sheets. Origin : metamorphic effect of intrusives (Lenthall, 1973).

ORIGIN OF THE LAYERING

Repetitive stratigraphy within the broader layers is a common feature of differentiated mafic complexes. Theories that employ an igneous mechanism to explain this layering, that is most strikingly developed in the Critical Zone of the Bushveld Complex involve (i) differentiation of a magma at depth with subsequent intrusion of the separate fractions with or without further differentiation *in situ*, or (ii) differentiation of a magma *in situ* with or without additions of magma to the differentiating body. A proposal (van Biljon, 1949, 1963) that the layering is inherited from metasomatized sediments of the Transvaal Supergroup has been made. However, if metasomatism did operate, it is remarkable that the sequence of differentiation products in other layered complexes, that could not have been formed by the transformation of a sedimentary sequence (e.g. the Great Dyke), should bear such a close resemblance to that in the Bushveld Complex.

Coertze (1958, 1970) argued in favour of separate intrusion of each layer of the mafic phase on the basis of transgressive relationships on both large and small scales. Coertze (1958) interpreted the presence of inclusions of pyroxenite and chromitite in anorthosite, of anorthosite in norite, and of porphyritic pyroxenite transgressive across the other rock types as evidence of multiple intrusion, the emplacement of each successive intrusion being controlled by planes of pseudostratification in the early-formed composite pyroxenite-chromitite sheet. By analogy, Coertze (1970) considered that the alternation of gabbro and anorthosite and the presence of fragments, derived from earlier sheets, in the ferrogabbro were intrusive phenomena, the layered mafic sequence being built up layer by layer so that each successive layer overlaps the previous one thereby giving rise to larger scale transgressive relationships.

Differentiation in depth as proposed by Lombaard (1932), Schwellnus (1956), and Coertze (1958, 1970) has been criticized (Hess, 1960; Ferguson and Botha, 1963; among others) and counter proposals supporting differentiation *in situ* by fractional crystallization or modifications of this process have been made (Hess, 1960; Cameron, 1963; Ferguson and Botha, 1963; Jackson, 1967). Ferguson and Botha (1963) point out that, whereas the Skaergaard intrusion is suited by its geometry to be a convective cell, the Bushveld Complex does not have such an ideal shape. These authors do not wholly reject the existence of small-scale convective cells for they present evidence that currents operated during the crystallization of the magma, but they interpret the persistence along strike for distances of several tens of kilometers of individual layers as being inconsistent with this mechanism as the primary cause of the layering. It is proposed (Ferguson and Botha, 1963) that a combination of undercooling and convective overturn of the metastable upper crystallizing layer in the magma chamber with additional winnowing effects consequent upon the relative lightness of plagioclase feldspar, kept in suspension by currents within the chamber, was responsible for the layering. These authors also note that the palaeomagnetic data (Gough and van Niekerk, 1959) yield a focal point when the layers of the Main Zone are rotated into a horizontal position, in contrast to the random scatter of points that results when the present attitude of the layering is used. It is concluded that gravity was an additional controlling mechanism to produce the layering. A review of mineral variation curves (Ferguson and Botha, 1963) shows the largest compositional break to lie at the Merensky 'reef' horizon. The authors suggest a new addition of magma to the chamber in view of the conjunction of the compositional break with the persistence of the Merensky 'reef'.

A study (Gijbels et al, 1974) of osmium, ruthenium, and iridium contents in orthopyroxene, plagioclase and chromite mineral separates has resulted in the proposal that, in the eastern Bushveld Complex, there are two separately injected magmas; the first yielding the Lower and Transition Zones (according to Cameron's classification of the rock units, 1970a) and the second producing the Critical, Main and Upper Zones. However, the broad trends in the major compositions of the same minerals (Cameron and Desborough, 1969; Cameron, 1970a), are regarded as being consistent with differentiation of magma *in situ* (Cameron, 1970a).

Cousins (1959a and b) has proposed that the layering results from successive extrusions, basing his postulation on the floor relationship of the mafic sequence and of the layering of the mafic rocks. He pointed to the general regional conformity between the rocks of the complex and the Transvaal Supergroup, the absence of intrusive contacts, and the local folding that affects the underlying sediments but not the rocks of the complex. He concluded that the mafic layers were extruded successively onto a folded and eroded surface of Transvaal rocks. Feringa's (1959) study of the footwall relationships of the Merensky 'reef' was taken as evidence that successive extrusions drowned depressions on the floor of the lava field, ultimately transgressing across 'islands'. The fragments of Transvaal rocks within the basal units of the mafic phase of the complex are interpreted as portions of the up-domed floor, but Coertze (1960) regards them as xenoliths. That pre-Bushveld folding of Transvaal rocks occurred is apparent from the studies in the western Bushveld Complex (Liebenberg, 1970; Vermaak, 1970), but neither of these authors supports an extrusive mode of emplacement for the mafic rocks.

Although an extrusive origin for the Bushveld Complex has been discounted, it should be remembered that Daly (1928) proposed that the complex represented a vast differentiating extrusive lava flow that was capped by a felsitic crust beneath which later felsic magmas (i.e. granites and granophyres) were retained, thereby building a strong roof at or close to the lower interface of which the mafic rocks were emplaced. Hamilton (1960) took this idea further and proposed that the Bushveld, Sudbury, and Wichita complexes represent extrusive lopoliths. He pointed out that plateau basalts as a consequence of repeated extrusion build up flows several kilometers thick. Had the extrusives followed each other in rapid succession, Hamilton (1960) considers that extrusive lopoliths would result.

MORPHOLOGY OF THE COMPLEX

The inward dip of the layering and the lobate outline of the complex suggested to early investigators that the complex had the form of a lopolith. Subsequently, Truter (1955) proposed that the complex was intruded through four or five separate loci extending along an approximately east-west tensional fracture, with the form of "pear-shaped" bodies. Cousins (1959a) deduced from the gravity data (Smit et al, 1962) the presence of two main fissures, one underlying the western Bushveld and one in the east, with a third, probable locus of emplacement, with concentrically arranged gravity contours, near Potgietersrus. Cousins (1959a) proposed that the fissures expanded near surface into synformal sill-like bodies. The isostatic gravity map (Smit et al, 1962) emphasizes the linearity of these two postulated fissures; the western gravity positive striking north-northwestwards, and the eastern anomaly having a north-north-easterly orientation that is parallel to the post-Transvaal dyke and fault swarm in the eastern Transvaal. The synformal shape (Figure 3) of the complex over the eastern gravity anomaly has been demonstrated by recent mapping southeast of Groblersdal (von Gruenewaldt, 1968, 1972, 1973).

The gravity data also reveal that mafic rocks do not extend beneath the centre of the complex. A number of small areas of positive gravity were located from north of Pretoria to Warmbaths, where an outcrop of Transvaal dolomite is coincident with one of these gravity highs. Smit (1959) suggested that these anomalies could be due either to the presence of feeders for the Karroo basalts that flooded the central Bushveld area, or patches of Transvaal dolomite brought close to the surface by deformation and subsequent erosion of overlying strata. The gravity data suggest that the mafic rocks of the complex do not form a continuous ring and that there is hence no continuity between outcrops near Potgietersrus and those reappearing from beneath the Karroo cover to the east of that town.

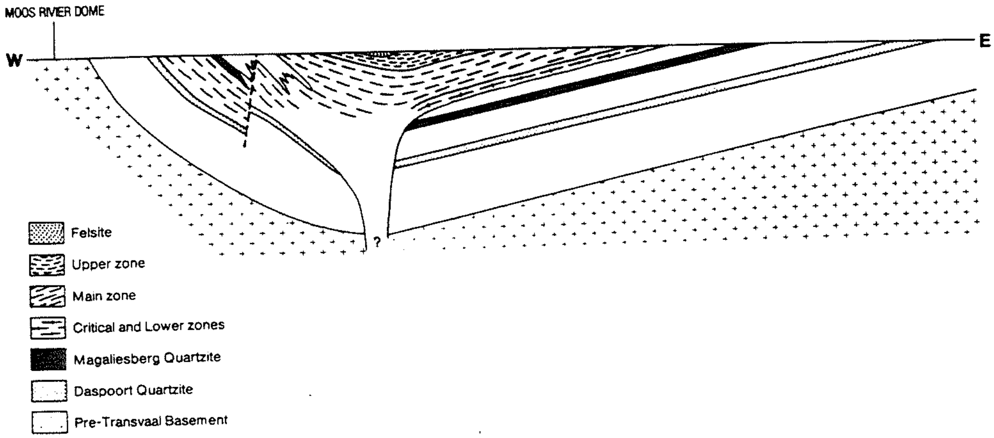

Figure 3 : Section across the Bushveld Complex mafic unit in the Bloed River valley, southeast of Groblersdal. Length of section 150 km. No vertical exaggeration of scale.

Gravity data from the area north of Zeerust have been interpreted provisionally (Biesheuvel, 1970) to indicate the presence of a lopolithic body of Bushveld rocks, with a feeder sited close to the position now occupied by the Goudini alkaline complex. The gravity contours within this lopolithic mass reflect elongation in north-northwesterly and east-northeasterly directions.

Two large outcrops of pre-Bushveld rocks, north of Rustenburg and near Groblersdal, known respectively as the Crocodile river and the Moos river - Marble Hall fragments, are significant in considering the form of the complex. The rocks forming these outcrops belong to the lower members of the Transvaal Supergroup and older rocks, and have been metamorphosed and deformed (Verwoerd, 1963; de Waal, 1970). Daly (1928) regarded the Crocodile river fragment as a great block stoped up from the floor of the complex by the Bushveld granite. Subsequent authors have questioned the mechanics of such an operation involving the floating upwards in granite of dense dolomitic rocks with a surface area of several hundred square kilometers. Alternative views have been reviewed by Verwoerd (1963) who considers that the available evidence can best be interpreted by regarding the fragment as the core of a Bushveld cone-sheeted complex.

The structural complexity of the Marble Hall fragment has been unravelled by de Waal (1970) who concluded that initial deformation occurred immediately prior to or during the initial stages of the emplacement of the mafic layered sequence of the complex. A second phase of folding further deformed and refolded the rocks during the main period of Bushveld plutonism. The fragment would then represent an up-domed portion of the floor of the complex.

Lying adjacent to, but separated by faults from, these floor fragments are less deformed sediments overlain by felsites that comprise the Rooiberg and Stavoren fragments, the field relationships of which are taken to indicate that they are remnants of the roof of the Bushveld granite.

As a result of the subsequent deposition of Karroo sediments within a trough in the central Bushveld, the structure of the Transvaal rocks in this region is uncertain. The probable existence of up-domed fragments of floor rocks in both the Marble Hall and Crocodile river fragments, together with the possibility that dolomite may lie at no great depth beneath the western end of the Karroo cover in the central Bushveld suggests the possible existence of a pre- or early Bushveld antiformal structure between the two main positive gravity features.

Willemse (1969) has rightly emphasized the transgressive relationships of the layered sequence to the encircling sedimentary rocks, which is particularly noticeable in the eastern Bushveld (Figure 2). He concluded that these relationships together with the presence of the deformed sedimentary fragments within the complex could be explained if the plutonic rocks were emplaced as cone-sheets, perhaps derived from a number of centres of eruption.

If the mafic rocks of the Bushveld Complex were intruded from a number of centres, all the sites of intrusion must have been subjected to the same or similar physicochemical conditions because of the remarkable correspondence in rock types, thickness and nature of layering in places several hundred kilometers apart (Ferguson and Botha, 1963; Willemse, 1969).

In considering the morphology of the intrusion, cognizance must be taken of the palaeomagnetic data (Gough and van Niekerk, 1959) and the gravitative crystallization history (Ferguson and Botha, 1963) both of which require a horizontal or near horizontal floor, neither of which can be wholly accommodated within a cone-sheet or a funnel-shaped intrusive.

DEPTH OF EMPLACEMENT

There is considerable uncertainty about the thickness and nature of the roof of the complex, or indeed, in Cousins's view, whether there was a roof at all. What is clear, however, is that crystallization of the original magma or magmas took place at shallow depth. Von Gruenewaldt (1972) has concluded from his studies in the eastern Transvaal that the mean composition of the granophyre, produced, in his opinion, as a result of the partial fusion of the metamorphosed felsites, corresponds closely to the minimum melt composition of these rocks at a pressure of 2 kb. A minimum thickness of 4 550 m of felsite and granophyre has been preserved in this area (von Gruenewaldt, 1968) corresponding to a lithostatic pressure of 1.8 kb. If, therefore, von Gruenewaldt's conclusions regarding the observed field relationships are correct, the Bushveld Complex can be assumed to have been emplaced at depths of 4-5 km. Cousins (1973) has raised a number of objections to this concept, basing his argument on the common associations of felsic rocks with other layered mafic complexes, the absence of felsites from the so-called undisturbed successions of the Pretoria Group, and the similarities in composition between the felsites and granites, only the latter being generally considered to be post-mafic phase as a consequence of the frequent presence of this rock in dykes intrusive into the mafic zone. Von Gruenewaldt (1973) considered that the present distribution of the felsites results from the fact that the mafic magma was emplaced along an irregularly undulating plane within the upper part of the Pretoria Group and that the highest beds of this group were lifted up by the emplacement of mafic rocks and have since been removed by erosion. He further proposed that the absence of felsite in the floor of the mafic intrusive could be due to the unfavourable section exposed at the present level of erosion or to the locus of emplacement of the mafic rocks lying consistently below the stratigraphic level of the felsites. Von Gruenewaldt contended that there is a distinct chemical difference between felsite and Bushveld granite, implying that there is no consanguinuity between them. In this respect, the trends of major, minor and trace element data have been interpreted as indicating the probability that the felsites and granites represent a fractionating series (Hunter, 1973a).

MINERALIZATION

The deposits of chromite, platinum minerals, and titaniferous magnetite associated with the mafic layered rocks have been the subjects of extensive research, and it is not proposed to discuss these in detail. Concentrations of tin and fluorite related to the felsic rocks have received less attention.

Chromitite layers have been traced along strike for 65 km in the eastern part of the complex, and for similar distances in the western lobe from Rustenburg. Cameron and Emerson (1959) have found no evidence to support the hypotheses that these seams result from the selective replacement of a particular layer in an originally sedimentary sequence, nor that the repetition of seams is a consequence of repeated injections of chrome-rich magmas. Rather they find the observed textural and compositional features to be consistent with magmatic sedimentation, with, however, part of the chromite and bronzite crystallizing *in situ*. Currents within the magma are considered to have had an important function in developing the contrasting rock types. The order of crystallization of minerals is taken as evidence that the chromite layers did not form by residual liquid accumulation. The authors recognize that liquid immiscibility may have been a supplementary feature but they do not consider it to have been significant. Coertze (1958) has suggested that successive intrusions of magma have split an originally compact chromitite layer but the detailed examination of the layering by Ferguson and Botha (1963) lends little support to this view.

The chromitite-bearing platiniferous Merensky 'reef' can be traced continuously for long distances of 120 km in the eastern and western parts of the complex, maintaining a remarkable stratigraphic persistence within the other layers. Liebenberg (1970) considered that variations in the S content of the mafic magma were responsible for varying concentration of sulphides. He finds evidence for a gradual decrease in the S content until it became so low that a mainly Cu sulphide immiscible liquid formed during the crystallization of the norite and anorthosite below the Merensky 'reef'. The Cu content was insufficient to remove all the sulphur with the result that the sulphur content of the magma gradually increased. Following a change in the composition of the magma and at low oxidation potential an immiscible copper-nickel-sulphide liquid developed, droplets from which settled down and formed an intercumulus liquid within the Merensky 'reef' horizon.

The Merensky 'reef' varies in thickness from a few meters to over 26 m, in part, due to the presence of depressions and domes. The 'reef' is stoped over an average width of about 75 cm within which the concentration of economic minerals varies in thickness from a pencil line to about 6 cm. The deepest borehole intersections have been made at depths of 1 700 m below surface. It is estimated that about 5 600 000 000 grams of platinum metals are available for exploitation and that a further 9 billion grams are contained in unproven potential reserves (Newman, 1973).

Chromitite reserves of 10 billion tons have been estimated (Newman, 1973) in seams that range up to 1.8 m in thickness and carry between 25 and 49 per cent Cr_2O_3.

Towards the top of the layered mafic sequence magnetitite layers make their appearance. Molyneux (1970) has recognized 21 such 'seams' some of which consist of two or more closely spaced magnetite layers, and which are remarkable for their persistence and regularity, implying, in Molyneux's view, tranquil, rhythmic crystallization conditions. In addition, there is a steady decrease in the content of V_2O_5 from approximately 2 per cent in the lowest to less than 0.3 per cent in the highest layer (Molyneux, 1970).

Pipe-like, pegmatoid bodies are found throughout the layered mafic sequence, but, with the exception of certain of the magnetite pipes in the Main Zone, these are no longer exploited commercially. The compositions of the pegmatoids range from nickeliferous bronzitite in the Basal Zone, through dunite in the vicinity of the main chromitite seam and diallagite in the Critical Zone and magnetitite and vermiculite in the Main and Upper Zones. The magnetitite pegmatoids have vanadium contents similar to that of the magnetite seams at the same stratigraphic level. It is evident that the pegmatoids were formed in a number of ways, i.e. by replacement (Cameron and Desborough, 1964), by foreceful emplacement (Ferguson and McCarthy, 1970), and by the filling of dilational fractures (Cameron, 1970b).

Lensoid bodies of apatite-bearing magnetitite are reported from the Villa Nora area (Grobler and Whitfield, 1970), that carry in excess of 10 per cent of apatite by volume and a P_2O_5 content of up to 9 per cent. The authors suggest that liquid immiscibility played a role in the formation of these particular magnetitite bodies, which have not so far been reported from other parts of the complex.

Wagner (1926a and b) reported the occurrence of gold 40 km northeast of Rustenburg associated with "pyroxenite quartz-bearing soda-gabbro" that forms a sill intrusive into highly metamorphosed sedimentary rocks of the Pretoria Group, lying at or near the interface between the mafic phase below and granophyres and granite above but, where the sill is auriferous, the metasediments are wholly enclosed within granophyre. The gold is found as scattered visible grains, often associated with limonitic patches resulting from the oxidation of original pyrite and pyrrhotite. Wagner (1926b) also reported the presence of gold telluride, identified as krennerite. The auriferous sill grades into pyroxenite, or into quartz gabbro and quartz monzonite which may be pegmatitic in texture.

Tin has been mined from six fields within the Bushveld Complex, of which three are still producing (see Figure 4). Of the recorded production during the period 1904 to 1971, 35.75 per cent. has been won from ore-bodies in granite, 56 per cent from exogranitic deposits in sediments of the Transvaal Supergroup, and 8 per cent from deposits in the felsites, while the granophyres have contributed 0.25 per cent (Lenthall, unpublished data). The geological environments of tin mineralization are shown schematically in Figure 5.

The endogranitic deposits are located in the roof of stocks of mairolitic granite that intrude the crudely stratiform Bushveld granite. Trace element studies (Fourie, 1969; Lenthall, 1972) which reveal a depletion in elements such as Ba, Sr, and Eu coupled with an enrichment in Rb and Cs in the younger mineralized stocks, are consistent with the view that the tin is concentrated in the terminal stages of fractional crystallization of the Bushveld granite. The mineralization is located in flat-lying zones, up to 12 m thick within 120 m of the roof of the stock, that carry disseminated cassiterite at Zaaiplaats, or associated with replacement about joints and fissures at the dormant Mutue Fides mine in the Olifants tin-field. Pipe-like ore-bodies, displaying a bewildering complexity of shape and attitude, were the main source of ore at Zaaiplaats until 1926, and similar deposits were mined at Mutue Fides. The pipes are roughly cylindrical bodies up to 12 m in diameter (mean 1 to 2 m) located within 275 m of the roof of the mineralized granite stocks, and traceable in length from 7 to 1 000 m. A typical pipe has a pronounced annular structure; a core of sericitized and/or chloritized granite carrying disseminated cassiterite, with variable amounts of pyrite, fluorite and scheelite is surrounded by successive rings of bright red feldspar, tourmaline, white quartz, and red silicified granite. Each individual ring is not always developed, and, in depth, the tourmaline ring may become increasingly larger, ultimately forming the core of the pipe or enclosing a silicified granite core that is barren of cassiterite. A vertical mineral zonation is suggested by the presence of increasing amounts of copper- and zinc-bearing sulphides in the pipes developed at the upper contact of the mineralized stock. The presence of scattered sericitized or intensely chloritized granite patches associated with irregularly shaped vugs, is a feature of the stanniferous granites.

In the Nylstroom tin-field, tin is found in or adjacent to fissures in felsite and an interlayered argillaceous bed that, in the vicinity of the main producing mine, is siliceous. The economically exploitable ore-bodies are located within this bed (the so-called Union shale) as a stockwork of fine-grained cassiterite associated with hematite, magnetite, and lesser amounts of chalcopyrite, arsenopyrite, and galena, adjacent to fractures but not actually filling them (Menge, 1963). Chloritization of the country rock is prominent although the degree of chloritization is not necessarily indicative of the grade of cassiterite mineralization.

The third main setting for mineralization lies in the arkoses and shales belonging to the Pretoria Group in the Rooiberg tin-field with which andesitic lavas are interlayered, the whole sequence being overlain by felsites. Leube and Stumpfl (1963) recognized two types of deposit, firstly ore-bodies formed by replacement within a stratigraphically defined arkose bed, the ore-forming fluids gaining access through a system of shear and tension fractures, and, secondly, ore-bodies located in fractures initiated as a result of the emplacement of the Bushveld granites. In the former case the cassiterite has low contents of Be, Nb, and Sc, the associated pyrite contains 300 to 400 ppm of both Co and Ni, and the ankerite is poor in $FeCO_3$. In contrast the structurally controlled ore-bodies of the second type are associated with the widespread occurrence of Fe-oxides, of pyrite, and chalcopyrite. The cassiterite has relatively higher concentration of Nb, Be, and Sc, while pyrite contains up to 6 000 ppm Ni and 5 000 ppm Co. An annular structure is apparent in the replacement type deposits; an outer rim of red quartzite surrounds a ring of white silicified quartzite that encloses a core of tourmaline, sulphides (mainly pyrite) and, locally, feldspar, with a ring of cassiterite and tourmaline. A notable feature of the pipe-like bodies and blows is that the prominent cross-bedding of the arkoses can be traced into the outer rims of the annular structure. Other ore-bodies have cores of cassiterite and tourmaline associated with orthoclase or sericite, and carbonate.

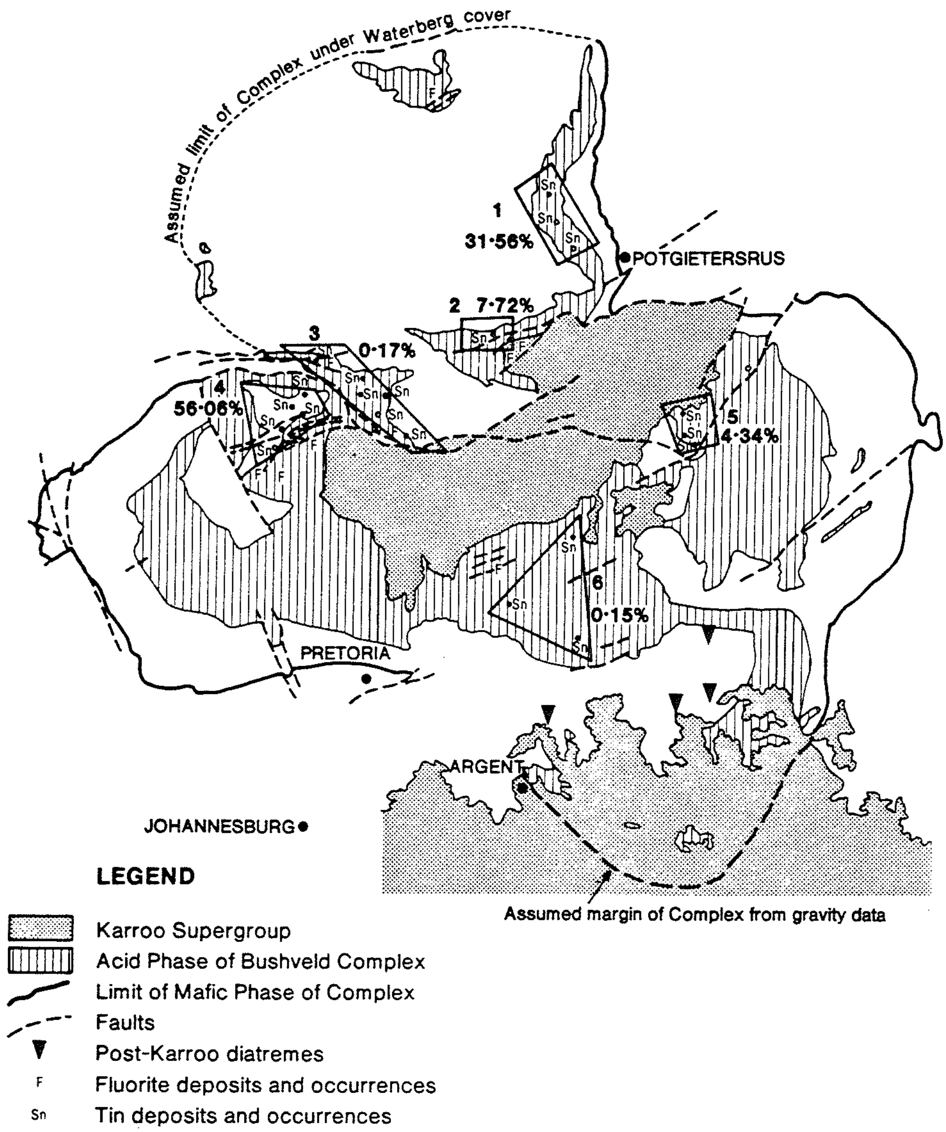

Figure 4 : Location of mineralization associated with the acid phase of the Bushveld Complex. The six main tin-fields are shown together with the proportion of the total tin production from the complex that each area has contributed. (Modified after an unpublished map by D.H. Lenthall).

Chloritization affects the wall-rocks adjacent to faults, fissures, and breccias. Many of the structurally controlled ore-bodies are located in fractures parallel to the bedding of the country rocks. Leube and Stumpfl (1963) support a hydrothermal origin for the ore-bodies at Rooiberg, this theory being attractive in view of the observed mineral and temperature zonation.

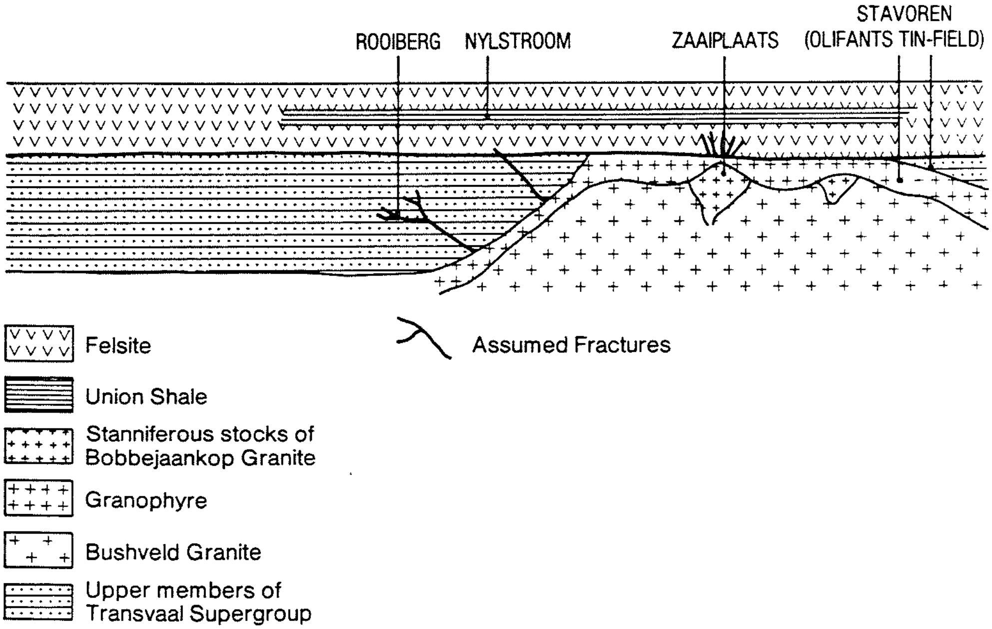

Figure 5 : Schematic representation of the main locales for tin mineralization in the Bushveld Complex.

In the Olifants tin-field, stanniferous pipes were mined in the granophyre that forms the roof of the granite in this area. The pipes, ranging in diameter from 5 cm to 5 m are aligned along a north-westerly trend, and display an annular structure. The core consists of calcite or fluorspar often containing patches of arsenopyrite, or a vug lined with quartz. A ring of tin-scheelite-arsenopyrite surrounds the core and is itself enclosed by a feldspar-rich rim that may have a selvedge of black mica and an outer rim of chlorite. Steyn (1962) did not find evidence to support Wagner's (1921) contention that the pipes were developed along fissures. Steyn envisaged that, as the ore-bearing solutions migrated upwards, they leached K and Na from the wall-rocks. When the now alkaline solutions moved into areas of lower temperature in the roof of the granite, the alkalis were returned to the wall-rocks, causing albitization and de-silicification of the granophyre. The remaining K and Si in solution supplied the source for the development of adularia and quartz that are prominent gangue minerals within the mineralized pipes. Chloritization both preceded and succeeded the deposition of cassiterite.

The quartzites overlying the granophyre are mineralized along fractures in which wolframite, chalcopyrite, pyrite and abundant specularite are associated with the cassiterite.

Deposits in the remaining tin-fields scarcely proceeded beyond the prospecting stage. These deposits, in both felsite and granite, are associated with fractures and joints, the host rock being heavily chloritized. In addition to cassiterite, pyrite and chalcopyrite are present in the fissures.

The origin of the tin deposits has been attributed to the Bushveld granite by most authors, with the exception of Recknagel (1909) who proposed that both the felsitic and granitic magmas were stanniferous. Those authors who subscribe to a metasomatic origin for the felsic rocks have failed to explain satisfactorily the mechanism whereby cassiterite was concentrated. Söhnge (1963) did tentatively suggest that the endogranitic deposits might represent deposits of Rooiberg type that were overwhelmed by the wave of metasomatism. This would pre-suppose that the sediments of the Pretoria Group were stanniferous, either presumably as a result of sedimentary or exhalative processes. There is no evidence that the former is true, but serious consideration should be given to a possible exhalative origin for deposits such as those in the Rooiberg and Nylstroom fields, particularly as volcanics are interbedded with the sedimentary succession. Insofar as the endogranitic deposits are concerned, the geochemical evidence points to the fact that the stanniferous granites are the end products of fractional crystallization, making it unlikely that these deposits owe their origin to metasomatic processes.

Attention has been drawn (Hunter, 1973b) to the fact that major tin deposits within the complex lie at the intersection of the Murchison lineament and the northwesterly trending basin containing the felsites. The Murchison lineament was the site of reactivation until after the deposition of the post-Bushveld, Waterberg Supergroup, and it is noticeable that the bulk of tin production has come from those areas of the Bushveld Complex that are adjacent to this direction. Volatiles within the granite are likely to be concentrated in structural highs in the roof of the granite, and it should be noted that the stanniferous granites of the Potgietersrus field are located in an antiformal warp, the axis of which trends parallel to the Murchison lineament.

In the latter years of the last century, a silver deposit was worked on the farm Roodepoortje in the Moloto tin-field. It was described (Hall, 1932) as a vertical replacement lode in a fissue zone, in which argentiferous bornite was accompanied by chalcopyrite, tetrahedrite, chalcocite, cuprite, malachite, native copper and gold. Quartz, specularite, and siderite formed the gangue minerals. A metazeunerite type mineral has been identified at this locality recently (Champion, 1973).

Eighty kilometers east of Johannesburg, a galena-bearing vein striking northwestwards was mined until 1925. The vein cuts through norite and hornblende granite (de Jager, 1966). Pyrrohotite, chalcopyrite, arsenopyrite, native silver and argentite, accompany the argentiferous galena, in a gangue of sideroplesite, with minor amounts of calcite and patches of chlorite. Uncertainty prevailed concerning the age of the norite but recent radiometric age determinations reflect a Bushveld age (Burger et al, 1967) but the age of the mineralization is still not known.

The majority of fluorspar deposits in the felsic rocks of the complex are associated with faults (see Figure 4), several of which can be demonstrated to be of post-Karroo age or reactivated at that time. Warm springs are located along some of these faults, particularly those striking northeast or east-northeast, and some of the fluorspar deposits are situated in close proximity to these springs. At other localities the fluorite veins are located along faults that lie at angles of about 30° with the main northeast or east-northeast faults.

Deposits south of the Rooiberg tin-field and adjacent to the Nylstroom tin-field differ from the fault or fissure-type occurrences. At the old Gilspar and Slipfontein mines (south of Rooiberg), the fluorite is found in pipe-like bodies in granite, the longer axes of which measure 160 m (Gilspar) and 90 m (Slipfontein). Specularite, hematite, and chlorite are associated with the fluorite at the Gilspar mine, whereas at Slipfontein, fluorite forms a ring within the quartz-filled pipe. The deposit near Nylstroom is located in gently westward dipping joints in granite and leptite. Faulting has affected this area and a thin veneer of Karroo sediments covers much of the granite.

The origin of the fluorite deposits has not yet been fully investigated. Kent et al (1943) drew attention to the association of warm springs and faults with many of the deposits, and to the high concentrations of sodium carbonate and fluorine in the spring waters. The Bushveld granite, particularly the stanniferous stocks, is known to have fluorine contents up to several thousand ppm (Lenthall, unpublished data). Although there is no proof at this stage, it is suggested that many of the fluorite deposits owe their origin to the movement of connate waters trapped in Karroo sediments, the fluorite being preferentially concentrated from these waters along post-Karroo faults and fissures. The pipe-like deposits may be related to volatiles concentrated near the roof of the Bushveld granite in structural highs in a similar fashion to the stanniferous stocks.

The emplacement of the Bushveld Complex is held responsible for lead-zinc-fluorite deposits in the enclosing Transvaal rocks. Those near Zeerust have been attributed to hydrothermal solutions derived from a hidden off-shoot of the complex, the existence of which being postulated on the evidence of the widening of the metamorphic aureole (Willemse, 1969). The deposits occupy distinct stratigraphic positions near the top of the Transvaal dolomites and also lie on the flank of the arch that now separates the two basins of Transvaal sedimentation. It is probable that this arch was a positive feature at various times during Transvaal sedimentation (Visser, 1971). It is not without significance that these deposits lie close to the margin of the possible sub-surface continuation of the pre-Transvaal Gaborone granite that is also a fluorine-rich granite. These relationships, together with the stratiform nature of some of the deposits in the Zeerust area, suggest analogies with the Mississippi valley type deposits. Lead isotopic compositions of galenas emplaced in Transvaal sediments have shown a particular pattern of variation of the isotopic ratios Pb^{206}/Pb^{204} and Pb^{207}/Pb^{204} that cannot be reconciled with theoretical models for lead isotope evolution, although the model ages for the galenas in the Zeerust district are in reasonable agreement with the age of the Bushveld Complex (Nicolaysen et al, 1958). The uncertainties in interpreting the isotope data do not permit a firm correlation between the Bushveld event and the mineralization.

Gold was won, until recently, on a moderate scale from stratified quartz-pyrite 'reefs' in Transvaal dolomite and, to a lesser extent, in the underlying, lower members of the Transvaal sedimentary succession, in the eastern Transvaal. Ore-bodies also had the form of cross-cutting veins, impregnations and "blows". The stratiform 'reefs' are localized along planes of intrastratal movement for which evidence exists in the form of slickensiding and off-setting of dykes. Several authors have postulated a hydrothermal origin for these deposits, consequent upon the emplacement of the Bushveld Complex, but reservations have also been expressed (Willemse, 1969). Like the Zeerust fluorite-lead-zinc deposits, the mineralization is unique but the stratigraphic and structural settings are repeated in other parts of the sedimentary envelope of the complex. The presence of a swarm of dykes and numerous sills of 'diabase' within the goldfield, that are assumed to be consanguinous with the Bushveld Complex has influenced genetic theories. Shales interbedded with dolomites north of the mineralized area, contain 0.1 ppm Au (Minnitt et al, 1973) and, as Willemse (1969) has previously suggested, the ore-bodies could have been derived from proto-ore of this type as a result of greater chemical mobility consequent upon the intrusion of the dykes.

DISCUSSION

The lack of unanimity concerning the temporal and spatial relations of the complex requires that, in the first instance, attention must be directed towards the resolving the problems of the components of the complex. Geochronologic data have shown that many of the mafic layered intrusives, formerly considered to be part of an all-embracing Bushveld petrogenetic cycle, have ages that are substantially older or younger than the Bushveld Complex, but uncertainty still remains as to whether the volcanics interbedded with the Transvaal sediments are the precursors of the plutonic event. Reasons for their exclusion have been given and it is relevant to consider the conceptual model that has been proposed (Pretorius, 1966) to account for the development of the Proterozoic sedimentary basins on the Kaapvaal craton. In this model it is envisaged that the basins developed in an environment where vertical tectonics prevailed and that a basin would remain active as long as the potential gravitational energy of the crust was sufficient to permit repeated elevation of the source areas around the basins. The nature of the basin-fill reflects the maximum energy level, and the number of repetitions of volcanics, coarse and fine clastics, and non-clastics is taken as a function of the intensity and number of cycles of waxing and waning of energy associated with periods of elevation and subsequent quiescence. The sequences of sediments and volcanics in the successive basins reflect a typical pattern when they are considered as functions of energy, and which it is possible to define in terms of the harmonics of wave forms. The first harmonic represents the overall life of the basin, while superimposed harmonics of higher order reflect the number and intensity of periods of uplift and subsequent periods of erosion and deposition. The volcanics in the Pretoria Group, together with those in the Wolkberg Group, deposited in the proto-basin that developed into the Transvaal basin, are in keeping with the conceptual model. Acceptance of this model implies that the various periods of volcanism within the Pretoria Group are fundamental components of the Transvaal depositional basin and, hence, are not necessarily consanguinous with the Bushveld plutonic event. The extrusion of lava would have taken place irrespective of whether the Bushveld Complex was emplaced or not. This argument, together with that presented by Truter (1955) is considered to be a compelling reason for discounting the volcanics as precursors of the Bushveld event.

The evidence cited by Frick (1973) when read with that presented by Truter (1962), Liebenberg (1970), and Vermaak (1970), raises serious doubts that the majority of the mafic sills that invade the Transvaal sediments represent the hypabyssal phase of the Bushveld Complex. The proposal by Cousins (1962) that many of the so-called sills are, in fact, flows, has been partially vindicated (Button, 1973) but transgressive sills can be demonstrated in the field as well. Cousins (1962) argues that the absence of related dykes casts doubt on the existence of sills, but this is a not uncommon feature and is understandable in the light of Roberts's (1970) theoretical treatment of the mechanisms of sill intrusion. The dykes that might be expected to feed these sills will not necessarily be exposed at the present level of erosion. Dallmus (in Judd, 1964) has drawn attention to the fact that, since the earth is spherical, subsidence itself will generate horizontal stresses. Roberts (1970), in developing this concept, has demonstrated that as the original arc subsides, it assumes the position of a chord where the strain in a direction perpendicular to the subsiding axis will have a maximum value. On further subsidence, the arc passes across the chord and could ultimately become a mirror image of the original arc, with the result that the horizontal strain gradually decreases. When this happens, a new level within the subsiding basin occupies the position of the chord. Translated into geological terms, it implies that sill-intrusion will occupy successively higher stratigraphic positions because intrusion is restricted to a specific level. Consequently, if a present day erosion surface lies close to this level, dykes will not be prominent. An explanation along these lines could account for the absence of dykes feeding mafic sills in the Transvaal rocks.

Despite the convincing arguments (von Gruenewaldt, 1968, 1972, 1973) to demonstrate the intrusive nature of the mafic layered sequence with respect to the Rooiberg felsites, neither the contrast in the deformational style between the upper members of the Transvaal Supergroup and the felsites, nor the structural relationship between the layered sequence and the felsites, is adequately explained. No consideration has been given to the possibility than the extrusion of the felsites and intrusion of the layered mafic rocks may be contemporaneous. Consanguinity of the tuff-sediment sequence within the Sudbury Irruptive basin and the norite-granophyre is suggested by the geochronologic data (Fairburn et al, 1968). Information of this kind is not currently available in respect of the Bushveld Complex, but the possibility deserves investigation. The simultaneous emplacement of felsite and mafic phase would satisfy observed field relationships and account for the consanguinity of the rare earth element and minor element data in the felsites and granites of the Bushveld Complex.

The deformation of the Transvaal Supergroup was related by Visser (1957) to the emplacement of the complex, but the evidence from the western Transvaal (Cousins, 1959a; Liebenberg, 1970; Vermaak, 1970) strongly supports the view that deformation preceded the intrusion of the complex. In a subsiding basin in which strain is a consequence of the subsidence, folding would be a response to this condition.

The actual emplacement of the Bushveld Complex can be explained by reference to the proposals of Dallmus (in Judd, 1963) and Roberts (1970). Sill intrusion of the layered sequence would take place at that stratigraphic level occupying the chord position, which, by definition, is a horizontal or near-horizontal surface and therefore meets the requirements of the gravity settling model to explain the layering (Ferguson and Botha, 1963) and the palaeomagnetic data (Gough and van Niekerk, 1959). The overlap of the Main and Upper Zones across the lower zones of the complex would mark a new surge of magma intrusion following subsidence of the Critical and underlying zones across the chord. This is in accordance with the view that new magma was added at the level of the Merensky 'reef' (Ferguson and Botha, 1963).

The small basin of Bushveld rocks north of Goudini is situated within the northwesterly trending structural arch which would cause a redistribution of the stress field, so that sill intrusion would either be restricted or take place at higher stratigraphic levels. This arch remained active after the intrusion of the Bushveld Complex with the result that upper parts of the Goudini intrusive would have been subjected to erosion, thus explaining its relatively small, present-day size.

It is important to note that the layered sequence of the Bushveld Complex cuts down across the lower members of the Transvaal Supergroup and intrudes the granitic basement north of Potgietersrus. Its intrusion does not, therefore, depend on differences in physical properties between basement and overlying sediments. The gravity data do not reflect a reticulate pattern of feeders that would be expected if Anderson's (1951) hypothesis of stress reorientation had influenced emplacement of the complex. The intrusion of the layered sequence requires that horizontal compression extended over a large area, and that the stress distribution is altered in such a way that the trajectories of maximum principal stress steepen towards the magma chamber from which the sills are supplied. Sanford (1959) has shown that vertical movement producing stepped blocks provides suitable conditions. Roberts (1970) has drawn attention to the coincidence of major monoclinal flexuring, dyke swarms and major sill intrusions. It is therefore noteworthy that the Bushveld Complex lies adjacent to the major northwest trending arch, the northeastern margin of which passes along the flanks of the Devon, Johannesburg and Makoppo domes, that became the site of the subsequent intrusion of alkaline plugs and an associated dyke swarm. The concept of a belt of subsidence provides a similar mechanism but has the advantage of postulating that sill intrusion is restricted to a specific level. The fact that successive intrusions of sills and the Bushveld Complex are stacked above each other and that the Main and Upper Zones overstep lower zones suggests that emplacement took place under conditions postulated by Roberts (1970) in a subsiding basin, bounded by major crustal flexures for which there is strong evidence in the western Bushveld. On the basis of calculations by Dallmus (in Judd, 1964), it can be calculated from the 3° of arc the complex occupies that emplacement took place under a cover of 2.2 km.

The overstep of the Main and Upper Zones would reflect further emplacement after a further period of subsidence. It is significant that it is at the level of the Merensky 'reef' (i.e. the base of the Main Zone) that Ferguson and Botha (1963) propose that new magma was added. The act of subsidence would lead to deformation of the older rocks prior to addition of any new magma.

In the preceding discussion it is assumed that the Bushveld Complex is wholly magmatic. It is considered that the geochemical and isotopic data are sufficiently compelling to discount a metasomatic origin for the mafic and salic rocks, although it is probable that minor contact metasomatism may occur. Partial melting and metamorphism of the type described in the eastern Transvaal (von Gruenewaldt, 1968, 1972) are in keeping with a magmatic origin.

Speculation regarding the genesis of certain of the mineral deposits associated with the acid phase is fruitless in the absence of adequate data. The endogranitic deposits such as those at Zaaiplaats are more clearly understood and reflect the concentration of volatiles in structural highs in the roof of the solidifying granite.

This review has identified some of the problems that concern the broader aspects of Bushveld geology. On a smaller scale there are features of the detailed chemistry and mineralogy of constituent minerals and mineral phases that still require investigation. It is fundamental that problems cannot be solved until they have been identified. If this review does no more than that, its purpose will have been served.

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