ECONOMIC GEOLOGY RESEARCH UNIT

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Johannesburg

THE BUSHVELD COMPLEX : A REVIEW

I. THE REGIONAL SETTING AND EXTENT OF THE BUSHVELD COMPLEX

D. R. HUNTER

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UNIVERSITY OF THE WITWATERSRAND
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by

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PREFACE

Forty years have elapsed since the publication of A.L. Hall's (1932) memoir on the Bushveld Complex, which provided a review of all the contributions to the study of this unique geological phenomenon to that date. During the years that followed the Complex has continued to be the subject of many investigations covering almost the whole gamut of geological science.

There is a need for an attempt to be made to bring together some of the considerable volume of data that has been accumulated and is now spread through a wide range of scientific journals.

In order that the task can be made more manageable it is proposed to prepare a series of reviews on different aspects of the geology of the Bushveld Complex.

At the outset consideration must be given to the name of the Complex. As far as Hall (1932) was able to establish the term Bushveld Igneous Complex was first introduced in Hatch and Corstorphine's (1905) text-book on the geology of South Africa. This term has been in general use ever since. It is suggested that the inclusion of the word "igneous" introduces a genetic connotation which several students of the Complex would not be able to accept. Whatever the merits of the proposals that the Complex originated by other than igneous activity, a more objective approach to a review of the evidence demands the removal of any term having a genetic implication from the name of the Complex. Thus the term Bushveld Complex will be used throughout.

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ABSTRACT

The main expression of the Bushveld Complex forms a geographically continuous unit located in the Kaapvaal craton. The opinions expressed regarding the inclusion of other layered intrusives within the Bushveld cycle are reviewed. Geochronological data suggest that the inclusion of the Great Dyke and the Trompsburg intrusive are not valid. The relationship of the volcanic horizons in the Transvaal Sequence to the Bushveld Complex is not clearly defined. Even if these extrusives and various layered intrusives are excluded, the Bushveld Complex underlies an area of 67 340 km^2 which exceeds by several orders of magnitude the size of any other layered mafic intrusive.

Seven models have been proposed to account for the location and development of the Complex. The extreme size of the Complex implies that a unique combination of factors controlled its localization, but a discussion of the validity of the several models must be deferred until additional data have been reviewed.

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INTRODUCTION

Hall (1932) regarded the Bushveld Complex to be the main expression of a major petrogenetic cycle that affected wide areas of the Transvaal province of the Republic of South Africa, Rhodesia, and Botswana. He referred to the geographically continuous unit that crops out from Pretoria in the south to beyond Potgietersrus in the north, and from the Botswana border in the west to Burgersfort in the east as the main or inner complex. A series of scattered, often quite minor occurrences, lying outside the confines of the main complex, he designated as satellites or members of the outer complex.

Hall (1932) wrote that "Though conclusive evidence of a direct genetic connection between a given satellite and the Bushveld proper is not available, there is in nearly all cases a distinct petrographical resemblance to one or other component forming part of the Main Complex, and it is this criterion which is the primary justification for setting up an Outer or Satellitic Complex, i.e. one having some form of petrogenic community with the principal magmatic domain". He further justified the inclusion of the various satellites within the Bushveld petrogenetic cycle on the grounds that a cycle as vast and as varied as that which gave rise to the Bushveld Complex is unlikely to "have run its course during a short span of geological time and within a single strictly defined geographical province ...". Having adopted this view, Hall (1932) was able to accommodate within his Satellitic Complex the following (see Figure 1):-

(i) the Crocodile Pools granitic and gabbroic masses,

(ii) the Balmoral granite,

(iii) the "Dwarsfontein-Nooitgedacht Complex" near Argent,

(iv) the Blaauwbank pyroxenite,

(v) the Kaffirskraal mafic and ultramafic rocks near Heidelberg,

(vi) the Kanye granite in Botswana,

(vii) the Great Dyke in Rhodesia, and

(viii) (tentatively) the "Palabora Plutonic Complex" in the northeastern Transvaal.

Hall supported Daly's (1928) suggestion that the first manifestation of the Bushveld petrogenetic cycle was the contemporaneous volcanism that accompanied sedimentation during Transvaal times, and he further proposed that the cycle terminated with the post-Waterberg intrusions of "diabase and felsite porphyry" which represent a renewal of magmatic activity constituting a younger phase of the cycle, "notwithstanding the lapse of much geological time".

The concept of a Bushveld magmatic episode has remained an essential element in several models based on an igneous origin for the Complex, but subsequent work has shown that certain members of Hall's Satellitic Complex are not related to the Bushveld Cycle, whereas others are in fact not satellites but part of the main complex, their continuity with which being obscured by a cover of younger rocks. The inclusion of the volcanic rocks contemporaneous with the sedimentation of the Transvaal Sequence has been questioned by some students of the Complex. It is, therefore, essential to the understanding of the regional setting of the Bushveld Complex that the geographical and stratigraphical extent of its components be defined.

COMPONENTS AND GEOGRAPHICAL EXTENT

Hall's model of the Bushveld petrogenetic cycle can be summarized as follows :-

10. Intrusion of diabase and felsite porphyry.

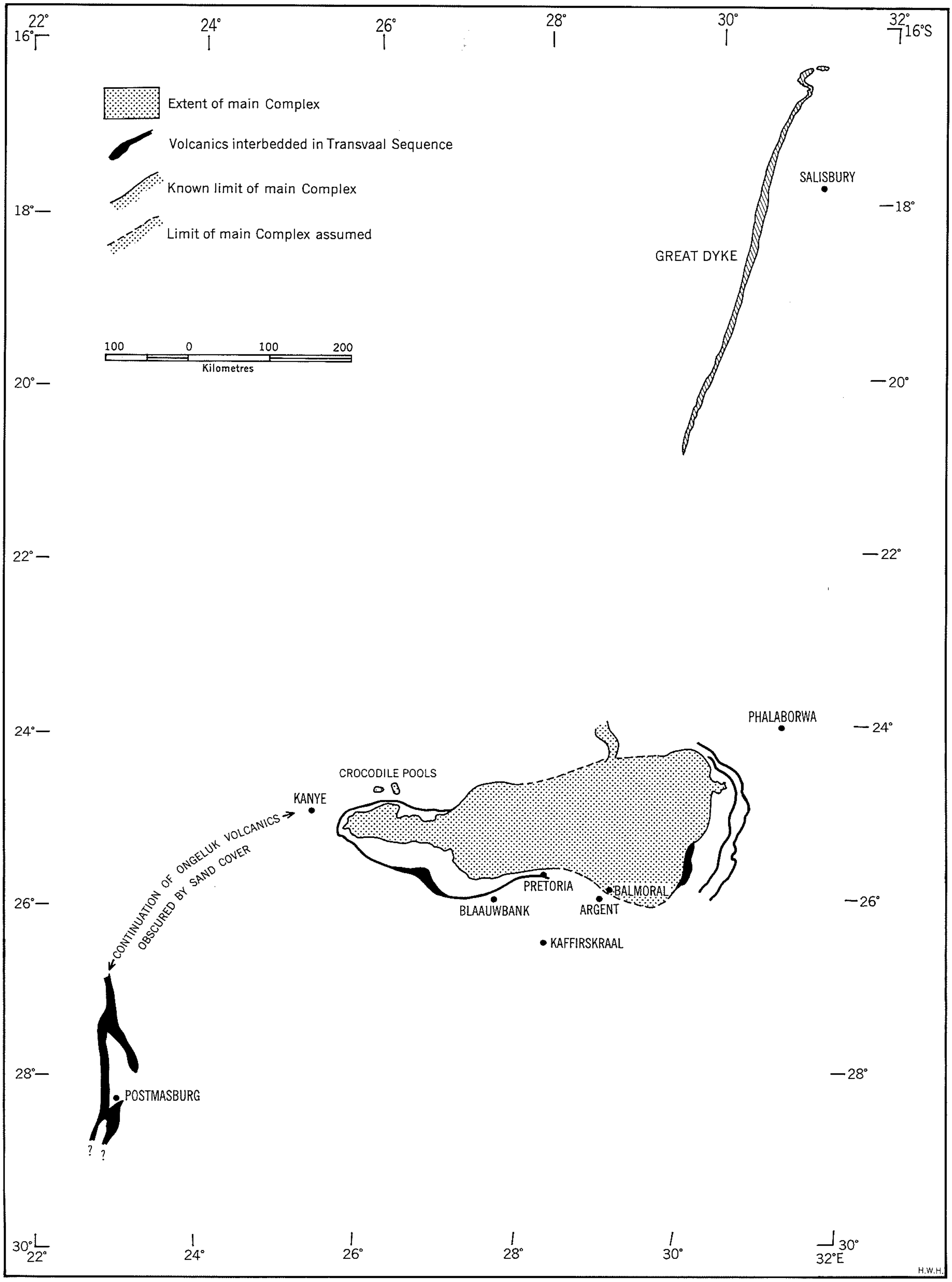

Fig.1. The extent of the Bushveld Complex proper and of its Satellites according to Hall (1932).

9. Warping of the Waterberg Sequence leading to a renewal of the Bushveld petrogenetic cycle.

8. Sedimentation of the Waterberg Sequence in part derived by erosion of the main Bushveld Complex.

7. Emplacement of the Bushveld granite, constituting the Acid Plutonic Phase.

6. Emplacement of pyroxenite, norite, and gabbro, constituting the Basic Plutonic Phase.

5. Injection of diabase dykes and sheets, constituting the Sill Phase.

4. Outpouring of acid volcanic rocks, the upper extrusive portion giving rise to the Rooiberg felsites, while the more deep-seated portions crystallized as granophyre.

3. Establishment of vents, the orientation of which is partially controlled by pre-existing structures in the basement.

2. Minor outpourings of felsitic and pyroclastic rocks contemporaneous with the topmost sedimentary members of the Transvaal Sequence.

1. Sedimentation of the Transvaal Sequence with contemporaneous flows of basic lavas at three stratigraphic horizons.

Truter (1955) regarded the felsites as the extrusive phase of the Bushveld Complex and considered them to be unrelated to the Transvaal Sequence, but the basic lava flows in the Transvaal Sequence were excluded from the Bushveld magmatic cycle because of their widespread distribution several hundreds of kilometres beyond the limits of the main Complex.

Truter considered that only the Blaauwbank pyroxenite in Hall's (1932) list was a satellite of the Complex, and thus reduced the geographical extent of the Complex considerably. The exclusion of the "Palabora Plutonic Complex" and the granitic and gabbroic masses along the Marico river (Crocodile Pools) has been accepted, but Willemse (1964) included the Balmoral granite within the southeastern lobe of the main Complex which geophysical evidence indicates to extend to the vicinity of Bethal (Smit et al, 1962). Geochronological studies of the rocks in the Argent area have given a date of 1950 ± 80 m.y. (Burger et al, 1967) which is in accordance with dates reported from the main Complex (Nicolaysen et al, 1958, Burger et al, 1967).

Willemse (1964) adopted Hall's view that the main Complex and various related intrusions were spread over a wide area of the Republic and Rhodesia. He considered that the volcanicity within the Transvaal Sequence heralded the magmatic event which culminated in the emplacement of the basic and acid phases of the main Bushveld Complex. Willemse (1969) included the following as related intrusions (see Figure 2):-

(i) the Trompsburg layered intrusion,

(ii) a sheet of gabbroic rocks near Brandfort,

(iii) the Losberg layered intrusion,

(iv) a pipe-like mass of mafic rocks on the farm Vogelstruisfontein 233 IQ near Roodepoort,

(v) the Kaffirskraal pyroxenite near Heidelberg,

(vi) the Koringkoppies chromiferous pyroxenite,

(vii) the Uitloop layered pyroxenite, and

(viii) the Great Dyke.

Davies et al (1970) have reported the results of their Sr-isotope studies on a number of layered mafic complexes included in the above list. These indicate that the Losberg intrusion has a date of 1881 ± 282 m.y., the Trompsburg intrusive a date of 1372 ± 142 m.y., and the Great Dyke 2541 ± 30 m.y. The considerably greater age of the Great Dyke and the younger age of the Trompsburg intrusive suggest that neither can be regarded as genetically related to the Bushveld Complex.

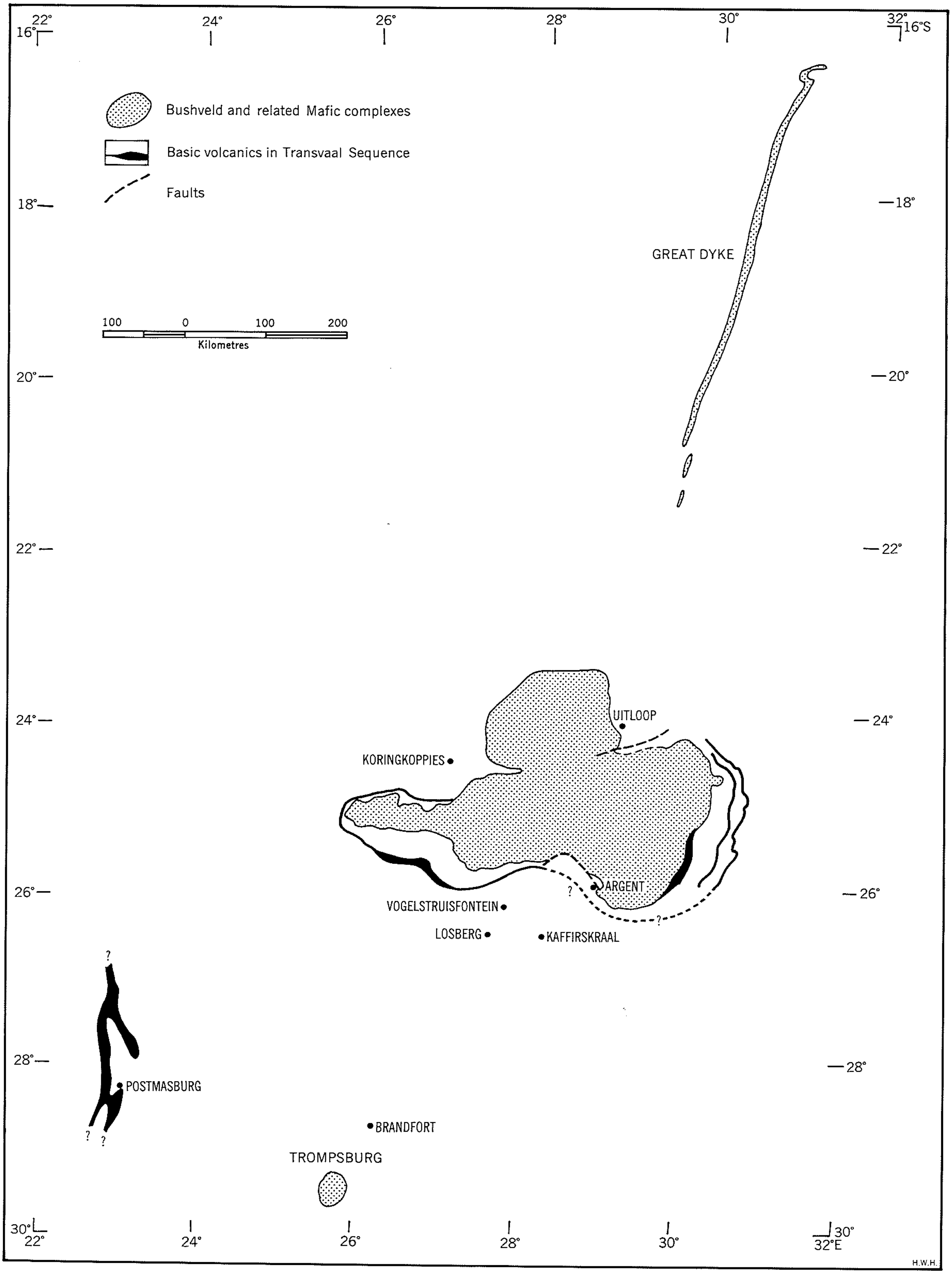

Fig.2. The Bushveld Complex and the positions of related layered intrusives according to Willemse (1969)

Willemse (1969) remarked on the eccentric distribution of the volcanic rocks in the Transvaal Sequence with respect to the basin structure of the Bushveld Complex, but he considered that the presence of volcanics 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.

The most recent provisional geological map of Botswana (Boocock, 1971) indicates the presence of a number of post-Transvaal ultramafic, syenitic, and granitic intrusives as far west as Bray on the Molopo river. Certain of these intrusives, including those in the Kanye area, are considered by Crockett (1971) to be of post-Waterberg age.

From the foregoing it is apparent that there is no certainty as to the geographic distribution of intrusive and extrusive rocks that can be regarded as being co-magmatic with the main Bushveld Complex. The most recent geochronological and field data favour the view that the Complex and its related intrusives are less widespread than envisaged by Daly (1928), Hall (1932), and Willemse (1969).

Acceptance of the concept of confining the Bushveld Complex to the original main Complex as defined by Hall (1932), together with a number of possible satellites in its immediate environs, still results in the recognition of an event of considerable magnitude. Willemse (1969) gave the areas occupied by a number of mafic layered intrusives which are repeated in Table 1.

TABLE I

Areas Occupied by Mafic Layered Intrusions
(after Willemse, 1969)

	km^2
Kapalagulu Complex, Tanzania	20
Tabankulu Complex, Pondoland, South Africa	35
Rhum Complex, Scotland	35
Ardnamurchan Complex, Scotland	60
Skye Complex, Scotland	72.5
Ingeli Complex, East Griqualand, South Africa	85
Skaergaard Complex, Greenland	105
Stillwater Complex, U.S.A.	200
Usushwana Complex, Swaziland	205*
Colony Complex, Sierra Leone	390
Insizwa Complex, Pondoland, South Africa	545
Sudbury Complex, Canada	1 340
Great Dyke, Rhodesia	3 265
Duluth Complex, U.S.A.	4 715
Kunene Complex, Angola-South West Africa	7 770
Bushveld Complex, South Africa	67 340

* Since this calculation, it has now been shown that the Usushwana Complex occupies an area of 1 650 km^2

Two other large mafic layered intrusions may be added to this list :-

(i) Muskox intrusion, Northwest Territories, Canada - 1 500 km^2 plus at least 2 000 km^2 beneath cover rocks inferred from geophysical surveys.

(ii) Dufek intrusion, Antarctica - 8 000 km^2 plus a greater area beneath ice sheets inferred from geophysical surveys.

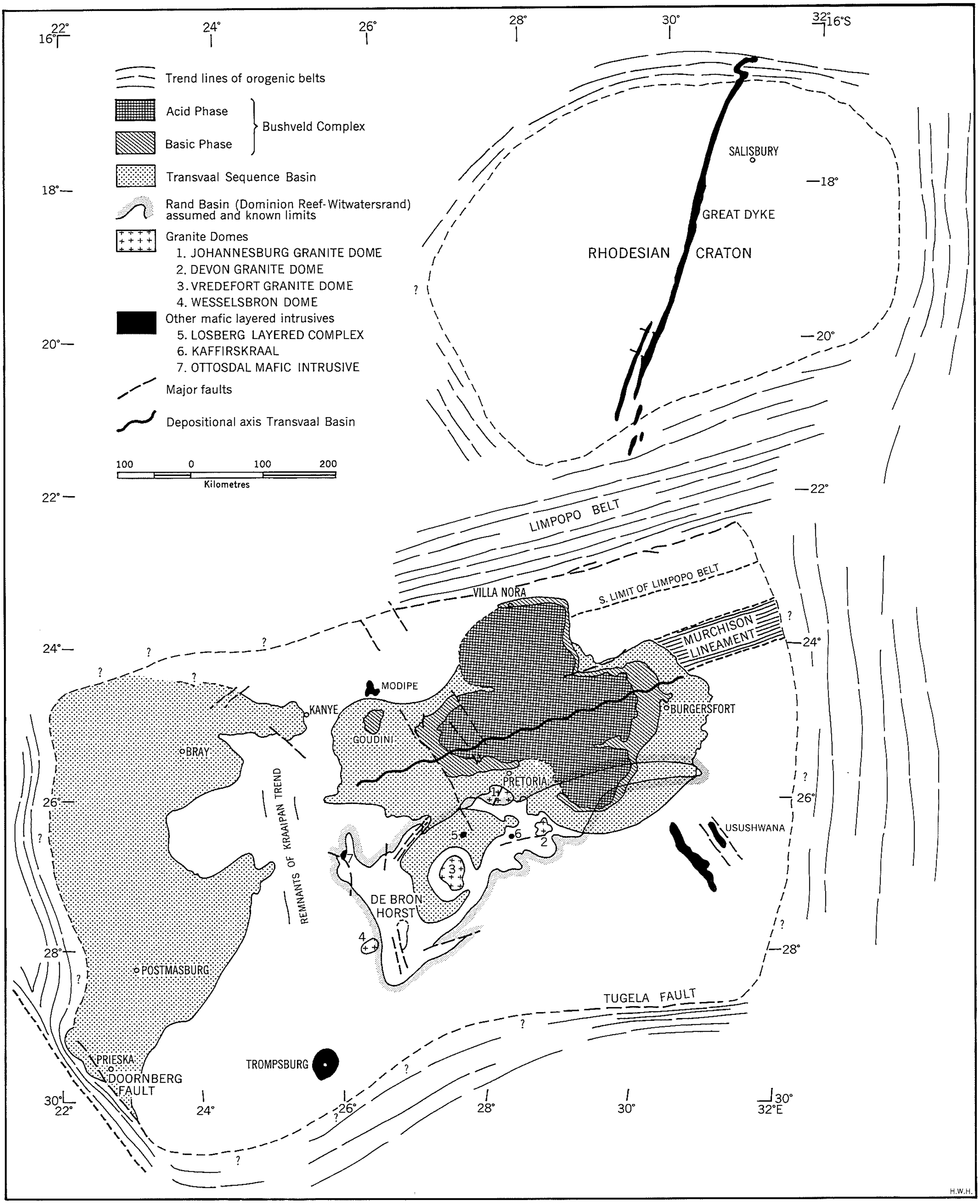

Fig.3. The main structural elements of the Kaapvaal craton in relation to the position of the Bushveld Complex

These figures reveal that only the Dufek intrusion may approach the dimensions of the Bushveld Complex, all the remainder being several orders of magnitude smaller.

REGIONAL SETTING

The Bushveld Complex is located in the northern portion of the Kaapvaal craton adjacent to the Limpopo belt. The broad regional structural features of the craton and their relationship to the site of the Complex are shown in Figure 3.

Hall (1932) drew attention to the fact that a "line drawn southwards along the alignment of the Great Dyke" not only bisects the Bushveld Complex but a prolongation of this line "passes almost through the centre of the updomed Pretoria-Johannesburg granite as well as through the Vredefort Granite ...". The Johannesburg dome is bisected by a major crush zone which is coincident with the Great Dyke lineament. He added that "this peculiar result may conceivably be in some way connected with the structural design of the Bushveld in its widest regional aspects". Hall (1932) also noted that the Pilanesberg ring structure is located at the intersection of the major east-west axis of the Bushveld Complex with the prolongation of the line of "alkaline and syenitic dykes, that extend from the Vredefort Mountain Land in a general north-northwesterly direction to beyond the northern margin of the Bushveld". Hall (1932) remarked on the location of the Pilanesberg at the junction of the western section and the main crescent of ultramafic and mafic rocks of the Bushveld Complex, which Wagner (1924) regarded as marking the axis of "severe torsional stress" (Hall's words) resulting from the deepening of the magma basin to the east. The Pilanesberg is considered to be located at the head of a "great boat-shaped tectonic trough". Hall (1932) added that "the extreme western, original end of which (i.e. the western edge of the Main or Eastern Section of the Norite) is traceable in the collective distribution of Magaliesberg fragments in the Matlapynsberg and to the north of it ...". (Figure 4).

Hall and Molengraaff (1925) discussed the possibility that both the Bushveld Complex and the Vredefort Dome belonged to one great igneous cycle, with each area developing its own petrogenetic characteristics. Strong tangential pressure was invoked to explain the development of the Vredefort Dome which was considered to be approximately contemporaneous with the basining of the Bushveld. Daly (1928) took this proposal further and proposed that the Bushveld basin was "the incidental product of orogenic doming on a scale still grander than that exhibited at Vredefort". Daly postulated that "a very broad, high geanticline, or dome, formed in this way might, through failure of its elastic strength, become centrally dimpled on a large scale". Daly considered that such a dimple basin would be forced down relative to the rim, as the tangential pressure continued. Increase in the mass of the dimpled dome would result in an increase in the vertical pressure on the subcrustal material. Tensional conditions, postulated to exist in the lower parts of the crust beneath the central dimple led to the formation of deep-seated fractures that were injected by magma. As more magma was withdrawn and extruded, the crust became overloaded and sagged, thereby contributing to the basining effect.

Hall (1932) postulated that the Great Dyke originated as "some form of complementary relief from the enormous stresses to which the crust was subjected when the Bushveld magma forced its path upwards". Hall considered that the existence of the Murchison direction, where the floor had already suffered "the most far-reaching diastrophism" influenced the siting of the Bushveld Complex, the east-west lateral extension of which is coincident with the Murchison direction. He concluded that the intersection of the Great Dyke and Murchison directions would form "the most effective venue for the principal channel of eruption" of the Bushveld Complex.

Brock (1956) discussing world-wide structural mosaics, concluded that the Bushveld Complex was situated at one of his vertices, i.e. at the intersection of groups of structural great circles. The latter "are found by projecting linear geological features on their respective great circles". Brock (1956) considered the characteristics of the Bushveld Complex to be appropriate to a geological vertex (25°S, 28°15E) of the first magnitude. In a subsequent paper (Brock, 1957) introduced the concept of "ghost" lineaments, which he regarded as being marked by "bundles" of many weak and localized lineaments. Brock (1957) considered that two such lineaments converge on the Bushveld vertex, one of which "marks a more northerly reach of

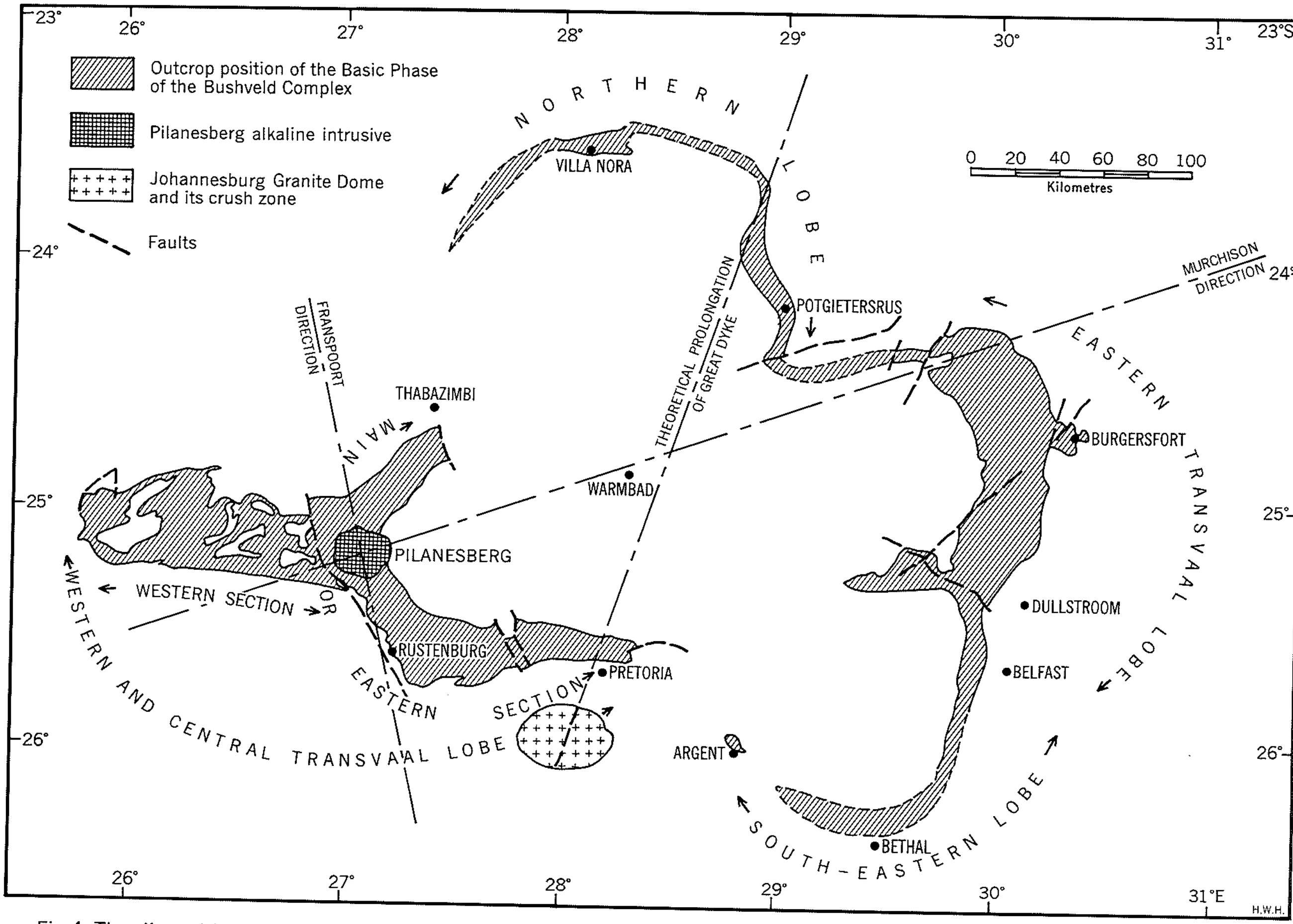

Fig.4. The disposition of the major structural trends according to Hall (1932). The names applied to the various portions of the Basic Phase are also shown.

the Eastern Rift from Baringo to Lake Rudolf. This is on the projection of the Great Dyke, in East Africa a line of little note, save that it lends weight to the bundle of lines that combine to make the Eastern Rift".

In a discussion of Brock's (1957) paper, Kent (1957) drew attention to the fact that "Since Hall's time a dome-like structure has been described from near Vereeniging and a post-Transvaal, non-alkaline complex at Losberg, near Fochville", both of which lie close to the southward projection of the Great Dyke lineament. Kent (1957) noted that the positive gravity anomalies centred about Potgietersrus, Brandfort, and Trompsburg are "also on the Great Dyke lineament". Kent continued "If the lineament is projected on a geological map until it crosses the Cape Fold Belt it will be observed that the fold axes to the west trend east-west, whereas those to the east become progressively more concave to the south and trend about east-southeast where they pass out to sea". Kent commented that "It seems hardly likely that this marked alignment of geological features and large gravity anomalies should be ascribed to mere chance", but Kent concluded that, while this arrangement seems to lend support to Brock's views on periodic rejuvenation of important lineaments, "further data are ... needed before the existence of a more or less continuous continental or supra-continental 'lineament' is proved".

Cousins (1959) was also attracted by the same linear arrangement of a number of basic bodies. He stated that "The Bushveld Igneous Complex appears to be one unit of a chain of bodies of apparently the same age which lie along a nearly straight line from the Zambesi River in the north to the Orange River in the south over a distance of a thousand miles". Cousins enumerated the following units which contribute to this chain :-

"1. The Great Dyke of Rhodesia.
2. A series of thinner Dykes between the Great Dyke and the Limpopo River.
3. The Bushveld Complex, including the Villa Nora outcrops.
4. A pipe-like body on the farm Vogelstruisfontein 12 (now 233 IQ) (4 miles south of Roodepoort).
5. The heavy body indicated by a gravity high under the granite boss of the Vredefort Dome, which appears to be responsible for its updoming.
6. The gravity anomaly near Brandfort, Orange Free State, which is possibly caused by basic rocks of the Bushveld type.
7. The mushroomed-shaped igneous complex at Trompsburg, Orange Free State, showing gravity and magnetic anomalies and proved by drilling".

Cousins (1959) considered that "This line may mark the position of a fracture in the Earth's crust reaching to extreme depths, through which the deep-seated magma was forced, at favourable positions, to sites at, or near, surface".

Worst (1959) in discussion of Cousin's (1959) paper suggested that the distribution of the Bushveld Complex, the Great Dyke, their various satellites, and other mafic bodies showed "the intrusives are not confined to a single line but are scattered over a wide zone or belt with its maximum width in the vicinity of the Bushveld Igneous Complex". By this statement Worst appears to accept the concept that, at least, the Bushveld Complex and the Great Dyke are located along a major lineament.

Truter (1955) summarized his views on the emplacement of the Bushveld Complex and came to the conclusion that the Complex was emplaced from a number of foci strung along a linear fracture conforming to the major axis of the Complex extending from "Goudini, or possibly Kanye, in the west and to Burgersfort" in the east. Truter's postulated axis of injection is considered to be the response to "crustal tension, ... with a north-south orientation". Truter envisaged that, subsequently, compression operating from the north superseded the earlier tensional conditions which had operated until the emplacement of the Critical Zone of the mafic phase of the Complex. Truter considered that the relationship of the Main gabbro could be explained if it was emplaced during the compressional episode. The idea that the Complex was emplaced along an east-west axis suggests that Truter found little reason to support the concept that the Bushveld Complex formed one of a series of mafic intrusives aligned along the southward projection of the Great Dyke. He, in fact, sounded a warning against "drawing conclusions from the linear distribution of igneous complexes as indicating that there might be a connection between them" in the discussion which followed the presentation of his paper (Truter, 1955), when McConnell (1955) drew attention to the fact that the Great Dyke "was exactly in line with the main Rift valley" running through Malawi, Tanzania, and Kenya.

The close proximity of the Bushveld Complex to the Limpopo mobile belt has been noted in more recent studies of the tectonic development of south central Africa, particularly in view of isotopic age measurements which suggest contemporeinity of emplacement of the Complex with a late event in the Limpopo belt. Crockett (1969), as a result of his mapping in southeastern Botswana, recognized the existence of "Shelf Province" and "Basin Province" environments in the Transvaal Sequence. In the former, Crockett considered that "there is little direct evidence that the Transvaal System was ever deposited although reasoning on indirect grounds suggests it may have been present over part of this province". Up to 7 500 metres of Transvaal strata are found within the Basin Province of Botswana. From this standpoint, Crockett (1969) developed the concept that two major tectonic elements existed in south-central Africa, namely the Limpopo Mobile Belt and the Kaapvaal Rise (Figure 5). The word "rise" is preferred by Crockett to the alternative "craton". He considered that "The Kaapvaal Rise can be further divided into relatively positive "shelves" and relatively negative "basins". The latter are the sites of the accumulation of considerable thicknesses of sedimentary and volcanic rocks. No well-defined orogenic episode is associated with the development of these basins. "Throughout a period of hundreds of millions of years the Kaapvaal Rise shows tectonic phenomena related to the vertical displacement of crustal blocks with little evidence of large-scale horizontal compressional forces" (Crockett, 1969). In this connection it is worthy of note that Brock and Pretorius (1964) have proposed that the Witwatersrand Sequence was deposited in a basin, in which vertical movements took place before, during, and after the period of Witwatersrand sedimentation. Crockett (1969) proposed that the sedimentary basins developed on his Kaapvaal Rise may be divided from the shelf areas by deep-seated arcuate fractures. "The cause of the subsidence affecting, in particular, the basins of the Kaapvaal Rise is suggested as being an intermittent ductile flow of mantle material away from the foci of subsidence" (Crockett, 1969). Crockett recognized that, if mantle withdrawal did, in fact, operate, the magnitude and persistence of the phenomenon suggest that "the cause of the mantle withdrawal must be sought in much larger scale terrestial processes". Crockett suggested that the operation of this process may be linked with the development of the Limpopo mobile belt wherein it has been postulated (Mason, 1969 and 1970) that transcurrent movement of continental dimensions may have reached its climax at nearly the same time as the major episode of granitization and metamorphism there, while in the basin of the Transvaal Sequence a marked period of subsidence occurred. These conclusions are based on one interpretation of the isotopic age data from the Limpopo belt and the views regarding the age of the tilting and warping of the floor of the Transvaal Sequence which are by no means unequivocal (see Figure 5).

Crockett (1969) suggested that the outbreaks of mafic andesitic volcanicity, which is a feature of the Kaapvaal craton, are the result of periodic heating of the base of the steadily sinking crust. He considered that "It is possible that the mobilization of the Bushveld Igneous Complex magma may result from essentially similar causes although it is interesting that this thermal event may be indirectly associated with a specific strong episode of subsidence (in turn perhaps linked with a major period of transcurrent movement further north) of the floor of the Bushveld Basin at the end of Smelterskop Stage times". The significantly different nature of the Bushveld Complex rocks, which display a differentiation between basaltic and granitic magma as compared to the andesitic volcanism of the earlier periods, is taken by Crockett (1969) as being possibly indicative of the suddenness of the collapse of the basin (and hence the more rapid movement of mantle away from the foci of subsidence) which would leave little time for magmatic mixing. He would then view the Bushveld granite "as the result of a certain amount of direct mobilization of sialic material during this thermal episode".

Visser (1957) reviewed the structural evolution of southern Africa, from the standpoint of repeated orogenic cycles. He developed the thesis that an orogenic cycle comprises four phases, namely (i) a tensional or geosynclinal phase; (ii) a compressional phase, characterized by folding and faulting; (iii) a tensional phase during which large gravity faults are formed; and (iv) a magmatic phase characterized by the invasion of bodies of intrusive rock. Visser recognized eight cycles in South Africa, not all the cycles being complete. The fifth and sixth Precambrian cycles he named the Transvaal-Kaigas and the Bushveld-Numees Cycles respectively. In the Transvaal-Kaigas Cycle in the Transvaal and northern Cape, Visser (1957) envisaged that the deposition of the Black Reef and Dolomite 'Series' took place during the geosynclinal phase, the close of which was marked by the onset of the deformational phase, which caused the most

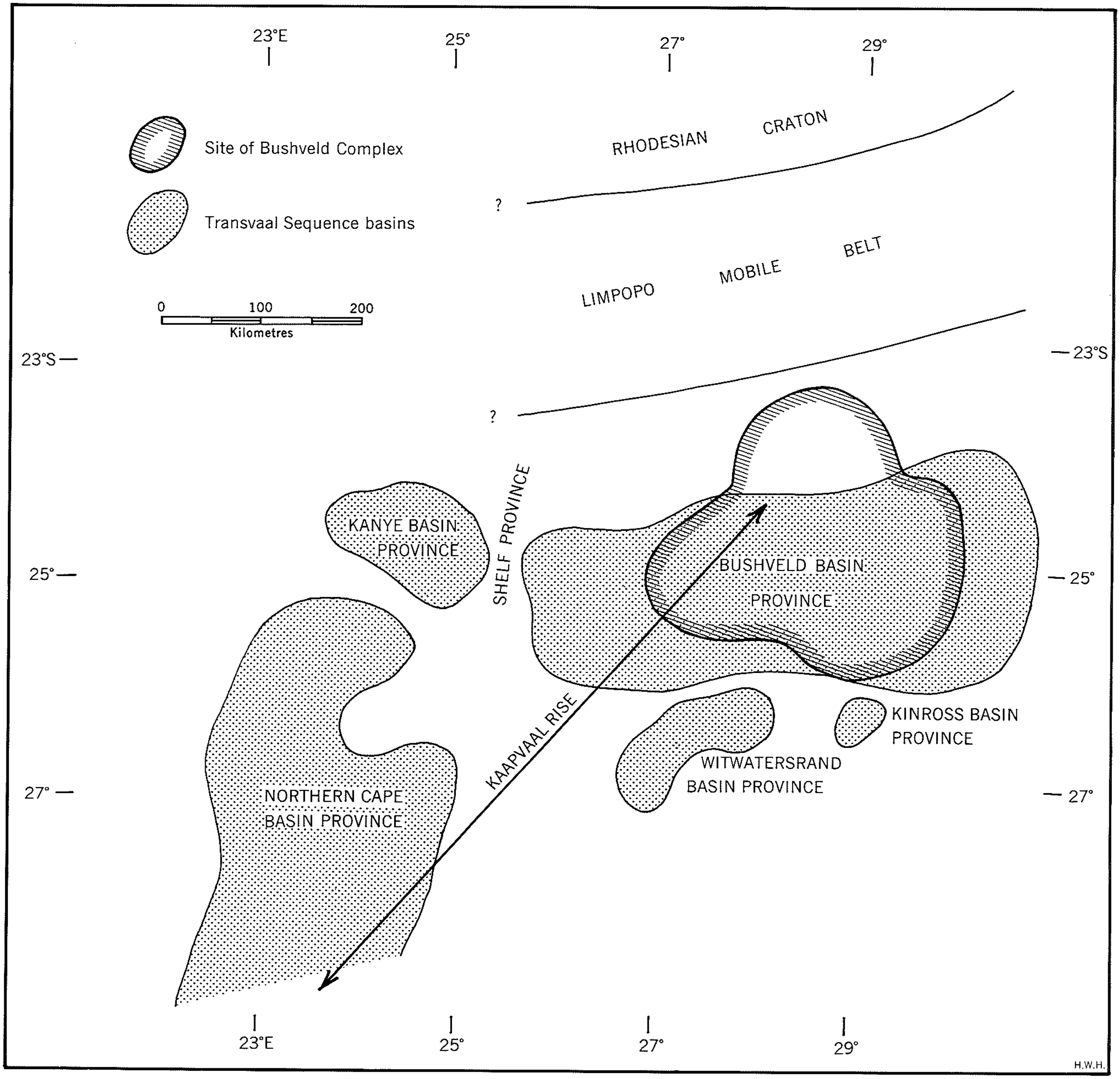

Fig.5. Principal geotectonic elements of Kaapvaal Craton at the end of Pretoria Sequence times (after Crockett,1969) showing site of main development of Bushveld Complex (cross hatched).

marked responses in the southeastern Transvaal. Visser considered that all but 120 feet of the Dolomite 'Series' was eroded away in this area as elevation proceeded. In the northern Cape there was no break in sedimentation. The Transvaal-Kaigas Cycle is attenuated as none of the remaining phases of the ideal cycle are recognized by Visser (1957).

The succeeding Bushveld-Numees Cycle saw the commencement of sedimentation with associated volcanism, culminating in a period during which "vast quantities of felsic lava, known as the Bushveld or Rooiberg felsite, were poured out over the central Transvaal, as a prelude to the Bushveld magmatic activity". Visser (1957) considered that it is "almost impossible to divorce" the magmatic phase from the deformational phase which are regarded as being "practically contemporaneous". In the northern Cape, folding increased in intensity towards Prieska, in the vicinity of which town the Transvaal Sequence is "compressed into a narrow syncline, the compression culminating in the formation of the Doornberg fault ...". Magmatic activity was negligible in the northern Cape. However in the central Transvaal, Visser (1957) considered that the "deformation of the Transvaal System was closely connected with and to a great extent controlled by the emplacement of the Bushveld Igneous Complex". Visser (1957) accepted that the mode of emplacement of the Complex was in the manner described by Truter (1955). It must be concluded that Visser (1957) saw the Bushveld Complex as being a response to an orogenic event, which leads to the consideration of the views of Sandberg (1926), who also regarded the emplacement of the Bushveld Complex as having taken place during an orogenic cycle. Sandberg (1926), however, viewed the orogenic forces as being vertical rather than tangential as proposed by Truter (1955) and Visser (1957). Whereas both these authors regarded the Bushveld Complex as truly magmatic, Sandberg held the view that wholesale melting of supracrustal rocks took place, resulting in the formation of "magmas" of the appropriate composition.

So far, the views which have been summarized above regarding the tectonic setting of the Bushveld Complex have been concerned with the tectonic controls which may have operated to permit a large-scale invasion of ultramafic, mafic, and acidic magma into the upper parts of the crust. There have, however, been opinions expressed that the Bushveld Complex is not truly magmatic. Even if this is so, it is reasonable to deduce that the localization of the transforming process or processes was tectonically controlled. Sandberg (1926) appears to have been one of the first to propose that no true magma was involved. Sandberg's opinion was based on the belief that during deposition in the Transvaal "geosyncline" the addition of younger sedimentary deposits would result in further depression so that parts of the "geosynclinal pile" and floor "were brought into the zone of liquefaction and magmatization". In the following year Sandberg (1927) divided the causes of mountain building into two classes, firstly, those resulting from oriented tangential pressure and, secondly, those related to vertical forces. Sandberg considered that, not only in Alpine-type orogenic settings were structures found which could not be adequately accounted for by tangential pressures, but also in other environments. In this connection he writes of the "Süd-Transvaalsche Orogen" within which he included the Bushveld Complex and the Vredefort and Johannesburg domes. Sandberg would appear to believe that the Bushveld Complex is thus related to the development of an orogen deformed by vertical movements. In his model he envisaged that the melting of dolomite would give rise to the norite magma while the Bushveld granite was derived from the melting of the more siliceous sedimentary rocks in the Pretoria Group.

In 1949, van Biljon expressed the view that the various units of the basic phase of the Bushveld Complex were derived by *in situ* transformation of appropriate members of the Transvaal Sequence. Van Biljon (1949) considered that the metasomatism took place by the upward migration of the "necessary chemical ingredients" to effect the required changes. He stated that "the nature of the elementary ingredients during the migratory stage is not known", and suggested that "the depression of the crust resulted in the escape and segregation of fugitive constituents, probably largely hydrothermal, which conveyed chemical ingredients to higher altitudes". He further considered that "faulting in the roof is the cause of the incompleteness of the metasomatic process", probably due to the "escape of large volumes of hydrothermal constituents in the roof". Van Biljon (1949) provided no reason for the localization of the transformation process in the rocks of the Transvaal Sequence in the selected areas. The Transvaal Sequence rocks in Botswana and the northern Cape Province are not apparently affected by transformation. The fact that van Biljon (1949) proposed that the metasomatizing solutions had great heat presupposes the existence of some zone of higher heat flow, which was presumably absent where the other outcrops of the Transvaal Sequence are not changed to the array of rock types seen in the basic phase of the Bushveld Complex.

Dietz (1961), following up a suggestion by Daly (1947), presented a case supporting the meteorite-impact theory for the origin of the Vredefort Dome. Shatter-cones in the encircling sedimentary ring of the dome were described by Hargraves (1961) and Manton (1965), both authors believing that this evidence was compatible only with an impact hypothesis. Dietz (1963) suggested that the Bushveld Complex was formed by a meteorite impact. Hamilton (1970) took the proposal further and speculated that the Bushveld Complex was formed not only by one impact but probably three. Thus he developed Dietz's (1963) two simultaneous impacts to a total of four, to explain the origin of the Vredefort Dome and the Bushveld Complex.

Hamilton's speculative interpretation of the Bushveld Complex structure envisaged three overlapping subcircular structures. Each structure consists of a central uplift surrounded in turn by a ring-syncline and a ring-anticline. The deeper part of each syncline is filled by the mafic rocks of the Complex, and the overlying granophyres and felsites lap onto the central uplifts. Two central uplifts are recognized, centred on the outcrops of deformed Transvaal Sequence rocks in the Crocodile river valley and around the Marble Hall-Groblersdal area. The third central uplift is postulated to lie under the cover of younger rocks building the Palala plateau (Figure 6).

Hamilton suggested that magmas were produced by "fusion of crustal and mantle rocks, either instantaneously by shock melting and explosive release of overburden pressure, or shortly after the event as a result of the establishment of a steep thermal gradient by conduction from the mantle through the explosively heated and thinned crust". The magmas so produced erupted, and differentiated to form the observed sequence of mafic and felsic rocks. If the Bushveld Complex can be considered to have been formed in this way, any tectonic control which earlier structures appear to exercise must be entirely accidental.

French and Hargraves (1971) have reported an absence of shock-metamorphic effects in the Bushveld Complex during a preliminary search. Labuschagne (1970) in the discussion of Hamilton's (1970) paper reported that he had found deformation-lamellae in quartz grains in two samples of quartzite from the Rooiberg area of the Bushveld Complex, and suggested that they originated through shock or impact at a pressure above 180 kb but below 300 kb. Hamilton (personal communication, 1972) subsequently considered that these features were due to shearing rather than impact. Hamilton (1970) recognized thermal metamorphism in the rocks of the dome near Groblersdal but found no signs of shock-metamorphic features. He considered that "if shock-metamorphism was present there initially it has been at least largely obliterated by thermal metamorphism".

The hypotheses which have been proposed to account for the siting of the Complex fall into the following categories:-

1. A response to the central collapse of a vast geanticlinal structure produced by tangential forces in a cratonic environment.

2. Alignment along a major lineament which is most prominently marked by the Great Dyke trending slightly east of north, the extent of this lineament being variously defined.

3. A response in the cratonic environment to deformation (particularly transcurrent movement on a continental scale) in an adjacent mobile belt.

4. Emplacement along an axis as a result of tension directed north-south, in an orogenic environment, with tangential forces.

5. Emplacement in an "orogen" deformed by vertical forces, in which supracrustal rocks are melted and, thereafter, injected as "magmas" of compositions appropriate to the original sedimentary rocks.

6. *In situ* replacement with no suggestion as to the nature of the factors controlling the localization of the metasomatic activity. By inference, it is concluded that the transformation was affected over an area of high heat flow.

7. Meteorite impact, by which theory it is implicit that there was no pre-existing tectonic or structural control.

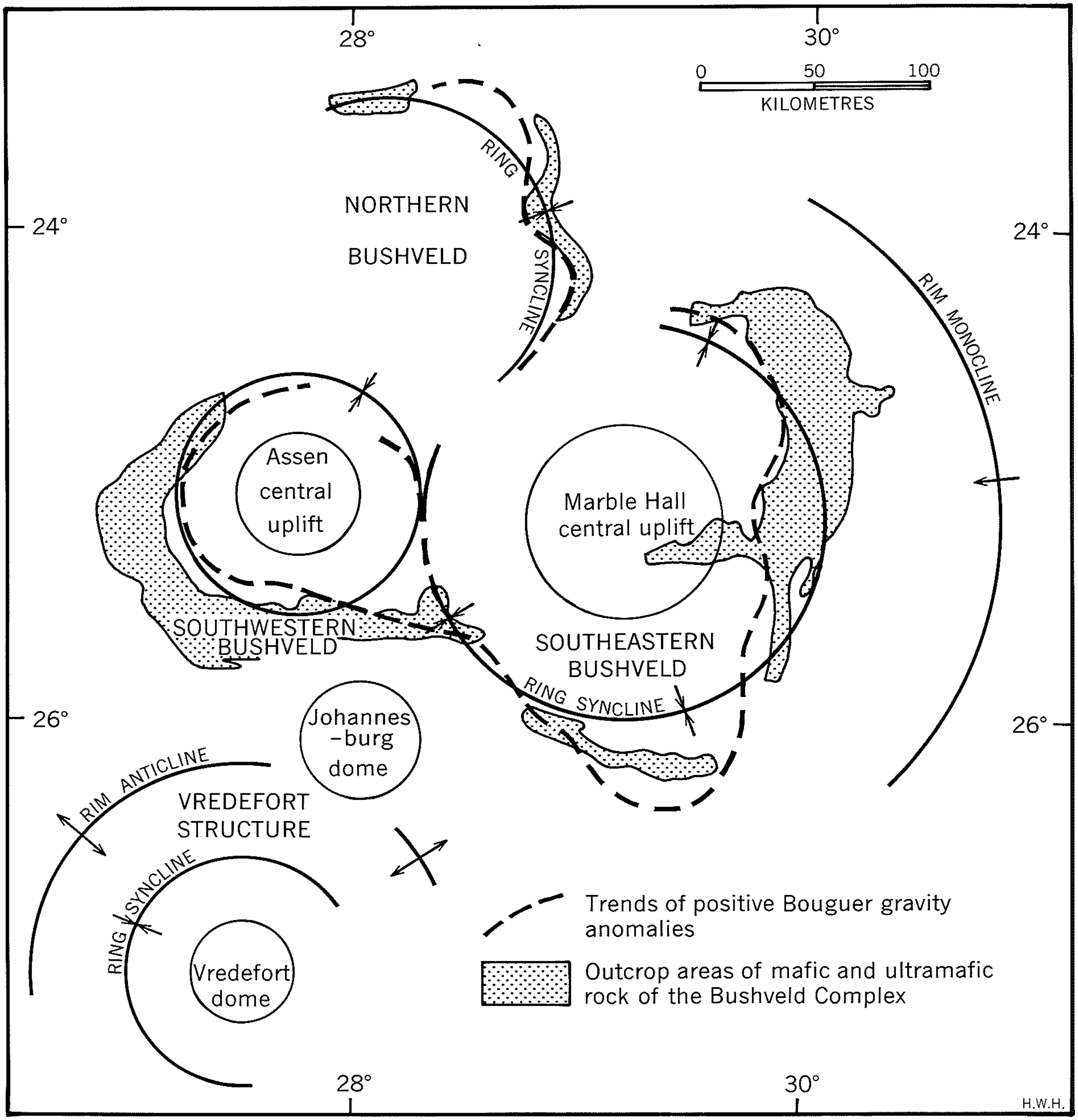

Fig.6. The schematic representation of the structural elements of possible impact origin in the Bushveld-Vredefort region, according to Hamilton (1970). Reproduced from Geological Society of S. Africa, Special Publication No. 1, page 371.

DISCUSSION

A full discussion of the validity of the various models to account for the location of the Bushveld Complex must await the presentation of other data, but some of the broad principles may be examined in brief.

The geochronological investigations on the Great Dyke and the Bushveld Complex (Davies et al, 1970) suggest that the former was emplaced about 500 m.y. prior to the formation of the Bushveld Complex. Hence, the postulation (Hall, 1932) that the Great Dyke was co-genetic with the Complex and was emplaced in a fracture developed as a response to stresses produced in the crust when the Bushveld magma was intruded is not tenable. Although the geochronological data do not directly invalidate the existence of a major lineament along which repeated emplacement took place of mafic magma at widely spaced intervals of time, the proposal (Mason, 1969; 1970) that the Limpopo belt marks the site of a major transcurrent fault raises the problem of how the mafic intrusives lying on this lineament on either side of the Limpopo belt were restored to their original disposition so that at the present time they are now found with a linear arrangement. Mason (1969) has reported that the sense of movement on the transcurrent fault is always dextral.

Sedimentological studies (Brock and Pretorius, 1964) in the Witwatersrand basin indicate that the northern shore-line of the Witwatersrand depository lay close to the present outcrop position of the Witwatersrand Sequence along the basement granitic ridge passing through Johannesburg. Eriksson (in Pretorius, 1971) has reported that sedimentological studies of the Transvaal Sequence southwest of Johannesburg confirm the view that the Johannesburg granite dome and its attendant west-southwesterly-trending ridge developed as structurally positive features during the sedimentation of the Transvaal Sequence. Similarly Button (in Pretorius, 1971) recognized the existence of a proto-basin in the eastern Transvaal in which the basal unit (the Wolkberg Group) of the Transvaal Sequence was deposited.

These investigations point to the existence of basins or of their development prior to the emplacement of the Bushveld Complex. Cousins (1970) drew attention to the remarkable coincidence of the sites of meteorite impact with specific structural positions in the centres of deep, sinking sedimentary basins, rather than being randomly located. Hamilton, in reply (1970), referred to the statement by Pretorius (1968) that the original depositional limits of the Witwatersrand Basin had not been recognized and questioned the validity of the assumption that the impact sites are in fact located in the centres of basins. However, Pretorius (1968) was referring not to the general limits of the Witwatersrand Basin but to the eastern and southern or southwestern extensions of the basin. Pretorius has not revised his opinion in so far as the northern and southeastern limits are concerned. The validity of Cousins' (1970) comment remains.

The depositional axis of the Transvaal Sequence in the Bushveld basin is coincident with the Murchison direction and it would seem that Hall's (1932) reference to the significance of this direction in influencing the location of the Bushveld Complex is important. Truter (1955) also suggested the possibility that the Complex was fed from a number of sites located along this trend.

The fact that the Complex is located in the Transvaal basin of the Transvaal Sequence and not in the northern Cape basin of the same sedimentary group points to the conclusion that the controlling factor in the location of the Complex was not simply a sinking sedimentary basin, but rather that the site for its emplacement was prepared as a result of events which preceeded the deposition of the Transvaal Sequence. The great size of the Bushveld Complex as compared to other layered intrusives implies that some unique combination of factors contributed to its development and formation. If this assumption is correct, it follows that models proposing the operation of vertical or tangential forces, whether in an orogen or a craton, provide only part of the mechanism. No discussion of the relative importance of these forces is possible until additional data have been presented. The same argument applies to theories invoking a metasomatic origin for the Complex.

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Key to Figures

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