ECONOMIC GEOLOGY RESEARCH UNIT

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STRATIGRAPHY AND ATTITUDE OF THE FLOOR OF THE BUSHVELD COMPLEX IN THE EASTERN TRANSVAAL

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UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

In the eastern Transvaal, the mafic phase of the Bushveld Complex rests on eight different formations, six of them situated stratigraphically above the Magaliesberg Quartzite. The latter formations, which are usually largely obliterated by the Bushveld intrusive in the rest of the Transvaal, are exceptionally well preserved in the study-area. Their stratigraphy, depositional environments, and stratigraphic relations are outlined. Most of the formations were deposited in marginal-marine situations, including offshore, nearshore-subtidal, beach, and intertidal mud-flat environments. The stratigraphic data collected were used to compile a panel-diagram in which two field-established isotherms were plotted. The quartzite-recrystallization line and the hornfels line are located, respectively, some 500-1 500 metres and 3 500 metres below the Complex. Both isotherms diverge from the basal contact of the Complex, when traced to the north. The deeper penetration of metamorphic effects in this direction is related to a complementary thicker pile of mafic igneous rocks and greater proportion of ultramafics. From south to north across the area, the basal contact of the Complex truncates up to 5 000 metres of the floor stratigraphy. The truncated pile is inferred to have been jacked up on top of the mafic phase, there to be metamorphosed and partly digested by the subsequent intrusion of the granitic phase of the Bushveld Complex. The highly altered array of sediments which have been mapped along the contact of the Bushveld mafic rocks and the overlying acid phase are thus thought to represent the strata "missing" from the Bushveld floor.

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STRATIGRAPHY AND ATTITUDE OF THE FLOOR OF THE BUSHVELD COMPLEX IN THE EASTERN TRANSVAAL

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STRATIGRAPHY AND ATTITUDE OF THE FLOOR OF THE BUSHVELD COMPLEX IN THE EASTERN TRANSVAAL

I. INTRODUCTION

In the eastern Transvaal, the Bushveld Complex rests on a stratified pile of sedimentary and volcanic rocks which constitute the Pretoria Group of the Transvaal Supergroup. Although parts of the area have been mapped during the past 60 years, no systematic stratigraphic compilation has been published. In this paper, the stratigraphy and stratigraphic relations of the uppermost portions of the Pretoria Group are documented. The conclusions derived have a bearing on the floor geometry and mechanics of intrusion of the mafic phase of the Bushveld Complex.

The area on which this paper is based is situated in the eastern Transvaal, between the town of Belfast, in the south, and Malipsdrift, near the northern boundary of the study-area (Figure 1).

(a) Geological Setting

In the area under discussion, sediments of the Transvaal Supergroup (*circa* 2 300-2 200 m.y. old) rest on an Archean granitic basement. They strike more-or-less north-south, and dip at gentle angles (5°-20°) to the west. The Pretoria Group rocks are overlain by the mafic intrusive suite of the Bushveld Igneous Complex, emplaced between about 2 100 and 1 950 m.y. ago (Davies and others, 1969). The Transvaal Supergroup comprises, in ascending order, the Wolkberg Group (0-2 000 metres), the Black Reef Quartzite (0-500 metres), the Chuniespoort Group (100-3 000 metres), and the Pretoria Group (up to 8 000 metres). This paper is based on relations within the upper parts of the Pretoria Group. This unit consists principally of a cyclical alternation of argillaceous and arenaceous sediments, with three volcanic formations and some minor carbonates. The thickness of this stratified pile has been greatly increased by the intrusion of numerous mafic sills. Near the top of the Pretoria Group, the combined thickness of the sills frequently exceeds that of the sediment intruded. The sediments are often metamorphosed, both through the agency of mafic sills and of the Bushveld Complex.

(b) Previous Work

The pioneer mapping by Hall (1911, 1913, 1914, 1918) established the broad relations between the mafic phase of the Bushveld and its floor in the eastern Transvaal. Willemse (1959) reviewed the relationships between the Bushveld Complex and its floor in the eastern Transvaal.

Van Biljon (1936, 1949, 1974) introduced the names *Steenkampsberg Quartzite* and *Lakenvalei Quartzite* for the two uppermost arenaceous units in the Pretoria Group of the eastern Transvaal. He recorded the presence of a calcareous horizon in a hornfelsic succession above the Magaliesberg Quartzite, and named it the *Berg-en-Dal Horizon*. Hiemstra and van Biljon (1959) described the Pretoria Group relations in the Steelpoort area, near Burgersfort, while Schwellnus (1956) documented the Bushveld floor geology in the Olifants River area, farther to the north. Frick (1967, 1973) mapped the basal contact of the Bushveld Complex in an area north of Dullstroom, and added materially to the knowledge of the stratigraphy of the uppermost units of the Pretoria Group, and of the petrology and chemistry of the intrusive sills. Groeneveld (1968, 1969) described the Dullstroom Volcanics and overlying rocks of the Bushveld Complex in an area west of Dullstroom. He recorded the metamorphic effects of the Bushveld on the lavas, and was the first to document volcanic rocks with a rhyolitic composition in the Dullstroom Lava.

Button (1971), in describing stromatolitic units in the Pretoria Group, published a stratigraphic column in which three new names (Vermont Formation, Nederhorst Formation, and Houtenbek Formation) were introduced. The chemistry of basalts associated with the Machadodorp Volcanics was described by Button (1973a). A detailed description of the stratigraphy of the Pretoria Group and its relation to the Bushveld Complex was given by Button (1973b).

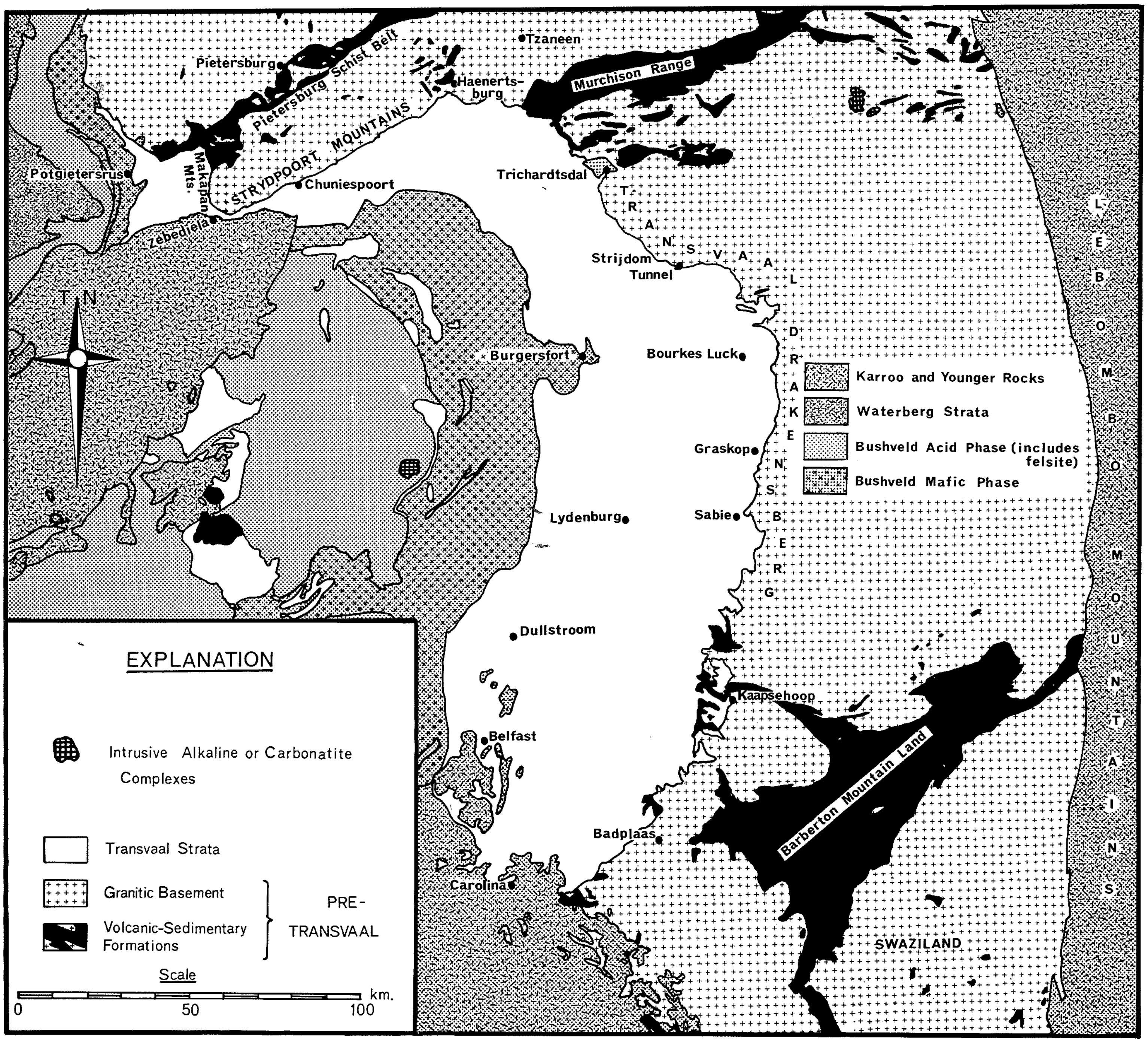

Figure 1 : Map showing location of area studied (modified after 1:1 000 000 geological map published by the Geological Survey of South Africa).

(c) *Scope and Method of Study*

In the type area of the Pretoria Group, the uppermost well-defined unit is the Magaliesberg Quartzite. Some sedimentary and volcanic rocks are developed above this unit (van Biljon, 1949; Visser, 1969), but their thickness and relations are confused by a combination of factors, including poor outcrops, intrusive diabase sheets, and metamorphism related to the floor of the Bushveld Complex. In the eastern Transvaal, up to 4 300 metres of well-preserved stratigraphic section are found above the Magaliesberg. This paper sets out to document the stratigraphy of these rocks and their relation to the Bushveld Complex.

The stratigraphy was studied by measuring a number of profiles, using a Jacob staff. The numerous mafic sills intrusive into the pile were removed in the compilation of stratigraphy. The profiles were used to construct a panel-diagram on which stratigraphy, stratigraphic relations, and the metamorphic effects of the Bushveld Complex are shown. Metamorphic effects documented are those noted macroscopically in the field.

During the course of fieldwork in the eastern Transvaal, a total of over 1 730 dip-and-strike measurements was recorded in rocks of the Transvaal Supergroup. A map of the area studied was overlaid by a 12 x 12 km grid, and all the dip measurements within each grid-square were averaged. The averaged values were then plotted in the centre of each square, and contoured in the conventional manner, to produce an isodip map (Figure 2).

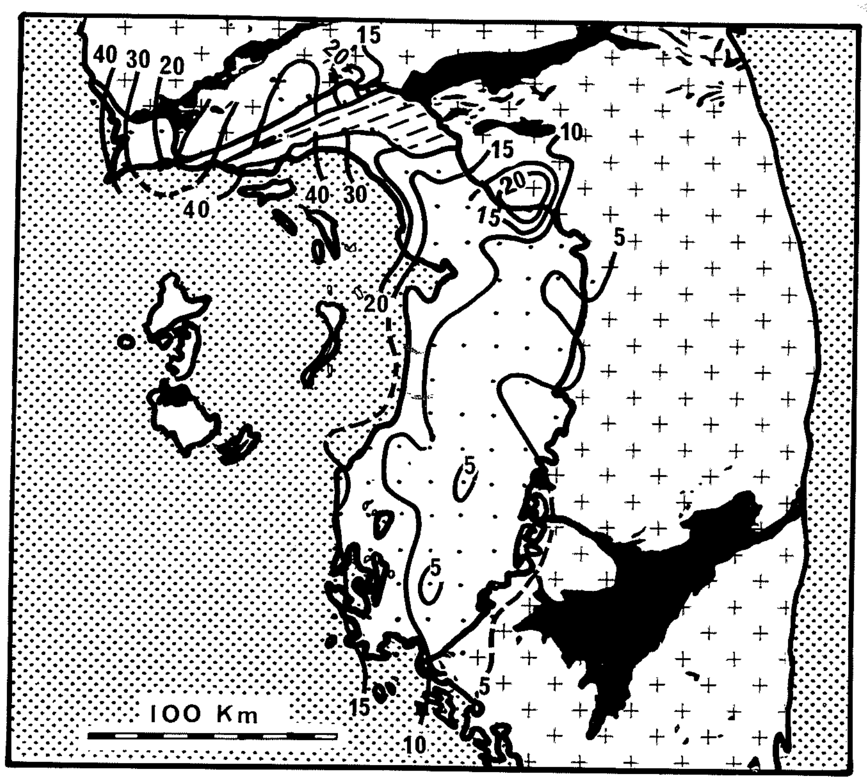

Figure 2 : Map showing variation in dip of the Transvaal strata in the eastern Transvaal. Black = Archean greenstone belts; crosses = Archean granites; white = outcrop of Transvaal strata; hatched = Mhlapitsi Fold belt; dotted = post-Transvaal formations. Larger dots represent centres of grid-squares. Contours are in degrees.

II. STRUCTURE OF THE FLOOR-ROCKS

Of importance to this study is the fact that dips increase as the contact with the Bushveld Complex is approached. In the eastern Transvaal, this increase is from less than 5° to over 15°, while in the northern Transvaal, dips in excess of 40° were recorded adjacent to the Complex. This relation is not restricted to the eastern Transvaal, but has been noted qualitatively around most of the Bushveld Complex. In the Delmas area, structural contouring of the base of the Transvaal Supergroup, using deep exploration borehole data, showed an identical relation (Button, 1968). Steepening of dips towards the Complex is a fundamental structural attribute of the Bushveld and its floor-rocks.

The interpretation placed on these observations is that the increase in the magnitude of the dips is a response to downbuckling of the Bushveld floor as the magmas accommodated themselves beneath a rigid roof (Figure 3). Downbuckling was probably the favoured deformational mode because, in the first instance, the roof-rocks of the Bushveld were a body of Rooiberg Felsites of over 3 000 metres thickness (von Gruenewaldt, 1968). Secondly, in that large volumes of magma were evacuated from the mantle, there was probably a tendency for crustal rocks to slump into the void so created.

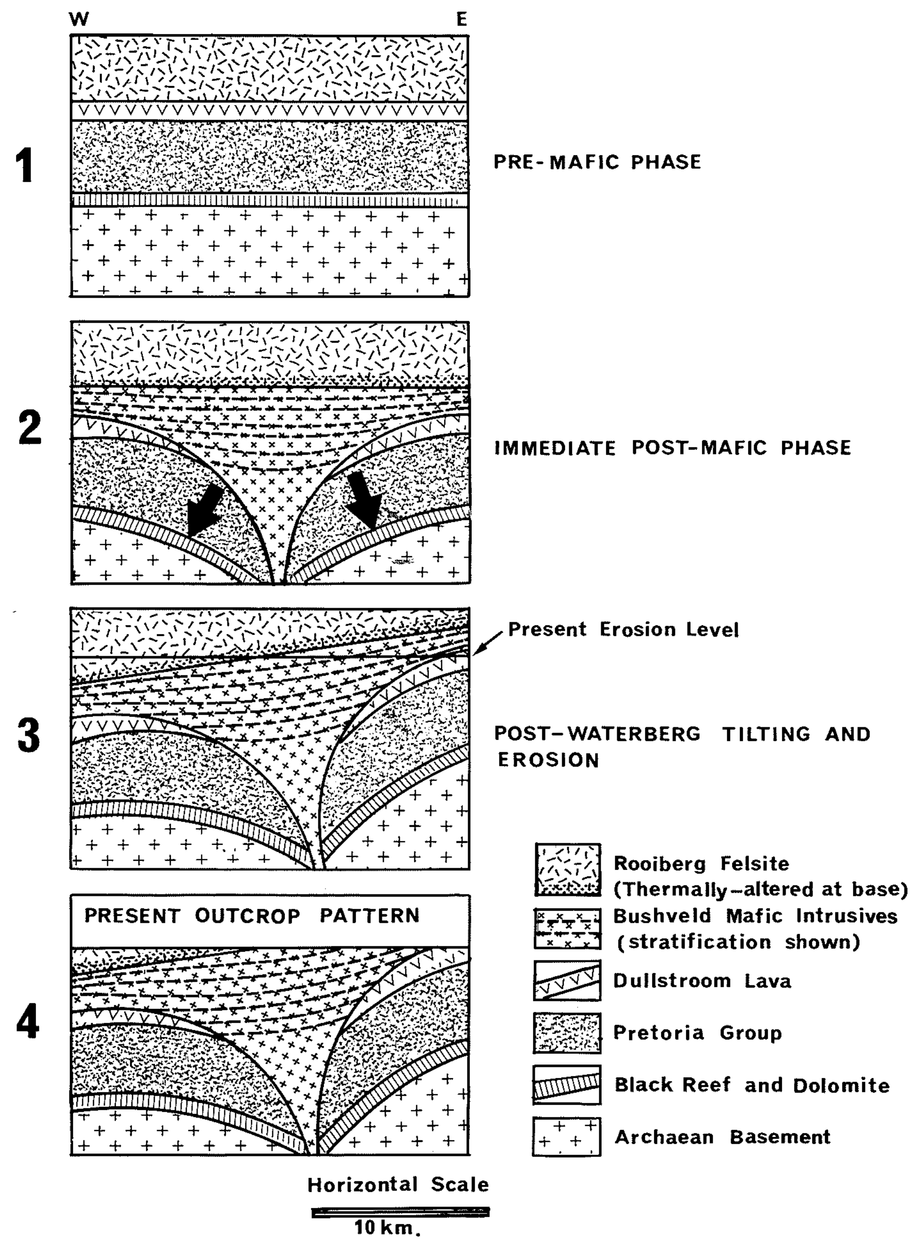

Figure 3 : Schematic diagrams showing sequence of events envisaged in the generation of steeper dips, as the Bushveld Complex is approached.

III. STRATIGRAPHY AND STRATIGRAPHIC RELATIONS

An understanding of the stratigraphy and stratigraphic relations within the upper members of the Pretoria Group is critical to an appreciation of the mode of emplacement of the Bushveld Complex. The grosser aspects of stratigraphy are outlined in the paragraphs which follow.

(a) Silverton Shale

The Silverton Shale comprises the great thickness of argillaceous sediment which is found between the Daspoort and Magaliesberg quartzites. The formation is logically subdivided into three units (Figure 4), from base to top, the Boven Shale Member, the Machadodorp Volcanic Member, and the Lydenburg Shale Member (Button, 1973b).

The Boven Shale Member varies from 170 to 300 metres in thickness, and thins perceptibly to the south. It comprises sheared and cleaved, greenish shales and mudstones, black carbonaceous and pyritic mudstones (mainly near the centre of the unit), and thin beds of tuff, chert, and carbonates. Very rare occurrences have been observed of chert breccia and diamictite. Thin, ferruginous gossans, probably derived from bedded pyritic layers, are fairly common, especially in the carbonaceous shale unit. There is a definite facies change in the unit across the study-area. In the south, chemical sediments are represented by lenticular cherts, some of them probably stromatolitic (Button, 1971). North of Lydenburg, dolomite and limestone lenses are present. These get thicker when traced to the north, and, in the Potgietersrus area, are represented by the Pruissen Dolomite Member, a stromatolitic unit which is over 200 metres thick.

The Machadodorp Volcanic Member is up to 400 metres thick in the south, and thins irregularly to the north. It comprises a basal pyroclast unit and an upper pillow-basaltic unit (Button, 1973a). In the pyroclastic unit, fine-grained, water-laid tuffs are followed by agglomerates and lapilli tuffs, which are capped by finer tuffs. Clasts in the agglomerates are largest in the Machadodorp area, some being nearly a metre in size. The contact of the Machadodorp Volcanic Member and the Lydenburg Shale Member is gradational over 20 to 50 metres, and comprises shale and tuff, with some chert and, rarely, some limestone.

The Lydenburg Shale Member (1 200-1 700 metres) is a monotonous succession of greenish shales and mudstones and, where heated by mafic sills or the Bushveld Complex, hornfelses. Thin and laterally-impersistent layers of carbonates and tuffs have been encountered (Figure 4). The Lydenburg Shale Member grades upwards to the Magaliesberg Quartzite, through an upward-coarsening transition composed of shale, ripple cross-laminated silty layers, and fine-grained, impure quartzites.

The Silverton Shale was deposited in an offshore marine environment. No signs of sub-aerial deposition were noted. This conclusion is supported by the pillowed nature of the Machadodorp Volcanics, and the obviously water-laid nature of the tuffs. Shallowing of the water can be inferred in places, as in the occurrences of stromatolitic carbonates near Potgietersrus.

(b) Magaliesberg Quartzite

The Magaliesberg Quartzite is a persistent unit, with an average thickness of around 500 metres. It consists of a medium-grained, generally pure arenite. Where well-exposed, a zone of mixed arenite and argillite can be made out in the lower one-third of the formation (Figure 4). Sedimentary structures are very common, and include symmetrical ripple-marks (with both sharp and rounded crests), interference ripple-marks, mud-cracked shaly veneers, and trough cross-beds in 10-15 cm units. Crumpled and overturned foresets were observed in places. Planar-bedded phases are also developed, especially near the base of the formation. Cross-beds are poorly oriented, except in the north, where they indicate transport to the south. The Magaliesberg Quartzite grades upwards to the Vermont Formation, through a suite of alternating impure quartzites, quartz-wackes, shales, and silts.

The Magaliesberg Quartzite was deposited in a complex of environments on a shallow-marine shelf. Much of it was probably laid down by migrating mega-ripples on a sub-tidal shelf. Intertidal conditions are suggested by the mud-cracked phases, while an approach to beaches or bars is indicated by the planar-bedded facies.

(c) Vermont Formation

The Vermont Formation comprises 100-480 metres of thermally metamorphosed shales and siltstones, with minor quartzites, carbonates, and cherts. The formation thins fairly regularly to the north. In this direction, there is a parallel increase in the number of thin quartzite lenses in the formation. The formation is very heavily intruded by mafic sills. In many measured profiles, the cumulative thickness of intrusive material exceeds that of sediment.

The most common sediment is a very fine-grained, dense hornfels. In general, the lower two-thirds and uppermost one-eighth of the formation are characterized by sedimentary structures indicative of deposition in an intertidal mud-flat, including abundant desiccation cracks, ripple-cross-laminated silty lenses (Figure 6.1), mud-chip conglomerates, rib-and-furrow structure on bedding planes, and a variety of ripple-marks. By contrast, the remainder of the formation has a higher proportion of massive, fine-grained hornfels, and probably represents a mudstone deposited in deeper water.

Carbonates and cherty rocks are encountered at three main levels in the Vermont Formation 100-150 metres above the base, just above the middle of the formation (in association with the quartzite lenses), and 80-100 metres from the top. The carbonates are frequently altered to marbles, serpentinous dolomites, and calc-silicate rocks. Stromatolites, generally of the linked domical type, are common (Button, 1971), and are associated with crinkly algal lamination, encapsulated algal biscuits, some oolites, cross-beds, and mud-cracks.

The Vermont Formation is the product of sedimentation on an intertidal mud-flat. For relatively short periods of time, deposition was in a deeper, sub-aqueous environment.

(d) Lakenvalei Quartzite

This unit was named from the farm Lakenvalei 355 JT in the Belfast district. It has been traced intermittently for a strike-distance of 175 km. Over this distance, it thins from 300 m in the south to about 160 m in the north. The formation has a gradational base (into the Vermont Formation) and a sharp top. In the basal transition zone, fine-grained, frequently feldspathic arenites are interbedded with mud-cracked shaly layers. The lowermost exposed portion of the Lakenvalei Quartzite frequently comprises a mud-flake conglomerate, which is a definitive and useful marker in the eastern Transvaal (Figure 6.2). The main body of the Lakenvalei Quartzite includes medium-grained, feldspathic quartzites and arkoses. Cleaner arenites are found near the base, and are invariably developed at the top of the formation. Up to four thin (a few metres) shaly layers are present in the formation.

Sedimentary structures include mud-crack casts, ripple-marks, shale flakes, black heavy-mineral layers, and cross-beds in sets 0,1 to 2 m thick. The foresets are consistently oriented, and indicate sediment transport to the west and west-northwest. The Lakenvalei Quartzite is thought to have been deposited in a littoral complex which probably included sub-tidal, bar, and beach elements. Rapid sedimentation is envisaged to explain the preservation of the mechanically-unstable feldspars in the quartzite.

(e) Nederhorst Formation

The Nederhorst Formation can be followed for 105 km along strike. It thins from 800 m in the south to 200 m in the north. The formation comprises a lower, hornfels unit and an upper, fine-grained arkose unit (Figure 4). The latter wedges out to the north, probably being erosively truncated by a minor unconformity developed at the base of the Steenkampsberg Quartzite in that direction.

The Nederhorst Formation outcrops poorly, due to the soft nature of the rocks, the abundant intrusive diabase sills, and a scree shed by the scarp face of the overlying Steenkampsberg Quartzite. The basal one-third of the formation consists of fine-grained hornfelses, generally with lenticular, centimetre-thick, ripple-cross-laminated silty layers and some mud-cracks. Minor constituents include lenses of quartzite (5 cm thick) and some calc-silicate rocks in beds up to 5 m thick. The remainder of the Nederhorst Formation comprises fine-grained arkose (Figure 6.3) and medium-grained feldspathic and argillaceous arenites. The latter are cross-bedded (sets 5-50 cm), carry some clay flakes and heavy mineral laminae, and are, in places, parallel-bedded and parting-plane-lineated. Some of the arenaceous sediments of the Nederhorst Formation have been caught up in mafic sills, to give rise to hybrid intrusion breccias (Figure 6.4).

The basal shaly sediments of the Nederhorst Formation were probably deposited, at least in part, on an intertidal mud-flat. The fine-grained arkosic suite probably represents the distal portions of an arkose wedge, and could be the lateral equivalents of the arkoses developed in the Rooiberg area (Boardman, 1946) and the Stavoren Fragment (Rhodes, 1972).

(f) Steenkampsberg Quartzite

This formation can be traced discontinuously for 110 km, over which distance its stratigraphic thickness varies between the limits of about 470 and 630 metres. Where fully developed, it can usually be subdivided into five units, lower, middle, and upper pure quartzites separated by two layers of impure arenite and argillite (Figure 4).

In the south, around Belfast, the Steenkampsberg Quartzite appears to grade down to the Nederhorst. Further north, a sharp contact and a thin basal conglomeratic unit are developed. The Steenkampsberg quartzites are generally medium-grained and exceptionally pure. Black heavy-mineral foresets and bedding planes are particularly prominent in the basal 60 m of the formation. Ripple-marks are very common, while mud-crack casts are not rare. Cross-beds include 20-cm-trough sets and tabular sets, from 0,5 to 2,0 m thick (Figure 6.5). Some 80 foresets were measured in four localities between Belfast and Dullstroom, and indicate consistently-oriented currents moving towards the west. The argillaceous units within the Steenkampsberg outcrop poorly. They comprise argillaceous and feldspathic arenites, with maroon-weathering, micaceous, shaly rocks, and grade into the overlying cleaner arenites.

The Steenkampsberg Quartzite was deposited in a neritic and littoral complex. The presence of prominent heavy-mineral laminae, traceable over some tens of metres, probably indicates a beach environment within this complex (Frick, 1967).

(g) Houtenbek Formation

The Houtenbek Formation can be traced laterally for about 50 km. It varies in thickness between limits of 138 and 255 m, and is exceptionally heavily intruded by mafic sills. The formation comprises two thin layers of extremely clean quartzite, set in an assemblage of hornfelsed shales, with some fine-grained arkoses, carbonates, cherts, and calc-silicate rocks. The altered shaly rocks show the same features as those taken to be indicative of an intertidal mud-flat in the Vermont Formation. The calcareous, cherty, and calc-silicate rocks are abundantly stromatolitic (Button, 1971), displaying algal lamination, linked domical forms, and mega-domes (10 metre-long axes) ornamented by finger-size columnar stromatolites.

The Houtenbek Formation was deposited in a number of related shallow-marine sub-environments, including the intertidal mud-flat, the subtidal environment, and, possibly, the beach.

(h) Dullstroom Lava

This unit, up to 1 400 m thick, comprises mainly basaltic-to-intermediate lava, with minor agglomerate, tuff, felsic lava, feldspathic arenite, and hornfels. In one measured profile, 15 separate lava flows were recorded, which range in thickness from 8 to 60 metres, and average 30 metres thick. The basal portions of flows are massive, with a few small feldspar phenocrysts. Flow-tops are highly amygdaloidal. Some flow-top breccias were observed. Amygdales are mainly of cherty silica and chlorite. Laterally-impersistent bodies of felsitic lava are present. The extrusion of acid lava probably represented a forerunner to the thick and extensive Rooiberg Felsite, which has been prised off from the Dullstroom Lava by the injection of the mafic phase of the Bushveld Complex. Some of the felsic rocks probably have a pyroclastic origin, being well-bedded and characterized by elongate, shard-like structures (Figure 6.6).

The Dullstroom lavas show no signs of sub-aqueous extrusion, and are thought to have been poured out onto a supratidal, marginal marine platform.

IV. ATTITUDE OF THE FLOOR OF THE BUSHVELD COMPLEX

The geological map of the Transvaal clearly indicates the intimate structural relation between the Transvaal Basin and the mafic phase of the Bushveld Complex. The gabbroic rocks outcrop in a series of arcs, in all but a few cases bounded on the outer periphery by strata of the Transvaal Supergroup. On a more local scale, the Bushveld cuts across formations in its floor, a fact appreciated by Hall (1911, 1913, 1914, 1918) and shown in his maps of the eastern Transvaal.

Lateral Stratigraphic Relationships in the Upper Formations of the Pretoria Group

Fig. 4

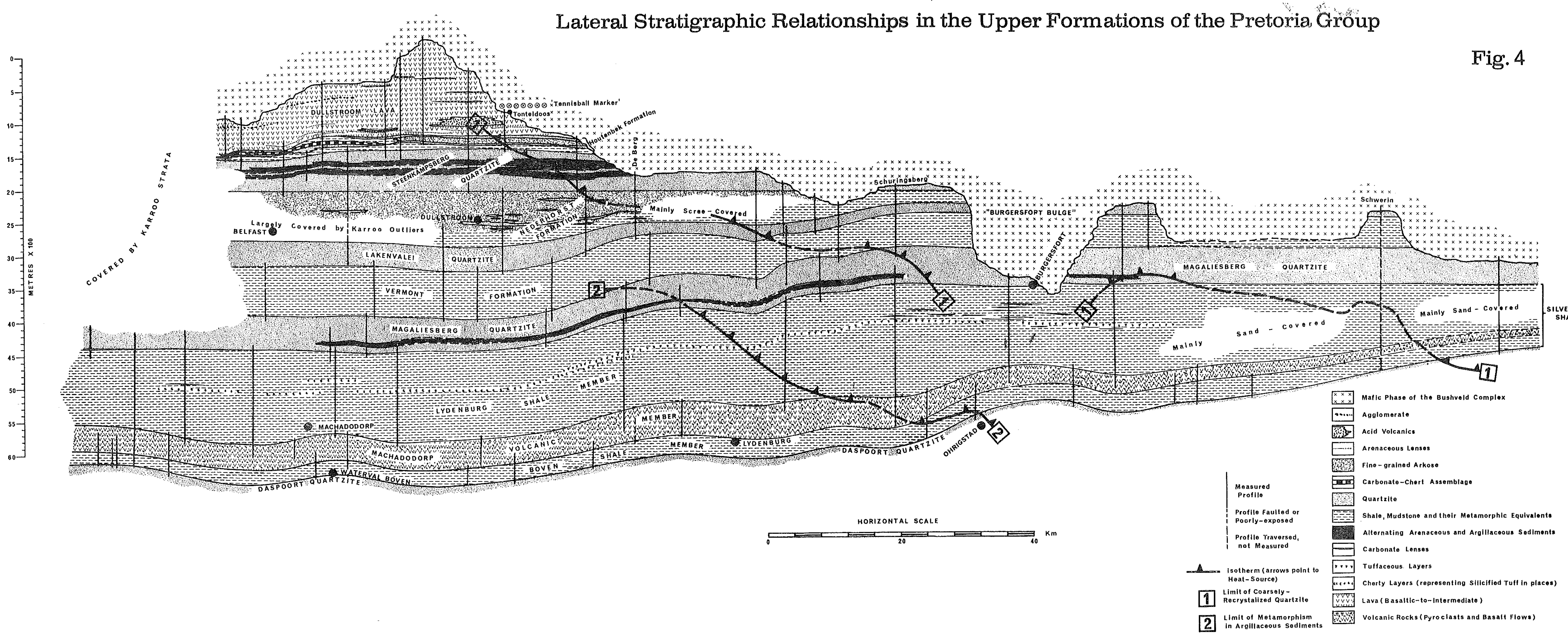

Figure 4 : *Stratigraphic panel-diagram showing stratigraphy, attitude, and cross-cutting basal contact of the Bushveld Complex.*

Referring to Figure 4, it is seen that the thickest section of floor-rocks is preserved west of Dullstroom. The Dullstroom Lava has a maximum thickness of over 1 400 m. To the south, it is reduced to 400 m; to the north, the entire thickness of the formation is truncated over a distance of 18 km. The Bushveld Complex then rests on the Houtenbek Formation and the upper portion of the Steenkampsberg Quartzite, for a short distance, before coming to rest on the lowest unit within the Steenkampsberg Quartzite for 28 km. After truncating the latter, it rests on the Nederhorst Formation for 13 km, before reverting to the Steenkampsberg level along the ranges of the Schuringsberg. At Burgersfort, the Complex cuts well-down into the Magaliesberg Quartzite, and, in places, down to the Lydenburg Shale Member. North of Burgersfort, the intrusive rocks rest at a level which alternates between the Lakenvalei Quartzite and the Vermont Formation. North of Schwerin, it rests on the Magaliesburg Quartzite. In all, a total of about 4 700 metres of the stratigraphic succession of the Pretoria Group has, in places, been eliminated by the intrusion of the Complex. The fate of this substantial thickness of stratified rocks is a puzzling question, and will be discussed in a subsequent section.

Two field-established isotherms have been plotted on the panel-diagram in Figure 4. The first is the *quartzite-recrystallization line*, and coincides with the first appearance of coarsely recrystallized quartzite (Figure 6.7). The second is the *hornfels line*, and corresponds with the appearance of crystalline hornfels in the place of shales. The *quartzite-recrystallization line* is much closer to the Complex than the *hornfels line*, since a much higher temperature was needed to recrystallize chemically-inert quartzite than to trigger metamorphic reactions in wet and chemically active shales.

A feature of the isotherms is their divergence from the basal contact of the Complex, when traced to the north. The *quartzite-recrystallization line* is 500 metres below the Complex in the Dullstroom region. In the Burgersfort area and to the north, it is 1 500 m below the floor. The *hornfels line* behaves sympathetically, and extends for a distance of up to 3 500 metres below the Complex in the Burgersfort region.

The greater penetration of metamorphism to the north is related to the stratigraphic interplay between the Bushveld mafic rocks and the uneven and sloping depositional floor of the magma chamber. The lowest ultramafic units in the Complex wedge out towards the south, in much the same way as basal sedimentary formations wedge out against topographic highs on a depositional floor. Higher units, principally gabbros, lap onto the floor in a southerly direction. Thus, the thickness of mafic rocks and the proportion of ultramafic rocks in the Complex increase in a northerly direction, and account for the greater penetration of the metamorphic aureole in that direction.

V. METAMORPHIC EFFECTS OF THE BUSHVELD COMPLEX

The floor-rocks of the Bushveld Complex represent a classical area for the study of thermal metamorphism. A wide variety of rocks (including basement granites, arenites, argillites, lavas, pyroclasts, iron formations, cherts, and carbonates) are affected by a transgressive thermal aureole. Rapid variation of rock-types allows comparison of metamorphic assemblages developed in different lithologies under the same thermal conditions. In addition, there are the problems introduced by poly-phase metamorphism (a contact effect related to sills was overprinted by heat from the main mass of the Bushveld) and structural deformation in limited areas, more-or-less contemporaneous with crystallization of metamorphic mineral phases. It is one of the objectives of this paper to focus attention on this unique opportunity for the study of metamorphic reactions, in hope that the relations will be tackled regionally with the full array of instrumentation available to the modern petrologist. The observations set out below are based solely on macroscopic, field relations, and are intended only as a broad outline within which a detailed study might be framed. Metamorphic effects related purely to sills will be described first, followed by an account of Bushveld metamorphic effects.

In their 'unaltered' state, sediments of the Pretoria Group are probably in the lower portion of the greenschist grade. Basic volcanics in the pile are characterized by the assemblage actinolite-albite. Adjacent to major sills, argillaceous rocks are altered to black, very fine-grained hornfelses or lydianites. These weather in discoidal slabs, and have a conchoidal fracture. Metamorphic minerals cannot be made out, except microscopically. The internal structure of the rocks is not seen on broken surfaces, but is frequently well-displayed on weather-etched faces. In rare instances, the shaly rocks have been rendered plastic, and have been squeezed back into the intruding magma (Figure 6.8). The best development of such rocks is in the Vermont Formation, which is affected throughout. This is due to the fact that the thickness of sills in the Vermont frequently exceeds that of sediment. Quartzites tend not to be macroscopically altered by sill intrusion, except perhaps in the introduction of albite-epidote films along joints, and the albitization (and reddening) of clastic feldspar grains. In carbonate rocks, magnesian sediments are usually de-dolomitized and serpentinized. Metamorphic minerals identified include olivine, antigorite, diopside, and magnetite. Under the microscope, Frick (1967) has recorded, in addition, grossularite, vesuvianite, and wollastonite.

The lowest grades of metamorphism directly related to the Bushveld Complex are seen in argillaceous rocks of the Boven Shale Member (near Ohrigstad) and the Lydenburg Shale Member (near Lydenburg). Here, scattered biotite flakes and andalusite crystals are developed in greenish, macroscopically-unaltered shales. At slightly higher grades, fine-grained hornfelses (lydianites) alternate with crystalline hornfels, while at higher grades still, crystalline hornfelses are developed exclusively. Biotite, cordierite, and andalusite are macroscopically distinguishable in the hornfelses. Very characteristic outcrops of hornfels are found in the Lydenburg Shale Member. The weakly outcropping shales are converted to hornfelses which crop out in large blocks and slabs. In argillites that are differentiated into quartzose silty and shaly fractions, the silty layers are impoverished in metamorphic minerals. Shaly rocks, where they are encountered within the *quartzite-recrystallization line*, tend to show signs of plasticity, mobilization, and partial melting. Sedimentary layering becomes deformed in a flow-folded fashion. Partially melted rocks show development of quartz-feldspar mobilisate, which is frequently injected into tensional fractures, and sometimes veins the rock in an irregular fashion. The bedding structures tend to be disrupted, and, eventually, destroyed (Figure 6.9).

The carbonaceous shales and mudstones of the Pretoria Group are extremely resistant to the metamorphic effects of the Bushveld Complex. Some of the moderately carbonaceous varieties develop scattered biotite flakes, but the highly carbonaceous types are macroscopically unaltered, even at the highest grades.

A fairly locally-developed style of metamorphosed shale is encountered within folds in the Bushveld floor, which are genetically linked to intrusion. The folds probably developed during intrusion of the mafic magmas, and stresses were probably present during crystallization of the metamorphic minerals, which are oriented parallel to fold axes. This type of fabric corresponds to what Hall (1932) referred to as the *Malips River-type* of metamorphism related to the Complex.

In Figure 4, it can be seen that the hornfels line (No. 2) cannot be extended in a southerly direction into the Vermont Formation. A well- defined lateral change from shale to hornfels, which can be easily detected in the Boven and Lydenburg shale members, is not seen in the Vermont Formation. The reason for this is the fact that the Vermont Formation is intensively intruded by sills, and is thoroughly converted to fine-grained hornfels by that mechanism. Consequently, the effects of later metamorphism related to the Bushveld Complex are not as readily seen. Even at the highest grades, the hornfelses derived by re-metamorphism of Vermont, Nederhorst, and Houtenbek lydianites do not attain the degree of granularity of their counterparts in the Silverton Shale formation. They change from dense black lydianites, in which individual minerals cannot be made out, to fine-grained hornfelses in which small crystals of biotite, cordierite, and, rarely, andalusite, can be distinguished. This metamorphic variety corresponds to what Hall (1932) termed the *Groothoek-type* of hornfels. In this paper, such hornfelses are regarded as the products of polymetamorphism, and reflect an earlier heating related to sills, upon which was superimposed a second heating related to the Bushveld Complex.

Arenaceous sediments tend to be recrystallized adjacent to the margin of the Complex. Medium- and fine-grained quartzites are converted to coarse-grained quartz mosaics, with individual crystals frequently up to 1 cm in size. An important observation made was that only the purest quartzites are amenable to recrystallization of this type. In less pure varieties, individual quartz grains were insulated from one-another, and could not easily coalesce to produce very coarse-grained quartz aggregates (Figure 6.7). Under extreme conditions, quartzite becomes mobile and intrudes into Bushveld mafic rocks.

The effects of Bushveld metamorphism on the Machadodorp and Dullstroom volcanic rocks has been described, respectively, by Button (1973a) and by Frick (1967) and Groeneveld (1968). A feature of the Dullstroom Lava beneath the Bushveld Complex is the presence of closely-spaced joints (Figure 6.10). The joints acted as passageways for fluids emanating from the cooling igneous rocks. The lava on either side of the joints is feldspathized and epidotized for variable distances. This feature is found for a stratigraphic thickness of up to 500 metres below the contact of the lava with the Bushveld Complex.

VI. MECHANISM OF EMPLACEMENT OF THE BUSHVELD COMPLEX

The cross-cutting nature of the Bushveld Complex across its floor has been clearly demonstrated in Figure 4. Elsewhere in the Transvaal, the Bushveld Complex displays similar relationships. This led van Biljon (1949, 1974) to propose his *transformation hypothesis* for the Complex. In terms of this theory, the cross-cutting contact is seen as a transgressive metasomatic front, which converted Transvaal sedimentary rocks to various igneous rocks in the Complex. While not gaining general acceptance, this theory raised the important question of the ultimate fate of the stratigraphic pile truncated by the Bushveld mafic phase. Some of the missing fragments are found as stratiform xenoliths, "floating" in the intrusive rocks of the Complex. The xenoliths can often be matched with their parent formations in the Pretoria Group. For example, pyroxene granulite xenoliths mapped by Groeneveld (1968) to the west of Dullstroom are altered volcanics, stoped off from the Dullstroom Lava. Similar relations pertain to both quartzitic and hornfelsic units. The volume of the xenoliths is, however, totally inadequate to account for the very substantial thickness of stratified rock apparently missing from the geological scene.

An alternative explanation is shown schematically in a series of block-diagrams in Figure 5. The first stage envisaged is of a gently-deformed pile of sediments cut across by a transgressive plane of weakness, subsequently to become the intrusion locus of the Complex. The second step involved the intrusion of the mafic magma into a chamber with a sloping floor. The first showers of cumulus crystals filled the hollows, while successive layers lapped higher and higher up the floor. The "missing" stratigraphic pile is inferred to have been jacked up on top of the mafic rocks. In this position they lie in the intrusion-path of the Bushveld granites. The hot sedimentary pile was then further heated, metasomatized, and structurally disturbed by the granite intrusion (Figure 5c), and resulted in the metasedimentary suite which can be mapped around the entire Complex at the contact of the mafic and acid phases.

A further important relationship is indicated in Figure 5c, and relates to the angular differences in dip between floor-rocks and layering in Bushveld rocks, when seen in an east-west cross-section. In many instances, it can be shown that the floor-rocks dip at a much steeper angle than the Bushveld layering. A consequence of this is that stratigraphic units within the Bushveld Complex must abut against, and wedge out onto, floor-rocks in an east-west sense, the same sort of relationship seen in the north-south direction. It follows that certain units in the Bushveld Complex, the Merensky Reef, for example, may be preserved down dip in a given locality, even though it has wedged out against the floor at the level of outcrop.

VII. CONCLUSIONS

The stratigraphic pile above the Magaliesberg Quartzite comprises up to 4 300 metres of well-preserved sedimentary and volcanic rock, in six formations. The sediments were deposited mainly in marginal-marine environments, including the offshore, subtidal, intertidal, and beach. It is proposed that the eastern Transvaal be regarded as the type-area for stratigraphic units of the Pretoria Group above the Magaliesberg Quartzite.

The sediments are metamorphosed, both through the agency of mafic sills and the main body of the Bushveld Complex. Sediments which were extensively metamorphosed by sills are less amenable to re-metamorphism by the Bushveld Complex, and result in polymetamorphosed hornfelses referred to as the *Groothoek-type* by Hall (1932). Metamorphic effects penetrate deeper into the floor in a northerly direction, probably due to a thicker section of mafic rocks, plus a greater proportion of ultramafics.

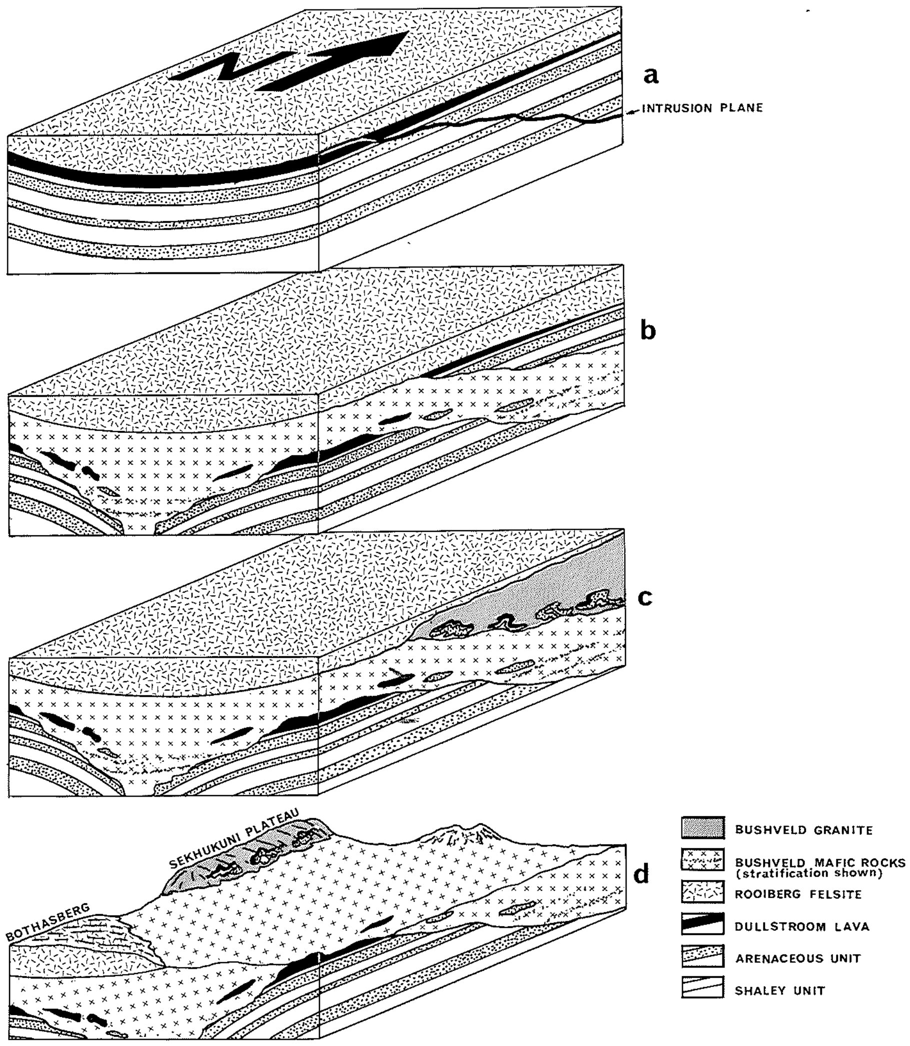

Figure 5 : Series of schematic block-diagrams showing the envisaged sequence of events during intrusion of mafic and acid phases of the Bushveld Complex.

The floor of the Bushveld Complex had a relief of up to about 5 000 metres, this being the thickness of stratigraphic units in the floor which were truncated by igneous rocks of the Complex. Stratigraphic units within the Complex wedge out against a sloping depositional floor. The pile of sediments truncated by the Complex is inferred to have been jacked up on top of the mafic intrusives, where they were subsequently intruded, deformed, and metasomatized by granitic rocks of the Bushveld Complex. They are presently seen as an assemblage of metasediments which have been encountered around the Complex, near the contact of the mafic and acid phases.

The step-like, transgressive nature of the Bushveld Complex with respect to its floor, seen in a north-south section in the eastern Transvaal, can be inferred in east-west sections as well. A consequence is that some economically important units in the mafic phase may wedge out onto the floor in a given region, and not be seen at the level of outcrop.

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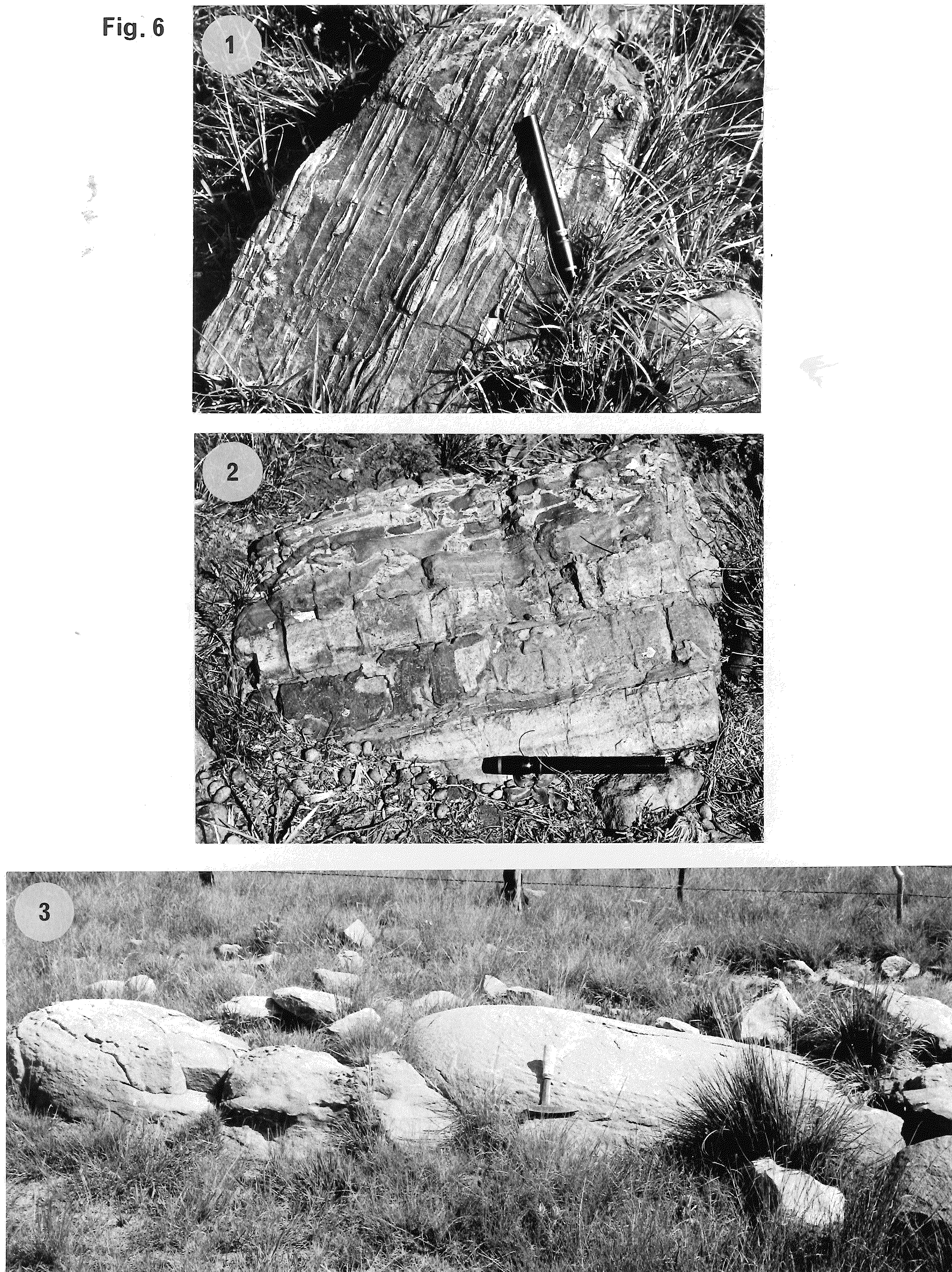
* *

<u>Figure 6.1</u> : *Lenticular, ripple-cross-laminated silty layers in finer-grained metamorphosed shale, Vermont Formation.*

<u>Figure 6.2</u> : *Mud-flake breccia at base of Lakenvalei Quartzite.*

<u>Figure 6.3</u> : *Rounded weathering pattern of fine-grained arkoses in the Nederhorst Formation.*

Fig. 6



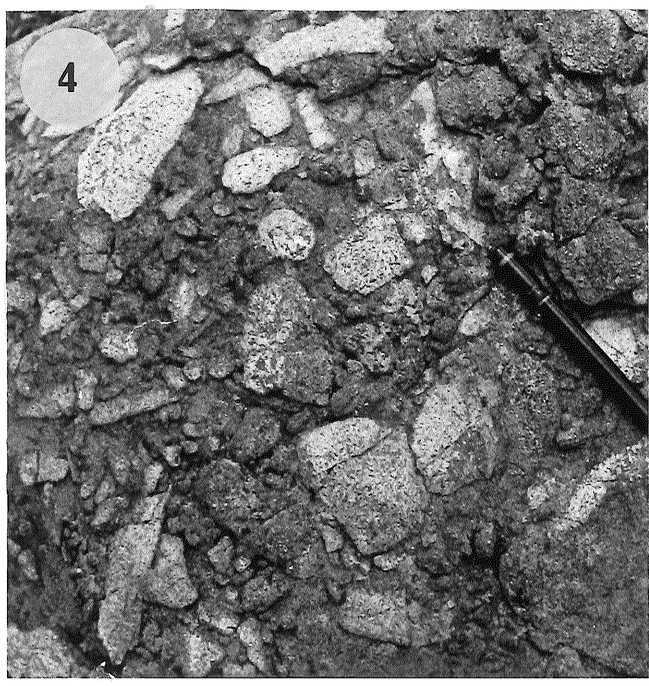
<u>Figure 6.4</u> : Intrusion breccia, composed of angular clasts of Nederhorst Formation arenites in a hybrid diabasic matrix.

<u>Figure 6.5</u> : Large-scale, planar cross-bedded unit in orthoquartzite of the Steenkampsberg Quartzite.

<u>Figure 6.6</u> : Bedded felsic tuff in the Dullstroom Lava. Note presence of elongate pyroclastic fragments.

<u>Figure 6.7</u> : Alternation of coarsely recrystallized (extremely pure) quartzite, with less recrystallized (impure) quartzite, belonging to the Steenkampsberg Quartzite.

Fig. 6 (continued)



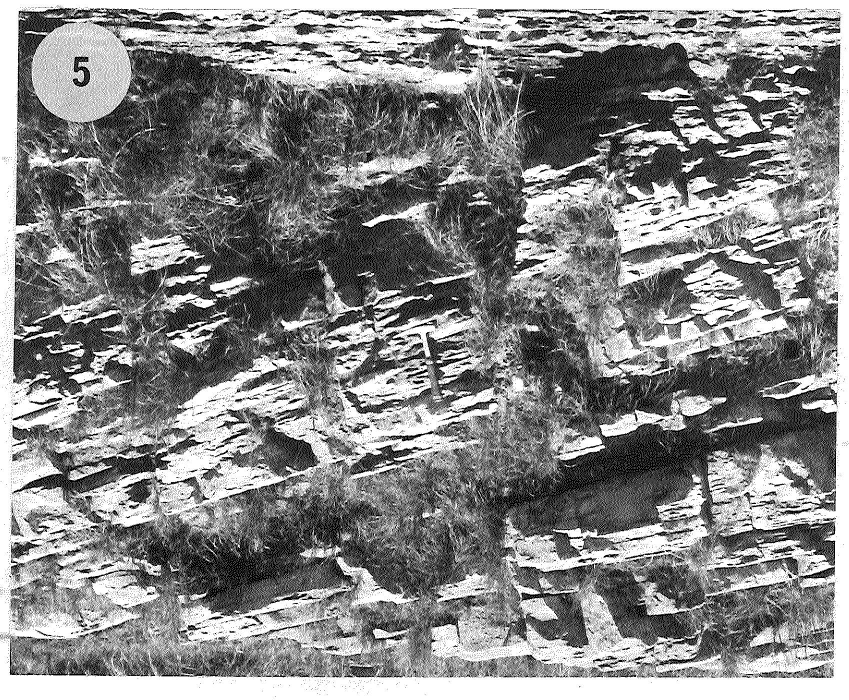


Figure 6.8 : *Top contact of sill intrusive into Vermont Formation. Hornfels above sill has become plastic and has been injected back into the chill phase of the sill.*

Figure 6.9 : *Partially melted hornfels of the Lydenburg Shale Member. Bedding is disrupted and flow-folded. Rock is veined by quartz-feldspar mobilisate.*

Figure 6.10 : *Closely spaced joints in Dullstroom Lava, where metamorphosed by the Bushveld Complex. Joints have acted as passageways for fluids emanating from the cooling Bushveld Complex.*

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Fig. 6
(continued)