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Geomorphology of the Bushveld Complex

Geomorfología del Complejo de Bushveld

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This paper deals with the different relation between structure and lithology in the geomorphology of the Bushveld Complex. The final results demonstrate that, even so different scale of size, wider for the epirogenic-tectonic movements and smaller for the lithology, the two factors need to be considered for a better understanding of the landscape evolution of the area.

Key words: ultrabasic and basic rocks, Bushveld Complex, structural geomorphology, lithological differences.

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INTRODUCTION

In spite of the strong emphasis on climatic topics in French geomorphology since the fifties, research dealing with structural landforms developed in crystalline shields pioneered by the late Professor P. Birot has been upheld. In numerous regional monographs, widely distributed between the Arctic Circle and the Tropic of Capricorn, special attention has been devoted to the relationships between landforms and geological structure, with the purpose to distinguish between the direct control of recent faulting and the response of contrasting rock units to differential erosion. This ambiguity may be easily overcome in the Bushveld Igneous Complex in the South African interior.

The Bushveld Complex is the largest exposed plutonic intrusion in the world, covering some 67 000 km^2 in the central part in the central Transvaal. Elliptical in plan, with a latitudinal long axis of 460 km, it consists of a granitic core ringed by exposures of basic and ultrabasic rocks which at the eastern and western margins extend over more than 12 000 km^2 (fig. 1). While most investigations in shield areas are concerned with acid plutonic rocks, the Bushveld Complex offers an opportunity to examine landforms deriving from lithologies which are rarely encountered at outcrop.

If, originally, the objectives of the field work were well defined, since the purpose was to establish a scale of relative resistance to weathering and erosion for the eastern rim of the Complex, which exhibits a well defined scarp-and-vale scenery, the investigation was subsequently extended to the western rim where the same exposed lithostratigraphic units only give rise to subdued topography. So, being concerned with the relationships between scenery and structure, the study will consider two different but complementary topics: differential erosion and regional evolution of a shield area (Y. LAGEAT, 1989).

GEOLOGICAL POTENTIAL

A presentation of the geology of the Bushveld Complex is essential to any understanding of its surface morphology. Ranging in composition from ultrabasic to acid, it outcrops largely within a region covered by a characteristic vegetation termed «Bushveld». Beneath its acid roof, the mafic sequence houses the world's largest reserves of platinum, chromium and vanadium (G. von GRUENEWALDT, 1979).

This intrusion was emplaced circa 2 050 M.y. ago in the Precambrian Kaapvaal craton which consists of an archaean crystalline basement locally overlain by remnants of the Transvaal Supergroup (mainly quartzites and shales) of Early Proterozoic age. Contrary to earlier interpretations it is now considered,

(i) that the overall structure of the Complex is not lopolithic but rather that several cone sheets, not necessarily connected at depth, have been intruded;

(ii) that differentiation did not take place in a single huge chamber but rather that several discrete magmatic pulses occurred, as shown by variations in mineral composition and a well established Sr-isotope stratigraphy.

Structure, which embraces both the lithological nature of rock types and the volumetric arrangement of rock units, is essential to any understanding of surface morphology in the Bushveld Complex. The

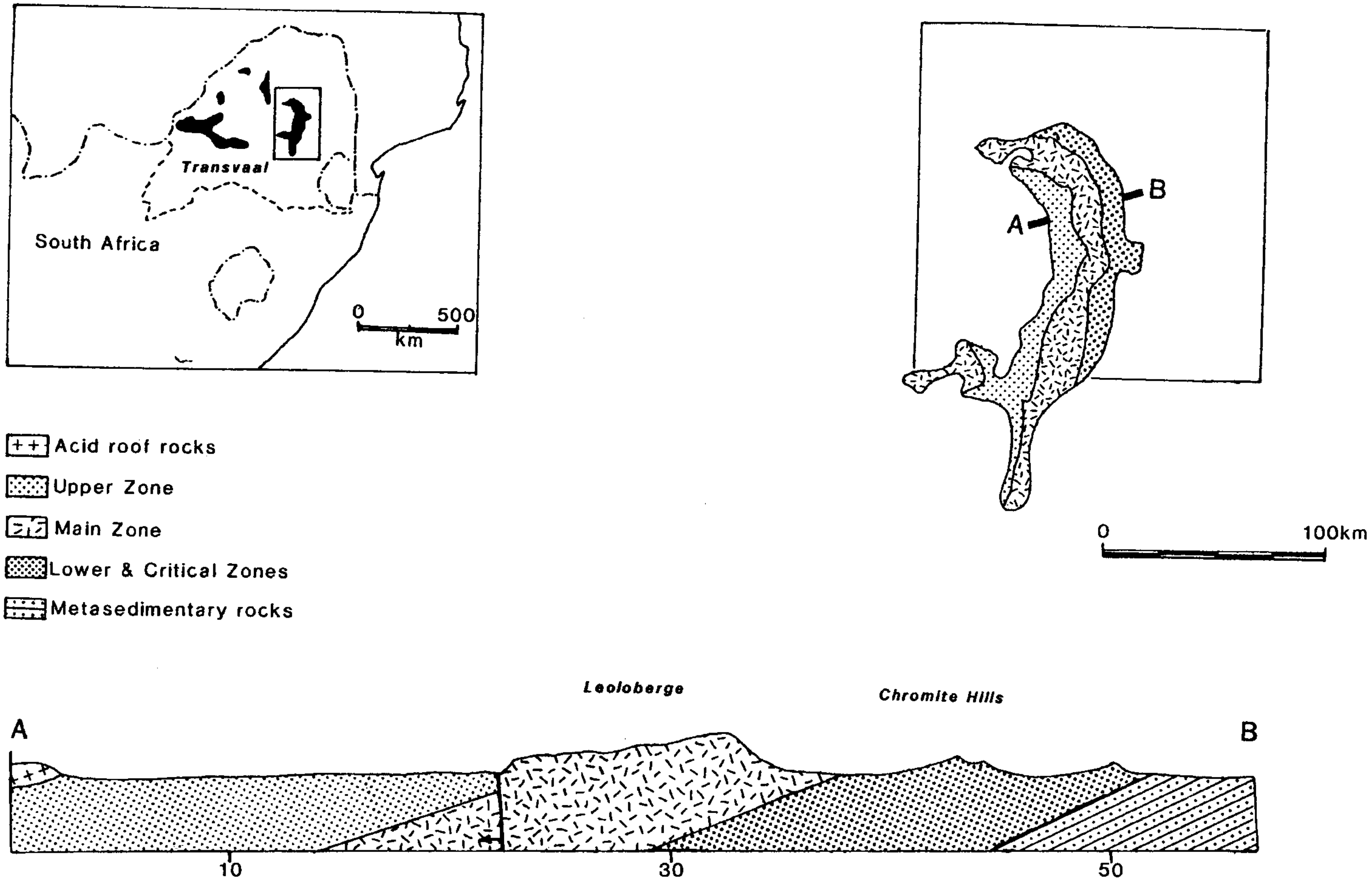


Fig. 1. The eastern Bushveld Complex: geological sketch of the layered suite and generalized cross-section.

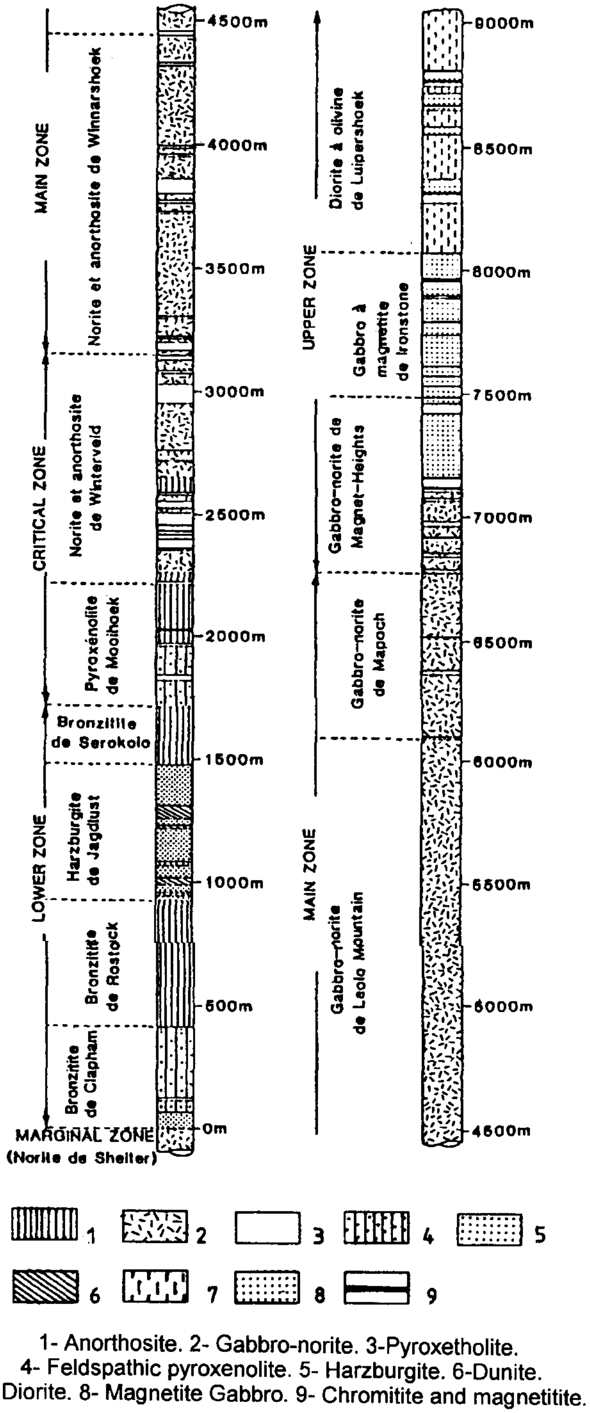


Fig. 2. Generalized columnar section through the eastern Bushveld Complex.

distribution of various crystalline rocks has been explained in terms of fractional crystallisation and segregation of different mineral aggregates from a basic magma, involving either the appearance and disappearance of liquidus mineral phases, or through variations in the chemical compositions of these minerals. They have led to the establishment of a stratigraphic succession comprising four distinct zones (fig. 2). From bottom to top, the thicknesses typical of the eastern rim are:

- 1,600 m for the Lower Zone,
- 1,000 m for the Critical Zone,
- 4,000 m for the Main Zone, and
- 1,500 m for the Upper Zone.

These zones consist of superposed layers characterised by lateral continuity but also by variations in thickness. The best example of this layering, analogous to bedding in sedimentary rocks, is provided by the strong contrast in colour between black chromite layers (chromitites) and white plagioclase layers (anorthosites) in the Dwars River bed in the eastern Bushveld (photo 1). However, beside these thin layers, others may be several hundred meters thick, according to whether the crystallization rates are rapid or slow. Thus dome-like forms are sometimes observable in homogeneous piles by contrast with the prevailing homoclinal pattern.

The layered rocks of the Bushveld Complex are believed to be the result of crystals settling out of a cooling magma. This peculiar arrangement reflects the decisive influence of gravity, but other factors have also been involved in the process of magmatic sedimentation : convective circulations have to be evoked in addition to the simple sinking of crystals, as evidenced by fluidal planes (photo 2).

Since they associate two classes of materials these magmatic «sediments» may be analysed in the same way as clastic sedimentary rocks as :

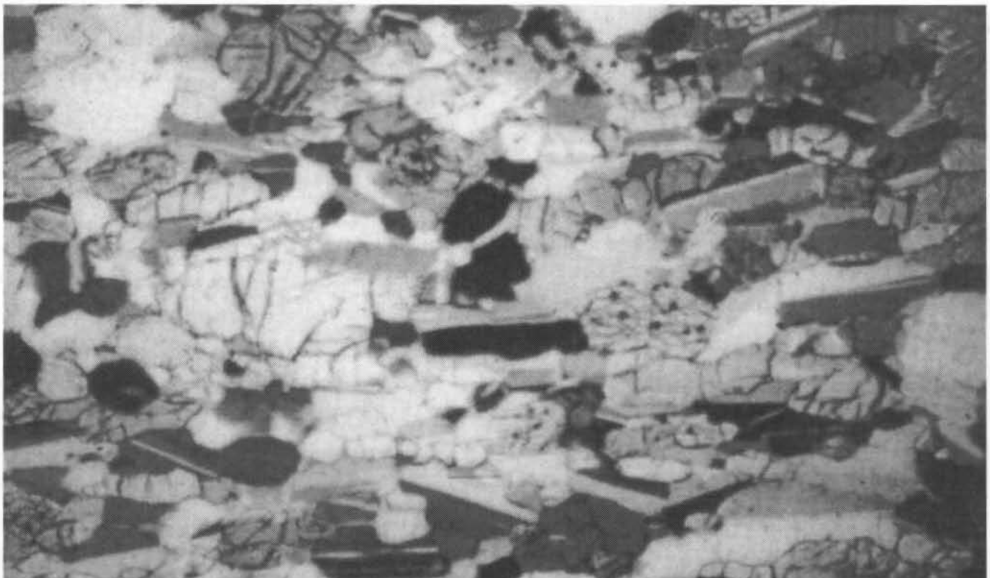
- the crystals that settled, known as the cumulus grains, and
- the intercumulus liquid which cristallized *in situ* cementing the detrital grains.

The consolidation of this interstitial magma produces rocks which are named cumulates. At least three important processes are involved in the cementation of cumulus crystals:

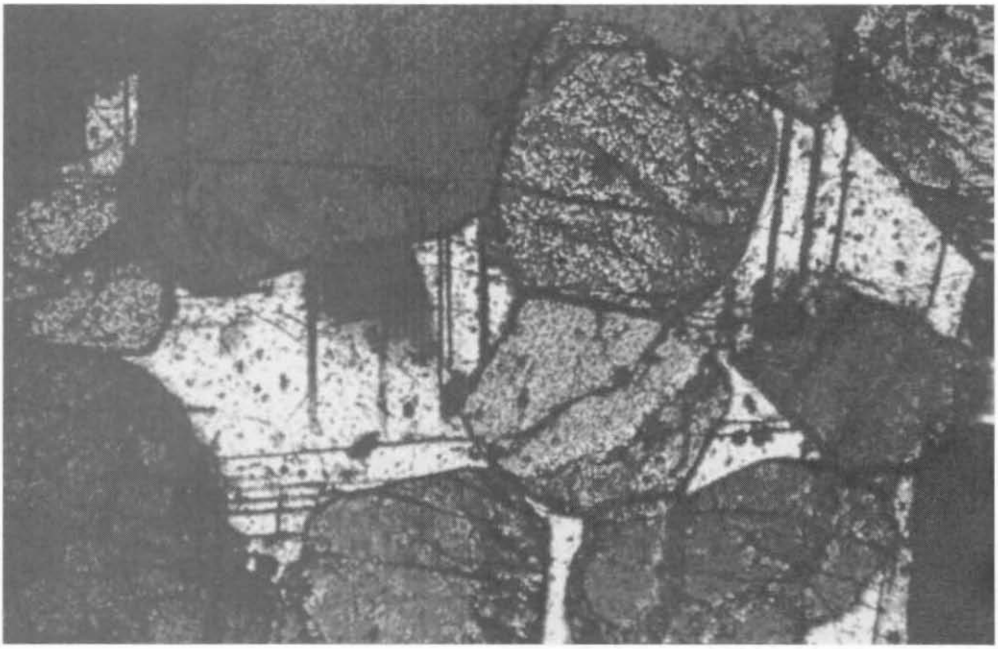
- simple space filling by minerals different from those the cumulus phase (photo 3);
- partial replacement, as shown by the resorption of rounded olivine grains enclosed in large orthopyroxenes produced by the crystallization of the trapped liquid (photo 4);
- overgrowth of the cumulus crystals by material of the same composition, a process which can produce completely monomineralic rocks (photo 5).

The basic and ultrabasic layers can, to all intents and purposes, be regarded as sedimentary formations dipping towards the centre of the Complex at angles between 10 and 30°. However, despite having seemingly identical structures, the morphologies of the eastern and western regions of the Bushveld differ substantially, for the former is characterised by a distinct scarp-and-vale topography, while the latter is a region of low relief. Showing the same asymmetry as observed in the sedimentary Paris basin, the eastern section, though in crystalline rocks, exhibits an unusual cuesta-like morphology (photo 6).

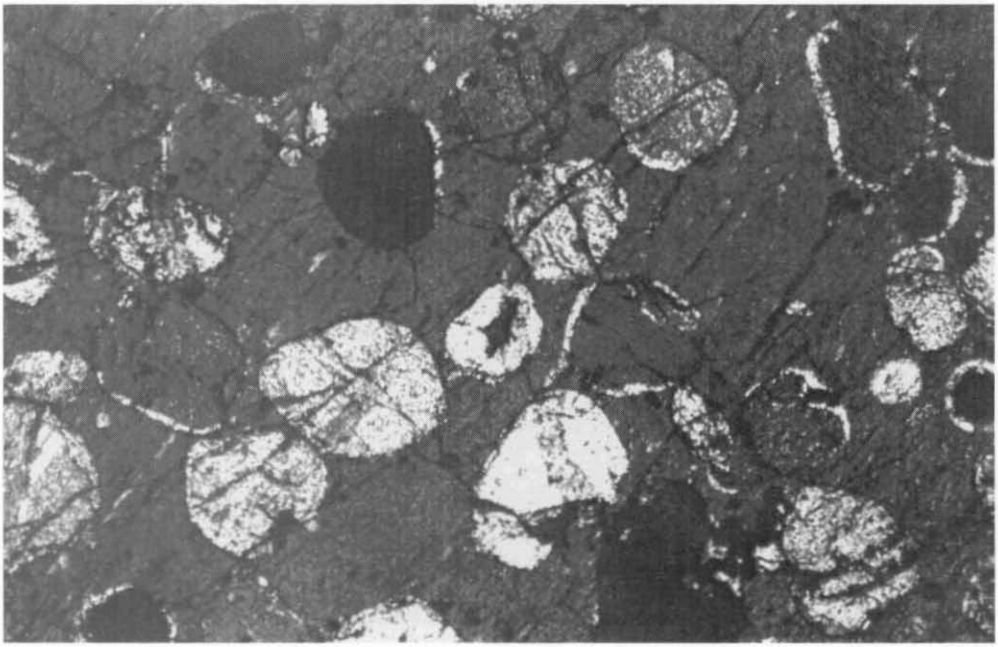
Pl. 1. Rythmic layering (anorthosite and chromitite).



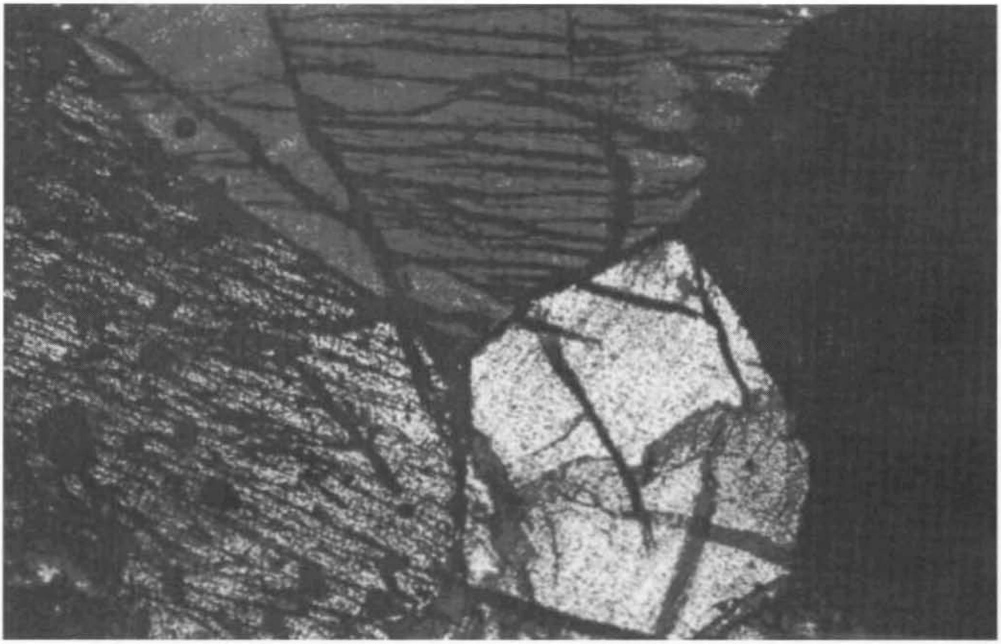
Pl. 2. Igneous lamination



Pl. 3. Feldespathic bronzitie (bronzite cumulus grains and interstitial plagioclase)



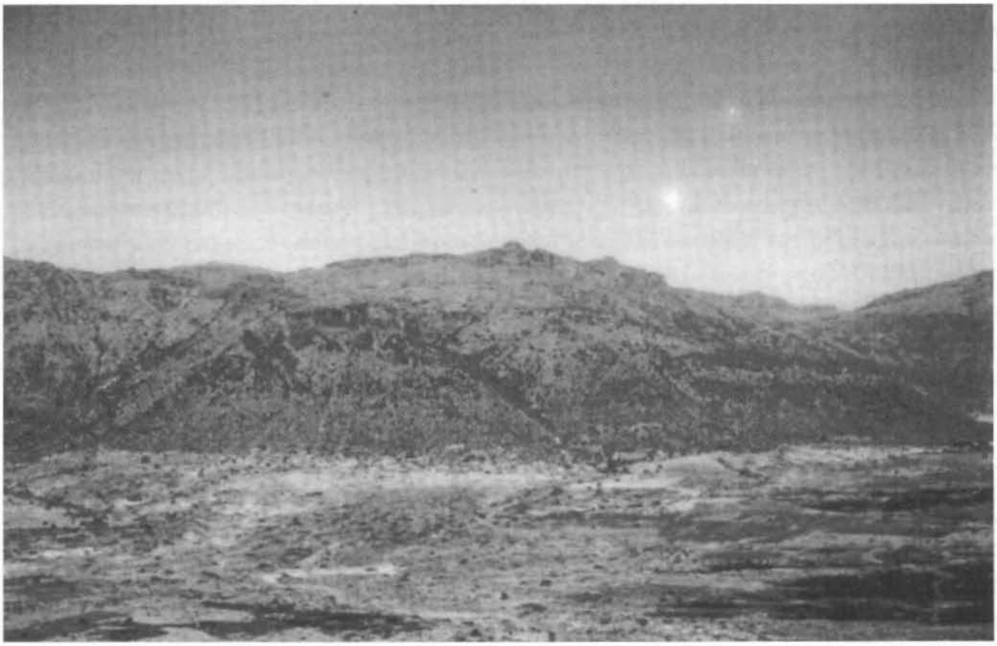
Pl. 4. Poikilitic harzburgite (rounded olivine grains enclosed in large bronzite crystals).



Pl. 5. Monomineral bronzitie (with interlocking grains)

Pl. 6. Chromite Hills: a cuesta-like scarp in the northeastern Bushveld

Pl. 7. The roof-rocks scarp above the depression carved out of the Upper zone rocks.



Pl. 8. The front scarp of the Leoloberge range.

LITHOLOGICAL CONTROL

By contrast with other shield areas the issue of differential erosion is fairly simple in the Bushveld Complex, with its superposition of differentially weatherable layers. However, just as in other crystalline rock suites, there is no direct relationship between lithology and relative resistance to erosion.

The morphology of the eastern Bushveld can be summarised by a section running between the Olifants and Steelport rivers, and along which the greatest variety of landforms is displayed. These include from southwest to northeast (fig. 1):

– a granitic cuesta which limits a plateau where remnants of a culminant erosion surface - the «Highveld surface» - are well preserved at a mean elevation of 1,500 m (photo 7);

– a depression formed in ferrogabbros and ferrodiorites of the Upper Zone between 1,200 and 1,000 m;

– the Leoloberge Range, culminating at 2,000 m, which coincides with the Main Zone gabbros : its western margin is controlled by a system of faults, while the eastern edge exhibits a 400 to 600 m high cuesta (photo 8);

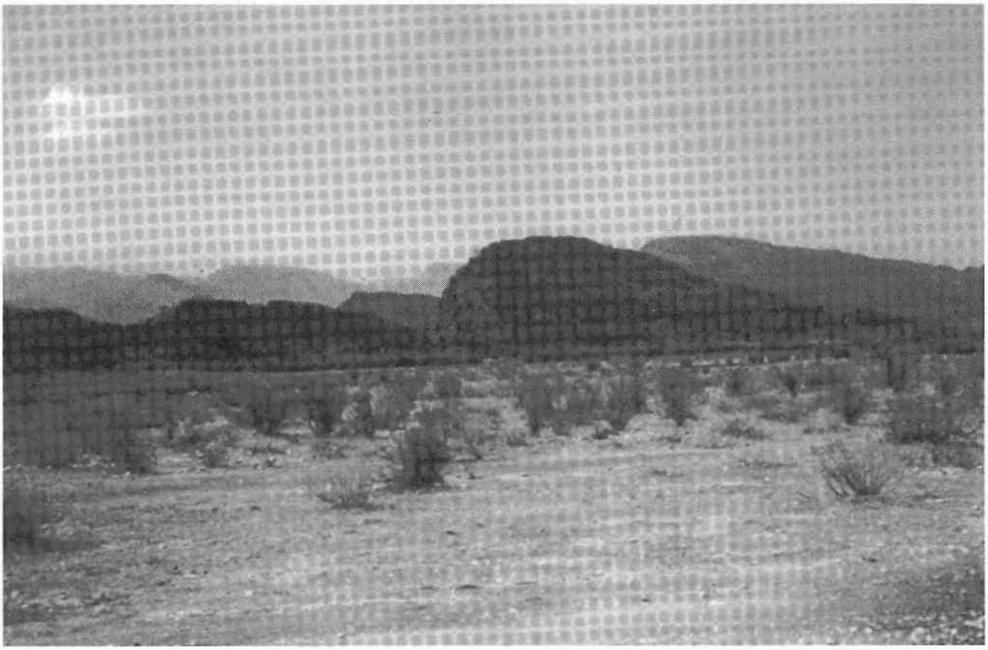
– at the foot of the latter a marginal plain extending across the Critical and Lower zones at an elevation of 800 m, with ridges of anorthosite and bronzitite (photo 9).

Differential weathering and erosion of the layered basic and ultrabasic rocks exposed in the eastern Bushveld Complex is readily demonstrated though the controlling factors are not simple.The scarp-and-vale topography reflects the relative resistance of individual magmatic layers, and a hierarchy of weatherability (and hence erodibility) can be readily established. The various rock textures can be correlated with weak and resistant layers, which in turn express the rhythmic macrolayering in the crystalline sequence. Figure 3 illustrates the relative weatherability of the various rocks in the study area.

At the intersection between a row and a column, the relative resistance between any two geologically adjacent layers is indicated by a plus or minus sign. Of course, if there is no indication of relative weatherability at any one intersection this implies that there is no contact between the two rock types in question. Blank spaces indicate that direct observation regarding relative weatherability cannot be made. From this figure it is possible to establish a crude hierarchy of weathering with respect to the main rock types.

Mineral composition has little influence on surface expression except for the major contrast between acid roof rocks and the upper part of the layered basic complex. Otherwise differential weathering and erosion in the mafic sequence is almost everywhere independent of mineralogy. For example, monomineralic anorthosites or bronzites, which, consisting as they do of such highly susceptible minerals (at least, according to the Goldich stability sequence), as plagioclase and pyroxene, could reasonably be expected to suffer deep weathering and erosion. Yet layers of such materials count amongst the most resistant to be found and are usually associated with ridges and other upland features.

The most resistant rock types are adcumulates in which the constituent grains are cemented, or which are densely packed with closely interlocking grains. Thus the gabbros of the central part of the Main Zone



Pl. 9. Dip-slopes of homoclinal bronzitite landforms north of the Chromite Hills.

which underlie the Leleoberge are composed of interlocking orthopyroxene, clinopyroxene and plagioclase. There is only one exception among these adcumulates: the peridotites which are largely or even completely converted into serpentines exhibing typical mesh textures.

By contrast with these densely packed textures, weaker members of the layered sequence are characterised by the presence of interstitial or poikilitic minerals more prone to alteration than the cumulus crystals. An analogy may usefully be drawn with a quartzite consisting of quartz grains cemented by silica, and, say, a calcareous sandstone with quartz fragments held together by a calcite cement.

Thus texture appears to be the major factor explaining differential weathering, especially in terms of strenght of the links between minerals, as the crystal faces evolve to minimum energy configurations in adcumulates. This factor has been underlined by porosity measurements and compressibility tests, but it does not however provide a satisfactory account of relative weatherability in all rock types.

There still remains a morphological enigma, regarding the susceptibility of the ferrogabbros and ferrodiorites of the Upper Zone, the fabric of which is unable to explain their weatherability, the only exception being magnetite monomineralic layers. These rocks are obviously subject to more rapid disintegration. Their comparatively greater susceptibility may be due to chemical environments and reactions peculiar to basic rocks. Laboratory experiments on the hydrolysis of fragments of these rocks using distilled water have shown that clinopyroxenes decompose more rapidly than do feldspars, a feature which is confirmed by the respective ratios of these minerals in sand fractions in the field (fig. 4).

The release of magnesium and calcium is favoured by a higher hydrogen ion concentrations in the solutions so that waters in contact with magnetite-bearing rocks, like the ferrograbbros and ferrodiorites, are more acid than those in contact with other rock types. The sulphur content of the rocks enhances their rapid breakdown.Sulphur is released during the oxidation of sulphides in the Upper Zone. This causes decrease in pH which in turn enhances the alteration of the iron rich ferromagnesian minerals, as shown by the chemical analysis of water samples (all units mg/l except pH):

	Main Zone (8 samples)	Upper Zone (8 samples)
pH at 25° C	7,98	7,74
Ca	32,3	58,4
MG	20,5	28,3
Na	10,0	18,4
K	<1,0	<1,0
CI	5,1	17,4
SO_4	7,5	48,3
Total alkalinity as	159,0	191,0

REGIONAL MORPHOLOGICAL CONTRASTS

Overall the landscape of the eastern part of the Complex is characterised by the rejuvenation of an initial surface, the «Highveld Surface», the remnants of which are well preserved on resistant acid roof rocks (felsites and granophyres). The structural relief of the region, with its a distinct scarp-and-vale morphology, has been developed during two subsequent stages of fluvial incision and lateral planation.

By contrast, despite a seemingly shared geological structure, the western region of the Bushveld Complex is a region of low relief known as the the «Bushveld Basin» which lies between 1,000 and 1,200 m. This planation surface is only punctuated by residuals belonging to the Main Zone of the mafic sequence. There is only one

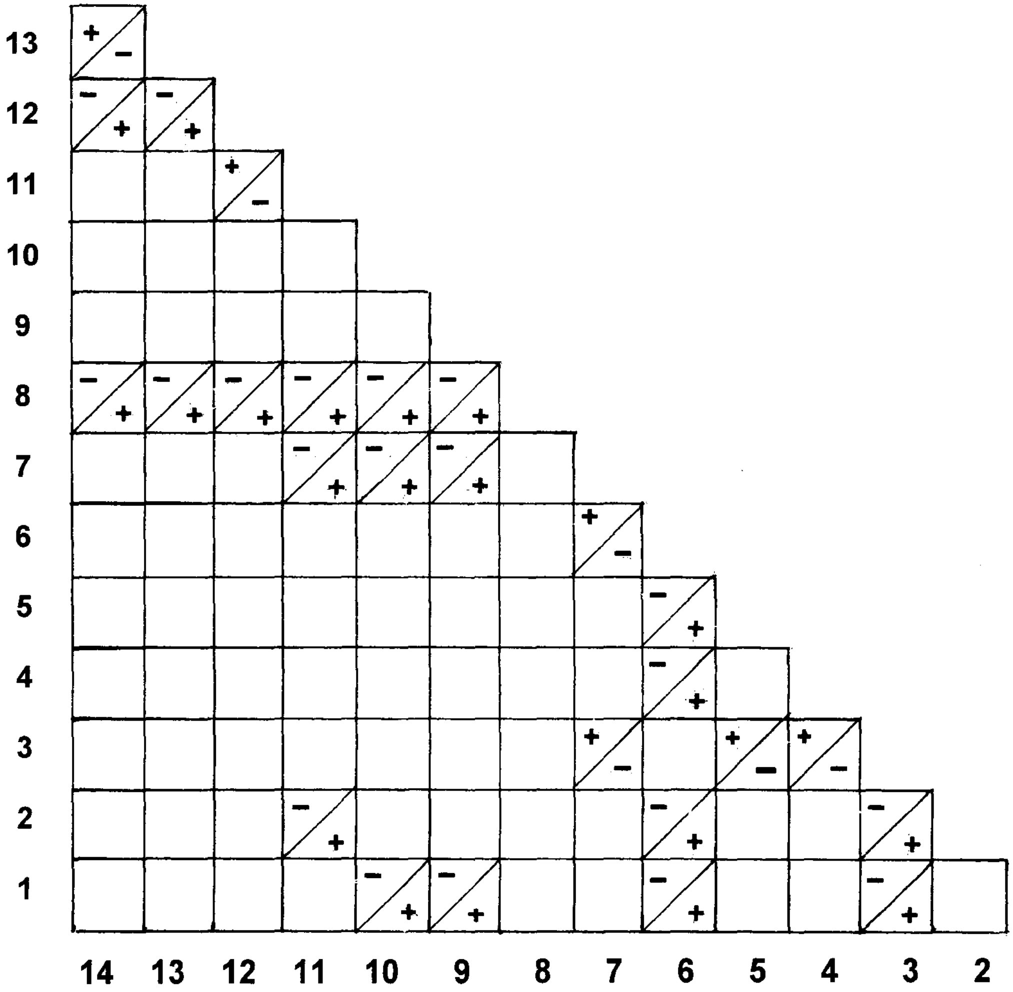


Fig. 3. Weathering scale of basic and ultrabasic rocks.

1- Marginal norite. 2- Feldspathic bronzitite. 3- Bronzitite (L.Z. and C.Z.). 4- Dunite (L.Z. and C.Z.). 5- Harzburgite (L.Z. and C.Z.). 6- Anorthosite (C.Z.). 7- Spottednorite. 8- Mottled anorthrosite. 9- Gabbro (Mza). 10- Gabbro (Mzb). 11-Gabbro (Mzc). 12. Magnetite gabbro and diorite (U.Z.). 13. Magnetitite (U.Z.). 14- Troctolite (U.Z.).

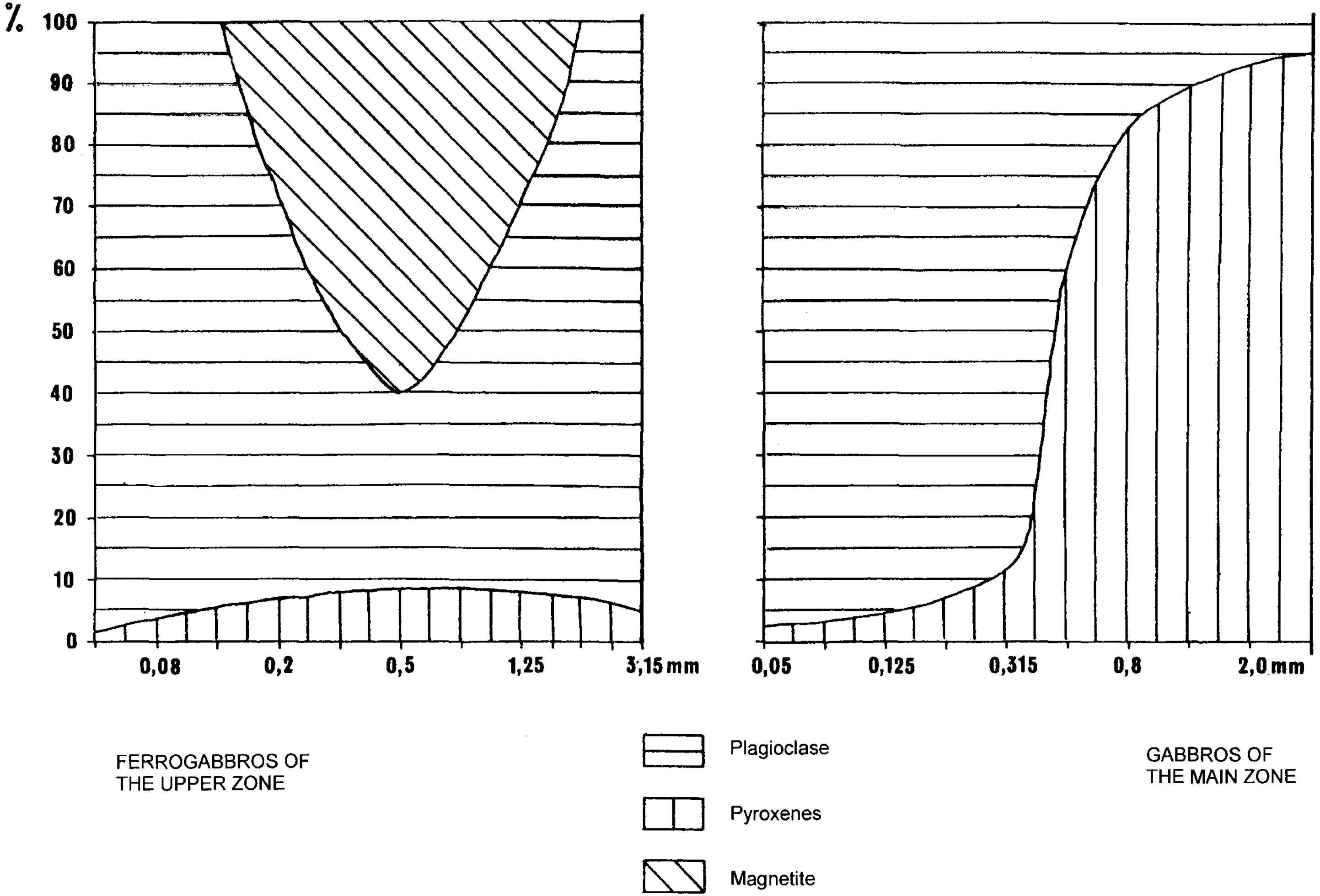


Fig. 4. Mean composition of the sandy fraction of regoliths.

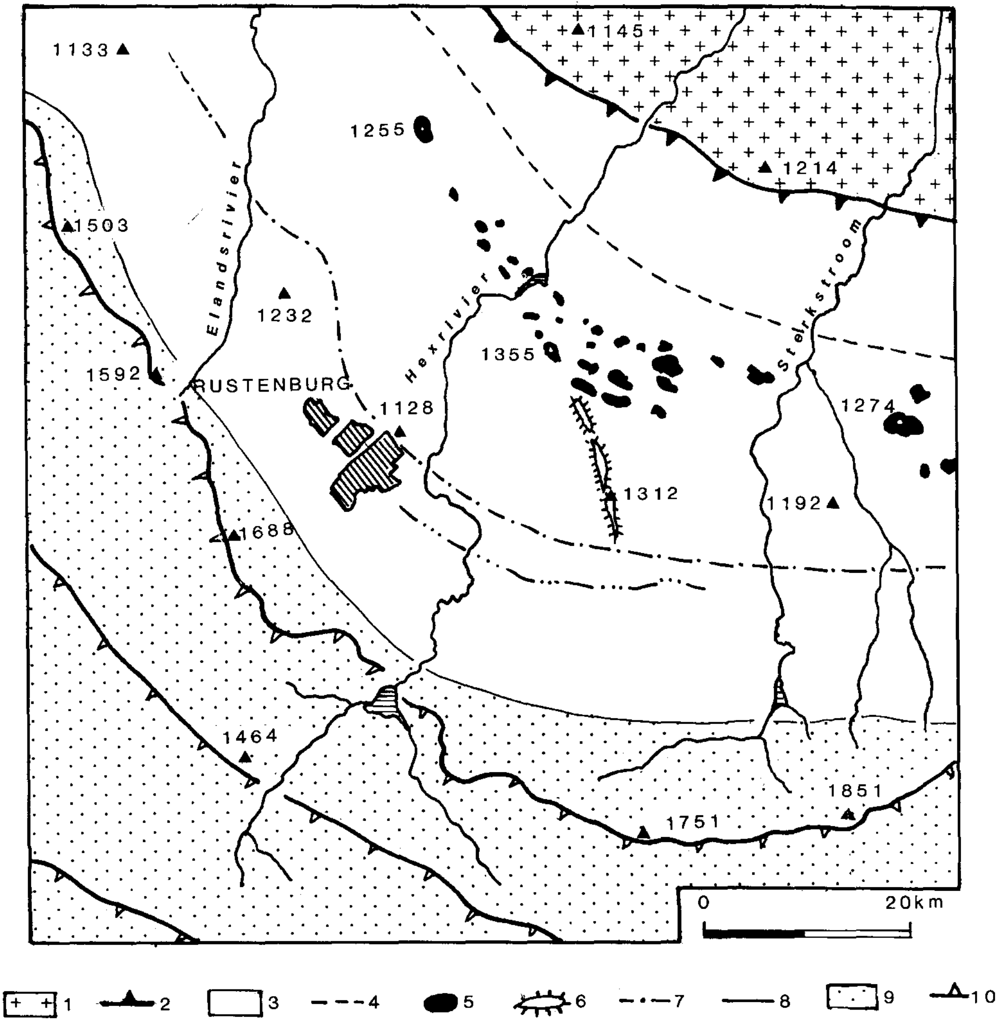
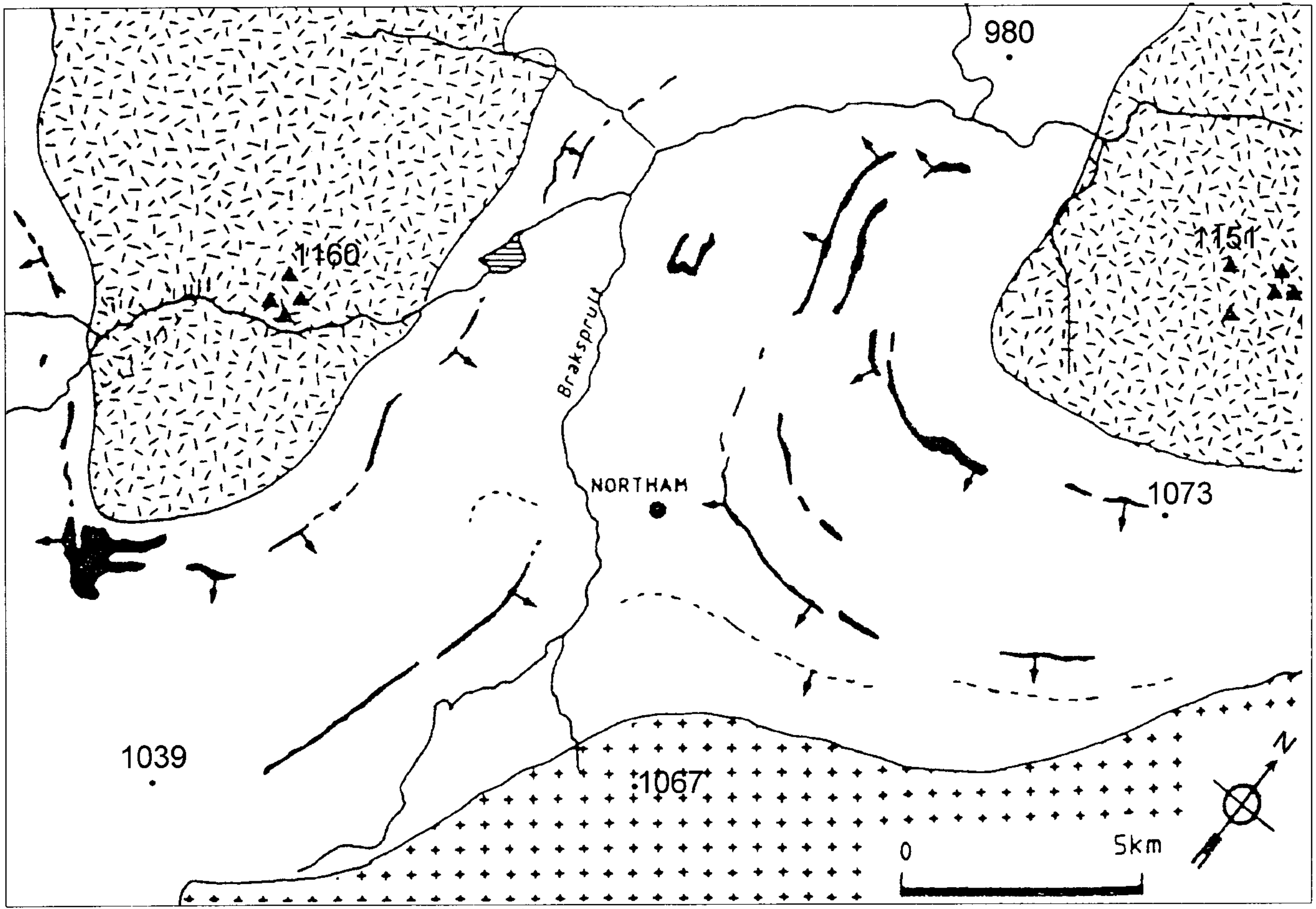


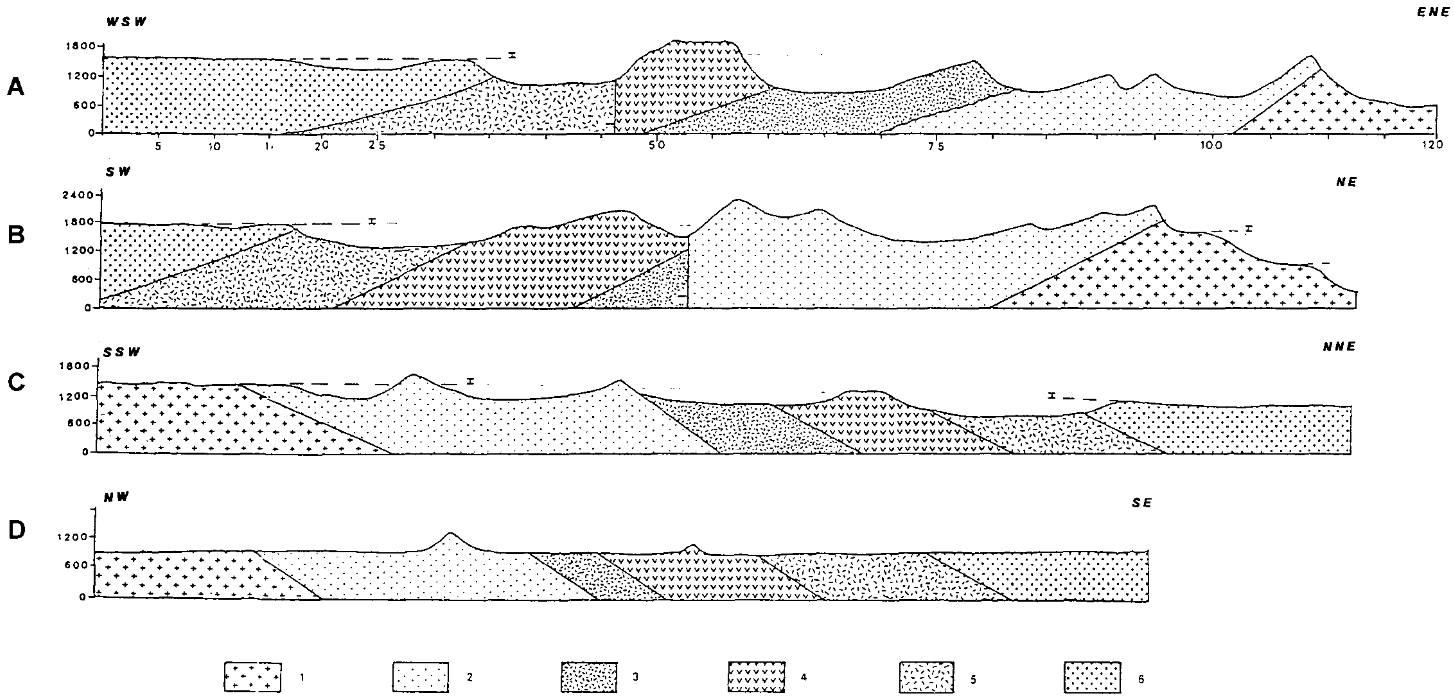
Fig. 5. **Geomorphological sketch of the Rustenburg area (Southwestern Bushveld).**

1- Acid roof rocks. 2- Granitic cuesta. 3- Basic and ultrabasic rocks. 4- Main Magnetite Seam. 5- Main Zone gabbroic residuals. 6- Syenitic dykes. 7- Merensky Reef. 8- Lower contact of the layered suite. 9- Sediments of the Pretoria Group. 10- Quartzite homoclinal landforms.



1- Upper Zone and magnetite layers. 2- Main Zone. 3- Acid roof rocks. 4- Gabbroic inselbergs

Fig. 6. Geomorphological sketch of the Northam area (Northwestern Buskveld).



1- Archaean basement. 2- Transvaal Supergroup. 3- Lower and Critical Zones. 4- Main Zone. 5- Upper Zone. 6- Roof rocks (I = Highveld surface).

Fig. 7. Generalized sections across the Bushveld Complex.

A. & B. Eastern Bushveld.
C. South-western Bushveld.
D. North-wester Bushveld.

exception, the prominent Pilanesberg Complex, an inselgebirge developed on a ring-complex mass of alkaline and hyperalkaline rocks, which is exposed as a result of the stripping of the Waterberg Sandstones into which the crystallines were originally intruded some 1,300 M.y. ago.

Elsewere the expression of differential erosion is quite discrete. Thus, in the southwestern sector the only manifestation of structural control in the landscape is associated with gabbros belonging to the central portion of the Main Zone : these outcrops occur as ridges (known as the "Pyramids") in a depression which has been excavated below the level of a culminant surface preserved on the roof of the intrusion (fig. 5). On the other hand, in the northwestern sector, the acid roof rocks and basic intrusives are truncated by the same planation surface, with just a few gabbroic inselbergs standing above the general level of the high plain, the «Bushveld Surface», which merges westwards with the depositional surface of the Kalahari Basin (fig. 6).

It is suggested that this contrast is due to recent tectonic events that have affected the rims of the «Bushveld Basin». The southern rim, which is also the divide between the Orange and Limpopo drainage systems, coincides with an asymmetrical updoming, whereas the northern rim is affected by vertical displacements associated with a major fault system known as the «Palala Shear Zone». As the eastern rim corresponds to a steepening of a marginal swell, this implies that this «basin» was produced by a «sagging process». This hypothesis has been thoroughly discussed by A L. DU TOIT (1933) and given more recent backing by T. STRATTEN (1979) and J.J. MAYER (1985) who demonstrated that some of the diamondiferous alluvial gravels in the Lichtenburg area in the southwestern Transvaal at an altitude of 1,500 m derived from a northern source region which now lies more than 400 m lower down.

Any analysis of the morphological evolution of the Bushveld Complex should involve a consideration of the epeirogenic deformations which have affected, albeit unequally, the whole region. These are apparent in the contrasted morphological expression of specific stratigraphic horizons. For example, the central part of the Main Zone forms the backbone of a prominent mountain chain in the eastern Transvaal, the Leoloberge which culminates over 1,900 m, the "Pyramids" north of Pretoria at an altitude of 1,400 m, and a few inselbergs in the northwestern Transvaal under 1,100 m. The Main Zone does not find any pronounced surface expression in the western Bushveld basin because of persisting subsidence and constant regradation of the initial Highveld surface which has been asymmetrically deformed. On the other hand upwarping of the eastern margin has led to repeated phases of differential erosion through polycyclical development with a marked structural imprint of the two latter planation cycles (fig. 7).

The planation surfaces of the eastern Bushveld are readily correlated with those recorded along the Great Escarpment of the Transvaal. Together with the intervening scarps they form a stepped sequence thought to be due to pauses in the uplift of the marginal swell. If we accept the traditional denudation model established by L.C. KING (1972): African, post-African I, and post-African II cycles, uncertainties remain concerning the chronology of this