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PRECAMBRIAN PALAEOWEATHERING AND EROSION SURFACES IN SOUTHERN AFRICA : REVIEW OF THEIR CHARACTER AND ECONOMIC SIGNIFICANCE

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by

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ABSTRACT

In southern Africa, Precambrian weathering and erosion surfaces are developed on granitic rocks, greenstone belts, acid and basic lavas, arenites, shales, carbonate rocks and banded-iron formations. The surfaces range from approximately 3400 to 600 m.y. in age. The data assembled suggests that the pre-2200 m.y. atmosphere-hydrosphere were geochemically harsh. Most evidence indicates strongly alkaline, reducing sulphidic palaeogroundwaters in this time bracket. Such waters stripped CaO, MgO, Na_2O and FeO/Fe_2O_3 from weathering profiles, which were residually enriched in Al_2O_3 and TiO_2. Many such profiles are strongly enriched in K_2O, suggesting potassium fixation from palaeogroundwater. There is some evidence of palaeogroundwater leaching of uranium from granitic rocks, followed by precipitation of the metal in contact with organic carbon or titanium-bearing minerals. These harsh groundwaters were also apparently capable of carrying some gold in solution, of causing pyritization of chert pebbles, and of leaching some of the components of platinoid grains.

A disproportionately large number of mineral deposits are associated with Precambrian unconformities. The vast period of geological time represented by these stratigraphic breaks was probably the most potent factor in mineral concentration. Other important factors identified include palaeotopography (due to differential erosion), solution and deposition by palaeogroundwater, mechanical sorting, biological action and porosity contrasts adjacent to unconformities. Continued study of Precambrian palaeoweathering and erosion surfaces promises to be an exceptionally fertile field for research, both in mineral deposits science, and in advancing our understanding of the fundamental questions of terrestrial atmospheric-hydrospheric evolution.

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PRECAMBRIAN PALAEOWEATHERING AND EROSION SURFACES IN SOUTHERN AFRICA: REVIEW OF THEIR CHARACTER AND ECONOMIC SIGNIFICANCE

I. INTRODUCTION

Palaeoweathering profiles and palaeoweathering surfaces are the products of interaction of rocks with the ancient atmosphere and hydrosphere. The rocks at and below unconformities must preserve details of the atmospheric, climatic, hydrologic, geomorphic and biologic conditions that prevailed on the Earth's surface. Since unconformities at least 3200 m.y. old can be recognized, they represent an excellent opportunity to study the evolution of these systems.

A disproportionately large number of ore deposits is controlled by unconformity - related processes (see for example Mills and Eyrich, 1966). This is particularly true of the Precambrian of southern Africa, where deposits of gold, uranium, manganese, iron, copper and fluorite (to name only some) can be linked to stratigraphic breaks. This is a region where sedimentary basins can be found through the entire Precambrian, and is thus suited to a preliminary search for evolutionary changes.

The purpose of this paper is to synthesize available data on Precambrian weathering and related ore deposits in southern Africa, and, to some extent, elsewhere. This data base should serve as a starting point for further research which has, as its ultimate aim, the elucidation of the chemical and physical evolution of the global atmosphere and hydrosphere.

II. SUMMARY OF PRECAMBRIAN STRATIGRAPHIC HISTORY OF SOUTHERN AFRICA

The Precambrian history of southern Africa spans a period in excess of 3000 m.y. In this summary, only the broadest stratigraphic developments are outlined. Emphasis is placed on those units pertinent to the study of palaeoweathering and erosion surfaces.

The oldest known rocks in southern Africa are the basement gneisses of the Limpopo Mobile Belt, which pre-date a suite of 3600 m.y. old tholeiitic dykes (Barton et al., 1977). Some greenstone belts are at least 3300 m.y. old. The majority of the Archaean granitoid rocks have been dated at between 3300 and 2600 m.y. (Anhaeusser and Button, 1976). Younger greenstone belts have, however, been reported. The Belingwe Greenstone Belt of Zimbabwe-Rhodesia has, for example, been dated at approximately 2770 m.y. old, and rests nonconformably on older granitic rocks (Bickle et al., 1975).

Some of the oldest known, well-preserved, cratonic sediments occur in Swaziland and adjoining parts of South Africa. Here, the Pongola Group (Fig. 1)which is approximately 3000 m.y. old, rests on an older granitic basement. The Pongola sequence comprises a lower, mainly volcanic unit (the Insuzi Subgroup) which is unconformably overlain by the sedimentary Mozaan Subgroup (Table 1).

The Dominion Reef Group (circa 2800 m.y. old) is a locally developed fore-runner of the Witwatersrand Supergroup, being confined to the western part of the basin (Fig. 1). It commences with basal conglomerates and arenites and is overlain by basic and acid volcanics. The Witwatersrand Supergroup (2600-2700 m.y.) follows unconformably on the Dominion Reef and rests elsewhere on the Archaean granite-greenstone basement. It comprises a lower division of shales and quartzites with minor conglomerate, iron-formation and mafic volcanics, which were deposited in marine and marginal-marine environments. The upper division is dominated by fluvial conglomerates and arenites but contains, in addition some shales and basic volcanics. The two divisions of the Witwatersrand Supergroup are separated by an angular unconformity (Table 1). Most of the payable gold- and uranium-bearing conglomerate sheets (locally termed "reefs") are developed on low-angle unconformities in the upper Witwatersrand.

In Botswana and the western Transvaal is a succession referred to as the Kanye Volcanic Group. This sequence has an age approximating that of the Witwatersrand succession. The Kanye Volcanic Group, which is intruded by the 2750 m.y. old Gaborone Granite, is composed mainly of acid volcanics which rest on the Archaean basement.

The 2500-2600 m.y. old Ventersdorp Supergroup (Fig. 2) follows unconformably either on the Witwatersrand, the Kanye or on the Archaean basement rocks. The Ventersdorp succession comprises mainly sub-aerial basalt flows with subordinate volumes of acid volcanics, volcaniclastic and chemical sediments. Two major unconformities are developed within the succession (Winter, 1965, 1976).

TABLE 1

Summary of the Major Precambrian Unconformities in Southern Africa - (modified after Anhaeusser and Button, 1976)

Supergroup	Group or Formation	Approximate Age (m.y.)	Rests Unconformably/Disconformably on:
Nama	Fish River Terminal Clastic Member of Schwarzrand Kuibis	600	Schwarzrand Formation Spitzkopf and Huns limestone members of Schwarzrand Formation Older granitic and metamorphic rocks
Katanga		600-700	Older (? Archaean) granitic rocks and metamorphics
Damara	Mulden Carbonates	600-700	Damara carbonates Older granitic basement, Dordabis and equivalents
Dordabis and equivalents		800-1000	Older (? Archaean) granitic rocks
Umkondo and equivalents		1100-1800	Archaean granites, Limpopo Belt metamorphics, greenstone belts
Waterberg and equivalents		1800-2000	Archaean granites, Limpopo Belt metamorphics, Transvaal, Bushveld Complex
Sijarira, Piriwiri, Lomagundi, Deweras		2500 ?	Archaean granites and greenstone belts overlain by Deweras and Lomagundi
Bushmanland		1800-2500	Basement of Namaqualand metamorphic region
Transvaal	Pretoria and Postmasburg) Black Reef and Chuniespoort) Wolkberg and Buffalo Springs)	2200-2300	Carbonates and iron-formation of Chuniespoort Group and equivalents Archaean granites, greenstone belts, Witwatersrand or Ventersdorp Archaean granites and greenstone belts
	Pniel) Platberg) Klipriviersberg	2500-2600	Platberg Group or Archaean granitic basement Klipriviersberg Group, Witwatersrand, Dominion Reef or Archaean granitic basement Mainly on upper Witwatersrand strata
Kanye		?2800	Inferred to rest on Archaean granitic basement
Witwatersrand	Upper) Lower)	2700	Lower division of Witwatersrand Supergroup Archaean granitic basement, greenstone belts, Dominion Reef Group
	Dominion Reef	2800	Archaean granitic basement
Pongola	Mozaan) Insuzi)	3000	Insuzi basalts and intercalated sediments Archaean granites and greenstone belts
Swaziland	Onverwacht	3400	Cherts rest paraconformably on aluminous schists in basalts

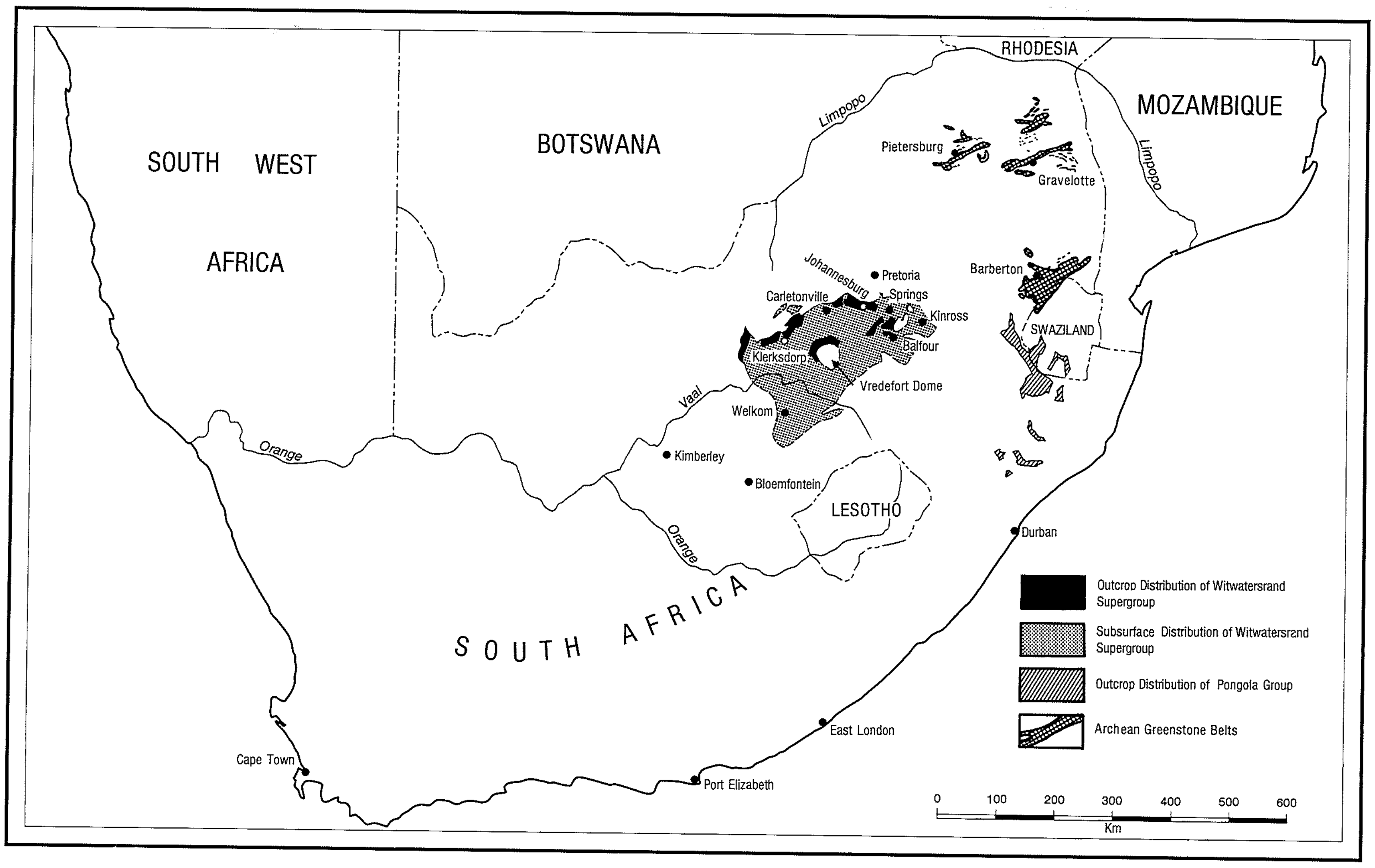

Figure 1: *Map showing distribution of Archaean greenstone belts, as well as Pongola and Witwatersrand basins.*

The Transvaal Basin (2300-2100 m.y. old) covers an area of approximately 250 000 km^2 in South Africa and Botswana (Fig. 3). It commences with clastics and volcanics of the Wolkberg Group (Button, 1973) and the Buffalo Springs Group (Tyler, 1978), which are developed only locally, adjacent to the basin axis. The Black Reef Quartzite is very wide spread, and laps across these units resting either on the Archaean basement, the Witwatersrand, or on the Ventersdorp Supergroup. The quartzite grades upwards into carbonates which, in turn, grade into banded iron-formation. Both the carbonate and banded iron-formations measure up to 2000 m in thickness. These chemical sediments were uplifted (and, in places, folded) and eroded before deposition of the Pretoria Group and its equivalents (Table 1). The Pretoria succession comprises mainly marine and marginal marine arenites and shales. One of the volcanic units within it, the Hekpoort Basalt, shows evidence of palaeoweathering along its upper surface. The Pretoria Group closed with the extrusion of a large thickness of rhyolitic volcanics, known as the Rooiberg Felsite (Fig. 3).

Following Transvaal sedimentation, the northeastern basin was intruded by the basic and acid magmas of the Bushveld Igneous Complex, from about 2100 to 2000 m.y. ago (Hamilton, 1976).

The Waterberg and equivalent units (1800-1900 m.y. old) rest unconformably on many older sequences, particularly the Rooiberg Felsite and members of the Bushveld Complex (Fig. 4 and Table 1). The Waterberg is composed mainly of coarse clastics and in southern Africa, it is the oldest unit containing significant volumes of red-coloured shale and sandstone.

In Rhodesia, the Deweras, Lomagundi and Sijarira successions follow unconformably on each other, and are underlain by the Archäean granite and greenstone basement (Fig. 4). Their age is unknown, but the lower units could be as old as 2000 to 2500 m.y. (W.D. Newham, personal communication, 1978). The Umkondo Basin (and equivalents) are developed in eastern Rhodesia. They contain red-coloured clastic sediments, and are probably between 1100 and 1800 m.y. old (Button, 1976).

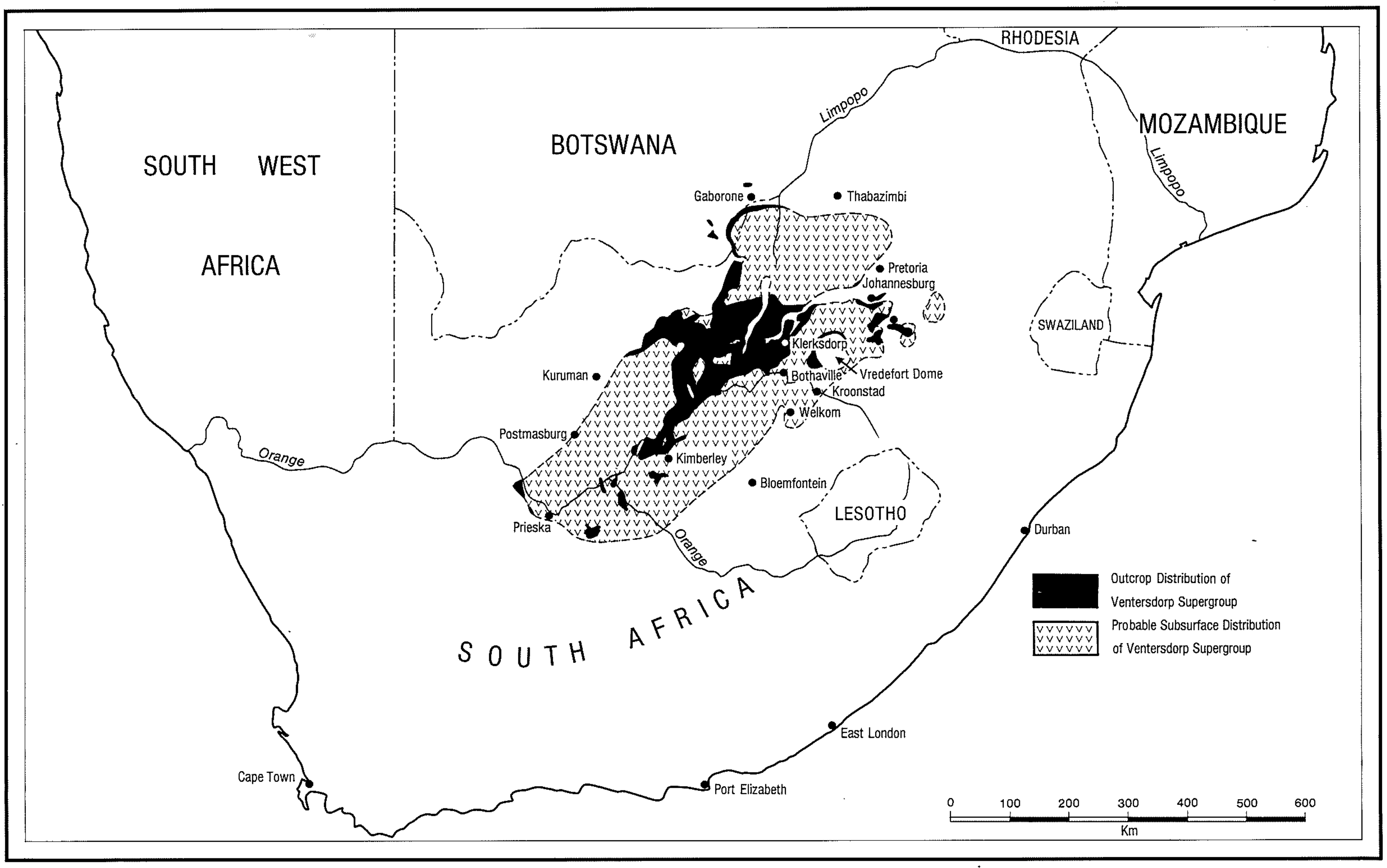

Figure 2: Map showing the surface and inferred subsurface extent of the Ventersdorp Supergroup.

The Bushmanland sequence is developed in the western Cape (Fig. 3), and comprises metamorphosed sediments with an age of between 1800 and 2500 m.y. (Moore, 1977). The sequence was strongly metamorphosed over a wide area approximately 1000 to 1100 m.y. ago. This supracrustal succession contains two alumina-rich zones, one of which underlies a quartzite and could represent an ancient weathering profile.

In South West Africa/Namibia and Botswana late Precambrian sequences are developed and are shown as the Dordabis and Konkip successions in Figure 4. The overlying Nama Group and equivalents cover large parts of South West Africa and the western parts of South Africa (Figure 4). Palaeontological and geochronological data suggest an uppermost Precambrian to lowermost Cambrian age for the Nama (Germs, 1972).

The Damara Supergroup of Namibia (Figure 4) may be slightly older than the Nama (Germs, 1972). It comprises a southern and western deformed and metamorphosed facies and a northern undeformed shelf facies. The succession extends northeastwards for approximately 500 km before being covered by younger formations. Its probable equivalents reappear in Zambia as the economically-important copper-bearing Katanga succession (Figure 4).

III. WEATHERING IN GREENSTONE BELTS

Altered Archaean felsic volcanic rocks are widely distributed in greenstone belts in southern Africa and elsewhere (Anhaeusser, 1969; Viljoen and Viljoen, 1969; Ferguson and Wilson, 1937; Swift, 1956; Joplin, 1963). The altered volcanics are normally schistose sericite-rich rocks. They are usually found above basalts and immediately below sedimentary units, most commonly cherts.

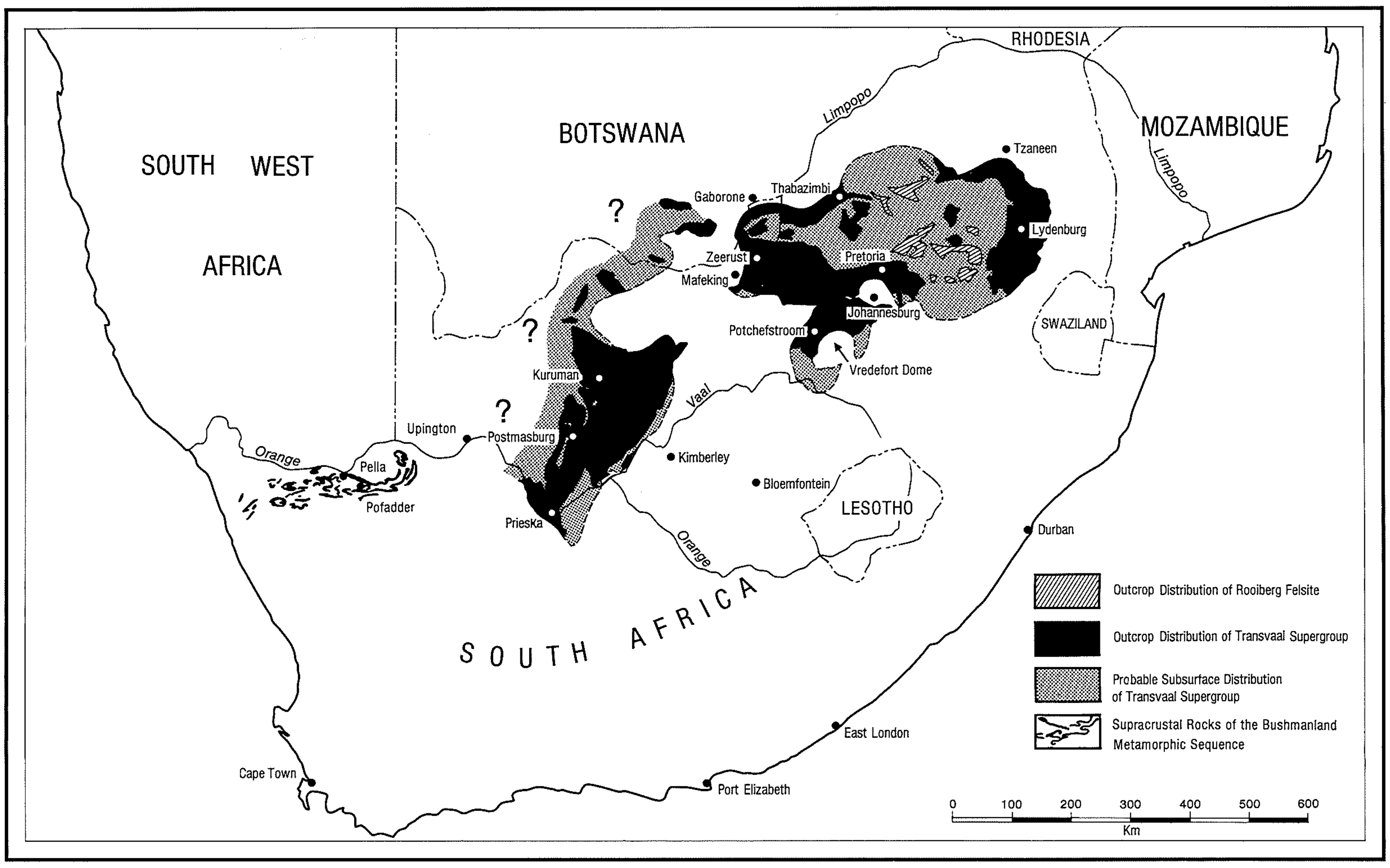

Figure 3: Map showing the distribution (surface and subsurface) of the Transvaal Supergroup (including the Rooiberg Felsite), and the Bushmanland Metamorphic Sequence.

A. Petrology

The alumina-rich schists found in greenstone belts are composed mainly of quartz and sericite (Anhaeusser, 1969). Andalusite, chloritoid, staurolite, muscovite, fuchsite, pyrophyllite and leucoxene-ilmenite are associated phases, while sillimanite is locally developed adjacent to intrusive contacts.

Marundites (margarite-corundum rocks) are infrequently developed and are thought to represent the metamorphosed-metasomatized equivalents of the aluminous schists. A reported occurrence of this type in the Barberton area consists of corundum, margarite, biotite and sericite (Anhaeusser, 1978).

B. Chemistry

Analyses of the Archaean sericitic schists reveals considerable variation in their composition (Figure 5 and Appendix 1). They tend to be depleted in iron, magnesium, calcium and sodium and are enriched to varying degrees in potash, alumina and silica.

C. Origin

The aluminous schists of most greenstone belts are located stratigraphically above thick basalt piles and below cherty sediments. Clasts have been recognized where the rocks are relatively undeformed (Anhaeusser, 1969; Viljoen and Viljoen, 1969). These authors concluded that the alumina-rich schists were originally pyroclastic rocks. In that they underlie cherts, it is tempting to speculate that they could represent the subaqueous weathering products of pyroclastic or volcaniclastic debris on the Archaean sea floor. Some could be the lithified and metamorphosed equivalents of bentonitic clays (Anhaeusser, 1969). They could be among the oldest known weathered materials on Earth, but much research on their distribution, petrology and chemistry still remains to be done.

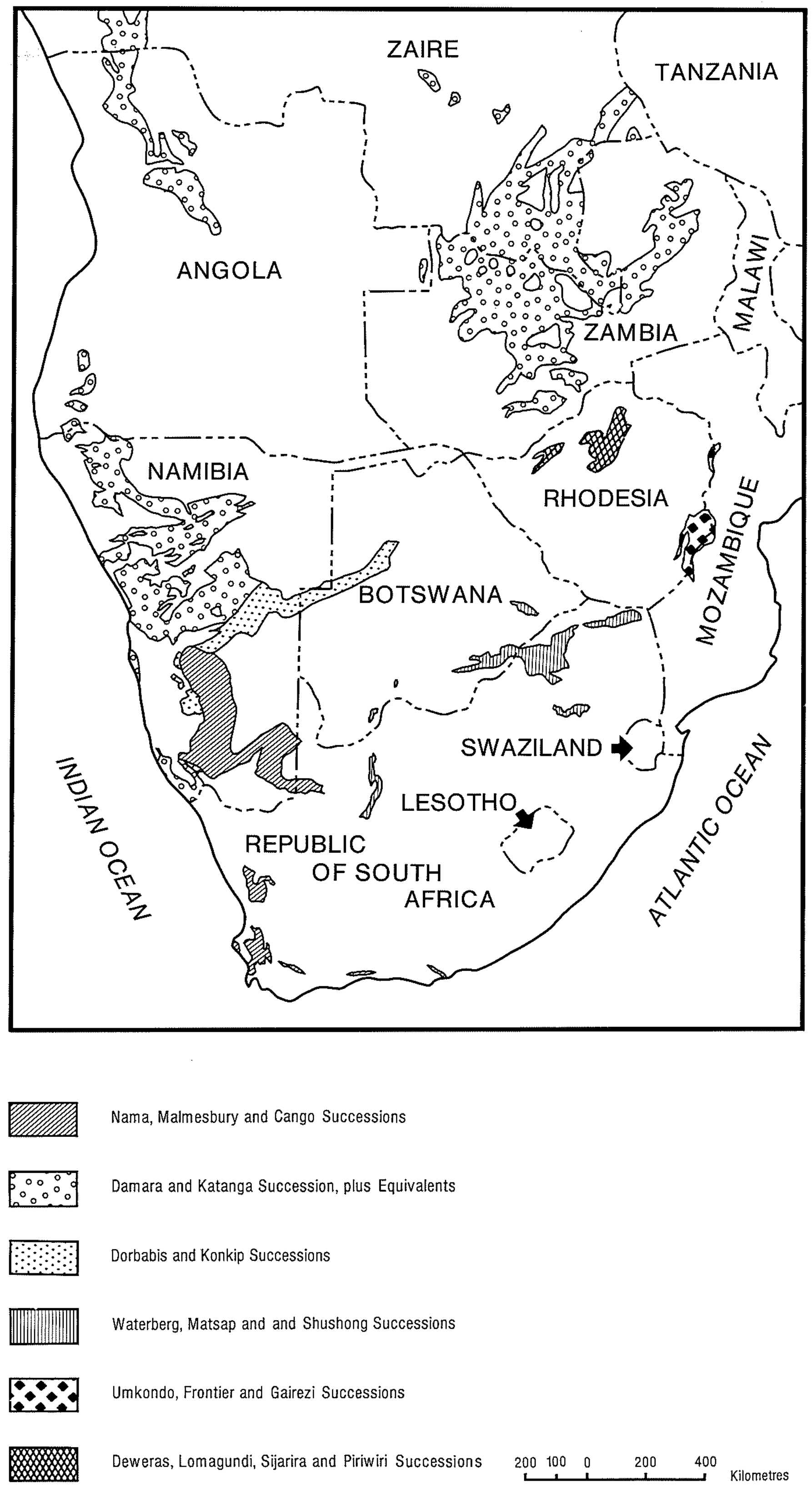

Figure 4: *Map showing the distribution of middle and upper Precambrian basins in southern Africa.*

IV. WEATHERING SURFACES ON GRANITIC AND METAMORPHIC BASEMENTS

A. Age and Distribution

Numerous granitic weathering profiles are known from beneath major unconformities. The oldest is that below the Pongola Basin (3000 m.y. old), and was described by Humphrey and Krige (1931) and by Matthews and Scharrer (1968). Similar profiles occur below the 2800 m.y. old Dominion Reef Group in the southwestern Transvaal (Nel, 1935), below the basal clastics of the 2700 m.y. old Belingwe Greenstone Belt in Rhodesia (personal observation, A.B., 1975) and below the 2600-2700 m.y. old Witwatersrand Basin (Pretorius, 1964a; Anhaeusser, 1973; personal observation, A.B., 1978). The Godwan Group of the eastern Transvaal is probably an extension of the Witwatersrand Basin (Button, 1978). A sericite-rich weathering profile is known where it rests on the Kaap Valley hornblende tonalite (Visser, compiler, 1956; personal observation, A.B., and N.T., 1978).

The 2200-2300 m.y. old Black Reef Quartzite at the base of the Transvaal Supergroup marks a very widespread unconformity. Granitic palaeosaprolites are widely developed beneath it, being recognized north of Johannesburg (Anhaeusser, 1973) and in the eastern Transvaal (Visser and Verwoerd, 1960). In this area, the altered rocks have been mapped over several tens of kilometres along strike.

The pre-Transvaal Supergroup palaeotopography has been established by stratigraphic mapping of the Wolkberg Group (Button, 1973). Over a strike length of 300 km, a palaeorelief of some 700 m has been established. The deepest valleys were situated over Archaean greenstone belts, while granitic tracts usually formed elevated ground (Figure 6). Similar relationships have been noted at the base of the Hamersley Basin of Western Australia (Hickman and Lipple, 1975) and of the Huronian of Canada (Robertson, 1976). In the latter case, the uraniferous Matinenda conglomerates are largely confined to the palaeovalleys.

In Rhodesia, quartz-sericite schists are developed along the basal contact of the Deweras arkoses and the underlying Mangula Granite (Jacobsen, 1964). The schists could represent sheared granitic palaeosaprolites.

A palaeoregolith is developed locally below the Middle Proterozoic Umkondo Group in Rhodesia (Button, 1977). It is composed of coarse-grained granitic detritus with scattered, angular vein quartz clasts.

In the Zambian Copperbelt, most of the payable mineralization is located at, and short distances above, the unconformity separating the upper Precambrian Katanga succession and an older basement comprising granites and low-grade metasediments (Mendelsohn, 1961). The palaeorelief was at least 300 m. Ancient steep-sided valleys were filled with poorly-sorted, coarse-grained detritus (Figure 7). A palaeosaprolite, up to 8 m thick, is developed on granites below the unconformity. Open cracks on this palaeosurface were filled by sand, pebbles and boulders.

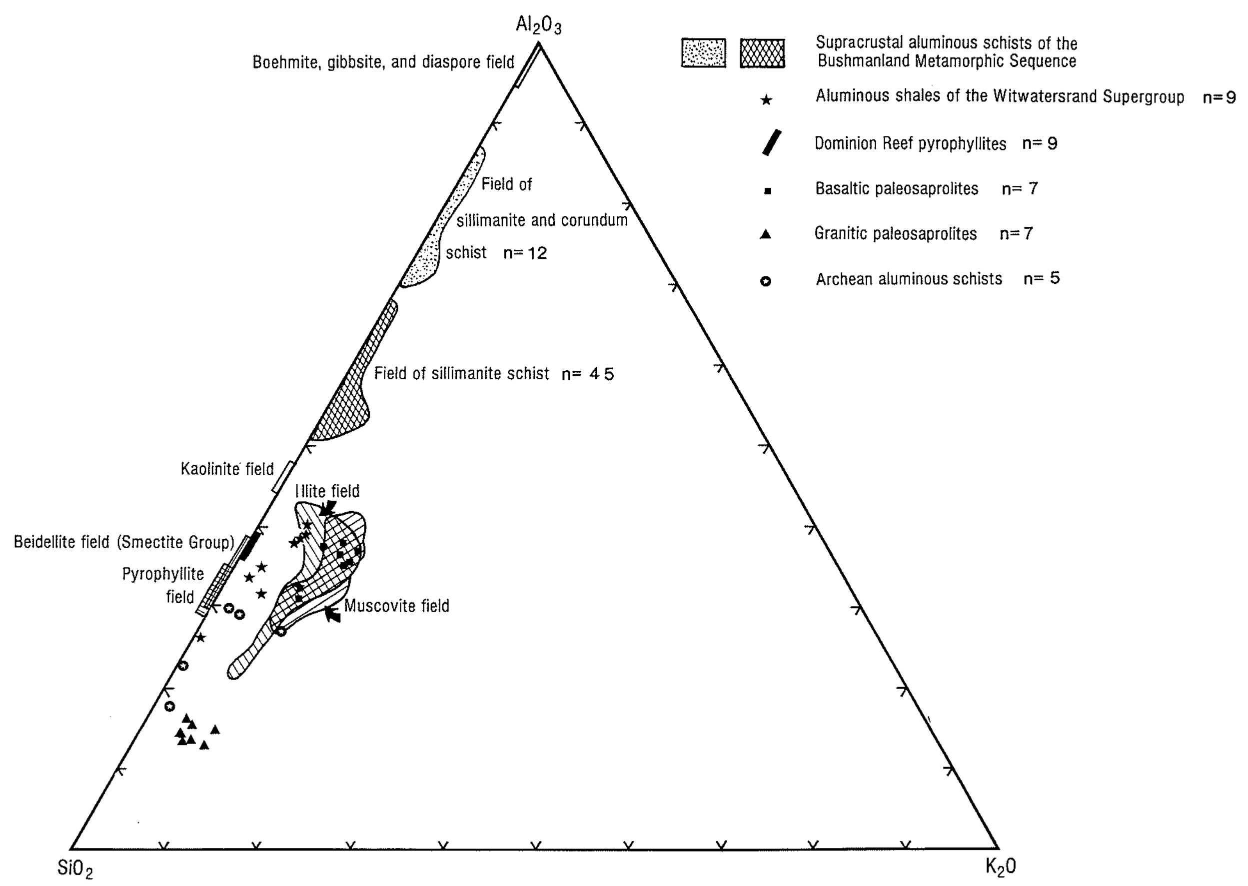

Figure 5: *Triangular plot of Al_2O_3, SiO_2 and K_2O, showing fields of certain aluminous minerals (after analyses in Deer et al., 1962) and analyses of certain palaeosaprolites and aluminous metamorphic rocks.*

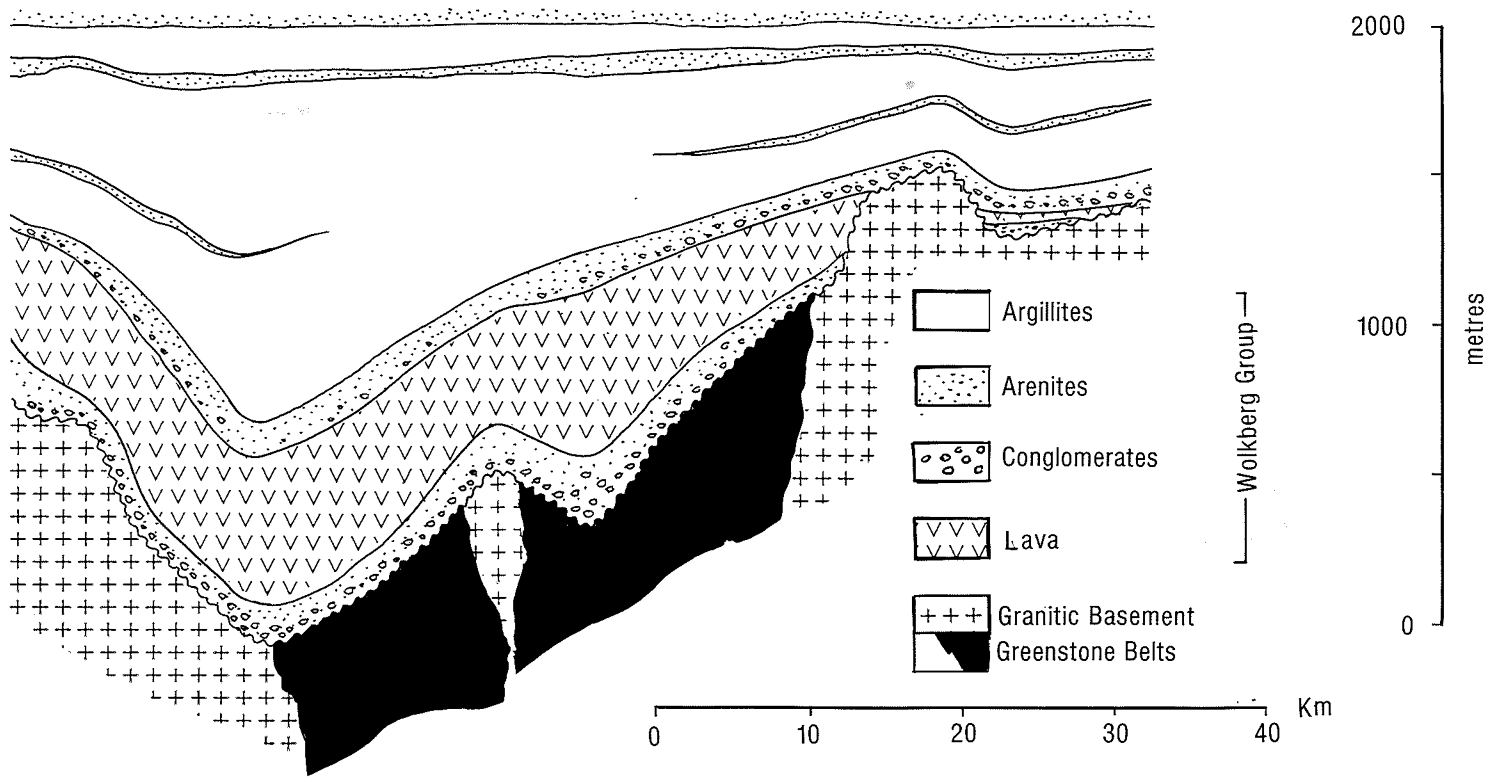

Figure 6: Restored stratigraphic profile through basal units of the Transvaal Supergroup in the northeastern Transvaal (after Button, 1973).

B. Thickness

The thicknesses of granitic palaeosaprolites have been estimated at up to 7,6 m for the Pongola Basin (Matthews and Scharrer, 1968), and from 1,5 to 15 m for the pre-Transvaal profile in the eastern Transvaal (Visser and Verwoerd, 1960). The sericitic schists mapped below the Black Reef north of Johannesburg have an outcrop width of 1,5 km, and are probably considerably thicker.

C. Petrology

Granitic palaeosaprolites are sometimes schistose, due to shearing along the planes of the major unconformities. They are composed mainly of quartz and greenish or grey sericite. Mafic minerals in the parent granitic rocks (hornblende, biotite) were destroyed during palaeoweathering. Quartz and felspar grains were partially replaced by sericite (Visser, compiler, 1956; Visser and Verwoerd, 1960). The latter authors noted that the pre-Black Reef palaeoregolith comprises 56-59 per cent sericite, 35-38 per cent quartz and up to nearly 8 per cent microcline. In this case, quartz has been enriched by a factor of 2 relative to the parent granitic rock.

Matthews and Scharrer (1968) described the progressive changes from the Archaean granite upwards into the Pongola palaeoregolith. Patchy sericitization of felspars is followed by their total destruction. Some felspars, pseudomorphed by sericite, can be made out. Biotite has been largely replaced by vermiculite, which has been altered in places to kaolinite. The vermiculite was bent, shredded and contorted by compaction. Small amounts of chalcedonic quartz and chlorite were detected. The top of the palaeosaprolite is marked by crude bedding and an increase in the proportion of quartz.

The palaeosaprolites described above all pre-date 2000 m.y., and without exception display colour shades of grey, green or khaki. Younger palaeosaprolites have not been described in detail from southern Africa. An ancient weathering profile on granodiorite has been described from below the middle to upper Proterozoic, Keweenawan Jacobsville Sandstone in Michigan (Kalliokoski, 1975). It contains hematite in addition to illite, sericite, chlorite, vermiculite, biotite, muscovite, K-felspar, dolomite, quartz and rutile. Schists below the Cambrian unconformity in Michigan have been altered to a soft, porous material composed of hematite and clay with residual quartz and mica (James et al., 1961).

D. Chemistry

Only a few analyses of granitic palaeosaprolites are available in southern Africa, and are all from unconformities at least 2000 m.y. old (Appendix 2 and Figure 5). Relative to a granitic parent rock, the saprolites are depleted in CaO, Na_2O, MgO and total iron. They are enriched in K_2O and in SiO_2, the latter probably by residual concentration of quartz grains and by addition of microcrystalline silica, liberated during destruction of silicate minerals.

On the Al_2O_3-SiO_2-K_2O triangular plot, the granitic palaeosaprolites plot on the quartz-muscovite join (Figure 5), which is in good agreement with their quartz-sericite mineralogy.

Analyses of the pre-Keweenawan granitic palaeosaprolite indicate that the weathering caused depletion of SiO_2, Al_2O_3, total iron and alkalies if the results are re-calculated to a uniform TiO_2 content. There are local enrichments of CaO, MgO and CO_2 in dolomitic palaeocaliche horizons within the profile (Kalliokoski, 1975). Despite overall loss of iron during weathering, there has been a residual concentration to 15 per cent Fe_2O_3 in the hematitic upper part of the profile.

E. Origin

The quartz-sericite rocks below the pre-2000 m.y. unconformities have been ascribed to differential movement along the unconformity (Nel, 1935), to Precambrian weathering (Matthews and Scharrer, 1968) and to weathering followed by hydrothermal action (Visser and Verwoerd, 1960). The quartz-sericite rocks below the Black Reef north of Johannesburg were regarded as sheared porphyritic felsic volcanics of the Ventersdorp Supergroup (Anhaeusser, 1973). Earlier they had been considered to be members of the Archaean Swaziland succession. Similar conclusions were drawn in Rhodesia, where quartz-sericite schists below the Early Proterozoic Deweras unconformity were considered to be Archaean metasediments of the Shamvaian Group (Jacobsen, 1964).

The consistent location of the quartz-sericite alteration zones below major unconformities leaves little doubt that they represent ancient weathering profiles. The ubiquitous presence of sericite suggests that an illitic clay may have been a significant mineral in the original weathered crust, and further suggests alkaline groundwater (Deer, et al., 1962). Alternatively, an original kaolin may have been transformed to illite by potassium fixation from palaeogroundwater or palaeoseawater. All except the Godwan and Deweras palaeosoils are overlain by mature quartz arenites, probably of marine origin.

F. Economic Significance

The arenites of the major gold-uranium producing basins (Witwatersrand, Blind River) are composed mainly of quartz, allogenic sericite and some pyrophyllite (Fuller, 1958; Roscoe, 1969; Robertson, 1976). This assemblage also characterizes the auriferous clastics of the Fortescue Group, Western Australia and the Deep Lake Group, Wyoming, U.S.A. (personal observations, A.B., 1974, 1978). The most likely source of these arenites are the palaeosaprolites described earlier. They have the appropriate mineralogy, and in some cases (for example, the Matinenda of the Huronian in Canada) they can be shown to rest on palaeosaprolite (Roscoe, 1969; Robertson, 1976).

Analyses of the Huronian palaeosaprolite showed that a 30 ppm U_3O_8 background in the granitic rocks was reduced to 13 ppm (Roscoe, 1969). During the Precambrian weathering, each tonne of granite could have yielded some 17 gm of U_3O_8. The possible connection between palaeosaprolite and uranium in quartz pebble conglomerates is vague. At the present level of knowledge, the association rests on the following facts :

(i) that the arenites associated with uraniferous quartz pebble conglomerates are frequently immature, and composed mainly of quartz and sericite;

(ii) that most (if not all) of the uranium-bearing basins of this type rest on quartz-sericite palaeosaprolites; and

(iii) that in one case (the Huronian of Canada; Roscoe, 1969) the palaeosaprolite can be shown to have been leached of uranium.

A logical speculation might be that the uranium was leached from a granitic basement by chemically-agressive alkaline groundwater, and re-precipitated within the soil profile as granules. Stripping of the palaeosaprolite and contained granules, followed by normal processes of concentration of heavy minerals in a fluvial system, could account for the observed association of uraninite and quartz-sericite arenites. Some uraninite is intimately associated with "carbon" seams of the Witwatersrand (Feather and Koen, 1975), and suggests precipitation of uranium by reactive carbon. Uraniferous leucoxenes and brannerites are associated with the Vaal Reef in the Witwatersrand, and could represent reaction products of uraniferous groundwater with detrital ilmenite, either in the soil profile, in the fluvial system, or in the unconsolidated Witwatersrand sediments.

This argument might be countered by the fact that Witwatersrand and Blind River uraninites show a considerable range in thorium content (Grandstaff, 1974). High-thorium in uraninite is usually considered to be good evidence of a magmatic origin for the mineral. It is possible that the uraninite in these basins was derived from a dual source, partly magmatic (the high-thorium species) and partly from solution out of palaeosaprolite, followed by a re-precipitation (the low-thorium species). The field requires further research, both in the uranium distribution in palaeosaprolites and the character of the uranium-bearing minerals in the Early Proterozoic quartz pebble conglomerates.

Some of the largest uranium deposits in the world, notably those in Saskatchewan, Canada, and the Northern Territory, Australia, are intimately related to post-2000 m.y. old erosion surfaces (Langford, 1977). They were formed where uranium-bearing oxygenated groundwaters moved into porous-permeable zones adjacent to the ancient erosion surfaces. Here, interaction of the rock with groundwater resulted in local rock oxidation and reduction of the groundwater, and hence fixation of uranium as uraninite. The porous-permeable structures are frequently fault zones, and mineralization can extend several hundred metres down from the unconformity. In some of the Northern Territory deposits, carbon-rich metasediments below the unconformity have acted as reductants, and the resulting orebodies are stratiform (Rowntree and Mosher, 1975).

In southern Africa, there are no published descriptions of deposits of this type. The correct stratigraphic circumstances for their development are present below many Proterozoic unconformities, particularly those associated with the Waterberg, Lomagundi, Umkondo, Nama, Damara and Katanga successions. Some of the base metal-bearing vein systems below the Waterberg (for example, those in the Balmoral area, east of Pretoria) may prove to be uraniferous on closer scrutiny.

The pre-Katanga erosion surface in the Zambian copperbelt plays an important part in controlling the distribution of mineralization. The lower sedimentary units in the Katanga succession (including, in places, the stratiform copper orebodies) wedge out against palaeohills. In such situations, the granitic palaeosaprolite carries ore-grade disseminated copper sulphides (Mendelsohn, 1961) for thicknesses of some 0,6 m, while mineralization in veins extends downwards for thicknesses of at least 8 m. Elsewhere, palaeohills of biotite schist are mineralized for up to 15 m below the unconformity.

Palaeorelief also plays an important part in controlling thickness of the ore-bed and sulphide zoning on some mines. On Mufulira, a "footwall formation", up to 170 m thick, is confined to palaeovalleys, and wedges out against basement hills (Figure 7). The overlying "ore formation" (up to 65 m thick) comes to rest directly on the hills. Due to differential compaction of the valley-fill arenites, the ore formation attains its maximum thickness over the valley axes.

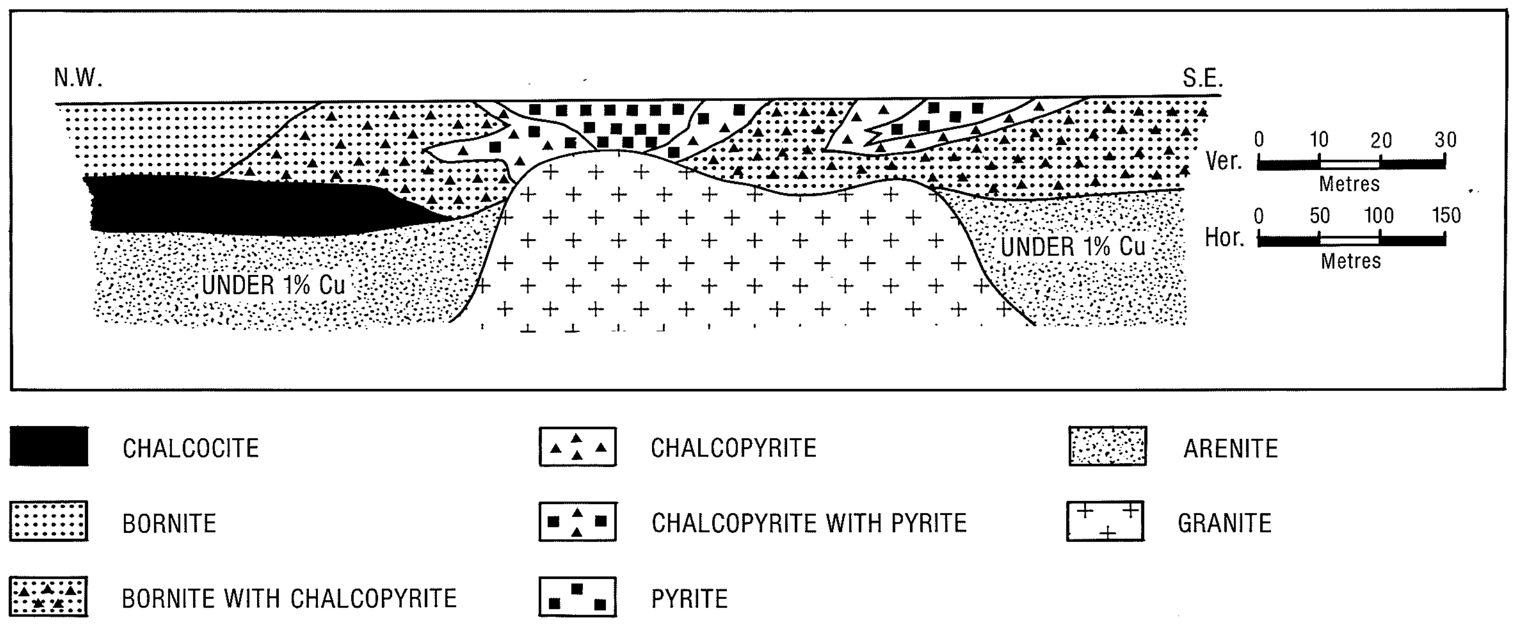

Figure 7: Stratigraphic profile through the basal units of the Katanga succession, showing sulphide zoning around a palaeohill (after Mendelsohn, 1961)

Palaeotopography also apparently controls sulphide zoning in the copperbelt. Bornite and chalcocite are developed over palaeovalleys (Figure 7), and grade laterally to chalcopyrite and pyrite over the palaeohills. The metal zoning could reflect a structural control, due to gentle dips away from the palaeohills caused by differential compaction. Circulating heavy brines may have been constrained to flow down-dip under the influence of gravity, away from palaeohighs.

In the Mangula Mine, Rhodesia, copper sulphides with minor uraninite are developed in folded, metamorphosed immature arenites of the Deweras succession, a short distance stratigraphically above the Mangula Granite (Jacobsen, 1964). The copper mineralization is stratiform and some sulphides are found in material which could represent a palaeoregolith, comprising large granitic clasts in an arkosic groundmass (W.D. Newham, personal communication, 1978).

The recently-discovered Olympic Dam copper-uranium occurrences in South Australia are found around a basement high, in granitic detritus at, and just above, the basal unconformity of the Late-Precambrian Adelaidean succession. The mineralization is reportedly in a palaeoscree, comprising granitic clasts in a finer-grained matrix (Youles, 1977). The regolith is mineralized for thicknesses of up to 170 m in places.

V. WEATHERING SURFACES ON BASIC INTRUSIVE ROCKS

A limited number of descriptions of palaeoweathering effects above basic intrusives have been reported. In the East Rand region of the Witwatersrand Basin dykes intrusive into Witwatersrand sediments are unconformably overlain by conglomerates of the Black Reef, at the base of the Transvaal Supergroup (Papenfus, 1964). The dykes were eroded to linear palaeotopographic lows, which were subsequently filled by auriferous Black Reef conglomerates.

In the eastern Transvaal, the Godwan Formation (probably of Witwatersrand age) rests disconformably on the Kaap Valley hornblende tonalite, and on diabasic sills intrusive into that body. Below the Godwan, a sill has been altered, for at least 2 m, into a rock with a "bright green colour" (Visser, compiler, 1956). It is probably composed largely of sericite.

Palaeoweathering effects have been noted where an Archaean peridotite and a dyke intrusive into it are unconformably overlain by the Keweenawan of Michigan, U.S.A. (Kalliokoski, 1975). The peridotite weathering profile comprises a lower zone veined by dolomite and silica, overlain by a leached zone which passes upwards into a reddish-brown stratified rock composed of chlorite, vermiculite and hematite with siliceous (sometimes jasperitic) veinlets. Vertical veinlets are contorted and suggest a threefold compaction. The uppermost zone is residually highly enriched in Fe_2O_3 and Al_2O_3. Cr and Ni contents correlate well with alumina, suggesting that these elements are contained in silicate phases. If analyses are normalized to constant TiO_2 content, an overall loss of SiO_2, Al_2O_3 and MgO can be detected. Kalliokoski suggested that the pattern was reminiscent of weathering in areas with "slight to moderate rainfall", and a soil water pH of about 9.

The diabase dyke intrusive into the peridotite has been altered to a mixture of hematite (replaces mafic minerals), quartz, chlorite and vermiculite (replaces felspar laths). The original diabasic texture has survived the period of palaeoweathering.

VI. WEATHERING OF ACID LAVAS AND TUFFS

A. Age and Distribution

A limited number of examples of Precambrian weathering of rhyolitic volcanic rocks is known. In the 2800 m.y. old Dominion Reef Group, water-laid rhyolitic tuffs, up to 90 m thick, have been converted to pyrophyllite (Nel et al., 1937; Von Backström, 1962). Porphyritic felsites of the 2750 m.y. old Kanye Volcanic Group have been converted to sericite along the unconformity at the base of the Ventersdorp Supergroup (Tyler, 1978). Similar material occurs below the Black Reef Quartzite near Thabazimbi in the northwestern Transvaal. Here rhyolites of the Buffalo Springs Group have been altered to sericite over several kilometres strike (Tyler, 1978).

B. Petrology

The Dominion Reef pyrophyllite is a bedded rock, occasionally showing ripple marks and cross-stratification. Vague outlines of shard-like clasts were recorded by Nel et al. (1937). The rock is composed of a very fine-grained aggregate of pyrophyllite, with some chloritoid and rutile. Small ($\pm$ 1 cm) concretions of radially-oriented muscovite and of pyrite have been recorded. Thin red-coloured laminae are occasionally developed in the pyrophyllite, and could be due to recent oxidation of pyrite. The volcanics below the pyrophyllite are extensively silicified.

The Kanye palaeosaprolites are laminated, fine-grained green-coloured rocks, composed of sericite with some opaque minerals (Tyler, 1978). Banding is due to the concentration of opaque minerals. The Buffalo Springs Group palaeosaprolite is similar, but is tan-coloured.

C. Geochemistry

The pyrophyllite deposits of the Dominion Reef Group are composed mainly of silica, alumina, titania and some iron, magnesium and calcium (Figure 5 and Appendix 3). The pyrophyllite becomes darker with depth, presumably due to increased carbon, which can make up to 1,04 per cent of the rock. The rock contains less than 0,1 per cent S.

On the triangular Al_2O_3-SiO_2-K_2O plot, the Dominion Reef pyrophyllites are somewhat more alumina-rich than the pyrophyllites analysed by Deer et al. (1962). They overlap the compositional field of beidellite, a clay mineral of the smectite group (Figure 5).

D. Origin

The Dominion Reef pyrophyllites are thought to have been derived by leaching of rhyolitic glass in bedded, water-laid tuffs (Nel et al., 1937). The pervasive alteration was probably promoted by the reactive nature of the original glass, the relatively large surface area per unit volume and its originally high porosity. Nel and co-workers suggested that the pyrophyllite could be the lithified equivalent of a bentonitic clay. The silica leached from the original glass appears to have been responsible for the silicification of the underlying volcanic rocks.

E. Economic Significance

Dominion Reef pyrophyllite, known locally as "wonderstone", has been quarried for several decades. It is a valued industrial mineral, being used as an electrical insulator, and in the production of synthetic diamonds.

VII. WEATHERING PROFILES ON BASALT SURFACES

A. Age and Distribution

Weathering profiles on basaltic surfaces have been recorded from a large number of formations. Aluminous phyllites, from 2,9 m thick, are developed in the Insuzi Subgroup of the Pongola Supergroup in Swaziland (Hunter, 1962). They probably represent sheared palaeosaprolites. Similar material occurs where the Mozaan Subgroup rests unconformably on Insuzi Subgroup basalts (C. Greathead, personal communication, 1978). Two sericite zones are known in the volcanic succession of the Dominion Reef Group (Brabers, 1974), one derived from amygdaloidal lava, the second from tuff. In the Witwatersrand Basin, sericitic zones occur at the upper and lower contacts of the two "Bird" lava units (Antrobus, 1964; Button, 1968). The "Bird Reef Marker", a sericite-rich layer, normally occurs in arenites some 3 m above the uppermost Bird lava.

In the Ventersdorp Supergroup, Winter (1965) recorded several oxidized and bleached flow-tops to depths of up to 925 m. Some "purple zones" in basalt occur to similar depths. In the Carletonville sector of the Witwatersrand Basin, sericitic alteration occurs along the basal surface of Ventersdorp basalts, where they rest on Ventersdorp basal conglomerates (A. Phillips, personal communication, 1978). Carbonated basalts have been encountered along the same horizon in the Heidelberg area (personal observation, A.B., 1978).

Tyler (1978) documented a 25 m thick, laminated sericitic rock in the Ventersdorp succession of the northwestern Transvaal. The altered zone rests on andesitic basalts, and is overlain by rhyolitic volcanics. In this area, and in an area south of Johannesburg, sericitic alteration of Ventersdorp basalt occurs immediately below the Black Reef Quartzite (Tyler, 1978; Wyatt, 1976). Similar material is found where the Black Reef rests on Godwan basalts in the eastern Transvaal (personal observation, N.T. and A.B., 1978).

In the Pretoria Group of the Transvaal Basin, a zone up to 5 m thick, at the top of the Hekpoort Basalt, is altered to sericite over an area in excess of 100 000 km^2 (Button, 1979). The zone has been positively identified around the eastern outcrop rim of the basin (Visser and Verwoerd, 1960; Button, 1973), to the east of Johannesburg (Liebenberg, 1961), around Rustenburg (Von Backström, 1960) and in the far western Transvaal (Engelbrecht, 1976).

The palaeosaprolites documented above are all greater than 2200 m.y. old. A weathering profile some 1100 m.y. old is developed on the Cardenas Lavas of the Grand Canyon Supergroup in Arizona (Elston and Scott, 1976). The weathering profile is some 10 m thick, and the basaltic texture is largely preserved within it.

B. Petrology

The dominant component of all the pre-2200 m.y. old basaltic palaeosaprolites is an exceedingly fine-grained sericite, usually some shade of grey, green or yellow in colour. The Witwatersrand occurrences carry a large proportion of chloritoid, rutile and leucoxene. The Bird Reef Marker is up to 6 m thick and contains chlorite and angular quartz grains in addition to the above minerals. Andalusite, diaspore and sericite are the principal minerals in the Insuzi Subgroup palaeosaprolites (Hunter, 1962).

Tyler (1978) noted a delicate silica stockwork in the lower part of the 25 m thick sericitic zone in the Ventersdorp of the northwestern Transvaal. The palaeosaprolite is composed of very fine-grained sericite with some opaque oxides and leucoxene.

The palaeoweathering profile on the Hekpoort Basalt has been described as a sequence of sericitic schists and shales (Liebenberg, 1961) and as a yellowish-green chloritic material (Visser and Verwoerd, 1960). The material actually consists largely of sericite with some chlorite and pyrite near the base (Button, 1978). It is vaguely stratified, and is normally sheared by movement of the overlying arenaceous formation (Button, 1973). Magnetite is associated with chlorite in the lower parts of the profile in some areas. In the western Transvaal metamorphism related to the Bushveld Complex has converted the sericite to an assemblage of muscovite and andalusite (Engelbrecht, 1976).

In the 1100 m.y. old Cardenas palaeosaprolite, ilmenite has been altered to specular hematite and leucoxene, while parts of the groundmass have been altered to red earthy hematite and siderite (Elston and Scott, 1976).

C. Chemistry

A few whole rock analyses are available for pre-2200 m.y. basaltic palaeosaprolites (Figure 5 and Appendix 4). All the available analyses plot within the region of overlap of the muscovite and illite fields on the Al_2O_3-SiO_2-K_2O triangular diagrams (Figure 5), reflecting the dominance of sericite in these rocks.

A characteristic of the analyses are the high K_2O, Al_2O_3 and TiO_2 contents of the palaeosaprolites relative to their parent basalts. MgO, CaO and Na_2O have been almost completely removed, while iron has been very strongly depleted (with the exception of analysis 4 of Appendix 4). The remaining iron is mainly divalent. Silica has been weakly depleted relative to the parent basalt, but probably strongly depleted if analyses were recalculated to a uniform TiO_2 level. At least some of the leached iron and silica are fixed in the lower parts of the profile in chlorite, pyrite, magnetite and cherty silica veinlets (Button, 1979).

The concentration of Al_2O_3 and TiO_2 is probably purely residual. Some of the parent basalts contain less than 0,1 per cent K_2O (Button, 1979), so that K_2O enrichment is of the order of 100 times for some samples. Residual enrichment alone could not account for this factor. Some of the K_2O is believed to have been added during palaeoweathering or diagenesis, through the action of potassium-bearing palaeogroundwaters. Many of the palaeosaprolites are overlain by marine arenites, so that interaction with palaeoseawater was also possible.

D. Origin

The sericitic intervals in the Dominion Reef were ascribed to a "hydrothermal replacement of the original material" (Brabers, 1974). The Bird Reef Marker and the sericitic zones on top of the Bird lavas in the Witwatersrand were thought to represent either tuffaceous zones (Antrobus, 1964) or zones of Witwatersrand-age weathering (Button, 1968). The Ventersdorp and Transvaal Supergroup sericitic zones were recognized as the products of Proterozoic chemical weathering (Visser and Verwoerd, 1960; Button, 1973; Tyler, 1978) on the basis of their widespread development below well-defined unconformities or paraconformities, as well as by their distinctive chemistry.

The sericitic alteration zones along the basal contacts of basalts, where they rest on arenites or conglomerates (e.g. base of Bird lavas in Witwatersrand, base of Ventersdorp lava) are thought to be due to weathering caused by palaeogroundwaters. The chemically active palaeogroundwaters can be inferred to have caused the alteration as they seeped through porous-permeable arenites and gravels below the lava flows.

The younger Precambrian palaeoweathering episodes, such as those that affected the 1100 m.y. old Cardenas lavas of Arizona, produced a hematite-rich product, totally unlike its equivalents in the pre-2200 m.y. old formations.

E. Economic Significance

Modest tonnages of pyrophyllite and diaspore have been mined from the Insuzi Subgroup palaeosaprolite of Swaziland (Hunter, 1962). As a group the sericites of pre-2200 m.y. old palaeosaprolites, represent a very large resource of Al_2O_3 and K_2O. Given the extremely large tonnages, economic extraction of these metals will depend on the development of economically viable metallurgical techniques.

Differential erosion of basalts has played an important part in the location of the Blind River uraniferous quartz pebble conglomerates. The latter are found in palaeovalleys cut across Archaean basalts (Robertson, 1976). The payable conglomerates wedge out against valley margins, composed of granitic rocks and steep-dipping banded iron-formations.

VIII. EROSION SURFACES ON ARENACEOUS SEDIMENTS

A. Age and Distribution

The best documented unconformities of this sort are found below most of the payable conglomerate sheets of the Witwatersrand basin. Mapping has shown that these sheets rest unconformably on the underlying beds. Examples include the Kimberley Reef of the East Rand (Armstrong, 1965), the Main Reef Leader of the Central Rand (Cousins, 1965), the Carbon Leader of the Carletonville Goldfield (De Kock, 1964), the Vaal Reef of the Klerksdorp Goldfield (Minter, 1976) and the Basal Reef of the Orange Free State Goldfield (Winter, 1964; McKinney, 1964). The basal conglomerates of the Ventersdorp Supergroup (the Ventersdorp Contact Reef; Knowles, 1966) and of the Transvaal Supergroup (the Black Reef; Papenfus, 1964) rest unconformably on Witwatersrand arenites and conglomerates in places.

B. Nature of the Unconformities

The character of the unconformities varies according to the degree of structural disturbance associated with the erosive event. Some are very gentle. For example, the Vaal Reef conglomerate truncates 49 m of its footwall over a distance of 6 km (Figure 8A), equivalent to a gradient of 1:120 (Minter, 1976). In the Central Rand, the Main Reef Leader erodes through underlying beds at a rate of 8 m/km, equivalent to a gradient of 1:125 (Cousins, 1965). Elsewhere, gentle folding during erosion resulted in elliptical topographic highs, coincident with structural domes. One such "island", in the footwall of the Kimberley Reef conglomerate of the East Rand, measures 1,3 by 0,6 km (Antrobus and Whiteside, 1964). The dome stood out several metres above the erosion surface, so that the auriferous-uraniferous Kimberley Reef conglomerate wedged out against the palaeohigh.

One of the most dramatic unconformities in the Witwatersrand is that developed below the "Boulder Beds" in the Orange Free State Goldfield (Figure 8B). Here,Witwatersrand strata have been repeatedly bevelled during erosive events related to uplift along the western margin of the basin (Winter, 1964; McKinney, 1964). Angular discordances of up to 90 degrees are developed.

On the West Rand, conglomerates of the Black Reef (base of Transvaal Supergroup) have been mined for gold in strike palaeovalleys on an erosion surface cut across inclined Witwatersrand arenite, shales and conglomerates (Figure 9A). The palaeovalleys are developed above either softer shaly formations (Kimberley and Jeppestown shales) or on an argillaceous quartzite formation, and are obviously a consequence of differential weathering (Papenfus, 1964).

Black Reef conglomerates in parts of the East Rand are developed in channels up to 600 m wide and 15 m deep (Papenfus, 1964). The north to south flowing palaeochannels were cut across southwest-dipping Witwatersrand strata (Figure 9B). They were fed by water and sediment from fluvial drainage basins cut into Witwatersrand beds.

Many of these erosion surfaces were apparently colonized by algal or bacterial communities, now seen as the "carbon" which is intimately associated with most of the payable Witwatersrand sheets (De Kock, 1964; Minter, in press). The carbon is several centimetres thick in places, suggesting a luxurious growth several tens of centimetres thick. Such a growth further suggests stagnant water pools on the erosion surface, and implies a very shallow palaeowater table.

C. Economic Significance

The importance of the erosion surface to the concentration of gold, uranium, platinoids and pyrite in the Witwatersrand basin is a recurring theme in many of the papers written on the subject, and is backed by an immense volume of observational data. Some conglomerate sheets on erosion surfaces are largely unpayable except where they have re-worked heavy minerals out of formations which they truncate. For example, the Kimberley Reef of the East Rand contains payable gold and uranium re-worked out of the underlying Middle Kimberley conglomerates (De Jager, 1964).

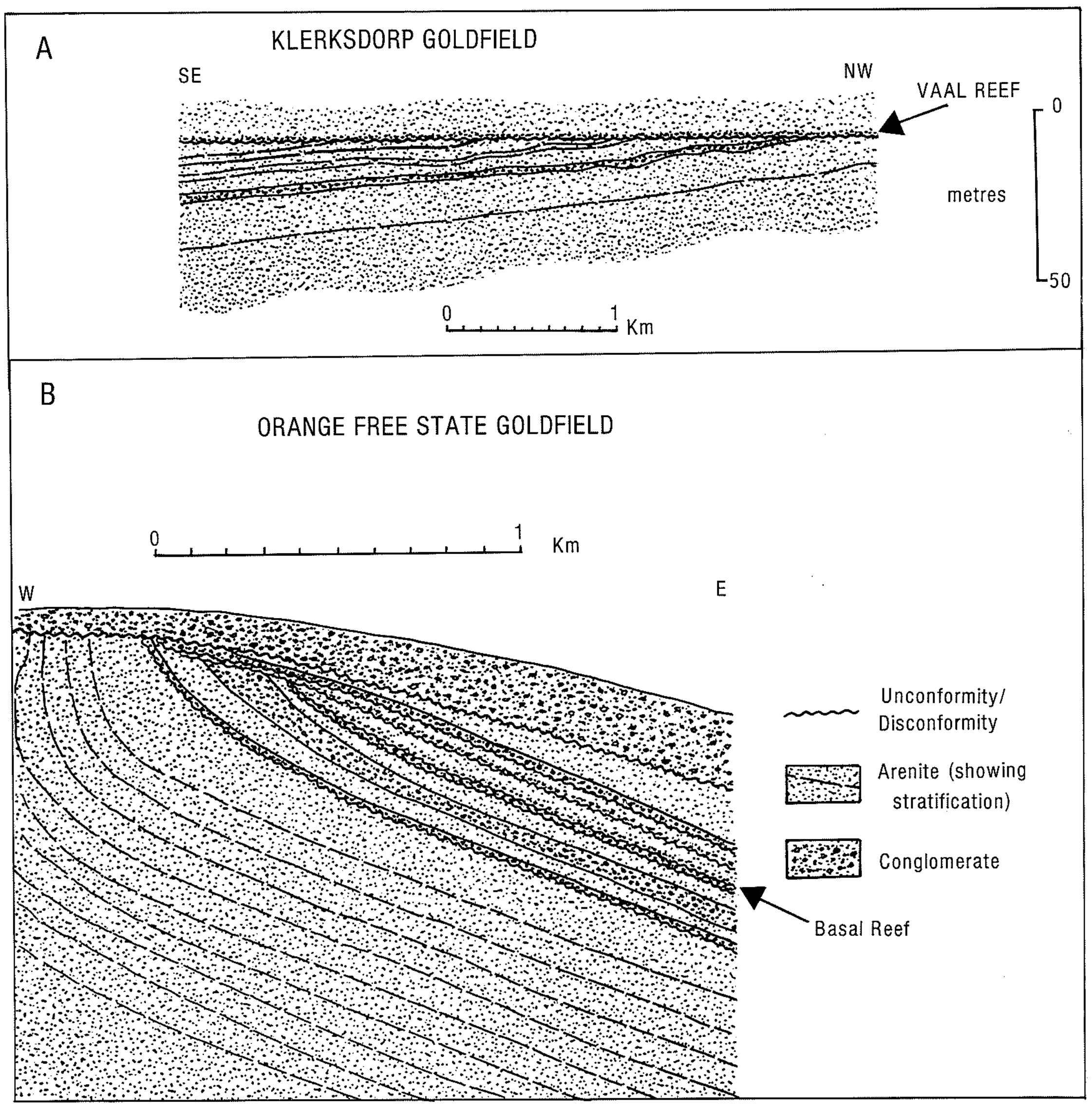

Figure 8: *Restored stratigraphic profiles through parts of the Witwatersrand Basin (A - after Minter, 1976; B - after McKinney, 1964; Winter, 1964).*

One of the best-documented examples of re-working of heavy minerals along an unconformity is that of the Black Reef in the East Rand (Papenfus, 1964). Over 30 million tonnes of Black Reef ore were extracted from one mine alone. Here, the Black Reef rests on Witwatersrand strata dipping southwest at 5-10 degrees (Figure 9B). North-south-trending channels cut on the Black Reef erosion surface, are filled by material re-worked out of the Witwatersrand, including auriferous conglomerates of the Kimberley Reef Group. They carry re-cycled Witwatersrand pebbles, as well as clasts of Witwatersrand rock up to 2,5 m in size. The Black Reef conglomerates are only payable downstream of the palaeo-outcrop of the auriferous Witwatersrand beds. Downstream from these palaeo-outcrops, the pyrite : gold ratio increases by a factor of 3 over a distance of 3 km, presumably due to the lag of the heavier gold particles relative to pyrite (Papenfus, 1964).

There is a significant body of evidence to suggest that the palaeogroundwater draining off Witwatersrand erosion surfaces was chemically very active. Many striking differences between the Black Reef and its parent Witwatersrand conglomerates have been noted. Firstly, the Black Reef has a pyrite : gold ratio some 5 times larger than the parent conglomerates. The high pyrite content is due to the abundance of very coarse-grained "buckshot pyrite". The coarse pyrite clasts were formed by replacement of chert and shale clasts out of the Witwatersrand (Papenfus, 1964). Carbon and gold are concentrated in the rims of the buckshot pyrite, and provide evidence of biological activity and of the mobility of gold, respectively.

Secondly, the Black Reef conglomerates contain up to 16 per cent silver, while Witwatersrand conglomerates contain 5-10 per cent of this element (Pretorius, 1974). This change suggests leaching of gold relative to silver.

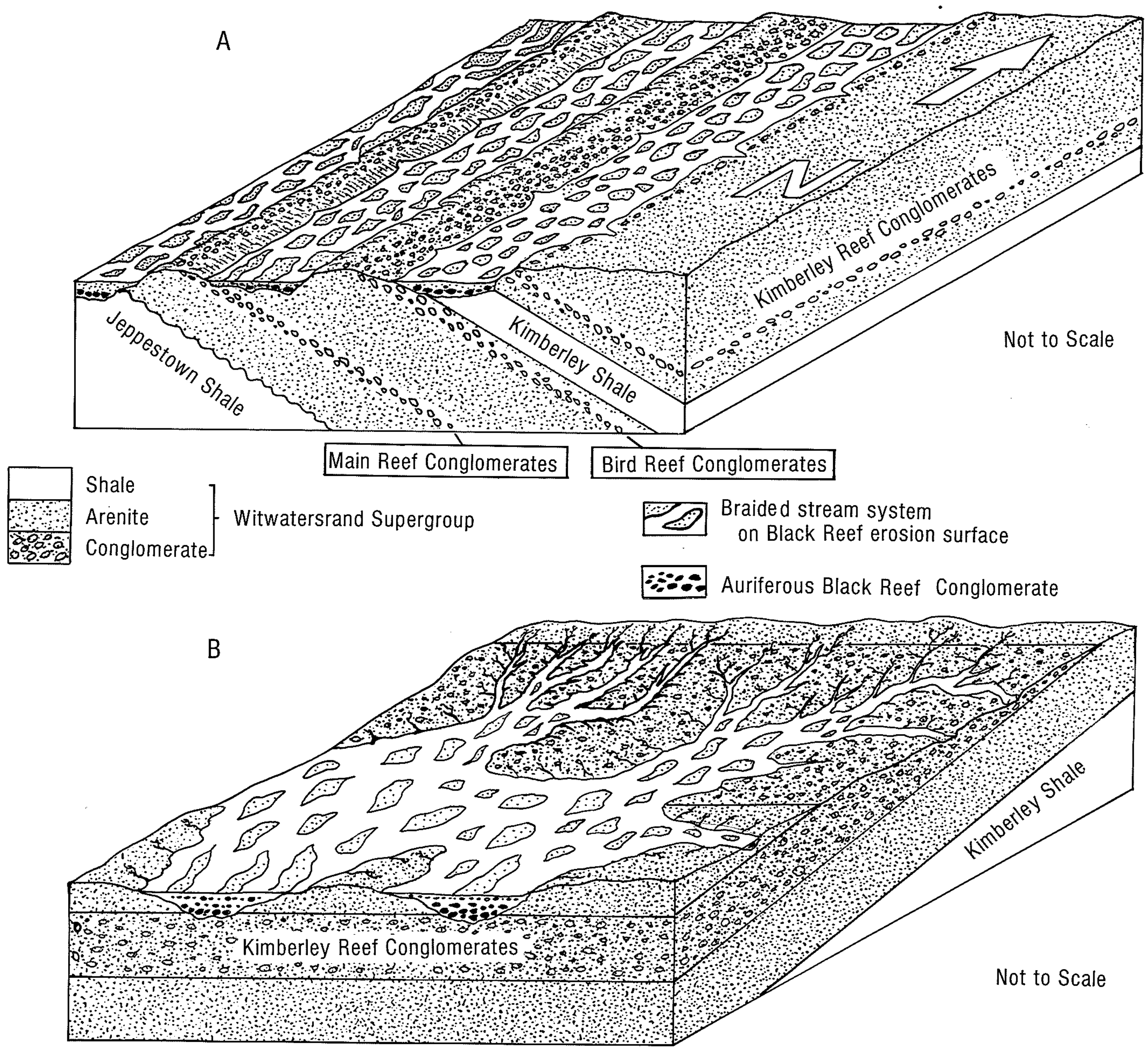

Figure 9: Schematic block diagrams showing the pre-Transvaal Basin erosion surfaces of the West (A) and East Rand (B) areas (drawn from maps in Papenfus, 1964). Not to scale, but each block diagram would measure 5-10 km.

Thirdly, the Black Reef has an anomalously high osmiridium content, with a gold: osmiridium ratio of 150 to 300. By comparison, the ratio varies from 1:700 to 1:10 000 for Witwatersrand conglomerates. Once again, removal of gold, presumably in solution, seems to be indicated.

Finally, Cousins (1973) has shown that Witwatersrand platinoid grains have been severely leached, being depleted in ruthenium, platinum and palladium (25,5 per cent combined) and enriched in osmium and iridium (74,5 per cent combined). According to Cousins, such a composition indicates chemical leaching by very agressive solutions, presumably the palaeogroundwaters.

In summary, erosion surfaces in pre-2200 m.y. old coarse clastic sequences can be economically important due to two related effects. Firstly, the re-working of units truncated by the unconformity provided additional gold, uraninite and heavy minerals to the surface of unconformity. Secondly, the unconformity surface lay above the base-level of deposition for considerable periods of time. Consequently, these surfaces were not surfaces of permanent deposition. Large volumes of coarse clastic detritus must have been moved across these surfaces, leaving behind no trace other than a lag of heavy and economically important minerals.

Those unconformities representing exceptionally long spans of time resulted in significant changes to the heavy mineral suites. Platinoids were leached of platinum, ruthenium and palladium. Extensive pyritization occurred on the Black Reef erosion surface and suggests the presence of reducing sulphidic groundwaters. Gold was apparently mobile in these waters, as evidenced by gold-rich rims around pyritized chert pebbles, and by the overall enrichment of the conglomerate in silver and platinoids relative to gold. Recognition of the effects of palaeogroundwater leaching and pyritization could go far to reconciling the conflicting evidence of the hydrothermal and placer theories on the origin of the Witwatersrand deposits.

IX. EROSION SURFACES ON SHALES

A. Age and Distribution

A major unconformity separates the upper from the lower division of the Witwatersrand Supergroup. In the eastern part of the basin the unconformity frequently rests on Jeppestown Shale, which is visibly discoloured for thicknesses of up to 4,6 m (Antrobus, 1964; De Jager, 1964; Button, 1968). The altered shales are yellowish-green in colour, in contrast to the green-grey unaltered shales. On outcrop, the palaeoweathered shale is resistant to weathering, and stands out as a 2-3 m high ledge (personal observation, A.B., 1978).

In the South Rand and Evander sectors of the Witwatersrand Basin, the UK9A (May) Reef rests unconformably on the Kimberley Shale of the Witwatersrand Supergroup (Pretorius, 1964b; Tweedie, 1968). The dark grey-coloured Kimberley Shale is altered to a khaki-coloured material for a few centimetres below the unconformity.

Within the lower division of the Witwatersrand Supergroup, the footwall shales to the Government and Coronation "reefs" are alumina rich, and contain diagenetic chloritoid (Wiebols, 1961). Their alumina-rich character suggests *in situ* chemical weathering of the shales before the conglomerates were deposited.

B. Petrology and Chemistry

De Jager (1964) noted that the palaeoweathered Jeppestown Shales contain abundant rutile and ilmenite, the latter altered to leucoxene to varying degrees. Shales underlying many of the payable Witwatersrand conglomerates are enriched in alumina and titania (Figure 5 and Appendix 5), containing up to 35,8 and 1,66 of these oxides (Wiebols, 1961). Alumina-rich minerals identified include sericite, pyrophyllite and chloritoid.

C. Origin

There is agreement that the discolouration of Jeppestown Shales below a major unconformity is due to *in situ* chemical weathering. De Jager (1964) was of the opinion that the high TiO_2 concentration was due to the presence of a large percentage of detrital ilmenite. The authors believe that the detrital ilmenites were residually concentrated by chemical weathering on the erosion surface.

Wiebols (1961) noted that many of the shales immediately below payable Witwatersrand conglomerate sheets were highly aluminous. He was of the opinion that this effect was due to weathering of parent rock in the provenance areas. Since many of the conglomerates rest unconformably on shales, the possibility of *in situ* chemical weathering should also be considered.

D. Economic Importance

The Jeppestown Shale palaeoweathering surface is the footwall for the deposition of the widespread and economically important Main Reef Leader conglomerate sheet of the East Rand. Some of the linear "payshoots" on this surface coincide with the palaeo-outcrop traces of arenaceous beds within the Jeppestown Shale (De Jager, 1964). The improved thickness of conglomerate was probably due to Jeppestown arenites weathering preferentially to subtle palaeo-valleys. The shales, at that time cohesive clays, formed more resistant higher ground.

On some mines of the East Rand, meandering erosion channels up to 100 m deep (Figure 10) were cut into Jeppestown Shales (De Jager, 1964; Antrobus, 1964; Antrobus and Whiteside, 1964). They owe their meandering pattern to the fact that they were cut in a clay-rich surface, which provided the bank stability necessary for the development of a sinuous stream course. The channels are filled by an assemblage of conglomerate, diamictite (termed "puddingstone" on the mines) shale-clast conglomerate, quartzite, banded pyritic quartzite and shale. Most of these rock types contain gold, and have been mined. The shales are usually alumina-rich and characteristically contain authigenic chloritoid. Their high alumina content is probably an indication that they represent the fine-grained fraction of the weathering products on the surface of unconformity.

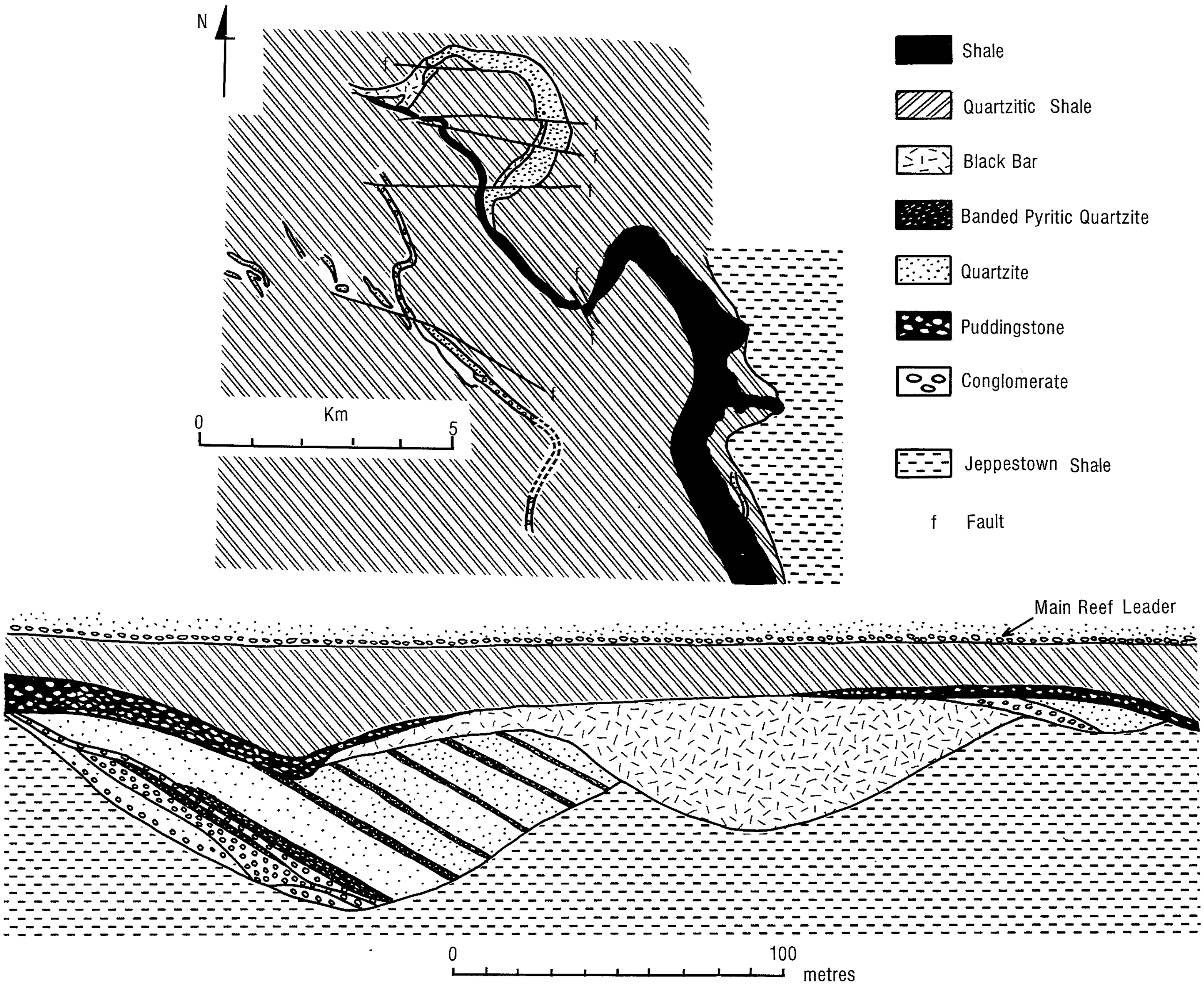

Figure 10: *Map and section of meandering channel deposits on the erosion surface separating the upper from the lower divisions of the Witwatersrand Supergroup (after Antrobus and Whiteside, 1964).*

The meandering channel system shown in Figure 10 shows many of the features of contemporary streams of similar sinuosity. The map shows a quartzite point bar in the meandor bend, and a neck cut-off channel. Some channels were filled with shale and "black bar" (chloritoid-bearing mudstone), suggesting channel abandonment and siltation. The fairly widespread "quartzitic shales" could represent overbank flood-basin sediments. The cross-section of Figure 10 clearly shows channel lag conglomerates covered by inclined point bar arenites. Banded pyritic quartzites within the latter could be due to cyclic flood events. The relatively high dips on the point bar surfaces have been related to post-depositional rotational slumping.

X. EROSION SURFACES ON CARBONATE FORMATIONS

A. Age and Distribution

The Malmani Dolomite and equivalents of the Transvaal Basin (ca. 2300 m.y. old) are preserved over an area of some 250 000 km^2 (Button, 1973). The carbonates grade upwards to banded iron-formation. However, over large parts of the basin, particularly in the south-central Transvaal, the iron-formation was removed during a period of intraformational uplift and erosion. In these areas, the Pretoria Group rests directly on the carbonate formations. This angular unconformity reduces the thickness of the formation from a maximum of over 2000 m to less than 100 m in the southeastern Transvaal. This unconformity is probably one of the oldest known karsted surfaces on Earth.

Germs (1972) noted an erosion surface at the base of the "Terminal Clastic Member" of the Schwarzrand Formation of the Nama Group in South West Africa. The unconformity rests on the Spitzkopf and Huns limestone members of this Late Precambrian succession (Table 1).

In the northern regions of South West Africa/Namibia, the Mulder felspathic quartzites rest unconformably on carbonates of the Upper Precambrian Damara succession (Haughton, 1969). Lower in the same succession, a widely-developed tillite rests disconformably on a thick (up to 2700 m carbonate sequence.

In Michigan, U.S.A., James et al. (1961) noted that a Cambrian formation unconformably overlies the Early Proterozoic Randville Dolomite.

B. Nature of the Unconformities

The angular unconformity at the top of the Malmani Dolomite has been relatively well-studied, having been penetrated by hundreds of cored boreholes sunk in search of covered parts of the Witwatersrand Basin. The surface is obviously karsted. It is covered by a palaeoregolith, composed of the insoluble residue from the underlying carbonates. This mantle varies from 0 to 110 m in thickness over short distances (Button, 1968), being thickest over solution depressions on the old landscape. It is composed mainly of chert clasts, varying in size up to slabs several metres long. Carbonate clasts are very rarely present. The matrix is a black, fine-grained material, rich in carbon and sometimes in manganese and iron. The character of the regolith can be linked to the nature of the underlying carbonates (Button, 1973). Where the substratum is chert-rich, a robust chert breccia of varying thickness is developed. On chert-poor or chert-free carbonates, a thin (1-2 m) chert-pebble conglomerate is usual. The palaeoregolith is particularly rich in iron and manganese where it rests on dolomite carrying a high proportion of these elements.

The upper parts of the residual mantle have frequently been reworked to a conglomerate with a quartzitic groundmass. In places, ancient sinkholes have been filled by quartz arenites, and provide a source of very pure silica in the Delmas area, east of Johannesburg.

The unconformity cut across the Schwarzrand carbonates of the Nama Group in South West Africa is characterized by steep-walled "channels" up to 200 m high. The channels are filled by carbonate-clast conglomerates, grading up to arenites and shales (Germs, 1972). The unconformity surface is grooved in places. The channels and their filling were interpreted as the products of glacial action.

At the Tsumeb Mine, in South West Africa, a palaeosinkhole extends downwards for at least 800 m (stratigraphic) below the unconformity situated at the base of the Mulden Formation (Figure 12). The pipe is filled with a felspathic sandstone, which carries carbonate wall rock clasts in places. At greater depths, the pipe cuts through relatively massive dolomites. Here, breccia is the main component of the pipe-filling, and comprises dolomite and chert clasts in a granulated carbonate or felspathic sandstone matrix. The pipe pinches and swells with depth, and has a maximum plan-view dimension of some 100 by 40 m. The wall rock around the pipe is cut by a system of concentric cylindrical fractures.

In Michigan, a mantle of yellowish ochre is developed where Cambrian sediments overlie unconformably the Proterozoic Randville Dolomite.

C. Economic Significance

The unconformity at the top of the Malmani Dolomite is associated with fluorite-lead-zinc mineralization and with manganese, silica and alumina concentrations. In the western Transvaal, collapse breccias in palaeocaves are mineralized by fluorite with some lead and zinc (Martini, 1975). Some uncollapsed caves are filled with massive fluorite, while the carbonates around the palaeocaves and palaeosinkholes are sometimes replaced by fluorite. In the same area, large (tens of millions of tonnes), stratiform, fluorite bodies are found in the Malmani carbonates, some 100 m below the unconformably overlying Pretoria Group. The fluorite fills pore spaces generated during diagenesis (Martini, 1975). There appears to be a palaeotopographic control to the mineralization, which is restricted to the vicinity of a palaeoridge in the dolomite, draped by the relatively impermeable Pretoria Group Shales (Martini, 1976).

Manganese deposits are associated with chert breccia palaeoregoliths in many areas of the Transvaal Basin, but most importantly in the Sishen-Postmasburg area of the northwestern Cape Province (Button, 1976). Here, the unconformity rests on manganese-rich dolomite (Figure 11). The chert breccia contains a high proportion of manganese minerals, which have been concentrated during the present and fairly recent erosion cycles to form small, but high-grade deposits, mainly of the manganese silicate, braunite. Very similar deposits are known from the Hamersley Basin in Western Australia, where the Pinjan Chert Breccia rests unconformably on the Carawine Dolomite (Button, 1976). In both basins, the shales above the palaeoregolith are appreciably manganiferous, and have been enriched during subsequent weathering episodes to produce important ferruginous manganese orebodies, in which bixbyite is the principal mineral. In the northwestern Cape, several tens of millions of tonnes of manganese ore have been mined from this type of deposit.

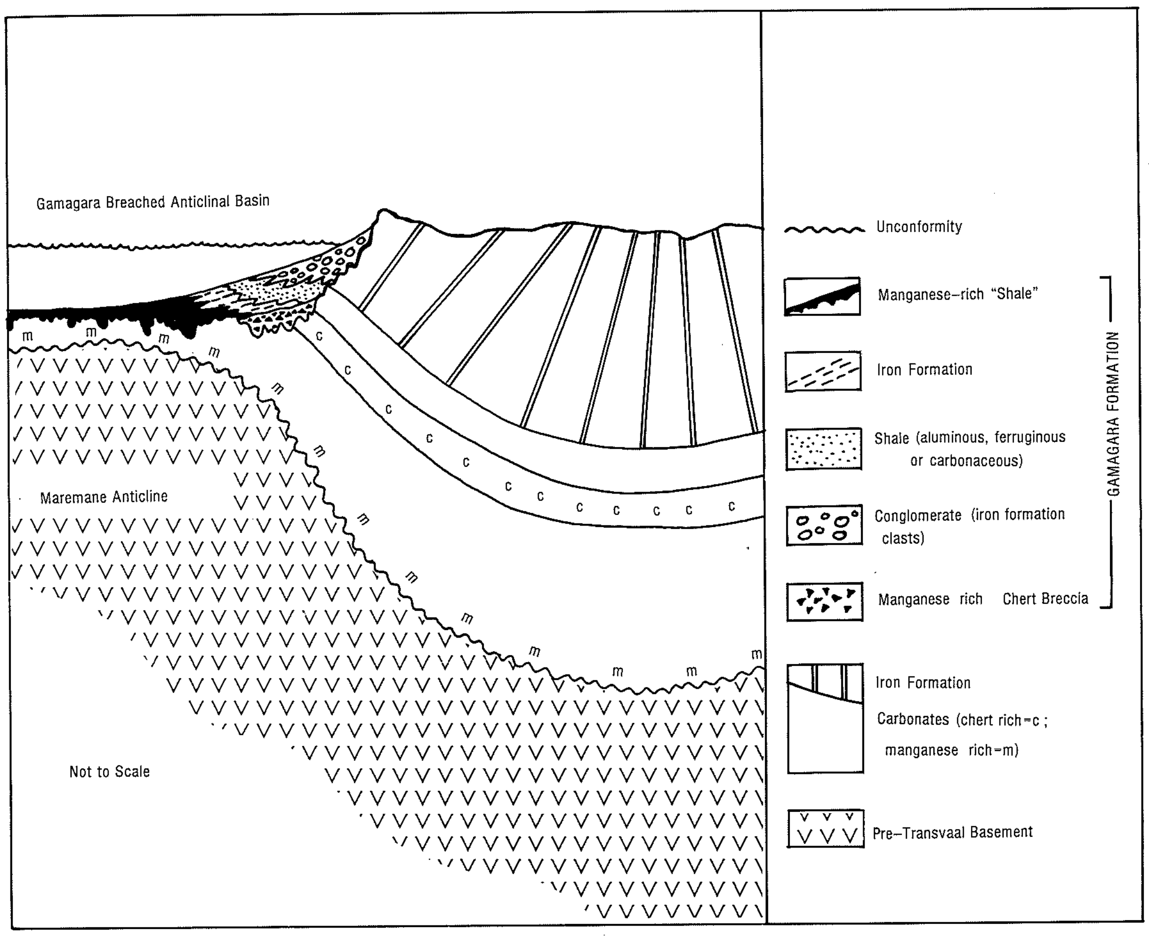

Figure 11: *Schematic section (not to scale, but representing 10-20 km across) showing erosive surface cut across folded carbonates and iron-formations of the Transvaal basin in the northwestern Cape Province.*

The shales above the chert breccia in the northwestern Cape are locally very rich in alumina. These hematitic shales contain diaspore, pyrophyllite, gibbsite, zunyite and kaolinite (Brabers, 1974). Locally, diaspore makes up as much as 40 per cent of the shale. These aluminous sediments, lying just above a palaeokarsted surface, can be compared to the geologically younger European bauxite deposits, which have a similar setting (Grubb, 1973).

In South West Africa lead, zinc and copper are being produced at the Tsumeb Mine (Sohnge, 1964). Recoverable germanium, silver and cadmium are associated with the sulphides. Mineralization is restricted to the vicinity of the sandstone-filled palaeosinkhole (Figure 12). Concentric fractures around the pipe are mineralized, as are stratiform breccias, the latter being developed preferentially in some of the beds cut by the pipe. Both massive and disseminated ores are developed in an elliptical pipe with plan view dimensions of up to 60 by 200 m. Silicification and calcitization are prominent around the orebody. Graphitization of the breccia within the pipe has been recorded, and could mark the passage of hydrocarbons through the porous pipe filling.

Other palaeokarst-related base metal deposits are present in the Damara carbonates in the Otavi Mountains. These include the Kombat Mine, where Cu-Pb mineralization is associated with palaeosinkholes filled by Mulden Formation arkoses.

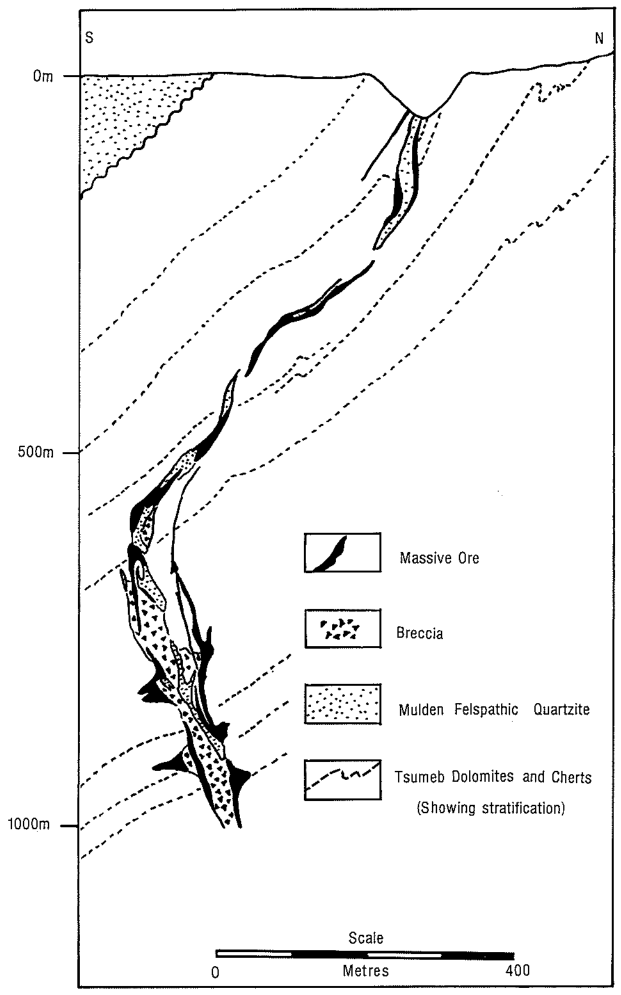

Figure 12: *Cross-section of the mineralized pipe of the Tsumeb Mine in South West Africa (modified after Söhnge, 1964).*

XI. EROSION SURFACES ON BANDED IRON-FORMATIONS

A. Age and Distribution

In southern Africa, only one erosion surface of this type is known. The iron-formation of the Transvaal Basin is overlain unconformably by the Pretoria Group (in the Transvaal) and by the Gamagara Formation (in the northwestern Cape). In most areas, the iron-formation was gently tilted prior to erosion. In other areas it was domed, while in yet other regions it was tightly folded.

A very similar stratigraphic situation is present in parts of the Hamersley Basin of Western Australia, where the Wyloo Group unconformably overlies iron-formations of the Hamersley Group (Button, 1976).

In Michigan, U.S.A., Proterozoic iron-formations are altered, for depths of "up to several hundred feet" beneath the Cambrian unconformity (James et al., 1961).

B. Nature of the Unconformity

Where the iron-formation of the Transvaal Basin was only gently warped prior to erosion, it is mantled by a conglomerate, comprising clasts of iron-formation and chert in an iron-rich arenaceous matrix. Where domed, as over the Maremane anticline in the northwestern Cape, the crest of the fold was breached by palaeoweathering and erosion (Figure 11). This resulted in a karst-floored basin (the iron-formation rests on carbonates), surrounded by iron-formation scarps (Button, unpublished information). Iron-formation conglomerate was deposited adjacent to the scarp, while further into the basin, fine-grained iron-formation detritus was deposited on a chert breccia palaeoregolith over a carbonate substratum (Figure 11). Even further basinward, iron-formation and carbonaceous shale were deposited. The facies belts shifted regressively with time, so that conglomerates came to rest on the finer-grained sediments. In places, the iron-rich sediments were brecciated, probably due to collapse of the underlying palaeocaves.

In the northeastern Transvaal, folded iron-formation is disconformably overlain by the Duitschland Formation (Button, 1973), which was in turn strongly folded prior to deposition of the Pretoria Group. The iron-formation is cut by deep palaeovalleys (over 200 m) filled by a diamictite comprising clasts of chert and iron-formation in a matrix of iron silicates (originally clays, but now recrystallized to fine needles of grunerite). The diamictite is probably a series of lithified debris-flows.

C. Economic Significance

The iron-rich detritus on the iron-formation palaeo-erosion surface of the Transvaal Basin is an important source of high-grade iron ore. In the northwestern Cape, the conglomerates, breccias, ferruginous shales and iron-formation have been hematized, and give rise to the Sishen and associated orebodies, with reserves of some 4 billion tonnes of high-grade hematite. The age of the hematization event is uncertain. It certainly precedes the Permian glaciation of southern Africa, and could have been caused by "fossil groundwaters" circulating at the time of accumulation of the iron-formation detritus (Wessels, 1967). Hematized iron-formation conglomerates are known from the stratigraphically analogous situation in the Hamersley Basin of Western Australia (Button, 1976). The removal of large quantities of silica in solution suggests rather high pH groundwaters, while pervasive hematization indicates the presence of significant levels of atmospheric oxygen.

Some of the largest iron deposits in the world are local stratiform enrichments in banded iron-formations. The orebodies were probably formed by circulating meteoric waters associated with one or more periods of Precambrian weathering (Porath, 1967; MacDonald and Grubb, 1971; Button, 1976). The largest concentrations are usually found where folded iron-formation, underlain by impermeable shale, dips towards, and is truncated by, a major strike fault. Enrichment was effected by solution of chert out of the iron-formation and the oxidation of iron silicates and carbonates (Blockley, 1969). It is thought that these hematite concentrations are thus basically related to groundwater activity associated with Proterozoic land surfaces. Once again, alkaline and oxidizing groundwaters are implicated.

No large deposits of "soft iron ore" are presently known in southern Africa. The orebodies of this type in North America are apparently related to palaeoweathering beneath the Palaeozoic unconformity (James et al., 1961). According to these authors, alteration to depths "in excess of 3000 feet" can occur.

A final effect of palaeoweathering may be the conversion of crocidolite asbestos (the fibrous soda-iron amphibole) to amosite (fibrous grunerite). Crocidolite is widely developed in the iron-formations of the Transvaal Basin. Where these iron-formations are unconformably truncated by the Pretoria Group, grunerite asbestos is developed in place of the crocidolite. It is possible that this change is related to leaching of sodium from the asbestos by groundwaters associated with this period of erosion (Button, 1976).

XII. METAMORPHOSED PALAEOSAPROLITES

A. Age and Distribution

Sillimanite deposits have been commercially exploited from the metamorphic Bushmanland sequence (depositional age from 1800 to 2500 m.y.;Moore, 1977) of the northwestern Cape Province for almost thirty years (Figure 3). The occurrences have been intensively studied by Coetzee, 1940; De Jager and Von Backström, 1961; Martin, 1965; Joubert, 1973; Frick and Coetzee, 1974; Paizes, 1975 and by Moore, 1977. The sillimanite deposits and associated aluminous schists generally rest upon a biotite schist and are overlain by a metaquartzite (Frick and Coetzee, 1974). Individual orebodies are lenses, varying up to approximately 308 m long by 86 m wide (De Jager and Von Backström, 1961). Paizes (1975) has interpreted the lenses as structural boudins.

B. Petrology

The sillimanite orebodies and associated aluminous schists are composed of varying proportions of sillimanite, corundum, muscovite and rutile. Common accessory minerals include quartz, plagioclase, biotite, ilmenite, chlorite, calcite, hematite and magnetite (Coetzee, 1940; Frick and Coetzee, 1974).

C. Chemistry

Over 120 partial and full-silicate analyses of sillimanite ores and aluminous schists of the northwestern Cape Province have been published (Coetzee, 1940; De Jager and Von Backström, 1961; De Jager, 1963; Frick and Coetzee, 1974; Moore, 1977). Some average analyses are presented in Appendix 6. The individual analyses have been plotted on the Al_2O_3-SiO_2-K_2O triangle in Figure 5. The aluminous rocks plot between the kaolinite and the boehmite, gibbsite and diaspore fields. The sillimanite schists probably consisted originally of kaolinite with some gibbsite, while the sillimanite-corundum schists comprised gibbsite with some kaolinite. The aluminous rocks are strongly enriched in Al_2O_3 and TiO_2, and are depleted in total iron, MgO and Na_2O relative to a presumed biotite schist parent rock (Appendix 6).

D. Origin

Coetzee (1940) suggested that the aluminous schists of Namaqualand represent metamorphosed bauxites. Later investigators (De Jager and Von Backström, 1961; De Jager, 1963; Frick and Coetzee, 1974; Paizes, 1975) concurred. Read (1952) believed that some of the sillimanite-corundum bodies might be the immobile residue of a migmatization event. Martin (1965) suggested that thermal waters charged with CO_2 may have played a role in the genesis of the deposits. Joubert (1973) thought that the aluminous schists might represent fumarolically-leached volcanic rocks. Finally, Moore (1977) proposed that the aluminous rocks were derived from transported aluminous clays deposited in a playa-lake environment.

The concentration of Al_2O_3 and TiO_2 certainly indicate extensive leaching of a parent rock. The depletion of iron suggests the action of oxygen-deficient waters, and could indicate fumarolic action or the action of reducing groundwaters. The general low concentrations of K_2O are an indication of a fairly low pH. Either of the two systems could produce the aluminous rocks. The authors favour the palaeobauxite interpretation on stratigraphic grounds. An aluminous horizon, overlain by a quartzite, is suggestive of a regional nonconformity, and is similar to many others in pre-2200 m.y. basins of southern Africa.

E. Economic Importance

The sillimanite-corundum deposits of the Bushmanland Sequence have been exploited for 30 years. In 1959, reserves of high-grade ore (58-84 per cent Al_2O_3) were estimated at 420 000 tonnes (De Jager and Von Backström, 1961). Some 115 000 tonnes remained in 1962. Reserves of low-grade sillimanite ore (over 20 per cent Al_2O_3) were estimated at 2 727 000 tonnes in 1963 (De Jager, 1963).

XIII. EVIDENCE OF ATMOSPHERIC-HYDROSPHERIC EVOLUTION

To date, no work has been specifically aimed at tracking atmospheric evolution. The oft-quoted presence of detrital pyrite and uraninite in quartz pebble conglomerates, followed by global "blooming" of iron-formation around 2200-2300 m.y. ago, certainly apply to southern Africa. In addition, the iron and manganese in carbonates of the Transvaal Basin are divalent (Button, 1973). The first significant redbeds appeared in the Waterberg Supergroup and equivalents, some 2000 m.y. ago, and indicate that the oxygen content of the Earth's atmosphere-hydrosphere exceeded some threshold at about that time.

The character of ancient weathering profiles appears to support an evolution in the oxygen content of the palaeoatmosphere. All of the major palaeoweathering profiles reviewed in the pre-2200 m.y. bracket show no evidence of hematite concentration. Rather, iron has usually been thoroughly leached from the palaeosaprolites, in some cases being fixed in the divalent form near the base of the profile. These relations suggest reducing conditions.

By contrast, palaeoweathering profiles below 1100 m.y. old unconformities in the Keweenawan and in the Grand Canyon Sypergroup (Kalliokoski, 1975; Elston and Scott, 1976) are characterized by abundant hematite. A great geographic and time gap exists between the North American and African examples but the start of oxidative weathering is certainly constrained between 2200 m.y. and 1100 m.y.

The presence of granular uraninite and pyrite in pre-2200 m.y. old conglomerates has been emphasized as further evidence of an oxygen-deficient atmosphere. The argument is over-simplified, since some uranium appears to have been precipitated in carbon, while some is intimately related with titanium-bearing phases (Feather and Koen, 1975), and could be the result of reaction of detrital ilmenite with uraniferous palaeogroundwater. Similarly, some of the pyrite clasts in quartz pebble conglomerates are demonstrably of replacement origin (Papenfus, 1964), due presumably to the action of reducing, sulphidic palaeogroundwater. The same meteoric solutions were apparently capable of leaching gold and removing some components of the platinoid grains (Cousins, 1973). There is some evidence to suggest that these ancient groundwaters were alkaline in nature. Silica mobility is indicated by the cherty veinlets found near the base of some palaeoweathering profiles. Potassium fixation in clays (both in weathering profiles and in sediments derived from stripped profiles) is the rule in nearly all pre-2200 m.y. occurrences. We might tentatively conclude that parts of ancient continents were leached by chemically-aggressive alkaline, sulphidic, reducing palaeogroundwaters, of a type not developed on Earth in post-2200 m.y. times. There is some evidence to suggest that these solutions were capable of transporting uranium in solution, despite their reducing character.

XIV. LOCALIZATION OF MINERAL DEPOSITS ON PRECAMBRIAN EROSION SURFACES

A number of factors, frequently acting together, tend to result in the concentration of minerals of economic importance at and near unconformities. The following are considered to be the most important for the Precambrian situations reviewed.

1. *Geologic Time*

Many of the major unconformities can be shown to represent time breaks of several hundred million years. Lesser unconformities could, and probably do, mark hiatuses of thousands to millions of years. These immense spans of time are probably the most potent factor in mineral concentration. Given time, normal geologic processes, working at relatively slow rates, can achieve a very high level of concentration of minerals or groups of minerals.

2. *Differential Erosion and Palaeotopography*

A number of the pre-2200 m.y. palaeoplacer deposits are restricted to palaeovalleys of varying types. Greenstone belts tended to erode to major valleys, hundreds of metres deep and up to a few tens of kilometres across. Similarly, basic dykes formed linear pallaeovalleys on some Precambrian erosion surfaces.

In shale-arenite sequences, the differential erosion was controlled by the degree of lithification. On the erosion surface separating the upper from the lower division of the Witwatersrand Supergroup, unconsolidated arenites were apparently weathered and eroded and more rapidly than cohesive silts and muds. A well-developed meandering river system, (with recognizable point bar arenites and conglomerates) was etched onto this muddy surface. By contrast, on the pre-Transvaal erosion surface, Witwatersrand arenites formed palaeocuestas, separated by strike valleys (floored by Witwatersrand shales). In both cases, auriferous conglomerates are largely confined to palaeochannels.

Erosion surfaces on folded sequences of iron-formation and dolomite are known from southern Africa. Anticlines were breached by erosion, and resulted in iron-formation scarps overlooking a karst-floored lowland. Fan-like aprons of iron-formation debris built out across the lowlands. At some subsequent stage, chemically active (alkaline and oxidizing) palaeogroundwaters draining through the conglomerates and breccias are inferred to have caused the leaching of silica and enrichment in hematite which resulted in the Sishen deposits of the northwestern Cape Province.

A palaeoridge, developed along the unconformity separating the Pretoria Group from the underlying Malmani Dolomite, has been implicated in the widespread fluorite mineralization of the Western Transvaal (Martini, 1976). Such a palaeoridge, draped by relatively impermeable Pretoria Group shales, is a logical locus for the concentration of ascending mineralizing basinal fluids.

Palaeohighs can also have the inverse effect on mineralization. For example, in parts of the Zambian copperbelt, the "ore horizon" carries pyrite over basement palaeohighs and is progressively enriched in copper away from such highs. This sulphide zoning, originally interpreted as due to depositional facies belts, could be due to relatively dense mineralizing brines (sabkha generated; Renfro, 1974) moving down a gentle dip caused by draping over the rigid basement hills.

3. *Solution and Deposition by Groundwater*

The great spans of time associated with unconformities have already been stressed. A factor that may have been underemphasized is that groundwaters were active along these ancient erosion surfaces throughout these vast periods of time. Groundwaters are capable of removing certain phases in solution, resulting in a residual concentration of some minerals. Conversely, they are able to deposit minerals within the palaeoregolith, particularly in zones of enhanced porosity, such as fault zones. We believe that both types are developed along the Precambrian surfaces we have reviewed.

There are indications that granitic palaeosaprolites in the pre-2200 m.y. time bracket were leached of uranium. Arguments have been put forward to suggest that some of this uranium may have been subsequently deposited through reaction of groundwater with carbon and with titanium-rich minerals in sediments at and above the unconformities. The same palaeogroundwaters were probably responsible for leaching gold from gold-silver alloys, for leaching platinum, palladium and ruthenium from platinoid alloys and for pyritizing certain pebbles in conglomerates.

Intense leaching of Fe, Mg, Ca and Na from basaltic palaeosaprolites older than 2200 m.y. has given rise to numerous sericitic blankets, some of which can be traced for hundreds of kilometres. These sericitic layers normally contain some 30 to 35 per cent Al_2O_3, as well as up to 10 per cent K_2O, and constitute an enormous resource of these oxides. Leaching of rhyolitic glass in Dominion Reef water-laid tuffs has resulted in significant deposits of pyrophyllite.

High-grade hematite deposits appear to be related to silica leaching by alkaline oxidizing palaeogroundwaters. At least in an Australian deposit, it has been shown that removal of silica and oxidation of divalent iron in iron-formation has resulted in a high-grade hematite deposit (Blockley, 1969). Fluxing by palaeogroundwater has been promoted by structure (strike faults, synclinal axes) and by an impermeable shaly footwall in many cases (Button, 1976). The precise age and identity of the period (or periods) of weathering with which these groundwaters were associated is not known in most cases. The action of similar meteoric waters are inferred to have caused hematization of iron-formation conglomerate on some of the ancient erosion surfaces.

Important manganese deposits in the Transvaal and Hamersley basins are located at and short distances above a palaeokarsted erosion surface resting on manganese-bearing dolomites. The manganese, iron and associated carbon and chert clasts are obviously an insoluble mantle on this erosion surface. These deposits, about 2200 m.y. old, appear to indicate that atmospheric oxygen exceeded some threshold, since divalent Fe and Mn previously held in carbonates were fixed at higher valance states on the palaeokarst surface.

Very significant uranium concentrations are located below post-2000 m.y. unconformities in Canada and Australia (Langford, 1977). They probably formed where oxidizing uranium-bearing palaeogroundwaters penetrated down fractures and fault zones and were reduced by reaction with wall rocks, causing precipitation of uranium and a variety of associated base metals. Where carbon-rich beds are intersected by fault systems, stratiform uranium orebodies may result. Many of the post-2000 m.y. southern African unconformities could be associated with such deposits, and are being investigated at present.

The origin of mineralizing fluids for Zambian copperbelt ores is still an open question. Nevertheless, the association with the unconformity is unquestioned. In this and similar recently-discovered Cu-U deposits in South Australia, palaeoregoliths immediately below the major basement unconformities are mineralized.

4. *Mechanical Concentration on Unconformities*

It is widely appreciated that unconformities are favoured locations for placer deposits, formed by specific gravity sorting of dense, stable mineral species. A study of Witwatersrand literature has added two extra dimensions to this observation. Firstly, angular unconformities are deflation surfaces, where large volumes of unconsolidated sediments were erosively removed. The heavy minerals contained in these sediments were contributed to the surface of unconformity. Secondly, during an erosive interval, Witwatersrand braided fan surfaces stood above the base-level of deposition. Consequently, any sediment moved across such surfaces would not find a permament resting place, but would move on down the fan. However, the heavy minerals in these bypassing sediments would remain behind on the surface of erosion.

5. *Biological Action on Unconformities*

To a greater or lesser extent, "carbon" is found on most of the Witwatersrand unconformities (De Kock, 1964). This material probably represents an ancient algal or bacterial colony, growing on a water-saturated sandy substratum on an erosion surface. Its concentration on erosion surfaces is logical, since such communities would be swamped by clastic sediments during depositional periods on the fan surface. Mineralogical studies indicate that some of the Witwatersrand uraninite is disseminated in carbon seams (Feather and Koen, 1975), and could have been precipitated out of solution. Gold is also found in this setting, mainly between the fibrous carbon columns.

6. *Porosity Contrasts Adjacent to Unconformities*

Palaeogroundwaters had the capacity to alter the porosity and permeability of rocks beneath erosion surfaces. In addition, the coarse regolith on an unconformity can also be relatively porous and permeable. This is particularly true of erosion surfaces on carbonate formations, where palaeocaves and cave fill breccias represent localized regions of very high porosity/permeability. Thus, some of the fluorite deposits of the western Transvaal were apparently localized in palaeocave systems related to the pre-Pretoria Group period of weathering. The Tsumeb pipe in the late Precambrian Damara carbonates is probably a palaeosinkhole, and is filled by arenites (from the unconformably overlying Mulden arkoses) and carbonate breccias. The pipe is mineralized, as are concentric cylindrical fractures around it.

XV. FIELDS FOR FUTURE RESEARCH

It has been the major objective of this review to take stock of the available data on Precambrian weathering and erosion that has been collected, often in passing, over the past 50 to 60 years. The review has indicated some very significant differences in the chemistry of Precambrian meteoric waters, particularly in the pre-2200 m.y. period. The precise nature of these differences remains to be determined. We believe that further research on ancient weathering profiles and erosion surfaces will materially advance our ability to understand and to predict the location of mineral deposits. Furthermore, it should greatly increase our knowledge on the fundamental questions of terrestrial atmospheric-hydrospheric evolution.

Some of the principal questions presently posed are the following:

(i) was submarine weathering responsible for the aluminous schists in Archaean greenstone belts? If so, what constraints does their composition place on Archaean sea water chemistry?

(ii) was there a significant rise in the oxygen content of the atmosphere-hydrosphere some 2200 m.y. ago? If so, was the buildup a sudden solitary event, or was there a gradual, possibly episodic increase in the abundance of the gas?

(iii) how much validity is there to the concept of reducing alkaline palaeogroundwaters in the pre-2200 m.y. period? Were such groundwaters widely developed, or were they developed in response to local climatic factors?

(iv) are all pre-2200 m.y. old granitic palaeosaprolites leached of uranium? Were strongly alkaline reducing groundwaters capable of transporting the metal in solution and precipitating it in contact with carbon or titanium-bearing minerals? Could some of the low-thorium uraninite grains represent precipitated material in the palaeosaprolite, or in the fluvial sediments?

(v) were alkaline reducing palaeogroundwaters capable of dissolving gold preferentially to silver, of pyritizing chert pebbles and shale clasts, and of leaching some components of platinoid grains?

(vi) did alkaline oxidizing groundwaters evolve relatively soon after 2200 m.y. ago, as is suggested by the desilication and hematization of iron-formation and iron-formation detritus?

(vii) how can we reconcile a proposed alkaline groundwater system 2200 m.y. ago with the well-defined carbonate solution surfaces at that period? What are the minimum oxygen levels that could immobilize iron and manganese on these ancient karst surfaces?

(viii) what were the sources of, and controls for, the deposition of copper and uranium in palaeoregoliths and fracture systems below post-2200 m.y. unconformities?

(ix) can we develop geochemical models which will allow us to understand and to predict the effects of terrestrial weathering in an oxygen-deficient environment? For example, what factors might promote leaching of the iron in the upper part of a weathering profile and precipitation of divalent iron in the lower part? How can we explain the common effects of K fixation and of silica precipitation low down in the profiles? and,

(x) having learned all we can about terrestrial palaeoatmosphere, how can we apply this knowledge towards understanding of atmospheric evolution on other planets? Conversely, do the known atmospheric conditions on other planets resemble those we infer for a Precambrian Earth?

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APPENDICES

APPENDIX 1: MAJOR ELEMENT CHEMISTRY OF ARCHAEAN ALUMINOUS SCHISTS

Sample	1	2	3	4	5	6
SiO_2	78,28	59,93	61,65	58,12	74,28	21,45
TiO_2	0,55	0,45	1,71	0,13	0,10	0,31
Al_2O_3	17,52	26,26	26,69	24,45	21,91	60,79
Fe_2O_3	0,39	0,29	0,42	1,31	tr	0,32
FeO	1,01	1,64	0,52	1,00	0,54	1,01
MnO	0,01	0,02	nil	0,06	0,05	0,03
MgO	0,46	1,26	1,34	2,85	0,33	0,60
CaO	0,30	0,42	0,30	0,23	0,12	6,43
Na_2O	0,53	3,75	0,22	0,40	0,38	0,78
K_2O	1,48	1,63	3,16	7,92	0,30	2,39
P_2O_5	0,11	0,05	0,02	-	tr	2,42
H_2O	1,08	4,04	3,10	3,47	0,61	3,08
CO_2	-	0,12	nil	0,03	0,02	0,11
Totals	101,72	99,86	100,32	99,95	100,29	99,63

1. Aluminous quartz-sericite schist (andalusite-chloritoid), Jamestown Schist Belt, Barberton area (Anhaeusser, 1978).

2. Aluminous felsic tuff (pyrophyllite), Theespruit Formation Komati River Valley, Barberton area (Viljoen and Viljoen, 1969).

3. Aluminous mica schist (fuchsite, andalusite), Somerset Farm, Mazoe District, Rhodesia (Ferguson and Wilson, 1937).

4. Mica schist, Montezuma Mine, Odzi Gold Belt, Rhodesia (Swift, 1956).

5. Andalusite schist, Yandanhoo Hills, Western Australia (Joplin, 1963).

6. Marundite (margarite, corundum, apatite), Lochiel area, (Anhaeusser, 1978).

APPENDIX 3: MAJOR-ELEMENT CHEMISTRY OF DOMINION REEF GROUP PYROPHYLLITES

Sample	1	2	3	4	5	6	7	8	9
SiO_2	56,18	57,19	54,56	56,76	55,50	56,71	56,84	54,96	54,20
TiO_2	2,45	2,08	2,58	2,80	2,60	2,30	2,25	2,75	2,50
Al_2O_3	32,76	32,78	32,83	32,39	34,30	33,27	33,57	34,03	34,94
Fe_2O_3 *	0,64	0,72	2,38	1,54	0,82	1,48	0,75	0,86	1,06
MgO	0,78	0,36	0,50	0,31	0,28	0,26	0,29	0,13	0,21
CaO	0,72	0,40	0,32	0,25	0,16	0,14	0,07	0,18	0,12
Loss on Ignition	6,60	6,54	6,82	6,37	6,71	6,15	6,42	7,63	7,40
Total	100,07	100,14	99,99	100,42	100,37	100,31	100,19	100,54	100,43

Analyses 1-9: Pyrophyllites from the Dominion Reef Group (Von Backström, 1962).

* Presumed to be total iron as Fe_2O_3; original source does not specify.

APPENDIX 2: MAJOR ELEMENT CHEMISTRY OF GRANITIC PALAEOSAPROLITES

Sample	1	2	3	4
SiO_2	75,99	72,60	62,21	76,90
TiO_2	0,18	0,20	0,52	0,06
Al_2O_3	12,16	13,88	15,89	13,50
Fe_2O_3	0,51	0,87	1,45	0,43
FeO	0,53	1,42	3,38	0,95
MnO	0,01	0,05	0,10	-
MgO	0,44	1,57	3,43	0,25
CaO	0,59	0,06	5,64	0,30
Na_2O	0,22	0,09	3,87	2,18
K_2O	7,36	7,50	1,58	5,10
P_2O_5	0,02	0,07	0,27	-
H_2O-	0,14	0,03	0,07	-
H_2O+	0,96	1,39	1,64	-
CO_2	0,37	0,05	0,17	-
Totals	99,48	99,85	100,18	99,67

1. Quartz-sericite rock below Black Reef Quartzite, north of Johannesburg (Sample KL11 of Anhaeusser, unpublished data, 1978).

2. Sheared, sericitized granite below Orange Grove Quartzite, Witwatersrand Supergroup (Sample LR2 of Anhaeusser, 1973).

3. Hornblende tonalitic gneiss, probably parent rock for LR2 palaeosaprolite (Sample PV2 of Anhaeusser, 1973).

4. Average of 5 granitic palaeosaprolites from below the Matinenda Formation, Huronian, Canada (Roscoe, 1969).

APPENDIX 4: MAJOR ELEMENT CHEMISTRY OF BASALT-DERIVED PALAEOSAPROLITES

Sample	1	2	3	4	5	6
SiO_2	43,90	46,80	47,06	47,42	45,60	42,50
TiO_2	2,95	1,02	1,33	0,92	1,70	4,30
Al_2O_3	30,10	34,35	31,70	24,38	33,10	28,30
Fe_2O_3	2,55	3,34Ψ	1,23	1,73	0,42	3,10
FeO	2,75	-	0,81	10,31	1,36	1,83
MnO	-	0,03	0,01	0,10	N.D.	N.D.
MgO	1,35	0,00	1,48	2,87	0,33	1,00
CaO	3,00	0,00	0,01	0,03	0,02	1,40
Na_2O)		0,23	0,00	0,00	0,72	0,14
)	8,65					
K_2O)		9,05	10,71	7,00	11,00	9,40
P_2O_5	-	0,14	0,00	0,00	N.D.	N.D.
H_2O+	4,65*	4,71*	4,84	5,51	N.D.	N.D.
H_2O-	-	-	0,10	0,03	N.D.	N.D.
CO_2	0,02	-	-	-	0,04†	0,11†
Total	99,92	99,67	99,29	100,30	94,29	92,08

1. Green fissile rock (palaeosaprolite) of Bird Lava, Witwatersrand Supergroup (Fox, 1939).

2. Palaeosaprolite, within Ventersdorp Supergroup (Tyler, 1978).

3, 4. Palaeosaprolites, on Ventersdorp Lava, below Black Reef (Wyatt, 1976).

5, 6. Palaeosaprolites, on Archaean metabasalts, below Matinenda Formation, Huronian, Canada (Roscoe, 1969).

N.D. = not determined

† = as elemental C

Ψ = Total Fe as Fe_2O_3

* = Loss on ignition

APPENDIX 5: MAJOR-ELEMENT CHEMISTRY OF SOME WITWATERSRAND SHALES

Sample	1	2	3	4	5	6	7	8	9
SiO_2	51,70	50,50	49,70	52,03	67,20	54,36	54,78	54,98	59,22
TiO_2	1,16	1,01	0,94	0,96	0,93	0,72	1,01	0,72	0,87
Al_2O_3	34,68	34,68	35,80	34,50	24,39	30,38	29,98	28,46	29,51
Fe_2O_3*	1,76	2,73	2,16	1,84	2,27	5,96	0,99	6,33	0,79
MgO	0,09	1,48	1,32	1,14	1,45	2,13	0,87	2,69	0,31
CaO	0,01	0,01	0,01	Tr.	Tr.	Tr.	0,48	0,06	0,09
Na_2O	0,46	0,37	0,37	0,60	0,11	0,48	0,52	0,30	0,71
K_2O	4,62	4,96	4,96	4,73	0,58	2,64	7,95	1,87	4,59
L.O.I.ϕ	5,02	4,70	5,16	5,05	2,92	3,95	4,12	4,77	4,51
Total	99,50	100,44	100,42	100,85	99,85	100,62	100,70	100,18	100,60

* = Total iron as Fe_2O_3 (All analyses from Wiebols, 1961)

ϕ = Loss on Ignition

Tr = Trace

1. Chloritoid-bearing shale, Grootvlei Mine.
2. Chloritoid-bearing shale, Marievale Mine.
3. Chloritoid-bearing shale, Marievale Mine.
4. Chloritoid-bearing shale, Grootvlei Mine.
5. "Black Bar", West Rand Consolidated Mine.
6. "Green Bar", Venterspost Mine.
7. Kimberley Footwall Shale, Van Dyk Mine.
8. Black Shale below the "Big Pebble Conglomerate", borehole in Orange Free State goldfield.
9. Shale in the "Middling Quartzite", St. Helena Mine.

APPENDIX 6: ANALYSES OF METAMORPHOSED ALUMINOUS ROCKS OF THE BUSHMANLAND METAMORPHIC SEQUENCE

Sample	1	2	3	4	5
SiO_2	26,01	18,67	32,71	44,59	63,13
TiO_2	5,55	2,31	1,99	1,45	1,40
Al_2O_3	66,30	74,62	59,95	49,11	32,55
Fe_2O_3	0,41	0,84	0,61	0,41	0,03
FeO	0,54				0,13
MnO	0,01	0,01	0,01	0,04	0,01
MgO	N.D.	0,12	0,11	0,13	0,03
CaO	N.D.	2,38	2,19	0,03	0,03
Na_2O	0,09	0,31	0,15	0,22	0,33
K_2O		0,46	0,36	1,59	0,95
P_2O_5	N.D.	0,20	0,10	0,03	N.D.
H_2O+	1,00	N.D.	N.D.	N.D.	1,22
H_2O-	0,08	N.D.	N.D.	N.D.	0,12
CO_2	N.D.	N.D.	N.D.	N.D.	0,02
Totals	99,99	99,92	98,18	97,60	99,88

1. Sillimanite - corundum rock, Pella area, Northwestern Cape Province (Coetzee, 1940).
2. Average sillimanite - corundum rock (3 analyses, Moore, 1977).
3. Average massive sillimanite rock (6 analyses, Moore, 1977).
4. Average sillimanite - quartz rock (4 analyses, Moore, 1977).