ECONOMIC GEOLOGY RESEARCH UNIT

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A REVIEW OF SOUTHERN AFRICAN STRATIFORM ORE DEPOSITS - THEIR POSITION IN TIME AND SPACE

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INFORMATION CIRCULAR No. 85

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ECONOMIC GEOLOGY RESEARCH UNIT
INFORMATION CIRCULAR No. 85
April, 1974

INFORMATION CIRCULAR No. 85

(for Restricted Distribution)

The information contained herein has been submitted for publication and represents a contribution to a volume, or series of books, relating to Sedimentary Ore Deposits, to be published by Elsevier Publishing Company under the editorship of Professor K. W. Wolf.

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ABSTRACT

The most important mineral occurrences in southern Africa (in terms of value) are the stratiform, non-magmatic ore deposits. Outstanding among these is the famous Witwatersrand gold and uranium producing region of South Africa which has dominated the mining scene both locally and abroad for close on 90 years. This unique mineral province has overshadowed a number of other important mineralized areas, many of which, in their own right, are among the world's great producers of mineral raw materials and precious stones. Included among the latter are the extensive iron, manganese, diamond and asbestos deposits, to name but a few.

This paper attempts to review the many mineral occurrences which broadly fall under the heading of stratiform, non-magmatic, ore deposits in southern Africa. A unique record of geological events dating back from the earliest Precambrian (Archaean greenstone belts, c.a. 3 400 m.y.) to the present day has promoted a study which portrays the evolutionary development and changes of mineralization over this immense time span.

To facilitate the handling of such a broad and diverse sequence of geological events, together with the innumerable mineral occurrences, a table has been devised which assists in classifying the nature and types of mineralization developed through space and time in southern Africa. Finally, for those interested in pursuing further the wealth of detail relating to southern Africa stratiform ore deposits, an extensive bibliography on the subject has been included.

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A REVIEW OF SOUTHERN AFRICAN STRATIFORM ORE DEPOSITS - THEIR POSITION IN TIME AND SPACE

INTRODUCTION

This paper attempts to summarize the more important features of the stratiform ore deposits of southern Africa. A fairly wide definition of the term stratiform is employed, and embraces all ore bodies, both syngenetic and epigenetic, which are bounded by planes of stratification in a sedimentary or volcanic succession. The area encompassed by the term southern Africa incorporates the territories of South West Africa, Botswana, Rhodesia, the southern half of Mozambique, the Republic of South Africa, Lesotho and Swaziland (Figure 1). The majority of the deposits are found in the Republic of South Africa, and are referred to in the text according to the provinces in which they occur. The four provinces (Figure 1) are known as the Transvaal, Natal, the Cape Province and the Orange Free State.

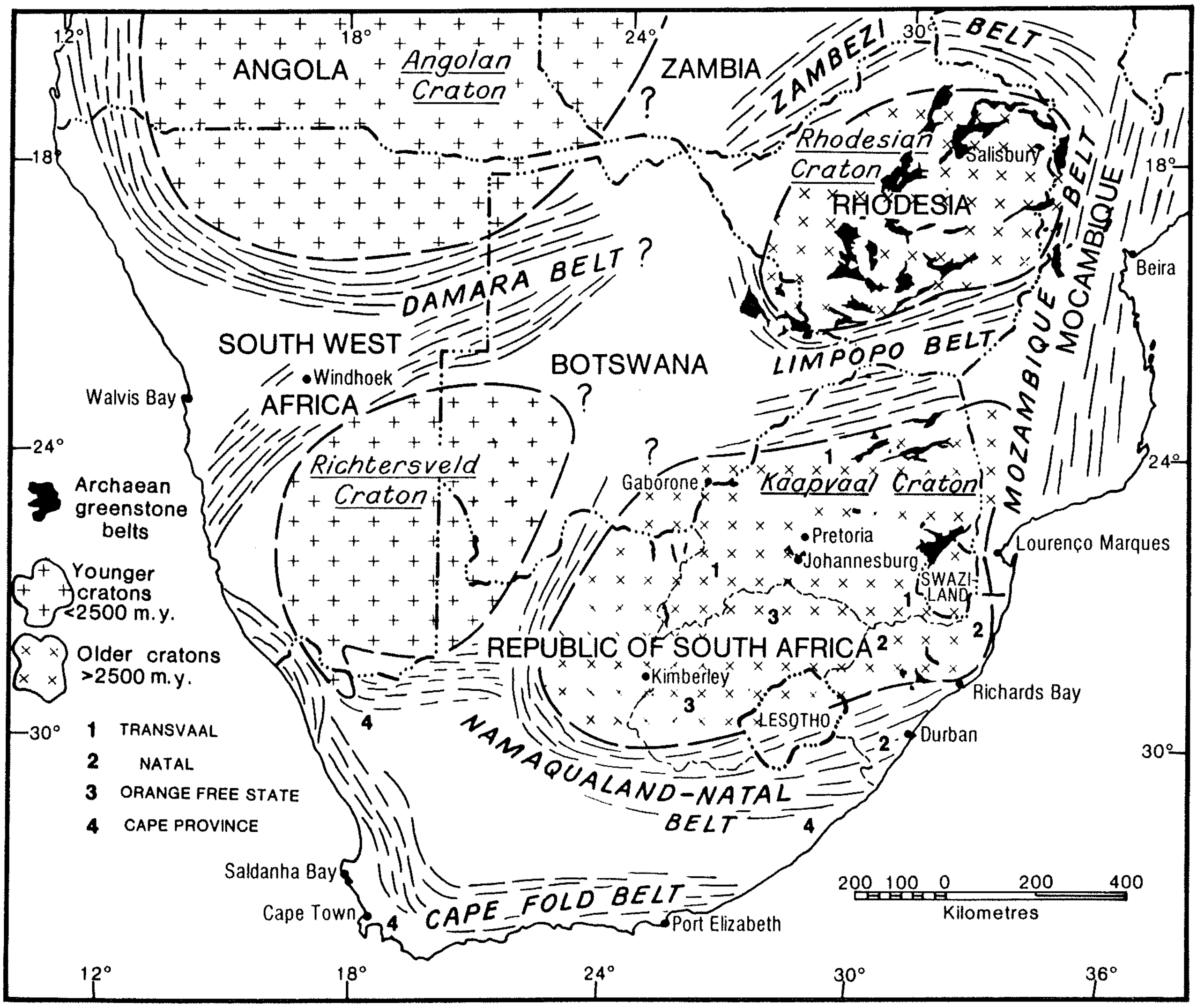


Figure 1 : Generalized geotectonic map of southern Africa illustrating the ancient and younger cratonic areas together with the encircling metamorphic and fold belts.

The scope of the paper is broad and consequently, even the most important mineral provinces have been described only briefly. Where possible, attempts have been made to fit the southern African mineral occurrences into world-wide classes of ore associations. Emphasis has been placed on the age of the host environment and a number of well-defined metallogenic epochs have been delineated. Consequences of this analysis are two-fold. Firstly, certain host environments which should carry a certain mineral suite, but which are not known to do so, have been spot-lighted, and constitute possible exploration targets. Secondly, certain known mineral provinces are shown to be possible hosts to other metals not presently exploited, so that exploration for the latter elements in already-delineated areas may be called for.

THE STRATIGRAPHIC HISTORY OF SOUTHERN AFRICA

In southern Africa the oldest rocks are developed mainly on the Rhodesian and Kaapvaal cratons (the older cratons of Figure 1) which together constitute part of the ancient crystalline shield. The two cratonic nuclei in their present form consist of Archaean granite-greenstone complexes together with cover sequences and both are encircled by younger, curvilinear metamorphic mobile belts such as the Zambezi, Mozambique, Limpopo and Namaqua-Natal mobile belts (Anhaeusser et al., 1969). Scattered within the expanse of granitic rocks are numerous greenstone belts some approaching, or even possibly exceeding, ages of about 3 400 m.y. These ancient greenstone belt remnants represent the earliest clearly decipherable geological events on the Earth's crust.

Most of the greenstone belts have a well-ordered stratigraphy and commence with a succession of mafic and ultramafic flows and comagmatic differentiated intrusive bodies. These *lower ultramafic unit* assemblages are succeeded by a *mafic to felsic unit* comprising basaltic, dacitic and rhyodacitic lavas and pyroclasts together with some chemical sediments, the latter usually a variety of cherts, iron formations or carbonates. In Rhodesia the former rock assemblage constitutes the Sebakwian Group (Table I) while the latter succession is known as the Bulawayan Group. In South Africa the various assemblages are referred to collectively as formations within the Onverwacht Group. The stratigraphy of many of the greenstone belts is commonly terminated by a sedimentary unit (Shamvaian Group in Rhodesia, Fig Tree and Moodies groups in the Barberton greenstone belt, South Africa). The Fig Tree Group is characterized by a submarine turbidite assemblage of greywacke and shale with some chemical sediments and subordinate volcanic and pyroclastic members, while the Moodies Group resembles a shallow marine shelf assemblage, comprising cyclical arenite-argillite units with some conglomerates, volcanic rocks, and iron formation.

The era of Archaean granite development overlapped, in part, the depositional period of the greenstone belts. Granite-derived detritus is present in the sedimentary units of greenstone belts, but not in the earlier volcanic units. The older cratonic areas of southern Africa stabilized sufficiently, about 3 000 m.y. ago, to permit the development of a number of interior, or cratonic-type sedimentary basins. *1 The first of these was the Pongola basin (Figure 7). Metamorphosed representatives of Pongola age cratonic sediments and volcanics are found in both the Limpopo mobile belt (Messina Group, Figure 7) and in the Namaqua-Natal belt (Kheis Group, Figure 7).

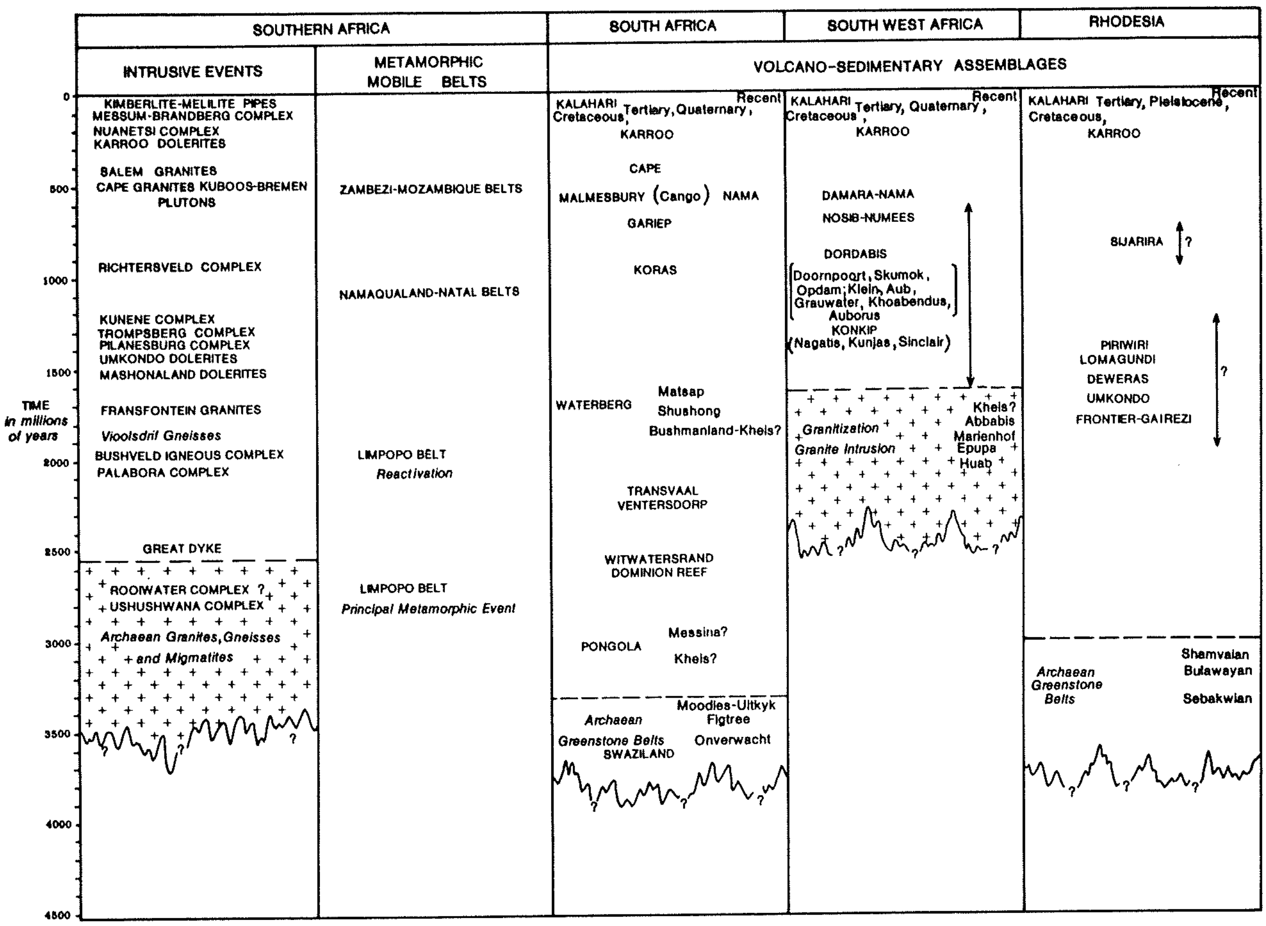
The next depositional event of importance gave rise to the Witwatersrand Supergroup (Figures 7, 9) and its localized fore-runner phase the Dominion Reef Group, the latter comprising continental clastics and volcanics (Haughton, 1969). The lower division of the Witwatersrand Supergroup is probably a marine-deltaic assemblage consisting of shale and quartzite with minor conglomerate, iron formation and mafic volcanics. The economically important upper division of the Witwatersrand comprises mainly continental and marginal-marine coarse clastics. The thick and areally-extensive Ventersdorp succession (Figure 7), consisting mainly of lavas and subordinate clastic sediments, was next to develop. Certain phases of the Ventersdorp follow conformably on the Witwatersrand rocks, while others are unconformable and lap onto Archaean basement.

At about 2 200 m.y. ago a period of marine sedimentation ensued, and is represented by the thick (up to 11 000 m) and extensive Transvaal Supergroup (Figure 9). This commenced with the deltaic-

*1. <u>Footnote</u>: For a summary of age measurements and Archaean-Early Proterozoic crustal development in southern Africa see Burger and Coertze (1973) and Anhaeusser (1973).

TABLE I

GEOLOGY AND GEOCHRONOLOGY OF SOUTHERN AFRICA



marine Wolkberg Group in the north-eastern Transvaal (Button, 1974), and was followed by a period of extreme stability, during which time the major carbonate and iron formation units of the supergroup were chemically precipitated. A period of intraformational erosion terminated the era of chemical sedimentation and was followed by the marine and deltaic clastic sedimentation of the Pretoria Group, and the extrusion of the acid volcanic pile (up to 4 000 m thick) of the Rooiberg Group. The intrusion of the mafic and acid phases of the Bushveld Complex (Figure 2), between about 2 100-1 950 m.y. ago, terminated the era of Transvaal sedimentation. The Rhodesian craton, during the corresponding 1 000 m.y. period of sedimentation on the Kaapvaal craton, appears to have accumulated no sediments. If some sedimentation did take place here then it must have been removed by erosion. In South West Africa (Figure 2), the Marienhof, Abbabis, Huab, and Epupa formations (all of which were affected by metamorphism and varying degrees of granitization approximately 1 700-1 900 m.y. ago - Martin, 1965) could have been deposited during the Transvaal depositional era. These rocks constitute the "basement" to all subsequent geological formations developed in this territory.

In the central Transvaal cratonic sedimentation continued with the deposition of the post-Bushveld Waterberg Supergroup (Figure 8). This unit consists principally of continental red beds (Haughton, 1969) and represents the first unit in the stratigraphic succession of southern Africa to have been deposited under oxygenous conditions. The stratigraphic history of the Kaapvaal craton is marked by a depositional hiatus of grand dimensions, extending from Waterberg (c.a. 1 800 m.y.) to Karroo times (c.a. 300 m.y.). During this interval, the focus of sedimentation shifted to other parts of southern Africa, particularly to Rhodesia, South West Africa, and the northwestern, western, and southwestern regions of the Cape Province.

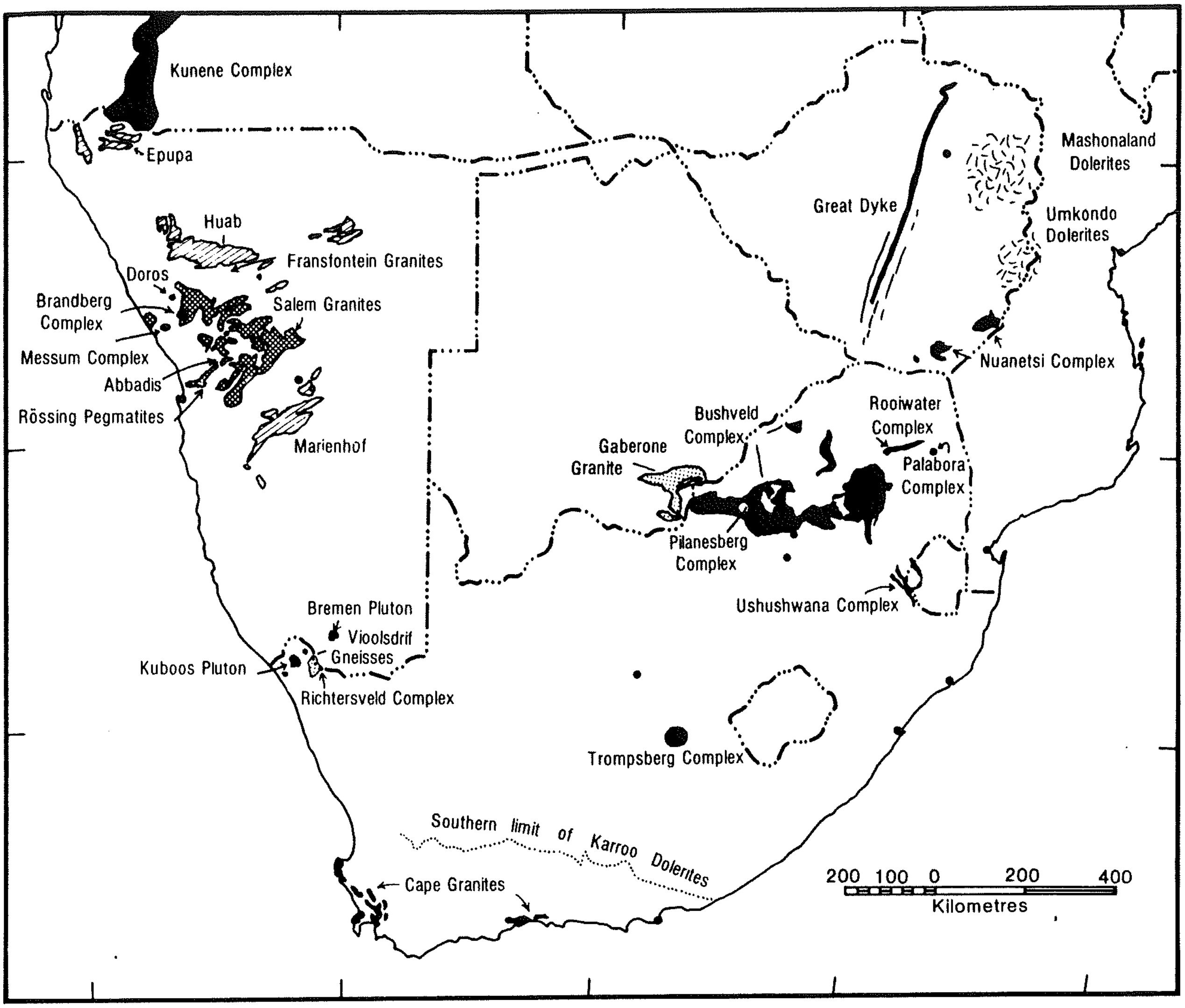


Figure 2 : Map showing the distribution of some of the more important intrusive complexes and granitized areas useful in dating stratigraphic units in southern Africa.

In Rhodesia the Frontier-Gairezi, Umkondo, Deweras, Lomagundi,and Piriwiri assemblages were deposited probably in the 1 300 to 2 000 m.y. time interval. The official Rhodesian Geological Survey viewpoint regarding these rocks remains that currently depicted on the 1971 edition of the 1:1 000 000 map of the country (J.G. Stagman, written communication, 1974). Stagman added that, despite the considerable amount of work that has been done on these rocks, there remains no certainty about their stratigraphic position, either absolutely or relatively. This uncertainty is reflected in Table I.

Similar problems, involving lack of geochronological control, are encountered in the western regions of southern Africa. Here doubt exists as to the age and extent of rocks classified as Kheis. Suggestions have been made, following recent mineral exploratory investigations, that rocks in the region west of the Brakbos Fault zone (Figure 7) are distinct from Kheis rocks and should be grouped separately into what has been called the Bushmanland Metamorphic Complex (Viljoen, 1973). The age uncertainty of the Kheis/Bushmanland problem is also reflected in Table I.

The Namaqua-Natal metamorphic event (c.a. 1 000 m.y. ago) affected large tracts of country extending from southern Natal in the east to the northwest Cape and beyond to the Richtersveld and southern parts of South West Africa (Figure 1). Much of this metamorphic belt lies obscured beneath a cover of Cape and Karroo rocks. In the west, along the coast, and for some distance inland, a suite of sedimentary and volcanic rocks is exposed for some distance both north and south of the Orange River. The stratigraphic relationships in this area remain confused. The rocks have been assigned numerous local stratigraphic names but as yet no widely accepted overall subdivision exists. As far as the authors are aware no stratiform mineralization of significance has yet been found in these rocks. North of the Orange River, in South West Africa (Figure 8), rocks grouped under the heading Konkip (Table I) rest on a gneissic basement and are intruded by granites of uncertain age. On the coast, extending from the Richtersveld into the adjoining parts of South West Africa, a great variety of sedimentary and volcanic rocks, together with a tillite member, forms part of the Gariep geosynclinal succession (Figure 8), largely built up of debris derived from the rising Bushmanland/Kheis basement to the east (Martin, 1965; Kröner, 1971). Again no certainty exists as to the age of these rocks, but they are considered to be younger than 1 000 m.y. Martin (1965) speculated that in a broader context the Gariep geosyncline may form a part of the great Late Precambrian geosynclinal belt which follows intermittently the western margin of the African continent from the Cape to Gabon. He considered it still too early to know whether the different sections of this belt, the Malmesbury, Gariep and Damara (Figure 8) as well as the West Congo geosynclines are strictly contemporaneous or not.

In central South West Africa rocks grouped together under the name Dordabis extend northeastwards across the border into Botswana - an outcrop length in excess of 800 km (Figure 8). Here again considerable uncertainty exists as to the age and stratigraphic relationships of the various sedimentary and volcanic units. According to Martin (1965) the Dordabis and Konkip successions may be time equivalents, but no isotopic age determinations are available to substantiate this possibility. The Dordabis rocks, which contain stratiform copper deposits, are clearly older than the Damara and Nama successions to the north and south and are thought to be approximately 800-1 000 m.y. old (Table I).

A period of widespread, largely marine sedimentation next covered extensive areas of South West Africa and parts of the northwest Cape Province. These rocks of Late Precambrian or Early Cambrian age (500-700 m.y.) are subdivided geographically into the Damara Supergroup in the north and the Nama Supergroup in the south (Figure 8). The two basins are separated by the belt of older Dordabis rocks referred to earlier, so that their mutual age relationships cannot be established. They are currently considered to be more or less contemporaneous. The Nama sediments are generally flat lying and relatively little disturbed as are the northern "foreland" or "platform" successions of the Damara geosyncline. These rocks appear to have been deposited on extensive stable platforms, or younger cratons, referred to as the Angolan craton in the north and the Richtersveld craton in the south (Figure 1).

These two stable blocks are separated by the northeast trending core of the Damaran geosyncline which, by contrast, consists of intensely deformed, metamorphosed, and, in places, granitized eugeosynclinal assemblages (Salem granites and pegmatites, Figure 2). The miogeosynclinal Outjo facies which onlaps onto the Angolan craton consists mainly of chemical sediments, principally dolomite and limestone, together with relatively well-sorted detrital sediments. The characteristic rocks of the eugeosynclinal Swakop facies include ill-sorted greywackes, schists, quartzites, itabirite, tillite, dolomite, marble,and a variety of metamorphosed mafic and ultramafic lavas (Martin, 1965).

The Cape Supergroup, of Devonian age (c.a. 400 m.y.), is largely confined to the southern Cape, but is also developed in Natal (Figure 4). The sequence is composed of marine and some fluvial sediments, those in Natal being relatively undisturbed, while those in the Cape are intensely deformed (Cape Fold Belt, Figure 1).

Rocks of the Karroo Supergroup blanket extensive areas of southern Africa (Figure 4). Fossil evidence indicates that the Karroo succession ranges in age from the Upper Carboniferous, through the Permian and Triassic into the Lower Jurassic (c.a. 300-200 m.y.). Although local variations and facies are developed, a four-fold subdivision of the assemblages can be implemented throughout southern Africa. The Karroo usually commences with the Dwyka Group, a fluvio-glacial and glacio-marine unit, and is followed by the Ecca Group of Permian age. This unit undergoes a marked facies change across the sub-continent (Ryan, 1968; Haughton, 1969). In the north, it comprises the coal measures and marginal marine sediments, while in the south it is represented by a marine, flysch-like, succession consisting essentially of great thicknesses of shales. The succeeding Beaufort Group incorporates sandstones, shales and siltstones, which are often coloured shades of maroon. The succession is host to a variety of amphibian and reptilian remains, including also the mammal-like reptiles (therapsids), and was probably deposited under continental to marginal marine conditions. The overlying Stormberg Group is a unit composed of shales, sandstones (including aeolianites), and some coal beds. It is capped by the Drakensberg volcanics, incorporating up to 1 400 m of basaltic lava and, along the eastern half of the sub-continent, large thicknesses of rhyolitic extrusives. Karroo dolerite dykes and sills occur over much of the sub-continent north of the "dolerite line" shown in Figure 2.

Cretaceous beds, some of which dip seawards, cover large areas of Mozambique and extend southwards into northern Natal. Further major developments of similar rocks occur in the Algoa basin, near Port Elizabeth and on the offshore Agulhas Bank. Post-Cretaceous igneous activity was responsible for the emplacement of numerous kimberlite pipes and fissures (Figure 3). Tertiary-to-Recent deposits cover extensive areas of the Mozambique coastal plain as well as a narrow coastal fringe of South Africa and South West Africa. The Kalahari beds (essentially clays, marls, gravels, and ubiquitous aeolian sands) cover vast areas of the interior regions of southern Africa, particularly the arid areas of Botswana and South West Africa.

CLASSIFICATION OF STRATIFORM ORE DEPOSITS

In this paper, a system of classification has been devised for stratiform, non-magmatic ore deposits. As with most other classifications, a fundamental distinction has been drawn between those deposits formed at the same time as the enclosing rock (syngenetic) and those introduced into the host formation at some later date (epigenetic). This two-fold subdivision encompasses most deposits. There is, however, one type falling into neither of these classes and which consists of metamorphic minerals formed by chemical re-ordering of the syngenetic mineral components of a rock. Nothing needs be added to the rock, so that a resulting ore deposit (e.g. andalusite hornfels) is neither epi- nor syngenetic. A distinction has also been drawn between those processes which can be considered to be part of the normal sedimentary-diagenetic cycle, such as the dolomitization of limestone, and thermally-induced metamorphic changes. Thus dolomites and the asbestiform amphiboles are grouped with the chemical precipitates, even though they were not deposited in these forms.

The secondary subdivisions within the two main classes are largely self-explanatory, and are defined in the text. It can be mentioned that three subdivisions of the hydrothermal class have been grouped together (hypo-, meso- and epithermal deposits) in that these types are not well-represented among stratiform ore bodies, being in most instances, cross-cutting vein and lode deposits.

In that it is an aim of this review to demonstrate the time-dependence of mineralization, this parameter has been incorporated in the classification of Table II. The geological timescale of southern Africa has been subdivided into four units, encompassing the Archaean greenstone belts (mainly > 3 000 m.y.), the Archaean and Early-Proterozoic (3 000-1 800 m.y.), the Middle- and Late-Proterozoic (1 800-600 m.y.) and the Phanerozoic (< 600 m.y.).

MECHANICAL CONCENTRATIONS

Mechanical concentrations (placer deposits) consist of accumulations of chemically stable heavy minerals. They form by weathering of a parent rock, liberation of the heavy mineral, and subsequent concentration by gravitational, aeolian, fluvial,or marine agencies. In southern Africa, minerals have been won from placers ranging in age from the earliest Precambrian to those forming at the present day. In the Archaean and Early-Proterozoic representatives of this class, gold, uranium, platinoids,and pyrite have been recovered. Some Karroo-age placers have been mined for diamonds and gold, while others are known to carry monazite and other heavy minerals. Tertiary-to-Recent deposits include diamondiferous marine and littoral gravels, marine phosphorite gravels, ilmenite-bearing beach sands,and alluvial-eluvial concentrations of diamonds, gold, cassiterite, platinoids,and andalusite.

TABLE II

CLASSIFICATION OF STRATIFORM (NON-MAGMATIC) ORE DEPOSITS IN SOUTHERN AFRICA

(Bold print denotes deposits which have been or are being fairly extensively exploited)

			ARCHAEAN GREENSTONE BELTS	ARCHAEAN AND EARLY-PROTEROZOIC BASINS (>1800 m.y.)	MIDDLE AND LATE PROTEROZOIC BASINS (600-1800 m.y.)	PHANEROZOIC UNITS (<600 m.y.)
SYNGENETIC	MECHANICAL CONCENTRATIONS		Gold *(Uitkyk Formation, Shamvaian Group)*	GOLD, URANIUM, Platinoids, Pyrite *(Pongola, Dominion Reef, Witwatersrand, Ventersdorp and Transvaal Supergroups)*.	Monazite, Zircon *(Nama Supergroup)* Wolframite *(Bushmanland/Kheis?)*	DIAMONDS, Ilmenite, Zircon, Monazite, Phosphorite, Rutile *(Beach or Marine sands and gravels)*, GOLD, Tin, Andalusite, Xenotime, DIAMONDS *(Alluvial and Eluvial Deposits)*. Diamonds, Gold, Monazite *(Karroo Supergroup)*.
SYNGENETIC	ORGANIC ACCUMULATIONS					COAL, Torbanite, Oil Shale *(Karroo Supergroup)*
SYNGENETIC	CHEMICAL PRECIPITATES (UNALTERED AND METAMORPHOSED)		Limestone *(Bulawayan Group)*	LIMESTONE, CROCIDOLITE, AMOSITE, Dolomite, Ironstone *(Transvaal Supergroup)*. Magnetite Quartzite *(Messina Group)*. Iron Formation *(Pongola, Witwatersrand, Transvaal and Shushong Supergroups)* Marble *(various formations)*	LIMESTONE *(numerous formations in the South-western Cape and South West Africa)* Marble *(various formations)*. Iron Formation *(Damara Supergroup)*. Manganese *(Damara Supergroup)*	Blackband Ironstone *(Karroo Supergroup)*. Salt *(Recent)*.
SYNGENETIC	VOLCANOGENIC PRECIPITATES	ESSENTIALLY UNMODIFIED	Iron Formation *(all greenstone belts)* Pyrite *(Shamvaian Group)* Barite *(Onverwacht and Figtree Groups)*			
SYNGENETIC	VOLCANOGENIC PRECIPITATES	METAMORPHOSED (LOW-TO-INTERMEDIATE GRADES)	ANTIMONY *(Murchison and other greenstone belts)* GOLD, Pyrite, Arsenopyrite, Scheelite *(most greenstone belts)* Copper, Lead, Zinc, *(Murchison greenstones)*		COPPER *(Khomas Group of the Damara Supergroup)*	
SYNGENETIC	VOLCANOGENIC PRECIPITATES	METAMORPHOSED (INTERMEDIATE-TO-HIGH GRADES)	Magnetite Quartzite *(Kraaipan and Messina Groups)*.		COPPER, LEAD, ZINC, Pyrite, Manganese, Barite, Magnetite Quartzite *(Bushmanland and Kheis Supergroups)*	
EPIGENETIC	HYDROTHERMAL	HYPOTHERMAL MESOTHERMAL AND EPITHERMAL		COPPER *(Messina Group)*. GOLD, Silver, Bismuth, Copper, Pyrite *(Transvaal Supergroup)*.		
EPIGENETIC	HYDROTHERMAL	TELETHERMAL		FLOURITE, Lead, Zinc, Vanadium *(Transvaal Supergroup)*	COPPER, Silver *(Dordabis and other formations)* COPPER *(Deweras Group, Lomagundi Supergroup)*. LEAD, VANADIUM, Zinc, Silver *(Damara Supergroup)*	Uranium *(Karroo Supergroup)*
EPIGENETIC	DEPOSITS RELATED TO WEATHERING AND TO CIRCULATING METEORIC WATERS		IRON *(Bulawayan and Figtree Groups)* Bauxite *(Archaean Granites)*	IRON, MANGANESE, Fluorite, Galena *(Transvaal Supergroup)*. Phosphates *(Waterberg Supergroup)*. Bauxite *(various formations)*.	Bauxite *(various formations)*	GYPSUM *(Dwyka Group)* PHOSPHATES *(Recent coastal sediments)* CALCRETE *(Recent)*
DEPOSITS RELATED TO METAMORPHISM			Kyanite *(Tati greenstones)* Corundum *(Various greenstone belts)*	Sillimanite *(Pongola Supergroup)* ANDALUSITE, Chrysotile *(Transvaal Supergroup)*.	Kyanite *(Umkondo Supergroup)* Sillmanite, Corundum, Wollastonite *(Bushmanland Supergroup)*.	

Ancient Placer Deposits

From an economic view-point, ancient placer deposits are the most important class of ore deposit in southern Africa. Pretorius (1973) has calculated that about 68% (by value) of the mineral production of the Republic of South Africa has been won from fossil placer deposits.

The oldest gold-pyrite deposits are in conglomerate-quartzite formations of the Archaean greenstone belts. These have been worked in a small way in the Transvaal (Uitkyk Formation) and in Rhodesia (Shamvaian Group). In the oldest of the cratonic basins (the Pongola), some auriferous conglomerates are known (de Villiers, 1959), while rudaceous sediments of the Dominion Reef Group carry uraninite with gold, pyrite, monazite, zircon, chromite, columbite and cassiterite (Liebenberg, 1955; Hiemstra, 1968a).

The Witwatersrand Supergroup, 7 600 m thick in its type area, is the host of the principal gold-uranium deposits in southern Africa. The Witwatersrand Basin (Figure 9) is an ovoid structural feature elongated in a NE-SW direction. Its known dimensions are approximately 290 by 130 km. The stratigraphic succession of the Supergroup is divided into a lower and an upper division. The former is a cyclically alternating assemblage (probably marine in origin) of quartzite, subgreywacke and shale, with some iron formation, tilloid, lava and conglomerate. It contains only relatively minor exploitable deposits of gold. The upper division (3 050 m thick) consists of a cyclical alternation of conglomerate and subgreywacke quartzite with one shale formation and one or two relatively thin volcanic units. This division is the host to most of the economic gold mineralization in the Witwatersrand.

Seven principal goldfields can be delineated within the Witwatersrand, all but one being situated along the northwesterly rim of the basin. Away from this margin, the succession as a whole becomes thinner, the proportion and average coarseness of conglomerates becomes lower and the average concentration of gold and uranium is low, only one significant and two subsidiary goldfields being known (Figure 9). The concentration of economic mineralization along the northwestern rim of the basin is considered to be due to the proximity to source-areas. All the palaeocurrent work done on the Witwatersrand confirms that the northwestern margin of the basin was the source-area of sediment.

Within the upper division of the Witwatersrand Supergroup, the gold, uranium, osmiridium and pyrite are found in three settings : (i) in the matrices of conglomerates, (ii) in carbon seams, and (iii) in erosion channels filled by banded pyritic quartzite. The latter are of relatively minor importance. In the first group, conglomerates which cover intraformational disconformities or unconformities are generally better mineralized than others, and, to some extent, carry gold derived by erosion of the immediately-underlying beds. The grade of mineralization along a stratiform conglomerate layer is never uniform, the gold and uranium being concentrated in linear or braided "pay streaks". The coincidence of the direction of elongation of the latter with palaeocurrent vectors has been demonstrated by numerous detailed studies throughout the Witwatersrand (Steyn, 1964; Armstrong, 1966; Knowles, 1967; Sims, 1969; Minter, 1973). A large volume of observational work on mines of the Witwatersrand, and on the ore mineralogy and chemistry of the conglomerates (Liebenberg, 1955; Koen, 1958, 1961; Ramdohr, 1958; Coetzee, 1965; Hiemstra, 1968a, b; Saager, 1970) has confirmed the fact that the gold, uranium, osmiridium and some of the pyrite, are detrital components of the conglomerates. Recently Köppel and Saager (1973) showed that the lead isotopic composition of detrital pyrite in the Witwatersrand is consistent with its having been derived from gold-sulphide vein-deposits in Archaean greenstone belts.

The gold and uranium in carbon seams are not as easily categorized, but are commonly regarded as being syngenetic deposits. Some workers hold that fine gold and uranium were mechanically trapped by the primitive life forms now seen as carbon seams, while others consider it possible that these elements were biochemically precipitated (Snyman, 1965).

Subsequent to the deposition of the Witwatersrand Supergroup, a number of major episodes of erosional bevelling of the Witwatersrand beds occurred. The first was at the onset of the outpouring of the Ventersdorp lavas (2 300 m.y.). The basal conglomerate of the Ventersdorp (known as the Ventersdorp Contact Reef) is economically exploited where it truncates underlying mineralized units. Similarly, the basal unit of the Transvaal Supergroup, known as the Black Reef Quartzite, is mineralized by gold, osmiridium, pyrite and uraninite where it unconformably overlies older mineralized reefs (Papenfus, 1964; De Waal and Herzberg, 1969). In one case, the mineralization (confined to conglomerates in braided stream palaeo-channels) was exploited downstream of the sub-outcropping Witwatersrand conglomerate bands (Papenfus, 1964).

Ancient placer deposits of Karroo age are known in Rhodesia and in South Africa. Diamonds and gold have been recovered from Karroo gravels in the Somabula Forest area (Figure 3) of Rhodesia (Macgregor, 1921). Ilmenite and monazite-bearing sandstones in the Karroo of South Africa have been described by Behr (1965), but have not been exploited to date. In the Springbok area of Namaqualand a variety of granites, gneisses, schists and granulites, together with metaquartzites are developed. These assemblages have been correlated with the Kheis rocks further to the east but could represent part of the Bushmanland succession which may be unrelated to the Kheis.

Intercalated within the gneisses is a well-defined marker of quartz-biotite-garnet rock, with subordinate sillimanite. The zone is also characterized by a widespread, yet sporadic, tungsten (wolframite) content (Benedict et al., 1964) which has been exploited successfully by the O'okiep Copper Company. No satisfactory explanation for the origin of this strictly stratigraphically confined tungsten mineralization has ever been offered. It is possible that the wolframite was originally deposited as a heavy mineral concentrate.

Recent Submarine, Coastal and Alluvial Placer Deposits

Included under this heading are the valuable mechanically concentrated diamond deposits of southern Africa, the offshore phosphate occurrences and the accumulations of ilmenite, rutile, zircon, monazite, xenotime, andalusite and tin found in beach sands and in interior alluvial tracts.

The diamond concentrations fall into two distinct categories; those found in present and fossil river gravels and terraces and those found in submarine and coastal gravels and beach deposits. The distribution of diamondiferous gravels in southern Africa is illustrated in Figure 3. Also shown are the known kimberlite pipes and fissures from which it is generally considered most of the alluvial diamonds were derived. Several major river systems have been responsible for the systematic erosion and dispersal of the diamonds from their primary kimberlitic host rocks. Notable among these distributaries are the Vaal, Harts, and Caledon rivers all of which drain into the Orange River which, in turn, makes its way westwards to the Atlantic coast. The Vaal and Harts rivers have, since Mid-Tertiary times, incised themselves below a smooth pediplain leaving depositional relics in the form of gravel terraces standing at various heights above, and distances from, the present river positions. Climatic changes during the Pleistocene are held responsible for the migration and incision of the rivers and for the deposition of the gravels and sands that yielded valuable concentrations of diamonds (Wagner, 1971; Söhnge et al., 1937; Partridge and Brink, 1967; Haughton, 1969). Diamondiferous gravels are also known to occur in the Molopo and Limpopo River valleys (Seta) but are not regarded as being of any great importance.

The most significant diamond production, apart from the mining of kimberlite pipes, is that of the coastal and submarine diamond-bearing areas along the west coast of southern Africa from the Olifants River in the south to Angola and beyond in the north (Figure 3). The main diamond fields are those of the Kaokoveld and Diamond Areas No 1 and 2 in South West Africa and the Namaqualand fields south of the Orange River. The usual mode of occurrence of the predominantly gem quality diamonds is in raised beaches or beach placers of Tertiary or Quaternary age (Wagner, 1971; Williams, 1930; Hallam, 1964; Keyser, 1972) but diamonds are also successfully recovered by offshore dredging of the unconsolidated submarine gravels along the west coast.

The development of the important series of raised beaches has been ascribed to the climatic changes during the Pleistocene. In South West Africa, at least four raised beach deposits formed by transgression and regression of the shore line. The diamonds occur in beaches 100-250 km long that are usually covered by variable thicknesses of wind-blown and/or marine sand and calcrete.

The gravels and their contained diamonds are generally considered to have been transported to the coast by the larger rivers (e.g. Orange River) and then redistributed by longshore currents associated with the dominant northward drifting Benguela current. This is manifest by the general diminution of diamond sizes northwards away from river mouths (Hallam, 1964).

Most diamond-bearing kimberlite pipes in southern Africa (excluding the Premier Mine pipe which is c.a. 1 750 m.y. old, Allsopp et al., 1967) are of Late Cretaceous age (c.a. 60 m.y.) and the sedimentary concentrations are generally Mid-Tertiary, Quaternary or Recent in age. Several interesting older, but economically insignificant, alluvial diamond occurrences are known in southern Africa. The Karroo placer gold and diamond occurrence of the Somabula Forest area in Rhodesia has already been mentioned while even older diamonds have been recovered from the

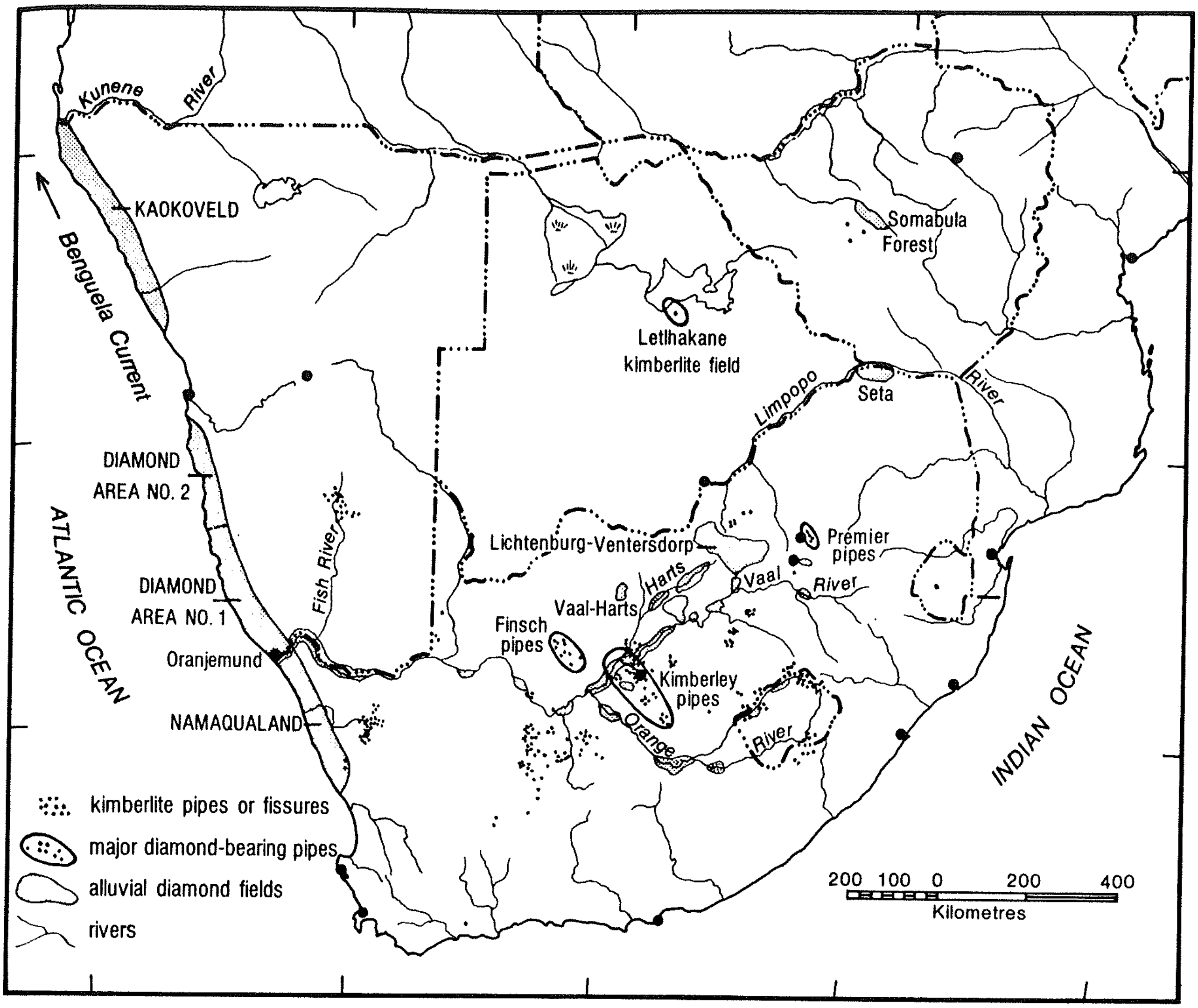


Figure 3 : Map showing the distribution of kimberlite pipes and alluvial diamond fields in southern Africa.

Witwatersrand gold-bearing conglomerates in the Klerksdorp area and from the Modder B Gold Mine on the East Rand (De Villiers, 1959).

Beach and dune sands along the east coast contain high concentrations of heavy minerals but only at Umgababa, 50 km south of Durban, has mining of ilmenite, rutile and zircon been undertaken (Langton and Jackson, 1961). Radioactive minerals including monazite and zircon, occur with these titanium-rich beach sands, the latter also being found together with xenotime in some river sands in the southwestern Cape. The east coast heavy minerals presumably derived largely from the granite-gneiss terrane of the Natal-Mozambique metamorphic belts (Figure 1) while the Cape granites and the Namaqualand gneisses probably provided the source for the west coast heavy mineral concentrations. Metamorphism of Transvaal succession shales by the Bushveld Igneous Complex and the subsequent erosion of these rocks has given rise to concentrates of andalusite-bearing sands in the Marico area of the western Transvaal (Van Rooyen, 1961). In Swaziland tin mining has been carried out with the entire production of cassiterite being recovered from recent alluvial and eluvial gravels derived from pegmatites and gneissic granites (Hunter, 1962).

Recent alluvial gold concentrations have been worked at Pilgrims Rest and in the Barberton greenstone belt (Anhaeusser, 1972; Viljoen et al., 1969) where the gold has been released from hydrothermal gold-quartz veins.

Finally, concentrations of offshore phosphatic sediments occur in the southwestern Cape. Phosphatic nodules occur embedded in sandy limestone and on the sea floor and appear to have been transported as clastic particles to their present locations (Visser and Schoch, 1973). A detrital origin for the phosphatic constituents of the sediments of the Agulhas Bank is also advocated by Summerhayes (1973). The phosphatic sediments (containing up to 10% P_2O_5) appear to be lag-type placer deposits concentrated in the vicinity of outcrops of their source rocks, outcropping Tertiary phosphorites.

ORGANIC ACCUMULATIONS

Coal and Oil Shale in the Karroo Supergroup

Organic accumulations of mixed plant debris derived from decaying trees, shrubs, reeds, creepers, ferns, water plants and mosses make up the bulk of the world's coal resources. Coal is thus the end-product of fossil vegetation deposited in shallow fresh water, such as large lakes, swamps, bogs and marshes fed by rivers. The coalfields of the northern and southern hemispheres differ markedly, both in the nature of the coal, the original vegetation from which it was derived, and the geological, geographical and climatic conditions under which it was developed. Northern hemisphere coals formed mainly during the Carboniferous period while the large scale formation of coal in the southern hemisphere did not occur until the Permian (Van Rensburg et al., 1969; Plumstead, 1957).

Coal formation began in the southern hemisphere over vast areas of "Gondwanaland" which, prior to continental breakup, consisted of large portions of Africa south of the equator, and parts of India, Australia, South America and Antarctica. In southern Africa coal occurs only in the Karroo Supergroup which ranges in age from Upper Carboniferous to the Late Triassic or Early Jurassic period. This thick (in places 7 500-9 000 m), extensive, group of rocks extends from near the southern tip of Africa to the equator.

In the Karroo Supergroup there are four major stratigraphic subdivisions, three of which are coal-bearing in places. The Dwyka Group at the base is largely a glacial unit and is generally devoid of coal. The Ecca Group of Lower Permian age contains the most important coalfields in Africa with the Middle Ecca beds often being referred to as the Coal Measures. Coal in this setting occurs almost entirely east of longitude 25° E and north of latitude 29° S (Figure 4), being mainly concentrated in the Transvaal, Natal and in the Wankie area of Rhodesia (Wybergh, 1928; Plumstead, 1957; De Villiers, 1959; Van Rensburg et al., 1969; Watson, 1960).

Above the Ecca is the Beaufort Group which, in northern Natal, Zululand and parts of the eastern Transvaal, has thin seams of semi-anthracitic coals with high ash contents. Beaufort coals also occur in the southern Transkei and in the eastern parts of Rhodesia but are not exploited. At the top of the Karroo sequence the Molteno beds of the Stormberg Group contain three coal seams (Turner, 1971) two of which have been mined near Indwe and Molteno around the southern margins of Lesotho (Figure 4).

In southern Africa coal is also developed in the Ecca formations of Swaziland (Hunter, 1962) and in Botswana (Boocock, 1965). Practically no coal is known to occur on the western half of southern Africa, the only exceptions being in parts of South West Africa where some boreholes in and adjacent to the Aminuis Reserve have yielded coal in rocks grouped in the Dwyka succession (Martin et al., 1963).

Coal is also known to occur in the Doros crater area approximately 50 km north of the post-Karroo Brandberg intrusion (Figure 2) and has been intersected in boreholes in the Toscanini Prospect area on the South West African coast (J.S. Smit, verbal communication, 1974).

The coal-bearing strata in southern Africa generally occur at depths of less than 200 m and much has been eroded away. The remaining coal-fields demonstrate little structural disturbance

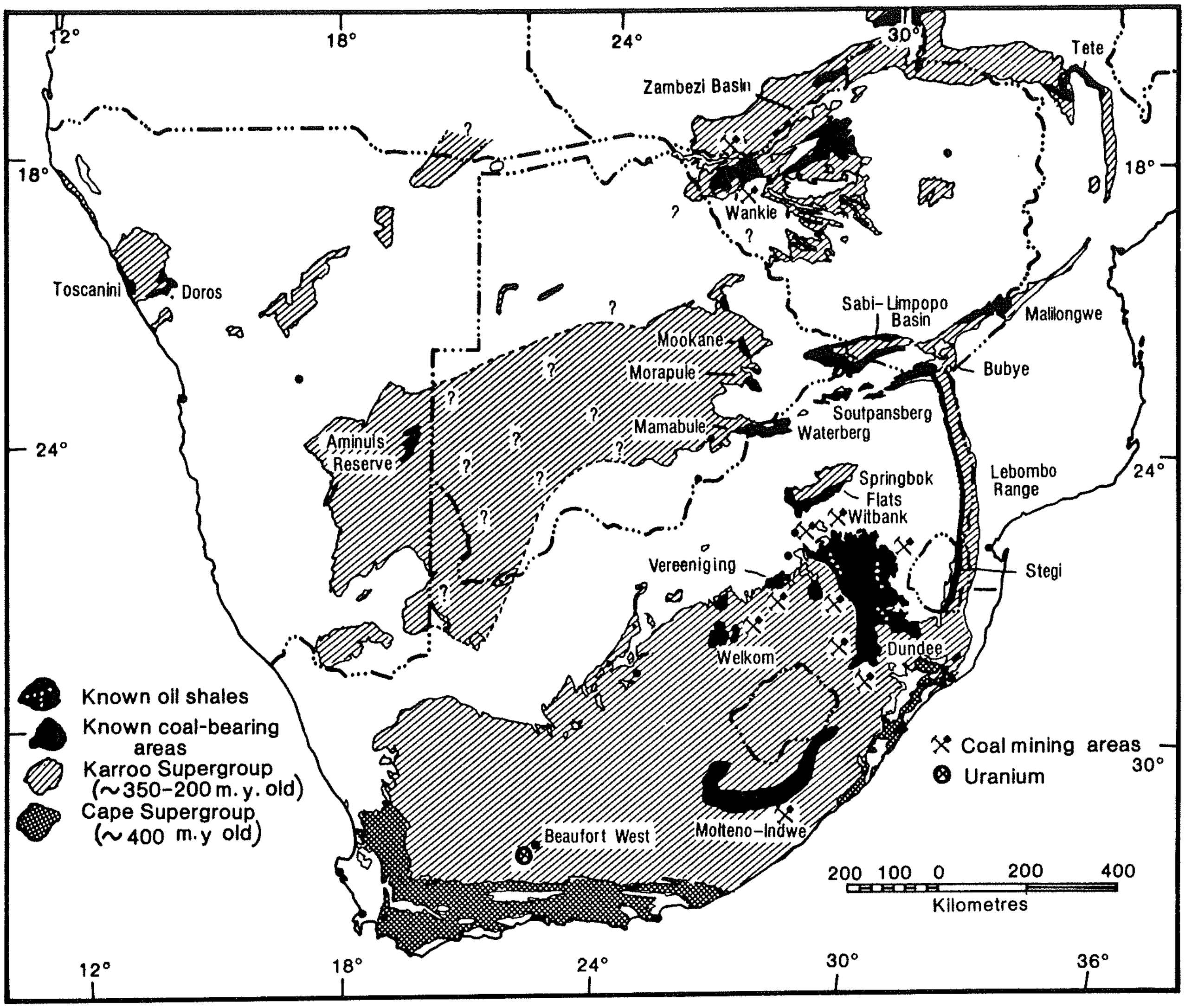


Figure 4 : Map showing the distribution of the Cape and Karroo Supergroups in southern Africa and the known occurrences of coal, oil shale and uranium mineralization.

since having been laid down with only some faulting and dolerite dyke and sill intrusions providing problems locally. The quality and thickness of the coals, and the number of seams is variable. By far the greatest proportion is bituminous steam coal, with a small percentage of coking and blending-coking coal and some anthracite in the Natal coal-fields. Reserves in existing mines and coal-fields so far prospected in South Africa alone have been estimated at 26 503 million short tons of coal of which about half this amount is considered extractable under present technological and economic conditions. Total reserves for South Africa are given as 48 577 million short tons of which 20 813 million tons are extractable (Van Rensburg et al., 1969).

The coal of the southern continents followed closely on a great ice age while in the northern hemisphere coals generally developed in a mild or tropical climate. The land plants forming the humic bituminous coals included the *Equisetales*, *Sphenophyllum*, *Lycopods*, *Pteridosperms* and *Gymnosperms*. The most important members of the southern flora were the *Glossopteridae*, a class of plants not represented at all in the northern hemisphere, but which formed the main component of the coals in India, Australia, Africa, South America, and Antarctica.

By contrast the composition of southern African sapropelic coals differs very little from those of the northern hemisphere. The torbanite and oil shale occurrences of the eastern Transvaal (Figure 4) fall into this class and were developed from algae comprising tiny water plants. The torbanites and oil shales, although frequently associated with coal may occur separately as unbanded, clean, fine-grained, compact seams. All are gas coals whilst the torbanites and oil shales yield oil on distillation. The South African torbanites are indistinguishable from the Scottish torbanites, the Kerosene Shales of New South Wales in Australia, or the oil shales of Kentucky in the United States (Plumstead, 1957).

Time, pressure and heat are the principal factors determining the quality or *rank* of coals. Generally all the bituminous coals of Natal, the Transvaal and Rhodesia are Permian (200-300 m.y.) in age. There are no large occurrences of Cretaceous (120 m.y.) brown coals as in many other countries although small Tertiary (c.a. 60 m.y.) lignite deposits are known in the southern Cape Province and on the Bluff at Durban. Minor occurrences of peat occur in Recent deposits where marshy or bog conditions prevail.

Petroleum

Despite minor indications of the existence of oil and gas on land and at sea around the coast of southern Africa no commencial exploitation has yet been attempted.

CHEMICAL PRECIPITATES

Ore bodies formed by chemical precipitation, with or without subsequent diagenetic modification, are an important source of metallic and industrial minerals in southern Africa. The principal limestone and dolomite deposits are classified here, as are ironstone, iron formation with no obvious volcanic affiliations and the asbestiform amphiboles, crocidolite and amosite. Where metamorphically modified, the altered products of chemical sedimentation are included in this group. Examples of the latter are the marbles encountered in various formations, and the metamorphosed manganese deposits of the Damara Supergroup in South West Africa.

Limestone, Dolomite and Marble

In the very ancient geological terrane of southern Africa, primary limestones are rare and, when found, constitute valuable ore deposits. Some of the oldest known primary limestones are those of the Archaean greenstone belts in Rhodesia, which are exploited for the cement industry. Carbonates are virtually absent from the ancient cratonic successions (Pongola, Dominion Reef, Witwatersrand). The Transvaal Supergroup saw the sudden and widespread precipitation of carbonates, most of which have been dolomitized. In places, generally just below the iron formation (Figures 6, 10), primary limestone is preserved in lenses up to 100 m thick (Toens, 1966; Button, 1974). Some of these primary limestones are exceptionally pure, quarries producing 98% $CaCO_3$ are known from Danielskuil region of the northwest Cape (Figure 9).

In younger units, limestones are more common. They are present in the Damara, Nama, Malmesbury, Cango and other formations of the southwestern and western Cape and South West Africa.

Marbles, derived by both regional and contact metamorphism of the formations listed above, are exploited in various parts of southern Africa. The deposits at Marble Hall were formed by contact metamorphism (related to the Bushveld Complex) of the Malmani Dolomite, while those at Marble Delta in Natal originated during the wide-spread Namaqua-Natal metamorphic event.

Ironstone

Ironstone, as distinct from iron formation, is a granular, often oölitic iron-rich sediment in which shallow-water sedimentary structures are abundant (James, 1966). Ironstones are typically Phanerozoic in age and occur in layers and lenses up to a few tens of metres thick which can be traced laterally for distances of up to 150 km.

Ironstones of the "minette" type are developed in the Pretoria Group of the Transvaal Supergroup (Figures 5, 6). These 2 200 m.y. old sediments are apparently the oldest ironstones

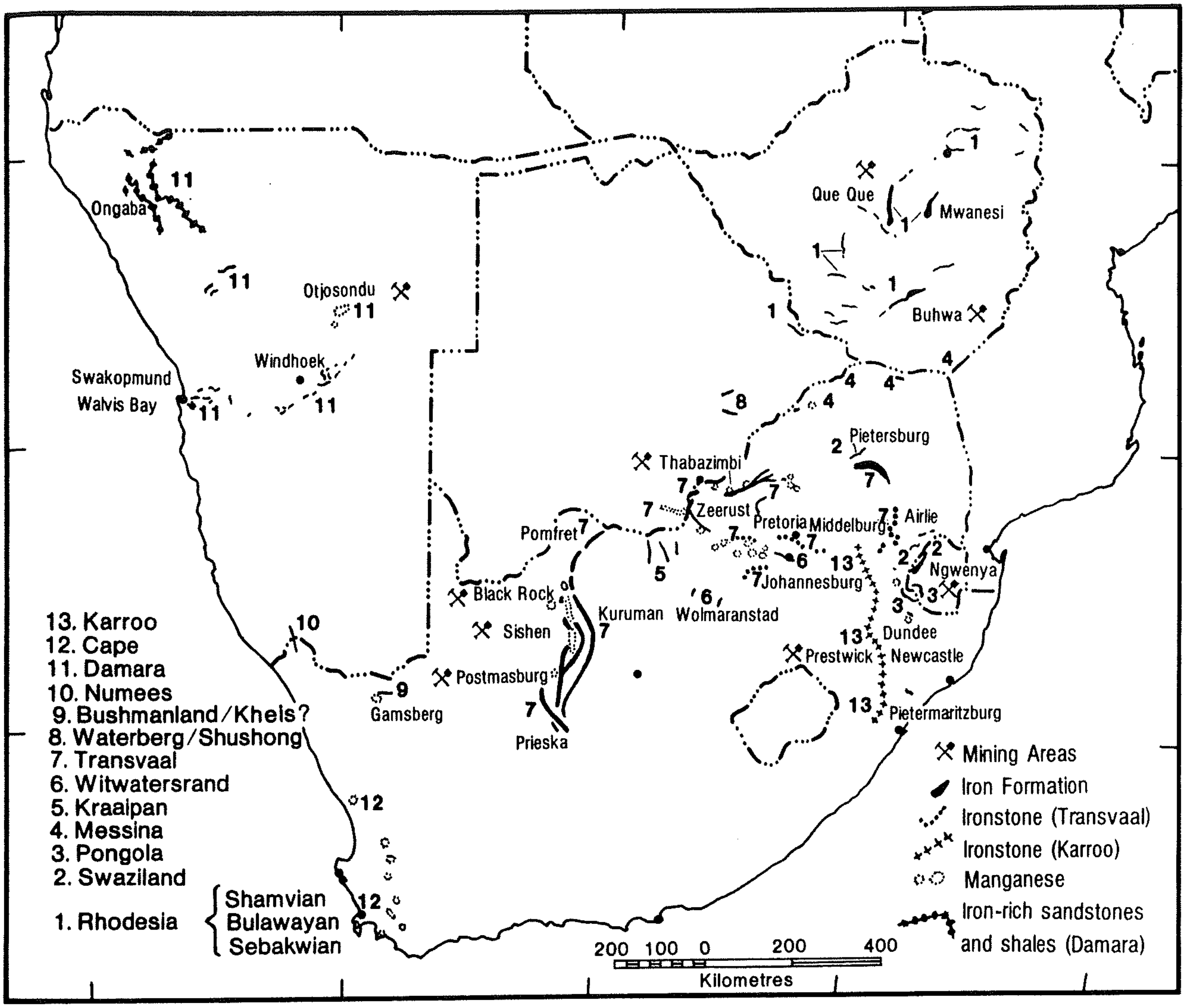


Figure 5 : The distribution of iron and manganese in southern Africa. Numerals refer to the formations in which iron and manganese are developed.

presently known. They occur as lenses, up to 8 m thick, interbedded in Pretoria Group shales. The ironstones are structured by chevron cross-bedding, ripple-marks, and, rarely, mud-cracks. Mineralogically, they are composed of quartz (generally in oölite cores) with chamosite, prochlorite, ankerite, kaolinite, magnetite, hematite, lepidocrocite and goethite (Wagner, 1928; Schweigart, 1965). Although Schweigart called upon volcanic exhalations to supply iron, no volcanic material is known to be associated with the ironstones. Button (1974) has documented an antipathetic relationship between quartzite and ironstone in the Pretoria Group, the latter only being developed near the feather-edges of major quartzite bodies (Figure 6). A purely sedimentary control for the development of ironstone seems certain as there is a clear parallelism of sedimentary facies belts with zones of ironstone

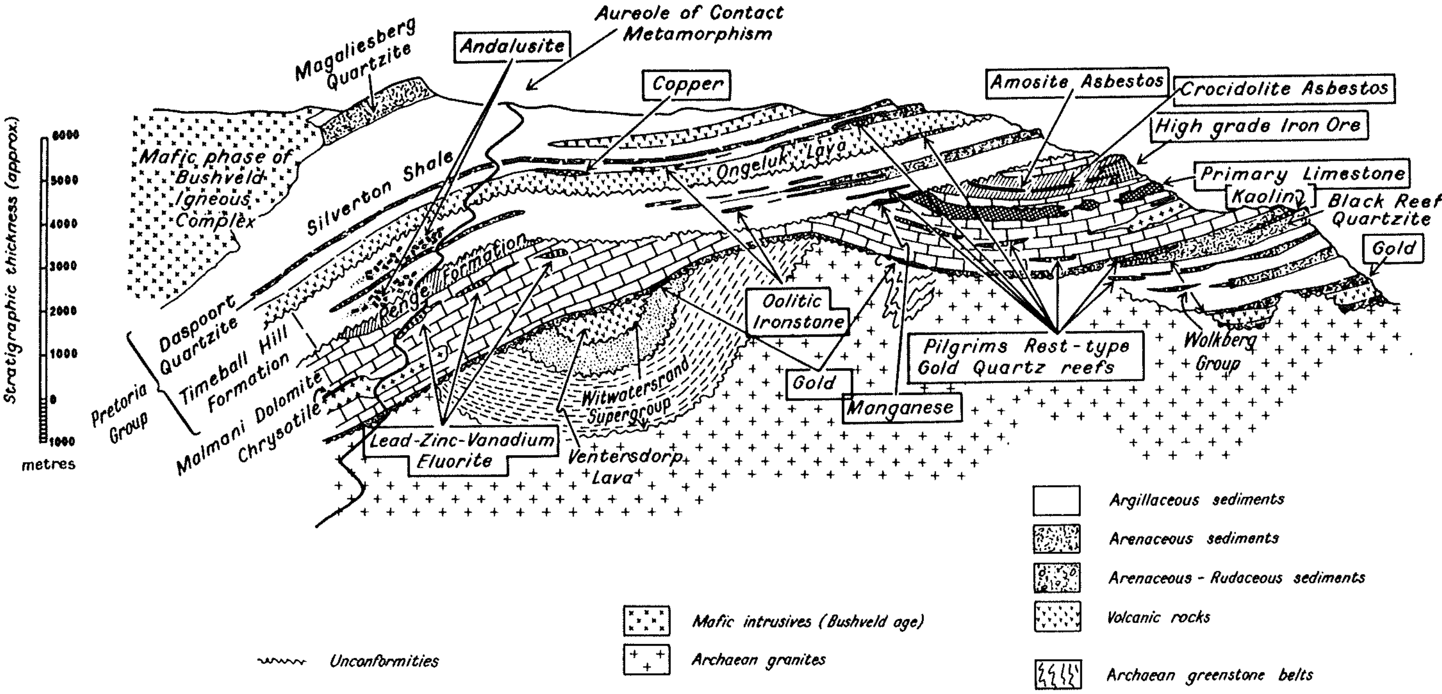


Figure 6 : Schematic diagram showing the stratigraphic setting of mineral deposits in the Transvaal Basin in the vicinity of the Bushveld Igneous Complex.

deposition. The relationships in the Pretoria Group led Button (1974) to propose that the ironstone depositional belt coincided with the interface of a zone of oxygenated, relatively shallow water and deeper, anoxygenous water. The iron, held in solution in the latter waters, was precipitated by oxygenation along the interface.

Reserves of iron ore in the Pretoria Group have been calculated at 6 x 10^9 tons at 45% Fe (Wagner, 1928). The ironstones have been worked in a small way around Pretoria but are not exploited anywhere at present, since large tonnages of higher grade material are still available elsewhere.

Lenses of "black band" ironstone occur at various stratigraphic levels in the Middle Ecca (coal measures) of Natal and the eastern Transvaal (Figure 5). They occur in lenticular beds up to a few metres in thickness. Mineralogically, the black band ores consist of granular siderite with chamosite, some ferroan dolomite and quartz (Wagner, 1928). These Permian deposits, like other black band ores the world over, are interstratified with sandstones and coal beds. The ores have been worked on a small scale in Natal. Reserves of iron ore are modest, probably not exceeding 10^6 tons (Wagner, 1928). No large-scale exploitation of these ores is likely in the near future.

Iron Formation

Although many of the iron formations in the Archaean greenstone belts of southern Africa are intimately associated with volcanic rocks, those in the cratonic basins have a very tenuous connection with volcanism. These iron formations, for want of conclusive evidence to the contrary, are grouped with the chemical precipitates.

Iron formation is developed in the Pongola, Witwatersrand, Transvaal, Shushong, and Damara successions (Beukes, 1973). Those in the Pongola, Witwatersrand, and Shushong are found interbedded with ferruginous shales and fine-grained ferruginous arenites. Economically, these are of little importance at present and will not be discussed further.

The iron formation of the Transvaal Supergroup is a very persistent unit, being developed throughout much of the Transvaal basin, over a distance of about 1 000 km (Figures 5, 9). It was probably more extensively deposited, but in places it has been removed during periods of intra-formational erosion (Figures 6, 10). Over this great basin, the iron formation consistently overlies and grades down to the thick carbonate succession (up to 2 000 m) of the Transvaal Supergroup.

In the essentially unmetamorphosed occurrences of the northern Cape, the iron formation consists of mixed or mono-mineralic layers of quartz, magnetite, stilpnomelane, riebeckite, minnesotaite and carbonates (Beukes, 1973). In the more metamorphosed equivalents of the iron formation in the Transvaal, the grain-size is coarser, stilpnomelane is altered to biotite, and minnesotaite has been metamorphosed to grunerite. Axiolotic shards have been described from the stilpnomelane bands of the northern Cape (La Berge, 1966). This finding represents the only substantial evidence of the contribution of volcanic processes to the iron formation of the Transvaal Supergroup. Another lithology represented in the iron formation, especially in the Transvaal, is carbonaceous (often pyritic) shale and mudstone.

Both deep-weathering and volcanic exhalations have been called upon by various authors to supply the iron and silica of the iron formation. The former is considered to be the more likely taking into account the stratigraphic setting of the iron formation. It has been shown that the iron formation is merely the culmination of a series of cycles of iron-enrichment in the underlying carbonates (Button, 1974). Early cycles involve iron-rich dolomite, later cycles include iron-rich carbonates with iron formation, the final cycle involving the iron formation itself. The iron and silica are believed to have been concentrated evaporatively in barred basins, separated from the open ocean by wave-built bands of carbonate detritus. Cycles are produced by transgressive and regressive shifts of the barrier.

In the northern Cape Province, a second iron formation (the Voëlwater Formation) is encountered higher up in the Transvaal Supergroup, overlying the Ongeluk Lava (Figure 10). Here iron formation with jasper, limestone, chert and (in places) manganese ore, overlie volcanic rocks (Beukes, 1973). Because of this stratigraphic relationship it is conceivable that volcanic exhalative processes contributed to the development of this iron formation.

The youngest of the iron formations in southern Africa is that of the Damara Supergroup, in South West Africa (Figure 5). According to Beukes (1973), the northern occurrences of iron (those in the Kaokoveld region) comprise iron-rich shales and sandstones, and not true iron formation. Those in the Windhoek and Otjosondu regions have been described as itabirites, and consist of layers of quartz, magnetite,and hematite, often with a schistose habit (Beukes, 1973; Roper, 1959). The iron-rich units are interbedded in an assemblage of amphibole schist, quartzite, and quartz-muscovite schist overlying a thick succession of carbonates, and underlying a widespread tillite formation.

Metamorphosed iron formation is found in the Limpopo mobile belt. Some of the iron formation is associated with greenstone belt relics and is considered to be volcanogenic in origin. Elsewhere, "banded magnetite quartzites" are interstratified with orthoquartzites and carbonates, in a succession similar to those in the cratonic basins described earlier. The banded rocks consist of quartz and magnetite layers with partings of actinolite, cummingtonite,and grunerite. They are low in alumina and probably represent highly metamorphosed iron formation (Beukes, 1973).

At present, few if any of the primary iron formations constitute workable ore bodies. However, surficial enrichment of iron formation protore accounts for a significant proportion of the iron ore presently mined in southern Africa. These ores are difficult to classify, some of the iron being syngenetic, some being epigenetic. In this paper, the enriched counterparts of both chemical and volcanogenic iron formation are discussed along with epigenetic ore deposits.

Manganese

Unlike the chemically deposited iron formations occurring in almost all the major stratigraphic units of southern Africa older than about 1 800 m.y., there are few known localities where economic quantities of manganese were deposited chemically.

One such example appears to exist in the Damara Supergroup in South West Africa. At Otjosondu (Figure 5) manganese ores have been mined that are intimately associated with itabirites. In arriving at the conclusion that the manganese was syngenetic, Roper (1959) maintained that the manganese ore bodies occupy a definite stratigraphic horizon and were deposited from manganese bicarbonate solutions following initial concentration of manganese from rocks subjected to weathering. The exposed Damaran rocks in the area include metamorphosed argillaceous, arenaceous, calcareous, manganiferous, and ferruginous rock types. Within the itabiritic schist zone, three manganese-rich units are developed. The ores, which have been affected by intermediate-to-high metamorphic grades, consist mainly of the minerals braunite, jacobsite, and vredenburgite, with subordinate rhodonite, hausmannite, bixbyite, hollandite, chalcophanite, and hematite. Secondary pyrolusite and psilomelane are also encountered in the ore bodies.

The Otjosondu deposits do not readily fall into any of the manganese associations outlined by Stanton (1972). However, since the deposits occur in the Damara geosyncline and are associated with marine dolomitic rocks they appear most similar to the "geosynclinal type" manganiferous limestone-dolomite association.

In the Transvaal Supergroup of the northern Cape, manganiferous-calcareous sediments are found interbedded in the iron formation immediately above the Ongeluk Lava (Figure 10). The manganiferous sediments, in three layers each up to about 25 m thick, contain about 27% Mn (De Villiers, 1971). This primary sediment is not mined at present, but its surface enriched counterparts are extensively exploited in the Kalahari manganese field (Figure 9) and will be more fully described in a subsequent section. The manganese-rich protore is thought by De Villiers to represent a chemical sediment, but a volcanogenic origin cannot be ruled out.

The Asbestiform Amphiboles

The iron formation of the Transvaal Supergroup is the world's major producer of asbestiform amphiboles. Most of the production is of crocidolite (blue) asbestos, the fibrous form of the soda amphibole riebeckite. Smaller amounts of amosite (the fibrous polymorph of grunerite according to Vermaas, 1952) are produced from a localized portion of the Transvaal basin, around Penge in the northeastern Transvaal (Figure 9). In the transitional area between the crocidolite- and amosite-producing regions, alternate layers of the two asbestos varieties are often found juxtaposed. In this region, some seams of asbestos consist of alternating fibres of riebeckite and amosite, and give rise to the "lavender blue" asbestos (Cilliers, 1964), which is mined locally.

The crocidolite is preferentially developed in a number of specific stratigraphic units within the iron formation (Figure 10). According to Hanekom (1966), crocidolite-rich units are also richer in layers of stilpnomelane. It is accepted by all investigators that the crocidolite is derived from a syngenetic precursor material, usually referred to as proto-riebeckite. Hanekom (1966) was of the opinion that this precursor might represent a volcanic ash. The balance of evidence would, however, favour an attapulgite-like clay as the forerunner of riebeckite (Cilliers and Genis, 1964). The soda is thought to have been incorporated into the clay molecule by base exchange prior to or immediately after deposition. The presence of riebeckite in the iron formation of the Transvaal Supergroup, and its relative scarcity in other iron formations around the world, is taken by Cilliers and Genis as a measure of the salinity of the waters in the Transvaal depository. The change from the precursor phase to riebeckite is seen as a process involving dehydration and some ionic reorganization. Such changes occurred at low (diagenetic) temperatures.

A puzzling question regarding crocidolite development is the mechanism of fibre orientation, since some layers consist of disoriented riebeckite needles (known locally as *mass fibre*), while others consist of perfectly oriented crystals (crocidolite). According to Cilliers and Genis (1964), a layer of magnetite, adjacent to or within a proto-riebeckite band, was essential to fibre formation. The magnetite, in providing a constant number of growth points per unit area, supplied the necessary orientating effect. Thus those layers of proto-riebeckite which were not in contact with a magnetite lamina merely crystallized as *mass fibre* riebeckite.

The control by deformational processes on crocidolite development is a controversial subject. In the northern Cape, an early, fairly open phase and a later, more intense phase of deformation have been recognized. Some investigators (Cilliers and Genis, 1964) contend that only the early phase of folding affected fibre development, while others (Hanekom, 1966; Fockema, 1967) are of the opinion that both phases of deformation are important. The evidence presented by Hanekom points conclusively to the latter view, at least in portions of the northern Cape asbestos field. It would appear that the proto-amphibole "flowed" towards the axes of folds, there to crystallize into crocidolite. Exploitable deposits of crocidolite are thus frequently stacked one above the other in the axial zones of folds, in a style reminiscent of "saddle reefs". The structural control on the economic development of fibre has been used in exploration, where detailed structural studies have resulted in the discovery of non-exposed ore bodies.

The amosite (grunerite) asbestos of the Penge area in the northeastern Transvaal is also thought to have been derived from an attapulgite-like clay, with ferrous cations instead of soda (Genis, 1964). According to Cilliers (1964), the lateral change from crocidolite- to amosite-depositing sectors of the basin is a result of a regional salinity gradient in the ancient depositional basin. A different interpretation can be made on the basis of the gross stratigraphic relationships of the iron formation in the Penge region. The amosite-bearing facets of the iron formation are restricted to those regions where the host rocks lie immediately beneath the pre-Pretoria Group unconformity (Figure 6). It is reasoned that circulating groundwaters operative during the pre-Pretoria erosion cycle leached the proto-riebeckite of its soda, the leached material subsequently crystallizing to amosite.

VOLCANOGENIC ORE DEPOSITS

Mineral deposits falling within this category include those which, by virtue of their association with volcanic rock types, appear to be linked genetically to the diverse processes embraced under the general heading of volcanism. In Table II it can be seen that deposits falling into this broad category require further qualification to include essentially unmodified deposits and those modified by either low-to-intermediate or intermediate-to-high grades of metamorphism.

Volcanogenic Deposits in Greenstone Belts

(a) Iron Formation

In the early Precambrian greenstone belts of Rhodesia and South Africa iron formations are almost invariably conspicuously associated with volcanic rocks. The iron formations are developed at various stratigraphic positions from the base to the top of the greenstone piles but are more commonly located in the lower, essentially volcanic environment as opposed to the terminal sedimentary parts of the stratigraphy (Beukes, 1973). Little detail of the mineralogy of the iron formations exists at present but it would appear that the order of abundance of iron compounds can be patterned on the findings of James (1966) and Stanton (1972) who reviewed the chemistry of iron formations of Early Precambrian age throughout the world. The iron oxides are most abundant followed by carbonates, silicates,and sulphides.

Almost without exception all the greenstone belts on the Rhodesian and Kaapvaal cratons (Figures 1, 5) have iron formations that may be grouped into one or more of the four abovementioned categories. By far the most important are the finely laminated, alternating, iron and silica-rich beds referred to locally as jaspilites or "banded ironstones". The general tenor of iron in these jaspilites varies from 30 to 40% Fe although in the Mwanesi Range in Rhodesia up to 50% Fe has been recorded (Worst, 1962b). Processes of enrichment of the protore give rise locally to deposits with 60-65% Fe, examples of which will be discussed later.

The banded iron formations occur in two environments. In the volcanic environment they are associated with mafic and felsic volcanics and are often members of a three-part cycle consisting of mafic lava, felsic lava, and chert or iron formation. Examples of this type are found commonly in the Sebakwian and Bulawayan Groups in Rhodesia (Bliss and Stidolph, 1969) and within the Onverwacht assemblages of the Pietersburg, Murchison,and Barberton greenstone belts. Iron formations also occur in an essentially sedimentary environment where they are associated with quartzites, phyllites, limestones, shales, greywackes, and minor lava flows. The role of volcanism and iron deposition in such settings is not easy to assess and inferences have to be drawn largely from associated rock types. A close and probable genetic relationship to volcanism, seems reasonable for some of the iron formations in the Shamvaian Group in Rhodesia and in the Barberton Mountain Land in South Africa. In the latter case, banded jaspilitic iron formations occur stratigraphically above amygdaloidal basalts in the Moodies Group (Anhaeusser, 1971) while in the underlying Fig Tree Group iron formations occur in a predominantly sedimentary assemblage but which includes lava and pyroclastic members with soda trachytic affinities (Visser et al., 1956).

Subordinate carbonate, silicate and sulphide facies iron formations also occur in the greenstone belts. In the Shamvaian Group north of Salisbury in Rhodesia the Iron Duke Mine constitutes one of the few sulphide facies stratiform ore occurrences to have been mined essentially for its massive pyrite (Ferguson and Wilson, 1937).

(b) Magnetite Quartzites

Iron formations, the origin of which appear to be linked directly to those of the Archaean greenstone belts, have in places been subjected to intermediate-to-high grades of metamorphism, and have undergone recrystallization to magnetite quartzites. These changes have occurred mainly in areas influenced by the dynamic and metamorphic effects of the mobile belts, the latter now superimposed upon, and encircling, the cratonic areas of the sub-continent. Many of the magnetite quartzite occurrences along the southern and southeastern margins of the Rhodesian craton (Worst, 1962a), including some of those included with the Messina Group in the Limpopo mobile belt (Söhnge et al., 1948), and with the Kraaipan Group in the western Transvaal, fall into this category (Figure 5).

(c) Barite

Several occurrences of stratiform barite are known to occur in southern African greenstone belts. In the Barberton Mountain Land the barite occurs both in the Onverwacht and overlying Fig Tree Group. Investigations by Viljoen and Viljoen (1969) and Reimer and Heinrich (1974) suggest that in both these settings the barite is of volcanogenic origin and probably formed from volcanic exhalations associated with explosive volcanicity as witnessed by numerous tuffs and tuffites found in the surrounding strata. Previous hydrothermal postulates appear untenable as it can be demonstrated that the Onverwacht barite has a marked stratigraphic control, being confined to the terminal phases of volcanic cycles in which mafic lavas, followed by felsic lavas or pyroclasts, are overlain by persistent cherty horizons containing both massive and banded barite.

(d) Copper-Lead-Zinc

No important copper-lead-zinc deposits, comparable to those of the Precambrian Superior Province of Canada ("Noranda-type"), have yet been found in southern African greenstone belts. These ores, which occur in the basalt-andesite-dacite-rhyolite sequences, show distinct preferences for the more siliceous, pyroclastic members (Goodwin, 1961; Wilson, 1967; Hutchinson, 1973).

Ores containing copper and zinc and which appear to be geologically similar to the Canadian examples occur in the Murchison Range of the northeastern Transvaal. The deposits, with the ore minerals pyrite, marcasite, chalcopyrite, cubanite, sphalerite, pyrrhotite, digenite, covellite, and galena (Hausmann, 1959), occur in quartz-mica and quartz-chlorite schists (low-to-intermediate metamorphic grades) considered by the writers to be the equivalent of felsic volcanic rocks.

(e) Antimony and Cinnabar

Also in the Murchison Range are stratiform deposits of stibnite and cinnabar of the Consolidated Murchison group of mines, one of the largest producers of antimony in the world. Earlier views that the ore bodies were of hydrothermal origin (Mendelssohn, 1938; Sahli, 1961) are now being challenged in favour of a volcanogenic origin. The mineralization consists mainly of the sulphides stibnite, berthierite, tetrahedrite, and chalcostibite and includes the antimony oxides stibiconite and kermesite. Gold, pyrite, arsenopyrite, and cinnabar occur locally, the mercury having been mined in the past while gold is still recovered as a by-product of the antimony mining. The ore bodies usually occur in lenses strung out along approximately 50 km of the so-called "Antimony Line" (Van Eeden et al., 1939) where the host rocks are now considered to comprise mostly sheared and carbonated (dolomitized) intermediate to felsic volcanic rocks of greenschist metamorphic grade. In Rhodesia (e.g. the NA antimony mine), and in the Barberton greenstone belt (e.g. Amo) numerous small-scale antimony occurrences similar to the Murchison deposits are known but are not extensively exploited.

(f) Gold-Pyrite-Arsenopyrite-Scheelite

Although most of the gold deposits occurring in Archaean greenstone belts are clearly related to hydrothermal processes there is growing evidence to suggest that some of the gold-pyrite-arsenopyrite mineralization may also be stratiform in character. Examples of this type are known in the Barberton greenstone belt (personal observations) and in many gold occurrences in Rhodesia, including more specifically the Vubachikwe Mine in the Gwanda greenstone belt (R.E.P. Fripp, personal communication, 1973). A possible genetic relationship linking these occurrences to volcanism is apparent. In many deposits, both in Rhodesia and in the Barberton area, the gold mineralization appears to be genetically linked with banded jaspilites or iron formations. This is particularly evident in many of the Rhodesian examples, like those of the Sebakwe group of mines near Que Que (Harrison, 1970). Here mines such as the Sherwood Star, J.B.B, and Broomstock, to name but a few, occur in jaspilitic iron formations terminating volcanic cycles of mafic-to-felsic lava and acid tuffs and pyroclasts.

Stratiform tungsten deposits, often containing gold, arsenopyrite, and stibnite, in addition to the scheelite, have been reported in Rhodesia by Cunningham et al., (1973). These deposits occur with submarine volcanic rocks now metamorphosed in the greenschist facies.

Volcanogenic Deposits in the Northwest Cape Province

The northwestern Cape Province of South Africa has recently received considerable attention from mineral exploration companies following the discovery in the area of a number of base metal deposits. In 1969 a major copper-zinc deposit was located 50 km southwest of Prieska and was followed by other significant lead-zinc-copper finds between this occurrence and the Springbok-O'okiep copper mining area near the west coast. Mineral deposits are known to occur at Aggeneys and Gams, near Pofadder, and at Rozynenbosch near Kakamas (Figure 7). Encouraging signs of additional mineralization are apparent in the region which appears to represent a metallogenic province of considerable economic potential.

Very little is currently known of the geology and mineral deposits of the northwest Cape. Much of the area remains geologically unsurveyed although many of the exploration companies have carried out detailed and reconnaissance mapping programmes in selected areas. Unfortunately, most of this information is still of a confidential nature and, in view of the competitive mineral exploration being carried out in the region, few details of many of the mineral finds have been released.

The main area of interest is an extensive tract of country referred to by Viljoen (1973) as the Bushmanland Metamorphic Complex, the latter forming the western part of the c.a. 1 000 m.y. old Namaqualand-Natal metamorphic mobile belt. This gneissic metamorphic terrain is terminated to the east of Upington by a major NNW-SSE zone of dislocation (the Brakbos fault zone) which separates the metamorphites from the older Kaapvaal craton (Figure 7).

The Bushmanland metamorphites have been linked with the Kheis assemblages but the correlations are speculative at this stage. The c.a. 1 000 m.y. old metamorphic overprint appears to have obliterated all older ages and the position of both the Kheis and Bushmanland successions in Table I remains inconclusive.

In the following sections an attempt is made to briefly piece together what is known of the geology and mineralization of this new base metal province.

(a) The Prieska Copper-Zinc Deposits

The massive sulphide ore bodies near the new town of Copperton, 50 km southwest of Prieska (Figure 7), occur in a volcanic pile which is preserved as an infold in rocks considered by Middleton (1973) to form part of the Kheis succession. Surface exposures in the mine area are virtually non-existent but borehole information shows that the Copperton volcanics are composed of a series of flows and pyroclastics with a calc-alkali basalt-andesite-dacite-rhyolite trend. These volcanic rocks, according to Middleton, are disposed around an oval, dome-like, feature which may represent a resurgent cauldron core. The rocks in the mine area have been subjected to high-grade metamorphism with diagnostic minerals allowing the regions flanking the ore zone to be classified

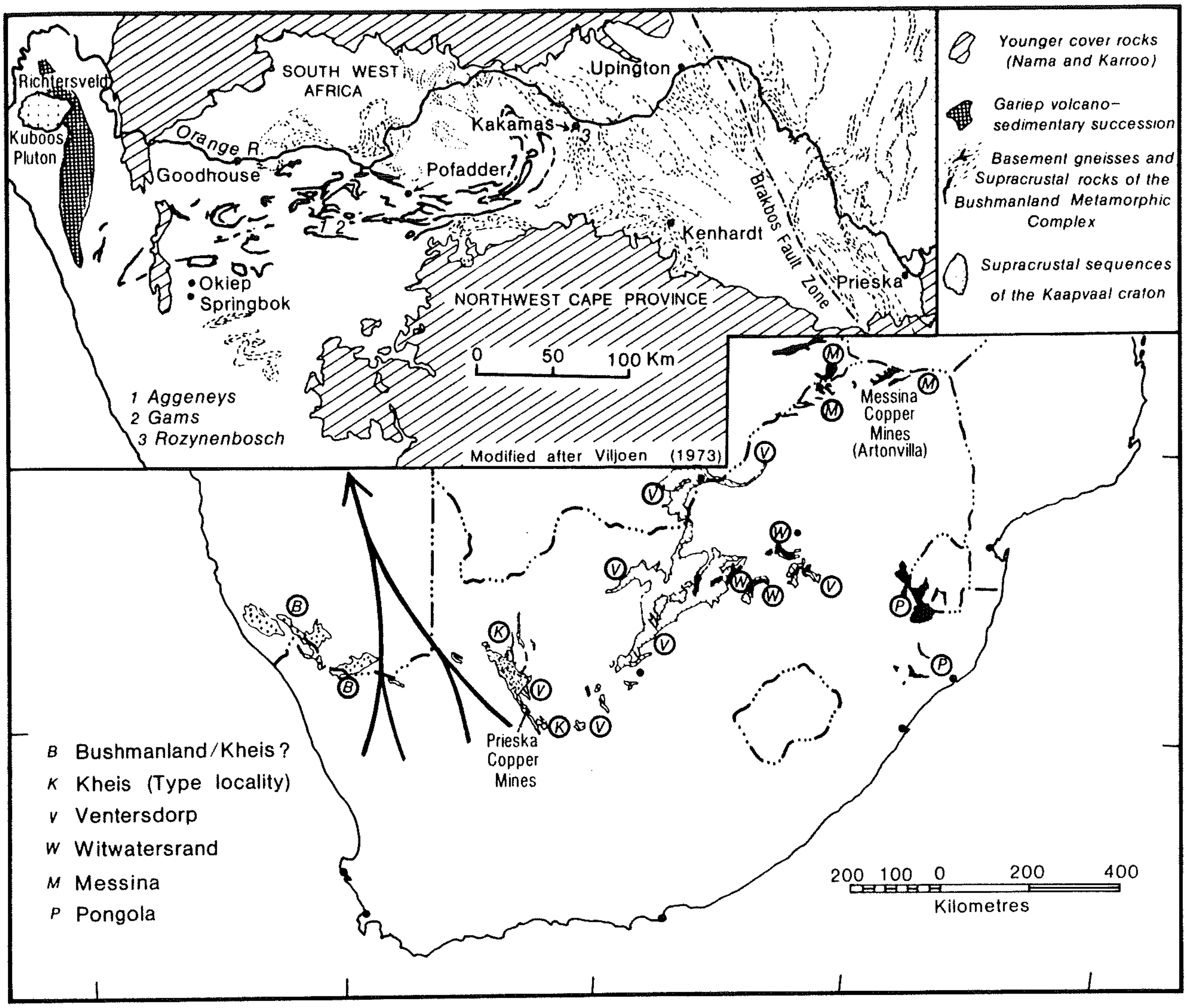


Figure 7 : Map showing the distribution of Archaean and Early Proterozoic volcano-sedimentary basins (excluding the Transvaal Basin). Inset map shows details of the northwest Cape Province.

into the sillimanite-cordierite-muscovite-almandine sub-facies, or the sillimanite-cordierite-orthoclase-almandine sub-facies, of the cordierite amphibolite facies (Anhaeusser and Lenthall, 1970). These assemblages fall into the Abukuma facies series of Winkler (1967) and represent the highest grade of regional metamorphism that is ever realized under low-pressure conditions. Low-pressure conditions in the Prieska ore body appear to be borne out by the findings of Middleton (1973) who commented on the remarkable preservation of both macro- and microscopic volcanic textures found in the rocks.

The main Prieska ore body occurs as a concordant tabular mass with a proved tonnage of 47 million tons of ore averaging 1,7% copper and 3,8% zinc (Middleton, 1973). A smaller massive sulphide deposit occurs 5 km south of the main ore body, on the flank of the dome mentioned previously. The main ore minerals encountered in the Prieska deposits include chalcopyrite, sphalerite, pyrite, and pyrrhotite (Anhaeusser and Lenthall, 1970). A wedge-shaped zone of alteration envelopes the ore body but its origin is not fully understood. According to Middleton (1973) the ore body has a syngenetic pyroclastic origin, the ore and gangue being derived from an earlier plug that was ejected and redeposited on the flank of the volcanic vent. Subsequent shearing and flattening has disturbed the original shape of the deposit in places but no large-scale migration of the mineralization is evident.

The Prieska ore bodies appear to represent one class of ore deposit found in the north-west Cape and may be linked genetically to the zone of dislocation between the Kaapvaal craton and the metamorphic terrane to the west.

(b) The Bushmanland Metallogenic Province

Centred about the town of Pofadder and situated mainly in the area south of the Orange River is a succession of strongly deformed, predominantly east-west striking, metamorphic rock types that act as host to the important lead-zinc-copper-silver finds at Aggeneys, Gams and Rozynenbosch (Figure 7). Although these deposits constitute discoveries made during the last three years, mineralization of a different type had long been known to exist in the region. Deposits of sillimanite, barite, manganiferous iron ore and hematite are present, but because of the remoteness of these deposits only the sillimanite has been exploited (Coetzee, 1958).

The principal rock types encountered in the region include a variety of quartzo-felspathic gneisses, amphibolites, calc-silicate rocks and metaquartzites. Although few details are known of the mineralization of the various deposits it would appear that lead and zinc (galena and sphalerite) are the most important constituents of the ore together with subordinate amounts of copper (chalcopyrite). Information released in the 1973 annual report of the holding company (Phelps Dodge of Africa, Limited) shows that two ore discoveries have been proved thus far at Aggeneys. At the Black Mountain ore body, 139 diamond drill holes have indicated that 30 million metric tons of ore can be mined by open pit methods (ore grade : 0,6% Cu; 2,3% Pb; 0,8 ozs Ag per ton). An additional 48 million metric tons has been proved that can be mined by underground methods (ore grade : 0,8% Cu; 2,9% Pb; 0,6% Zn; 0,8 ozs Ag per ton). The second ore body (Broken Hill) is located approximately 6 km from the Black Mountain deposit. 84 diamond drill holes indicate that 38 million metric tons of ore can be mined by open pit methods (ore grade : 0,4% Cu; 4,5% Pb; 2,3% Zn; 1,7 ozs Ag per ton), while another 25 million metric tons have been proved for underground mining (ore grade : 0,36% Cu; 3,0% Pb; 2,2% Zn; 1,0 ozs Ag per ton).

The relationship of the mineralization to the host rocks has never been made known but reports from reliable sources appear to leave little doubt that the mineralization is stratiform in character. Some geological detail is available for the areas around both Aggeneys and Gams (Coetzee, 1958; Joubert, 1971) but these investigations preceded the base metal discoveries in these areas. According to Joubert (1971) the succession, which he and Coetzee (1958) correlated with the Kheis Supergroup, consists of a variety of gneisses, including paragneisses and bands of calc-silicate rocks, plagioclase amphibolites, boulder conglomerates, aluminous schists, and quartz-mica schists together with thin bands of quartzite. These are overlain by black, usually finely-banded magnetite quartzites, which are present as thin layers below the metaquartzites in many parts of the area. The former metasediments are associated with barite at a number of localities including Aggeneys and Gams. Above the banded magnetite quartzites are brown ferruginous metaquartzites, white metaquartzites and, in the north, some mafic rocks. Although most indications are that the successions largely comprise metasediments, Joubert (1971) is of the opinion that some of the basal gneisses and plagioclase amphibolites may represent altered acid and mafic volcanic rocks respectively.

The stratiform sillimanite occurrences at Gams are located in the aluminous schist zone while the manganiferous iron ore, hematite and barite deposits are developed at and near the contact of the quartz-mica schist and the overlying metaquartzites (Coetzee, 1958). The base metal deposits are also believed to occupy this zone. Reports indicate that the gossan associated with the mineralization has been traced over a strike length of about 4 500 m. Drilling done over a portion of this length has yielded significant intersections, 10 to 30 m wide, of sulphides assaying 6-10% zinc and less than 0,5% lead (E/MJ, 1973). The zinc mineral, believed to be marmatitic, is associated with iron sulphides consisting mostly of pyrite.

The origin of the lead-zinc-copper mineralization remains speculative. The presence of manganese and barite in or near the ore occurrences suggests a relationship linking the mineralization to volcanogenic processes. Stanton (1972, p. 460) cites numerous examples where manganese compounds occur as exhalative products in volcanic regions. He furthermore provides examples

(p. 522) which demonstrate the close ties of barite to Pb-Zn or Pb-Zn-Cu-Fe deposits. The famous Kuroko (black ore) of the Kosaka mine in Japan (Ohasi, 1919) is but one example demonstrating the link of barite to the Pb-Zn-Cu-Fe deposits of unequivocal submarine volcanic origin. These ores were deposited essentially as sinters about hot springs on the sea floor.

The authors are aware that the classification of the Bushmanland deposits under the general heading of volcanogenic precipitates (Table II) may be totally eroneous. Volcanic rocks, if present at all in the Bushmanland successions, do not appear to be common. An alternative mode of origin (R.P. Viljoen, verbal discussion, 1973) might equally well be sought by comparing these deposits with sulphide occurrences forming in hot brines, as is the case in the Salton Sea (White, 1968) and in the Red Sea (Bischoff, 1969). Craig (1969) maintained that in the latter area there is no evidence requiring sulphides to be contributed from volcanic or magmatic sources to the brines. Bischoff (1969) suggested that a variety of solids were precipitated out of the Red Sea brines by simple cooling as well as by mixing of the brine with sea water. He pointed out, moreover, that in addition to sulphides (mainly Pb and Zn), compounds of iron and manganese, as well as anhydrite, were deposited in bedded units. He furthermore noted a strong correlation of Ba with the sulphides and even one barite occurrence. Interesting speculations by James (1969) suggest that if Red Sea sediments were to be lithified and metamorphosed without significant chemical modification, the resultant rock would consist of hematite, minor magnetite, quartz and mica, plus abundant sulphides of zinc, copper and lead - an assemblage not unlike that in the Bushmanland region. Thus, instead of being deposits of volcanogenic origin, the base metal occurrences of the northwest Cape Province might eventually prove to be deposits precipitated from metal-bearing brines.

Volcanogenic Copper Deposits in the Damara Supergroup, South West Africa

A number of important copper deposits have recently been proved along the so-called Matchless amphibolite belt of the Khomas succession of the Damara geosyncline (Figure 8). Information made available to the writers by M.J. Viljoen (written communication, 1974) indicates that the belt is composed of several bands and lenses of amphibolite occupying a narrow zone varying in thickness from a few metres to about 3 km. This long narrow belt extends ENE from the vicinity of the old Gorob and Hope mines in the Namib Desert Park, approximately 225 km southwest of Windhoek, through Windhoek, to a point some 110 km northeast of this town where it appears to continue under a thin veneer of Kalahari sand.

The main copper occurrences associated with the belt are the Gorob and Hope mines noted above, the Matchless Mine 30 km southwest of Windhoek and the Otjihaze Mine 20 km northeast of Windhoek. Mineralization of importance is also known from a number of other localities.

According to Viljoen, the amphibolite belt is considered to be an altered basic to intermediate volcanic unit and structures resembling pillows have been observed at the Matchless Mine. The enveloping quartz-biotite schists are considered to represent altered shales and greywackes but it is equally probable that some of this material represents metamorphosed tuff and volcanoclastic sediments of intermediate to acid composition.

The mineralization is confined to discrete, well-defined tabular masses of siliceous, cherty and/or quartzitic (sericitic) rock. Pyrite is the main sulphide and occurs as disseminated and massive beds and layers within the quartzite assemblage. Chalcopyrite occurs interstitially to the pyrite and tends to increase in abundance with increasing amounts of iron sulphide. Other minerals include pyrrhotite, sphalerite and subordinate galena. Silver and gold are also generally present in small amounts.

The mineralization, although somewhat structurally disturbed in places, is clearly bedded and is considered by Viljoen to belong to the class of eugeosynclinal submarine exhalative volcano-sedimentary deposits. Each mineral deposit along the belt he considers might well represent a discrete submarine, siliceous (acid), volcanic centre or vent.

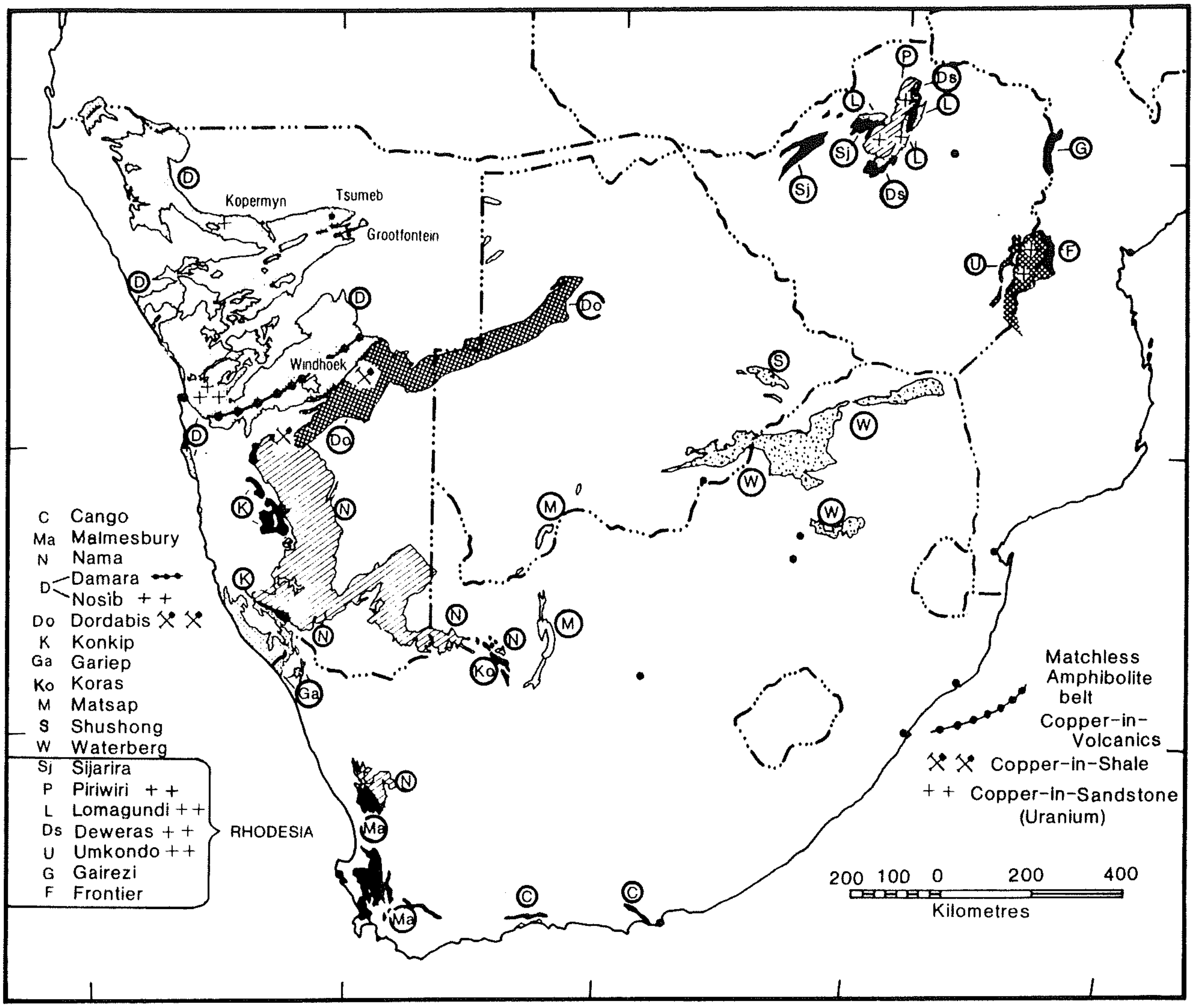


Figure 8 : Map showing the distribution of Middle and Late Proterozoic basins and associated copper mineralization.

STRATIFORM EPIGENETIC DEPOSITS

Based on the classification of Lindgren (1933), hydrothermal deposits are subdivided according to the depth and temperature of ore deposition on the assumption that changes in temperature and pressure are the most significant factors causing the minerals to precipitate. Included under this heading and grouped together for simplicity, both here and in Table II, are the hypothermal, mesothermal and epithermal subdivisions of Lindgren's original classification. Telethermal deposits are treated separately in this paper.

Park and MacDiarmid (1970) have defined hypothermal deposits, at the one end of the scale, as having formed at high temperature (300-500°C) and great depths, where connection with the surface is impeded. At the other end of the scale these authors have defined the epithermal deposits as being of direct magmatic origin, formed at shallow depths (within 1 000 m of the surface) and low temperatures (50-200°C). As far as the authors are aware the only stratiform epigenetic deposits that need be considered in this paper both fall within the mesothermal class. The latter formed at moderate temperatures (200-300°C) and pressures from solutions that probably have at least a tenuous connection with the surface. The mesothermal zone, according to Park and MacDiarmid (1970), is, in effect, intermediate between the two other classes and is not totally distinctive as it possesses both hypothermal and epithermal characteristics.

The deposits that will be discussed under this heading include the Artonvilla copper mine, in the Messina Group, and the gold-silver-bismuth-copper-pyrite-arsenic mineralization of the Pilgrims Rest-Sabie Goldfield in the Transvaal Supergroup.

Brief reference will also be made, in this section of the paper, to the pyrometasomatic copper-lead-zinc occurrences, including the Copper Queen and Copper King ore bodies in the Piriwiri Group, northwest Rhodesia. Pyrometasomatic deposits, which are essentially synonomous with contact-metasomatic deposits, were defined by Lindgren (1933) as having "formed by metasomatic changes in rocks, principally in limestone, at or near intrusive contacts under influence of magmatic emmanations".

The Artonvilla Copper Deposit

The Artonvilla Mine is one of five producing mines in the Messina area of the northern Transvaal (Figure 7). These mines, which are situated near the Rhodesian border, occur in complexly folded meta-sediments of the Messina Group (c.a. 3 000 m.y. old). The ore bodies differ from one another (Söhnge, 1945) in that some consist essentially of breccia pipes, while in others the mineralization is either associated with fissure veins or with breccias formed adjacent to the Messina Fault. Yet another variety are the sheet-like replacement ore bodies formed at the contacts of two physically and chemically differing rock types. It is into the latter class that the Artonvilla deposit may be grouped.

The geology of the mine comprises a lower leucocratic garnet-quartz-felspar granulite followed by a seemingly conformable sequence of melanocratic rocks, which in turn are overlain by a thick succession of meta-quartzites and garnet amphibolites (Jacobsen, 1967). The melanocratic zone comprises a mixed layered sequence of ferruginous amphibolites, garnet-biotite-cordierite granulites, and quartzites as well as an impersistent calc-silicate (diopside) biotite-quartz granulite. The ore bodies, being of a disseminated replacement type, are largely concordant with the layered sequence encountered in the melanocratic zone, the sulphide minerals selectively replacing the ferromagnesian components of the host environment.

The main ore minerals include pyrite, chalcopyrite, bornite, chalcocite and native copper, and the deposition of the ores, and the formation of the hydrothermal alteration minerals associated with them, took place in a concentric zonal pattern. According to Jacobsen (1967) the Artonvilla ore bodies display features corresponding most prominently with mesothermal conditions of ore deposition.

The mineralization is furthermore considered by him to be genetically unrelated to the Messina Group host rocks and the granulite facies metamorphism of the region. Jacobsen is of the opinion that the ore fluids are of epigenetic origin, the mineralization and associated greenschist grade alteration products being possibly of post-Karroo age. He relates them to the post-volcanic and intrusive cycle of the Nuanetsi Igneous Province near the southeastern border of Rhodesia (Figure 2).

The Pilgrims Rest-Sabie Gold Deposits

The first major goldfield in South Africa was the Pilgrims Rest-Sabie Goldfield in the eastern Transvaal, discovered in 1872. The first few years saw the washing of eluvial and alluvial materials for gold. Subsequently, both oxidized and sulphidic ores were exploited. The goldfield has recently ceased production, after nearly 100 years of exploitation.

The ores of the area are principally stratified quartz-pyrite "reefs", a few centimetres or tens of centimetres in thickness. Cross-cutting veins (known locally as leaders), "blows" (sausage-like swellings in stratiform quartz veins) and impregnations (some of them stratiform) have also been mined (Hall, 1910; Wybergh, 1925). The discussion below will be limited to the first (and economically most important) group.

The host rocks of the stratified auriferous veins are the basal formations of the Transvaal Supergroup. The major production was from reefs in the Malmani Dolomite, but some were also mined in the upper phases of the Wolkberg Group, the Black Reef Quartzite and the basal 1 700 m of the Pretoria Group (Figure 6). The ore was localized by intrastratal movements, which resulted in conformable passageways for mineralizing fluids. Evidence of intrastratal movement is abundant, and includes slickensided surfaces (above, below, and within the reefs), offsetting of dykes by movement parallel to bedding planes (Visser and Verwoerd, 1960) and non-penetrative cleavage in shaly rocks. The locus of intrastratal movement was lithologically controlled. In the thicker arenaceous and carbonate formations, movement was along shale and carbonaceous shale intercalations. In the cyclically alternating arenites and argillites, most of the bedding plane faults are found at quartzite-shale contacts.

Individual ore bodies dip gently to the west, in conformity with the Transvaal Supergroup as a whole. Along strike, reefs have been traced for distances of up to about 10 km. Internally, the reefs are often banded due to variations in the proportions of quartz, pyrite and carbonates. They carry fragments of the wall rock streaked out parallel to bedding. Wall rocks are pyritized for some distance on either side of the reef. Within some of the more extensively mined bodies, pay-shoots trending north or north-northeast, have been delineated. It has been pointed out (Visser and Verwoerd, 1960; Zietsman, 1967) that this is a prominent structural direction in the area, both dykes and the axes of minor folds having this trend. The ore shoots are often coincident with, or adjacent to, the axes of anticlinal warps, which have resulted in localized openings in the bedding plane faults.

Mineralogically, the reefs consist of early-phase quartz, carbonates and pyrite with some scheelite, arsenopyrite, pyrrhotite, sphalerite and galena. Later mineralization included gold, chalcopyrite, bismuthinite, tetrahedrite and galeno-bismutite (Swiegers, 1949). Most of the production from the area has been of gold, but some silver, copper, arsenic, bismuth, and pyrite have been won from the ore bodies.

The origin of the ore is considered by most investigators to be purely hydrothermal, of mesothermal grade, the mineralizing fluids filling spaces and replacing wall rock adjacent to the stratiform passageways (Swiegers, 1949; Visser and Verwoerd, 1960; Zietsman, 1967). The Bushveld Complex, which lies some 80 km west of the goldfield, is the source most frequently called upon to supply the fluids. Some investigators have, however, proposed a lateral secretion origin, it being reasoned that the gold could have been derived from the Transvaal strata. A recent investigation (Minnitt et al., 1973) has shown that, outside of an area of known mineralization, the shales in the dolomite may carry up to about 0.1 ppm Au, and could conceivably have acted as protore for the gold deposits of the Pilgrims Rest type.

The Pyrometasomatic Deposits of the Copper Queen and Copper King Mines, Rhodesia

The Copper Queen and Copper King ore bodies are two pyrometasomatic copper-lead-zinc occurrences in intensely folded micaceous and quartzose schists of the Piriwiri Group (Figure 8), of Late Precambrian age, located in the northwestern part of Rhodesia (Bahnemann, 1961). In this region a sequence of shales and sandstones, containing a calcareous member, has been strongly deformed into regional anticlines and synclines. The cores of these folds have been invaded by synkinematic granodiorite bodies in a manner resembling the "mantled gneiss domes" of Eskola (1949).

According to the description by Bahnemann (1961) the ore-emanations, generated and mobilized during the period of granitization and emplacement of the granodiorites, moved in to replace the sporadically developed calcareous unit in the succession. All ore indications are confined within a zone not extending further than 11 km from the contact of the granitic rocks. The localization of the ore bodies was determined jointly by the presence of the calcareous unit located at a favourable distance from the granite and a large anticlinal structure.

The main ore minerals of the deposits include pyrrhotite, sphalerite, chalcopyrite, and galena. In addition, lesser amounts of arsenopyrite, cubanite, valleriite, marcasite, pyrite, and magnetite are found. From his study of the ore-textures Bahnemann (1961) concluded that the sulphides were emplaced after the final stage of the regional metamorphism accompanying the deformation of the Piriwiri succession.

Telethermal Deposits

Telethermal ore bodies are thought to have formed by hydrothermal fluids that have migrated so far from their source that they have lost most of their heat and most of their potential to react chemically with surrounding rocks (Park and MacDiarmid, 1970). According to these authors, telethermal deposits cannot, in many cases, be established as cogenetic, or even contemporaneous with nearby igneous activity. Deposits of this class have often been ascribed to migrating connate brines or to mixtures of connate and meteoric waters.

In southern Africa, supposed telethermal deposits are of various types. The lead, zinc, vanadium,and fluorite occurrences in the Malmani Dolomite probably constitute the oldest known "Mississippi Valley" type mineral province. Younger examples of the "limestone-lead-zinc association" (Stanton, 1972) are in the carbonates of the 600 m.y. old Damara Supergroup.

A second, recently-discovered mineral province of the telethermal type is the uranium province of the Beaufort Group, Karroo Supergroup. These deposits are probably of the "Colorado Plateau" type (Von Backström, 1973), and can be assigned to Stanton's "sandstone-uranium-vanadium-copper association". The copper-in-sandstone occurrences of the Deweras Group of Rhodesia and the Damara Supergroup of South West Africa can probably be included in this grouping. The copper-in-shale deposits of South West Africa (Anhaeusser and Button, 1973) are a third type which may be accommodated in the class of telethermal deposits.

(a) Fluorite-Lead-Zinc-Vanadium Deposits in the Malmani Dolomite

Scattered occurrences of lead-zinc mineralization have been reported from widespread areas of the Malmani Dolomite (Willemse et al., 1944). It is only in the western Bushveld, especially in the vicinity of the town of Zeerust (Figure 9), that any significant tonnages have been mined. In this area, the ore bodies are found at and near the top of the shallow-dipping Malmani Dolomite, beneath the unconformity which marks the base of the overlying Pretoria Group (Figure 6). Deposits are known to occur over a strike-length of about 60 km. Ore bodies are of various types, and include breccia pipes, veins, disseminations and stratiform replacements. Production of lead and zinc has ceased, but the area is likely to become a significant producer of fluorite.

Extensive stratiform fluorite ore bodies have been delineated, and bear a strong resemblance to the deposits of southern Illinois, described by Grogan and Bradbury (1967). The Zeerust ores include fairly coarse-grained replacements as well as finely-laminated fluorite-carbonate rocks. According to Grogan and Bradbury, the coarser textured ores in the Illinois deposits were formed in and adjacent to the main pathways of fluid movement, while the finely laminated ones occur in quiescent "back-water" areas, which are only weakly affected by the telethermal solutions. Typically, the latter are found around the peripheries of the replacement lenses. The southern Illinois deposits are located adjacent to fractures, and are typically capped by an overlying formation of relatively impermeable rock. The latter feature is reminiscent of the deposits under consideration, which, on a regional scale, lie beneath a capping of chert found at the top of the Malmani Dolomite.

Many investigators (e.g. Willemse et al., 1944) regard the acid phase of the Bushveld Complex as the source of hydrothermal fluids, citing as additional evidence the effects of Bushveld metamorphism on the carbonates in the vicinity of Zeerust. However, the stratigraphic and metamorphic situation of the Zeerust area is not unique, while the mineralization apparently is. A second possible source is the alkaline intrusive dyke system found radiating from the Pilanesberg Complex, situated some 100 km northeast of the mineralized area (Figure 2).

(b) The Limestone-Lead-Zinc-Vanadium Mineralization of the Damara Supergroup

Mineralization of a similar character to that found in the dolomites of the western Transvaal is also found in the Otavi Dolomite formations that form part of the Damaran geosyncline in northern South West Africa (Figure 8). In the Otavi mountains, located approximately 400 km north of Windhoek, numerous lead-zinc-vanadium deposits occur in the dolomitic rocks centred about the town of Grootfontein, while 50 km to the northwest lies the famous copper-lead-zinc ore body at Tsumeb.

Few of these deposits can be regarded as stratiform ore bodies but they may be genetically linked to their enclosing limestone environment in a manner similar to the Mississippi Valley type lead-zinc mineralization. Only at the Abenab West Mine north of Grootfontein has a stratiform deposit of vanadium and lead been exploited. The ore minerals include descloizite, vanadinite, cerussite, minium, anglesite, smithsonite, hemimorphite,and galena. Brecciated limestones flank the ore zone. In the opinion of Willemse et al., (1944) the ores in the stratiform "reef" horizon appear to have been introduced by secondary processes which included mechanical introduction of vanadium into the breccia zone as well as the permeation of the zone by vanadiferous solutions.

(c) Sandstone-Uranium-Vanadium-Copper Associations

Deposits of this general association occur in continental and marginal marine sedimentary rocks and, like the Colorado Plateau regions of the western and southwestern United States, constitute one of the more important sources of uranium, copper and vanadium in the world (Fischer, 1968; Stanton, 1972). These three metals are rarely, if ever, of equal importance in any given deposit and in some instances occur either individually or in various combinations, excluding that of copper-vanadium, with uranium absent.

In southern Africa deposits which might conceivably be grouped with the sandstone-uranium-vanadium-copper association include the recently discovered uranium occurrences in the Karroo (Figure 4) and the copper-in-sandstone occurrences of the Umkondo-Deweras-Lomagundi successions in Rhodesia (Figure 8) as well as the Nosib succession in South West Africa. Little information is available on the Karroo uranium mineralization which, up to the present, appears to be confined to the lower formation of the Beaufort Group (Von Backström, 1973). The succession consists of alternating sandstone, shale and mudstone beds with cherty lenses aligned along certain zones. Bedding irregularities prevent lithological units being traced for more than a few kilometres and the uranium mineralization is most frequently associated with flat lying deposits formed along erosion channels and washouts. Clay pellet conglomerate lenses, fragments of clay, rolled pieces of bone and carbon trash accumulations are common. This may be either fossil flora and carbonaceous matter or the fossilized bones of the diversified fauna of fossil reptiles, most of which, according to Von Backström (1973), can be assigned to the *Order Therapsida* of mammal-like reptiles.

The age of the Beaufort Group according to fossil evidence, is Middle Permian (c.a. 250 m.y.). These sediments are therefore slightly older than the Colorado Plateau deposits they strikingly resemble, but which achieve greater prominence in rocks of Triassic and Jurassic age (c.a. 180 m.y.). In the Karroo deposits the mineralization appears to occur as fillings of pore spaces in the clastic sediments and as replacements of the fossil fauna and flora. It is not yet known whether copper or vanadium accompanies the uranium mineralization.

Copper mineralization occurs sporadically in the Late Precambrian (c.a. 600 m.y. old) sediments of the Nosib Group in South West Africa (Söhnge, 1958; Martin, 1965; Smith, 1965). The copper minerals occur disseminated in felspathic and argillaceous sandstones but only the conglomerates of the Kopermyn deposit northeast of Kamanjab (Figure 8) have so far warranted exploitation. The cupriferous sediments have, however, been involved in the Damaran orogeny and have been partly altered to granite, gneiss, and granulite. In this strongly metamorphosed region, stratiform pegmatitic copper deposits, such as the Khan Mine, are considered to have originated from the stratigraphically controlled mineralization by metasomatic reconcentration processes. Similarly, metasomatic uraniferous pegmatites in the Rössing area are confined almost exclusively to the Lower Hakos beds of the Damara Supergroup. These rocks display a conformable transitional relationship with the underlying Nosib successions (Martin, 1965) and the uranium mineralization may, in a manner similar to the copper mineralization, have concentrated from an original sedimentary source (Smith, 1965).

In Rhodesia, copper-in-sandstone also occurs in the Precambrian formations of the Umkondo, Deweras, Lomagundi and Piriwiri Groups. As can be seen from Table I no certainty exists as to the absolute ages of these successions. Only the Umkondo Group, which is intruded by dolerite dykes dated at approximately 1 500 m.y. (Allsopp et al., 1971), can be positioned in the table with any degree of confidence. The Umkondo assemblage, correlated by some with the Waterberg Supergroup, contains numerous copper showings. At the Umkondo Mine in southeastern Rhodesia, bornite occurs as nodules in shale and disseminations in quartzites. Although the origin of the ore body remains speculative Swift (1962) reported that copper-bearing solutions replace syngenetic iron pyrites in the sediments. These solutions may have been derived from the copper-bearing Umkondo lavas overlying the arenaceous units.

Copper mineralization is also widespread in the northwestern regions of Rhodesia where it occurs in rocks of the Deweras, Lomagundi and Piriwiri groups. The Deweras and Lomagundi rocks are exposed in a strip of country approximately 250 km long and which is seldom more than 30 km wide (Figure 8). Scattered from north to south within this belt are numerous copper mines and prospects including among others, the Shamrocke, Mangula, Silverside, Norah, Shackleton, Angwa, Hans, and Alaska deposits. Descriptions of the Mangula deposits by Stagman (1959) and W. Jacobsen (1964), and the Alaska deposits by J.B.E. Jacobsen (1964) favour a hydrothermal origin for the copper, the mineralization being linked genetically to the emplacement of granitic rocks in the area. An alternative interpretation, if not for all the copper deposits in the area then for some of them, is that proposed by the writers. The widespread extent of the copper in the generally arenaceous sediments (arkoses, grits, felspathic quartzites, conglomerates, argillaceous dolomites); the "red bed" character of many of the clastic sediments; the presence in the Mangula Mine of uraninite, metatorbernite and uranophane (Stagman, 1959; W. Jacobsen, 1964); the nature of the primary ore minerals which include chalcocite and bornite, and some chalcopyrite; the presence in the copper sulphides of notable quantities of silver (W. Jacobsen, 1964), and the continental and marginal marine nature of the host sediments suggests a strikingly similar relationship of the mineral deposits to the sandstone-uranium-vanadium-copper association outlined by Stanton (1972). Mineralization of this type may have entered the host environment at the time of deposition or shortly thereafter, thereby being available, during subsequent geological events, for upgrading into localized ore concentrations.

(d) Copper-in-Shale Deposits of South West Africa

Extending from an area southwest of Windhoek to the Botswana border and beyond in the northeast (Anhaeusser and Button, 1973) are the copper-bearing strata collectively grouped in this paper into the Dordabis Supergroup (Figure 8). Stratigraphic relationships and ages of the rocks in this region have still to be resolved (Table I) but it is believed that the copper-bearing formations are approximately 1 000 m.y. old.

The Klein Aub Mine, situated approximately 70 km southwest of Rehoboth, is the only copper producing mine although potential deposits exist at a number of localities including those in the Witvlei area 150 km east of Windhoek. Chalcocite is generally the main copper ore-mineral and in the Witvlei area occurs together with the sulphides chalcopyrite, bornite and digenite. Secondary minerals include covellite, chrysocolla, cuprite, malachite and azurite. In addition, the ore contains pyrite, native copper and a variety of iron ores. Silver, which is present in variable amounts in the ore, occurs in solid solution in the sulphides and not as a separate mineral (Anhaeusser and Button, 1973).

The copper-silver ores are contained in calcareous argillites comprising greenish-grey or dull red silty sediments with carbonaceous partings. In the Witvlei area a progressive sequence of copper-enriched sulphide minerals occurs commencing with the replacement of early diagenetic pyrite by chalcopyrite. The progressive replacement produces the minerals bornite, digenite, chalcocite, and native copper, in that order. The primary source of copper found in the copper-shales remains enigmatic. It is possible that the copper was derived from lavas occurring stratigraphically below the copper-shale and in which small copper showings are evident. Whatever the source of the copper, it is clear, from the study of the Witvlei ores, that the copper shales resulted from the replacement of early diagenetic pyrite in carbonaceous partings in the calcareous argillites. The stratiform mineralization is thus epigenetic in character and, although similar in many respect to the Kupferschiefer and Copperbelt ores, may best be compared with the Nonesuch Shale deposits in the White Pine area of Michigan (Ensign et al., 1968).

DEPOSITS RELATED TO SURFICIAL PROCESSES

This subdivision is a broad grouping of all deposits which were formed as a direct result of the operation of surficial chemical processes during the present or previous cycles of weathering and erosion. Many of the ore bodies in this class have a dual origin. For example, the iron in the high-grade hematite deposits, derived from iron formation, is partly syngenetic and partly epigenetic.

The principal iron deposits of southern Africa are grouped in this class, as are the most important manganese ore bodies. Many of the bedded phosphate, calcrete and gypsum occurrences in southern Africa are related to circulating meteoric waters. Residual deposits, formed by solution of the dolomite of the Transvaal Supergroup, have resulted in small concentrations of manganese, fluorite,and galena.

High-Grade Iron Deposits

In southern Africa, the principal iron mines exploit hematite formed by enrichment of a ferruginous protore, often iron formation. The oldest host rocks of deposits of this type are the iron formations of the Archaean greenstone belts of Rhodesia and Swaziland. In Rhodesia iron formation and jaspilite have been enriched to high-grade hematite deposits in the Que Que, Buhwa and Mwanesi Range areas (Worst, 1962a, b), while in Swaziland, enriched iron formation of the Fig Tree Group is mined at the Ngwenya Mine (Bursill et al., 1964). In most cases cited above, the iron formation gives rise to a ridge standing out above the surrounding country. Within the generally steeply dipping iron formation, lenticular bodies of hematite are found, their long axes lying parallel to the regional strike. In depth, the hard hematite ores tend to give way to soft, powdery ores (Worst, 1962a). By analogy with other occurrences in iron formation, the powdery ores probably finger out to iron formation at greater depths.

In the iron formation of the Transvaal Supergroup, high-grade hematite is mined at Thabazimbi and around Sishen (Figure 9). At Thabazimbi, the east-west striking, south dipping iron formation is repeated three times by strike faulting, giving rise to three ridges (Wagner, 1928). The iron formation, at and near its contact with the underlying dolomite, has been enriched to a high-grade hematite ore. Large blocks of unaltered iron formation are found within the hematite. The hematite preserves the delicately banded structure of the parent iron formation. In one instance, an asbestiform variety of hematite, formed by replacement of blue asbestos, was noted (Du Preez, 1944). At depth, the hematite bodies tend to finger out, firstly, to vuggy friable ores carrying specularite, silica and limonite, and then to calcite-hematite-minnesotaite rocks (Strauss, 1964a). Within the principal ore body, in a plane parallel to bedding, a westerly plunging shoot of hematite has been delineated which parallels the outcrop configuration of the iron formation. According to Strauss (1964a) the ore formed principally through supergene processes. He was of the opinion, however, that only iron formation which had been previously "conditioned" by hypogene solutions was prone to subsequent hematization. The latter processes were said to be related to the period of thrusting which affected the Thabazimbi area.

In the Sishen region, in the northwestern Cape, some of the hematite ore mined was formed by enrichment of iron formation. In this region, both the iron formation and the underlying dolomite are truncated by the intraformational unconformity which marks the base of the Gamagara Formation (Figure 10). A remarkable feature of the hematized iron formation of this area is that the enrichment process can be inferred to have taken place during the pre-Gamagara cycle of weathering. This deduction was made on the basis of the high-grade hematite clasts, found along with clasts of iron formation and quartzite, in the basal Gamagara conglomerate (Strauss, 1964b). The hematized iron formation occurs in tabular stratiform bodies up to 500 m along strike and 24 m thick. This type of ore contributes only a few per cent to the iron reserves of the area.

The Gamagara Formation, which unconformably overlies the Campbell Rand Dolomite and the Asbestos Hills iron formation, is the host to the principal iron deposits of the region (Figure 10). The Gamagara, deposited on an uneven land-surface, commences with a basal shale (20 to 60 m) and is overlain by conglomerate (6 to 30 m). The former wedges out in places, so that the conglomerate rests directly on the surface of unconformity. The conglomerate is overlain by aluminous shale, which passes up to ferruginous shales and flagstones, a shaly quartzite, a quartzite and finally, a shale. The entire Gamagara Formation is generally of the older of 200 m in thickness (Strauss, 1964b), but developments of up to 400 m are known (De Villiers, 1960).

The Gamagara sediments rest either on iron formation or on the underlying dolomite (Figure 10). Where they cover iron formation, the basal shale and conglomerate are extensively ferruginized

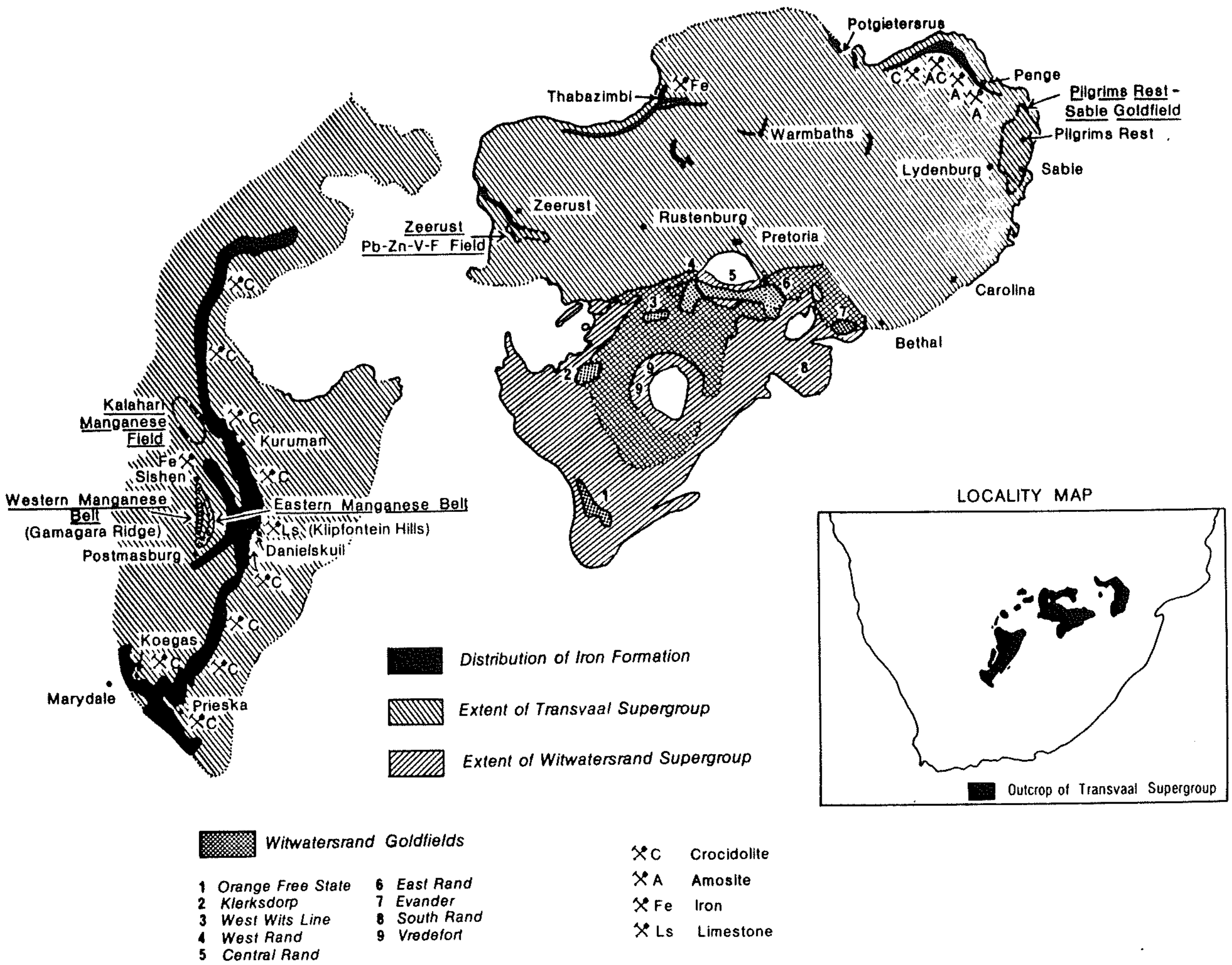


Figure 9 : Map showing the distribution of the Witwatersrand and Transvaal basins and their principal stratiform mineral occurrences. Inset map shows outcrop of Transvaal Supergroup in South Africa.

to high-grade hematite ore. The ore derived from shale is finely-laminated in places; elsewhere it is massive. It contains inclusions of unmineralized shale, especially where the latter is abnormally thick. An interfingering contact of shale and hematite ore is present in such situations.

The Gamagara conglomerate, generally more in the nature of a sedimentary breccia, is a crudely-bedded rock consisting of clasts of iron formation, jasper, hematite,and some quartzite in a red clayey matrix. It is converted to a hematite rock of exceptional purity, in which the original conglomerate structure can still be made out. It is speculated that these ferruginized conglomerates and breccias may represent fossilized "Canga" deposits, which formed by the ferruginization of iron formation rubble. This rubble was probably shed off topographic highs in the uneven pre-Gamagara land surface.

The origin of the high-grade hematite deposits seems to involve mainly processes of circulating meteoric waters. The up-graded iron formation is clearly related to an ancient, intra-formational period of weathering. The more-extensive ferruginized shales and conglomerates are less easy to categorize. Although the hematization seems to die out under cover of the Ongeluk Lava (Strauss, 1964b), some high-grade hematite has, nevertheless, been intersected at depths of up to 1 000 m (Wessels, 1967). Secondly, it has been pointed out (Strauss, 1964b), that extensive high-

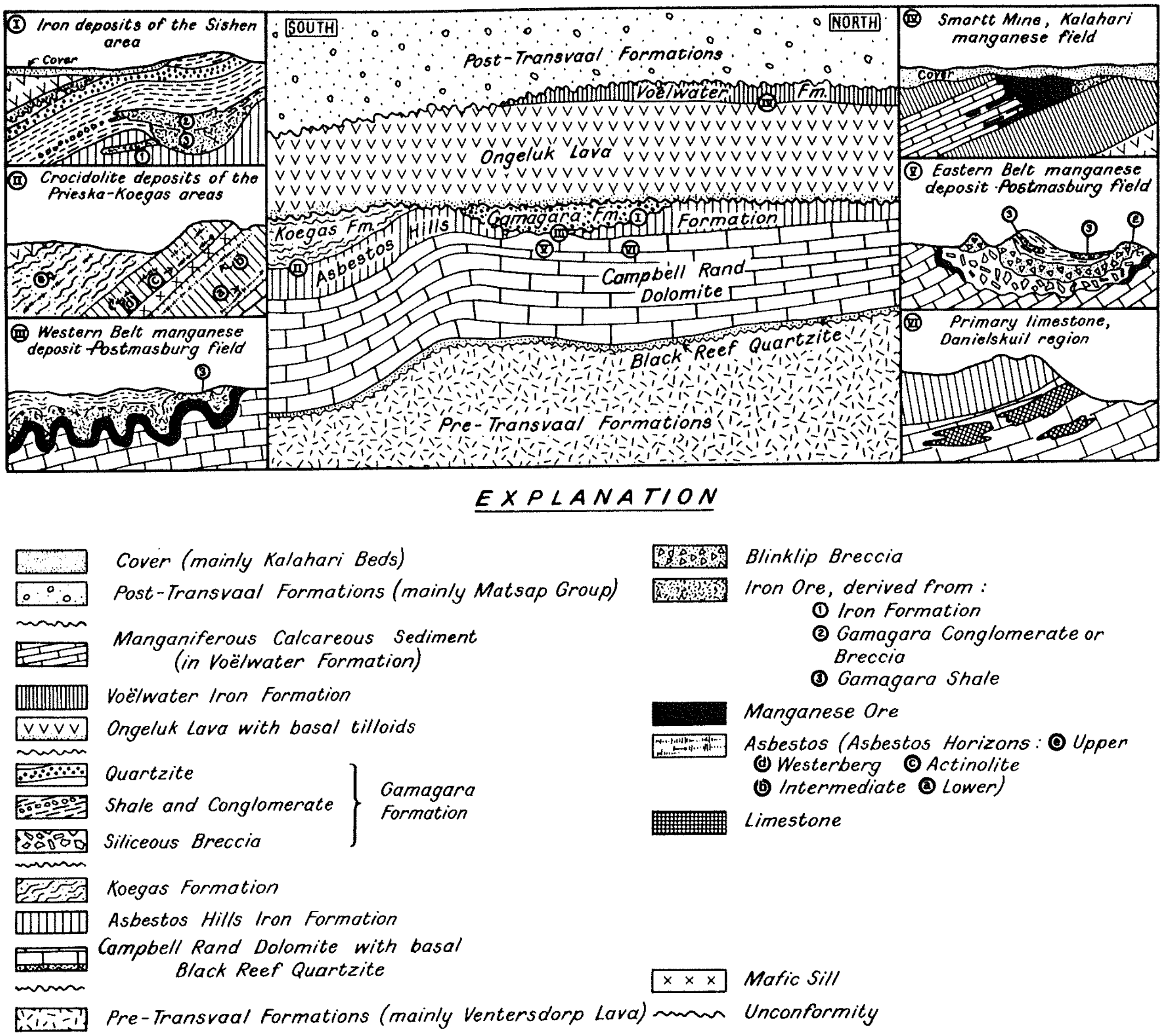


Figure 10 : Schematic diagram showing the stratigraphic setting of mineral deposits in the Transvaal Basin in the northwestern Cape Province.

grade hematite is only found where the Gamagara sediments rest on iron formation. An inescapable conclusion appears to be that much of the iron was derived by solution in the iron formation and re-deposition in the overlying shale and conglomerate. The suggestion is made here that the ferruginization is related to an early period of erosion, possibly the erosive period which terminated the Gamagara depositional cycle. Such an explanation would account for the persistence in depth of the ferruginized sediments.

Manganese

The principal manganese deposits of South Africa are associated with carbonate sediments. The most widespread are the residual pockets of psilomelane, pyrolusite, and wad, found associated with the Malmani Dolomite in the western Transvaal (Figure 5). Though widespread, these deposits are of minor economic importance. Their genesis involves solution of dolomite (carrying up to 3% MnO) and the precipitation of manganese (De Villiers, 1960). Stratigraphically, most of these deposits are found near the base and top of the Malmani Dolomite, where dolomites contain higher than average quantities of manganese. An interesting, though economically unimportant, occurrence of manganese is developed along the unconformable contact of the Malmani Dolomite and the overlying Pretoria Group, in the eastern Transvaal (Figure 6). This deposit appears to be a palaeowad, formed by solution of manganese-rich dolomite in pre-Pretoria times.

The largest producers of manganese in southern Africa are situated in the northwestern Cape (Figure 5). The host formations to the manganese are various members of the Transvaal Supergroup. Geographically, two fields can be distinguished; the Kalahari field in the north, and the Postmasburg field in the south (Figure 9). The former field, with reserves conservatively estimated at 9×10^9 tons (at 30% Mn) constitutes one of the largest known manganese deposits in the world (De Villiers, 1971).

(a) <u>The Postmasburg Field</u>

Two geologically distinct types of manganese deposit are exploited in the Postmasburg region. The first type is found in an arcuate belt of breccia outcrops which give rise to the Klipfontein Hills, extending from Postmasburg to near Sishen (Figure 9). These "Eastern Belt" ores are found at or near the contact of a pre-Gamagara residual chert breccia and the underlying Campbell Rand Dolomite (Figure 10 V). They consist principally of braunite with lithiophorite, psilomelane, and hausmannite, the main gangue being silica from the chert breccia (De Villiers, 1973). Although these ores tend to be of a fairly high-grade, the ore bodies are extremely irregular and reserves are hard to estimate, but are probably about 0.5×10^6 tons (Boardman, 1964). The mineralization, widely accepted as being due to circulating meteoric waters (De Villiers, 1960; Boardman, 1964), is limited to depths of about 30 m. The ultimate source of the manganese is usually considered to be the Campbell Rand Dolomite, which contains up to 6% MnO in places (K.A. Eriksson, personal communication, 1973). The restriction of mineralization to the present-day surface, or near surface regions, suggests a young age (probably post-Karroo) for the manganese mineralization.

The second major type of deposit in the Postmasburg field is found in the "Western Belt", confined to the central portions of the Gamagara ridge (Figure 9). The ore, which is of a ferruginous type, occurs close to the unconformable contact of the Gamagara Formation with the underlying Campbell Rand Dolomite (Figure 10 III). This low-dipping contact has a sinuous outcrop pattern, due mainly to the slumping of the Gamagara beds into solution depressions in the dolomite. The manganese ores are replacement deposits after the Gamagara shale. The original lamination of the shale is visible in the manganese except where the latter has been recrystallized. The manganized shale is frequently overlain by, and grades into, variable thicknesses of hematized shale, which, in turn, grades into the aluminous Gamagara shale. Slumping of the manganized shale into dolomite solution depressions has resulted in the ore being fragmented into disjointed blocks set in an earthy fill.

The principal manganese mineral in these deposits is bixbyite. Other ore-minerals include jacobsite, braunite, hausmannite, pyrolusite, lithiophorite, and partridgeite (De Villiers, 1973). Reserves of manganese have been calculated at 20×10^6 tons of 30% Mn (Boardman, 1964). The Western Belt ores, though of lower grade (being contaminated mainly by iron) are more predictable and more extensive than the higher-grade Eastern Belt deposits.

The Western Belt ores are only developed where the Gamagara Formation rests directly on the Campbell Rand Dolomite. They are thought to have formed by near surface leaching of manganese from the Dolomite and replacement of the Gamagara shale by the manganiferous solutions.

(b) <u>The Kalahari Field</u>

This manganese field is situated about 100 km due north of Postmasburg (Figure 9). Seven producing mines are situated within the field. The host rocks to the mineralization are primary manganiferous calcareous sediments (containing, on average, 27% Mn) interbedded with the iron formation which follows directly on the Ongeluk Lava (Figure 10 IV). Within the basal 100 m of the iron formation, up to three protore layers are developed. The lowest of these layers can measure up about 25 m in thickness, and lies about 30 m above the Ongeluk Lava. The middle layer of protore is thin and impersistent, while the upper layer is some 6 m thick (Boardman, 1964; De Villiers, 1971). The economically exploited ores are confined to the near surface regions, where the calcareous protore has been upgraded by surficial processes (Figure 10 IV). The enrichment was probably a multi-stage process. Some manganese ore occurs as clasts in a Waterberg-age conglomerate (De Villiers, 1971), while the Dwyka tillite rests with a sharp contact on older manganese ore (Boardman, 1964). These features provide conclusive proof that the enrichment processes had reached an advanced stage before the onset of Karroo sedimentation.

The various deposits in the field are not uniform. They vary according to which layer of protore is exploited, to the metamorphic grade imposed by bostonitic and gabbroic intrusives, to the effects of hydrothermal action, and to the intensity of surface-enrichment processes (De Villiers, 1971). The supergene process is well-illustrated at the Smartt Mine (Figure 10 IV). Here, the manganiferous protore, found at depth, interfingers with manganese ore (40 to 50% Mn) near the surface, which grades in turn into a ferruginous zone. The separation of iron from manganese, the latter moving further down-dip in a "front" ahead of the iron, probably reflects the greater solubility of Mn under most conditions of pH and Eh.

The Kalahari manganese ores are mineralogically complex and variable. Of the 30 minerals described from the ores by De Villiers (1971), 17 are manganiferous. The principal ore minerals appear to be braunite, bixbyite, rhodocrosite, hausmannite and jacobsite.

The protore of the Kalahari field is a laminated, fine-grained calcareous rock carrying about 27% Mn. It is a primary chemical precipitate, and was originally deposited as a mixture of manganese hydroxide and calcium, magnesium, and manganese carbonates (De Villiers, 1973). The ultimate source of the manganese is unknown. It could have been derived by weathering of pre-existing formations (such as the Campbell Rand Dolomite) or have been contributed to the depository by volcanic exhalative processes (the manganese-bearing units occur no great distance above the Ongeluk Lava).

Phosphates

In southern Africa phosphates are derived principally from igneous intrusive bodies such as the Palabora carbonatite complex in the northeastern Transvaal. Next in importance are the coastal phosphate occurrences of the southwestern Cape Province, particularly those centred about the Saldanha Bay area. Here some of the deposits of aluminium phosphate were formed by solutions of organic phosphate percolating downwards from guano deposits on the roosting places of sea birds. This process resulted in the local phosphatization of several rock types, particularly quartz porphyry hills flanking the coast (Visser and Schoch, 1973).

In the same general region brown, medium-grained, calcium phosphatic sandstones containing rounded quartz grains and small shell fragments rest on the underlying granites. Deposits of predominantly unconsolidated phosphatic sand with calcium carbonate contents of between 20 and 50% occur in places. This phosphatic sand consists mainly of brown to yellow collophane, and, in some deposits, the sediments consist predominantly of sandy limestone, some layers of which are very rich in shell fragments, shark teeth, and calcareous sand. Brown phosphatic nodules may be found scattered through the soil in large numbers in places and represent either the outcrop or sub-outcrop of ore bodies, but elsewhere indicate enrichment of low grade material.

Although the majority of investigators regard the lime phosphates as replacement deposits consisting of phosphatized beach accumulations (Haughton, 1933; De Villiers, 1969) it is the opinion of Visser and Schoch (1973) that many of these deposits are of primary sedimentary origin. These authors ascribe the accumulations of phosphate in the beach and marine sediments to the abundance of organic life found in the upwelling cold oceanic waters along the Atlantic coast. They suggest, however, that some of the hard phosphatic sandstone resembling silcrete may have formed at depth with the assistance of groundwater. As these rocks are generally richer in lime than in P_2O_5, the lime may have played a major role in consolidation and cementation of the sediment.

The known reserves of calcium phosphate in the southwestern Cape amount to approximately 124×10^6 metric tons of concentrate containing 32% P_2O_5 (Visser and Schoch, 1973).

Further small replacement phosphate deposits occur as bedded ore veins in Waterberg sediments in the northern Transvaal (De Villiers, 1959). Some veins, up to 2 m thick, consist of pink phosphate, and although the vein-material has the appearance of a breccia, it is composed entirely of phosphate and a few quartz grains. The phosphate presumably originated from the offal of birds roosting in the cliffs overhanging the deposits.

Gypsum

In many parts of the world gypsum deposits were formed by the evaporation of sea water in marginal sea-basins or inland saline seas or lakes. In South Africa most of the inland gypsum occurrences owe their origin to the reaction of sulphuric acid on surface limestones. The conditions essential to their formation are outlined by Visser (1963). These include :

(i) the presence of rocks that supply the necessary calcium and sulphate in the zone of surface weathering

(ii) areas having restricted drainage such as shallow depressions, pans, and inland lakes which could promote concentration and,

(iii) suitable climatic conditions, including low rainfall and long dry periods.

Most of the deposits are located in the more arid western half of the country extending from Kimberley to the Atlantic coast. In the areas where gypsum is found, the underlying successions are either Upper Dwyka or Lower Ecca shales of the Karroo Supergroup, or Ventersdorp lavas as is the case north of Kimberley. Deposits centred about the Vanrhynsdorp District of the western Cape are associated with marbles of the Malmesbury succession.

In practically all deposits, surface limestone or calcrete formed first, later to be transformed into gypsum by groundwater containing sulphuric acid derived from the weathering of pyrite which is locally plentiful, as for example in many of the Karroo shales. Capillary action assisted in drawing the acidic solutions to the near surface regions during dry seasons.

Some of the deposits that formed in pans differ in that the gypsum entered in solution, and became concentrated by natural evaporation. Salt is also produced from many of these pans from borehole brines which are allowed to evaporate naturally. In South West Africa in the vicinity of Swakopmund and Walvis Bay extensive areas of the Namib desert are covered by gypsum deposits and gypsum-cemented sand and gravel. The latter are correlated with the upper Kalahari beds of the interior and are probably of Tertiary age. Considerable reserves of low-grade material exist together with several million tons of gypsum with a purity in excess of 90%. According to Martin (1963) the gypsum is an alteration product of Tertiary and Pleistocene calcretes that ranged in composition from pure calcium carbonate rocks to lime cemented sands and gravels. This alteration proceeded from surface to a maximum depth of 4 m (average 0,3 - 1 m). As a source for the enormous quantities of sulphur required for this transformation Martin (1963) suggested the hydrogen sulphide being generated under anaerobic conditions on the Atlantic sea bottom in a deposit of sulphide-bearing, diatomaceous ooze. This azoic zone measures about 15 000 km^2 and is situated immediately off-shore to the west of the deposits. The hydrogen sulphide, it is maintained was blown inland and precipitated with mist and dew to react with the calcrete.

Numerous other inland gypsum deposits exist but will not be elaborated upon. It should, however, be mentioned that some occurrences along the Cape west coast originated from gypsum precipitated directly from sea water. The South African deposits are thus mainly of replacement origin although minor marine evaporites exist.

Calcrete

A wide variety of rock types give rise to surface limestone or calcrete deposits exploited mainly by the cement industry. The calcretes form in the lower rainfall areas and develop by the precipitation of calcium carbonate from solutions finding their way to surface either by capillary attraction, or along sub-surface drainage.

In South West Africa in the Swakopmund-Rössing region, sub-economic concentrations of uranium are found in calcretes formed in dried-up river courses (P.D. Toens, personal communication, 1973). This type of uranium occurrence can probably be compared with the recently discovered uranium-in-calcrete deposits in Western Australia (F. Langford, personal communication, 1973).

Salt

Salt is recovered mainly from inland pans and coastal lagoon areas in the more arid parts of the country. The salt is concentrated where impervious clays prevent downward seepage of brine. There are no beds of pure natural salt.

Bauxite

Bauxite is mainly a residual material formed as the result of weathering a large variety of rocks containing alumina. Although adequate host rocks of all ages exist, no bauxite of any significance has been found in South Africa. In some localities, mainly the tropical and subtropical areas of the northeastern Transvaal and Natal, lateritic clays with fairly high gibbsite contents have formed mainly from the weathering of diabase sheets. Minor occurrences of bauxite are found in the eastern parts of Rhodesia and across the border into Mozambique but are not mined.

DEPOSITS RELATED TO METAMORPHISM

Certain sedimentary and volcanic rocks, when metamorphosed, give rise to minerals which are economically exploitable. In southern Africa, examples of such minerals are the alumino-silicates andalusite, kyanite,and sillimanite, the aluminous oxide, corundum, and other silicates such as wollastonite and chrysotile. These are exploited either in their host rock, or, in some cases, in eluvial and alluvial deposits derived from them.

Metamorphic Minerals in Carbonate Rocks

The most important mineral in this group is chrysotile asbestos, derived by thermal alteration of dolomite (Van Biljon, 1964). Deposits are known from around the Transvaal Basin, where dykes and sills have altered the Malmani Dolomite (Figure 6). The principal deposits are in the eastern Transvaal, especially the southeastern Transvaal east of Carolina (Figure 9). Here, Bushveld-age sills, intrusive into the dolomite, are very abundant. The controls on the mineralization involve :

(i) a source of both Mg and Si (the former is supplied by dolomite, the latter by interbedded chert).

(ii) a source of H_2O (this is supplied by volatiles streaming off the cooling sill) and,

(iii) a source of heat to drive the thermal reaction (supplied by the sill itself).

The first control is illustrated by the fact that, adjacent to sills intrusive into chert-free dolomite, no fibre is developed; the second by the fact that the fibre is invariably found above the sill, the expected position of volatiles (Button, 1974).

The sills commonly result in a metamorphosed assemblage extending for a metre or two above the upper chilled contacts. In these alteration zones, the dolomite is partly de-dolomitized so that a calcitic rock occurs along with serpentine and talc. The serpentine is often clearly pseudomorphous after chert, inheriting its nodular form and sometimes picking out delicate depositional structures such as ripple marks, algal laminations and stromatolites (Button, 1974). Within the serpentine, fibres of chrysotile asbestos are developed. According to Van Biljon, fibre-development is related to minor deformations in the dolomite. He is of the opinion that the reaction can occur at temperatures of below 500°C.

Wollastonite has been described from the Namaqualand metamorphic terrane by De Jager and Simpson (1962). The wollastonite-rich rocks were derived by metamorphism of pre-existing calcareous sediments. They consist of wollastonite with diopside, garnet,and some vesuvianite and plagioclase. A wollastonite skarn also occurs at some of the intrusive granite-marble contacts in the Damara succession, and have been mined in the Karibib area (Martin, 1965).

Silicates and Oxides of Alumina

Metamorphism, either thermal, dynamic, or in combination, is responsible for the development of a wide variety of aluminous minerals where its effects are superimposed on originally aluminous sediments. The emplacement of the Bushveld Complex into rocks of the Transvaal Supergroup has, for example, produced a thermal aureole in which vast quantities of andalusite, together with staurolite and some sillimanite, are developed in metamorphosed shales of the Pretoria Group (Figure 6). Only the andalusite is recovered, either by quarrying or by the concentration of the mineral from the fluviatile sands in the Marico District of the western Transvaal, described previously.

Important sillimanite deposits are widespread in the ultrametamorphosed terrane of the Namaqualand regions of the northwest Cape Province (De Jager and Von Backström, 1961; De Jager, 1963; Coetzee, 1958). Lenticular occurrences of sillimanite and corundum-sillimanite rocks south of the Orange River near Pella and Poffader are considered by De Jager and Von Backström (1961) to occupy one stratigraphic position in the Bushmanland/Kheis succession. Most investigators of these Namaqualand deposits consider that the sillimanite originated from aluminous sediments, possibly bauxite, which may have existed in the form of lenses within the original stratigraphy. It is, however, equally possible that the primary host material may have been an aluminous tuff or tuffite. The nature of all the rocks in the area is now being examined more critically following the discovery of copper-lead-zinc-barite mineralization in the region.

Uneconomic sillimanite deposits are also known to occur in folded quartzites of the Mozaan Group (Pongola) in Swaziland (Jones, 1964). The sillimanite-bearing zones within the quartzites can be attributed to dynamo-thermal metamorphism due to the combined agencies of regional folding and the intrusion of granite. Also in Swaziland are several deposits of diaspore and pyrophyllite (Davies et al., 1964). These occurrences are found interbedded with phyllites in the lavas of the Insuzi Group (Pongola). A variety of andalusite-diaspore and pyrophyllite-bearing rock types, in various combinations, has resulted from dynamic metamorphism of alumina-rich phases of the phyllite zone. Minor showings of pyrophyllite also occur in rocks of the Mozaan Group. The alumina deposits in the Pongola rocks are of added interest because of their great age (c.a. 3 000 m.y. old; Table I).

Even older sources of the Al_2SiO_5 polymorphs are to be found in the Archaean greenstone belts of Rhodesia, Botswana,and South Africa. In the Tati greenstone belt in Botswana, kyanite, occurring in massive pods and veins surrounded by pyrophyllite schists,has been quarried at the Halfway Kop Mine near Francistown (Mason, 1970). The deposit occurs in a succession of bedded felsic tuffs and agglomerates, the kyanite-rich pods and quartz-kyanite veins having formed as a result of metamorphic differentiation processes operating under greenschist facies conditions. Elsewhere in the southern African greenstone belts,aluminous pyroclastic deposits, which are found typically in the volcanic sequences (Anhaeusser et al., 1969), give rise locally to metamorphic alumina-rich deposits. In addition to kyanite, sillimanite, andalusite,and pyrophyllite, there are occurrences of corundum, both within alumina-rich beds in the greenstone belts (Morrison, 1972), or in metamorphosed greenstone xenoliths scattered in the granites, gneisses,and migmatites (Anhaeusser, in preparation).

Kyanite,and kyanite-corundum,deposits also occur in granitized metasediments of the Marienhof Formation which forms part of the 1 900 m.y. old basement in South West Africa (Martin, 1965). Further sporadic occurrences of kyanite are found in the northeastern parts of Rhodesia in pelitic gneisses correlated with the Umkondo Supergroup (Talbot, 1973). These rocks have been involved in high-grade regional metamorphism and deformation in the Zambezi mobile belt (Figure 1). The kyanite, which occurs in places with sillimanite, has been mined near the Mazoe River at the Prylin, Chimanda,and Ky mines (Warner, 1972) and is potentially exploitable at Kyanite Hill

(H.D. le Roex, personal communication, 1973), where the succession consists of inter-digitating pelitic and semi-pelitic Umkondo gneisses (Talbot, 1973).

SOUTHERN AFRICAN METALLOGENIC EPOCHS

The time-dependence of certain minerals and metals in southern Africa is illustrated in Figure 11. In this diagram, the ages of the host environments are plotted horizontally (0-4.5

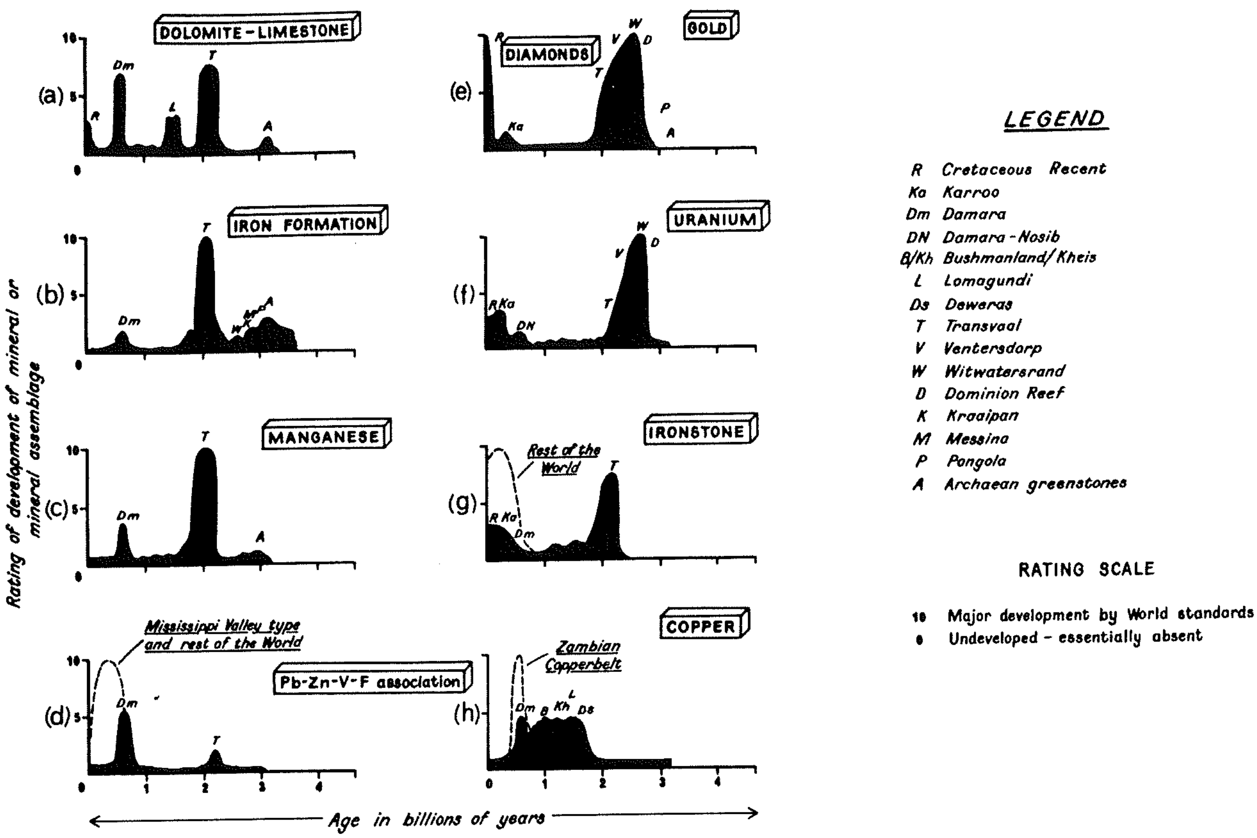


Figure 11 : Schematic diagram illustrating the time-dependence of some stratiform ore deposits in southern Africa.

billion years), while a qualitative rating of the importance of the mineral occurrences is plotted on the vertical axis. The rating is based on a comparison of a particular mineral province with similar provinces around the world. A major development is rated at 10, while non-development is rated at 0.

The diagram for dolomite and limestone (Figure 11a) indicates five principal peaks. These peaks coincide with major marine incursions over the interior of southern Africa, the most widespread marine carbonates being found in the Transvaal and Damara successions. Fairly major occurrences are also developed in the Lomagundi (and to a lesser degree the Umkondo) succession in Rhodesia, while the carbonates of Archaean and of Recent times are, volumetrically, relatively minor.

The broad coincidence of the iron formation peaks (Figure 11b) with the carbonate peaks (an obvious exception being the Lomagundi and Umkondo) suggests that iron formation formed principally in some facet of the marine depositional system. Manganese (Figure 11c) is also clearly confined to the principal periods of marine sedimentation. The absence of both iron formation and manganese in the Lomagundi succession is striking. The literature is not clear on this point but the "Striped Slate Series" of the Lomagundi (Stagman, 1959) could represent a type of iron formation. The succession might also represent a target area in any search for manganese mineralization.

The Mississippi Valley type of Pb-Zn-F mineralization in carbonate assemblages is a well-known mineral association. Stanton (1972) has pointed out that occurrences of what he terms the *limestone-lead-zinc association* are more-or-less confined to the Phanerozoic, especially the period from the Lower Palaeozoic to the end of the Mesozoic era. Stanton further remarked on the apparent confinement of major deposits of this type to the northern hemisphere. The first restriction might imply that biological processes have been an important factor in the development of this mineral association, while the second, from the southern African standpoint at least, must be due to the fact that no major carbonate sequences (except possibly those of the Damara) were deposited during Phanerozoic times. The Cape and Karroo successions, for example, are essentially devoid of carbonate sediments, and consequently, did not provide the important dolomite-limestone host environment which appears to be a fundamental pre-requisite for this type of mineralization.

In southern Africa, only two metallogenic epochs of Mississippi Valley type are known and are to be found in the Transvaal and Damara successions (Figure 11d). The Damaran deposits are of greater importance and coincide, in terms of age, with the development of this type of deposit in Phanerozoic times. Those of the Transvaal Supergroup are of lesser economic importance but are noteworthy for the fact that they possibly represent one of the oldest occurrences of Mississippi Valley type mineralization known in the world.

If the dolomite-limestone and Pb-Zn-V-F curves of Figure 11 are compared, it is evident that the Lomagundi (and Umkondo) carbonates are apparently devoid of this type of mineralization. It is suggested that a careful search of these carbonates might yet reveal some small (but possibly economic) ore bodies of the Mississippi Valley type. These thoughts might equally be extended to the carbonate unit (the Schwarzkalk Formation) in the Nama succession in South West Africa which is broadly coeval with the development of the Damaran carbonates.

Although detrital diamonds have been found in sediments as old as the Witwatersrand, by far the most important occurrences are found in younger sediments. A small showing of diamonds in the Karroo sediments of Rhodesia (Figure 11e) appears to mark the start of this major mineralogical epoch, with the Tertiary and Recent alluvial and marine gravels marking its culmination. It might be concluded from this that the strict time-dependence of economic diamond deposits of mechanical-sedimentary origin appears to be a function of mantle evolution, with the main kimberlite intrusive activity taking place during, or immediately following, Late Cretaceous times (c.a. 60 m.y. ago). From what is known it would appear that sediments deposited subsequent to this era have the greatest potential as sources of detrital diamonds. With this in mind, the Tertiary and younger sediments of the Kalahari and the Mozambique coastal plain appear to offer the principal alternative areas (other than the South West African and Namaqualand coastal regions) for detrital diamond exploration.

One of the most spectacular metallogenic epochs is that of mechanically deposited gold which spanned about one billion years of time from the Archaean to the depositional era of the Transvaal Supergroup (c.a. 3 200-2 200 m.y., Figure 11e). In the final analysis, the peak of this epoch, in Witwatersrand times, must reflect the period of most intense erosion of the auriferous hinterland, widely accepted as a hydrothermal gold province in the Archaean greenstones. The world-wide occurrence of gold in ancient greenstone belts must, in turn, be a function of mantle-crustal evolution in the Archaean. A return to these conditions, but on a somewhat reduced scale, is evident in the mother-lode environments of the gold deposits of the early Triassic circum-Pacific orogenic belts and the Palaeozoic tectonic regimes like those of the Uralide and Tasman-New England-New Zealand orogenic belts.

The gold curve of Figure 11e is fairly steep-sided on the Archaean side but tails off more gradually on the Proterozoic side. This progressive decline results from the re-cycling of gold from the Witwatersrand into the Ventersdorp and from these two successions, in turn, into the Transvaal Supergroup.

The uranium curve incorporates two metallogenic epochs of differing origins (Figure 11f). The older of the two is that associated with the ancient cratonic basins of southern Africa, and coincides almost precisely with the gold peak above it in Figure 11e. The asymetrical nature of this curve is also probably due to the reworking, into progressively younger formations, of uranium thought to have been first introduced into the crust along with various Archaean granites some

3 000 or more million years ago. The younger uranium peaks are those associated with the Damara-Nosib and Karroo successions, and coincide time-wise with the *copper-uranium-vanadium-sandstone association* of Stanton (1972). This class of ore deposit is largely confined to the Phanerozoic. There is, however, some evidence to suggest that similar mineralization may have formed as early as about 1 800 m.y. ago (Figure 11h) when an oxygenic atmosphere first became prevalent. Copper deposits, associated with some uranium (admittedly very locally), are found in the Middle Proterozoic Deweras Group in Rhodesia, associated with arkosic red-beds. Red-bed copper deposits are also known from the basal arenaceous unit (Nosib) of the Damara succession. It would thus appear that all continental and marginal-marine red-bed arenites younger than 1 800 m.y. in age might possibly be hosts to mineral deposits of the copper-uranium-vanadium association. Formations in southern Africa possessing such red-bed arenites include the Waterberg and Matsap in South Africa and Botswana, the Sijarira in Rhodesia, and some of the assemblages broadly grouped under the headings of Konkip and Dordabis in South West Africa (Table I).

Copper mineralization is spread quite widely through the period Middle to Late Proterozoic and Early Phanerozoic (c.a. 1 800-600 m.y.), but is poorly represented in the Early Proterozoic and Archaean as well as in Late Phanerozoic times (Figure 11h). Apart from the red-bed copper deposits already mentioned, stratiform copper mineralization, mainly of volcanogenic origin, is now known to exist in the Damara and Bushmanland/Kheis successions. The copper in these deposits is often accompanied by important developments of lead and zinc. While the southern African copper deposits are individually important sources of base metals they nowhere compare with the magnitude of occurrences in the Zambian Copperbelt (Figure 11h).

Two epochs of ironstone deposition are known from the stratigraphic record of southern Africa. The most important occurrences are those of the Pretoria Group, Transvaal Supergroup, and are thought to be about 2 200 m.y. old. The Pretoria Group examples therefore probably represent the oldest reported occurrences in the world.

The scarcity of southern African ironstones in the Phanerozoic (Figure 11g) is probably due to the fact that the correct shallow-marine depositional environment is not represented in the stratigraphic record. Such an environmental control appears to be well-established for the Clinton ironstones (Silurian) of North America and the Jurassic minette ores of Alsace-Lorraine in Europe. The iron-rich clastic sediments in the Damara Supergroup of the Kaokoveld in northern South West Africa may, on closer examination, prove to be ironstones deposited in the shallow sea which covered this region in Early Cambrian-Late Precambrian times.

The second significant development of ironstone is in the coal measures of the Karroo Supergroup, where "black band" ores are developed. In contrast to the marine ironstones, the black band ironstones of the Karroo, like others from around the world, were probably formed in a fresh-water lacustrine environment.

The remaining stratiform mineral deposits appear to be largely independent of geological time. Their appearance can be related to the chance intrusion of magmatic bodies (as in the case of metamorphic minerals, hydrothermal,or pyrometasomatic deposits) or to the exposure of older rocks to the agencies of surficial processes (e.g. the hematized iron formations). Prediction of the presence of mineral deposits in the former class hinges about such considerations as regional setting, metamorphism, structure, igneous and volcanic activity, while in the latter group, geomorphological history and the nature of the primary rock are important.

* *

ACKNOWLEDGEMENTS

The writers wish to acknowledge the helpful advice and information supplied to them by a number of colleagues. Their willingness to assist in providing information on matters not yet freely available enabled a more complete documentation of southern African stratiform ore occurrences to be undertaken. In particular, thanks are due to Dr. P. R. de Villiers and Mr. G. P. Fourie (Iscor, Pretoria), Dr. J. B. E. Jacobsen, and Mr. R. E. P. Fripp (University of the Witwatersrand, Johannesburg), Dr. M. J. Viljoen and Dr. R. P. Viljoen (Johannesburg Consolidated Investment Company, Geological Research Department, Randfontein), Dr. H. von Rahden (Messina Transvaal Development Company), Dr. P. D. Toens (Atomic Energy Board, Pelindaba), Dr. P. J. Ryan (Phelps Dodge, S.A.) and Dr. J. G. Stagman and Mr. F. P. Tennick (Geological Survey of Rhodesia, Salisbury).

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REFERENCES

Allsopp, H.L., Burger, A.J. and Van Zyl, C., 1967. A minimum age for the Premier kimberlite pipe yielded by biotite Rb-Sr measurements, with related galena isotopic data : Earth Planet Sci. Lett., 3 : 161-166.

Allsopp, H.L., Erlank, A.J. and Horning, G., 1971. Rb-Sr age measurements on the Umkondo dolerites of Rhodesia : Abstracts of Symposium on the Granites, Gneisses and Related Rocks of Rhodesia, 1971. Salisbury, Rhodesia : also Spec. Publs. geol. Soc. S. Afr., 3 (in press).

Anhaeusser, C.R., 1971. Cyclic volcanicity and sedimentation in the evolutionary development of Archaean greenstone belts of shield areas : Spec. Publs. geol. Soc. Aust., 3 : 57-70.

Anhaeusser, C.R., 1972. The geology of the Jamestown Hills area of the Barberton Mountain Land, South Africa : Trans. geol. Soc. S. Afr., 75(3) : 225-263.

Anhaeusser, C.R., 1973. The evolution of the early Precambrian crust of southern Africa : Phil. Trans. R. Soc. Lond. A. 273 : 359-388.

Anhaeusser, C.R., Mason, R., Viljoen, M.J. and Viljoen, R.P., 1969. A reappraisal of some aspects of Precambrian shield geology : Bull. geol. Soc. Am. 80 : 2175-2200.

Anhaeusser, C.R. and Lenthall, D.H., 1970. A petrographic and mineragraphic study of selected borehole intersections of the Prieska Copper-Zinc lode, northwestern Cape Province : Unpub. Rep. Anglo-Transvaal Consolidated Investment Co., Ltd., Johannesburg : 47 pp.

Anhaeusser, C.R. and Button, A., 1973. A petrographic and mineragraphic study of the copper-bearing formations in the Witvlei area, South West Africa : Trans. geol. Soc. S. Afr., 76(3) : 279-300.

Armstrong, G.C., 1965. A sedimentological study of the UK9 Kimberley Reefs in part of the East Rand : Unpub. M.Sc. thesis, Univ. Witwatersrand, Johannesburg : 59 pp.

Bahnemann, K.P., 1961. The ores of the "J-Lines", Sanyati copper mine, Southern Rhodesia : Trans. geol. Soc. S. Afr., 64 : 193-219.

Behr, S.H., 1965. Heavy-mineral beach deposits in the Karroo System : Mem. Geol. Surv. S. Afr., 56 : 116 pp.

Benedict, P.C., Wiid, D. de N., Cornelissen, A.K. and Staff., 1964. Progress report on the geology of the O'okiep Copper District. In: S.H. Haughton (Editor) "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 239-302.

Beukes, N.J., 1973. Precambrian iron-formations of southern Africa : Econ. Geol., 68 : 960-1004.

Bischoff, J.L., 1969. Red Sea geothermal brine deposits : their mineralogy, chemistry and genesis. In: E.T. Degens and D.A. Ross (Editors), "Hot Brines and Recent Heavy Metal Deposits in the Red Sea". : Springer-Verlag, New York : 368-401.

Bliss, N.W. and Stidolph, P.A., 1969. The Rhodesian basement complex : a review : Spec. Publs. geol. Soc. S. Afr., 2 : 305-333.

Boardman, L.G., 1964. Further geological data on the Postmasburg and Kuruman manganese ore deposits, northern Cape Province. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits of Southern Africa. : Geol. Soc. S. Afr., 2 : 415-440.

Boocock, C., 1965. Mineral resources of the Bechuanaland Protectorate : Overseas Geol. and Min. Res., 9(4) : 369-417.

Burger, A.J. and Coertze, F.J., 1973. Radiometric age-measurement on rocks from southern Africa to the end of 1971 : Bull. Geol. Surv. S. Afr., 58 : 46 pp.

Bursill, C., Luyt, J.F.M. and Urie, J.G., 1964. The Bomvu Ridge iron ore deposit. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 405-413.

Button, A., 1974. A regional study of the stratigraphy and development of the Transvaal Basin in the eastern and northeastern Transvaal : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 352 pp.

Cilliers, J.J. le R., 1964. Amosite at the Penge Asbestos Mine. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 579-591.

Cilliers, J.J. le R. and Genis, J.H., 1964. Crocidolite asbestos in the Cape Province. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 543-570.

Coetzee, C.B., 1958. Manganiferous iron ore, hematite, barite, and sillimanite on Gams (Portion 1), Namaqualand : Bull. Geol. Surv. S. Afr., 28 : 25 pp.

Coetzee, F., 1965. Distribution and grain-size of gold, uraninite, pyrite and certain other heavy minerals in gold-bearing reefs of the Witwatersrand Basin : Trans. geol. Soc. S. Afr., 68 : 61-88.

Cunningham, W.B., Höll R. and Taupitz, K.C., 1973. Two new tungsten bearing horizons in the older Precambrian of Rhodesia : Mineral. Deposita 8 : 200-203.

Craig, H., 1969. Geochemistry and origin of the Red Sea brines. In: E.T. Degens and D.A. Ross (Editors), "Hot Brines and Recent Heavy Metal Deposits in the Red Sea". : Springer-Verlag, New York : 208-242.

Davies, D.N., Urie, J.G., Jones, D.H. and Winter, P.E., 1964. The alumina, pyrophyllite and silica deposits in the Insuzi Series, Mahlangatsha and Mkopeleli areas, Shiselweni and Manzini Districts : Bull. Geol. Surv. Swaziland, 4 : 5-22.

De Jager, D.H., 1963. Sillimanite in Namaqualand : review of reserves and report on some low-grade deposits : Bull. Geol. Surv. S. Afr., 40 : 42 pp.

De Jager, D.H. and Von Backström, J.W., 1961. The sillimanite deposits in Namaqualand near Pofadder : Bull. Geol. Surv. S. Afr., 33 : 49 pp.

De Jager, D.H. and Simpson, W., 1962. Wollastonite near Garies, Namaqualand : Annals, Geol. Surv. S. Afr., 1 : 127-135.

De Villiers, J.E. (Compiler), 1959. "The Mineral Resources of the Union of South Africa". 4th Edition : Geol. Surv. S. Afr. : 622 pp.

De Villiers, J. (Compiler), 1960. The manganese deposits of the Union of South Africa : Handbook Geol. Surv. S. Afr., 2 : 280 pp.

De Villiers, P.R., 1971. The geology and mineralogy of the Kalahari Manganese-Field north of Sishen, Cape Province : Mem. Geol. Surv. S. Afr., 59 : 65 pp.

De Villiers, P.R., 1973. The geology and mineralogy of the manganese ore deposits of the northern Cape : Abstracts of 15th Congr. Geol. Soc. S. Afr., Bloemfontein : 34-37.

De Waal, S.A. and Herzberg, W., 1969. Uranium and gold mineralization of the Black Reef Series in the Kaapsehoop area, Nelspruit District, eastern Transvaal : Annals, Geol. Surv. S. Afr., 7 : 111-124.

Du Preez, J.W., 1944. The structural geology of the area east of Thabazimbi and the genesis of the associated iron ores : Annals, Univ. Stellenbosch, xxii, Sect. A : 263-360.

Engineering and Mining Journal, 1973. E/MJ exploration round-up. Sept. 1973 : 17

Ensign, C.O., White, W.S., Wright, J.C., Patrick, J.L., Leone, R.O., Hathaway, D.J., Trammell, J.W., Fritts, J.J. and Wright, T.L., 1968. Copper deposits in the Nonesuch Shale, White Pine, Michigan. In: J.D. Ridge (Editor), "Ore Deposits of the United States 1933/67". : American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, 1 : 460-488.

Eskola, P.E., 1949. The problems of mantled gneiss domes : Quart. J. geol. Soc. Lond., 104 : 461-476.

Ferguson, J.C. and Wilson, T.H., 1937. The geology of the country around the Jumbo Mine, Mazoe District : Bull. Geol. Surv. S. Rhod., 33 : 137 pp.

Fischer, R.P., 1968. The uranium and vanadium deposits of the Colorado Plateau region. In: J.D. Ridge (Editor), "Ore Deposits of the United States 1933/67". : American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, 1 : 735-769.

Fockema, P.D., 1967. Crocidolite and associated rocks of the Kuruman area in the northern Cape Province : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 189 pp.

Genis, J.H., 1964. The formation of crocidolite asbestos. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 571-578.

Goodwin, A.M., 1961. Some aspects of Archean structure and mineralization : Econ. Geol., 56 : 897-915.

Grogan, R.M. and Bradbury, J.C., 1967. Origin of the stratiform fluorite deposits of southern Illinois : Monograph Econ. Geol., 3 : 40-51.

Hall, A.L., 1910. The geology of the Pilgrims Rest gold mining district : Mem. Geol. Surv., Transvaal Mines Dept., 5 : 158 pp.

Hallam, C.D., 1964. The geology of the coastal diamond deposits of southern Africa (1959). In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 671-728.

Hanekom, H.J., 1966. The crocidolite deposits of the northern Cape Province : Unpub. D.Sc. thesis, Univ. Pretoria : 213 pp.

Harrison, N.M., 1970. The geology of the country around Que Que : Bull. Geol. Surv. Rhod., 67 : 125 pp.

Haughton, S.H., 1933. On the phosphate deposits near Langebaan Road : Trans. geol. Soc. S. Afr., 35 : 119-125.

Haughton, S.H., 1969. "Geological History of Southern Africa". : Geol. Soc. S. Afr. : 535 pp.

Hausmann, S.G., 1959. A mineralogical investigation of the Letaba copper-zinc ores and the Monarch cinnabar deposits located in the Murchison Range of the eastern Transvaal : Unpub. M.Sc. thesis, Univ. Witwatersrand, Johannesburg : 49 pp.

Hiemstra, S.A., 1968a. The mineralogy and petrology of the uraniferous conglomerate of the Dominion Reefs Mine, Klerksdorp area : Trans. geol. Soc. S. Afr., 71 : 1-65.

Hiemstra, S.A., 1968b. The geochemistry of the uraniferous conglomerate of the Dominion Reefs Mine, Klerksdorp area : Trans. geol. Soc. S. Afr., 71 : 67-100.

Hunter, D.R. (Compiler), 1962. The mineral resources of Swaziland : Bull. Geol. Surv. Swaziland, 2 : 111 pp.

Hutchinson, R.W., 1973. Volcanogenic sulphide deposits and their metallogenic significance : Econ. Geol., 68(8) : 1223-1246.

Jacobsen, J.B.E., 1964. The geology of the Alaska Mine. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 353-366.

Jacobsen, J.B.E., 1967. The geology of the Artonvilla mine, Messina District : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 123 pp.

Jacobsen, W., 1964. The geology of the Mangula copper deposits, Southern Rhodesia. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 339-351.

James, H.L., 1966. Chemistry of the iron-rich sedimentary rocks : U.S. Geol. Surv., Prof. Paper 440-W : 61 pp.

James, H.L., 1969. Comparison between Red Sea deposits and older ironstone and iron-formation. In: E.T. Degens and D.A. Ross (Editors), "Hot Brines and Recent Heavy Metal Deposits in the Red Sea". : Springer-Verlag, New York : 525-532.

Jones, D.H., 1964. Report on two sillimanite-bearing zones occurring on lapsed mineral concession 50, Mahlangatsha area, Manzini District : Bull. Geol. Surv. Swaziland, 4 : 25-28.

Joubert, P., 1971. Geological survey of part of Namaqualand and Bushmanland. In: J. de Villiers (Compiler), "7th-9th Ann. Reps: 1969-1971". : Precamb. Res. Unit, Univ. Cape Town : 51-57.

Keyser, U., 1972. The occurrence of diamonds along the coast between the Orange River estuary and the Port Nolloth Reserve : Bull. Geol. Surv. S. Afr., 54 : 23 pp.

Knowles, A.G., 1967. A palaeocurrent study of the Ventersdorp Contact Reef at Western Deep Levels Limited, on the far West Rand : Unpub. M.Sc. thesis, Univ. Witwatersrand, Johannesburg : 125 pp.

Koen, G.M., 1958. The attrition of uraninite : Trans. geol. Soc. S. Afr., 61 : 183-191.

Koen, G.M., 1961. The genetic significance of the size distribution of uraninite in Witwatersrand bankets : Trans. geol. Soc. S. Afr., 64 : 23-46.

Köppel, V.H. and Saager, R., 1973. Lead isotope evidence for the detrital origin of Witwatersrand pyrites and its bearing on the provenance of the Witwatersrand gold : Inf. Circ. No. 79, Econ. Geol. Res. Unit, Univ. Witwatersrand : 17 pp. (Also Econ. Geol. In Press).

Kröner, A., 1971. Preliminary resumé of the geology of the Gariep geosyncline in the Orange River area. In: J. de Villiers (Compiler), "7th-9th Ann. Reps: 1969-1971". : Precamb. Res. Unit, Univ. Cape Town : 51-57.

La Berge, G.L., 1966. Altered pyroclastic rocks in South African iron-formations : Econ. Geol., 61 : 572-581.

Langton, G. and Jackson, E.J., 1961. Recovery of ilmenite, rutile, and zircon at Umgababa : Trans. 7th Commonwealth Min. and Metall. Congr., 3 : 1073-1091.

Liebenberg, W.R., 1955. The occurrence and origin of gold and radioactive minerals in the Witwatersrand System, the Dominion Reef, the Ventersdorp Contact Reef and the Black Reef : Trans. geol. Soc. S. Afr., 58 : 101-223.

Lindgren, W., 1933. "Mineral Deposits". (4th ed.) : McGraw-Hill Book Co., Inc., New York : 797 pp.

Macgregor, A.M., 1921. The geology of the diamond-bearing gravels of the Somabula Forest : Bull. Geol. Surv. S. Rhod., 8 : 1-38.

Martin, H., 1963. A suggested theory for the origin and a brief description of some gypsum deposits of South West Africa : Trans. geol. Soc. S. Afr., 66 : 345-351.

Martin, H., 1965. "The Precambrian Geology of South West Africa and Namaqualand". : Precambrian Research Unit, Univ. Cape Town : 159 pp.

Martin, H., De Villiers, J., Wiid, B.L., Kleywegt, R.J. and Heath D.C., 1963. Geological map of South West Africa showing mineral occurrences and gravity contours (Bouguer anomalies). 1:1 000 000 scale : Geol. Surv. S. Afr.

Mason, R., 1970. The geology of the country between Francistown and Madinare - northeastern Botswana : .Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 186 pp.

Mendelssohn, E., 1938. Gold deposits of the central Murchison Range, Transvaal : Trans. geol. Soc. S. Afr., 41 : 249-272.

Middleton, R.C., 1973. The geology of Prieska Copper Mines (Pty.) Limited : Abstracts of 15th Congr. Geol. Soc. S. Afr., Bloemfontein : 17-18.

Minnitt, R.C.A., Button, A. and Kable, E.J.D., 1973. The gold content of pre-Malmani argillaceous sediments in the Transvaal Supergroup, northeastern Transvaal : Inf. Circ. No. 52, Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg : 11 pp.

Minter, W.E.L., 1973. Sedimentology of the Vaal Reef in the Klerksdorp area : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 170 pp.

Morrison, E.R., 1972. Corundum in Rhodesia : Min. Res. Ser. Geol. Surv. Rhod., 16 : 24 pp.

Ohashi, R., 1919. On the origin of Kuroko of the Kosaka mine : J. Geol. Soc. Tokyo, 26 : 107-132.

Papenfus, J.A., 1964. The Black Reef Series within the Witwatersrand Basin with special reference to its occurrence at Government Gold Mining Areas. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 1 : 191-218.

Park, C.F. and MacDiarmid, R.A., 1970. "Ore Deposits". (2nd ed) : W.H. Freeman and Co., San Francisco : 522 pp.

Partridge, T.C. and Brink, A.B.A., 1967. Gravels and terraces of the lower Vaal river basin : S. Afr. Geog. J., 49 : 21-38.

Plumstead, E.P., 1957. "Coal in Southern Africa". : Witwatersrand University Press, Johannesburg : 24 pp.

Pretorius, D.A., 1973. The role of E.G.R.U. in mineral exploration in South Africa : Inf. Circ. No. 77, Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg : 16 pp.

Ramdohr, P., 1958. New observations on the ores of the Witwatersrand in South Africa and their genetic significance : Annex. Trans. geol. Soc. S. Afr., 61 : 1-50.

Reimer T.O. and Heinrichs, T.K., 1974. A sedimentary barite deposit from the early Precambrian Fig Tree Group : In preparation.

Roper, H., 1959. The geology of the Otjosondu manganese area, South West Africa : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 164 pp.

Ryan, P.J., 1968. Stratigraphy of the Ecca Series and lowermost beds (Permian) in the Great Karroo Basin of South Africa : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 219 pp.

Saager, R., 1970. Structures in pyrite from the Basal Reef in the Orange Free State Goldfield : Trans. geol. Soc. S. Afr., 73 : 29-46.

Sahli, E.W., 1961. Antimony in the Murchison Range of the northeastern Transvaal : Trans. 7th Commonwealth Min. and Metall. Congr., 1 : 181-199.

Schweigart, H., 1965. Genesis of the iron ores of the Pretoria Series, South Africa : Econ. Geol., 60 : 269-299.

Simms, J.F.M., 1969. The stratigraphy and palaeocurrent history of the upper division of the Witwatersrand System on President Steyn Mine and adjacent areas with special reference to the origin of auriferous reefs : Unpub. Ph.D. thesis, Univ. Witwatersrand, Johannesburg : 181 pp.

Smith, D.A.M., 1965. The geology of the area around the Khan and Swakop rivers in South West Africa : Mem. Geol. Surv. S. Afr., 3 : 113 pp. (South West Africa Series).

Snyman, C.P., 1965. Possible biogenetic structures in Witwatersrand thucolite : Trans. geol. Soc. S. Afr., 68 : 225-235.

Söhnge, P.G., 1945. The geology of the Messina copper mines and surrounding country : Mem. Geol. Surv. S. Afr., 40 : 280 pp.

Söhnge, P.G., 1958. The environment of copper deposits in South West Africa : Joint Meeting reg. Com. Geol., Leopoldville, Publ. C.C.T.A., 44 : 231-248.

Söhnge, P.G., Visser, D.J.L. and Van Riet Lowe, C., 1937. The geology and archaeology of the Vaal river basin : Mem. Geol. Surv. S. Afr., 35 : 192 pp.

Söhnge, P.G., le Roex, H.D. and Nel, H.J., 1948. The geology of the country around Messina. An explanation of Sheet No. 46 (Messina). : Geol. Surv. S. Afr. : 74 pp.

Stagman, J.G., 1959. The geology of the country around Mangula Mine, Lomagundi and Urungwe Districts : Bull. Geol. Surv. S. Rhod., 46 : 84 pp.

Stanton, R.L., 1972. "Ore Petrology". : McGraw-Hill, Inc., New York : 713 pp.

Steyn, L.S., 1964. The sedimentology and gold distribution pattern of the Livingstone Reefs on the West Rand : Unpub. M.Sc. thesis, Univ. Witwatersrand, Johannesburg : 132 pp.

Strauss, C.A., 1964a. The iron ore deposits in the Thabazimbi area, Transvaal. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 383-392.

Strauss, C.A., 1964b. The iron ore deposits in the Sishen area, Cape Province. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 393-403.

Summerhayes, C.P., 1973. Distribution and origin of phosphate in sediments from the Agulhas Bank South Africa : Tech. Rep. Marine Geology Programme, Joint Geol. Surv. S. Afr.,/Univ. Cape Town, 5 : 94-114.

Swiegers, J.U., 1949. Gold deposits of the Pilgrims Rest gold mining district, Transvaal : Trans. geol. Soc. S. Afr., 51 : 81-132.

Swift, W.H., 1962. The geology of the Middle Sabi Valley : Bull. Geol. Surv. S. Rhod., 52 : 30 pp.

Talbot, C.J., 1973. The geology at the eastern end of the Zambesi orogenic belt, Rhodesia : Trans. geol. Soc. S. Afr., 76(2) : 113-133.

Toens, P.D., 1966. Precambrian dolomite and limestone of the northern Cape Province : Mem. Geol. Surv. S. Afr., 57 : 109 pp.

Turner, B.R., 1971. The geology and coal resources of the northeastern Cape Province : Bull. Geol. Surv. S. Afr., 52 : 74 pp.

Van Biljon, W.J., 1964. The chrysotile deposits of the eastern Transvaal and Swaziland. In: S.H. Haughton (Editor), "The Geology of Some Ore Deposits in Southern Africa". : Geol. Soc. S. Afr., 2 : 625-669.

Van Eeden, O.R., Partridge, F.C., Kent, L.E. and Brandt, J.W., 1939. The mineral deposits of the Murchison Range east of Leydsdorp : Mem. Geol. Surv. S. Afr., 36 : 163 pp.

Van Rensburg, W.C.J., Bishopp, D.W. and Savage, W.H.D., 1969. South Africa's coal resources : S. Afr. Coal Advisory Board : 38 pp.

Van Rooyen, D.P., 1951. Fluvial andalusite deposits in the Marico District : Bull. Geol. Surv. S. Afr., 19 : 18 pp.

Vermaas, F.H.S., 1952. The amphibole asbestos of South Africa : Trans. geol. Soc. S. Afr., 55 : 199-229.

Viljoen, R.P., 1973. ERTS 1 imagery as an aid to the understanding of the regional setting of base metal deposits in the northwest Cape Province, South Africa : 3rd Symp. of Significant Results obtained from ERTS 1 held at Goddard Space Flight Center. N.A.S.A., Washington, D.C. (In press).

Viljoen, R.P. and Viljoen, M.J., 1969. The relationship between mafic and ultramafic magma derived from the upper mantle and the ore deposits of the Barberton region : Spec. Publs. geol. Soc. S. Afr., 2 : 221-244.

Viljoen, R.P., Saager, R. and Viljoen, M.J., 1969. Metallogenesis and ore control in the Steynsdorp Goldfield, Barberton Mountain Land, South Africa : Econ. Geol., 64 : 778-797.

Visser, D.J.L. (Compiler), 1956. The geology of the Barberton area : Spec. Publ. Geol. Surv. S. Afr., 15 : 253 pp.

Visser, H.N. (Compiler), 1963. Gips in die Republiek van Suid-Afrika : Handbook, Geol. Surv. S. Afr., 4 : 152 pp.

Visser, H.N. and Verwoerd, W.J. (Compilers), 1960. The geology of the country north of Nelspruit. An explanation of Sheet 22 (Nelspruit) : Geol. Surv. S. Afr. : 128 pp.

Visser, H.N. and Schoch, A.E., 1973. The geology and mineral resources of the Saldanha Bay area : Mem. Geol. Surv. S. Afr., 63 : 150 pp.

Von Backström, J.W., 1973. Uranium amongst the fossils : Nuclear Active, Journal of the South African Atomic Energy Board. July, 1973 : 31-34.

Wagner, P.A., 1928. The iron deposits of the Union of South Africa : Mem. Geol. Surv. S. Afr., 26 : 268 pp.

Wagner, P.A., 1971. "The Diamond Fields of Southern Africa". : C. Struik (Pty.) Ltd., Cape Town : 355 pp.

Warner, S.M., 1972. Check list of the minerals of Rhodesia : Bull. Geol. Surv. Rhod., 69 : 101 pp.

Watson, R.L.A., 1960. The geology and coal resources of the country around Wankie, Southern Rhodesia : Bull. Geol. Surv. S. Rhod., 48 : 57 pp.

Wessels, J.T., 1967. Teorie bewys daar is baie meer erts op Sishen : Iscor News, Pretoria. December, 1967 : 2-7.

White, D.E., 1968. Environments of generation of some base-metal ore deposits : Econ. Geol., 63(4) : 301-335.

Williams, A.F., 1930. Diamond-bearing alluvial gravels of the Union of South Africa : 3rd Empire Min. and Metall. Congr., S. Afr. : 1-169.

Willemse, J., Schwellnus, C.M., Brandt, J.W., Russel, H.D. and Van Rooyen, D.P., 1944. Lead deposits in the Union of South Africa and South West Africa with some notes on associated ores : Mem. Geol. Surv. S. Afr., 39 : 177 pp.

Wilson, H.D.B., 1967. Volcanism and ore deposits in the Canadian Archean : Trans., Geol. Ass. Can., 18 : 11-30.

Winkler, H.G.F., 1967. "Petrogenesis of Metamorphic Rocks". : Springer-Verlag, New York : 237 pp.

Worst, B.G., 1962a. The geology of the Buhwa iron ore deposits and adjoining country : Belingwe District : Bull. Geol. Surv. S. Rhod., 53 : 114 pp.

Worst, B.G., 1962b. The geology of the Mwanesi Range and the adjoining country : Bull. Geol. Surv. S. Rhod., 54 : 63 pp.

Wybergh, W.J., 1925. The economic geology of Sabie and Pilgrims Rest : Mem. Geol. Surv. S. Afr., 25 : 124 pp.

Wybergh, W.J., 1928. Coal resources of the Union of South Africa : Mem. Geol. Surv. S. Afr., 19, Volumes I, II, III.

Zietsman, A.L., 1967. The relationship between mineralization and structure in the Pilgrim's Rest-Sabie Gold-field : Unpub. D.Sc. thesis, Univ. of the Orange Free State, Bloemfontein : 197 pp.

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