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THE NATURE AND DISTRIBUTION OF ARCHAEAN GOLD MINERALIZATION IN SOUTHERN AFRICA

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by

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SYNOPSIS

Archaean gold deposits are considered in the context of their geological setting in southern Africa. A brief historical review is followed by data on gold production from the Rhodesian and Kaapvaal cratons. A comparison is made with available information on gold outputs of other Archaean regions in the World and it is shown that southern Africa presents an anomalous picture of gold metallization. The geological setting of the Archaean gold occurrences of Rhodesia, Botswana, Swaziland, and South Africa, is outlined, and maps illustrating the nature and distribution of some of the 4000 gold deposits in the region are provided. The gold occurrences are discussed in terms of the various classification criteria that have been devised by mineralogists as well as structural and economic geologists. The mineralogy of Archaean gold deposits and the composition of the gold is briefly described and problems relating to the refractoriness of some of the gold ores are outlined. Particular attention is devoted to the geological controls of gold deposits in the Barberton Mountain Land and in selected areas of Rhodesia. Emphasis is placed on illustrating, with the aid of maps and diagrams, the controlling influences of stratigraphy, structure, metamorphism, and granite emplacement on the localization of economic gold ore deposits. Finally, the origin and genesis of Archaean gold mineralization is reviewed. It is concluded that field and experimental evidence supports the view that gold is stratigraphically controlled in the first instance but may be relocated with respect to its host environments by structural and metamorphic events that followed the intrusion of the wide-ranging granite types developed on the cratons.

HISTORICAL INTRODUCTION

Just when the early mining of gold by the 'ancients' first began in southern Africa remains obscure. Archaeological evidence suggests, however, that mining in the State of Mysore in India may have provided the inspiration for the 'Rhodesian' ancient workings to have developed from the third century A.D. onwards[1].

By the time the early European explorers arrived on the scene during the nineteenth century, the ancient workings of Rhodesia had long been abandoned and largely forgotten. In 1866 Carl Mauch, a German geologist and explorer confirmed that the old diggings seen a year earlier by the elephant hunter Henry Hartley were indeed ancient gold workings and he announced the discovery of the Tati goldfield in Botswana and the Umfuli goldfield in Rhodesia[2,3,4].

Between 1868 and 1870 further gold discoveries were made by Mauch and Messrs. Button and Sutherland in the Olifants River area, in the Murchison Range and in the Pietersburg schist belt at Eersteling and Marabastad. The first gold mined in the Transvaal came from Eersteling in 1871[2].

In 1873 gold was reported from the Lydenburg-Spitskop-Pilgrims Rest-Sabie areas and in 1881 alluvial gold was discovered in Swaziland near Pigg's Peak. By 1882 alluvial gold was being mined in the Jamestown schist belt in the Barberton Mountain Land and a year later the first payable vein or lode gold was found in the district[5].

Dr C. R. Anhaeusser obtained his degrees in geology from the University of the Witwatersrand in Johannesburg. In 1962, he joined the Economic Geology Research Unit of this University and received an M.Sc. degree for work on various aspects of the geology and gold mineralization in the Barberton Mountain Land. In 1964, he was appointed to the post of Research Fellow on the staff of the Economic Geology Research Unit and from then until 1969, when he obtained his Ph.D. degree, he was engaged in further research work in the main gold-producing regions of the Barberton Mountain Land. Also in 1969, he spent several months examining the Archaean geology and mineral occurrences in the Pilbara and Yilgarn regions of the Western Australian Shield. His work since then has been primarily concerned with geological mapping and geochemical studies of the Archaean granite-greenstone terrane in southern Africa. In particular, he has used the knowledge gained from studies of the Archaean to formulate ideas and models relating to the development of various types of mineralization as well as to the evolution of the early Precambrian crust of southern Africa. Dr Anhaeusser currently holds the position of Senior Research Fellow in the Economic Geology Research Unit and is still engaged mainly on studies relating to some of the oldest rocks on earth and is collaborating with fellow scientists on a research programme that forms part of South Africa's contribution to the International Geodynamics Project.

FIGURE 1 Alluvial gold diggings in the Jamestown Schist Belt, Barberton Mountain Land – circa 1884.

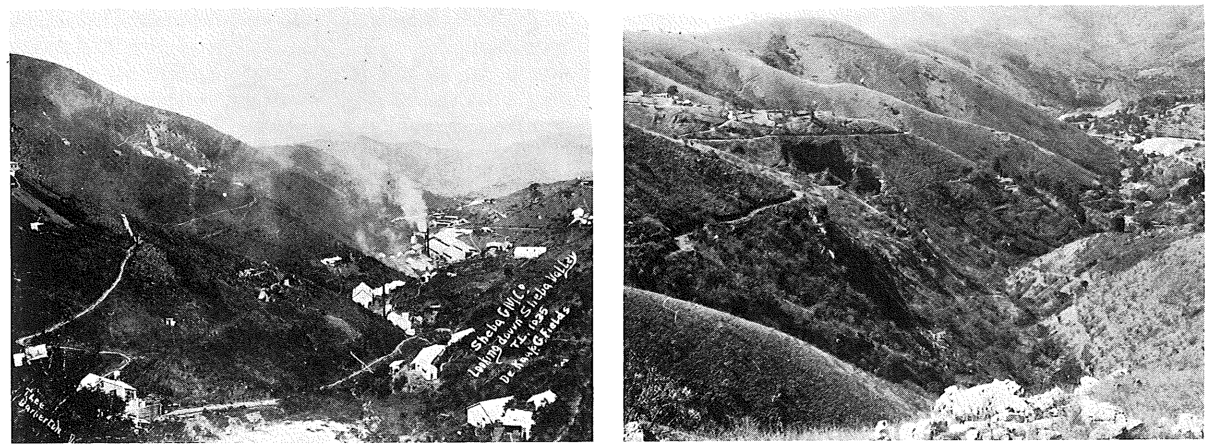

FIGURE 2 Left. View east down Sheba Valley in the Barberton Mountain Land showing the numerous workings and intensive activity of the Sheba Gold Mining Company – circa 1890. Right. Recent view down the same, yet almost deserted, Sheba Valley. On the left can be seen the famous Golden Quarry workings. In the distance on the right are mine dumps of the Sheba Gold mine, while in the foreground are cherts forming part of the Sheba Fault.

The reports of 'fabulous gold finds' in the Barberton region started one of the most spectacular gold rushes in South African history. This was, however, soon to be eclipsed by the historic discovery, by George Harrison and George Walker in March 1886, of auriferous conglomerates on the farm Langlaagte, which eventually led to the establishment of the Witwatersrand goldfield.

ARCHAEAN GOLD PRODUCTION

The task of establishing accurately the quantity of gold that has been mined from the Archaean terranes of southern Africa is beset with difficulties and, at best, only estimated yields can be hazarded. Even the number of workings that have been mined for gold remains uncertain. In 1934, Lightfoot[6] quoted the following numbers for gold mines in Rhodesia:

Very large mines (producing between them over half the total gold of the country)	20
Medium mines (responsible for about one-quarter of the gold produced)	90
Small mines (responsible for about one-fifth of the gold produced)	3 660
Total number of mines	3 770

Summers[1] considered that approximately 90 per cent of these were pegged on ancient workings (i.e. 3 393) and he indicated that to this number would have to be added many old workings that, having been almost completely stoped out by the ancients, have recorded no modern production. Taken together with gold mines in adjoining territories of Botswana, Mozambique, Swaziland, and the Transvaal, a figure of about 4000 is arrived at.

Estimates of production from the ancient workings have included figures ranging from 1,25 million ounces to just over 21 million ounces. In an attempt to resolve this disparity, Summers[1] provided a set of new estimates of total output based on an objective appraisal of the number of workings, their size, values, and recovery methods, as well as eluvial and alluvial production. Summers concluded that the 'ancient' output, from the commencement of the gold trade to 1890, totalled between 20 and 25 million fine ounces.

Apart from the difficulties of estimating the production of the ancient workers, the gold finds at Tati and in the Barberton and Pietersburg areas, during the latter stages of the nineteenth century, went largely unrecorded until governmental controls were instituted. Gold outputs are thus generally reliable only from about 1900. A further difficulty, applicable to Rhodesian gold outputs, resulted from this government's decision, taken in 1965, to withhold mineral production statistics for political reasons.

Phaup[4] listed Rhodesia's production to the end of 1959 as being 35 602 087 ounces of gold and 8 984 515 ounces of silver. Since then, an additional 3 378 788 ounces of gold and approximately 550 000 ounces of silver were recorded to the end of 1965[7,8]. Based on an average production figure for the five-year period prior to 1965, it is estimated that a further 5,5 million ounces may have been recovered to date. It thus appears that the Rhodesian Archaean goldfields, since their inception, have possibly yielded between 65 and 70 million ounces of gold.

Further south in Botswana and the Transvaal, the goldfields in the Archaean formations at Tati, Barberton, Pietersburg, and elsewhere on the Kaapvaal craton, have contributed an estimated additional amount of approximately 8 million ounces of gold. Bearing in mind all the uncertainties, the total output from Archaean sources in southern Africa up to the present time, therefore has been approximately 80 million ounces of gold.

Gold production data from other Archaean regions in the World are also generally incomplete but the outputs available do permit broad comparisons to be made with the southern African outputs. For Western Australia, and including all the goldfields in the Pilbara and Yilgarn divisions of the shield, 64 875 630 ounces of gold had been recorded to the end of 1964[9]. Since then to the end of 1972 a further amount of approximately 3,8 million ounces were recorded[10]. To present, the total recorded production from Western Australia is about 70 million ounces.

Production data for the Archaean goldfields of India and Brazil are also incomplete. By far the bulk of India's recorded production of just over 24 million ounces[11,12,13] has come from the Kolar goldfield situated in the Dharwar schist belt of Mysore State in southern India. Outputs prior to 1882 are unknown but stemmed mainly from the

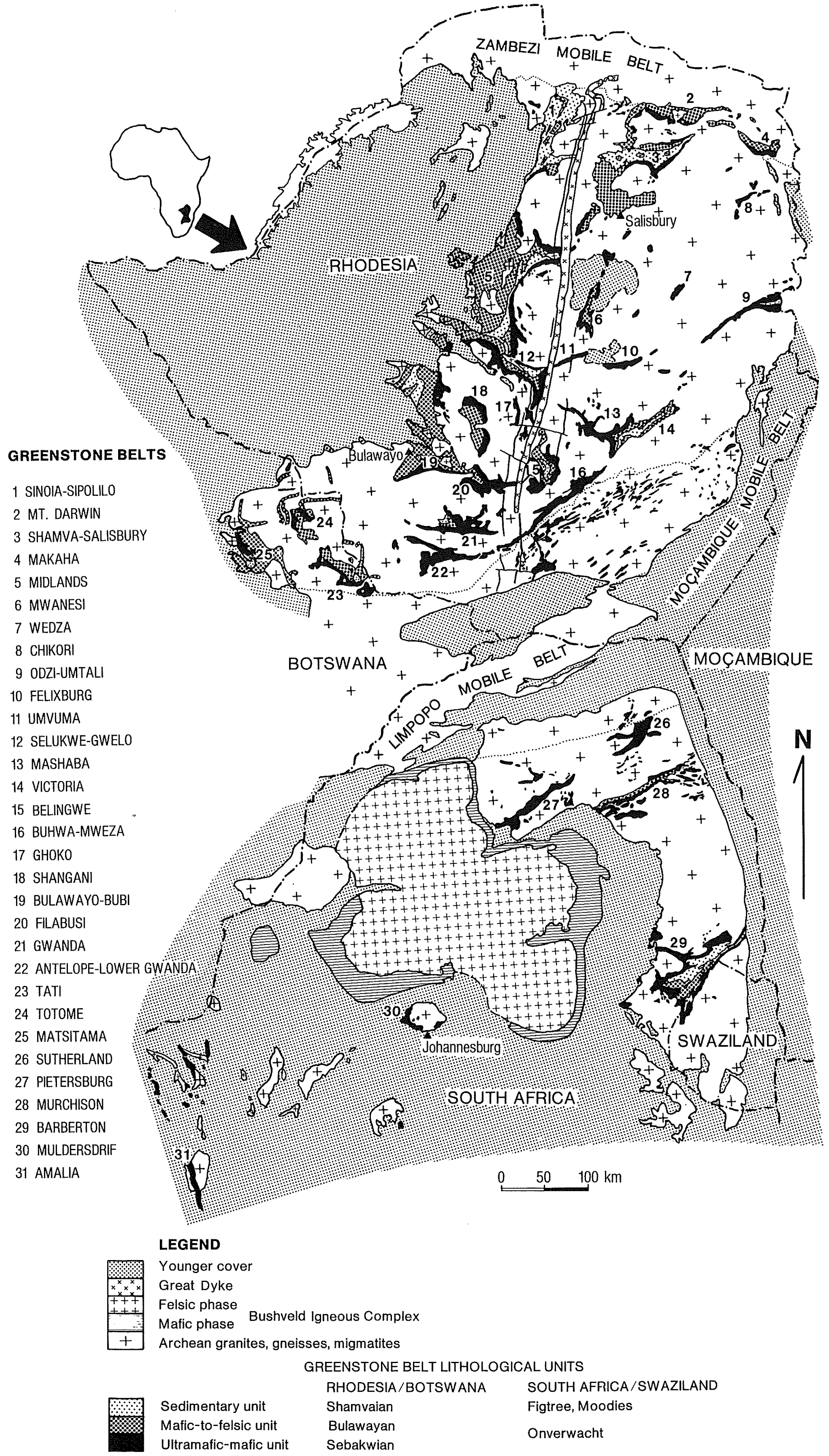

FIGURE 3 Map illustrating the exposed Archaean granite-greenstone terrane of the Rhodesian and Kaapvaal cratons, southern Africa (after Anhaeusser[19]).

activities of ancient workers who mined gold at least as far back as 2000 years ago.

Figures for Brazilian gold production for the period 1681-1927 indicate that 37 958 117 ounces were recovered[13]. From 1927 onwards, it is estimated[12] that a further 6 million ounces of gold were produced, bringing the total output from Brazil to about 44 million ounces. Although the bulk of this gold came from the Archaean successions in the province of Minas Gerais, no accurate breakdown of gold output can be given.

Lastly, figures for the Canadian Shield show this to be the largest producer of Archaean gold in the World. According to Gill[14], 74 761 635 ounces of gold had been mined from the shield area during the period 1858-1946. Thereafter it has been estimated from available statistics[12,15] that a further amount of approximately 98 million ounces have been mined from this region, making a total production of about 173 million ounces to the present.

By comparison with the Archaean goldfields of the World, the output from the Witwatersrand goldfield emphasizes the remarkable nature of this unique mineral occurrence. Production figures recorded to the end of 1973 indicate that 999 774 462 ounces of gold were mined from the area since 1886[16]. To this can be added at least a further 50 million ounces for the period 1974-1975 providing the Witwatersrand with the distinction of having yielded well over 1 thousand million ounces of the metal. Since the recorded history of gold mining this amount has accounted for approximately 55 per cent of all the gold so far mined in the World[17].

The Archaean gold production calculated on the basis of ounces per square kilometre (Table 1) shows that

TABLE 1

AREAL EXTENT, GOLD PRODUCTION, AND OUNCES OF GOLD PER UNIT AREA OF ARCHAEAN TERRANES IN SOUTHERN AFRICA, CANADA, AND WESTERN AUSTRALIA

Crustal fragment	Area (km²)	Estimated gold production (in millions of oz)	Gold in oz per km²
Rhodesian and Kaapvaal Cratons	897 000	78	91
Superior and Slave Provinces, Canada	2 195 000	173	79
Pilbara and Yilgarn Blocks, Western Australia	1 200 000	70	58

southern Africa occupies first place in comparison with the Canadian and Western Australian shield areas. In Table, 2 calculations are based on the degree of Archaean rocks exposed in southern Africa. This places the yield, per square kilometre, at more than double that of the Canadian Shield and over four times that of Western Australia. Bearing in mind that the latter two areas expose essentially Archaean rocks it can be seen that the southern African Archaean terrane possesses an anomalously high proportion of gold. Coupled with the fact that the Witwatersrand clearly derived its auriferous reefs from the erosion of such terrane[18] it appears that gold featured more prominently in sоuthern African greenstone belts than elsewhere in the World. A calculation based on the inclusion of the gold production from the Witwatersrand with that found in the Archaean suggests that the Kaapvaal craton has yielded approximately 1 700 ounces per square kilometre. If the gold production from Rhodesia, and its areal extent, are included in the calculations, the yield per square kilometre for the combined regions of the Kaapvaal and Rhodesian cratons amounts to approximately 1 200 ounces per square kilometre.

Anhaeusser[19] showed that the southern African greenstone belts, relative to their counterparts in other Archaean terranes, and particularly those of Canada, contain a greater proportion of ultramafic and mafic rocks, and are deficient in rocks of intermediate-to-felsic character. It was suggested that the prevalence of these assemblages probably represented a function of the greater age of the latter successions and attention was drawn to the development of greater abundances of the siderophile elements (e.g. Au, Ni, Fe, and the platinum-group metals), as well as chromium, in rocks of this character.

TABLE 2

AERIAL EXTENT OF EXPOSED ARCHAEAN FRAGMENTS IN SOUTHERN AFRICA AND OUNCES GOLD PRODUCED PER UNIT AREA

Crustal fragment	Exposed Archaean granite-greenstone terrane (km²)	Estimated gold production (in millions of oz)	Gold in oz per km²
Rhodesian and Kaapvaal Cratons	276 422	78	224
Rhodesian Craton	195 762	70	358
Kaapvaal Craton	80 662	8	99

OUTLINE OF SOUTHERN AFRICAN ARCHAEAN GEOLOGY

The early Precambrian (Archaean) granite-greenstone terrane that forms part of the southern African shield constitutes one of the oldest known fragments on the earth's surface. Underlying Rhodesia, the eastern part of Botswana and the northeastern segment of South Africa, the shield consists of two cratons – the Kaapvaal and Rhodesian cratons – separated by the Limpopo high-grade metamorphic belt. Ranging in age from 2700 to 3500 m.y. (or even older), the region acts as basement to a unique series of cratonic basins that developed under continental conditions as far back as 3000 m.y. ago[20,21].

Nature and distribution

A great variety of volcanic, sedimentary, and granitic elements make up the Rhodesian and Kaapvaal cratons. Scattered within the expanse of granitic rocks are numerous volcanic (greenstone) belts, the present-day configuration of which is shown in Figure 3. Much of the southern African Archaean is covered by younger geological formations that obscure approximately 70 per cent of the cratonic crustal area[19]. The exposed Archaean consists of granite-greenstone terrane, the latter occupying approximately one-third of the area of the Rhodesian and Kaapvaal cratons (cp. Tables 1 and 2).

Both the Rhodesian and Kaapvaal cratons are bounded by high-grade, polymetamorphic, mobile belts that are considered to represent reworked Archaean cratonic material, with or without, infolded, younger, supracrustal rocks[20,22].

TABLE 3

SUGGESTED LITHOSTRATIGRAPHIC CORRELATION OF RHODESIAN AND SWAZILAND ARCHAEAN ROCKS WITH THE BARBERTON STRATIGRAPHIC MODEL

SOUTH AFRICA Barberton belt		SWAZILAND	RHODESIA	UNIT	
MOODIES		MOODIES	SHAMVAIAN	arenaceous	SEDIMENTARY UNIT
FIG TREE		FIG TREE		argillaceous	
GELUK SUBGROUP	Swartkoppie	UPPER ONVERWACHT	BULAWAYAN	MAFIC-TO-FELSIC UNIT	
Upper Onverwacht	Kromberg				
Middle Marker	Hooggenoeg				
TJAKASTAD SUBGROUP *Lower Onverwacht*	Komati	LOWER ONVERWACHT	SEBAKWIAN	LOWER ULTRAMAFIC UNIT	
	Theespruit	Ancient gneiss complex	Pre-Sebakwian		
	Sandspruit				

Stratigraphy

The volcanic and sedimentary successions that comprise the Archaean greenstone belts of southern Africa fall into one or other of the lithostratigraphic subdivisions shown in Table 3. Investigations in the Barberton greenstone belt[30–33,63] led to the formulation of a stratigraphic model that is also considered to be applicable to greenstone belt occurrences in southern Africa as well as to Archaean greenstone belts elsewhere in the world[20,22,36].

At the base of the greenstone successions are rocks characterized by a variety of mafic and ultramafic metavolcanic[32] and plutonic rocks[31,33] together with subordinate interlayers of felsic volcanic and pyroclastic rocks and chemical sediments (including banded iron-formations, cherts, and calc-silicate rocks)[31]. This assemblage is collectively referred to as the *Lower Ultramafic Unit* and in many places has been extensively invaded, fragmented, and often apparently granitized[27,28,37] by the intrusion of a wide variety of granitic rock types.

Above the Lower Ultramafic Unit there is an abrupt change in the nature of the volcanicity in the successions that are collectively grouped into the *Mafic:to:Felsic Unit*[30]. Cyclically alternating mafic and intermediate to acid volcanic rocks, as well as a wide variety of pyroclastic and chemical sedimentary rocks predominate (tholeiitic basalts, andesites, dacites, rhyodacites, cherts, banded iron-formations and phyllites, as well as some stromatolitic limestones)[25,26,29–31].

Overlying the volcanic sequences in the greenstone belts are rocks of essentially sedimentary character made up of either an argillaceous assemblage, consisting of greywackes, shales, and siliceous chemical precipitates (banded ferruginous cherts and iron-formations), or an arenaceous assemblage, consisting of conglomerates, quartzites, sub-greywackes, sandstones, and shales, with subordinate jaspilitic cherts and banded iron-formations.

It has been proposed that successions older than the greenstone belts exist both in Rhodesia (the Pre-Sebakwian)[34] and in Swaziland (the Ancient Gneiss Complex)[35], but Viljoen and Viljoen[36,37] and Anhaeusser[20,31], regard these rocks as metamorphosed xenolithic equivalents of assemblages to be found in the Lower Ultramafic Unit. The granitic components of the two abovementioned units are also considered to post-date the Lower Ultramafic Unit[20,31,37].

Granites

The exposed Archaean of southern Africa consists predominantly of granitic rock types (approximately 85 per cent) with the greenstone belt relics making up the remaining 15 per cent of the present basement (Table 4).

Many detailed descriptions of the granites, gneisses, and migmatites are available, particularly in the bulletins of the Rhodesian Geological Survey as well as in other publications[20,23,24,31,35,37,40–42]. In Figure 4 the distribution of the soda- and potash-rich granite varieties is shown in relation to the greenstone belts.

Maximum preservation of the greenstone belts occurs in areas intruded by tonalites or trondhjemites and, where more potassic granites are found, greenstone remnants are either absent or are preserved only as small xenoliths. The areas of prominent migmatite development occur mainly in the regions adjacent to the greenstone belts or their xenolithic remnants and coincide largely with the areas underlain by sodic granite varieties. Most of the gold so far recovered in Rhodesia has been located in greenstone belts situated to the west of the Great Dyke where maximum development of the volcano-sedimentary greenstone accumulations are to be found and where also the bulk of the soda-rich granites are located.

The eastern half of the Rhodesian craton is made up mainly of homogeneous massive granodioritic and adamellitic rocks, some phases of which are porphyritic or porphyroblastic in character. Ghost remnants or nebulites of banded gneisses and migmatites, as well as isolated mafic xenoliths occur in places, the latter believed to be relics of what was probably once an extensive development of these rocks and that subsequently underwent transformation or granitization to a more homogeneous state. The general absence of greenstone belts and the small size of the few that do exist in the area east of the Great Dyke provide less suitable auriferous host rocks. Coupled with the fact that the eastern half of the Rhodesian craton has been subjected to more stages of granite reworking (potassium metasomatism) only the larger greenstone remnants still possess any appreciable quantities of gold.

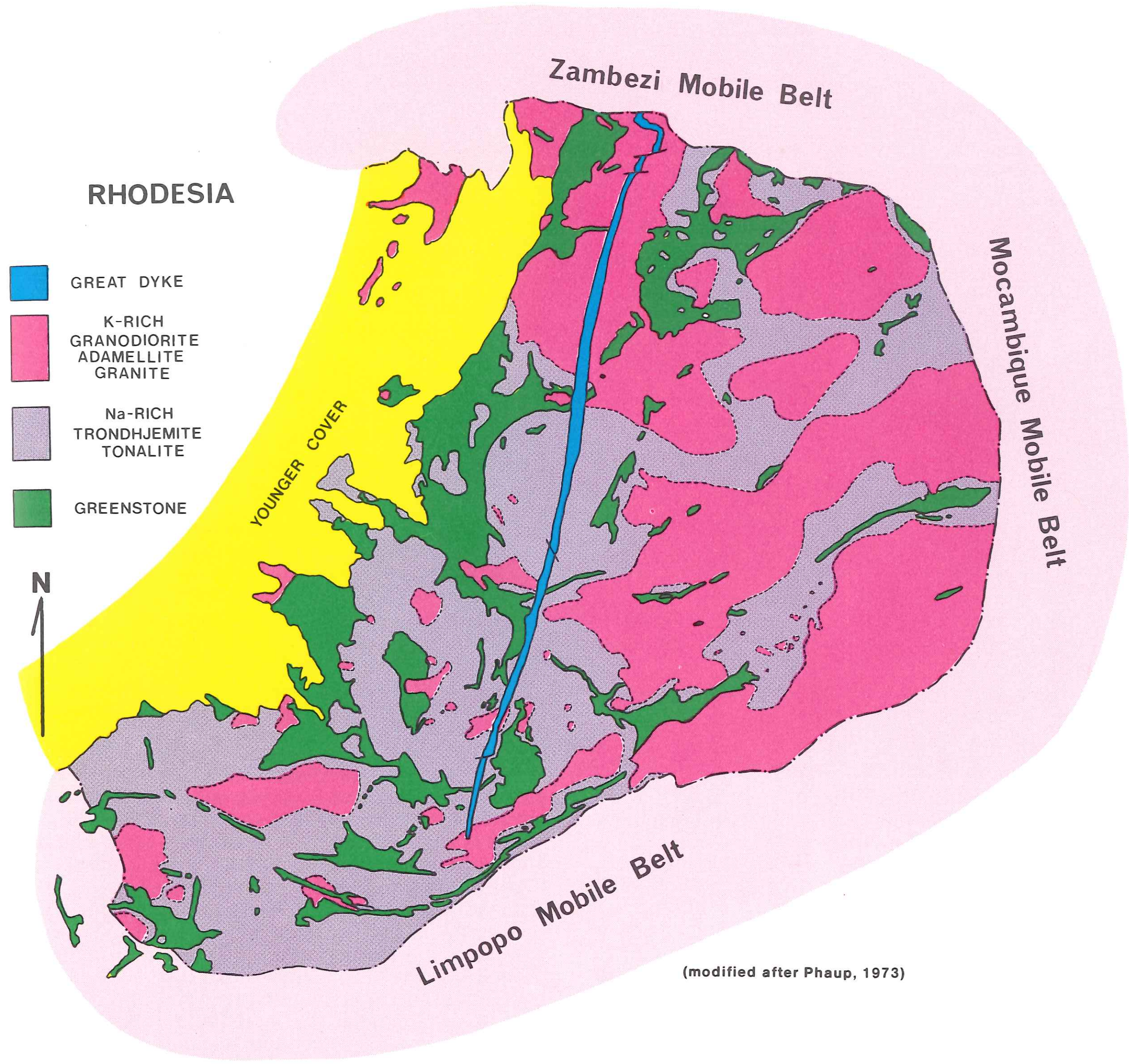

FIGURE 4 Simplified geological map of the Rhodesian craton and surrounding high-grade metamorphic mobile belts showing the distribution of the Archaean greenstone belts in relation to the various granites of the region. Maximum preservation of the greenstone assemblages and gold mineralization occurs in regions intruded by soda-rich granite types. The area east of the Great Dyke has largely been granitized by potash-rich granites (modified after Phaup[40]).

Geochronology

Isotopic age determinations carried out in southern Africa have confirmed that the majority of rock types grouped within the Archaean exceed 3000 m.y. in age. Davies *et al*[43] reported an age of 2530 m.y. for the Great Dyke of Rhodesia and thus established the minimum age for the Basement Complex into which the Great Dyke was intruded. Subsequently, ages ranging between 2600 and 3600 m.y. have been reported from various parts of the Rhodesian craton[44–46]. The areas of greatest antiquity occur between the Belingwe and Victoria greenstone belts where granites as old as 3600 m.y. have been reported[44,45]. These ancient granitic rocks contain xenolithic remnants of rock types similar to those of the Sebakwian succession.

Macgregor[23], and others[28,29] reported the presence of an unconformity between the granite basement and rocks classified with the Bulawayan succession[29] in the Belingwe greenstone belt. According to Morris[28], these basement gneisses also contain Sebakwian remnants.

Rocks of the Bulawayan Group have yielded ages of between 2600 and 2700 m.y.[45] but recently the opinion has been expressed that these ages may be more consistent with a metamorphic interpretation, and it has been suggested that the Bulawayan rocks may have erupted approximately 3100 m.y. ago[46].

Macgregor[27] considered that notable unconformities separate the main stratigraphic groups in Rhodesia. The granites, according to Phaup[4,40], appear to range from pre-Sebakwian to post-Shamvaian in age and most investigators consider that the greatest influx of granites occurred in post-Shamvaian times.

TABLE 4
AREAL EXTENT AND RELATIVE PROPORTIONS OF ARCHAEAN GRANITES AND GREENSTONES DEVELOPED ON THE RHODESIAN AND KAAPVAAL CRATONS

Crustal fragment	Exposed Archaean granite-greenstone terrane (km^2)	Exposed granites (km^2)	Exposed greenstones (km^2)	Exposed granites (%)	Exposed greenstones (%)
Rhodesian Craton	195 762	162 027	33 735	82,8	17,2
Kaapvaal Craton	80 662	73 778	6 884	91,5	8,5
Combined Rhodesian and Kaapvaal Cratons	276 424	235 805	40 619	85,3	14,7

(Modified after Anhaeusser[19])

CLASSIFICATION OF ARCHAEAN GOLD OCCURRENCES

Gold, although rare in quantity, nevertheless is a widely distributed mineral and occurs in a host of geological settings and rock types. Because of its widespread development there have been many attempts to classify the existing gold occurrences with the aim of being able to use these criteria to seek out new gold, either in existing deposits, or in areas where gold is known to occur, or is likely to occur. A feature of the Archaean gold deposits, not only of southern Africa but elsewhere in the world, is the remarkable dissimilarity between the different mines, not only from one goldfield to the next, but within individual goldfields. Nevertheless, the generalizations that have been attempted show that the majority of deposits fall into a few main classification types together with some intermediate varieties.

Two of the main types, according to Phaup and others[55,57], are the *gold-quartz lodes* and the *sulphide replacement bodies* or *impregnation lodes*. Of a subordinate nature are the eluvial and alluvial deposits, most of which occur in the rubble derived from the erosion of auriferous greenstone belts. Some Archaean placers, containing gold and pyrite, occur in conglomerate-quartzite formations and have been worked in a small way in the Transvaal (Uitkyk Formation) and in Rhodesia (Shamvaian)[58].

Over half the Archaean gold production has been derived from gold-quartz lode deposits. These are invariably directly related to structural influences caused by regional and local deformation[56,60-63]. The gold mineralization in deposits of this nature is dominantly structurally controlled and numerous descriptions of individual ore bodies (in Geological Survey bulletins as well as in theses[28,56,57,64,65]) stress the relation of ore veins and ore shoots to faults, fractures, fissures, shears, lineations, and folds.

In Rhodesia, Goldberg[60], Mehliss[56,62,73], Stowe[66], and others[57,61,67,74], provide detailed accounts of fracture systems that have played a dominant role in controlling the localization and distribution of auriferous deposits. Similarly, in the Barberton Mountain Land, investigations by Gribnitz[68], Poole[69], and Anhaeusser[70-72], have also stressed the part played by regional, as well as local, tectonics in influencing the development and distribution of gold lode deposits in the area. These structural studies have not been restricted to individual ore shoots or mines but have also been sub-regionally orientated and have been employed successfully in exploration to locate extensions to known ore bodies as well as new deposits[62].

Emphasis has largely been placed on structural controls to mineralization in lode deposits by some writers. Others agree that tectonic influences have played a significant role in localizing this type of gold occurrence, but place importance on the combined influences of tectonic and stratigraphic controls in the distribution of lode deposits. Because much of the gold occurs in fissures, and because the latter are often controlled by structural features such as folds, rolls, and other irregularities in the fissures, the influence of the host rocks in determining the localization of ore deposits has generally received only cursory attention. Only in a few cases have there been reports that the wall rocks influenced the deposition of ore. Phaup[4] quotes examples of how rock types such as serpentinites acted as impermeable barriers to ore fluids and how hard, brittle, rocks such as banded iron-formations and quartz porphyries shattered during deformation to produce numerous fractures and fissures. Banded iron-formations deformed in this way came to be regarded as favourable host rocks for the development of sulphide replacement ore bodies.

More recently there has been a tendency throughout the World to deviate from some of the earlier theories of ore generation and several investigators have argued that many of the ore deposits can be genetically linked to their host rock environments[75-79]. In southern Africa examples of this type include the deposits described by Viljoen *et al*[80] in the Steynsdorp goldfield in the Barberton greenstone belt and the numerous examples of stratabound gold occurrences in the Archaean banded iron-formations in Rhodesia, reported by Fripp[38,39,59].

From very early on it was realized that the majority of gold deposits occur in the greenstone belts, the latter also known locally as 'gold' or 'schist' belts. A lesser number of ore bodies were found within the granite batholiths, frequently alongside or inside inclusions of schist, and generally located within a few kilometres of the main granite contact and not in the middle of the batholiths[4]. In an attempt to establish the regional and stratigraphic controls of gold occurrences in Rhodesia, Collender[57] suggested that the deposits could be classified in terms of the rock types in which the ore bodies are found. His six-fold scheme of classification is listed as follows:

- Deposits in the granites,
- Deposits in ultrabasic rocks,
- Deposits in Bulawayan-jaspilites,
- Deposits in Bulawayan lavas,
- Deposits in Shamvaian sediments, and
- Gold deposits in stocks and intrusives.

Recently Fripp[59] introduced a four-fold classification of gold deposits in Rhodesia based upon the geological nature of the ore bodies. These were listed as:

- stratiform deposits of mineralized banded iron-formation,
- stratabound 'massive' sulphides,
- quartz lodes, veins, stockworks and siliceous shear zones, and
- stratabound disseminated mineralization in clastic rocks.

According to Fripp[59] about 25 per cent of Rhodesia's gold has been derived from mineralized banded iron-

FIGURE 5 Gold in dark vein quartz from the supergene enriched oxidized zone of the Lily gold mine, Barberton Mountain Land. Approximately 60 ounces of gold were recovered from the specimens. The scale, from left to right, across the samples is 27 centimetres.

formations and his stratiform deposits may be regarded as synonymous with gold occurrences previously termed sulphide replacement lodes[4,6,55,56,60]. Likewise, deposits referred to previously as impregnations lodes[6,55,60] would qualify mainly for inclusion with Fripp's category of stratabound disseminated ore bodies.

Stratabound 'massive' sulphide deposits like those in Canada[78], and that have produced gold, are uncommon in southern Africa. Fripp[59] quotes several examples of this type from Rhodesia, including the Iron Duke mine[82] in the Salisbury greenstone belt, which was initiated by gold extraction from the supergene enriched capping of massive sulphide, but which is now merely a pyrite producer. A further example of this type would be the Consolidated Murchison antimony-gold deposit[58,81,83] in the Murchison greenstone belt on the Kaapvaal craton (Figure 3). Deposits of the massive sulphide type occur interlayered with extrusive volcanic rocks.

Fripp[38,39,59] produced a regional map showing the position of some of the larger Rhodesian gold mines, the latter located with respect to his reinterpretation of the Archaean stratigraphy of the region. In Table 5, which is after Fripp[59], the lithostratigraphic distribution of 100 mines is shown, all of which have produced more than 20 000 ounces of gold up to the end of 1964. The table also provides a guide to the nature and relative numbers of deposits in specific parts of the Rhodesian Archaean stratigraphy.

Mineralogical classification

In 1934 Lightfoot[6] employed distinctive mineralogical characteristics of the gold lodes to classify 110 of the larger gold mines in Rhodesia. Five groups emerged from the study:

- pyritic gold-quartz veins in 73 lodes,
- pyritic impregnations along shatter belts in 26 lodes,
- antimonial impregnations along shatter belts in 6 lodes,
- antimonial quartz veins in 4 lodes, and
- cupriferous gold-quartz veins in 1 lode.

This oversimplification of the mineralogy was designed to emphasize the dominant ore mineral in each category, there being numerous others besides gold and the particular mineral singled out for special mention. According to Lightfoot[6] the pyrite-gold-quartz deposits are accompanied by ore minerals such as galena, sphalerite, or scheelite. Secondly, the pyrite impregnation lodes may be accompanied by one or more of the following ore minerals: arsenopyrite, sphalerite, chalcopyrite, galena, or

TABLE 5
LITHOSTRATIGRAPHIC DISTRIBUTION OF DIFFERENT TYPES OF GOLD DEPOSIT IN RHODESIAN GREENSTONE BELTS

Type	Sebakwian group	Bulawayan and Shamvaian groups	Granitoids	Total
Stratiform	27	3	0	30
'Massive'	3	4	0	7
Quartz lode	18	30	8	56
Dissemination	2	5	0	7
Total	50	42	8	100

(after Fripp[59])

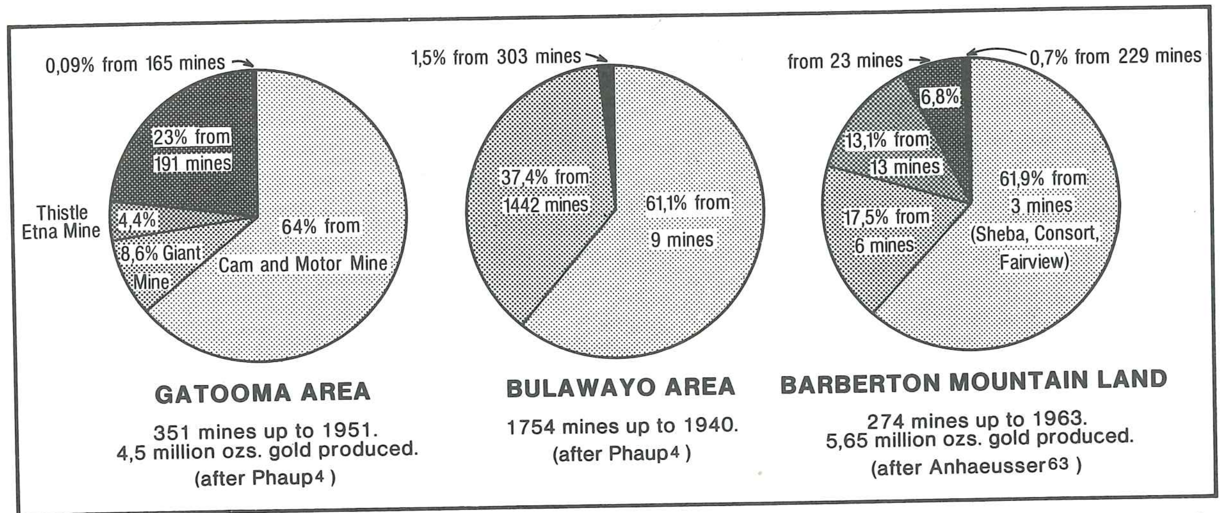

FIGURE 6 Pie charts illustrating the localized nature of gold mineralization in the Gatooma and Bulawayo regions of Rhodesia, and in the Barberton Mountain Land, South Africa. Most of the gold production stems from only a few mines in any one region.

pyrrhotite. Thirdly, the antimonial impregnations have the same general characteristics as the pyritic variety. In some cases, these lodes carry free gold or gold-bearing stibnite. Some lenses also consist of stibnite barren of gold. Pyrite, arsenopyrite, galena, sphalerite, and chalcopyrite are rare in these ores. The fourth category listed by Lightfoot contains stibnite as the main associate of the free gold and the stibnite is also gold-bearing. The single cupriferous gold-quartz ore body is that of the Falcon mine in the Umvuma greenstone belt. In this deposit free gold, auriferous pyrite, and chalcopyrite occurred together, with pyrrhotite replacing the chalcopyrite at depth. To the end of 1958, 391 957 ounces of gold and 34 420 tons of copper[84] had been mined from this ore body, the sulphide content of which often rose as high as 8 per cent. Between 1914 and 1925 the average copper grade of the ore was 1,6 per cent.

Lightfoot's account of the mineralogy of the Rhodesian gold lodes remains the only regional compilation of this type. Fripp[39] has since carried out a more restricted study of sulphide mineral assemblages associated with 14 gold deposits occurring in banded iron-formations in various localities across the Rhodesian craton. He concluded that there are differences in the sulphide minerals at the deposits examined and that, furthermore, there appeared to be regional mineralogical variations. It was found, for example, that the sulphide facies iron-formation in the Odzi-Umtali belt in the east (Figure 3) is characterized by Pb, Cu, and Ag (Neardy mine). To the west, in the Umvuma belt, this changes to Cu, Co, and Au with lesser amounts of Pb and Ag (Athens mine). Northwards from here, into the Gwelo and southern Midlands belts, the deposits are characterized by abundant pyrite and pyrrhotite (Connemara mine). As this line is followed north, into the central and northern parts of the Midlands belt, As and Au become prominent with subordinate amounts of pyrite and pyrrhotite (Beehive, Sherwood Starr, and Pickstone mines). In the Salisbury-Shamva belt, pyrite and pyrrhotite most commonly accompany the gold. South of the Gwelo-Selukwe belt, the deposits in the Shangani-Bulawayo belts are also characterized by Au with pyrite and pyrrhotite (Nelly 404 and Tin Hat mines), but changes to Au with As further south in the Gwanda and Victoria belts (Marvel, Empress, and Vubachikwe mines).

The significance of the regional differences in the metals concentrated in the iron-formation beds remains obscure but Fripp[39] suggested that they may reflect regional differences in their availability and transport and in their depositional environment.

Phaup[4] also attempted to ascertain whether regional variations existed with respect to the types of minerals found in the gold occurrences of Rhodesia. He reported that pyrite is found in gold reefs everywhere and that pyrrhotite, which is invariably free of nickel, is found around Shamva, Mazoe, Gadzema, Gatooma, Golden Valley, Hunter's Road, Gwelo, north Selukwe, Bulawayo, Essexvale, west of Gwanda, and Antelope (for localities consult Geological Survey map of Rhodesia).

Arsenic and antimony minerals, it was pointed out[4], occur mainly in gold deposits at Bindura, Odzi, Chakari, Gatooma, Battlefields, Que Que, the Bembezi Valley, west of Gwanda and at the Sun Yet Sen mine (Lower Gwanda belt). Lead, zinc, and copper minerals occur in mines near Penhalonga, Bindura, Que Que, south Selukwe, Umvuma, Filabusi, and the Lonely and Queen's mine areas (Bulawayo belt) as well as east of Gwanda. Copper metal has been produced from gold reefs of the Falcon mine at Umvuma, the Hanover mine at Filabusi, and the Valley mine near Gwanda. Lead has been a by-product of the Penhalonga, Old West, and Clutha mines at Penhalonga and Umtali.

Molybdenum has been reported from the Mont d'Or area near Selukwe[66] and molybdenum and tungsten minerals have been found in gold lodes at Bindura, Golden Valley, west of Gwelo, Filabusi and Essexvale. According to Phaup[4], these usually occur in an older, almost gold-free quartz, the latter incorporated in later gold-quartz veins. Bismuth minerals have been recorded at the Anzac

FIGURE 7 Simplified geological map of the Barberton greenstone belt and surrounding granitic terrane. Superimposed on the geology are the main regional structural trends (folds and faults) as well as the positions of 196 of the 274 reported localities where gold has been mined. From southwest to northeast the Barberton belt measures approximately 130 kilometres.

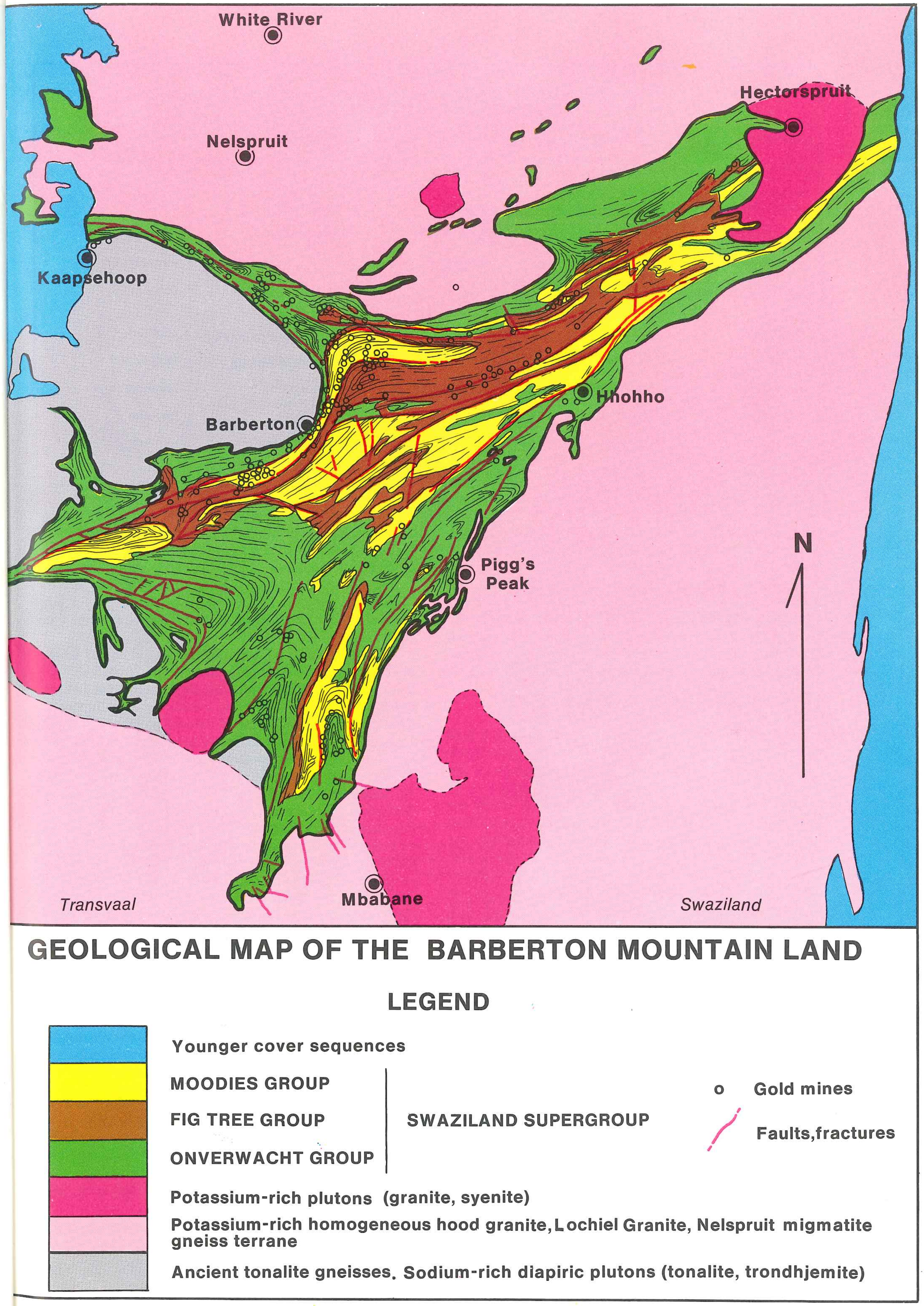

TABLE 6

ORE MINERALS ASSOCIATED WITH GOLD DEPOSITS IN THE BARBERTON MOUNTAIN LAND

ankerite	chalcopyrite§	franklinite	magnetite§	pyrite§
anglesite	chloanthite‡-skutterudite*	galena§	malachite	pyrrhotite§
native antimony‡		graphite	marcasite†	safflorite
argentite	chromite	geothite‡	maucherite	siderite
arsenopyrite†	cobaltite‡	native gold†	melnikovite-pyrite†	native silver§
berthierite	native copper‡	hematite		sphalerite§
metallic bismuth‡	corynite	ilmenite	millerite	stibnite§
bornite	covellite‡	jamesonite§	molybdenite	tetradymite
bournonite	cubanite	lepidocrocite	neodigenite‡	tetrahedrite†§
bravoite	electrum‡	leucoxene‡	niccolite	trevorite
cerrusite	enargite‡	linnaeite	pentlandite	ullmanite‡
chalcocite‡	famatinite‡	loellingite‡	pyrargyrite	vallerite
*(types 2 and 3[99])	†main ore minerals	‡found with gold	§(two types)	

mine (north of Que Que), in the Makaha greenstone belt, at Penhalonga, at the Step Lively mine near Hartley, at Gatooma, and the Horn mine in the Gwanda belt. Nickel-cobalt minerals occur at the R.A.N. mine near Bindura, at the Gaika mine near Que Que, at the Glen Rosa mine near Selukwe, and at the Legion mine in the Lower Gwanda greenstone belt. Tellurides appear to be rare but have been reported from the New Mystery mine (Lower Gwanda belt) and from the Glen Rosa mine (Selukwe)[66].

MINERALOGY OF THE ARCHAEAN GOLD DEPOSITS

A number of publications describing the geology of gold deposits in the Archaean terranes of southern Africa also contain valuable information on the mineralogy of the ores[56,66,69,73,80,85-98]. Apart from a brief mention by Phaup[4] and Fripp[38], no summarized account of the ore mineralogy of the Rhodesian gold mines is available. Comprehensive mineralogical syntheses, however, are available for the gold ores in the Barberton Mountain Land. In 1957, De Villiers[87] provided mineralogical details of 21 mines in the area, and described 27 ore minerals, as well as various associations of gold with sulphide minerals. From his study, De Villiers advocated the division of the ores in the Barberton area into four main types:

- ☐ ore containing arsenopyrite and pyrrhotite,
- ☐ pyritic ore,
- ☐ lead-bearing ore, and
- ☐ antimonial ore.

Problems relating to gold extraction forced many small mines in the Barberton area to close down. These events prompted a subsequent detailed mineralogical examination of the ores at the National Institute for Metallurgy in Johannesburg. Sixteen localities were sampled where refractory gold ores did not respond to the conventional methods of treatment. The ores considered included the four main producers in the region – the Sheba, New Consort, Fairview, and Agnes mines. The study, by Schweigart and Liebenberg[92], led to the identification of a further 28 ore minerals. To this total of 55 ore minerals can be added five others (and possibly a sixth, the latter tentatively identified as the gold-silver telluride *petzite)* found by Viljoen *et al*[80] in the ores of the Steynsdorp goldfield on the southern flank of the Barberton greenstone belt (Figure 8).

Table 6 lists the 60 ore minerals found so far in the Barberton ores, gold being associated with 26 of them[92,98]. It is considered likely that the ore minerals listed in Table 6, together with several others, would be encountered in Rhodesian gold ores. Some of the additional ore minerals already known to occur in Rhodesia include the tungsten minerals scheelite and wolframite, and tellurides[4,66].

The most important gold-bearing sulphide in the Archaean ores is pyrite[4,92,98]. In some cases, as at Barberton, there are two generations of pyrite. The mineral is generally associated with a large number of other ore minerals of which arsenopyrite and pyrrhotite are by far the most important. Where oxidized, the pyrite is altered to goethite, lepidocrocite, and/or hematite. Second in importance, as a host of gold in the ore, is arsenopyrite, the latter occurring commonly with pyrrhotite.

The investigations of Schweigart and Liebenberg[92] and Liebenberg[98] led these authors to the conclusion that the division of the Barberton gold ores into four ore types, as advocated by De Villiers[87], is not strictly correct because most of the ores contain a large number of minerals. No one mineral distinctly predominates in any of the ores examined although pyrite is usually a major constituent. They proposed that is was justifiable to distinguish only three ore types. These they listed as follows:

- unoxidized, complex sulphidic ore that is the main ore type present,
- gold-bearing quartz veins, containing only negligible amounts of sulphide minerals, that are common throughout the area, and
- weathered ore, occurring in the oxidized zone, that

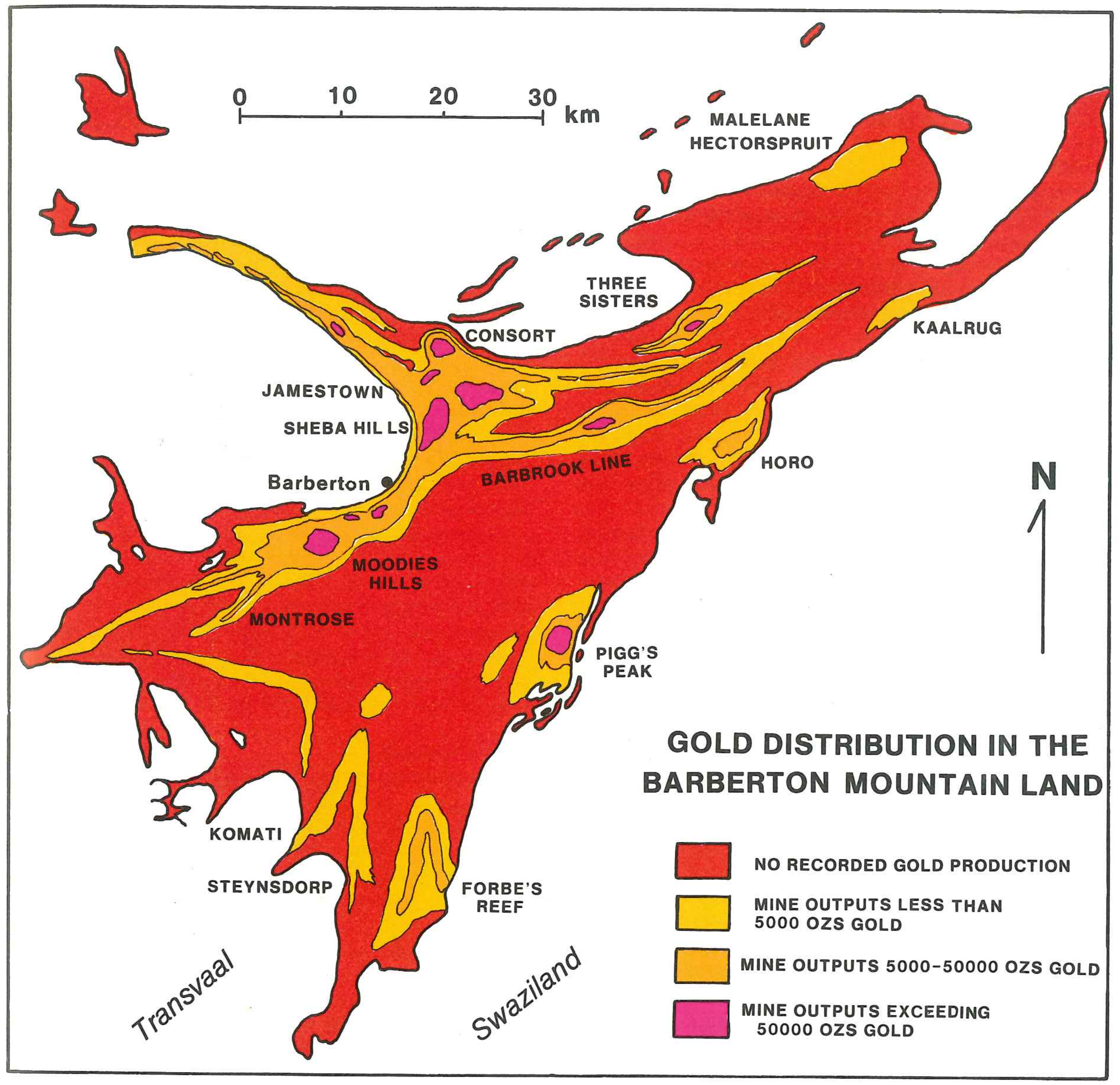

FIGURE 8 Map of the Barberton greenstone belt showing the regional distribution of gold mineralization in Swaziland and the Transvaal. Approximately 95 per cent of all the gold recovered from the area occurs on the northwest flank of the greenstone belt with the major concentrations being found in the Jamestown, Sheba and Moodies Hills regions (after Anhaeusser[63]).

represents the main gold supplier of the past.

This simple three-fold ore classification would apply equally to all the other Archaean gold deposits in southern Africa.

Although mineralogical investigations have not yet provided evidence that they are useful as guides to ore, the studies have been invaluable in establishing the nature of the refractory gold ores and have assisted with the design of metallurgical techniques for improving the recovery of gold from low-grade sulphidic ores. A knowledge of the ore mineralogy has also been helpful in ore genesis deliberations.

Refractory gold ores

The locking of gold particles in sulphide minerals, especially in pyrite, and to a lesser degree in arsenopyrite, is a common feature of Archaean gold ores and this encasement appears to be the most general cause of the refractoriness of the gold ores. The gold, surrounded by sulphides, may occur in the form of particles visible under the microscope or, in a form too small to be observed except with the aid of specialized microscopes. This latter variety has led some investigators to refer to 'a solid solution' of gold in pyrite, and, although some gold may occur in this manner, there is no experimental evidence to confirm its existence[100].

The methods of treatment of refractory gold ores vary, but the commonest approach is to roast the ore, thereby oxidizing the sulphide minerals to porous hematite and so to expose or release the locked-up gold making it available for subsequent cyanidation.

The many problems associated with the treatment of refractory gold ores have been outlined by Liebenberg[98]. *Particle size of gold* ores entrapped in sulphides is important and the fineness of grind employed by the mines has to be controlled. In some cases exceptionally fine grinding is required and this can prove uneconomic. Certain *decomposition products* of sulphide minerals in cyanide solutions also cause refractoriness. Two main groups of interfering compounds have been identified[92], namely,

★ the cyanicides (compounds that combine with cyanide ions and reduce their concentration in the leaching solution), and

★ oxygen-consuming constituents (reducing agents derived from the decomposition of sulphide minerals in the ores).

In the first category are the thiocyanates and complex copper cyanides, whereas typical examples of the second class of compounds are the sulphide ions, thiosulphates, arsenites, and ferrous ions.

It has been found from studies of the Barberton ores[92,98] that *carbonaceous materials* can act as precipitants for gold dissolved by cyanide solutions. Not all forms of carbon act as gold precipitants and graphite, which is frequently encountered in the ores, is largely inactive. In some cases an inactive form of carbon can become an active form following roasting.

Film-forming constituents, in certain refractory ores, produce *coated gold* preventing attack by cyanide. These compounds include oxides of iron, silver chloride, antimony, manganese, and lead. *Insoluble alloys* of gold are also produced during roasting of ores containing antimony or lead and the naturally occurring mineral aurostibite ($AuSb_2$) further contributes to the refractoriness of some gold ores.

In addition to the abovementioned disadvantages associated with the roasting of refractory ores, there is the change that sometimes occurs in the roaster, when pyrite loses sulphur and is converted to pyrrhotite – the latter also interferes with the cyanidation process. Although alternatives to roasting processes have been employed effectively (e.g. aqueous oxidation of gold ores under pressure and elevated temperatures, and the use of chlorine for the dissolution of gold) these methods are only chosen following consideration of the factors contributing to the refractoriness of ores as outlined above.

Treatment

Many of the problems encountered with the roasted refractory ores in the Barberton Mountain Land could be remedied once their nature had been established[98]. The addition of reagents, such as ammonium hydroxide, successfully retarded the formation of copper cyanide complexes and significant improvements in the gold extraction of ores affected by oxygen-consuming constituents were achieved either by pre-aeration, or by dilute leaching techniques, the latter resulting in a decrease in the concentration of harmful reducing agents (and cyanicides) in the pulp.

Problems with carbon in the ores were overcome by introducing kerosene and similar compounds to poison the carbonaceous material, thereby saturating the adsorption sites and preventing the adsorption of gold. Finally, the difficulties encountered with coated gold were effectively controlled by chemical treatment of the ore using a wash of either hydrochloric or sulphuric acid, prior to leaching with cyanide.

Composition of gold

Gay[88,89] investigated the minor and trace-elements of samples of visible gold from mines in the Barberton area. A regional plot of the fineness values revealed the outline of a possible pattern with values decreasing in all directions from high points around the Agnes, Sheba, and New Consort mines. It was suggested that the source of the auriferous fluids may have lain beneath these areas. Gay also reported traces of Be, Bi, Co, Mn, Hg, Mo, Pd, Pt, Ag, Sn, V, Sb, Cu, Fe, Pb, Ni, Ti, and Zn with the gold. It was suggested that many of these elements were present as alloy constituents in solid solution with the gold, but it was pointed out that the analytical methods used (optical spectograph) did not allow any definite conclusions to be reached on the form in which the elements detected are present. Liebenberg[98] indicated that many large particles of gold, irrespective of whether they occur free or are included in the sulphides, contain small inclusions of sulphides. As it virtually is impossible to separate these inclusions from the gold he maintained that they had a distorting effect on the results of studies of the trace-element content of gold by optical spectrographic methods. He considered that the trace elements reported by Gay[89] were probably derived mainly from sulphide and other mineral inclusions in the gold.

Electron-microprobe analyses of gold from the Barberton area[92,98,101] showed that silver, copper, nickel, and traces of iron were the only elements alloyed with the gold. Silver ranged between 3,6 and 21,6 per cent (average about 10 per cent), copper between 0,05 and 0,3 per cent, and nickel, which appears to be responsible for *pink gold*, was present to the amount of 0,5 per cent. The amount of gold in the alloys ranged between 73,9 and 96,7 per cent.

Gold fineness

Silver-bearing minerals, including argentite, tetrahedrite, galena, and native silver, occur in the Archaean gold ores but have contributed only a small proportion of the total recorded silver output that, for Rhodesia, amounts to approximately 10 million ounces. Most of the metal is alloyed with gold, the fineness of which is expressed in the form:

$$1000 \times \frac{Au}{Au + Ag},$$

the base metal content of the ores being ignored[102].

Eales[102] showed that, in hydrothermal deposits, a relation exists between the fineness of the gold, the tenor of the ore, and the paragenesis of the gold. Based on studies of gold fineness in some Rhodesian mines he demonstrated that, in the same ore body, high-grade ore contains silver-poor gold, and low-grade ore contains silver-rich gold – a conclusion verified in some of the Barberton mines by Anhaeusser[63]. Eales[102] also showed that the composition of gold precipitated during ore deposition may change from silver-rich in the early stages to silver-poor in the late stages of deposition. Furthermore it was claimed that consistency in the silver content of bullion is characteristic of gold that has been precipitated at only one stage in the paragenesis of the ore.

Considering the usual sequence of ore deposition, as postulated by Emmons[103], fineness would be expected to increase with depth since gold tends to be precipitated at greater depths than silver. The results obtained by Gay[89] in the Barberton area agree with this generalization as do the majority of published data, but Macgregor[104] and Eales[102] noted exceptions in Rhodesian mines. Anhaeusser[96] also found that the gold content of ores from the Lily mine in the Barberton region increased upwards in the deposit but these changes were ascribed to processes of supergene enrichment.

Gold enrichment

The tenor of Archaean gold ores is relatively low, varying from less than 2 to about 20 dwt/ton (3,5 to 35 g/t) (1 dwt/ton ≡ 1,714 g/t). In the Barberton area, the grade averages about 5 dwt/ton (8,5 g/t). Megascopically visible gold is sometimes present in the ores, particularly those in the oxidized zone where secondary enrichment has taken place. Almost all the 'ancient' workings of Rhodesia and the early mines in the Barberton area commenced mining operations in oxidized ore and ceased production once the sulphide ores were encountered in the deeper workings of the ore bodies.

A number of reports provide accounts of the general characteristics of the old mines and prospects[1,96,105,106]. In many cases where high gold values were found, the workings define ore shoots or pipe-like structures. Often these shoots extend the oxidized or semi-oxidized zones below the average regional depth of the sulphide zone. In hilly terrane workings were often located on the down-slope side of ore bodies where alluvial gold concentrations developed. Roper[106] contended that in this zone of alluvial gold concentration residual enrichment, together with supergene effects, gave rise to the high gold yields of the early mining days at Barberton. In some cases the sulphide ores that remained unmined by the old workers have a very low-grade protore suggesting that some form of enrichment must have taken place in the oxidized formations. Other deposits had a sufficiently high-grade protore to warrant reconsideration from the mining viewpoint, although low tonnages proved disadvantageous. It was suggested[105] that the grade of secondary ores might provide a guide to the tenor of the protore. The secondary ore grade was reported to be approximately two to three times that of the sulphide ore.

Anhaeusser[96] provided an account of a small gold mine northeast of Barberton (Lily) regarded as typical of a secondarily enriched oxidized deposit that ceased production when sulphide ores were encountered. The relation between gold fineness and depth in the Lily mine suggested a form of enrichment in the upper oxidized workings where some exceptionally rich pockets of gold were found concentrated in favourable structural traps (Figure 5). The gold is considered to be essentially of secondary origin, derived from the altered protore, and was concentrated by supergene and residual processes in the oxidized and semi-oxidized sections of the mine.

Megascopically visible gold is not confined to the oxidized zone. Reports of exceptionally rich veins containing gold are not uncommon in the Barberton area (New Consort, Sheba) as well as for some Rhodesian mines. Phaup[4] noted that, in general, quartz veins are of higher grade and carry less refractory ore. Some quartz veins have been incredibly rich, like the Waterlily mine at Hartley where 850 ounces of gold were extracted from one ton of rock. The Globe and Phoenix mine near Que Que has also consistently produced blocks of ore containing many ounces to the ton.

ARCHAEAN GOLD DISTRIBUTION IN SOUTHERN AFRICA

Introduction

It has been mentioned that gold is a widely distributed, yet rare element. This is the case even in the Archaean greenstone belts of the world, which are generally regarded as the principal host environments of the precious metal. Although, as has also been pointed out, there are approximately 4000 recorded localities where gold has been mined in Rhodesia, Botswana, Swaziland, and the Transvaal, the bulk of the production has come from about 10 per cent of these mines. As an indication of the degree of localization of the gold mineralization, a series of pie charts were constructed (Figure 6) from information pertaining to mines in the Gatooma, Bulawayo, and Barberton areas of southern Africa. It is evident that the pattern of mineralization in these widely separated regions is much the same, with a few large deposits, like those of the Cam and Motor, New Consort, Sheba, and Fairview, to name a few, contributing the bulk of the recorded production.

In the sections that follow the distribution patterns of gold mineralization in the Archaean formations of the Rhodesian and Kaapvaal cratons will be illustrated. The regional distribution patterns provide a basis for any discussion that may involve questions of controls to mineralization (including structural and stratigraphic controls, and the role of the granites), as well as the problems relating to the origin of the metal.

Gold in the Barberton Mountain Land

The Barberton greenstone belt, located in the eastern part of the Kaapvaal craton (Figure 3) has been, and still is, an important gold producer. A simplified geological map of the region (Figure 7) shows the distribution of the principal subdivisions of the Swaziland Supergroup and the wide range of granites, gneisses, and migmatites that surround this area. Superimposed on the geological map are shown the main structural features that occur in the Barberton Mountain Land, as well as the localities of 196 of the 274 reported gold workings or prospects in the region.

The greenstone belt, which is approximately 130 km long from SW to NE, is comprised of a huge basal volcanic sequence (Onverwacht) overlain by sedimentary successions (Fig Tree and Moodies). The tectonic history of the region has been long and complex and is seen as having developed in two stages[107], the first involving the gravitational slumping and downfolding of the troughs of lavas and sediments on a thin, unstable crust. As the gravity-induced deformation proceeded, variably-plunging isoclinal folds formed in preferentially-developing synclinoria, and steeply inclined longitudinal faults or slides were generated, the latter frequently eliminating intervening anticlinal folds. The partial melting of deeply infolded root-zones of the greenstone belt produced diapiric tonalite/trondhjemite plutons that were emplaced around the margins of the greenstone belt (Figure 7).

The granite diapirism produced the second-stage of deformation and was responsible for the intensification of the structural complexity of the greenstone belt. Several periods of superimposed deformations are recognized[70,107,108], the latter involving folding, faulting, fracturing, and shearing of the rocks.

Gold distribution

Investigations established that structural control was an important factor in the localization of gold in all parts of the Barberton Mountain Land[63,70,80,108], but particu-

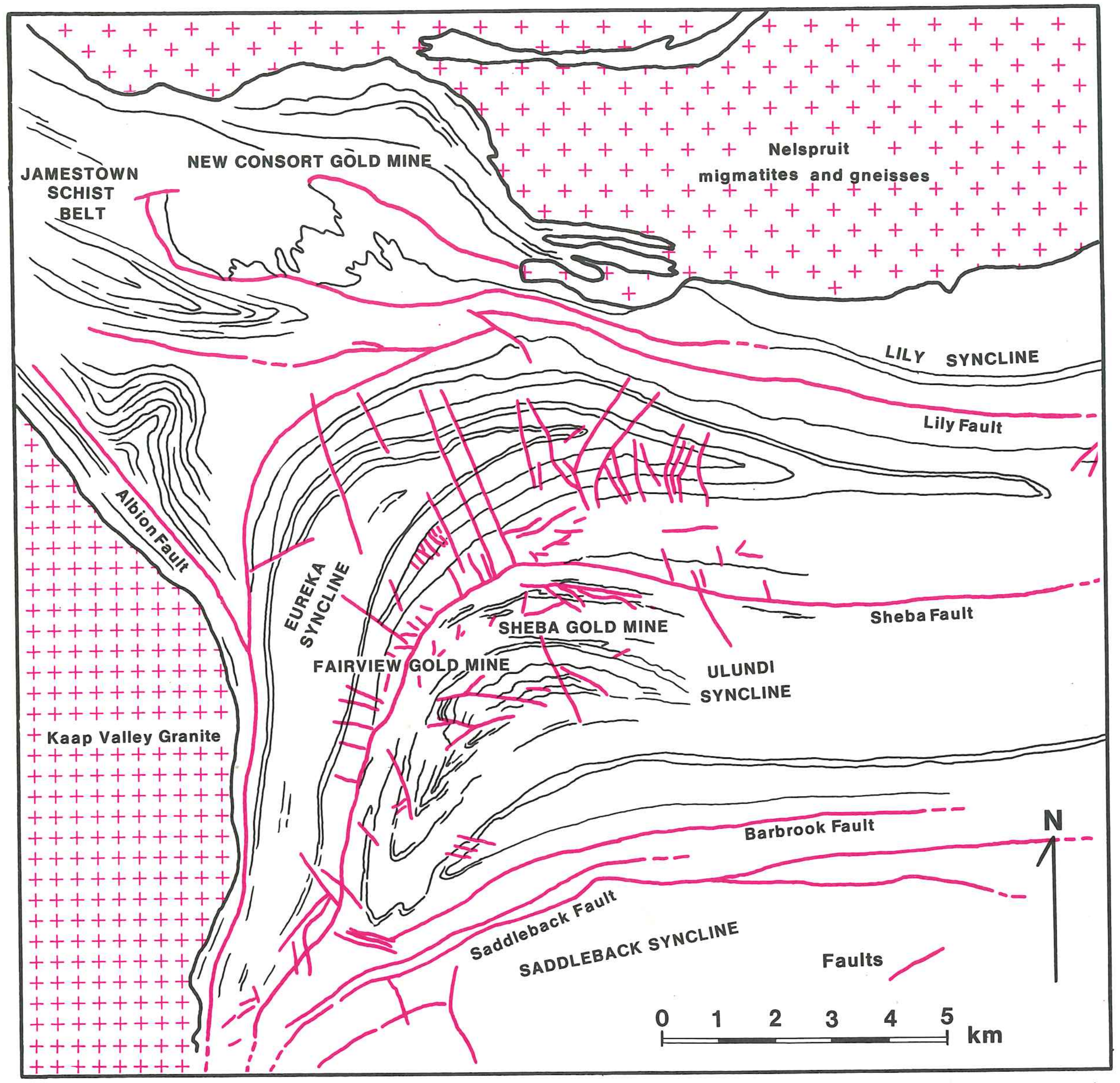

FIGURE 9 Simplified structural map of the Jamestown and Sheba Hills area of the Barberton Mountain Land showing the positions of the more important folds, faults, and fractures in the region. Approximately 75 per cent of all the gold mined in the Barberton area has come from this region which also has the three largest gold deposits in the district (New Consort, Sheba, and Fairview gold mines). (modified after Anhaeusser[71,72]).

larly in a relatively restricted portion of the area – namely in the region to the north and northeast of Barberton, in the Jamestown and Sheba Hills area (Figure 8)[63,71,72]. Immediately southwest of Barberton, in the Moodies Hills, other important gold deposits also occur[65,68,69,109] indicating that some particular controlling factor or factors must have been responsible for the localization of the mineralization on the northwest flank of the Barberton greenstone belt.

From Figures 8 and 9 it can readily be seen that the area flanking the eastern edge of the Kaap Valley Granite has the greatest concentration of gold mineralization, the main production stemming from the New Consort, Sheba, and Fairview mines in the Jamestown-Sheba Hills region and from the Agnes mine southwest of Barberton in the Moodies Hills. Apart from these areas, further gold concentrations occur along, and adjacent to, the major regional strike faults (namely the Scotsman, Lily, Albion, Sheba, Barbrook, and Moodies faults, Figures 7 to 9), as well as in a few localities in Swaziland near the granite-greenstone contacts (namely the Hhohho, Pigg's Peak, and Forbes Reef areas). Mineralized occurrences of minor significance are also developed in the northeastern part of the Mountain Land and in the Komati and Steynsdorp valleys in the southwest (Figure 8).

The central regions of the Mountain Land, southeast of the Barbrook Fault, are notably barren of mineralization. Several reasons for the absence of gold in these areas are suggested:

- there is a general absence, in the central Mountain Land, of Onverwacht Group assemblages – rock types considered to have been the primary source of most of the gold and sulphide mineralization[63,80], and
- the influence of the granites in the central areas (particularly the thermal conditions) was minimal away from the greenstone belt contacts. Suitable structural environments are available in the central areas so that it would appear that the general absence of gold mineralization in this region hinges essentially on the distance from the granite contacts and the non-availability of suitable source rocks.

The northwest flank of the Barberton greenstone belt, between Montrose in the southwest and Three Sisters in the northeast has accounted for approximately 95 per cent of all the gold and 99 per cent of all the silver so far recovered from the area[63]. The Jamestown and Sheba Hills areas have been responsible, up to the end of 1967, for the production of approximately 4,5 million ounces of gold, the latter representing close on 75 per cent of the entire production from the Barberton greenstone belt.

Gold mineralization in the Eureka Syncline

Although a large number of gold workings occur in the Moodies formations of the Eureka Syncline (Figure 7) only a few of them are currently being mined. All the reefs presently being exploited constitute sections of either the Fairview or the Sheba gold mines, and occur on the inner arc of the Eureka fold. The mineral deposits in the Eureka Syncline owe their origin to structural control, with faulting, in particular, playing the dominant role in determining the locations of the ore bodies[72]. As can be seen in Figure 9, a great number of tension fractures radiate about the arcuate fold structure, which consists geologically of a variety of structurally competent Moodies quartzites interlayered with shales, sandstones, and subgreywackes. It is in most of these tension fractures that gold-quartz veins have been mined.

Also in the Eureka Syncline are numerous fractures that are orientated approximately parallel to the Sheba Fault. These occur mainly on the southern and eastern limbs of the Eureka fold, particularly in the core of the structure between the Fairview and Sheba groups of mines. The origin of these fractures is considered to be due to concentric shearing, the latter resulting from strike-slip movements between the folded stratigraphic units. The concentric shearing, coupled with over-thrust movements from the southeast, produced many structures that were subsequently infiltrated by hydrothermal mineralizing solutions containing gold and vein quartz, together with only minor amounts of pyrite and/or arsenopyrite.

Most mineralized deposits in the Eureka Syncline occur in the quartzitic units where faulting and fracturing is best developed. Mining operations in the Fairview mine have shown that fractures, strongly developed in the quartzites, also penetrate the surrounding shales but these are almost invariably hairline breaks only sometimes occupied by thin quartz stringers, the latter being generally barren of gold or poorly mineralized (L. M. J. van Rensburg, *personal communication*).

Only a few mines occur around the outer arc of the Eureka Syncline. Almost all of these are situated in structures located close to the Lily Fault. The majority of mines in the Eureka fold occur on the southern or eastern limbs of the structure and become progressively more important, in terms of production yields, as the Sheba Fault is approached. Among the numerous deposits in the area north of the Sheba mine is the Golden Quarry (Figure 2), one of the fabled discoveries of the early gold rush days. The region where these mines occur possibly has suffered the greatest degree of structural disturbance in the entire Eureka Syncline.

The Sheba Fault was responsible for the disturbances of the successions early in the tectonic history of the area. Later, during the arcuation of the Eureka Syncline, the inner arc was subjected to intense compression as well as thrusting from the southeast, as arcuation and overriding of the Ulundi Syncline to the northwest progressed (Figure 9). The Sheba Fault subsequently underwent several phases of reactivation, there being evidence of thrust and wrench faulting in addition to the numerous second-order structures that can be ascribed to the parent dislocation[70].

Gold mineralization in the Ulundi Syncline

The principal components of the Fig Tree and Onverwacht stratigraphy in the Ulundi Syncline are greywackes, shales, and banded chert or banded ferruginous chert horizons. Two of the largest mines in the district (Sheba and Fairview) are located symmetrically about the northwest-orientated fold axis of the Eureka and Ulundi synclines and virtually merge into one another in the faulted, fractured, and isoclinally folded successions developed in the Ulundi Syncline, southeast of the Sheba Fault. A number of studies have been carried out in and around these mines and the reader is referred to them for further details[63,68,70,86,88,110-112].

Gold production data from the Sheba Hills[63,72] shows that most of the mineralization recovered so far has come from the Ulundi Syncline, the Sheba and Fairview mines between them having produced over one-third of all the gold recovered from the entire Barberton greenstone belt.

Although most of this mineralization is clearly hydrothermal in character (since it occurs in fracture networks parallel to and cross-cutting the strata) some of the gold and sulphides may have been introduced contemporaneously with the enclosing rocks. Such a syngenetic origin warrants further investigation particularly in view of the presence of a stratiform sulphide layer occurring widespread in the Ulundi Syncline and reported by Van Vuuren[112]. The position of much of the gold and sulphide mineralization in, or near to, the siliceous, cherty zones of the Swartkoppie Formation (uppermost Onverwacht rocks) suggests that some of the mineralization may be genetically associated with the volcanism[72] considered to be responsible for the development of this rock assemblage[30].

Gold in the Jamestown Schist Belt

Practically all the gold mineralization in this area is structurally controlled, being particularly confined to fold, fault, and shear zones. The most important deposit in the area is the New Consort gold mine situated in a siliceous cherty zone at the contact between Onverwacht Group mafic and ultramafic schists and the overlying Fig Tree assemblage, the latter consisting of shales, greywackes, and cherts[71,86,113]. The mineralization is related to the chert zone, referred to in the mine as the Consort 'Contact' or 'Bar', but is also found in some of the mafic and ultramafic schists and serpentinites in the near vicinity of the siliceous unit. Figure 10 shows an unusual occurrence of visible gold associated with chrysotile asbestos in serpentinites found in the mine.

The Consort 'Contact' has suffered several phases of

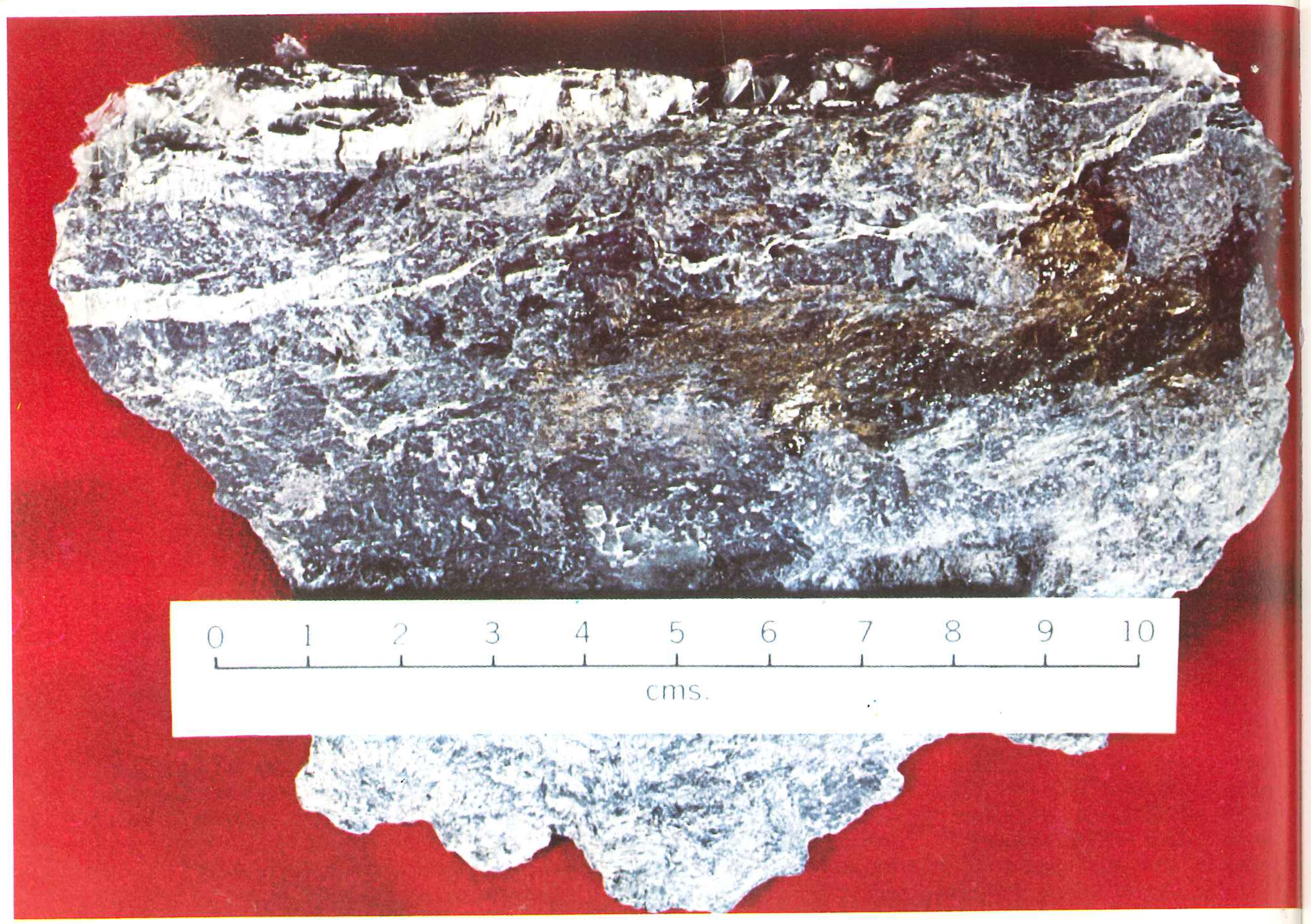

FIGURE 10 Specimen of serpentinite from the New Consort gold mine north of Barberton showing visible gold and chrysotile asbestos fibre seams. Gold is commonly encountered in a wide variety of ultramafic rocks in the mine but the major production comes from a silicified cherty zone (Consort "Contact") separating Onverwacht schists from Fig Tree shales and greywackes.

deformation, one superimposed on the other, producing a series of tight isoclinal folds, the latter greatly disturbed by faulting and pegmatitic intrusion in the hinge zone of the western extension of the Lily Syncline (Figure 9).

The origin of the 'Bar' separating the competent Fig Tree rocks from the less competent Onverwacht schists has been explained as having resulted from the silicification of the intensely sheared zone at the junction of the two rock groups[86,113,114]. Hearn[86] was of the opinion that the silicification and gold mineralization of the 'Contact' took place after the pegmatite intrusion but, as mining continued, it became evident that the mineralization was truncated by the pegmatites. Age determinations, carried out by Allsopp *et al*[115] on the pegmatites showed them to be 3030 m.y. old.

The banded nature of some of the gold ores from the New Consort gold mine leads the writer to suspect that the mineralization may originally have taken the form of a stratiform syngenetic deposit, possibly of volcanogenic exhalative origin. Subsequent deformation and hydrothermal activity has since reconstituted much of the ore yet the mineralization rarely departs from the intricately folded chert zone, which may be viewed as forming part of the stratigraphy. The mineralized zone may, in fact, be similar to that encountered in the Swartkoppie Formation, in the workings of the Sheba and Fairview mines – a suggestion made in 1946 by Van den Berg *et al*[114].

Gold in the Steynsdorp goldfield

Although little gold was ever recovered from the Steynsdorp goldfield on the southern flank of the Barberton greenstone belt, investigations by Viljoen *et al*[80] revealed important structural and stratigraphic controls to the gold mineralization in the area. The auriferous veins in the Steynsdorp Valley were emplaced in volcanic and associated rocks of the Onverwacht Group. Incomplete records indicate a production of only 2173 ounces of gold, most of this apparently being extracted from a large alluvial digging known as Fullerton Creek.

The dominant geological feature of the Steynsdorp goldfield is the well-developed Steynsdorp Anticline plunging steeply to the north (Figure 11). The broad southern core of this structure is occupied by a diapiric tonalitic gneiss pluton, around which are wrapped successively younger formations of the Onverwacht Group.

The basal members of the stratigraphy comprise a variety of mafic and ultramafic rocks, mostly lavas, but also include felsic tuff interlayers, the latter mainly in the form of quartz-sericite schists. The mafic and ultramafic rocks, particularly of the Komati Formation, are altered to serpentinites and tremolite-actinolite, chlorite, and talc schists. In some places the rocks have undergone extensive carbonitization.

The rock unit known as the Middle Marker[30,80] separates the lower ultramafic-mafic assemblage from the more massive and generally extensive jointed basaltic lava succession of the Hooggenoeg Formation. The Middle Marker consists of a well-layered sedimentary unit formed of tuffaceous shales, carbonaceous and carbonate-rich bands, chlorite schists, and iron-oxides, rutile, and sulphides (mainly pyrite and chalcopyrite).

The auriferous lodes in the Steynsdorp goldfield are

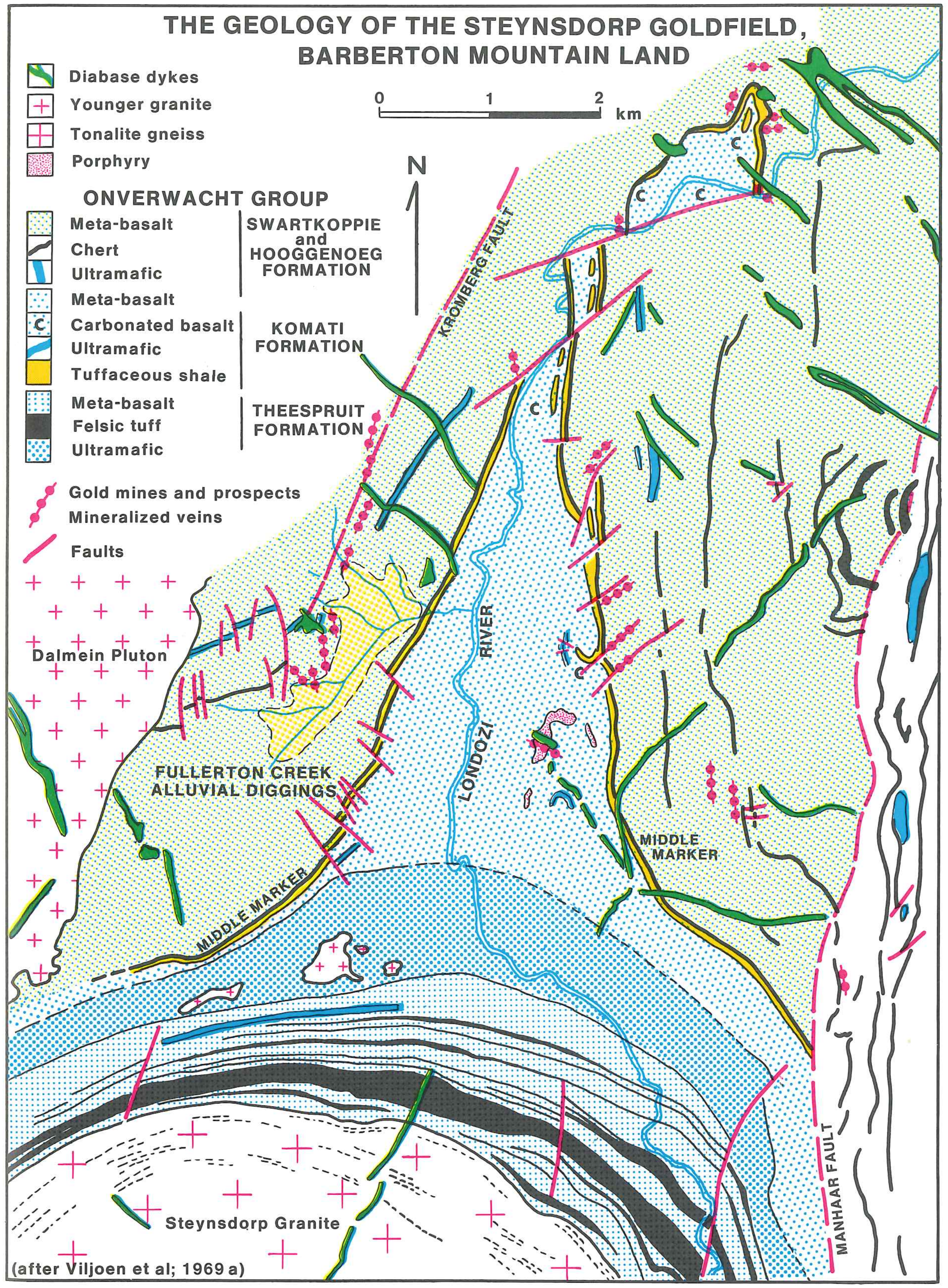

FIGURE 11 Geological map of the Steynsdorp goldfield in the Barberton greenstone belt showing the position of mineralized veins on the limbs of the Steynsdorp Anticline. The auriferous reefs are located in the more massive and brittle basaltic lavas that occur above the Middle Marker sedimentary unit. Some gold also occurs in the more competent porphyry bodies intruded into the lower ultramafic-mafic assemblages. Alluvial gold was recovered from the Fullerton Creek diggings (after Viljoen et al[80]).

confined to the more competent rock types of the upper portion of the volcanic sequence, as well as to a few intrusive porphyry bodies found in the lower formations. Four types of gold occurrences have been recognized in the region[80].

☆ *Gold-quartz veins* form the main type and have been emplaced into dilatant zones associated with faulting and jointing in the more competent rock types – mostly the volcanics of the lower portion of the Hooggenoeg Formation in near proximity to the Middle Marker (Figure 11). Most of the mineralized veins on the western limb of the Steynsdorp Anticline appear to be related to the Kromberg wrench fault. Veins, lenses, and stringers of quartz vary in width from a few millimetres to three metres, and carbonate, commonly in the form of ankerite and siderite, generally accompanies the quartz as gangue.

☆ *Pyritic ores in fractured chert horizons* constitute the second ore variety and may represent stratiform mineralization disturbed by structural influences. The cherts containing the mineralization almost invariably overlie banded carbonate sediments in felsic volcanics.

☆ *Complex sulphidic ores associated with intrusive porphyries* make up the third type of occurrence. The most significant of these deposits was the Gypsy Queen mine, east of the Londozi River in the central portion of the Steynsdorp Anticline. Here mineralized veins were emplaced in fracture systems within the porphyry body, which behaved as a more competent mass surrounded by less competent schists.

☆ *Alluvial diggings* associated with a braided drainage system of gulleys and channels, and known as Fullerton Creek (Figure 11), makes up the fourth gold occurrence. The gold in the alluvial deposits was derived from the many quartz veins associated with fractures related to the Kromberg Fault. The locality provides an example of small sub-economic auriferous lodes that have given rise to a payable alluvial deposit.

Gold mineralization elsewhere in the Barberton Mountain Land

Space does not permit an exhaustive account of all the gold regions in the Barberton greenstone belt. Descriptions of the mineralized occurrences in the Moodies Hills, southwest of Barberton include those of Gribnitz[68], Hall[109], and Poole[65,69], whereas accounts of the gold deposits along the Barbrook fault zone (Figure 8) are provided by Anhaeusser[70], Hall[109], and Macaulay[116].

Gold mineralization in Swaziland is concentrated in three areas, all of which are close to the granite contacts (Figure 8). In the Hhohho (Horo) area, Jones[94] maintained that the gold deposits were closely associated with the granites but considered that both lithological and structural controls also influenced the localization of gold. Up to 1969, the recorded production from Swaziland amounted to 210 306 ounces of gold[63], most of this total coming from the mines in the Pigg's Peak and Forbes Reef areas. Descriptions of these deposits are provided by Hunter[117] and Davies and Hunter[118].

Gold distribution in Rhodesia

Although gold mines occur in practically all the Rhodesian greenstone belts, as well as in many of the larger xenolithic remnants scattered throughout the granites of the territory, it has become evident[19] that the greatest concentration of gold deposits (and gold) occurs in the more centrally situated regions of the Rhodesian craton. In support of this the distribution of 279 of the most important gold occurrences in Rhodesia are shown in Figure 12. In locating these mines, use has been made of a number of bulletins of the Geological Survey of Rhodesia[6,55,82,84,104,119-152]. Of this number, 48 ore deposits have each yielded in excess of 100 000 ounces of gold. Breaking this figure down still further, 11 deposits have produced more than 500 000 ounces of gold, 12 deposits have yielded between 250 000 and 500 000 ounces of gold, and 25 deposits have produced between 100 000 and 250 000 ounces of gold.

In a manner similar to that used by Fripp[38,39,59], an attempt has been made in Figure 12 to show the position of the 279 mines, the latter located with respect to a reinterpretation of the Archaean stratigraphy of Rhodesia in terms of an ultramafic-mafic, mafic-to-felsic, and a sedimentary subdivision. The accuracy of this subdivision will be a matter for debate until detailed lithostratigraphic information becomes available. The majority of these larger mines occur in rocks included with the Sebakwian Group, followed by those that occur in the Bulawayan and Shamvaian groups. Only a few mines are located in the granites. The general pattern of gold distribution, as shown in Figure 12, provides independent support for the findings of Fripp[59], and listed earlier in Table 5.

Most of the larger gold mines of Rhodesia are located in the Midlands greenstone belt between Hartley and Gatooma in the north and Gwelo and Selukwe in the south. In Figure 13, all the known gold mines in this region are plotted using various colours to denote the nature of the host rocks in which the deposit occurs. There is a tendency (also displayed in Figure 14) for most deposits to be located around the periphery of the greenstone belts, not on the contacts with the main granite batholiths but, as pointed out by Phaup[4], usually a few kilometres in from the margins of the belts. Exceptions occur where some gold deposits flank small stocks or granite cupolas.

FIGURE 12 Map of Rhodesia showing the distribution of 279 of the more important gold deposits in relation to the three-fold lithostratigraphic subdivision of the Archaean stratigraphy of the region. The names of 48 of the larger gold mines and their map locality numbers are listed below.

1. Muriel
2. Eldorado
3. Prince of Wales
4. Shamva Group
5. Jumbo
6. Connaught
7. Arcturus
8. Giant
9. Dalny
10. Golden Valley
11. Patchway
12. Pickstone
13. Inez
14. Thistle Etna
15. Eileen Alannah
16. Cam and Motor
17. Owl
18. Kanyemba
19. Inkerman/Invincible
20. Sherwood Starr
21. Sebakwe Group
22. Moss/Pipe Moss
23. Globe and Phoenix
24. Bell
25. Gaika
26. Connemara
27. Falcon
28. Wanderer
29. Surprise
30. Bonsor
31. Tebekwe
32. Motapa/(B and S)
33. Lonely
34. Turk/Angelus
35. Barberton/Dawn
36. Queen's
37. Sunace
38. Bushtick
39. Fred
40. True Blue
41. Vubachikwe
42. Freda
43. Horn
44. Farvic/Prince Olaf
45. Geelong
46. Jessie
47. Antelope
48. Penhalonga

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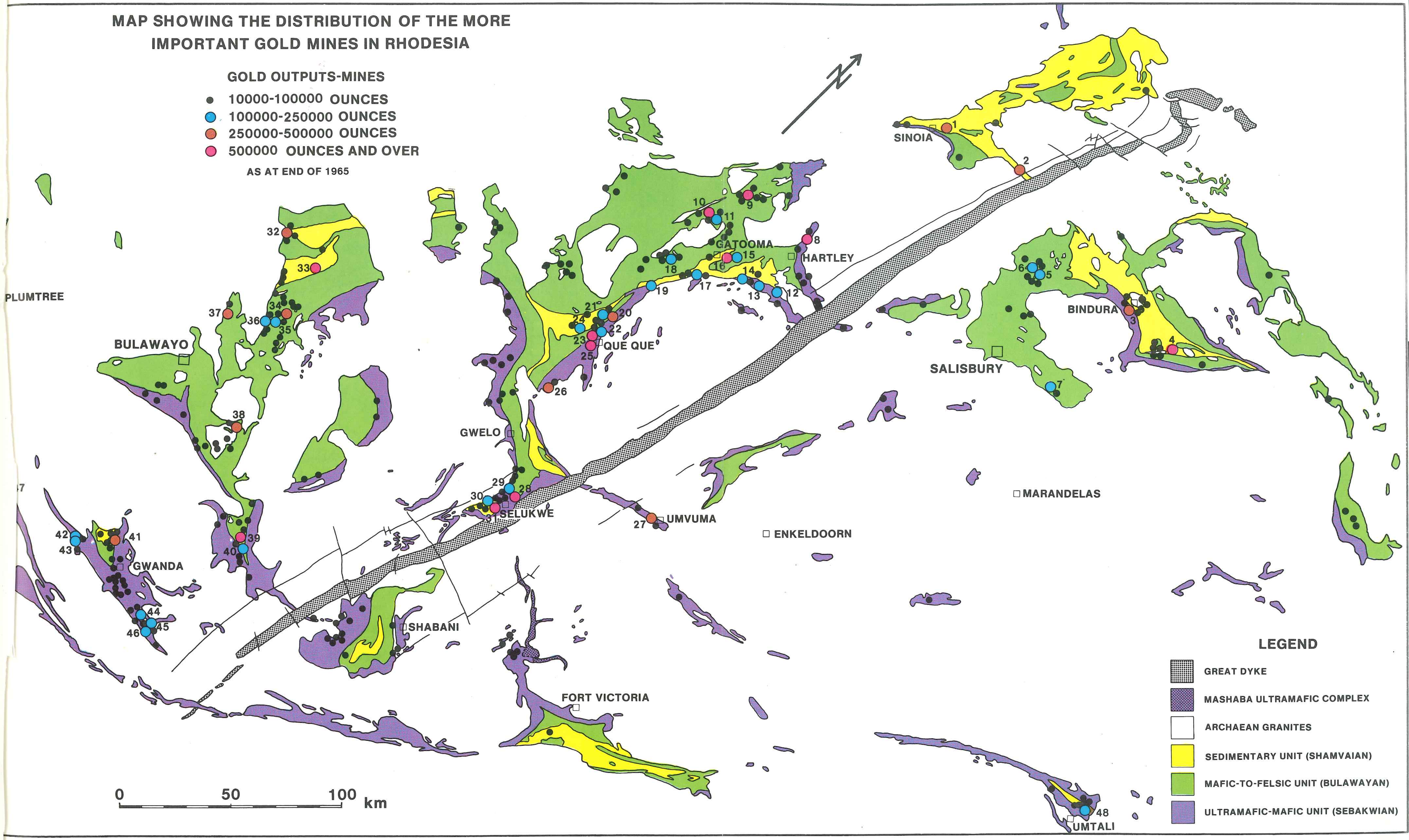
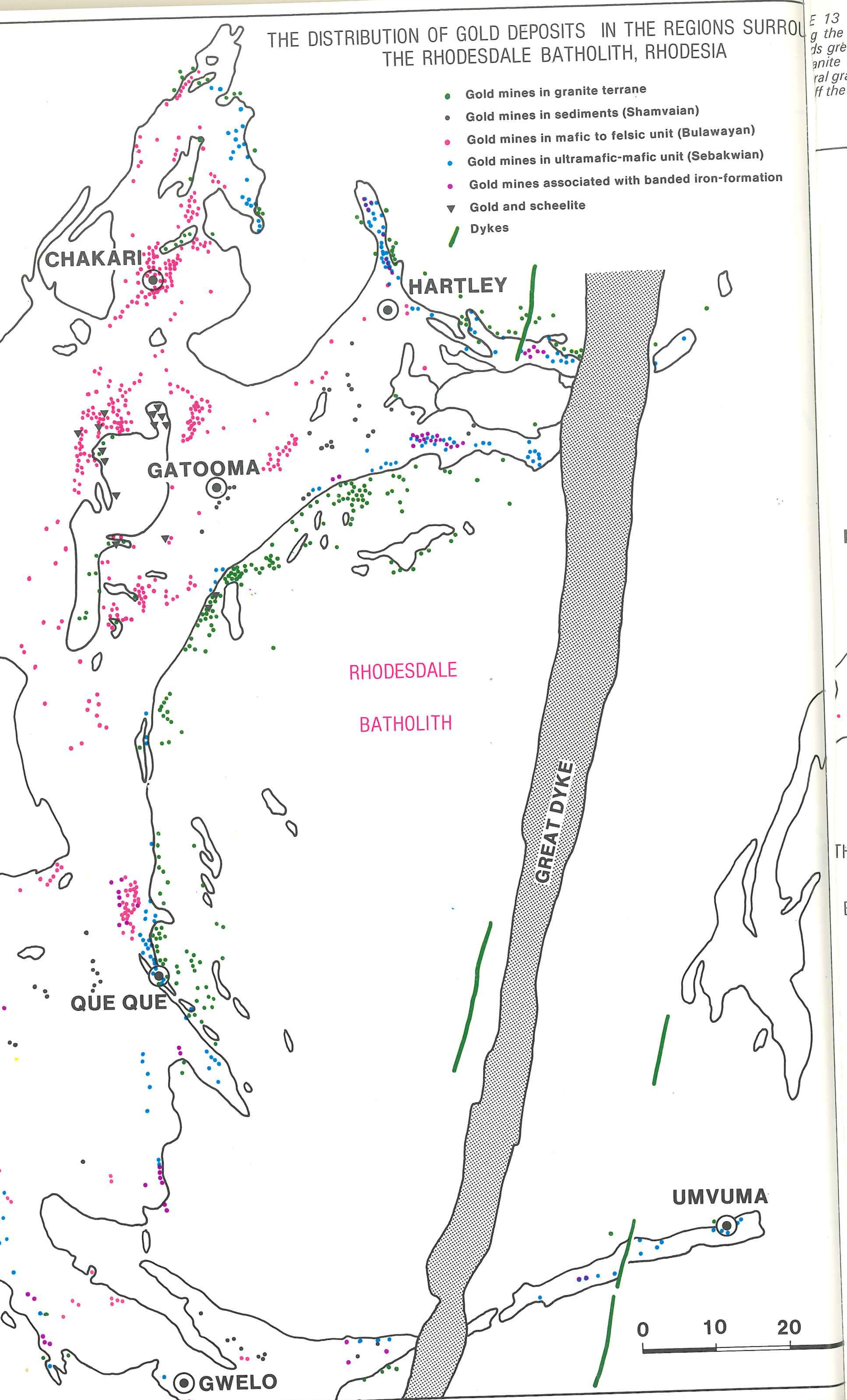
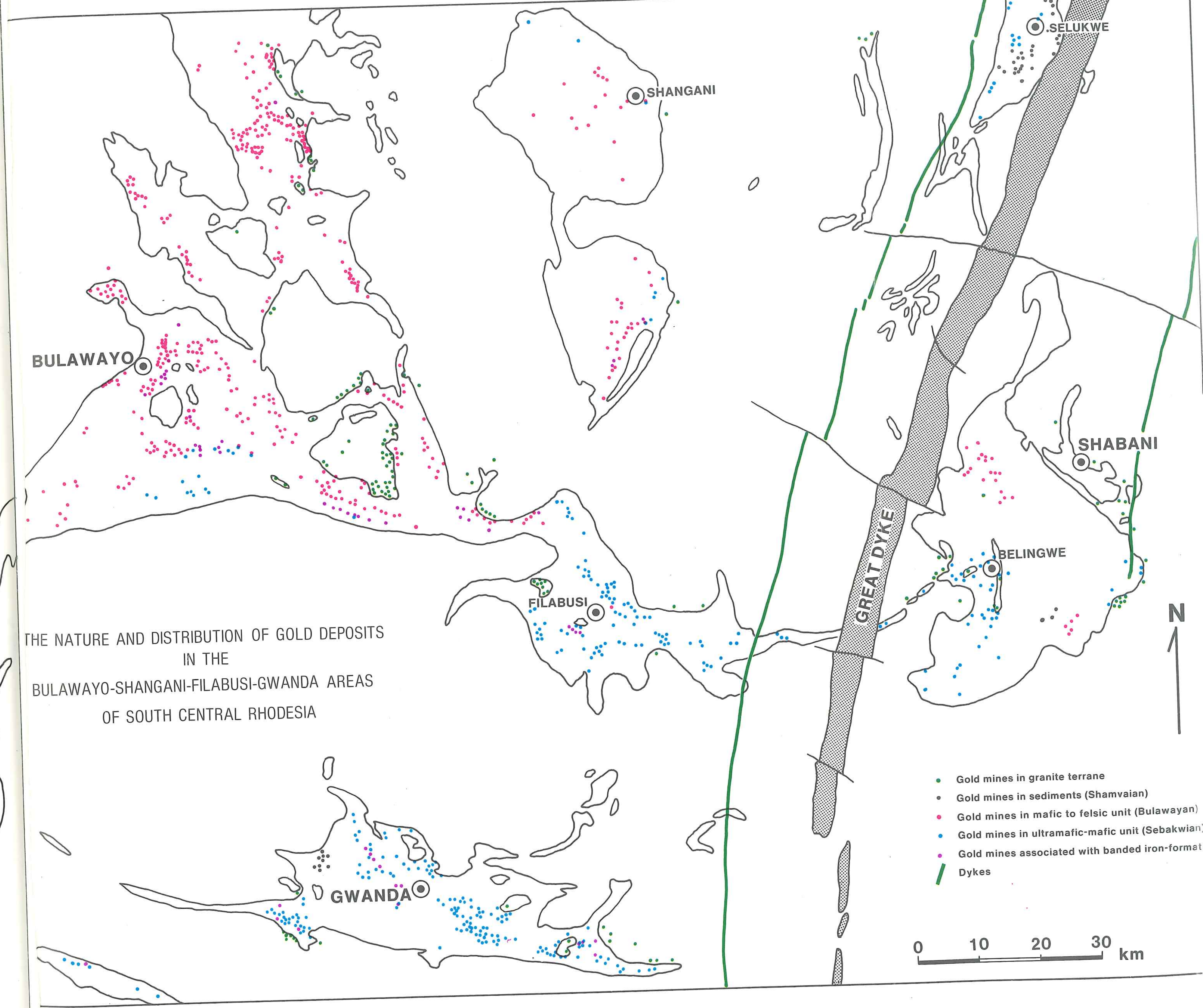
26. Connemara
27. Falcon
28. Wanderer
29. Surprise
30. Bonsor
31. Tebekwe
32. Motapa/(B and S)
33. Lonely
34. Turk/Angelus
35. Barberton/Dawn
36. Queen's
37. Sunace
38. Bushtick
39. Fred
40. True Blue
41. Vubachikwe
42. Freda
43. Horn
44. Farvic/Prince Olaf
45. Geelong
46. Jessie
47. Antelope
48. Penhalonga

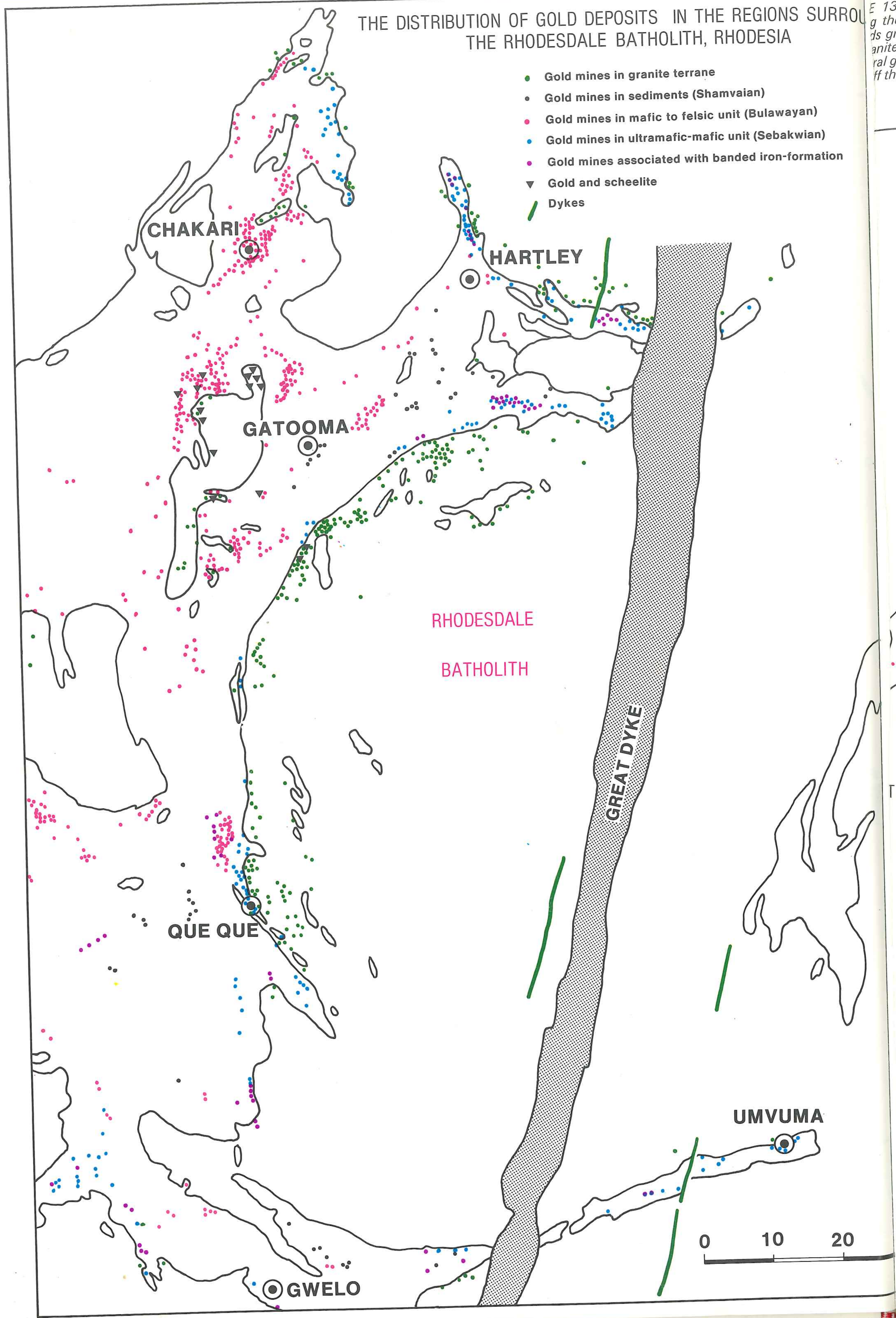




E 13 Map of the west-central region of Rhodesia g the nature and distribution of gold deposits in the ds greenstone belt and areas surrounding the Rhodes- anite batholith. Most of the gold occurrences in the ral granite contact zones are associated with xenoliths ff the main greenstone belt masses.

FIGURE 14 Map of the south-central region of Rhodesia showing the nature and distribution of gold deposits in the Bulawayo-Shangani-Filabusi-Belingwe-Gwanda greenstone belts. An estimated 90 per cent of all Rhodesia's gold has been recovered from the mines shown in Figures 13 and 14.





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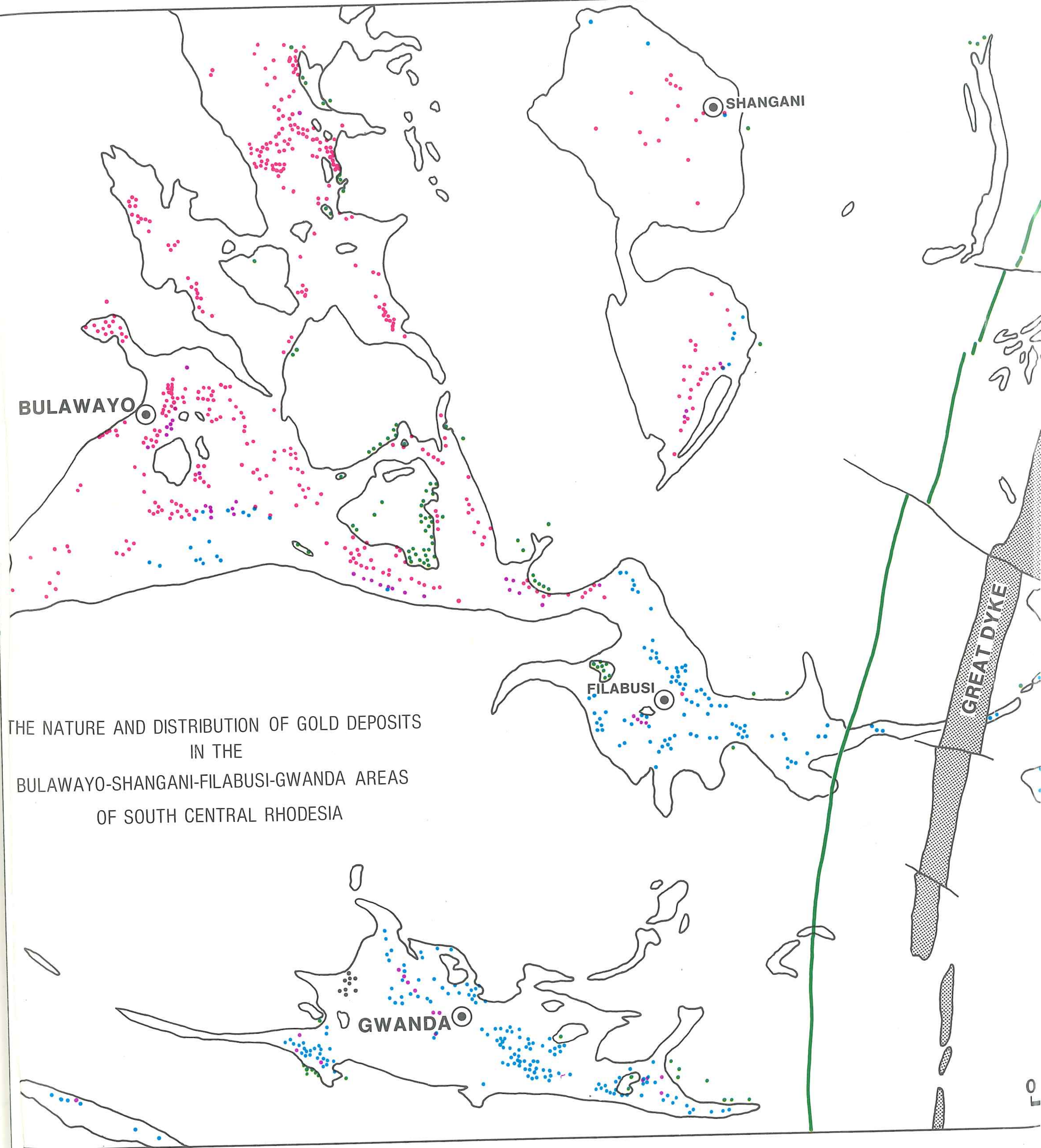
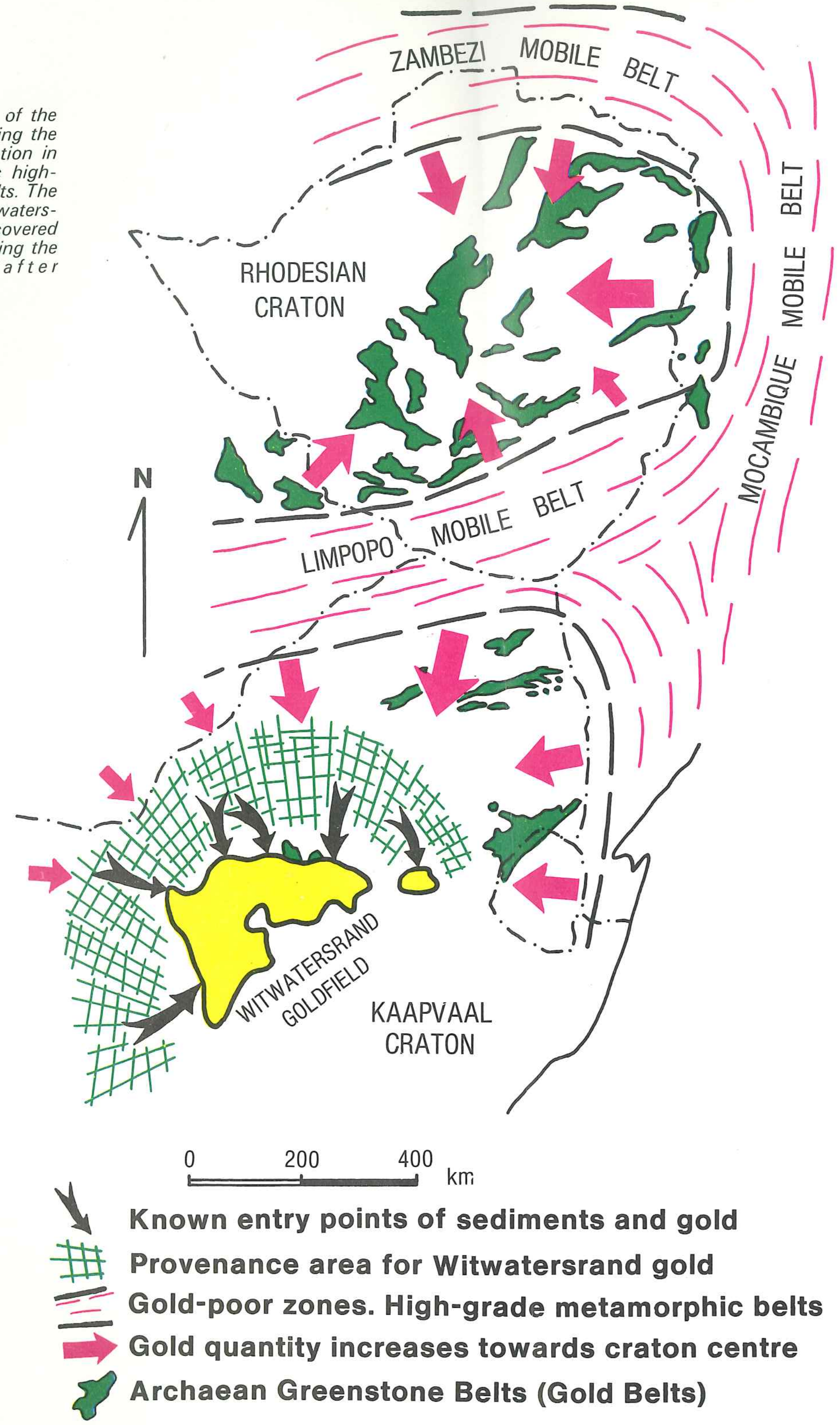


FIGURE 15 Schematic map of the southern African Shield showing the distribution of gold mineralization in relation to the circumcratonic high-grade metamorphic mobile belts. The provenance area of the Witwatersrand goldfield is now largely covered by younger formations, including the Bushveld Complex (after Anhaeusser[19]).



A number of deposits (green dots) occur in the granites. Most of these are of the quartz-lode type and are developed within a few kilometres of the greenstone belt contacts, and often close to xenolithic remnants that were rafted off the main greenstone belt masses. The close association of the gold with the xenoliths suggests a genetic link between the two and questions the validity of proposals relating the gold to the granites.

Although lode gold deposits occur in rocks of the Sebakwian Group, they have a greater tendency to develop in the more massive volcanic piles that make up the Bulawayan stratigraphy. On average it appears that the physical characteristics of the mafic-to-felsic assemblages led to the development of greater numbers of fracture systems that acted as loci for the subsequent deposition of gold-quartz lode deposits. The hydrothermal solutions

entering these fractures are commonly responsible for wall-rock alteration of the lavas (propylitization) that can extend for several metres either side of the mineralized veins. The alteration that commonly gives rise to chlorite, epidote, tremolite and albite assemblages is also frequently accompanied by carbonation or silicification.

Lode gold deposits are frequently grouped in some localities. Fripp[59] suggested that these concentrations may indicate local metallogenic sub-provinces of the order of 100 km^2 in extent. Within any group the individual lodes tend to have a similar mineralogy and base metal association, distinct from groups elsewhere[4,154]. It appears certain that the grouping of mines is also controlled by structural influences, the latter commonly associated with deformational effects produced by the emplacement of granite batholiths, diapiric plutons, or stocks. Examples of this nature are common throughout Rhodesia[4,57] and will be discussed further in a later section.

CONTROLS OF GOLD MINERALIZATION

Anhaeusser[19] suggested that there appeared to be an 'optimum thermal zone' in greenstone terranes wherein the gold and associated sulphide mineralization tended to concentrate preferentially. This suggestion would have to be modified to include, more specifically, the quartz lode type of deposit that has probably undergone some transport by means of hydrothermal solutions from the site of origin. Gold mineralization of the stratiform type has presumably suffered less redistribution owing to the fact that it is often intimately linked mineralogically with the wide-ranging sulphide ore minerals, particularly pyrite and arsenopyrite. Evidence from the metamorphic mineral assemblages in which the gold deposits are found led Anhaeusser[19] to suggest that the thermal regime most conducive to gold accumulation was probably akin to middle or upper greenschist facies of regional metamorphism ($\sim$ 450 to 550 °C). However, the gold solubility studies of Fyfe and Henley[180] suggest that the gold will still be in transit at these temperatures but could be expected to precipitate at temperatures more in the range 300 to 400 °C (lower greenschist facies).

Additional support for an optimum thermal zone for gold mineralization follows from the studies of Pretorius and Hempkins[153] who investigated data concerning gold production in Rhodesia. Analyses of the general statistics of population frequency distributions indicated a pattern of more favourable intensity of gold mineralization associated with ores containing the low temperature minerals chalcopyrite, stibnite, and galena, than from ore characterized by the presence of the higher temperature minerals pyrrhotite, arsenopyrite, and sphalerite.

Thermal influences controlling the distribution of gold in the Archaean can also be demonstrated on a regional scale[19]. In Figure 15 it is shown schematically that the high-grade metamorphic belts rimming the cratons are not only virtually barren of gold mineralization but that they have influenced (mainly thermally) the greenstone belts in their immediate vicinity – only very minor quantities of gold having been located in areas flanking the mobile belts (cp. Figure 12).

Gold and sulphide mineralization was probably unstable in the high temperature/pressure regimes of the mobile belts and consequently moved away from these areas, as well as from the greenstone belts located near the craton margins, towards the craton interiors. Some of the mineralization in the thermally affected regions may have survived as metamorphosed sulphide deposits (mainly pyrrhotite with subordinate pyrite and arsenopyrite), but most was probably dissipated (as opposed to being concentrated) throughout many rocks in the heat affected regions. Some of the migratory gold mineralization may have eventually ended up in the Witwatersrand sedimentary basin (or other interior basins), together with gold and sulphides derived from the erosion of the greenstone belts on the cratons.

Figure 15 also illustrates the provenance area of sediments and gold that led to the development of the Witwatersrand goldfield. It is assumed that this region must have had anomalously high concentrations of gold, similar to if not higher than the gold areas of the Midlands-Gwelo-Bulawayo-Gwanda regions of the central and south-central areas of the Rhodesian craton (Figures 13 and 14). These speculations are supported by the fact that all the greenstone belts presently exposed on the Kaapvaal craton (excluding the Barberton greenstone belt) have yielded only minimal quantities of gold.

However, it should be remembered that sedimentological processes can concentrate heavy minerals from even the lowest grade protores, as evidenced by the example of the Fullerton Creek alluvial deposits in the Steynsdorp goldfield described earlier.

Gold deposits controlled by granite emplacement

Just as the main gold deposits in the Barberton area were controlled by structures produced by granite diapirism, so too did similar granite intrusions in the Rhodesian Archaean produce tectonically favourable areas for gold concentration. To the northwest of Gatooma, in the Midlands greenstone belt (Figure 16), rocks forming part of the Bulawayan Group have been folded into the northeast-trending Gatooma Anticline with minor folds on both the NW and SE limbs. Despite the various interpretations that have been suggested for the structure of the region[59,150] it is evident that the superimposed fold events in the area northwest of Gatooma resulted from several stages of granite emplacement.

According to Bliss[150] two periods of mineralization occurred in the area shown in Figure 16. The first formed the arsenical shear zone deposits in the felsic volcanic and sedimentary rocks and are best developed around Chakari, where drag folding, on what Bliss considers to by the northwest limb of the Gatooma Anticline, has enhanced the structural control. This first period of mineralization is also reported to be present in the Eiffel Flats area on the southeast limb of the anticline. Apart from arsenopyrite, the older mineralization is accompanied by gold, pyrite, and pyrrhotite.

The younger mineralization, essentially consisting of gold, pyrite, and galena occurs in quartz-filled dilation fractures in the basaltic greenstones between Gatooma and Chakari. Fripp[59] considers that these lode deposits occur at a particular stratigraphic level in the Bulawayan assemblage. Although lithological controls may be applicable, it is equally possible, judging from the distribution of mines in an arc around the northern periphery of the Whitewaters pluton and the smaller Lion Hill stock, that the emplacement of these tonalitic bodies was responsible for the development of a concentric tensional system around the areas of intrusion. Coupled with this would entering these fractures are commonly responsible for wall-rock alteration of the lavas (propylitization) that can extend for several metres either side of the mineralized veins. The alteration that commonly gives rise to chlorite, epidote, tremolite and albite assemblages is also frequently accompanied by carbonation or silicification.

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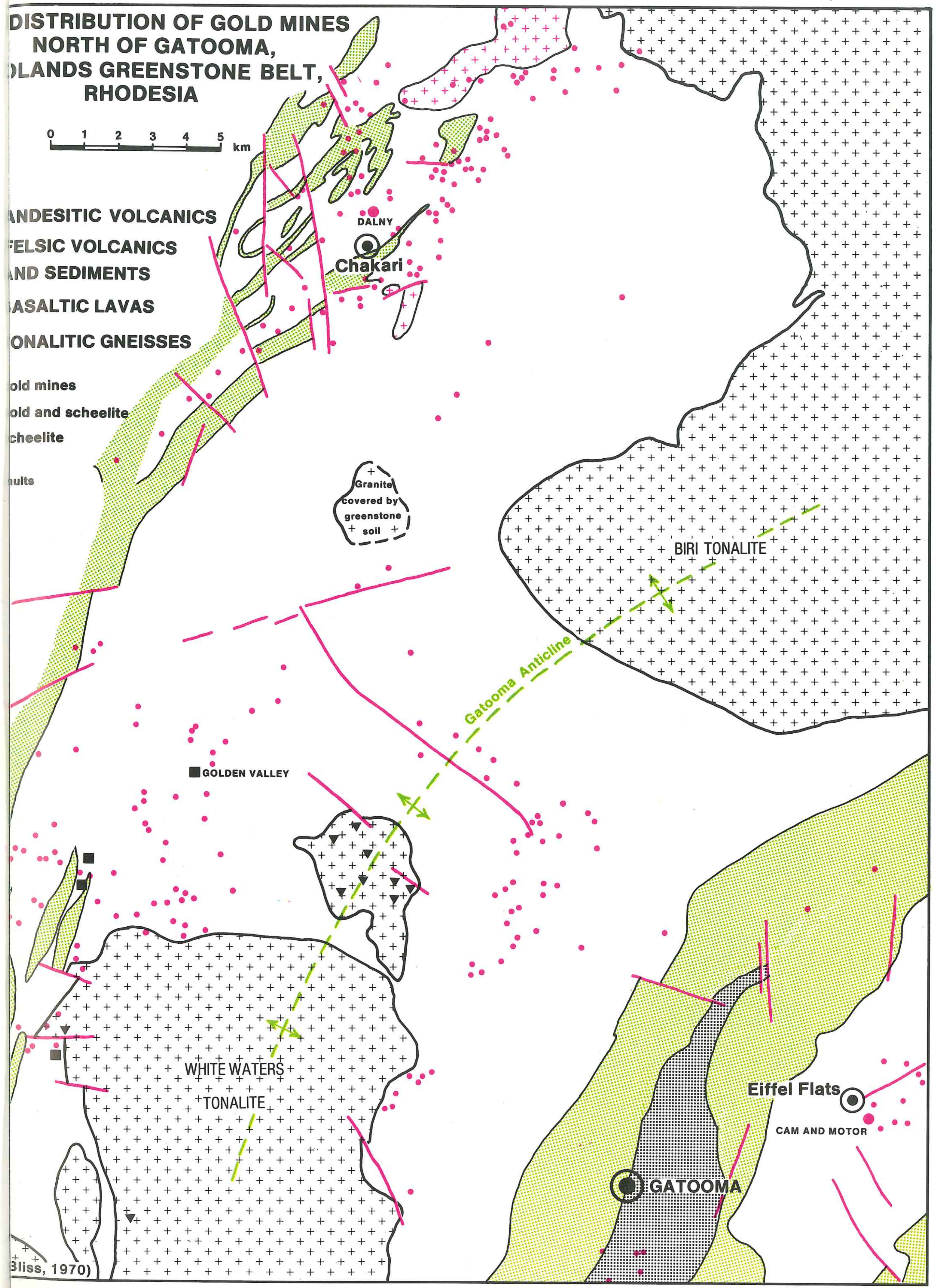

be the thermal controlling influence of the granites, the latter generating the epithermal solutions that migrated away from the pluton margins to the low-pressure tension zones. Higher-than-average temperatures probably accompanied the emplacement of the plutons along the axial zone of the Gatooma Anticline, as is evidenced by the prominent development of scheelite in the Lion Hill stock and in many of the gold mines rimming the Whitewaters tonalite (Figure 16).

It is interesting to speculate further on the geology, structure, and mineralization potential of the Midlands greenstone belt north of Gatooma. According to the mapping of Bliss[150] a small patch of granite, covered by greenstone soil, occurs in the region south of Chakari. The pattern presented by this granite body and the neighbouring Biri tonalite is not unlike that of the Whitewaters and Lion Hill tonalites through which the axial trace of the Gatooma Anticline passes. If an east-west anticlinal fold axis were to be established between the Biri diapiric granite and the covered granite body, might not another arc of mineral deposits encircle this structure? The isolated gold mines scattered about the poorly exposed area may be pointers to such a possibility.

A further example of the controlling influence of granite diapirism on the distribution of gold deposits is shown in Figure 17, which represents part of the Lower Umfuli region of the Midlands greenstone belt. This region, described by Phaup and Dobell[134], occurs approximately 40 km north of Gatooma, where a protuberance of the Biri tonalite diapir, referred to as the Shangwe tonalite, intrudes and deforms rocks mainly included with the Bulawayan Group. In the northeast quadrant of Figure 17 serpentinites, basalts, and banded iron-formations are prominent, the latter forming part of the older ultramafic-mafic assemblage considered to sweep in a northwesterly arc from the Hartley area (Figure 12) around the southwestern margin of the Zwimba batholith[24].

The intrusion of the Shangwe tonalite produced a series of broad folds in the basaltic greenstones encircling the granitic body. Tensional fissures striking in three principal directions (NE, N 80° E, and N 30°W) were formed, the last two containing large veins of quartz[134]. Most of the quartz veins in the Lower Umfuli gold belt are narrow and impersistent, although frequently rich in gold. The majority of the mines work quartz lodes that contain only a small percentage of sulphide minerals.

The largest gold deposit in the Lower Umfuli region is the Bay Horse mine located in rocks that include serpentinites, basalts, and banded iron-formations of the ultramafic-mafic assemblage. Some of the ore is associated with the banded iron-formations suggesting a stratiform volcanic exhalative origin for the gold and sulphides. Gold also occurs in quartz veins. Chalcopyrite is the commonest sulphide in the mine and occurs together with lesser quantities of pyrite, pyrrhotite, magnetite, and galena[134].

FIGURE 16 Simplified map of the area north of Gatooma in the Midlands greenstone belt showing the distribution of gold mines in the region in relation to intrusive granite diapirs and stocks as well as granite porphyries (red crosses in the Chakari area). Although a stratigraphic control to mineralization may be effective the influence of the granites in producing favourable structures and heat energy requirements for lode gold deposits to form cannot be discounted (modified after Bliss[150]).

Gold deposits associated with granitic stocks

Numerous granitic stocks or cupolas are intrusive into the greenstone belts of Rhodesia[4,24,57] and Botswana[155]. Many of these bodies deform the country rocks into which they are emplaced and the stocks themselves are commonly fractured and replaced by quartz vein networks. Gold mineralization may extend from the granite-greenstone contacts into the granites, as is the case at Bindura[125] and Jumbo[82] (in the Salisbury-Shamva greenstone belt), the Bill's Luck stock[156] (Filabusi belt), the Colleen Bawn stock[136] (Gwanda belt), and numerous small granitic-to-dioritic stocks south of the main mass of the Sesombi tonalite pluton west of Que Que[151] (central Midlands belt). In addition to several others, as well as intrusive porphyry bodies, there is also the Penhalonga quartz-diorite stock[133] intruded into basalts, serpentinites, and iron-formations of the Sebakwian Group in the eastern part of the Umtali greenstone belt (Figures 3 and 12). The majority of mines in the Umtali belt occur in the Penhalonga valley, and practically all the gold mined has come from quartz veins in the Penhalonga stock or in the greenstones within about 2 km of the eastern lobe of the stock, which is located directly north of Penhalonga (Figure 18). Away from the stock the mineralized occurrences decrease in importance but there are a number of ore bodies associated with banded iron-formations[38,133].

The Bindura stock is intrusive into a variety of arkoses, greywackes, conglomerates, quartzites, and grits of the Shamvaian Group and the gold deposits are closely associated with the granite, as is well-demonstrated near Bindura[129]. The main gold mines in this area are concentrated around and within the boundaries of the Bindura granite stock (Figure 12). Approximately 20 km west of Bindura is the Glendale granite stock, which occupies a position in the greenstone belt similar, with respect to the other formations, to that of the Bindura stock, but there are no mines either within or in close proximity to it. Tyndale-Biscoe[129] pointed out that the country around this stock is poorly exposed and, in addition, is partially surrounded by a later gabbro or diabase sill-like body. It was suggested that these two factors might explain the absence of gold mines in this region.

Gold deposits controlled by structure

Practically all the gold mines in the greenstone belts of the Rhodesian and Kaapvaal cratons are influenced, to varying degrees, by structural disturbances that may be regional, or local, or both[56,60,63]. Individual mine descriptions, provided in the Geological Survey bulletins of Rhodesia, Botswana, Swaziland, and South Africa, also testify to this important factor in ore control.

From the many examples that could be discussed it was decided to single out the detailed study carried out by Stowe[66,146] on the fissure patterns and their relation to mineralization, in the Mont d'Or area south of Selukwe in the central part of Rhodesia.

The Mont d'Or sediments, regarded by Stowe as forming part of the Sebakwian Group, consist of structurally homogeneous arkoses, grits, and greywackes in which six distinct sets of fissures were recognized (Figure 19). Included within the Mont d'Or complex are mafic and ultramafic schistose inclusions that have absorbed shearing movements parallel to their foliation without them

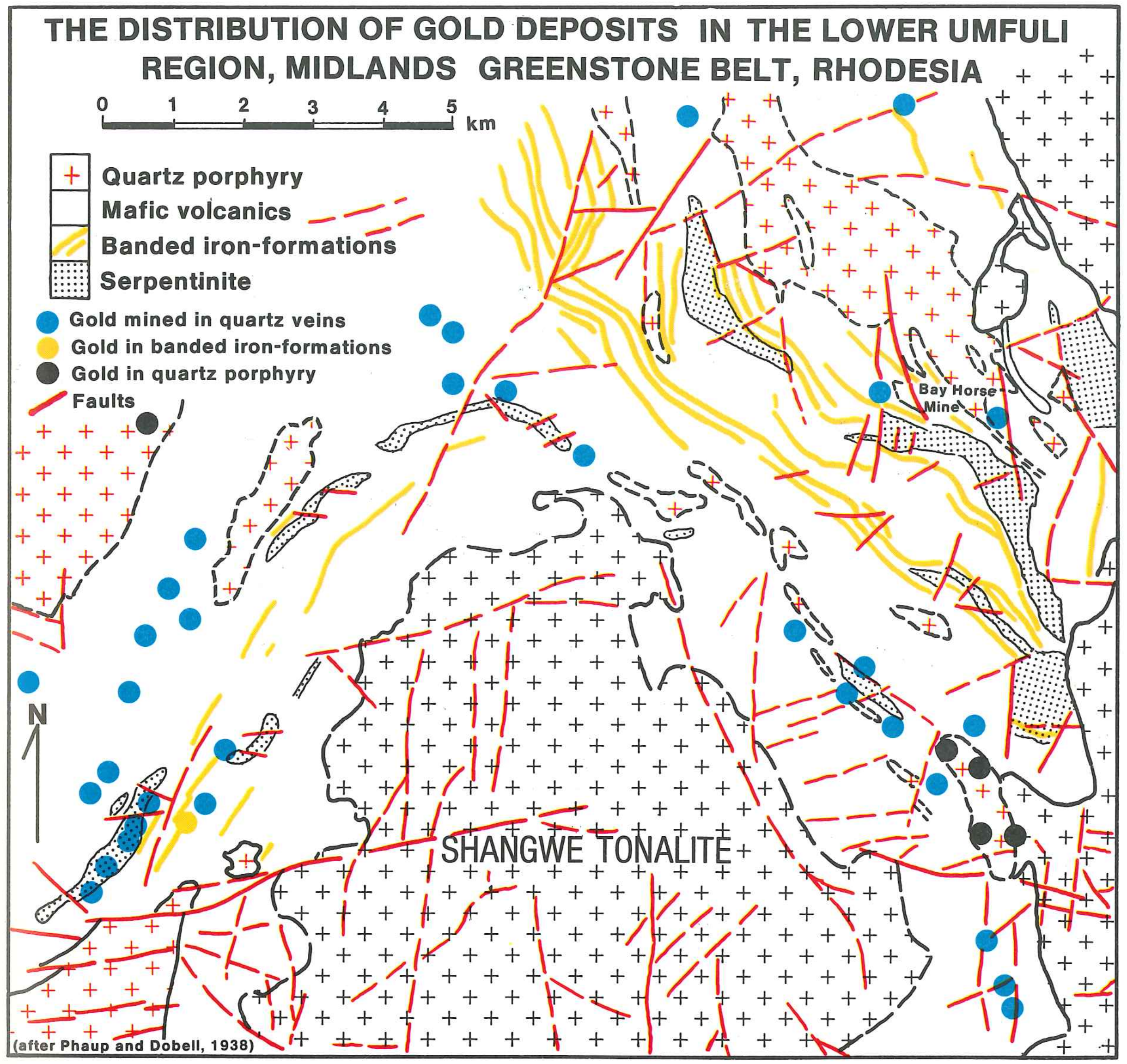

FIGURE 17 Simplified geological map of the Lower Umfuli region of the Midlands greenstone belt, Rhodesia, showing the distribution of gold deposits in an arc rimming the Shangwe tonalite body. Most of the mineralization occurs in quartz lode ore bodies in dilation fractures produced by the intrusive granite. The largest mine in the area (Bay Horse) is, however, associated with banded iron-formation (modified after Phaup and Dobell[134]).

fissuring. The majority of these inclusions are orientated in a WNW direction and have steep dips. The Mont d'Or succession lies in a basin-shaped structure about 7 km across and 10 km long, the rim of which mainly consists of serpentinite and magnesian schists together with banded iron-formations and phyllites. On the west side, the basin is bounded by the Surprise Fault zone, which might be related to the Great Dyke that it parallels. A variety of Archaean granites, gneisses and migmatites occur to the west of the Surprise Fault zone.

Several periods of deformation affected the rocks in the Mont d'Or area[146]. These events led to the development of the intense fracture and fissure system shown in Figure 19. On the basis of dip and strike, the fissures were classified into six groups (see below), of which the first two are by far the most important. About 170 gold mines occur in an area of about 60 square kilometres and between them they have produced more than 1 million ounces of gold up to 1960[146]. Of these, only 27 mines produced over 1000 ounces each and only the Bonsor and Tebekwe mines (Figure 12) produced more than 100 000 ounces each.

The fissures were classified by Stowe[66,146] into:

1. North-south trending fissures,
2. East-northeast trending fissures,
3. West-northwest trending fissures,
4. Flat-lying fissures,
5. N 20° E trending fissures, and
6. Early-formed saddle veins or lenses following the fold axes.

Group 1 fissures are 'tensional' and show a échelon arrangement and a tendency to occur in synclines formed during post-Shamvaian folding. The N-S trending veins are wider than most others and are also more important economically – both the Bonsor and Tebekwe ore bodies are related to this group.

The second set of fissures are developed on one of the main shear directions and are seldom wide but are

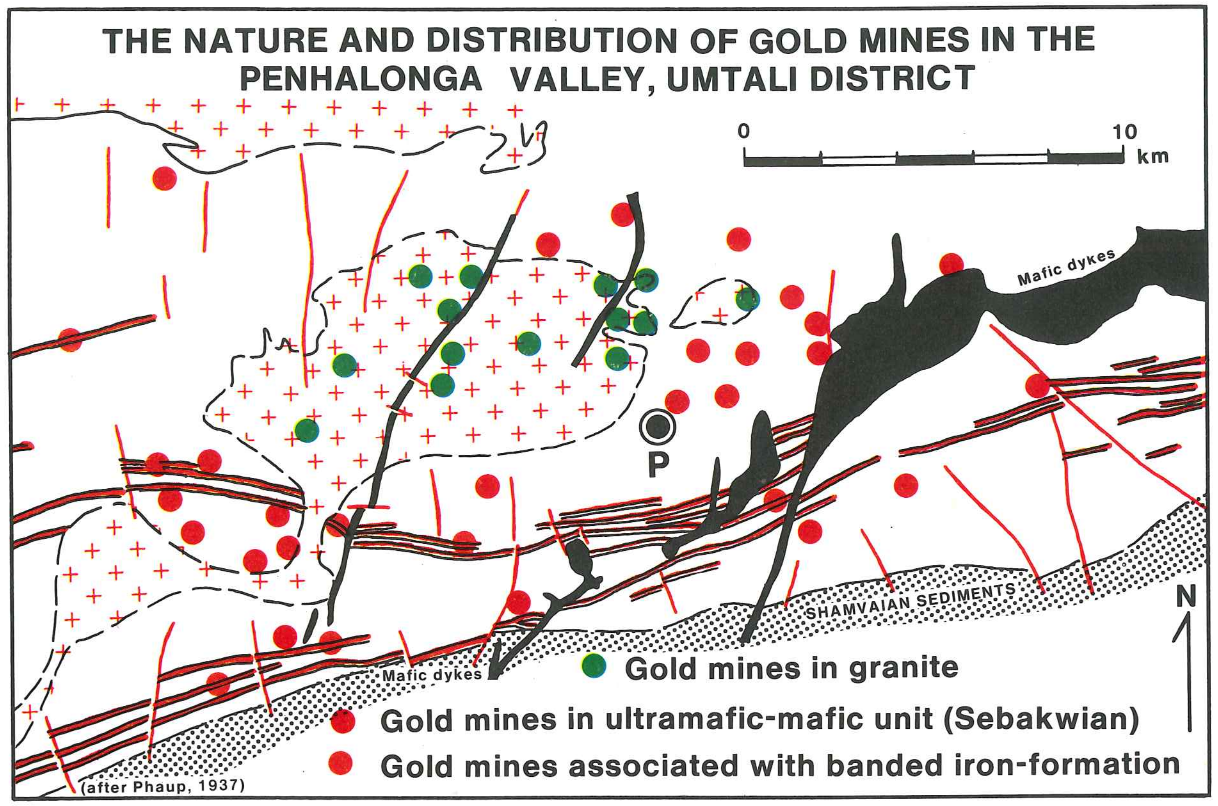

FIGURE 18 Geological map of the Penhalonga Valley region of the Umtali greenstone belt, Rhodesia. The majority of the gold mines in the area are associated with the Penhalonga quartz-diorite stock which is intruded into basalts, serpentinites and banded iron-formations of the Sebakwian Group. Almost all the gold mined in the area has come from quartz veins in the quartz-diorite stock or in the greenstones within about two kilometres of the eastern lobe of the stock. Some ore bodies in the region are associated with iron-formations (modified after Phaup[133]).

persistent along their strike. They show a preferred tendency to occur in zones along the main post-Shamvaian anticlinal fold axes along which there was a local 'tensional' component caused by warping movements (see inset block diagram, Figure 19). These fissures developed obliquely across schist inclusions and contain a number of economically important gold deposits.

The third group of fissures are developed along the WNW shear direction and are rare owing to the movement being absorbed in the mafic schist inclusions, and also owing to their not being parallel to the anticlinal fold axes. They are of little economic significance having no important mines on them.

The fourth set of fissures are flat-lying and 'tensional', are usually wide but are seldom extensive, and occur mainly in the foliation of anticlinal structures, and are well-mineralized in places.

The fifth fissure set all lie in the Surprise Fault zone, which has been affected by several stages of fault movement, culminating with displacement associated with the intrusion of the Great Dyke. Gold deposits occur in this fissure set but are low grade and few in number. The sixth fracture set only occurs in the extreme south of the area, the quartz lenses being emplaced into the fold axes as saddle reefs. Only a few gold deposits belonging to this group were mined.

According to Stowe[66] there were three main stages of mineralization in the sets 1 to 4 fissures, each separated from the other by minor deformation stages. Early white quartz was followed by grey quartz and carbonate and pyrite. This, in turn, was followed in stage three by two divergent types of mineralization – pyrrhotite/chalcopyrite and galena/sphalerite. The mineralization is also related to a molybdenite/pyrite/chalcopyrite source in aplogranite porphyries, the latter associated with group two fissures. The mineralization of the N 20° E veins is different, with cobalt and nickel arsenides present.

Gold deposits associated with banded iron-formation

As mentioned earlier, stratabound mineral deposits, particularly of gold and associated sulphides, are widely distributed within beds of banded iron-formation in the greenstone belts of southern Africa. Although the association of gold and banded iron-formation and banded chert had long been recognized as important in exploration for the precious metal little thought was given to the possibility that there might be a genetic link between the two. Investigations in Canada, from about 1965 onwards[77,78,157-160], led to the development of new concepts of metallogeny in Archaean volcano-sedimentary successions and, in particular, it was established that gold and iron mineralization was genetically related to cycles of volcanism in the greenstone terranes.

In southern Africa, Fripp[31,39,59] was able to confirm the close genetic ties linking many of the gold deposits to banded iron-formations following investigations in selected areas of the Rhodesian craton. Most attention was given by Fripp to the gold/iron-formation occurrences at the Vubachikwe, Connemara, Giant, Pickstone, and Sherwood

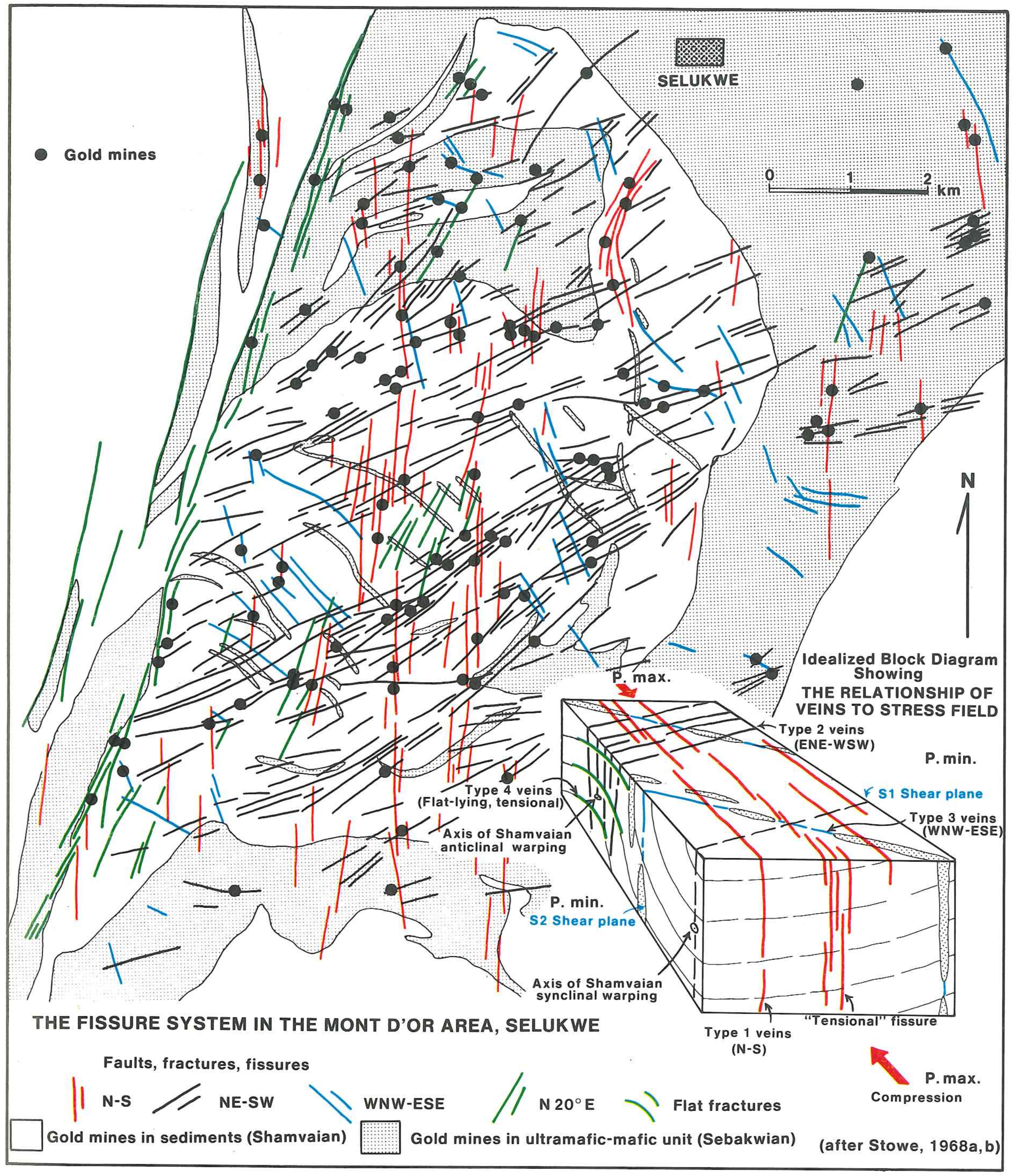

FIGURE 19 Map (after Stowe[66,146]) showing the complex fissure system in the Mont d'Or area, near Selukwe, Rhodesia. The gold mines, of which there are about 170 in the area, are principally located in the N-S tensional veins and, to a lesser extent, in the ENE-WSW shear planes (S1) that have been warped, thereby producing dilation structures. An inset block diagram shows the relation of the fissure system to the regional stress field. The sediments in which the mines occur are considered by Stowe[146] to be part of the Sebakwian Group. In the map they are shown as Shamvaian.

Starr mines (Figure 12) as well as the Athens (Umvuma greenstone belt), Beehive (10 km northwest of Que Que, Midlands belt), Camperdown (Selukwe belt), Empress (Victoria belt), Marvel (Filabusi belt), and the Nelly 404 and Umzingwane Group of mines (including the Tin Hat, Seymour, Vale, Red Hill, and Redbank mines) in the Bulawayan greenstone belt.

To this list can be added many more occurrences where the gold, the sulphides, and the iron-formations are consanguineous. This would be true of some deposits in the Tati greenstone belt in Botswana[155,161] as well as some deposits in the Pietersburg[162], Murchison[81,83], Amalia[163], Barberton[68,72,90,109,118], and Sutherland greenstone belts on the Kaapvaal craton.

Banded iron-formations and related ferruginous cherts and argillites are widespread throughout the greenstone belts of southern Africa where they serve as useful stratigraphic marker beds over great distances, and are generally 20 m or less in thickness. The iron-formations occur as oxide, silicate, carbonate, and sulphide facies variants and, as shown by Beukes[164], occur in three distinct lithologic and stratigraphic situations:

- interlayered with the various rock types that constitute the Lower Ultramafic Unit (Sebakwian, Tjakastad),
- interlayered with basalts, basaltic andesites and felsic volcanic and pyroclastic rocks of the Mafic-to-Felsic Unit (Bulawayan, Geluk), and
- interlayered with argillaceous and arenaceous sedimentary rocks (Shamvaian, Fig Tree, Moodies).

According to Fripp[38], most of the auriferous mineralized deposits in Rhodesia occur in iron-formations associated with the lower ultramafic-mafic volcanic assemblage (Sebakwian Group).

The gold bodies are stratiform and are confined to beds of sulphide and mixed sulphide-carbonate facies banded iron-formation, which consist of layers alternatively rich in one or more combinations of silica (quartz, chert), arsenopyrite, pyrrhotite, pyrite and layers rich in iron-carbonates (ankerite, siderite). In some cases, carbonaceous shaly or cherty layers or jaspilite may also be present. Microscopically visible gold is found as inclusions in arsenopyrite ores but in ores wherein pyrite dominates, the *gold* is generally sub-microscopic[38]. On average, the arsenopyrite-rich varieties contain most gold, those with arsenopyrite and pyrite lesser amounts and the pyrite-pyrrhotite combinations significantly less.

The nature of some typical ores associated with iron-formations are illustrated in Figures 20 to 22. In Figure 20, the alternating layers of carbonaceous chert and sulphides (mainly pyrite, with some arsenopyrite and pyrrhotite) from the Belvedere mine (Belingwe belt) are clearly stratiform.

Disseminated euhedral pyrite grains, also in well-defined bands (Figure 21), occur in carbonaceous argillites from the Montrose mine in the Barberton greenstone belt and, in Figure 22, alternating cherty and sulphide layers (pyrite, pyrrhotite) from the Neardy mine in the Umtali greenstone belt show signs of having been deformed by folding. In examples of this nature, it has been established that the gold-bearing sulphide-rich layers pre-date the metamorphism and the deformation[38,39], and the mineralization is regarded as syngenetic with respect to the enclosing sedimentary strata.

The distribution of some of the ore deposits with banded iron-formations in the central regions of Rhodesia is shown in Figures 13 and 14. The region north of Hartley, in the Midlands greenstone belt, serves to illustrate the geological setting of ore deposits associated with iron-formations in the area (Figure 23). A narrow schist belt, mostly comprising Sebakwian ultramafic and mafic rocks together with banded iron-formations and minor felsic schists and sediments, protrudes northwards into the Biri tonalite pluton. A number of gold mines occur in the granitic terrane immediately flanking the schist belt but are mainly associated with xenoliths rafted off the main Gadzema greenstone tongue. The majority of ore bodies making up the Gadzema group are associated with banded iron-formations[55,134] despite the fact that many are shown to occur in the ultramafic-mafic units in Figure 23. Narrow bands of iron-formation, too small to indicate on the map, occur interlayered with the mafic and ultramafic schists and are hosts to much of the gold mineralization. It is interesting to note that as far back as 1957, Wiles[165] considered many of the serpentinites in the Gadzema area to be contemporaneous with the iron-formations and he suggested they might represent ultrabasic volcanic rocks.

The largest mines in the area are the Giant, which has produced over 500 000 ounces of gold, and the New Found Out mine located about 2 km northwest of the Giant ore body. Up to 1945, 20 991 ounces of gold had been mined from this deposit. After this period, the output was included with that of the Giant mine. The Giant ore body consists of mineralized chloritic schists in banded iron-formation, while the New Found Out deposit consists of a sulphide 'impregnation' in banded iron-formation[55].

Despite the narrowness of the Gadzema schist belt ($\sim$2 km wide) the metamorphism produced by the enveloping Biri tonalite pluton has not forced the sulphide and gold mineralization to migrate far from its original depositional environment although some local hydrothermal redistribution has taken place into fractures and fissures created in the various successions, in the area.

ARCHAEAN PLACER GOLD DEPOSITS

A final mineralization type for brief consideration are the gold occurrences associated with sedimentary assemblages in the greenstone belts and which qualify for inclusion as auriferous placer deposits. None of these have yielded much gold but it is doubtful whether they have all been adequately investigated.

A possible exception appears to be the Uitkyk Formation in the Pietersburg greenstone belt where extensive prospecting has been carried out. Rocks in this succession, which is 1100 m thick, include feldspathic quartzites, conglomerates, grits, shales, and boulder beds[95,166]. Gold occurs together with pyrite in the polymictic conglomerates and has been mined sporadically in the past in a small way. The trenching and sampling of the conglomerates indicated a widespread distribution of gold in the sediments but the ore grade has been found too low to warrant exploitation on a large scale.

In Rhodesia, placer gold deposits occur mainly in sediments classed with the Shamvaian Group. In the Victoria greenstone belt[145], gold was found in conglomerate bands south and southeast of Fort Victoria. One of the main producers in this area was the Coronation mine where gold occurs in a rubble-bed containing quartz pebbles, clay seams, and films of clay around brecciated quartz. Some large gold nuggets (weighing up to 4,5 ounces) were found in the mine that produced over 16 000 ounces of gold up to 1950[145]. Some of the Bulawayan grits in the Wanderer mine[56,138] in the Selukwe area are possible placer deposits as are the arenaceous 'Shamva Grits' in the Shamva mine[56,125] (Salisbury-Shamva greenstone belt). In the Mwanesi greenstone belt (Figure 3) gold occurs in an iron-rich quartz-breccia developed in conglomerates and grits in the Kismet mine. The sediments here are classified with the Bulawayan Group[143].

The Eldorado mine (Figure 12), one of Rhodesia's larger gold deposits, occurs in Shamvaian conglomerates[141]. When discovered it was believed to be a fossil placer analogous to those on the Witwatersrand. The conglomerate formed the subject of much controversy[167,168] as it soon became apparent that away from the Eldorado mine very little of the sediment was

auriferous. The ore bodies at the mine consist of two parallel zones of mineralization in a sheared conglomerate. It was eventually agreed that the mineralization was epigenetic and occupied shear zones in the conglomerate. According to Stagman[141], there was no difference in appearance between ore and barren country rock and the deposit had to be mined to assay walls.

Investigations in the Witwatersrand goldfields have clearly demonstrated that gold distribution is strongly influenced by sedimentological controls. For example, conglomerates are not uniformly mineralized and it becomes essential to understand the nature and style of sedimentation so that mineralized channels and pay streaks might be delineated. No systematic work of this nature has ever been attempted in the Archaean sediments and it appears there may be scope for such an approach in many of the areas outlined above.

THE ORIGIN OF ARCHAEAN GOLD DEPOSITS

Apart from sedimentary or placer-type mineralized occurrences most of the World's gold has been mined from epigenetic hydrothermal deposits[169-174]. The close association, World-wide, between gold lodes and intrusive rocks led Emmons[169] to conclude that a strong kinship existed between the two and gold deposits came to be linked genetically to granitic source rocks by many. Based on his experiences in Rhodesia, Macgregor[27], in 1951, suggested that the gold originated in the sima and was brought to the surface of the earth in basaltic lavas. Thereafter he visualized the granite taking over and providing the silica, water, and other fluxes necessary to extract the gold from the lavas and to redistribute the metal in mineral deposits, either in the already crystallized portion of the granites, or in nearby greenstone belts.

The source-bed concept for the origin of gold received further attention by Boyle[75,76] who adduced geologic and geochemical evidence from gold deposits in the Yellowknife greenstone belt of Canada, suggesting that the gold had its ultimate source in the supracrustal rocks, volcanic and sedimentary, and not in the associated intrusive granites.

A number of papers followed dealing with the relation between mineralization and stratigraphy, structure, and volcanism, particularly on the Canadian Shield[77,78,157-160], but also in southern Africa[18,19,27,58,59], and elsewhere. Where applicable to gold mineralization most authors concede that intrusive granites did play an important role in producing the heat energy requirements and structural environments necessary for the migration and redeposition of gold and other elements to form pseudo hydrothermal deposits. As pointed out by Viljoen *et al*[18] the volcanic and other source rocks, in some instances, have been modified to such a degree that the fundamental volcanic-mineralization relation has become blurred and the granites have been held solely responsible for the mineralization.

Because much of the gold occurred in epigenetic lode deposits its origin generally provided controversy. By contrast, the origin of the stratiform gold-sulphide mineralization associated with the banded iron-formations is apparently less doubtful, and is linked genetically to volcanogenic exhalative processes[38,39,59,77-79,157-160]. The metallogenic conceptual framework within which the mineralization and associated rocks must be considered is shown in Figure 24, which represents a possible interpretation based on the views of Goodwin and Ridler[175] and Hutchinson *et al*[78].

The exhalative sedimentary environment with its various facies and subfacies of iron-formation is extremely widespread in volcano-sedimentary complexes. Depending on conditions of anion supply and proximity to exhalative source, the sulphide or carbonate subfacies of exhalite was deposited under reducing conditions whereas under oxidizing conditions the oxide facies developed. According to their anion content these exhalative iron-formations have been subdivided into four facies – sulphide, oxide, carbonate, and silicate[176]. The spatial association of gold with oxide iron-formation has been employed by prospectors for decades and the characteristic presence of the metal in massive pyritic base metal ores, now widely believed to be of volcanogenic origin, suggests that the gold in the exhalite iron-formations may also be a primary constituent of exhalative volcanism[38,77-79].

Experimental data on gold solubility has been reviewed by Fripp[38,39]. Gold in hydrothermal alkaline sulphide solutions was found[177] to be soluble in the range 100 to 200 p.p.m. at temperatures ranging from 150 to 280 °C owing to the formation of a stable gold complex involving H_2S and HS. Seward[178] studied gold solubility in aqueous sulphide solutions for the pH values ranging from 4 to 9,5 and found that in the temperature range 160 to 300 °C gold is soluble from 40 to 230 p.p.m. at a pH value of 6. It was concluded that three gold-thio complexes dominate in these solutions: $Au(HS)_2^-$ in neutral solutions, $Au_2(HS)_2S^{2-}$ in alkaline solutions, and $AuHS^0$ in acid solutions. Seward also suggested that arseno-thio and antimino-thio complexes may also be important gold-transporting compounds in the relatively low temperature solutions. Henley[179] and Fyfe and Henley[180] investigated the solubility of gold using chloride solutions. It was found that gold solubility increased steadily from 10 p.p.m. at 300 °C to 200 p.p.m. at 450 °C. From 380 °C it increased markedly to about 1000 p.p.m. at 510 °C[179]. It was suggested[180] that if water moves out of amphibolites in the temperature range 500 to 700 °C, and if chloride is present, then most of the gold will move with the water in solutions undersaturated with respect to gold. Furthermore, it was suggested that major gold precipitation would occur in the range 300 to 400 °C in the greenschist facies. These observations seem consistent with the distribution

FIGURE 20 Top. Hand specimen of sulphide facies banded iron-formation from the Belvedere gold mine in the Belingwe greenstone belt. The dark layers consist of carbonaceous chert and the sulphide bands contain mainly pyrite, together with some pyrrhotite and arsenopyrite. The ore is clearly stratiform (sample loaned to the author by R.E.P. Fripp).

FIGURE 21 Bottom left. Hand specimen of stratiform, disseminated, sulphide facies iron-formation from the Montrose gold mine, Barberton greenstone belt. Euhedral pyrite grains occur in well-defined bands in the ore. The dark host rock consists of carbonaceous argillite. The pyrite and gold are syngenetic components of the ore.

FIGURE 22 Bottom right. Hand specimen of massive sulphide variety of iron-formation from the dormant Neardy lead-copper-gold deposit in the Odzi-Umtali greenstone belt, Rhodesia. The dark grey layers are cherty, the remainder, dominantly pyrite and pyrrhotite, also arranged in layers. The sample (loaned to the author by R.E.P. Fripp) provides a good example of folded stratiform ore. The sulphides clearly pre-date the deformation.

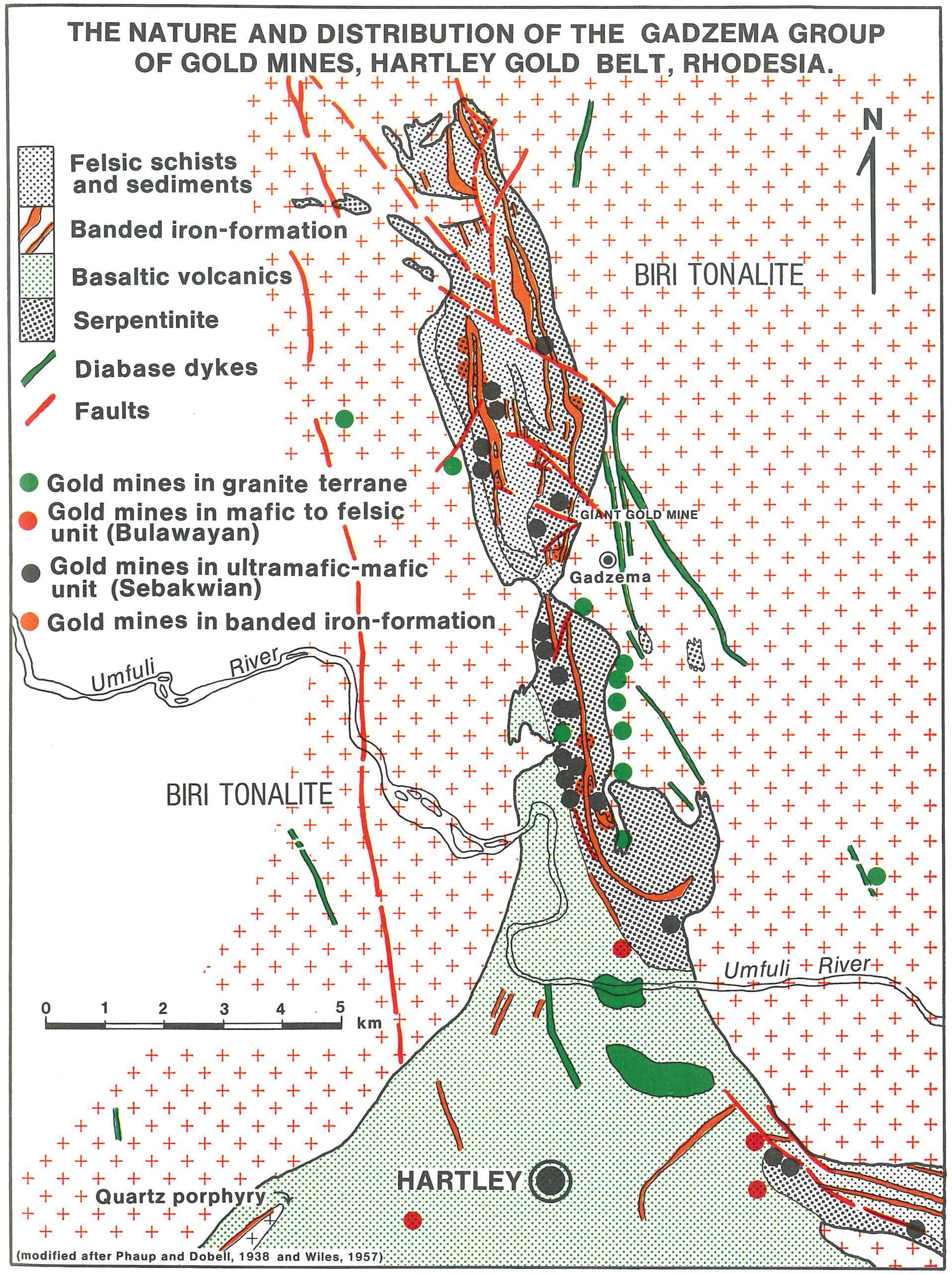

FIGURE 23 Geological map of the Gadzema schist belt located north of Hartley in the Midlands greenstone belt, Rhodesia. The gold mines in the narrow schist belt tongue are mainly associated with banded iron-formations that occur as narrow interlayers in the ultramafic and mafic volcanic sequences, here included in the Sebakwian Group. Many of the gold mines occurring in the granites are also associated with iron-formations in xenoliths rafted off the main schist belt by the Biri tonalite (modified after Phaup and Dobell[134] and Wiles[55]).

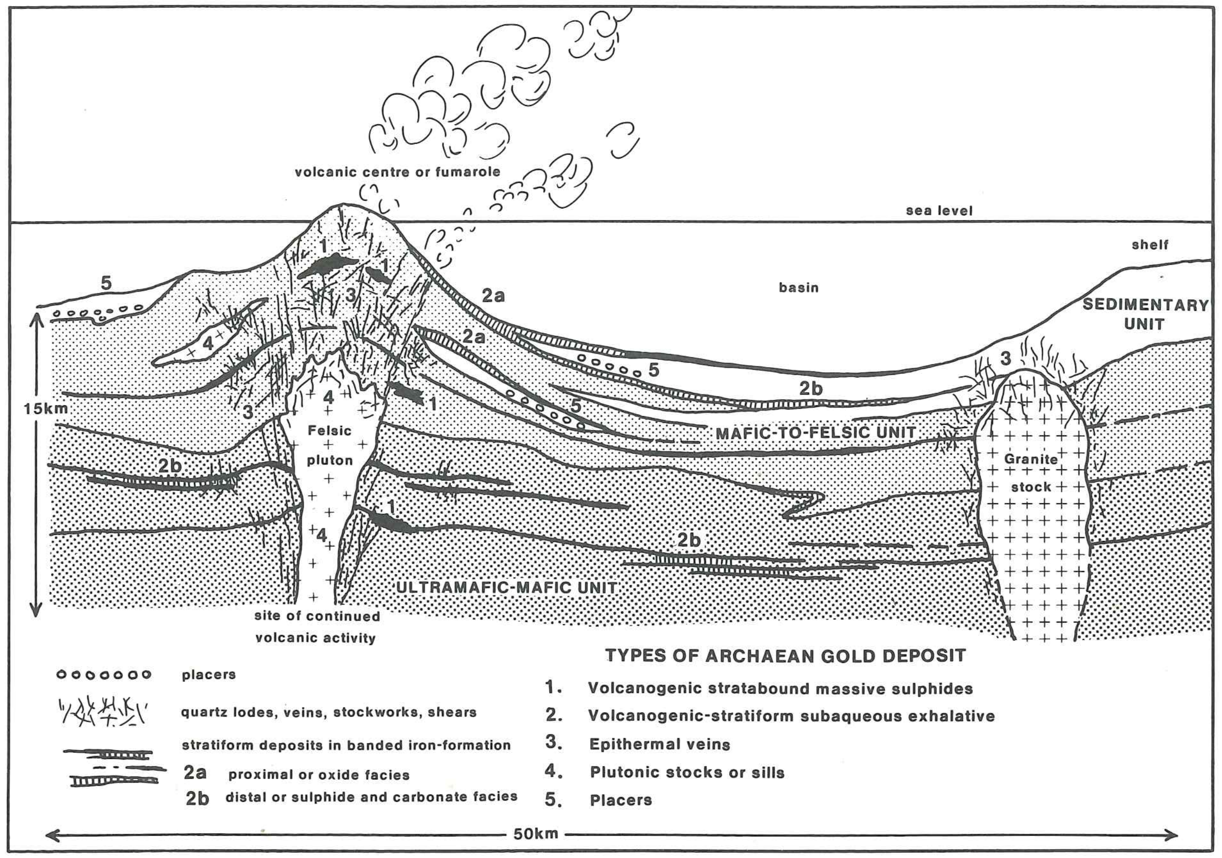

FIGURE 24 Schematic diagram of an Archaean volcano-sedimentary complex showing the possible relation of mineralization (gold and sulphides) to various parts of the volcanogenic model (modified after Goodwin and Ridler[175] and Hutchinson et al[78]).

of gold occurrences relative to granitic heat sources in many southern African greenstone belts.

Gold transport and deposition may also have been influenced by very high partial pressures of carbon dioxide in the auriferous fluids (as suggested by fluid inclusion data (F. J. Sawkins, *personal communication*). The presence of carbonates in both the stratiform and lode gold deposits supports this view.

Using the available data on gold solubility Fripp[38,59] proposed a metallogenic model of the evolution of gold deposits in the Archaean, the latter reflecting the changing gold-transport mechanism and the changing geothermal gradient with time. Supported by the concept of a thinner crust in Rhodesia in pre-Bulawayan times Fripp[38,59] suggested that temperature gradients in Sebakwian times were generally greater than during the Bulawayan period. Thus, as shown in Figure 25A, the 100 °C isotherm, in submarine and near or on-shore environments, could have been above the sediment-water interface and close to the ground-atmosphere interface during the Sebakwian, and appreciably lower during the Bulawayan (Figure 25B). The diagrammatic mineralization model proposes that during Sebakwian (or Tjakastad) times, geothermal brines containing significant dissolved amounts of the Au-thio-complexes, and Au-As-S species together with variable amounts of Fe, As, Si, S, Mn, Ti, Cu, Pb, Zn, Sb, Co, Ag, and carbonate, were deposited as stratiform beds of iron-formation on the sea floor. Facies variations would account for mineralogical differences, the iron-formations in the oxide zone containing cherty hematitic and magnetitic layers, as well as low-tenor gold-bearing sulphides and associated carbonate layers. In the deeper regions, carbonates, higher tenor gold, and iron and arsenic sulphides, would develop. In yet deeper water, under reducing conditions, gold concentrations would again dilute to form low-tenor gold deposits in iron-formation containing both sulphides and carbonates.

During the Bulawayan or Shamvaian (or Geluk, Fig Tree, Moodies) times the thicker volcano-sedimentary pile would reduce the geothermal gradient and therefore reduce the gold content of hydrothermal brines at surface[38]. Instead, the gold may have been in solution as chloride species[179] and could conceivably have precipitated in buried fracture systems in the 300 to 400 °C range. The rare and relatively small gold deposits known in iron-formations in the mafic-to-felsic and sedimentary units were probably generated close to fumarolic outlets and may have largely been dispersed into the oceans.

The solubility studies and modelling attempts all hinge on the postulate that the ancient volcanic rocks in the greenstone belts contained unusually high levels of the noble metals. Viljoen *et al*[18] and Saager[181] have, for example, reported gold concentrations of between 5 and 20 p.p.b. in basaltic and ultramafic komatiitic lavas from the Steynsdorp goldfield in the Barberton greenstone belt. However, these analyses were carried out by the fire assay method and it has since been shown by Anhaeusser *et al*[182] that gold concentrations determined by neutron-activation analyses of komatiitic lavas, from two of the best preserved sections of the Lower Ultramafic Unit in

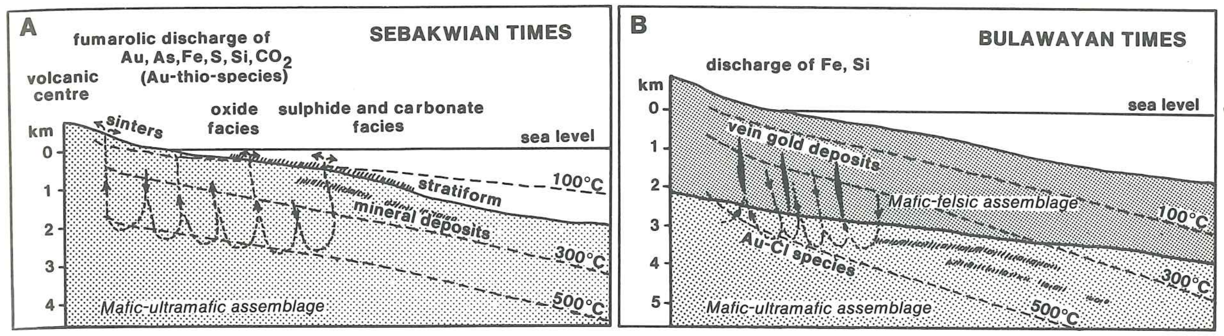

FIGURE 25 Model of the evolution of gold deposits in the Archaean, dependent largely upon the concept of convecting brines. Left, A. Stratiform mineral deposits formed in Sebakwian/Tjakastad banded iron-formation and siliceous ferruginous limestone. Right, B. Later lode or vein gold deposits in cross-cutting fractures with reduced geothermal gradient (after Fripp[38,39,59]).

the Barberton greenstone belt, yielded Au values in the range 1 to 1,5 p.p.b. These data show that the komatiites of the Barberton area now contain Au levels comparable with the present-day crustal average and substantially less than the world-wide tholeiite average of 2,5 p.p.b.[183]. Two interpretations of the new Barberton data are possible. One view is that these are primary concentrations – the alternative is that the lavas originally conformed to the model of Boyle[76], Viljoen *et al*[18], and others, in having primary levels significantly higher than today's basalt averages, but that later metamorphism and hydrothermal activity has erased all record of the fact from the Barberton komatiites.

Examination of the chemistry of the mafic and ultramafic komatiites[32,182] shows that, despite the seemingly unaltered nature of the samples chosen for analysis, these rocks have suffered a fairly uniform secondary hydration (7,5 to 10,3 per cent H_2O) the latter also indicated by the presence of actinolite and antigorite. This event may have been accompanied by the leaching-out of metals such as gold[177,180] although this is by no means certain. The data of Anhaeusser *et al*[182] place doubt on existing evidence for present-day high levels of Au in Archaean volcanic rocks and there is clearly a need for additional data from other areas using modern methods of analysis to bring a solution to the problem nearer.

Despite the lack, so far, of supporting analytical data, the field relations weigh favourably towards some of the gold, at least, being linked with the primitive mafic and ultramafic greenstone components. As early as 1908, Maclaren[172] remarked on the association of gold in India, Western Australia, East Africa, Canada, and the Appalachian region of the U.S.A. with Archaean basic schists of igneous origin and with later diabasic dykes. In considering the available evidence in Rhodesia, Macgregor[27] was also drawn to the conclusion that gold and other metals were mobilized from essentially mafic source rocks whereas, in Canada, Pyke[184] presented evidence to show that the ultramafic volcanic rocks in the Timmins areas of northeastern Ontario appear to have provided the main 'source bed' for the gold mineralization. The gold, he considered, was subsequently mobilized, possibly in large part during carbonatization of the ultramafic rocks and deposited in structurally favourable sites.

Finally, mineralogical support for a genetic link between gold and ultramafic rocks stems from ore microscopic studies undertaken by R. Saager (*personal communication*, 1975) who found the metal in olivine crystals in the ores of the Louis Moore mine in the Sutherland greenstone belt in the northeastern part of the Kaapvaal craton.

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BOOK REVIEWS

SEA LEVEL CHANGES

by EUGENIE LISITZIN

Amsterdam. Elsevier Scientific Publishing Co.

This book, Number 8 in Elsevier's Oceanography Series, deals with the history, causes and effects of sea level changes, with the emphasis on long-period tidal constituents.

The author points out that the Baltic Sea is a very interesting research region with regard to sea level variations, because the tidal phenomenon is rather insignificant in this area.

Astronomical tides and other periodic sea level variations, including seasonal changes, are dealt with. Special attention is paid to the world-wide distribution of mean sea level and its local and regional variations. Phenomena such as seiches and tsunamis are discussed, and the effect of earthquakes upon the mean sea level is examined. Finally, the chapter on the practical usefulness of this branch of scientific research could be of interest to navigators and persons concerned with coastal protection and water pollution control.

Greater coverage could have been given to instrumentation for sea level recordings. However, despite this omission this is a useful reference on the subject of sea level changes.

W. C. J. van Rensburg