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CONTROLS ON POLYMETALLIC MINERALISATION IN THE ACID PHASE OF THE BUSHVELD COMPLEX – A CASE STUDY FROM THE AREA NORTH OF BRONKHORSTSPRUIT, SOUTH AFRICA

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by

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ABSTRACT

The acid rocks of the Bushveld Complex are host to a large number of mineral occurrences showing a wide range of metal associations and broad paragenetic relationships. Fractionation of the granitic magma has served as a primary control in the localisation and nature of the mineralisation.

Mineralisation is most often associated with highly fractionated granites, which have high Rb and low Ba and Sr contents. A trace element differentiation index (TEDI), given as Ba ? (Sr / Rb), may be used to determine the amount of fractionation a granite has undergone. Low TEDI values are associated with highly fractionated granites, such as the Bobbejaankop granite, often host to tin mineralisation. Mineralisation in the highly fractionated granites passes from an early Sn-dominated mineralisation style (Type I) through base metal-dominated mineralisation styles to a precious metal-dominated mineralisation style (Type IV) hosted either in highly fractionated, low TEDI value granites or the overlying roof rocks, which are typically granophyres.

The changing nature of the mineralisation is a function both of the variability of the mineralising fluid with time as well as an interaction between the primary magmatic fluid and an external, possibly meteoric / connate, fluid. Various external fluid incursions are proposed to allow for the broad paragenesis brought about by fluid mixing between the changing magmatic fluid and the meteoric / connate fluids. When the system is dominated by the meteoric / connate component a late-stage oxidised assemblage of hematite - pitchblende - fluorite is precipitated on the earlier sulphides. This fluid mixing affects the nature of the mineralisation, as do structural features which influence the localisation of the mineralisation. In particular, two major crustal features, the Steelpoort and Laersdrif faults, and lineaments parallel to them, have influenced granite emplacement, the siting of mineralisation and local structure.

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INTRODUCTION

The Bushveld Complex of South Africa is subdivided into two suites of rocks, the mafic phase and the acid phase. The mafic phase, represented by the Rustenburg Layered Suite (RLS), contains large deposits of platinum and nickel and has been the subject of numerous studies. The RLS rims the acid phase, consisting of granites, granophyres and rhyodacitic to rhyolitic volcanic rocks. To date, these rocks have not been studied in as much detail, both scientifically and economically, as the mafic rocks. The granites of the Lebowa Granite Suite are, however, host to abundant, albeit small, polymetallic mineral deposits. This paper focuses on the mineralisation styles in the acid rocks and the various controls on the nature and formation of this mineralisation.

Mineralisation at Olympic Dam in South Australia is dominated by a Cu-Au-Fe-U association spatially related to felsic intrusives (Davidson and Large, 1994). As deposits related to the Bushveld granite, such as the Vergenoeg fluorite mine on Kromdraai 209 JR, fit into a general Fe-F dominated mineralisation style associated with felsic intrusives (referred to as the Olympic Dam type; Gan and Lingenfelder, 1998), the granites of the Bushveld Complex are worthy of more intensive exploration. The Olympic Dam mineralisation types, which vary from Fe-F dominated systems, such as at Vergenoeg, to higher level Cu-U-Au dominated systems, such as at Olympic Dam, are major mineralisation types associated with granite intrusives and are host to rich gold deposits, such as the Olympic Dam and Mount Elliot deposits in Australia (Oreskes and Hitzman, 1993; Davidson and Large, 1994).

The area examined in this study is an arc 62-km wide by 45 km long, situated 25 km north of Bronkhorstspruit and approximately 60 km northeast of Pretoria, that is underlain predominantly by the acid phase of the Bushveld Complex (Fig. 1). A more detailed map of the study area is given in Figure 2 which shows the geology of the study area and the localities of the more important mineral occurrences.

ROCK TYPES IN THE STUDY AREA

The roof rocks to the Lebowa Granite Suite in the study area consist of the upper Rooiberg Group and the Rashoop Granophyre Suite. The upper Rooiberg Group consists of the predominantly massive rhyodacites of the lower Kwaggasnek Formation overlain by the predominantly flow-banded rhyolites of the upper Schrikkloof Formation (Schweitzer et al., 1995).

The granophyres of the Rashoop Granophyre Suite in the study area occur between the volcanic rocks of the Rooiberg Group and the underlying granites of the Lebowa Granite Suite. They are considered to have formed as the hypabyssal equivalent of the same magma which extruded to give rise to the volcanic rocks of the Rooiberg Group (Walraven, 1982).

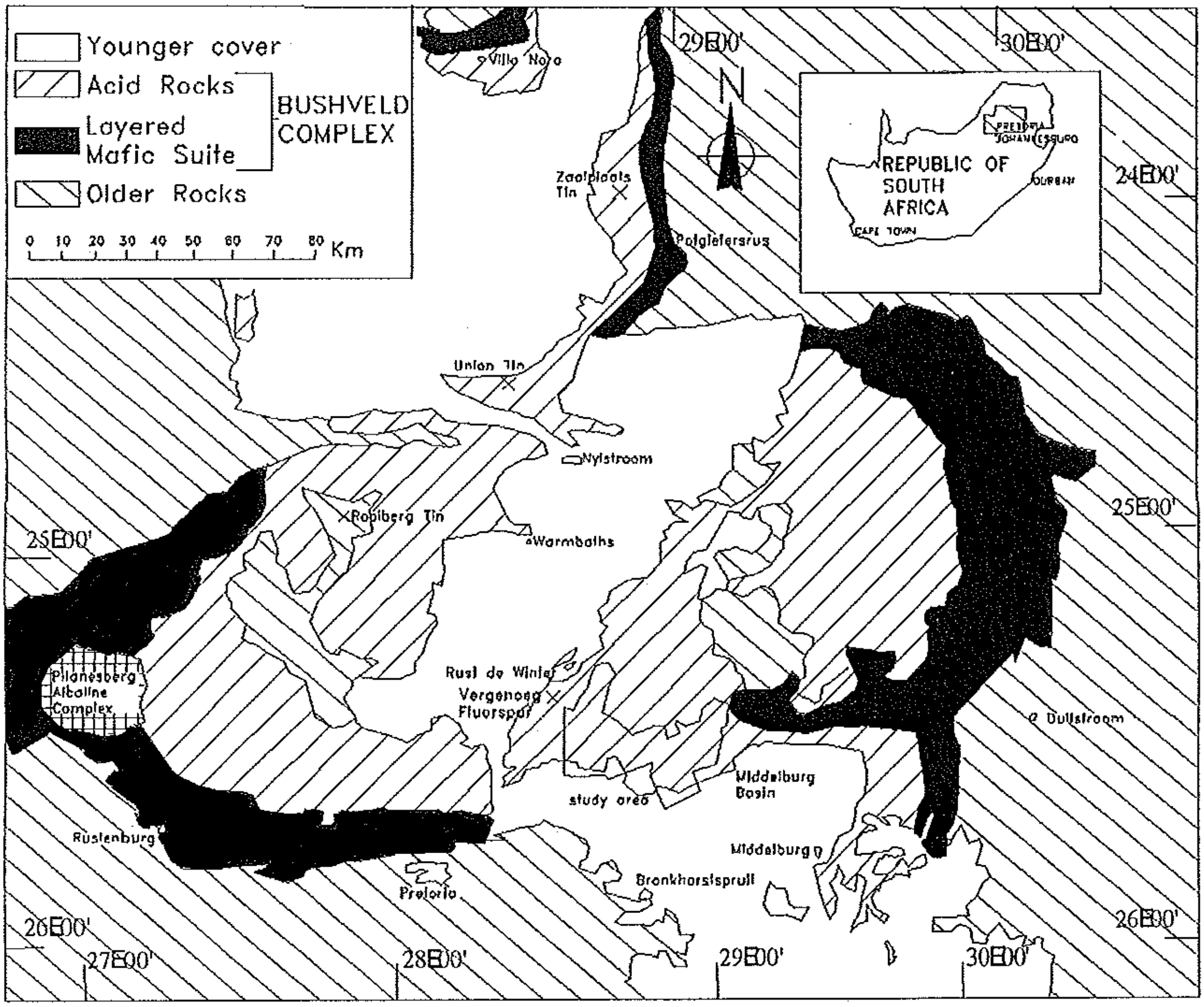


Figure 1: Location and generalised geology of the Bushveld Complex (inset shows position of larger map). The study area is indicated on the map

The granites are believed to have solidified by a process of in situ crystal fractionation from the base of a granite sheet (where the least fractionated granites occur) upwards to the most fractionated granites (Groves and McCarthy, 1978; Kleeman and Twist, 1989). As a result of this process numerous granite varieties have developed, in various localities, reflecting different levels and differing degrees of fractionation in the granite body. The main variety of granite is termed the Nebo granite, while the Sekhukhuni and Verena granites are local varieties within the study area (Fig. 2).

Other granites associated with the Nebo granite are a deep-red, K-feldspar, quartz-rich granite called the Bobbejaankop granite (Strauss, 1954) and a pinkish-brown, fine-grained aplitic phase termed the Klipkloof granite. Both varieties are believed to represent highly fractionated equivalents of the Nebo granite. The Bobbejaankop granite is often mineralised and hosts the tin mineralisation at the Zaaiplaats tin mine (Strauss 1954). The Klipkloof aplitic phase is often associated with the Bobbejaankop granite, but is mainly found as dykes and sills cutting across the Nebo granite (SACS, 1980).

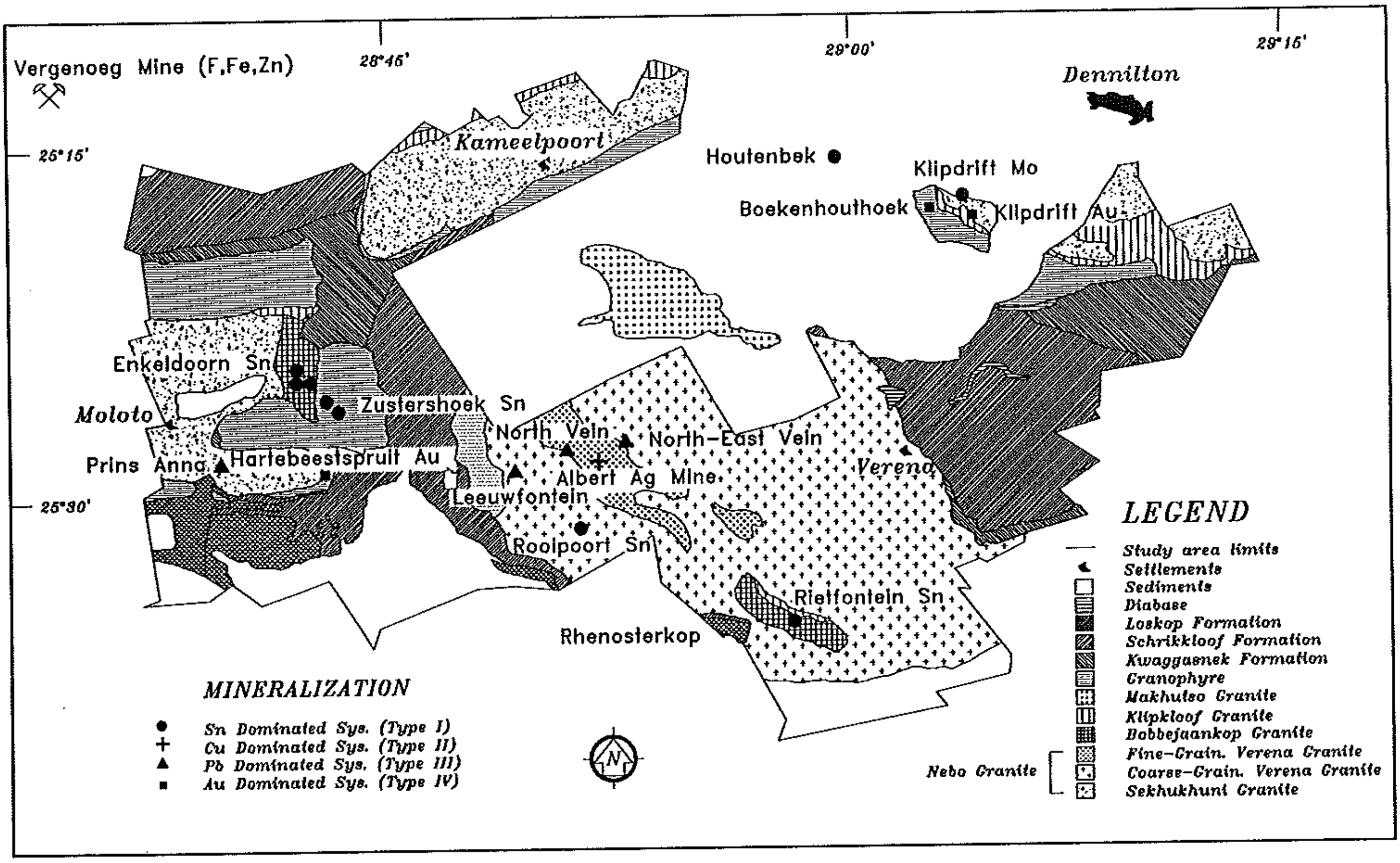


Figure 2: Simplified geology of the study area, emphasizing the subdivision of the mineralisation styles (or types) within the acidic rocks of the Bushveld Complex.

GEOCHEMISTRY

Granite Classification

A-type granites, such as the Bushveld granites, are known to have characteristic metallogenic signatures. The acid rocks in the study area show typical characteristics of A-type granites, as shown in Figure 3. Collins et al. (1982) pointed to the alkaline composition of A-type granites, along withtheir high Ga/Al2O3, Fe/Mg, SiO2, Zr and F contents and their low Ca and Sr characteristics, as well as a Sn-Mo-Bi-Nb-W-Ta-F metallogenic association. The granites plotted in Figure 3A, C and D all fall within the field of A-type granites as defined by Collins et al. (1982). Figure 3 B similarly indicates that the granites plot in the A-type granitoid field (as used by Kleeman and Twist, 1989). Figure 3E illustrates a within-plate setting for the granites, as defined by Pearce et al. (1984), and corresponds with the emplacement of the granites within the Kaapvaal Craton after collision of the Kaapvaal and Zimbabwe Cratons.

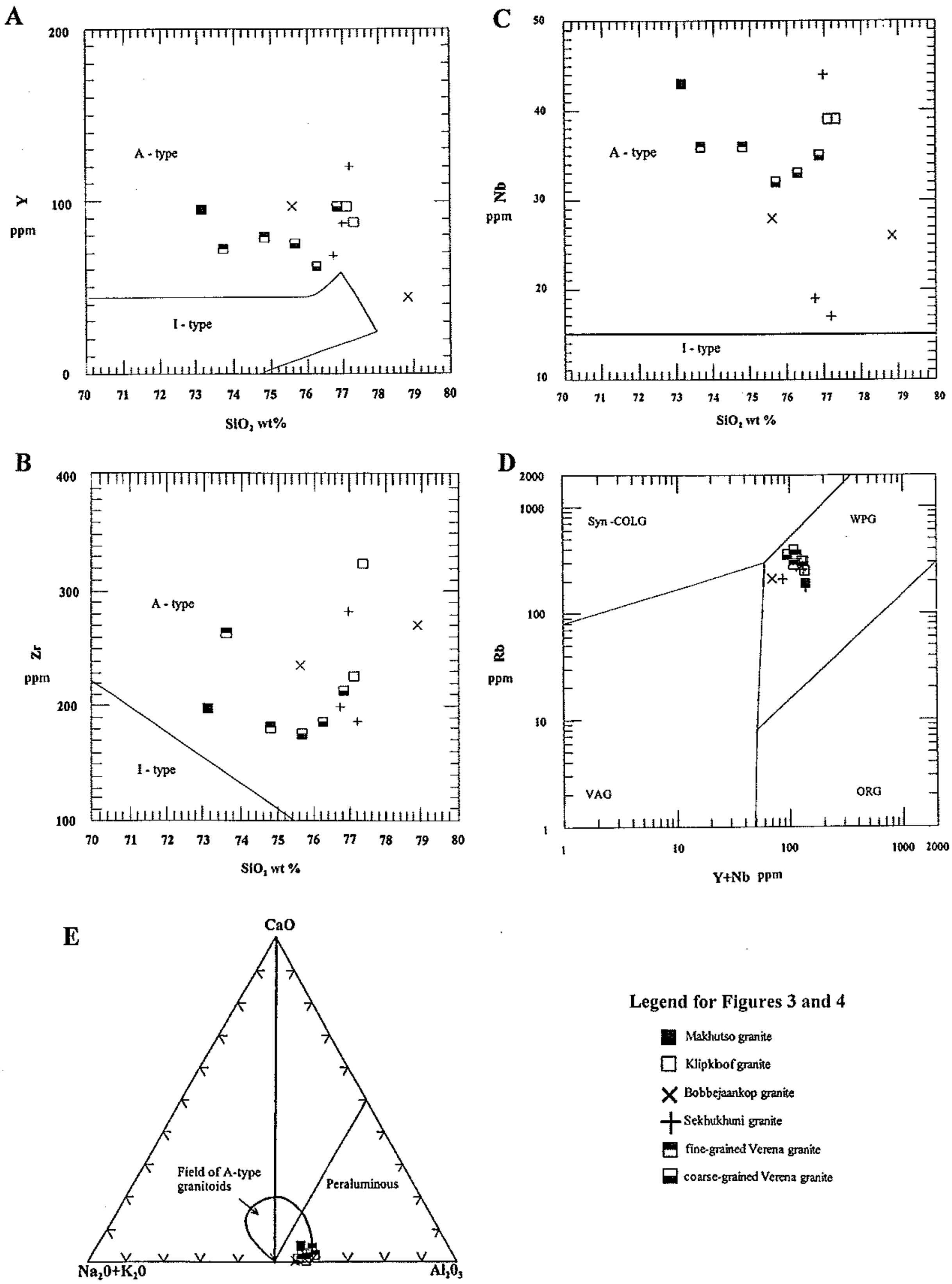


Figure 3: Diagrams illustrating the A-type nature of the granites in the study area. A, C and D are diagrams used by Collins et al (1982) to distinguish between I- and A-type granites. The granites of the study area clearly plot in the A-type field. B: As used by Kleeman and Twist (1989) illustrates the A-type nature of the granites. E: After Pearce et al (1984), illustrates the within plate granite (WPG) nature of the granites in the study area. Data from Table 1.

Degree of Fractionation of the Granitic Magma

The granites in the study area have low Ba and Sr and high Rb contents, indicating their highly fractionated nature, as defined by El Bouseily and El Sokkary (1975)(Table 1; Fig 4). The degree of fractionation of the granites is proportional to the extent to which incompatible elements, such as Rb and the base and precious metals, will be concentrated, as well as being related to the degree of H2O saturation in the evolving magma. Highly fractionated granites, which exhibit H2O saturation features, are found at the top of any given granite sheet and are likely to be mineralised (Groves and McCarthy, 1978; McCarthy and Hasty, 1975; Kleeman and Twist, 1989). The two most mineralised plutons in the study area, the Moloto and Verena plutons, situated around the settlements of Moloto and Verena respectively (Fig. 2), exhibit highly fractionated characteristics, as shown for the coarse-grained phase of the Verena granite (Figure 4).

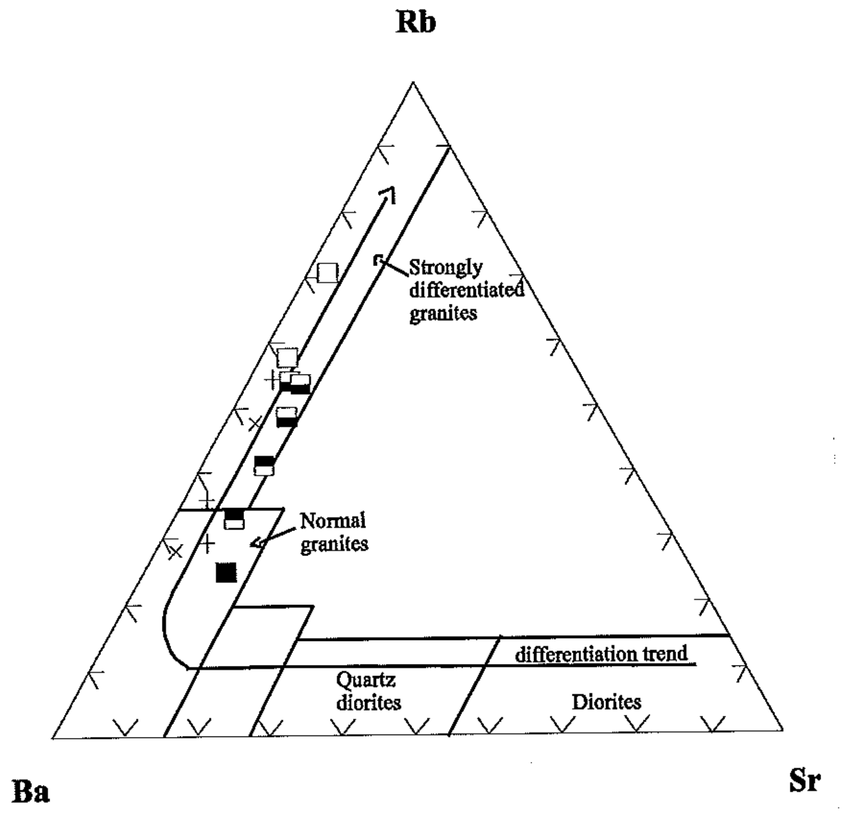


Figure 4: Rb-Ba-Sr ternary diagram illustrating the highly fractionated nature of the granites of the study area. After El Sokkary and El Bouseily (1975). Data from Table 1.

The trace elements Rb, Ba and Sr may be used in a more quantitative manner to indicate the degree of fractionation a granitic magma has undergone. Walraven (1986) defined the trace element differentiation index (TEDI) as Ba ? (Sr / Rb). The TEDI value decreases with increasing degrees of fractionation owing to the compatible natures of Ba and Sr and the incompatible nature of Rb. Walraven (1986) stated that TEDI values of around 5000 represent relatively unfractionated granites, which are typically grey and hornblende-rich at the base of any given granite sheet, whereas TEDI values of between 1000 to 500 could be expected for the middle regions. Highly

Table 1: Compositions of samples of some of the granite varieties found in the study area

type	Sekhukhuni			f/g Verena		coarse-grained			Bobbejaankop		Klipkloof		Makhutso
sample	1	2	3	1	2	1	2	3	1	2	1	2	1
SiO_2	76.75	76.97	77.18	73.64	74.80	75.70	76.28	76.86	78.84	75.60	77.30	77.10	73.12
TiO_2	0.14	0.10	0.09	0.30	0.17	0.17	0.18	0.17	0.13	0.18	0.13	0.10	0.17
Al_2O_3	11.78	10.87	11.81	13.11	13.40	12.30	12.22	11.66	11.11	11.97	11.19	11.67	12.65
Fe_2O_3	2.05	2.49	1.78	2.82	2.05	2.14	2.16	2.36	0.98	3.13	2.28	1.63	1.70
MnO	0.05	0.03	0.02	0.07	0.03	0.01	0.03	0.04	0.00	0.04	0.03	0.00	0.03
MgO	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.54	0.03	0.14	0.42	0.93	0.45	0.44	0.52	0.02	0.14	0.02	0.15	1.10
Na_2O	3.78	3.38	3.88	3.72	4.12	3.89	3.98	3.38	3.76	3.41	2.89	4.01	4.81
K_2O	4.98	5.30	5.11	4.68	4.70	5.27	4.80	4.80	5.26	5.26	5.12	5.16	4.70
P_2O_5	0.02	0.02	0.01	0.07	0.02	0.03	0.04	0.02	0.01	0.01	0.01	0.01	0.03
L.O.I.	0.43	1.73	0.55	1.16	0.61	0.95	0.99	0.87	0.81	0.99	1.59	0.82	0.40
TOTAL	100.51	100.92	100.56	100.29	100.82	100.90	101.11	100.68	100.92	100.71	100.57	100.65	98.60
Sr	48	16	17	75	76	56	60	33	19	27	12	17	89
Rb	211	259	173	285	358	392	354	307	212	275	309	250	191
Ba	461	201	293	507	437	285	316	229	215	678	116	168	492
Nb	19	44	17	36	36	32	33	35	26	28	39	39	43
Zr	198	283	187	263	182	175	186	213	269	236	323	225	198
Y	68	87	120	72	79	76	62	97	44	97	88	97	95
TEDI	105	12	29	133	93	41	54	25	19	67	5	11	229
Fe^{2+}	1.5	1.1	1.3		1.7					1.6	0.8		
Fe^{3+}	0.6	1.4	0.4		0.4					1.6	1.5		
Fe^{2+}/Fe^{3+}	2.53	0.79	3.05		4.54					1.01	0.55		

fractionated granites in the upper levels of a given pluton are characterised by TEDI values of 50 or less, are reddish in colour and have biotite as the dominant mafic mineral, having replaced hornblende at intermediate levels in the sheet. The Bobbejaankop and Klipkloof granites typically have TEDI values of less than 50 and less than 10 respectively (Table 1), indicating their highly fractionated nature.

The granites within the study area all have relatively low TEDI values (Table 1) and are to mineralised to varying degrees (Fig. 2). The plutons occur near the centre of the eastern lobe of the Bushveld Complex (Fig. 1), where fluids would have preferentially concentrated during fractionation owing to centripetal crystallisation.

Within an individual pluton the TEDI values vary, demarcating areas where the granite has undergone greater degrees of fractionation. The TEDI contour maps of the Moloto and Verena plutons given in Figure 5 illustrate this point. The Moloto pluton exhibits high TEDI values in its centre, decreasing in value toward the margins (Fig. 5A). The TEDI values to a large extent reflect the domical nature of the pluton with lower level, less fractionated granites uparched and exposed in the central regions, and higher level, more fractionated granites occurring along the margins, where mineralisation is concentrated.

The Verena pluton exhibits low TEDI values along a northwest - southeast trend near its western margin, adjacent to a prominent hill known as Rhenosterkop (Fig. 5B). Along this trend a fine-grained chilled margin is preserved, probably as a direct consequence of downwarping and the development of a synclinal flexure in the area (Stear, 1977 - Fig. 1). This area is underlain by red biotite-rich granites with low TEDI values and is host to abundant Cu-Ag mineralisation at the Albert Silver Mine and its related veins, and the Rooipoort tin prospect to the southwest (Figs. 2 and 5B). The Rietfontein tin occurrence, to the southeast, occurs along the same downwarped, low TEDI value trend with the host granites displaying a deep red colour and numerous Klipkloof granite sills. To the east lower levels of the sheet are found, the TEDI values are higher, the granite is grey and hornblende-rich and is barren of mineralisation (Fig. 5B). Proceeding toward the rhyolite contact to the east the TEDI value decreases and higher level, more fractionated granites are found.

The Verena pluton thus shows a gentle northwest-southeast warping or synclinal flexure which has exposed high level rocks in an axis to the east of Rhenosterkop, and has preserved a fine-grained chill phase as well as the mineralisation at the Albert Silver Mine. High level granites have also been preserved along the pluton margins. Uparching of the granites to the east, beneath the rhyolites of the Rooiberg Group, has occurred and the topography has caused low-level granites to be exposed between the synclinal flexure running through the centre of the pluton and the anticlinal flexure to the east beneath the Rooiberg Group volcanics (Fig. 5B and Fig. 9).

MINERALISATION STYLES IN THE STUDY AREA

Although Sn and F are the dominant commodities associated with the acid phase of the Bushveld Complex it is now recognized that there is considerable potential for other commodities, such as Cu, Ag, Mo, Au, Pb and Zn. Mining companies are actively exploring the acid rocks for Cu-Au-Fe-REE-U-F styles of mineralisation similar to the Olympic Dam type of deposit.

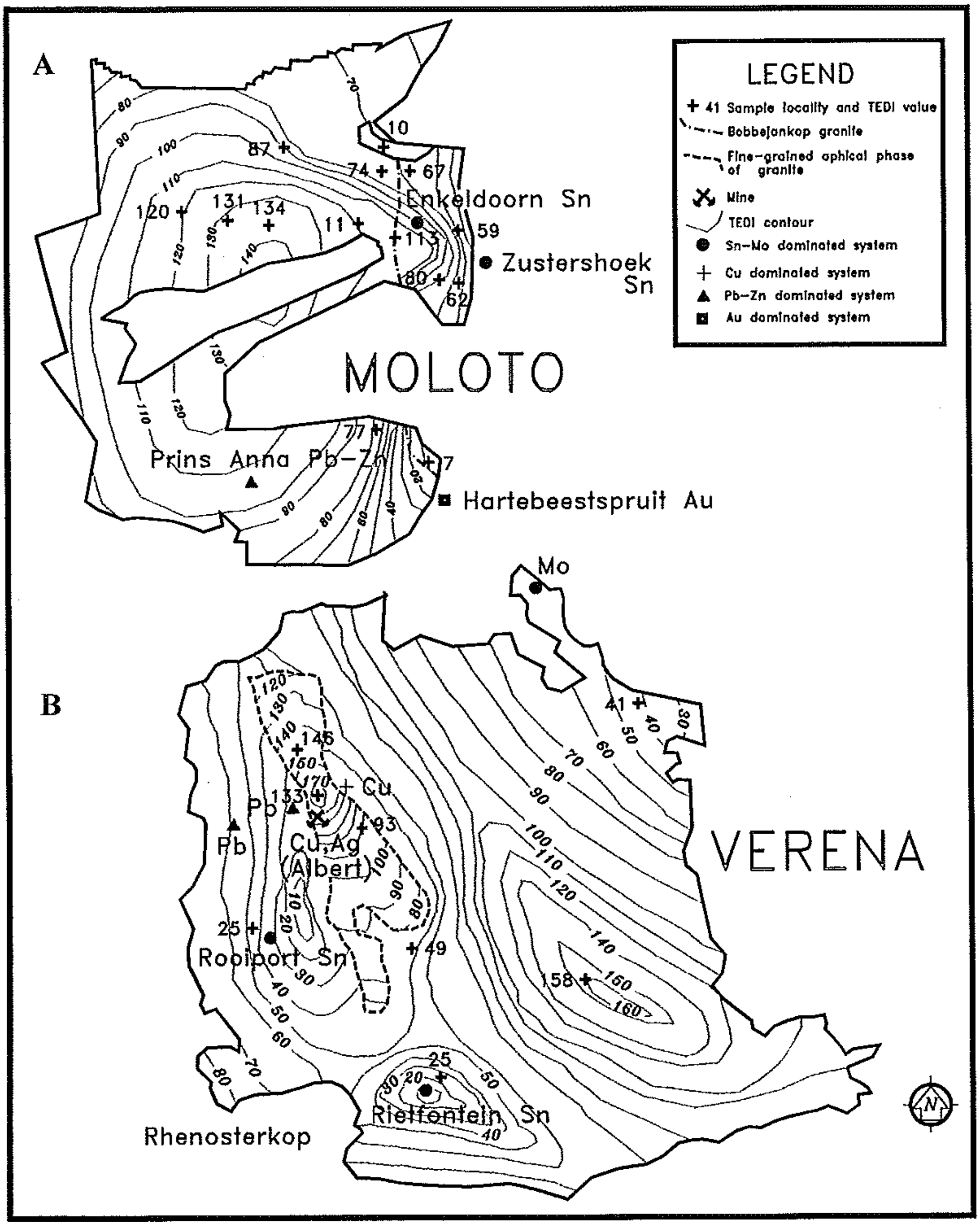


Figure 5. TEDI contour maps of the Moloto and Verena plutons. A. The Moloto pluton with the TEDI values clearly illustrating the domical nature of the pluton. B. The Verena pluton with TEDI values indicating crustal warping in a northwest- southeast orientation.

A wide range of metal associations and commodities are associated with the acid rocks of the Bushveld Complex. There is a progressive evolution in mineralisation styles from Sn-dominated occurrences, through base metal-dominated occurrences, to those where Au, together with U, Fe and F, are significant. As such, the mineralisation styles can be subdivided into four main types depending on the dominant metal. Data from some of the mineral occurrences in the study area is given in Table 2.

Table 2: Mineralisation in the acid rocks. Metal contents of the major mineral occurrences in the study area

mineralisation types	ppm Sn	ppm Mo	ppm Cu	ppm Pb	ppm Zn	ppm As	ppm Ag	ppm Au
TYPE I								
Rietfontein Sn	**686**	-	11	52	43	<15	<1.0	0.03
Rooipoort Sn	**29100**	95	**7800**	2100	199	**38000**	**7.3**	**1.35**
Klipdrift Mo	15	-	840	990	121	**28000**	1.9	**7.6**
Enkeldoorn Sn	202	-	**2618**	1150	1508	403	**4.8**	0.02
Zustershoek Sn Mine	**21700**	62	**20.90%**	143	31	1100	**12.3**	0.37
TYPE II								
Albert Ag Mine	36	27	**55200**	**27800**	2900	4700	**566**	0.5
TYPE III								
Prins Anna	20	<5	147	**12700**	**8400**	134	**10.3**	<0.01
Leeuwfontein vein	34	-	250	**811**	15	**1437**	**27.6**	0.01
Albert north vein	26	-	140	**1691**	860	1499	-	-
TYPE IV								
Hartebeestspruit Au	166	139	271	2323	233	**118483**	<1.0	**5**
Klipdrift Au	10	-	<5	194	54	138	<1.0	0.02
Boekenhouthoek Au	<10	-	22	92	60	**>5%**	0.3	0.57

Type I: Tin-dominated Systems

This system is typically dominated by tin, with lesser copper and lead being present. Examples in the study area include the Rietfontein tin occurrence on Rietfontein 446 JR and the Rooipoort tin prospects straddling the boundary between the farms Rooipoort 440 JR and Hartbeestfontein 441 JR (Fig. 2). The Enkeldoorn tin field and the Zustershoek Tin Mine, within and adjacent to the Moloto pluton on the farms Enkeldoorn 217 JR and Zustershoek 246 JR, respectively, are included, despite having significant amounts of copper (Fig. 2 and Table 2).

The Type I occurrences are typically hosted in Bobbejaankop granite or a reddish variety of the Nebo granite. In some cases, fine-grained Klipkloof granite is found associated with the Bobbejaankop granite either as sills of limited extent, or as dykes. The Zustershoek Tin Mine is hosted in coarse-grained granophyre underlain by Bobbejaankop granite.

In most of the occurrences propylitic alteration dominates in the immediate vicinity of the mineralisation, giving way to an outer zone of phyllic alteration and into granite exhibiting incipient alteration features. Incipient alteration involves partial sericitisation of the feldspars, particularly orthoclase, and pseudomorphous replacement of the mafic minerals, biotite and hornblende, by chlorite. In the phyllic alteration zone, which varies from 5 to 20 m away from the mineralisation, the feldspars are totally sericitised and chlorite, which is subordinate, totally replaces the mafic minerals.

The inner propylitic zone is typically within 2 m of veins which host the mineralisation. The rock is almost totally chloritised, with quartz having been broken down by recrystallisation to smaller grains. Epidote grains are also found associated with thin quartz veining cutting across the rock.

Cassiterite is the dominant ore mineral, as at Rietfontein and Rooipoort (Fig. 6A and Fig. 7A and B), but molybdenite may also be the dominant ore mineral, as at the Klipdrift Mo occurrence on Klipdrift 62 JS (Fig. 2 and Fig. 6B), where cassiterite is absent. A first generation of pyrite and arsenopyrite may also be present (Figs. 6B and 7B), as well as an early generation of fluorite, which is typically clear.

Type II: Copper dominated Systems

Copper is the dominant ore metal with Pb and Zn being subordinate and Sn of minor importance. The Albert Silver Mine on the farm Roodepoortje 250 JR is the main example of this type in the study area (Fig. 2).

Alteration envelopes associated with this style of mineralisation, such as at the Albert Silver Mine, can extend up to 20 m from the main vein (Champion, 1970). And are seen to pass from a zone of incipient alteration through sericitisation, chloritisation and through to hematisation adjacent to the vein.

The paragenetic sequence in this mineralisation style, as exemplified by the Albert Silver Mine, is 1. cassiterite (very minor, if present at all) 2. pyrite - bornite - chalcopyrite - galena - sphalerite (Fig. 6D,E and Fig. 7E, F) 3. arsenopyrite - tetrahedrite (Fig. 6F and Fig. 8B and C) and finally, 4. hematite-pitchblende-uranium (Fig. 6G, Fig. 7F, Fig. 8D-F)(Robb et al., 1994; Bailie, 1997). A later oxidised assemblage of hematite (often the variety specularite), with concomitant precipitation of pitchblende, chlorite and dark purple fluorite overgrows the earlier sulphides (4. above)(Fig. 8D-F). The Fe-rich chlorite and dark purple fluorite are found in open space vugs in massive hematite masses at the Albert Silver Mine (Fig. 9E) (Robb et al., 1994).

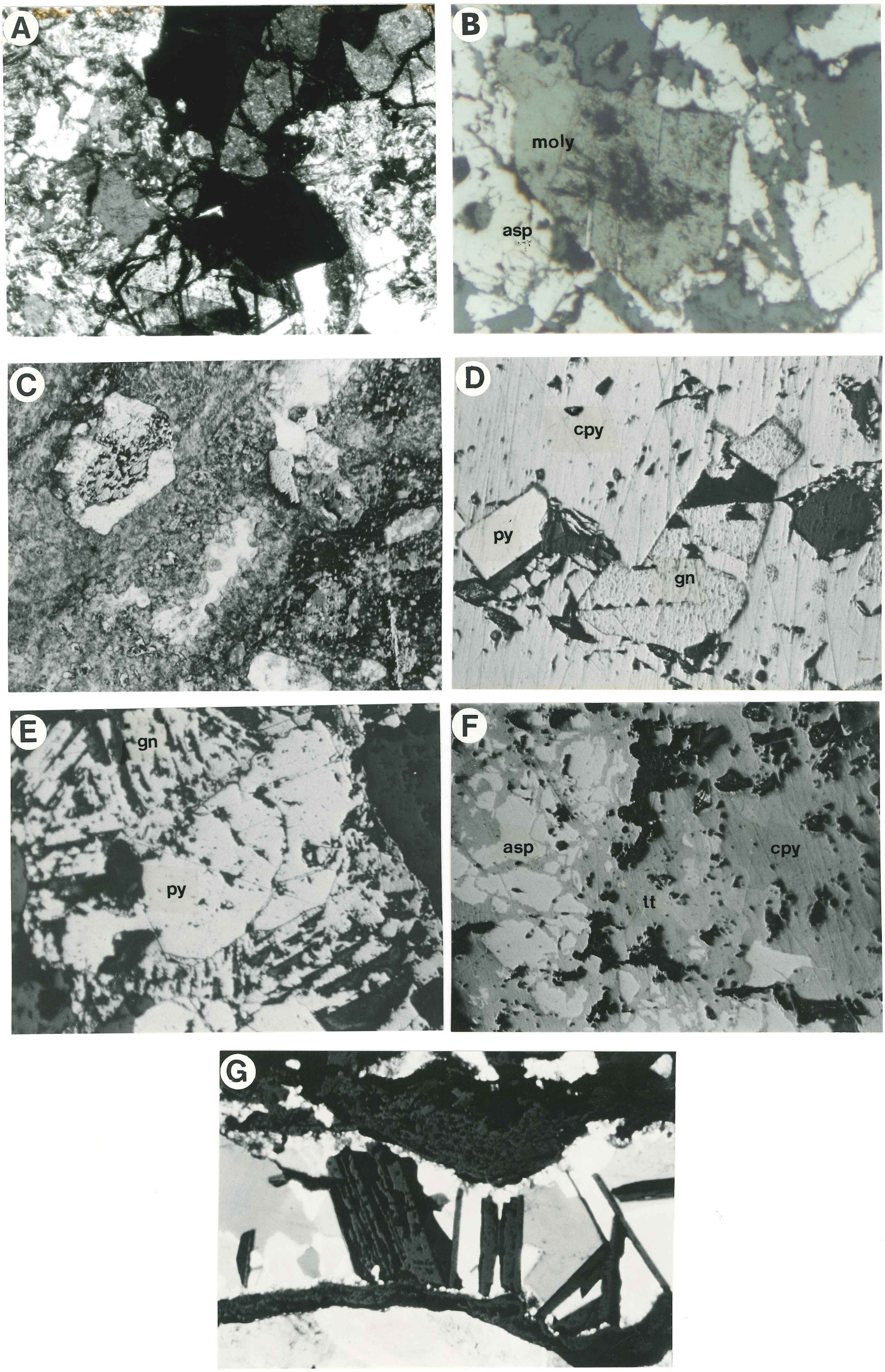
The Albert Silver Mine exhibits a broad paragenesis ranging from early magmatic mineralisation in the form of minor cassiterite (Robb et al., 1994), through base metal deposition, to a late-stage oxidised assemblage superimposing itself on the earlier sulphides (Robb et al., 1994).

Type III: Lead-zinc-dominated Systems

Type III style mineralisation is characterised by a dominance of Pb and Zn, with Sn present in small amounts and Cu of little or no importance. Arsenic and antinomy are present in significant quantities and precious metals (Au, Ag) are also present. The study area contains four examples of this type, with the Prins Anna structure, stretching from Prins Anna 234 JR through Sybrandskraal 244 JR and south into Van Dykspruit 431 JR, being the largest and most significant (Fig. 2).

Pb-Zn mineralisation occurs as hematite-quartz gossanous ridges on surface in the study area with very few sulphides preserved and exhibiting small alteration envelopes. Alteration starts from a zone of incipient alteration a few metres from the veins, involving sericitisation of plagioclase, kaolinisation of a large degree of the feldspars and chloritisation of the biotite. Nearer the vein the host granite is extensively sericitised giving way to quartz veining and large-scale introduction of quartz and hematite replacing the feldspars and micas adjacent to the vein.

Fig. 6: Photomicrographic examples of the five different mineralisation styles from mineral occurrences in the study area. A and B are examples from Sn-Mo-dominated systems, C and D from a copper dominated system, E represents mineralisation characteristic of type III mineralisation, F pictures type IV mineralisation and G shows the hematite charateristic of the late-stage oxidised assemblage. A: Cassiterite crystals within a quartz vein associated with radiating muscovite fibres. Rietfontein tin prospect, Rietfontein 446 JR. Crossed nicols. Field of view (FOV) is 2,2 mm wide. B: Molybdenite (moly) overgrown by arsenopyrite (asp). Klipdrift Mo prospect, Klipdrift 62 JS. FOV = 2,2 mm. C: Chalcopyrite associated with quartz in a chloritic matrix. Albert Silver Mine. Roodepoortje 250 JR. Crossed nicols. FOV = 3,55 mm. D: Galena (gn) and pyrite (py) overgrown by chalcopyrite (cpy). Albert Silver Mine. FOV = 0.5 mm. E: Pyrite overgrown by galena. Albert Silver Mine. FOV = 1,89 mm. F: Early arsenopyrite overgrown by chalcopyrite and both overgrown by tetrahedrite (tt). Albert Silver Mine. FOV = 3,55 mm. G: Late-stage hematite crystals within a quartz vein. Albert Silver Mine. Crossed nicols. FOV = 2,2 mm.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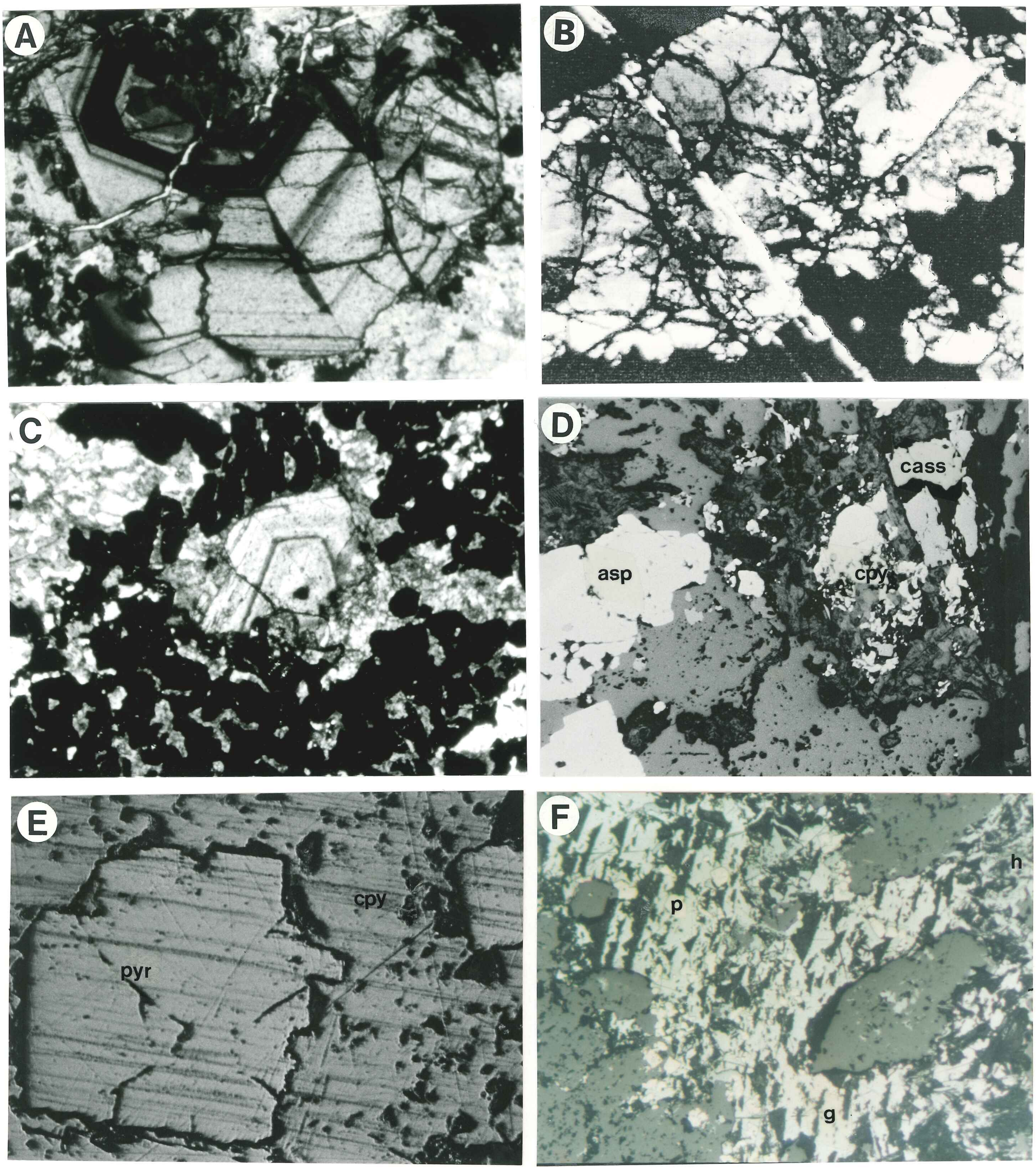

Fig. 7: Overall paragenetic sequence of mineralisation in the Bushveld granites from the mineralogy of mineral occurrences in the study area. The sequence proceeds from early Type I tin-dominated systems through Type II and III base metal dominated mineralisation to superimposition of the late-oxidised assemblage of hematite, pitchblende and fluorite on the earlier sulphide assemblages. A: Growth zoned cassiterite crystal. Rooipoort 440 JR. Uncrossed nicols. FOV = 3,55 mm. B: Cassiterite overgrown by arsenopyrite, and both being cut by later secondary quartz veins. Rooipoort 440 JR. Uncrossed nicols. FOV = 3,55 mm. C: Euhedral cassiterite crystal surrounded by and overgrown by chalcopyrite in a chloritic groundmass. Enkeldoorn 217 JR. Uncrossed nicols. FOV = 3,55 mm. D: Cassiterite (cass) overgrown by chalcopyrite. Arsenopyrite is also found. Rooipoort 440 JR. FOV = 2,2 mm. E: Early pyrite partially corroded and replaced by chalcopyrite. Albert Silver Mine. FOV = 0,5 mm. F: Pyrite (p) overgrown by galena (g). In the upper right hand corner hematite (h) crystals have overgrown galena. Albert Silver Mine. FOV = 1,89 mm.

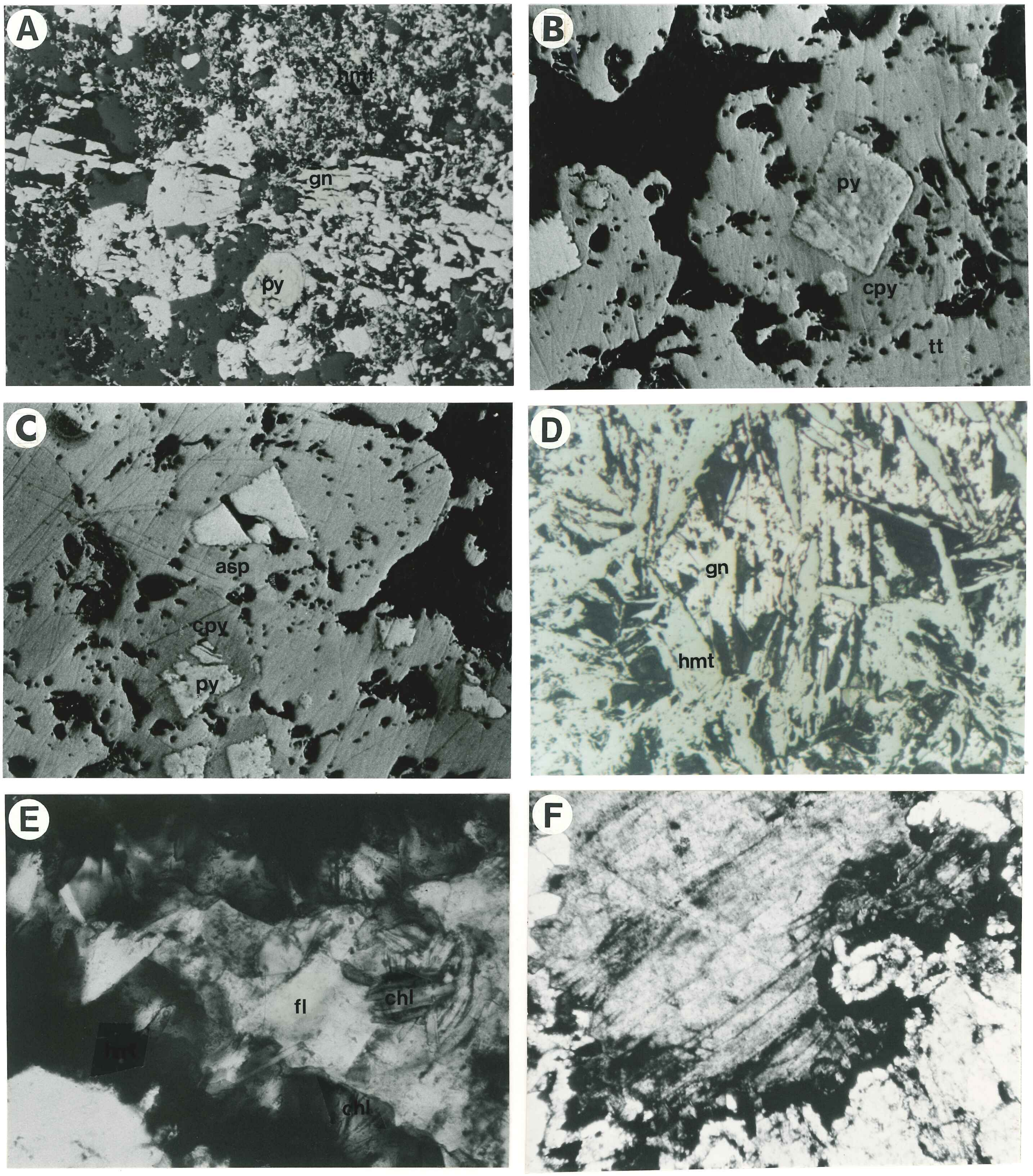

Fig. 8: Overall paragenetic mineralisation sequence continued, showing, in particular, overgrowth of the late-stage oxidised assemblage on the earlier sulphide assemblages. A: Rounded pyrite grains overgrown by galena, itself having been overgrown by late-stage hematite (hmt) crystals - upper margin. Albert Silver Mine. FOV = 3,55 mm. B: Pyrite overgrown by chalcopyrite and both overgrown by later tetrahedrite. Albert Silver Mine. FOV= 0,2 mm. C: Fragmented pyrite successively enveloped by chalcopyrite and arsenopyrite. Albert Silver Mine. FOV=0,2 mm. D: Galena overgrown by late-stage hematite crystals. Albert Silver Mine. FOV= 1,89 mm. E: Vug in massive late-stage hematite infilled by dark purple fluorite (fl) and Fe-rich chlorite (chl) representing the final stage of alteration/ mineralisation. Albert Silver Mine. FOV= 0,2 mm. F: Dark purple second generation fluorite in a quartz vein. Albert Silver Mine. FOV= 0,2 mm.

Type IV: Gold-dominated Systems

Type IV mineralisation is either hosted in granites associated with Klipkloof granite dykes or sills, or, more typically, in the granophyric roof rocks. This system is enriched in gold, but also contains lesser amounts of As and Pb. Silver is not present in large amounts and Cu and Sn are insignificant. Cobalt may be present in some occurrences. This mineralisation type usually has a simple sulphide mineralogy, comprising arsenopyrite, pyrite and lesser amounts of chalcopyrite (Fig. 10). Some deposits are transitional with regard to Type III mineralisation, such as the Hartebeestspruit Au occurrence on Hartebeestspruit 434 JR. Gold-dominant mineralisation types are found predominantly on the southern margin of the Dennilton granite pluton where two occurrences, the Klipdrift and Boekenhouthoek Au occurrences, are found on Klipdrift 62 JS (Fig. 2).

Type IV mineralisation is characterised by carbonate alteration in the form of siderite and ankerite along with minor phyllic and hematitic alteration. The sulphide phases are typically disseminated. Gold and Ag mineralisation is associated with disseminated sulphides, which are typically pyrite or arsenopyrite.

Paragenetic Sequence

The Albert Silver Mine exhibits a broad paragenesis ranging from early pyrite and arsenopyrite through Cu, Pb and Zn sulphides to the fahlores with a late-stage oxidised assemblage superimposing itself on these earlier assemblages. As such, the Albert Silver Mine, despite being classified as a Type II deposit, exhibits ore minerals covering all four mineralisation types. It is not the only occurrence to do so as others contain ore minerals that may be distinctive of other mineralisation types. As such, the four mineralisation types subdivide a broad paragenetic sequence recognised in the granites and shown, from Type I style mineralisation through to type IV mineralisation and including the late-stage oxidised assemblage, here called Type V, in Figures 7 and 8.

Crocker (1979) described the tin and fluorite mineralisation in the granites in detail. He recorded the abundances of the ore and gangue phases in the tin fields, the molybdenum occurrences and the fluorite deposits and drew up a table recording the abundance of the observed ore and gangue mineralogy. Assuming the four-fold subdivision of the mineralisation associated with the granites the ore and gangue minerals recorded by Crocker (1979) may be subdivided into one of the mineralisation styles according to order of deposition as follows:

Type I:
Ia: Tourmaline and cassiterite introduction
Ib: Scheelite, wolframite and bismuthnite introduction
Ic: Rare earth element minerals allanite, bastnaesite and britholite introduction
Id: Molybdenite, pyrite (I) and arsenopyrite (I) introduction
Ie: Halide introduction in the form of apatite and fluorite (I)
If: Removal of fluorine leaves iron to form actinolite, magnetite and hematite (Crocker, 1979).
I g: Iron carbonate introduction in the form of ankerite and siderite.

Type II: Introduction of the copper minerals bornite, chalcopyrite and later chalcocite

Type III: Introduction of lead and zinc minerals galena and sphalerite

Type IV:
IVa: Introduction of the iron sulphides pyrite (II), tennantite-tetrahedrite, and possibly very minor pyrrhotite
IV b: Introduction of the arsenides: arsenopyrite (II), cobaltite and nicolite

Type V: Late-stage oxidised assemblage of hematite (with the specularite variety sometimes found), pitchblende, fluorite (II), which is typically purple in colour, and Fe-rich chlorite.

The mineral occurrences in the study area are classified according to which mineralisation type they best describe. Most occurrences show a broad mineral assemblage so that the occurrences were ordered according to the metal contents, as listed in Table 2, and the mineralisation style they best represent. The occurrences are plotted against the subdivided paragenetic sequence given in Table 3, which shows that the occurrences in the study area exhibit a progressive evolution from a Type I-dominated assemblage through to later mineralisation types, which represent a later part of the extensive paragenetic sequence found in the granites.

CONTROLS ON MINERALISATION

A number of related factors, such as fractionation, structure and hydrothermal fluid evolution and mixing, and their interaction, have given rise to the localisation and varied nature of mineralisation in the acid rocks of the Bushveld Complex.

In Situ Crystal Fractionation

The granites show a progressive evolution from grey hornblende-rich granites at the base of any given sheet passing upwards to red biotite-rich granites. Concommitant with this is a decrease in the abundance of hornblende and plagioclase and an increase in biotite and K-feldspar (Kleeman and Twist, 1989). The TEDI value indicates the degree to which fractionation has occurred, with the upper, highly fractionated levels of the granite sheet, which are often host to mineralisation, having low TEDI values (Walraven, 1986). The Bobbejaankop and Klipkloof granites, typically near the top of the granite sheet, have low TEDI values (Table 1) and are thought to represent the last phases of crystallisation of the granitic magma (McCarthy and Hasty, 1976; De Bruiyn, 1980).

As the granitic magma crystallised, incompatible elements, such as the base and precious metals, concentrated in the last remnants of magma and were fractionated into the vapour-rich phase associated with these last remnants of magma. This vapour phase gave rise to the mineralisation in the acid rocks (Groves and McCarthy, 1978).

The Verena and Moloto plutons serve to illustrate the point. The Moloto pluton was domed and subsequently eroded so that lower level, less fractionated granites are found in the centre of the pluton and more highly fractionated granites are preserved on the margins (Fig. 5A). This is particularly true of the eastern margin where Bobbejaankop granite, with low TEDI values, is found hosting the Enkeldoorn tin field

Table 3: Mineral assemblages of ores of the acid phase ranked according to relative order of deposition and subdivided into the four main mineralisation types. The ore minerals have been subdivided into the four main mineralisation types and further subdivided into associated assemblages, such as the rare-earth minerals or the iron oxides, in the order in which they are believed to be deposited. The mineral occurrences/ deposits are ordered according to the contents of the ore metals (Table 2). A broad paragenetic sequence is seen from orthomagmatic tin through the base metals to the fahlores and a late-stage oxidised assemblage of hematite- pitchblende and second generation fluorite

Paragenetic Sequence		Tin fields / deposits			Molybdenite Deposits	Fluorite Mines				
		1. Rietfontein 446 JR	2. Rooipoort	3. Moloto	4. Houtenbek / Klipdrift	5. Kromdraai (Vergenoeg)	6. Albert silver mine	7. Prins Anna	8. Hartebeestspruit gold	9. Klipdrift gold
Ia	Tourmaline	●			⊠					
	Cassiterite	●	●	●			♦			
Ib	Scheelite									
	Wolframite									
	Bismuthnite						♦			
Ic	Allanite									
	Bastnaesite			♦						
	Britholite									
Id	Molybdenite				●		♦			
	Pyrite (I)	⊠	⊠	⊠	⊠	♦	⊠			
	Arsenopyrite (I)	♦	●		❖		⊠			
Ie	Apatite									
	Fluorite (I)	❖	❖	⊠	❖	■	♦			
If	Actinolite					♦				
	Magnetite	♦				■	●			
	Hematite (I)					●				
Ig	Ankerite									
	Siderite			⊠			●	⊠		
II	Chalcopyrite	⊠	⊠	❖	⊠		❖		⊠	
	Bornite					♦	❖			
	Chalcocite						⊠			
III	Galena			♦			❖	♦		
	Sphalerite			⊠	❖		❖	♦		
IVa	Pyrite (II)						⊠		❖	❖
	Tennantite						⊠			
	Tetrahedrite						❖			
IVb	Arsenopyrite (II)						❖		❖	♦
	Cobaltite		♦				♦			
	Nicolite									
V	Hematite (II)			❖		●	■	■	⊠	♦
	Pitchblende						⊠			
	Fluorite (II)		❖		⊠		❖			

Legend	
■	Major
●	Common
❖	Percent
⊠	Accessory
♦	Trace
	Not observed

on Enkeldoorn 217 JR and underlying the granophyres hosting the Sn mineralisation at the Zustershoek Tin Mine on Zustershoek 246 JR (Fig. 5A).

The Verena granite has been subjected to post-emplacement warping in a northwest-southeast orientation that has preserved high-level granites near the pluton centre. A synclinal flexure trending northwest-southeast adjacent to Rhenosterkop (Fig. 5B)(fig. 1, Stear, 1977) is a zone of downwarping wherein high level granites have been preserved. Within this synclinal flexure the fine-grained chill phase of the Verena granite, found at the Albert Silver Mine, has also been preserved and is host to the gossanous veins hosting Cu-Pb-Zn mineralisation. Tin mineralisation is also found within the downwarped area to the southeast on Rietfontein 446 JR. Adjacent to this zone, to the east, and following the same trend, low level granites, with high TEDI values, are found. These granites are grey, hornblende-rich and are barren of mineralisation. On the northeast pluton margins, where the TEDI values are low, minor Mo mineralisation is found and Co mineralisation occurs in the Rooiberg volcanics a little further to the northeast.

Another useful measure of height in the granites, and the degree of fractionation, is the Fe2+/ Fe3+ ratio. The Fe2+ ion decreases in content with increasing height in any given granite sheet, with a concomitant increase in the Fe3+ ion. The Fe2+ is oxidised to Fe3+ with progressive oxidation of magnetite to hematite in the crystal lattices of feldspars of high level granites (Crocker, 1979), causing a decrease in the Fe2+/ Fe3+ ratio with increasing degree of fractionation (Table 4, Fig. 9). Granites hosting mineralisation are highly evolved, have low TEDI values, and have a low Fe2+/ Fe3+ ratio due to the oxidation of Fe2+ to Fe3+ in the upper, highly fractionated portions of a given granite sheet (Fig. 9). Fe2+/ Fe3+ ratios, hence, could be used in conjunction with TEDI values to indicate the most fractionated granites.

Table 4: Fe2+/ Fe3+ determinations for certain altered and unaltered granite samples in the study area.

unaltered granites					
sample	FeO_T %	Fe^{2+} %	Fe^{3+} %	Fe^{2+}/Fe^{3+}	TEDI
1	2.28	0.81	1.47	0.55	5
2	2.49	1.1	1.39	0.79	12
3	1.78	1.34	0.44	3.04	29
4	3.13	1.57	1.56	1.01	67
5	2.05	1.68	0.37	4.54	93
6	2.05	1.47	0.58	2.53	105
altered granites					
sample	FeO_T %	Fe^{2+} %	Fe^{3+} %	Fe^{2+}/Fe^{3+}	TEDI
7	5.46	1.97	3.49	0.56	18
8	4.54	1.11	3.43	0.32	5
9	3.39	0.72	2.68	0.27	5
10	3.97	0.68	3.29	0.21	3
11	1.42	0.16	1.25	0.13	2
12	5.23	0.51	4.72	0.11	3
13	4.29	0.23	4.07	0.06	5

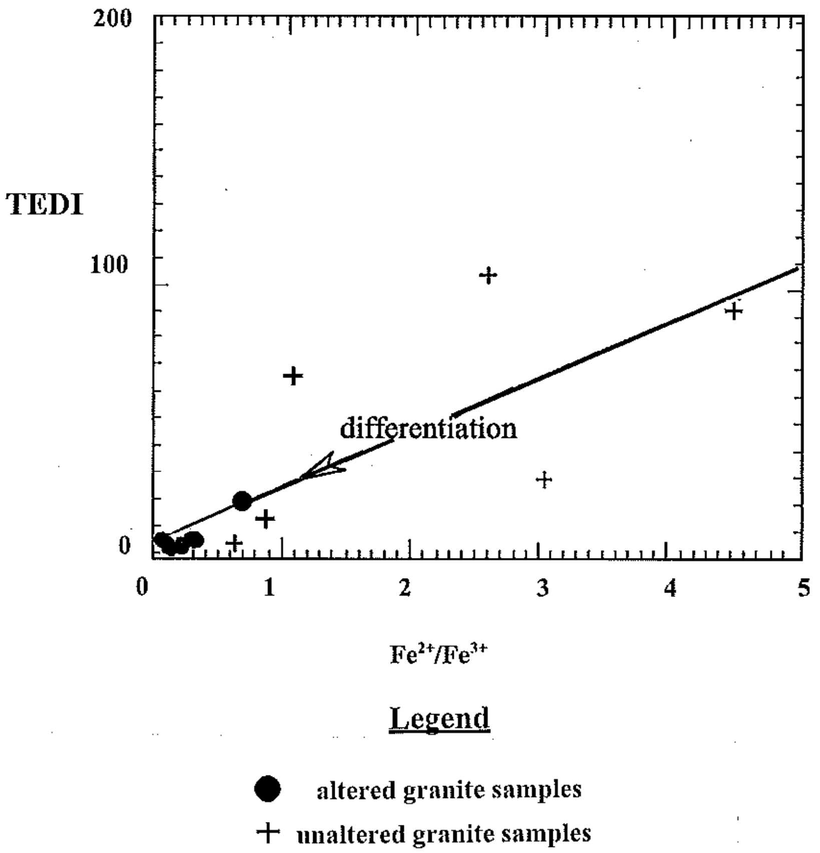

Figure 9: Plot of TEDI versus Fe2+/ Fe3+ illustrating decreasing TEDI values and decreasing Fe2+/ Fe3+ with increasing degree of fractionation. Altered granite samples exhibit very low TEDI and Fe2+/ Fe3+ values. Data from Table 4.

Altered granites have different TEDI values to the surrounding unaltered granites. Walraven et al. (1990a) demonstrated how Sr is preferentially leached within or adjacent to tin mineralisation. The alteration assemblage changes from propylitic, in an orthomagmatic Sn-dominated system where Sr will substitute into the chlorite structure, to phyllic alteration in mineralising systems where other, later minerals predominate. In these mineralising systems Sr is not as preferentially substituted. The subsequent effect is that the TEDI value of the altered granites differs substantially from that of the surrounding unaltered granites.

Fluid Evolution, Mixing and Paragenetic Sequence

The Bushveld granites exhibit broad metal associations and, despite the recognition of four mineralisation types, many occurrences are transitional between two or more mineralisation styles, indicating a broad-scale paragenetic sequence for the granites (Table 3). Table 3 further illustrates the fact that many metals may be present in any one particular occurrence and that there are few simple metal associations.

A change in metal associations, and associated mineralogy is observed from one where cassiterite is predominant, through precipitation of pyrite and chalcopyrite, followed by galena and sphalerite (Figs. 7 and 8 and Table 3). Type III and IV mineralisation have an increasing amount of arsenopyrite and tetrahedrite (Table 3). In addition, later fluid incursions may superimpose themselves on earlier mineralisation. This is the case at the Rooipoort tin occurrence where early cassiterite and arsenopyrite are brecciated and overgrown by secondary chalcopyrite and fluorite. In certain occurrences, such as the Albert Silver Mine, and to a lesser extent the Zustershoek Tin Mine, a late-stage hematite-pitchblende-fluorite assemblage superimposes itself on the earlier sulphides. This late-stage assemblage has been attributed to late-stage meteoric/ connate fluids which had various incursions into the granites (Robb et al., 1994; Freeman and Robb, 1995; Freeman, 1998).

The mineralising event is not simply magmatic driven, but has a large meteoric / connate influence which has affected the paragenesis and given rise to the broad paragenetic sequence recognised in the granites (Table 3). Shortly after crystallisation of the granites mineralising hydrothermal magmatic fluids circulated in the granites and country rocks for a certain period of time. If the mineralisation event had been purely magmatic it would have been short-lived (in the order of hundreds of thousands of years to a few million years at most)(Cathles et al., 1997) and would not have shown as broad a paragenesis. Type I-style Sn, Mo and F mineralisation would have been preferentially developed at this stage, but base metal mineralisation would not have developed to any large extent. As such, the permeability of the country rocks and the high heat producing (HHP) nature of the granites resulted in longer fluid circulation of a few million years at most and gave rise to orthomagmatic (Type I) mineralisation. It is now recognised that fluid mixing between the evolving magmatic fluid and an external meteoric / connate fluid took place giving rise to the broad paragenesis (Freeman and Robb, 1995; Freeman et al., 1997; Freeman, 1998). Higher level granites would have been more subjected to later mineralisation styles (Types III and IV) owing to an evolution of the orthomagmatic mineralising fluid with an increasing degree of fractionation of the host granites, coupled with a greater degree of fluid mixing with time. The subsequent effect is that with increasing height in any given granite sheet, or more correctly increasing degree of fractionation of the granites, there is generally a greater degree of fluid mixing between the evolving magmatic fluid and an external meteoric / connate fluid (Robb et al., 1994; Freeman and Robb, 1995; Bailie and Robb, 1997), although structure will also affect this fluid mixing (Fig. 10).

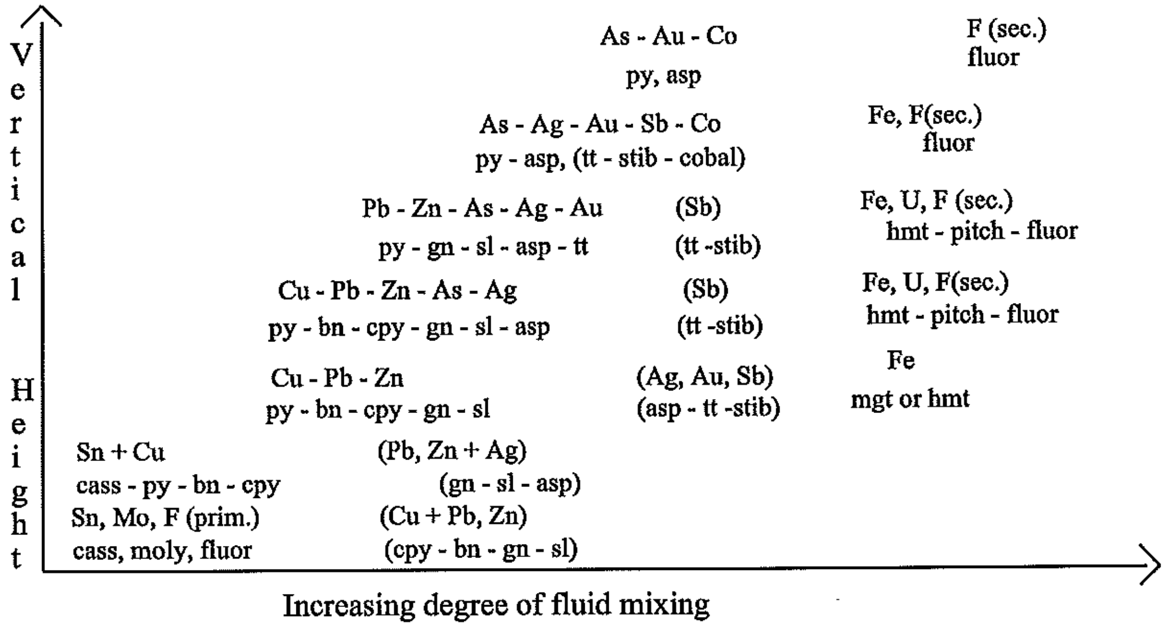

Figure 10: Metal associations and changing paragenetic sequence with increasing height in any given granite sheet and increasing degree of fluid mixing

Propylitic alteration associated with Type I mineralisation would have been caused by high temperature fluids in excess of 300o C (Pollard et al., 1991). As the fluids decreased in temperature so the alteration passed into phyllic alteration in Type II and III mineralisation, through to a hematitic type of alteration associated with low temperature fluids giving rise to the late-stage Fe-rich assemblage.

Longevity of Hydrothermal Fluid Circulation in the Acid Rocks

New age data combined with pre-existing data place constraints on the age of the Nebo granite, and related phases, as well as resetting events (Walraven et al.,1990b). The ages of the Nebo, Klipkloof, Makhutso and Lease granites, as well as the mineralisation at the Albert Silver Mine, are shown in Figure 11. The Nebo granite is accepted to have an age of 2054 ± 1.8 Ma (Walraven and Hattingh, 1993; Walraven, 1997) from single zircon dating. The age of the Makhutso granite, the youngest granitic

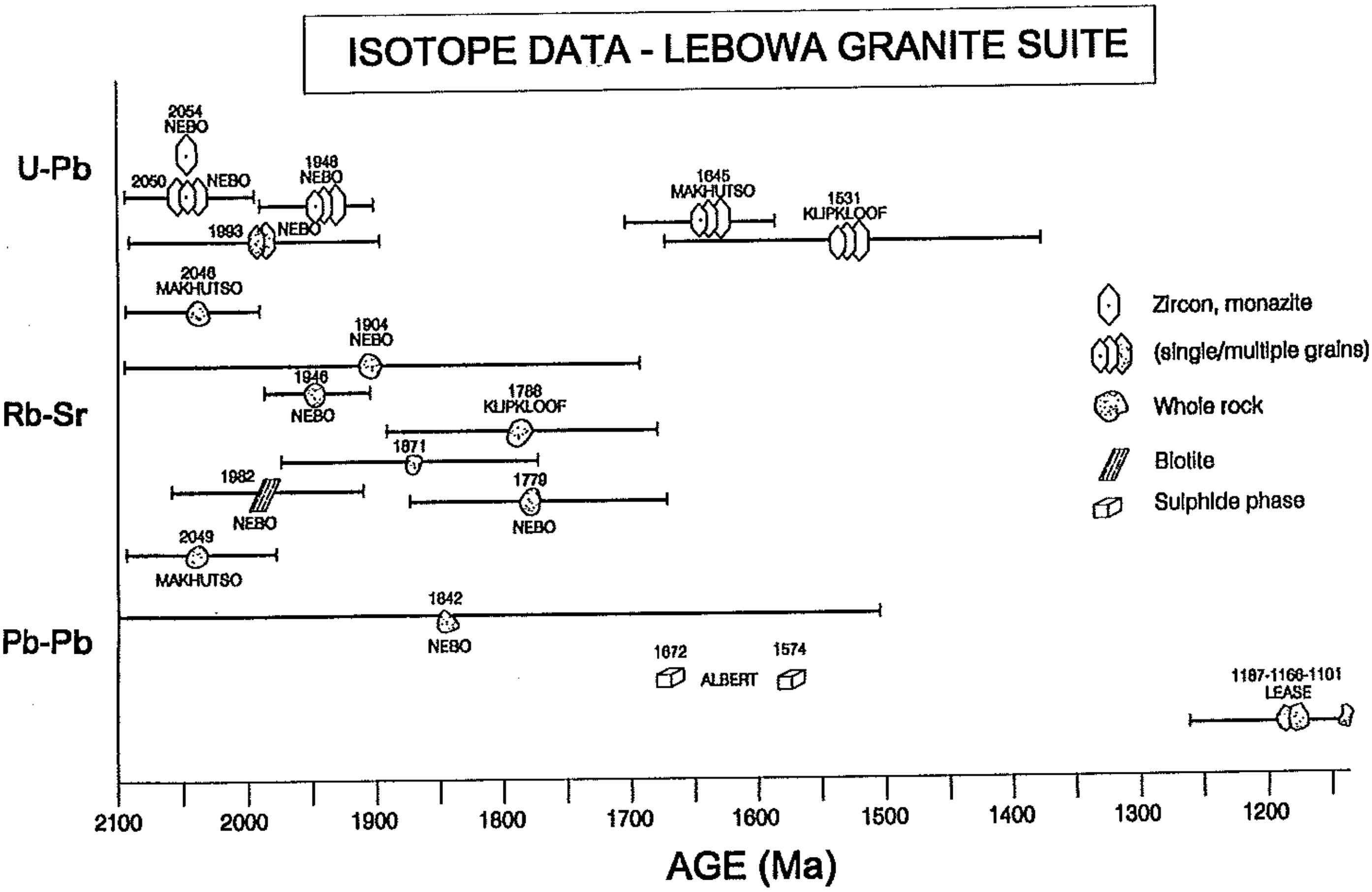

Figure 11: Age data for various phases of the Lebowa Granite Suite along with the dating method. The age of the Nebo granite is clearly delineated at 2054 Ma. Three other broad age ranges are identified: (i) 1900 - 1780 Ma, (ii) 1675 - 1500 Ma and (iii) 1250 - 1100 Ma. These age groups are thought to represent the ages of various meteoric / connate fluid incursions into the Nebo granite. These fluid incursions mixed with the evolved magmatic fluid giving rise to the broad paragenesis seen in the Bushveld granites, as well as giving rise to the late stage hematitic assemblage which overgrew the earlier sulphides.

phase in the Lebowa Granite Suite (De Bruiyn and Rhodes, 1975; Walraven, 1988), is in the range 2046-2049 Ma (Fig. 11) from whole rock dating methods. Younger ages for the Nebo and Klipkloof granites have been obtained by previous workers, with age ranges of 1871 Ma to 1779 Ma and 1645 to 1530 Ma having been obtained (Fig. 11). The Lease granite has been dated by whole rock dating at 1187, 1166 and 1101 Ma (Fig. 8). These age ranges are likely to represent resetting of the minerals (Walraven and Hattingh, 1993), the first caused possibly by Waterberg erosion and unroofing of the Bushveld Complex. It is suggested that these three broad age ranges may represent three separate meteoric / connate fluid incursion episodes which, by their very nature, would have caused isotope resetting. These meteoric / connate fluids mixed with any remnant magmatic fluid resulting in mineralisation not typically associated with A-type granitic magmas. The precious metal episode (Type IV) and the late stage hematite-pitchblende-fluorite episode is likely to be associated with these episodes. It is worth noting that the age of mineralisation of the Albert Silver Mine (Fig. 11) is around 1600 Ma. As the mineralisation exhibits a broad paragenesis and a late-stage oxidised assemblage these younger ages seem reasonable for later meteoric / connate fluid incursions after the magmatic event had essentially ended.

Structural Controls

Two major crustal lineaments dominate the structure in the eastern lobe of the Bushveld Complex and have influenced granite emplacement as well as the localisation of mineralisation. The first is the northeast-southwest-trending Steelpoort fault (Fig. 12), with the parallel trending Wonderkop fault to the northwest. The second is the southeast- northwest-trending Laersdrif fault lineament found to the southeast (Fig. 12).

The orientation of these faults and lineaments and major crustal flexures parallel to these two major crustal lineaments and their relation to mineralisation is given in Figure 12 (after Lee and Sharpe, 1986; Stear, 1977). The Kameelpoort pluton, to the northeast of the Moloto pluton (Figs. 2 and 12) outcrops on a anticlinal flexure parallel to the Wonderkop fault lineament. This anticlinal flexure continues to the southwest where it intersects another anticlinal flexure parallel to the Laersdrif fault lineament (Fig. 12). The intersection of these two anticlinal flexures led to the doming of the Moloto pluton (Fig. 5A).This, in part, was responsible for the fracturing and shearing of the granites and overlying roof rocks along a dominant north - south fault / shear pattern, particularly along the eastern margin, which was used by mineralising fluids to give rise to extensive mineralisation, as found on Zustershoek 246 JR and Enkeldoorn 217 JR (Fig. 2 and 5 A). The shear zones and hematite-gossans, particularly in the host granophyre on Zustershoek, developed due to tensional fracturing of the earlier crystallising domical rind, in this case Bobbejaankop granite. This followed from the volumetric contraction on final crystallisation of the core, and compressional forces developed due to doming of the pluton, which resulted in the escape of volatiles and depressurisation of the system (Crocker, 1979).

The emplacement of the Verena and Makhutso granites was influenced by the Laersdrif fault lineament, with both being elongated southeast-northwest parallel to this lineament (Fig. 12) and developed preferentially along a synclinal flexure parallel to the Laersdrif fault which, along with erosion and present day topography, has influenced the present-day shape of the plutons (Fig. 12)(see Stear, 1977, fig. 1). Intersection of two synclinal flexures, parallel to the two major lineaments, gave rise to a depression been developed in the vicinity of the Albert Silver Mine, causing the fine-grained apical phase of the Verena granite to be preserved along with highly fractionated, coarse-grained granites below (Fig. 5B). Intersection of the lineaments may have given rise to an east-west fracture system found in the morphologies of the mineral occurrences of the area. To the southeast, mineralisation is found in high-level granites exposed due to this synclinal flexure of the Verena granite parallel to the Laersdrif lineament. The barren region of the Verena pluton, adjacent to this synclinal flexure, occurs between this flexure and an anticlinal flexure found beneath Rooiberg Group volcanics to the northeast (Fig. 12). Erosion of the pluton has given rise to these low-level granites been exposed in this area to the east of the Albert Silver Mine (Fig. 5B)

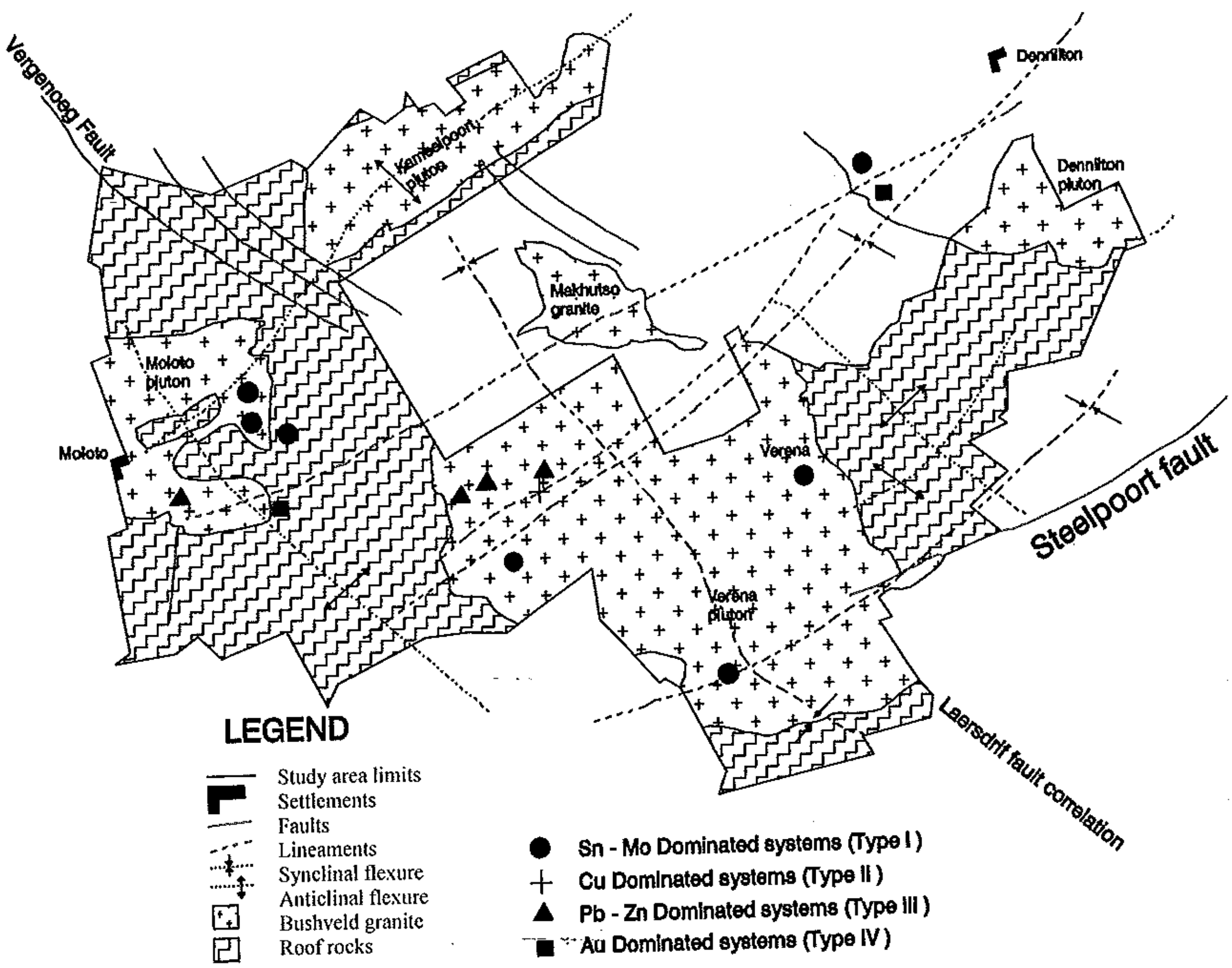

Figure 12: Major structural features including faults, lineaments and crustal warps which have influenced granite emplacement and mineralisation localisation in the study area.

Local structure, including quartz veining, jointing and dyke orientations, has been directly influenced by the larger-scale features with jointing and veining in the individual plutons being parallel or sub-parallel to these orientations. Certain vein orientations, such as those trending northeast-southwest, are generally barren (Scogings, 1991), suggesting some later reactivation or movement parallel to the lineaments after the mineralising event had come to an end. Local faults and structure are also important

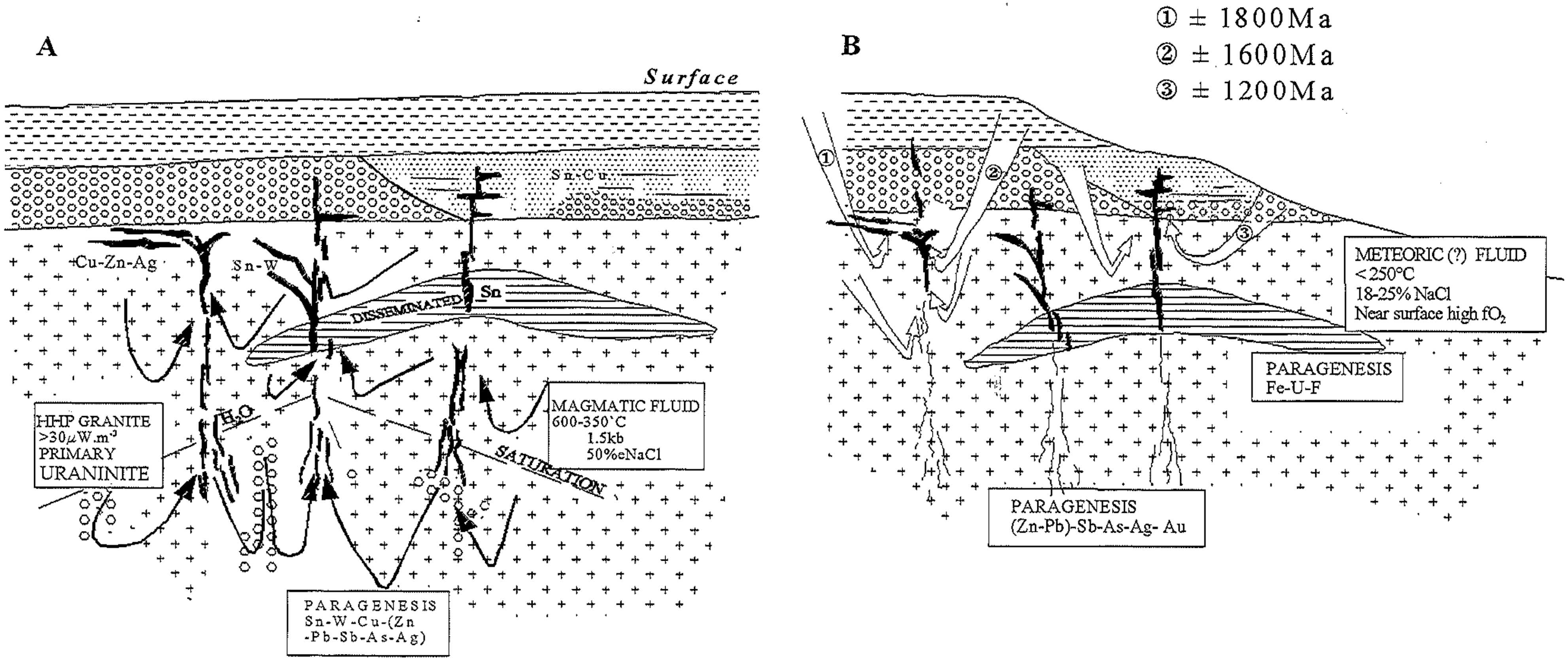

Figure 13: Generalised model for mineralisation in the acid rocks of the Bushveld Complex. A. Late stage crystallising granites had an associated magmatic fluid associated with them giving rise to the early styles of mineralisation. B. Later fluid incursions at differing times mixed with any remnant magmatic fluid causing fluid mixing and the deposition of later styles of mineralisation. When the meteoric / connate component was dominant a Fe-U-F assemblage was deposited on the earlier assemblages.

as hosts to mineralisation, acting as permeable conduits for fluids, whether they be magmatic or meteoric / connate in nature.

CONCLUSIONS

The acid rocks of the Bushveld Complex formed as a result of crystal fractionation that gave rise to highly fractionated granites at the roof of any given granite sheet. A metal-rich vapour phase formed as a result of this crystal fractionation and gave rise to the mineralisation seen in the granites of the Bushveld Complex.

Figure 13 illustrates a simplified model of mineralisation in the granites. Early magmatic mineralisation occurred contemporaneously or shortly after crystallisation of the highly fractionated granitic magma. This gave rise to the early mineralisation styles such as Type I and, to a lesser extent, Type II. Hydrothermal fluid circulation may have continued for a few hundred thousand years to one or two million years at most owing to the HHP nature of the granites. At later times uplift, tilting or unroofing of the granites allowed the incursion of meteoric / connate fluids, which would have mixed with any remnant magmatic fluid, giving rise to later mineralisation types. Later meteoric / connate fluid incursions are considered to have given rise to the late-stage Fe-U-F assemblage which superimposed itself on the earlier assemblages long after magmatic fluid circulation and fluid mixing had ceased.

Structure played a major role in determining fluid flow and localisation of mineralisation. Two major crustal features, the Steelpoort and Laersdrif faults, were fundamental to both granite emplacement and later tectonism and hydrothermal fluid flow of either a magmatic or meteoric / connate nature. These large-scale features have influenced local small-scale structures.

The roof rocks often act as host to mineralisation derived from the underlying granites, particularly the late-stage mineralisation styles. They are not host to mineralisation derived from their own crystallisation or extrusion.

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