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A PRELIMINARY REVIEW OF TIN MINERALIZATION WITH PARTICULAR REFERENCE TO THE BUSHVELD IGNEOUS COMPLEX

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ABSTRACT

Primary tin deposits are invariably associated with acid igneous rocks ranging in age from Precambrian to Tertiary with an apparent increase in the economic importance of deposits of lesser antiquity. A review of world-wide data on the nature of tin-bearing granites, their tectonic setting and the genesis of primary deposits reveals that much of the data is conflicting. Tin deposits are, however, uniquely related to the roof zones of granitic intrusives and to the late stages of polyphase intrusives. Tin deposits are related to granitoid rocks located in major regional belts but only very small areas within these regional trends are stanniferous. It has been suggested that tin deposits are located at the intersections of two or more of these regional tectonic features. Alternatively it is suggested that tin deposits are located in granitic intrusives where slow differentiation took place or in intrusives, emplaced at higher levels, which were rich in volatiles. The implication of this view is that all granitic rocks carry sufficient tin to give rise to economically important deposits provided that the appropriate crystallization conditions are attained. On the other hand there are those who believe that original inhomogeneities in the mantle or lower crust were responsible for the preferential concentration of tin in some granitic rocks. The fact that tin deposits are located at or near the roofs of granitic intrusives is regarded as a contributory factor in the younger granitoids being apparently enriched with respect to tin. In older intrusives, exposed for longer periods to the processes of erosion, the likelihood of the roof zones being preserved is less.

Tin deposits in southern Africa are briefly summarized. The main South African production of tin has come from the Bushveld Igneous Complex, and attention is drawn to some of the problems which remain to be solved before a model for the emplacement and origin of the acid phase of the Complex can be devised. Until these problems have been resolved no adequate prospecting model can be attempted. The acid phase of the Complex is considered to be a significant prospecting target in the light of the world-wide data because the emplacement of the granitic rocks appears to have been polyphase and because large areas of the roof or parts adjacent to the roof have been preserved.

Preliminary investigations suggest that geochemical prospecting techniques may be employed to locate stanniferous areas, but more systematic work is required to establish which pathfinder elements or combinations of such elements are likely to prove the most effective. There can be no doubt from results obtained in other parts of the world that determinations for tin alone either in soils or hard rock will be of little value in defining prospecting targets.

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I. INTRODUCTION

The object of this review is to summarize basic data on world-wide tin mineralization as a preliminary step in the establishment of parameters which can be used to define an exploration model. Tin mineralization of economic importance is located in widely divergent geological environments, invariably, however, associated with acidic rocks as indicated by the position of the mineralization relative to these rocks. The ages ascribed to tin mineralization range from Precambrian to Tertiary with an apparent increase in the economic significance of deposits of lesser antiquity.

Primary tin deposits occur in pegmatites, pneumatolytic/hypothermal, epithermal and xenothermal veins and replacements. More rarely important deposits are found in contact metamorphosed limestones adjacent to granites or as segregations in granite.

Although granitic rocks are common in the crust, tin deposits of economic importance are associated with a relatively small proportion of them. Even within a tin province the majority of the granitic intrusives or effusives and their adjacent country rocks are devoid of tin. The recognition of this fact has led investigators to attempt to detect differences which may exist between tin-bearing and barren granites as regards their mineralogy, chemistry, tectonic setting, relation to regional and local structures, spatial relation to tin mineralization and time of emplacement.

(a) Nature of Tin-Bearing Granites

Jones (1925) drew attention to the fact that the Benom Range granites of Malayasia are barren of tin although lying within 20 km of the tin-bearing Main Range granites. He noted that the tin-bearing granites carried muscovite and lepidolite which are rare or absent in the Benom Range granites. The Benom Range granites are, however, richer in hornblende.

Sullivan (1948) considers that, in the presence of abundant ferromagnesian minerals, large scale concentration of tin may be practically impossible because of the similar ionic radii of iron and magnesium to tin, and the relatively low valency of iron and magnesium. On the other hand, Barsukov (1957) claims that tin-bearing granites do not differ essentially from barren granites in mineralogical composition. Westerveld (1936) also concluded that "tin" granites do not possess any particularly remarkable features in so far as their most apparent characteristics are concerned. He established that "tin" granites are biotite-bearing, sometimes with a little muscovite, and are often porphyritic. However, Westerveld noted some differences in regard to the micas of the tin-bearing granites of Malaya, Indonesia, Cornwall and Saxony. He found "an exceptional content of rare earths in the granites of Malaya; small quantities of tin in the black mica, in the quartz and the feldspar of the Banka granites; some traces of Li, Sn, Bi, Cu, Co and U in the zinnwaldite mica of the tin-bearing granites of Saxony, and of Ga, Sn, and W in the biotite of the granite of the East Pool mine near Redruth, Cornwall".

Edwards and Gaskin (1949) hold that "tin" granites are truly magmatic and that they are conspicuously rich in silica but abnormally low in Mg and Ca. To support their point of view they quote the silica content of "tin" granites from New South Wales (74.6 to 76.5 per cent SiO_2), Queensland (76.5 to 77 per cent SiO_2) and Tasmania (74.5 to 77 per cent SiO_2). Hosking (1965) countered this argument by drawing attention to the Portuguese and Bolivian granites associated with tin deposits which have 67.96 per cent SiO_2 and 65.39 per cent SiO_2 respectively. Furthermore the Mountsorrel granite in Liecestershire contains 76.70 per cent SiO_2 but is not related to any known tin mineralization. In southwest England the Dartmoor granite has an average SiO_2 content of 75.09 per cent, whereas the Carnmenellis granite, with which more important tin deposits are associated, has between 71 and 73 per cent SiO_2. The average values of MgO and CaO for the previously mentioned granites are :

	MgO	CaO
Dartmoor	0.74	0.66
Carnmenellis	0.40	1.18

	MgO	CaO
Mountsorrel	0.65	1.10
Bolivia	1.87	3.07
Portugal	0.29	1.87

In the case of the Carnmenellis granite the MgO and CaO contents of the postulated youngest phase of emplacement are 0.03 and 1.15 per cent respectively (Ghosh, 1934).

Rattigan (1960) concluded that tin appeared to be fractionated in magmas having a higher proportion of alkalies (particularly potassium) relative to calcium and magnesium, and that a high silica content is not necessarily critical. The ratio of $K_2O + Na_2O$ to $MgO + CaO$ in the Australian examples he quotes is close to 15. The same ratios for Bolivian and Cornish granites is, however, 1.5 and 3.7 respectively. Zimmerman (1965) considered that Australian tin deposits are located "in particular structural and lithological environments close to the roof zones during the closing stages of crystallization of granitic intrusives which contain high silica, high potash and very little lime or magnesia".

Tauson et al (1968) calculated the average Sn content in granitoids, ranging in age from early Precambrian to Jurassic, in eastern Siberia, and concluded that there was no significant variation, as the following table demonstrates.

Age	Complex	Sn, p.p.m.	No. of Samples
Mesozoic	(Amudjulano-Sretinski	4.0	49
	(Shaktaminski	2.9	114
Palaeozoic	(Verchne-Undinski	4.6	33
	(Jidinski	3.1	69
	(Kondudero	3.7	84
	(Cholderminski	2.7	162
Proterozoic	(Gunikski	4.2	29
	(Ignokski	4.4	31
	(Onotski	4.0	17
Archaean	(Kitoiski	3.6	18
	(Aldanski	3.8	17

These authors consider that factors which determine whether a granite will or will not be ore-bearing are composition, size and depth of formation. In contrast to the findings of Tauson et al, Rankama concluded from a world-wide review of trace element contents of granite that Li, Be, Rb, Cs, Ba and Pb were apparently enriched in granites of lesser antiquity, although he did not have at that time adequate data on the concentration of tin.

Beus and Sitnin (1968) consider that ore-bearing granites can be distinguished by reference to the ratios of elements having different properties of migration, e.g. Mg/Li. The authors claim that, from a study of no more than 20 or 30 samples, it is possible to distinguish mineralized granites by reference to analyses for Li and Sn, and the ratios of Mg/Li and Zn/Sn.

Jebwab (1955) contrasted the content of lithium and tin in feldspars and micas from two adjacent Hercynian plutons in Brittany, one carrying tin deposits and the other being barren. Jebwab concluded that :

(i) Tin is never absent from micas of granites

(ii) There are greater differences in the Sn content of biotites than of muscovites in mineralized granites as compared to barren granites

(iii) The Li content of feldspars is higher in mineralized granites

(iv) The Sn content of feldspars and micas increases as the lodes are approached.

Hawkes and Webb (1962) have advised caution in regard to trace element studies of granitic bodies, in view of the fact that there may be inherent geochemical differences in successive heaves of magma in composite intrusions. These authors obtained the following results for the three granite types recognized by Ghosh (1934) at Carnmenellis :

	Phase I	Phase II	Phase III
Co p.p.m.	8	4	2
Ni p.p.m.	10	4	2
Sn p.p.m.	25	5	20
Li p.p.m.	700	1500	3000

Hawkes and Webb (1962) emphasize the need for systematic and adequate sampling. Jedwab (1955) based his conclusions on 11 feldspar and 10 biotite samples from the mineralized granite, and 30 feldspar and 25 biotite samples from the unmineralized, La Villeder granite.

Interesting data have been supplied by Tauson et al (1968) in comparing the trace element content of barren and mineralized granite complexes in eastern Siberia. They find that the concentration of F, Nb and Ta average 4 to 5 times higher in the mineralized granitoids. The contents of Sn, Li, Rb, and Be are 2 or 3 times higher than in the barren granites, but variations in the contents of Pb, Zn and Mo are negligible. The authors regard the concentration dispersion to be more significant, the difference being as much as 17 times higher in the mineralized granites as compared to the barren granites.

The same authors have also studied the distribution of tin in minerals in the granitoids, finding that in barren granites the bulk of the tin is accommodated in the crystal lattices of the hornblende and sphene. In the mineralized granites tin is concentrated in late biotite which is paragenetically associated with accessory fluorine. Hosking (1970) reports the presence of stanniferous ilmenite and zircons in the Malayan granites, while Desborough and Sainsbury (1970) have found ex-solved cassiterite in magnetite occurring in skarn at the Lost River mine, Alaska. The latter authors suggest that, if ilmenite and magnetite in granitic rocks are found to contain cassiterite, either ex-solved or in solid solution, these oxides may account for a large share of the tin dispersed in the acid rock.

Dudykina (1959, quoted in Leube and Stumpfl, 1963) has reported that the geochemistry of cassiterite itself varies according to the genetic environment from which it is derived. The following tabulation gives the average content in p.p.m. of five trace elements in cassiterite from deposits in Siberia :

		No. of Samples Analysed	Nb	Ta	Sc	Be	Ti
I	Tin-bearing pegmatites	37	6000	5300	650	10	4100
II	Quartz-cassiterite						
	(a) Greisens and quartz-feldspar veins with topaz, tourmaline and beryl	38	5200	1570	580	20	7500
	(b) Quartz veins	129	600	150	400	10	3500
	(c) Transitional deposits	24	30	-	140	50	4000
III	Sulphide-cassiterite deposits	43	20	-	4	10	1700

The above results suggest that there is a distinct relation between the temperature of formation and the trace element content of cassiterite. In addition to the diminishing content of Nb, Ta, Sc and Ti with decreasing temperature, Dudykina also found that Pb, Ag, As and Sb show a sympathetic increase.

No clear cut mineralogical nor chemical distinctions have been defined which can be used to distinguish mineralized from barren granites. It has long been recognized that the gross chemistry of granitoids varies according to their tectonic settings. Syn-kinematic, acid plutonic rocks are characteristically granodioritic in composition and the late- and post-kinematic granites are markedly potassic. It may well prove, as more geochemical data becomes available, that there are significant differences in trace element content related to a particular granitoid's tectonic setting. It has been proposed that one of the factors which determines whether a granite will be mineralized or not is the depth at which the granite crystallized. Before considering the influence on mineralization of the tectonic setting of granitic rocks, it is relevant to note the geographical distribution of the major tin-fields in southeast Asia, eastern Australia, Nigeria and the Andean chain of South America. The question must arise whether these concentrations reflect original inhomogeneities in the crustal distribution of tin or whether subsequent geological events have eliminated economic tin deposits in areas which are now barren. In this connection the Andes-Rocky Mountain chain built of Mesozoic intrusives and Tertiary volcanics contains major tin deposits only in the Andean portion.

(b) Tectonic Setting

Major tin deposits are associated with granitoids in different tectonic settings. In Bolivia tin deposits are closely related to acid effusives and quartz porphyry intrusives, and in Nigeria the Younger Granite ring complexes, consisting of rhyolitic lavas and pyroclastics erupted from vents situated on ring fractures and of granitic intrusives, provide the source of the important placer deposits. Linear bodies of granite lying along the axis of the Tasman geosyncline in eastern Australia give rise to significant tin mineralization. In southwest England, tin mineralization is associated with coarse-grained granite plutons, regarded by Read (1949) as the final expression of his granite series. Important, but smaller, tin deposits derived from pegmatites in orogenic settings are worked in South West Africa and Rhodesia.

Bilibin (1955) related the different types of mineralization found in an orogen to a model of the tectonic evolution of a geosyncline. Suites of plutonic and volcanic rocks are intruded or extruded at various times and are regarded as characteristic of a particular stage in the development of the orogen. Associated with this activity equally characteristic mineral deposits are formed. Bilibin considers that although granitic rocks are developed at several times in such an environment, tin will only be deposited in association with high silica, potassic granites in his middle tectonic stage and with granite, and its hypabyssal and volcanic equivalents, during the late tectonic stage. The mineralogy of the ore bodies will also differ. In the middle stage W, Mo, Bi, F, Li, Be, Ta and Nb will occur with the tin while in the later stage the tin will be associated with Pb, Zn, Ag, As and, possibly, W and Mo.

Tauson et al (1968) divide granitic complexes into four groups :

(i) Abyssal batholiths

(ii) Meso-abyssal batholiths

(iii) Hypabyssal intrusions with a low level of volatile content

(iv) Hypabyssal intrusions with a high level of volatile content.

These authors consider that abyssal batholiths formed at depths between 8 and 10 km in quiet tectonic conditions where crystallization was slow, permitting differentiation and resulting in leucogranites enriched with respect to the volatile components. These late differentiates, which may reach higher crustal levels through zones of weakness, are regarded as being potentially ore-bearing.

Meso-abyssal batholiths forming at depths of 4 to 5 km under more active tectonic conditions are not considered to provide exploration targets because the less stable environment hinders differentiation and leads to an increased dispersion of the rare elements. In support of their argument the authors quote the Verchne-Undinski and Jidinski complexes where there is a decrease in the contents of F, Li, U and Sn in the late leucogranitic phase as compared to the main granite phase, but there is slight increase in the U content of aplite veins at Verchne-Undinski and in Sn at Jidinski.

Hypabyssal intrusives, forming at depths of 2 to 4 km, are of smaller size than batholiths. Differentiation is considered to be less active at these levels, from which it follows that there is less contrast in the trace element content of the different phases of intrusion. However, due to the high pressure gradient of the volatiles, the authors consider that there may be an enrichment with rare elements in the apical parts of hypabyssal intrusives. Tauson et al (1968) find that further enrichment takes place in the apices during post-magmatic greisenization.

The authors conclude that the ore-bearing potential of a granitic intrusion depends on its size, depth of formation and composition. For elements such as Li, Be, Sn, W, Nb and Ta a high concentration of volatile matter having a steep pressure gradient is a requirement for the concentration of the rare elements and their further enrichment by post-magmatic metasomatism.

Schuiling (1967) has studied the distribution of tin on the continents of North and South America, Africa and Europe by plotting all the reported deposits and occurrences (see Figures 1 and 2). He finds that approximately 90 per cent of the deposits are concentrated in 11 elongated, belt-like zones and one province. Only the Erzgebirge province of central Europe does not occupy a linear belt. On the African continent three belts are distinguished : (i) the Central African belt extending from Natal through Swaziland, Transvaal and Rhodesia into Uganda, (ii) the South West Africa-Nigeria belt stretching from near Cape Town through Angola, Gabon and Cameroon to Nigeria, and (iii) a poorly defined belt which extends from Liberia to Morocco. Having defined these linear belts of tin concentration, Schuiling plotted the belts on Bullard's reconstruction of the continents before drifting in Mesozoic times. The author finds that the belts can be traced from one continent to another, e.g. the east Brazilian belt seems to be a direct counterpart of the South West Africa-Nigeria belt and the Appalachian belt appears to join the Hercynian belt of Europe. The ages of tin mineralization in the various belts ranges from Precambrian (pre-dating Mesozoic continental drift) through Jurassic (contemporaneous with drifting) to Eocene (post-drift or at a late stage of drifting). This is interpreted to mean that throughout this time the source of tin must have been carried along by the continents and, hence, this source must be located in the crust or that part of the upper mantle which remained attached to the crust during drifting. Schuiling considers that, if the source of tin lies in a linear zone in the mantle, mineralization would have been located in belts which would be displaced relative to each other as the crust drifted over the source.

In North and South America and Europe the tin belts are broadly concordant with orogenic trends (i.e. Andes, Rocky Mountains, Appalachians and Hercynian) but only very localized portions of these belts are the sites of large concentrations of tin. Schuiling finds some evidence to suggest that concentrations of economic importance are located where two belts intersect. Along the Andean-Rocky Mountain belt a major concentration occurs in Bolivia where it is intersected by the Rondonia-Guyana belt. Schuiling speculates that economic concentrations are located where subsequent geological events have affected those portions of the lower crust in which there was a primary, preferential concentration of tin.

Wright (1970) has attempted a regional synthesis of the controls of tin mineralization in Nigeria. He considers that the distribution of the stanniferous pegmatites in the Nigerian basement and of the Younger Granite ring complexes can be more plausibly related to a proposed ancient lineament system than to regional structural trends. The foci of most intense mineralization in both the older and younger tin-fields lie close to the intersection of a prominent east-northeast lineament across central Nigeria with the northward projection of the line of later continental separation (see Figures 3 and 4).

The implication in the work of Tauson and his co-authors is that there was no primary, inhomogeneous distribution of tin in the crust but that suitable conditions prevailed during the crystallization and emplacement of certain granitoid rocks to produce an economic concentration of tin. The average Sn content of the eastern Siberian granitic complexes listed by Tauson et al (1968) range from 2.7 to 4.6 p.p.m., while the world average for the concentration of tin in massive rocks of the lithosphere has been estimated at about 5 p.p.m. Taking the latter figure it is necessary to achieve an enrichment of at least 2500 times to reach the lower limits of economic concentration, but concentration of as much as five thousand times would be required in the case of the Siberian granitoids. When degrees of concentration of this magnitude are considered it is attractive to speculate on the existence of zones of primary enrichment in the crust and upper mantle.

Hosking (1970) has proposed a provisional model for tin mineralization in Malaya. He postulates a process of re-cycling whereby tin is weathered from earlier formed lodes, is transported, deposited, buried and suffered diagenesis. Renewed orogenic activity leading to the generation of granitic magma by anatexis of the geosynclinal sedimentary pile, which includes beds containing detrital cassiterite, results in the emplacement of stanniferous granites. Granitic intrusion is regarded as multi-phase with the result that late, more differentiated phases either assimilate early formed lower grade lodes or such lodes are enriched by addition from a younger, subjacent body of granite. In the Canadian Appalachians, McCartney (1965) notes that tin mineralization occurs at or close to the time of the generation of anatectic granites but he does not imply that the tin was derived from the mobilization of originally stanniferous sediments.

The orogenic model for mineralization proposed by Bilibin (1955) does not accommodate the stanniferous anorogenic complexes such as volcanic-plutonic ring complexes of Nigeria nor the plutonic Bushveld Complex of South Africa. Both these examples represent thermal events and, according to Schuiling's hypothesis, the coincidence of a major geological process with a primary geochemical culmination would provide a suitable catalyst for mineralization irrespective of the orogenic or anorogenic nature of the process.

(c) Genesis of Primary Tin

The existence of metallogenetic provinces characterized by the dominance of a particular mineral or suite of minerals has been recognized by economic geologists for over 65 years. The close association between magma-type and ore deposit led to the conclusion that specific ore minerals were genetically related to basic, intermediate or acid magmas. In recent years an increasing body of evidence suggests a more tenuous connection between ore deposition and intrusive rock.

Burnham (1959) studied a large number of mineral deposits and occurrences in southwestern United States and summarized his findings as follows :

(i) metallogenic belts are of vast extent,

(ii) they are largely unrelated in time to the associated tectonic features,

(iii) relatively small segments of them contain deposits that represent as many as four widely separated metallogenic epochs, and

(iv) they are not uniquely associated with a particular kind of intrusive or wall rock, for the same kinds of rock occur within and outside the belts.

Burnham demonstrated the existence in the southwestern United States of belts of concentration of copper with some gold and silver in the east, and in the west of gold and silver with only rare copper. On a continental scale Schuiling (1967) has postulated the existence of belts in which there is a geochemical culmination of tin, resulting from a primary inhomogeneous distribution in the lower crust and/or upper mantle.

Studies on the isotopic composition of lead (Cannon et al, 1961) and sulphur (Jensen, 1959) from major ore deposits in the Americas produced evidence in favour of their derivation from the mantle. Darnley (1965) has suggested that at an early stage in the fractional melting of mantle material it is probable that "at least three liquids will exist, a predominantly silicate liquid, a predominantly sulphide liquid and a volatile-rich liquid such as produces carbonatites". Darnley expressed the view that it would be reasonable to believe that elements will be accommodated in the silicate or sulphide liquids in accordance with "their geochemical affinities and abundance in the mantle". He envisages that the greater abundance of silicate liquid over sulphide liquid would lead to some incorporation of the latter in the silicate liquid as it coalesced, thus giving rise to the sulphides commonly associated with basic rocks. Darnley further points out that sulphide deposits of economic importance are associated with silica, carbonates, water, alkali elements and the rarer volatile elements such as halogen and boron. He interprets this as evidence for an interaction between the "dispersed droplets of sulphide-rich liquid and dispersed droplets of volatile-rich liquid within the mantle to give rise to volatile-rich sulphide liquid" of relatively low density. Accumulation of such a liquid would necessarily be slow and, being composed of trace elements from the mantle, might show variations in composition from place to place, reflecting original mantle inhomogeneities. Darnley suggests that such ore-liquids are continuously accumulating as a result of convectional creep of the mantle at the base of active orogenic zones. The fact that the granitic fractions of the silicate liquid would have relatively low density favours gravitational ascent. Structural dislocation resulting from the upward rise of a large mass of granitic magma would provide channel-ways for the ascent of the ore-liquid in the wake of the magma and result in the spatial association of the two fractions at surface.

Wright (1970) contends that the ore minerals in the Younger Granite ring complexes of Nigeria were not "basement-derived, but originated at deeper levels as part of the primary melts". He bases his argument in favour of this contention on the thesis that "the Younger Granite magmas probably originated in the upper mantle, as salic melts, generated by pressure relief, partial melting, and a concentration of low melting constituents beneath a broad crustal dome ..., and modified by interaction with basement rocks". The presence of a marked negative gravity anomaly over the Younger Granites is taken as evidence that they were not derived by differentiation from a subjacent basic magma body, or which could have induced crustal melting. Wright poses the question that, if the granite magma had its origin in the upper mantle, "are the ore mineral constituents similarly derived, or were they extracted and concentrated from the crustal rocks through which the salic magma rose?" The second alternative fails to explain :

(i) the greater volume of Younger Granite mineralization as compared to the basement, and

(ii) the contrasting mineral assemblages associated with the basement tin mineralization and the Younger Granites. Boron, beryllium and tantalum are rare in the Younger Granites but common in the basement pegmatites. Conversely, fluorine, tungsten and hafnium are common in the Younger Granites but rare in the basement.

Turning aside from the ultimate source of tin, consideration must be given to views expressed on the concentration and crystallization of tin from a granitic magma.

"Emmons (1940) has suggested that during the crystallization of a granitic magma "pools" of residuum collect under cupolas or high spots in the roof, and as this takes place vapour pressure develops which may reach such a magnitude that the overlying rocks are fractured, and the residuum, which is thus enabled to escape, entirely or in part, is instrumental in the formation of mineral deposits. If the fracture takes place at a comparatively early stage, before the "granitic" components have been completely eliminated from the liquid phase, pegmatites develop : if fracturing is delayed somewhat, the escaping products cause the generation of hydrothermal bodies, and if the vapour pressure never exceeds that of the confining rocks the residual liquid remains in the cooling igneous mass where it may react with the granitic materials effecting marked changes and its heavy metal ions may be incorporated in part, or entirely, in new silicates : alternatively the heavy metal ions may report in new accessory minerals which may be disseminated and/or locally concentrated in the igneous mass. Thus in the last case tin may be incorporated, in part, at least, in secondary micas; it might report as disseminated cassiterite grains or, on comparatively rare occasions, it may segregate as cassiterite together with species commonly found in hypothermal lodes, in pipes just beneath the roof".

In the above words Hosking (1965) summarizes Emmons' view and suggests that it may need some amendment in the light of other evidence. Hosking has found that within the Cornish granites biotite is replaced by muscovite in lode areas. During this conversion Cu, Zn, As, Li, etc. are lost by the biotite, but the resulting muscovite contains at least as much (sometimes more) Sn and Be, as the parent biotite. He also finds that the tin content increases sympathetically with degree of griesenization, but when the greisen is locally silicified the tin content drops. Cassiterite is then found in the quartz in voids after feldspar. He concludes that muscovitization of biotite liberates large quantities of metal and the silicification of muscovite mobilizes tin.

Hosking suggests that mineralization of lodes results from multi-phase action. Elements such as Cu, Zn, As, Li are added to the lodes as a result of the alteration of biotite to muscovite, and tin is mobilized and migrates to the developing lodes as a result of silicification of the muscovite. Both these reactions take place as a result of the action of metal mobilizing agents derived from the granite residuum. In addition Sn, Cu, Zn and other metals are deposited in the lodes directly from the granitic residuum. This concept can be related to the views already expressed. Enrichment to an economic grade could depend on the availability of additional mineralizers derived possibly from an ore-liquid as visualized by Darnley. If the ore-liquid originated in a portion of the lower crust or upper mantle coincident with a primitive enrichment in tin, the ore-liquid could generate a tin deposit. On the other hand the possibility of an economic deposit being generated would be reduced if the ore-liquid was unable through lack of suitable channel-ways to pass into the lodes, or if the ore-liquid was not stanniferous.

Barsukov (1957) holds that some Russian tin deposits owe their origin essentially to release of tin from biotite caused by ascending sodium and fluoride ions. This view would seem to be in accord with Hosking's suggestion that part of the tin in stanniferous lodes is derived from this source.

Darnley (1965) devised a model, based on Taylor's (1963) work, showing how the partition of elements is envisaged as taking place when the silicate and sulphide liquids are fractionated. Tin is considered to enter late-stage minerals in silicate liquids and into structures of principal minerals in sulphide liquids. The results obtained by Tauson and his co-authors (1968) show that Sn also enters into sphene which is usually regarded as an early accessory mineral. Darnley's model would accommodate the concept that Sn is mobilized from biotite, as well as providing a source for further enrichment via the sulphide liquid.

Sullivan (1948) presented the view that quartz crystals having a very closed lattice because of the small size and high valence of the Si ion make solid solution difficult. He regards rocks rich in quartz as the most likely to reject many metallic ions which then become concentrated as ore-bodies and deposits around granite bodies. An objection to this concept lies in the fact that lead and zinc should be captured in the lattice of minerals occurring in granite. Lead can replace K in feldspars and biotite, and zinc can replace bivalent iron and magnesium in mafic minerals. It would be expected that lead and zinc would be impoverished in ore deposits associated with granites. In the case of tin it may well be that grains of cassiterite disseminated through a granite as a primary constituent originate in this way confirming the views previously reported that stanniferous granites are essentially high silica rocks. It does not, however, satisfy the condition when granites with high contents of silica are barren of tin. It must be concluded that the content of tin in a granite is determined by the quantity of Sn available at the time of the generation of the granitic magma.

(d) Spatial Relation of Tin Veins and Lodes to Granite

Almost invariably stanniferous veins and lodes are located close to clearly defined, usually steep-sided, cupolas in the roof of the granite. The richest ore veins are usually those which are related to the cupola which reaches highest into the country rock. Veins with greisenized walls carrying cassiterite, wolframite, arsenopyrite, etc. are located in the apex of cupolas. External pegmatites, hypothermal lodes and replacement deposits lie on the flanks of the cupolas. These deposits, which are usually the most important economically, are equally well developed in the granite and in the adjacent country rocks, into the latter of which they may persist for considerable distances. It has been suggested that the almost complete absence of lodes and veins in the Nigerian Younger Granites is due to the original flat roof of these granitic bodies which contributed to the dispersion of mineralization.

Porphyry dykes which are common in many tin-fields have had a controlling effect on tin deposits, which may be developed on one or both flanks of the dyke or within it.

(e) Mineralogy of Tin Deposits

The tin-bearing minerals of the major deposits are confined almost exclusively to cassiterite (tin oxide) and stannite (iron-tin-copper-sulphide), of which the former is the more abundant. Exotic sulphostannites, canfieldite, colusite, cylindrite, franckeite and teallite, are confined mainly to the Bolivian epithermal and xenothermal deposits.

The mineralogy of tin lodes and veins varies widely and is dependent on a number of factors such as temperature/pressure conditions, rate of flow, degree of differentiation of magma, and nature of channelways. As a general rule endogranitic deposits usually have a more simple mineralogy than exogranitic deposits.

A distinct zonal arrangement is recorded in lodes. In Cornwall tin oxides and some wolfram occur nearest the granite, and are followed by a zone containing copper and high temperature zinc together with some tin, which, in turn, is succeeded by an outer zone with low temperature zinc and lead. Blake and Smith (1970) have found that the arrangement of mineralized zones associated with the Elizabeth Creek granite in the Herberton tin-field of Queensland differs from that in Cornwall. In the inner zone wolframite is predominant over cassiterite which appears in the next zone to be succeeded, as in Cornwall, by zones of copper and lead.

At Zeehan in Tasmania the mineralogy in the inner zone is cassiterite, tourmaline, quartz, pyrite, and arsenopyrite. This assemblage is endogranitic. The contact aureole carries pyrrhotite, pyrite, chalcopyrite, sphalerite and galena. Copper mineralization appears in the third zone which grades into a zone wherein sphalerite is more abundant than galena. The outer zone is marked by a decrease in sphalerite and the appearance of antimony and silver-rich galena - tetrahedrite ores in a sideritic gangue. At the Oonah mine in the outer zone stannite is the main sulphide, but some cassiterite is found in all zones.

In addition to the above mentioned minerals arsenopyrite, wolframite, bismuthinite and molybdenite, are also reported from stanniferous ores.

Gangue minerals include quartz, sericite, topaz, muscovite, chlorite, lithia mica, fluorite and tourmaline. The last named mineral although very common in many deposits is conspicuously absent from others.

In pegmatites cassiterite is often introduced at a late stage accompanying albitization. Minerals of the columbo-tantalate group, some minor sulphides, magnetite, tourmaline, beryl and mica are also present in mineralized pegmatites. A zonal arrangement of mineralization has been reported from external pegmatites. Agassiz (1954) found that, in Kivu Province, Central Africa, the pegmatites nearest the granite are potassic and carry Sn, W, Au, Nb and Ta. Further away from the granites the stanniferous pegmatites are sodium- and lithia-rich. Finally an outer zone of quartz veining is found carrying Sn, Au, Fe, As and S.

Hydrothermal and replacement deposits are frequently bounded by wall rocks which have been subjected to a number of different types of alteration. The normal sequence found in granitic and non-calcareous sedimentary rocks is sericitization, tourmalinization, kaolinization, chloritization and haematitization. Silicification can occur alone or in association with any of the other processes. Where the wall-rocks are calcareous sedimentary or basic rocks, they tend to be altered to a skarn-type suite of rocks in which axinite, epidote, zoisite, garnet, tremolite and calcite are developed.

In the apices of granite cupolas the early veins are bordered by narrow bands of greisen which may be subsequently modified by the introduction of tourmaline, zinnwaldite, chlorite, fluorite and haematite.

Xenothermal deposits are formed close to the surface under initially high temperatures and consequently many of the deposits display a marked telescoping of the mineral zones. Turneaure (1960) reports that in Bolivia vertical zoning cannot be clearly demonstrated but that lateral zoning on a local scale can be observed. In these cases a tin-bearing zone is partly surrounded by several low-grade sulphide zones.

(f) <u>Vertical Extent of Mineralization</u>

Dewey (1925) considered that the widths of the Cornish zones are as follows :

Zone of carbonates (iron, manganese, etc.)	700 feet (250 metres)
Zone of sulphides of antimony etc.	200 feet (75 metres)
Zone of sulphides of lead and silver, giving place to zinc and copper in depth	1800 feet (660 metres)
Zone of sulphides of copper, intermixed with wolfram and tin for some 700 feet at base	2500 feet (900 metres)
Zone of oxide of tin with wolfram in upper parts	2500 feet (900 metres)

Hosking (1965) regards these figures as "very debatable", and expresses the opinion that it is only on rare occasions that economic tin mineralization persists in excess of 350 metres. This is borne out by reference to some Australian lode deposits. The Vulcan mine in Queensland, the deepest in the country, has been mined to 1220 feet (440 metres). Many lodes extending to only 10 metres are reported and there is a range of values between these limits. Endogranitic pipes have been worked in the Herberton area to depths of 250 metres.

The vertical extent of mineralization is controlled by a number of factors such as nature of country rock (in exogranitic lodes), degree of fracturing, age of fracturing, rate of flow, and temperature/pressure conditions. Clearly no deposition of cassiterite will take place if suitable channelways for the egress of the mineralizing solutions do not exist. Furthermore solutions will preferentially pass into more open fractures. Some tin deposits are located on the contacts of dykes and even within dykes where fractures associated with the emplacement of the granite intersect the dykes. It is self-evident that the fractures must be sufficiently extensive to tap the ore-bearing fluid.

Deposition of tin takes place only when the flow of the mineralizing fluid reaches a critical velocity. Hosking (1965) considers that the field evidence suggests that this velocity is very low and is reached in the vicinity of marked constrictions, such as (i) at or near the junction of one rock type with another, (ii) at places immediately below points where the dip of a lode decreases, (iii) at the intersections of lodes, and (iv) at loci where chemical reaction is enhanced.

These factors will all influence the vertical extent of mineralized lodes, particularly in exogranitic environments, so that in any one district individual lodes may well display highly variable vertical extents.

(g) Local Structural Controls

Lode deposits are located around cupolas, which are steep-sided. Little published data is available regarding optimum sizes of cupolas but this is presumably a reflection of the widely varying degrees of erosion which have taken place since the emplacement of the granite. The Story's Creek mine, Tasmania, cupolas are reported to be 500 feet (185 m.) across and of elliptical shape. The flanks dip at 30° or steeper.

The majority of tin lodes in Cornwall strike E-W or NE-SW, these directions being parallel to anticlinal axes in the country rocks. Intersecting these directions are a series of less frequent N-S fissures which are known locally as cross-courses when filled with quartz. Some lead and zinc mineralization is located in the cross-courses but they are usually barren of tin. Both the tin lodes and the cross-courses occupy fractures which were formed before the tin mineralization. Garnett (1961) has demonstrated that faulting occurred along the N-S fractures now occupied by the cross-courses to give a horst and graben structure. Subsequent movement along the E-W fissures permitted the egress of the first phase of tin mineralization. Depending on the attitudes of the mineralized fissures the mineralization crosses or is terminated by the cross-courses. Later displacements along the lode fissures and the cross-courses allowed the egress of further mineralized solutions, the disposition of the stress field precluding the entry of these solutions into the cross-courses. Finally tear faulting was initiated along the cross-courses, with the development of post-mineralization conjugate faults. The cross-courses were filled by quartz and low temperature minerals when the stress was relaxed.

At Mt. Bischoff mine a radial swarm of quartz-feldspar porphyry dykes is located in the hinge of the Bischoff anticlinorium. It is believed that these dykes were emplaced into radial tension faults related to the rise of a granitic cupola which is assumed to underlie the area. Mineralization is centred near the focus of the dyke swarm and formed lodes (i) in favourable host rocks, (ii) in pre-ore faults, (iii) disseminated in the dykes and (iv) in joints in the dykes. The occurrence of ore at this locality represents some of the typical controls found in other deposits. Favourable host rock may be dolomitic or incompetent thinly bedded shales tectonically disturbed between more massive beds. Similar to the latter is the location of lodes where more intense folding and faulting fractured competent beds in a sedimentary sequence of incompetent shales and thinly bedded quartzites.

Faulting and fracturing, either re-activated or newly formed as a result of the emplacement of the granite, are common to most deposits whether of the lode or replacement type. Commonly the fractures are steeply dipping but instances of flat ore-bodies associated with tangential joints are reported. These may occur in the country rock or in the granite itself.

Disseminated deposits are most commonly associated with greisenization which has spread from joints within the host rock.

(h) Size and Grade of Lodes

The dimensions of pipes and lodes vary considerably. In economic terms size is very often determined by the cut-off grade which may vary from mine to mine. Consequently references to size can be misleading if it is not clearly understood in what sense the term is being used. Some pipes have sharply defined contacts with the enclosing rock but deposits contained, often as disseminations, in greisenized rock have gradational margins.

Pipes, particularly those associated with fissure deposits, are subject to highly erratic pinching and swelling, but several are reported to maintain a consistent diameter when traced into lower levels of a mine. The maximum diameter of a pipe can be taken as 10 to 12 metres, there being a wide range of dimensions below this size. Many pipes are elliptical in plan and the figure quoted above represents the length of the longer axis.

Fissure lodes have been found to be mineralized over lengths up to 1000 metres but this is exceptional. Many fissure lodes have strike lengths in the range 75 to 150 metres. Such lodes rarely attain great thicknesses except where two fissure systems intersect. Maximum thickness of 1.0 to 1.5 metres are reported.

The grade of primary tin deposits is typically erratic. In order to give some impression of overall grades some examples from mines are given covering a number of years of production. It is estimated that over 2,000,000 tons of ore averaging 0.2 per cent Sn have been won from lode deposits in the Blue Tier district of Tasmania, the bulk of the production coming from the Anchor mine where the most important deposit consists of a series of flat-lying greisenized zones. A stockwork of veins has been prospected at Ardlethan in New South Wales with the result that 3,000,000 tons of proved and inferred ore at a grade of 0.4 per cent Sn have been delineated. In the same area the Carpathia mine was developed on a pipe which yielded 53,000 tons at a grade of 4.2 per cent Sn over a period of 30 years, and adjacent mines located on quartz-cassiterite veins produced 13,100 tons of tin concentrates, 5,150 tons wolframite concentrates, 182 tons of copper and 59,506 ounces of silver from 966,000 tons of ore. In the period 1958-1961, the grade of the ore was 0.7 per cent Sn and 0.3 per cent WO_3. Replacement deposits, such as those at Mount Bischoff and Renison Bell have grades between 0.75 and 1.0 per cent Sn.

(i) Tin in Pegmatites

Although the bulk of primary tin deposits is confined to pipes, fissure lodes and veins, tin is also won from pegmatites. Pegmatites have a reputation for being unreliable on account of the irregular distribution of tin within them. Detailed studies of pegmatites in North America and Brazil suggested that in many of the large, zoned pegmatites it is possible to develop techniques which enable the economic potential of a pegmatite to be assessed and also to guide mining.

Two theories on the origin of pegmatites find the most general acceptance. The first envisages their crystallization from an alumino-silicate residuum, rich in volatiles genetically related to granitic rocks. The second theory calls for the operation of metasomatic processes. Pegmatites which are believed to have been formed in this way are usually simple quartz-feldspar rocks with some mica, hornblende, garnet or other minerals which often reflect the nature of the host rock being replaced or from which the pegmatite has been segregated. These pegmatites are typically found in the deep roots of orogens and are bereft of economic mineralization.

Pegmatites which are found to be genetically related to granite are the main carriers of economic mineralization. Their mineralogy is often complex. However detailed studies show that a zonal arrangement of different mineral assemblages can often be observed. In an ideal case these zones are arranged concentrically in successive shells around a quartz core. It is usual, however, that many of the zones are not developed, are incomplete or vary in thickness. In some pegmatites these variations can be related to structural features of the wall of the pegmatite. Further complications are recognized in these pegmatites. Fractures in a zoned pegmatite can be the site of minor mineralization. It is from these fractures that replacement may take place, which may be selective along centain zones in the pegmatite.

The recognition of zones in pegmatites resulted primarily from attempts to predict the presence of beryllium- and lithium-bearing minerals. In the case of tin most workers find that this mineral was introduced during a replacement phase late in the crystallization history of a pegmatite, although some cassiterite, usually finely disseminated through the pegmatite, is considered to have crystallized with the other pegmatite minerals. Albitization, muscovitization and kaolinization are the more typical replacement processes with which tin is associated. It is this later generation of cassiterite which gives rise to economically important deposits.

Cassiterite often appears to be preferentially located in pegmatites along the roof, particularly where this wall bulges out or some other similar and suitable structure exists. This is, however, not a universal truth for Fick (1960) reports that, at Kamativi, Rhodesia, "normally greater concentrations of cassiterite occur above the quartz-mica footwall selvedge". These pegmatites are flat dipping.

Columbite, tantalite, magnetite, sulphides, gold, beryl, tourmaline, monazite and lithia-mica all occur in greater or lesser amounts in complex, stanniferous pegmatites.

In a pegmatite field many pegmatites are barren while others are mineralized. As with granites attempts have been made to compare and contrast the trace element content of minerals such as micas and feldspars in an effort to distinguish what controls this variation. These attempts have been inconclusive and are subject to considerable criticism. The choice of mineral is important for it has been shown that these complex pegmatites have acquired their character as a result of successive events. Some feldspars crystallized prior to the introduction of the cassiterite and these are richer in trace amounts of tin than those which crystallized contemporaneously with the cassiterite.

Hornung (1962) has determined the trace amounts of lithium, niobium and beryllium occurring in the wall-rocks of pegmatites carrying minerals of these elements. He finds that this method is of value as a guide to mineralization. A similar approach is worthy of consideration in the case of cassiterite-bearing pegmatites.

Complex pegmatites are located in or near granitic bodies. Late-tectonic granites appear to be the most common sources of mineralized pegmatites. Structure plays an important role in the emplacement of pegmatites, tensional openings being favoured locations, but no systematic distribution of mineralized pegmatites on a local scale can usually be detected. In regional terms mineralized pegmatites are sometimes confined to belts. In South West Africa stanniferous pegmatites lie in four belts parallel to the regional strike of the enclosing schists (Martin, 1965). This suggests that some deeper structure controls their localization.

Pegmatites appear to be poor exploration targets but it is suggested that a closely spaced stockwork of pegmatites might constitute a low grade/large tonnage prospecting target.

(j) Age and Environment of Tin Deposits

Major tin production comes or has come from Cornwall, Malayasia, Nigeria, eastern Australia, Bolivia, Thailand and Indonesia. Some examples will suffice to show the very varied ages and geological settings of the deposits.

Cornwall : stanniferous lodes and veins are found in folded Palaeozoic slates and sandstones, clustered around five granite plutons emplaced in post-Carboniferous, pre-Triassic time. Dykes of quartz porphyry were intruded into both the granites and country rocks prior to the period of mineralization. Ore shoots within the veins plunge parallel to the roof of the plutons. A later series of veins carrying unimportant amounts of lead and silver is also present. The mineralization is related to high level granite plutons emplaced into low grade metamorphites.

Bolivia : The Andean region was the site of intermittent magmatism during mainly Cretaceous and Tertiary times. It is with the acid volcanic rocks and quartz-porphyry stocks of this period that tin-silver mineralization is associated. Deposits are located in veins, stockworks and breccia pipes. In addition to cassiterite, exotic stanniferous sulphides are found. Although the more important deposits are associated with volcanism some tin mineralization is found in the granitic rocks which are believed to be genetically related to the volcanics.

Nigeria : The Younger Granites of Nigeria, emplaced during the Jurassic period, are the source of the rich alluvial deposits of tin found on the Jos Plateau. Greisenized biotite granite is the host rock of the mineralization. The Younger Granite cycle of magmatism was initiated by a volcanic phase during which rhyolitic lavas and pyroclastics were erupted from vents situated on ring fractures. The volcanism was succeeded by granitic intrusions the emplacement of which was controlled by ring fracturing and large scale cauldron subsidence. In addition to normal granites and rhyolites, varieties with riebeckite and aegirine also occur. Wolfram, galena, sphalerite, fluorite and topaz are found in the veins but tourmaline is absent. No economically important lodes are known, the tin being disseminated through greisenized granite.

Less important deposits contained in pegmatites, related to the Older Granites, also occur in Nigeria. The tin mineralization is associated with late-stage albitization. Tourmaline is a common constituent of the pegmatites, which are related to a 500 m.y. granitic event.

Australia : The more important tin deposits are genetically related to certain highly silicic, potassic granites which are the late phases of composite granitic intrusives emplaced during the late orogenic stages of the Tasman geosyncline (Zimmerman, 1965) in eastern Australia. Greisenized zones, pipes, lodes, replacement deposits and quartz veins have all been worked economically. Quartz-feldspar porphyry dykes preceed mineralization at some localities. The granitic intrusives range in age from Devonian to Permo-Triassic.

Deposits of Precambrian age are found in the Northern Territory. Here the tin is genetically related to Lower Proterozoic granites (2200-1800 m.y.) which were intruded during the closing stages of the history of the Pine Creek geosyncline. The principal deposits are quartz-tourmaline veins, greisens and stockworks in iron-rich breccias close to granite contacts. In Western Australia pegmatite dykes carry cassiterite. The age of these deposits is also Lower Proterozoic.

Malayasia : The great arc of tin-bearing granites which extends from Indonesia up the spine of the Malayan peninsula contains primary deposits of tin which include disseminations in granites, pegmatites, pipes and cassiterite-bearing veins in the country rocks. Pipes are also found in Permo-Carboniferous dolomitic limestones close to the granite. The majority of the tin is won from alluvial deposits derived from the erosion of the Jurassic tin-bearing granites.

Bolivian type deposits are rare as this type of near-surface mineralization is more readily subjected to erosion. However similar stanniferous mineralization has been preserved at Mount Pleasant, New Brunswick in Canada. The rhyolitic rocks forming the host to the mineralization are of Mississipian age (Late Palaeozoic).

From the foregoing it is clear that significant tin mineralization has occurred repetitively through geological time. Pereira and Dixon (1965) consider, however, that statistical analysis shows that tin deposits are more common in younger rocks.

(k) Types of Deposits

Various types of primary tin deposits are recognized. It is useful to make a distinction between endogranitic and exogranitic deposits, but, as similar types occur in both environments, it is repetitive to describe each separately. Mineralogical differences of importance, however, exist between the two environments.

(i) Pipe and Fissure Deposits

In many tin-fields pipe and fissure deposits have proved to be the main producers. They are usually located on, or near, steeply dipping fractures. All variations from true cylindrical pipes through bulging fissures to thin tabular fissures can be found. Some deposits resemble an irregular string of disconnected pods rather than a continuous pipe or tabular fissure-filling (Blanchard, 1947). Typical features of this type of deposit are their very irregular shapes, numerous breaks and unusually high grade. In endogranitic deposits the mineralogy is simple, cassiterite occurring in a gangue of quartz, quartz-chlorite or quartz-kaolin. Exogranitic pipes have a more complex mineralogy, minerals such as magnetite, bismuthinite, galena, and chalcopyrite being present. Alteration of the wall rock is common. Some pipes can be followed from the granite into the country rocks.

Pipes in the Bushveld granite are unique on account of their annular structure in cross-section. These will be described in more detail in a later section.

(ii) Vein Deposits

Quartz and quartz-tourmaline veins are also an important source of primary tin. Endogranitic veins are commonly enclosed in greisenized or tourmalinized granite. The veins can be traced laterally into the quartz cores of greisens. Some veins consist of a high concentration of veinlets building a complex stockwork. Exogranitic veins have a more complex mineralogy and carry minerals such as wolframite, fluorite, pyrite, chalcopyrite, sphalerite and silver.

(iii) Greisens

Deposits of this type are confined to granites and porphyry dykes. They result from the alteration of granite along fractures or in roof zones immediately beneath impermeable country rocks. The greisens consist of quartz and mica. The cassiterite is disseminated through the greisen together with such minerals as wolframite, fluorite, topaz, tourmaline, arsenopyrite and copper sulphides. Columbite occurs in Nigerian greisens. Fracture planes within the greisens often contain rich pockets of tin. Greisen lodes are usually steeply inclined and, where several are in close proximity, they constitute a large tonnage/low grade reserve. The apices of some cupolas may be completely greisenized with the result that these too constitute ore-bodies.

Some flat-lying greisens associated with altered granite are reported at the Anchor mine, Tasmania (known locally as floor deposits). They occur beneath the gently domed contact of the tin-bearing granite and the overlying barren porphyritic granodiorite. Pegmatite containing cassiterite is often developed along the contact. The "floors" are known to extend to over 30 metres below the pegmatite and the rich "floors" are separated by sheets of low grade granite. The "floors" are believed to be flat joints penetrated by mineralizing fluids. Wolframite, scheelite, chalcopyrite, galena and molybdenite occur as accessory minerals in the deposits (Jack, 1965).

(iv) Dyke Deposits

These deposits are of several kinds. Dykes of granite have been reported in which short ore-shoots of greisenized granite occur. Pegmatite borders some of these dykes. A dyke-like body of kaolin with pegmatite walls constitutes an ore-body at the Ransom mine. The dyke contains numerous irregular veins of quartz carrying cassiterite.

Quartz porphyry dykes contain stockworks and ladder veins carrying cassiterite. Some of the dykes may be altered or greisenized. Joint planes within the dyke are a favoured location for tin mineralization. Some dykes have a complex mineralogy, arsenopyrite, sphalerite, chalcopyrite, pyrrhotite, stannite, galena and tetrahedrite occurring with the cassiterite.

(v) Replacement Deposits

Replacement deposits develop where fractures and joints intersect beds favourable to replacement, such as carbonate rocks, but replacement of shale beds is also reported (Renison Bell). The presence of multiple plications and intense folding of thinly bedded shales between massive competent volcanics above and sandstones below can provide a suitable host for mineralization. These deposits display the complex mineralogy found in the outer zones of mineralization.

(vi) Disseminations

Magmatic disseminations of cassiterite are comparatively rare. Occurrences of cassiterite in this form have been reported from the Nigerian plateau. Similarly the Bushveld granites contain disseminated cassiterite, which however appears to be segregated to form a distinct zone.

(vii) Pyrometasomatic Deposits

Deposits of this type are located within the metamorphic aureole of a granite. True skarns are developed which may carry tin. Garnets and sphene may be stanniferous. There are similarities between this type of deposit and certain replacement deposits wherein skarn-like mineral assemblages are produced.

(viii) Epithermal and Xenothermal Deposits

Veins, stockworks and breccia pipes are associated with these deposits. Veins and stockworks are similar to those already described, but the lode patterns are highly complex. Breccia pipes display evidence of explosive pressure release. The mineralogy of deposits of this type is complex and the normally rare stanniferous sulphides are abundant.

(ix) Pegmatites and Aplites

The occurrence of pegmatites has already been discussed. Aplitic veins carry tin in some cases, usually in association with greisenization.

II. TIN MINERALIZATION IN SOUTHERN AFRICA

Primary tin mineralization in southern Africa is all of Precambrian age. The occurrence of tin deposition can be related to four main age groups. (Figure 5).

(i) Pre-2000 m.y. deposits

(ii) 2000 m.y. deposits associated with the Bushveld Complex

(iii) 1000 m.y. deposits

(iv) ±500 m.y. deposits

(a) Pre-2000 m.y. Deposits

Tin deposits occur sporadically in the granite-greenstone terrain building the Kaapvaal and Rhodesian cratons. Despite the wide areal distribution of these rock types, deposits of economic significance are not common. Possibly the largest tonnage has been won from eluvial and alluvial deposits resulting from the weathering and erosion of pegmatites in the homogeneous biotite granite around Mbabane in Swaziland.

(i) Swaziland

Production of tin was almost entirely derived from eluvial and alluvial gravels, but some tin was won from weathered decomposed pegmatites where these formed the bedrock of the gravel deposits. Little or no prospecting has been undertaken on the primary deposits, because of their low-grade and the small size of individual pegmatites.

Mineralized pegmatites are confined to a belt of country some five kilometres broad, extending in a southeasterly direction from Makwanakop beacon on the Transvaal border to Nyonyane Hill. Other mineralized pegmatites are located on the same southeasterly trend at the confluence of the Ngwempisi and Usutu rivers (Star tin mine) and near Sitabela (Pentouyz).

One area of pegmatite has been investigated near Mbabane where boreholes revealed that there is a complex stockwork of vertical and near horizontal pegmatites which carry cassiterite. This preliminary work suggested that the higher concentrations of cassiterite occurred in those portions of the pegmatite which were located in biotite-rich granite. It could not be established whether this patch of biotite-enrichment represented a nearly wholly digested gneiss remnant or whether it resulted from wall rock alteration accompanying the emplacement of the pegmatites. Individual pegmatites range in size from 15 cm to 1 metre in thickness and are separated from each other by up to 7 metres of granite. Cassiterite tends to concentrate on the hanging-wall side and its introduction is related to late albitization. Magnetite is a common accessory and lesser quantities of yttrotantalite, monazite, garnet and beryl are also present.

At Nyonyane Hill, Star tin mine and Pentouyz pegmatites occur in various tonalitic and biotite gneisses and migmatites : the pegmatites are believed, however, to be related to the younger, homogeneous granite in which the Mbabane pegmatites are located. At Pentouyz and Star tin mine pegmatites attain widths of 3 m. and can be traced along strike for several tens of metres. At Pentouyz there is a distinct antipathetic relationship between tourmaline, beryl and cassiterite. Along the northeastern edge of the field tourmaline is predominant, in the central area beryl and in the southwest cassiterite.

A unique occurrence of cassiterite is found at Forbes Reef. Hall (1913) reported cassiterite associated with an aplite intruding talcose schists about 0.5 km from the main granite mass. No trace of this aplite can be seen today but irregular pockets of large cassiterite crystals are found on the foliation planes of the schists. This cassiterite is of the ruby variety.

The most notable feature of the tin mineralization in Swaziland is its confinement to the northwest belt (the so-called Tin Belt). Northwesterly trends are an important element in the tectonic framework of Swaziland and the adjoining areas of the Republic of South Africa.

(ii) Northern Transvaal

Cassiterite has been reported from quartz-mica pegmatites at Palakop in the Klein Letaba district. Columbo-tantalate minerals are also found in the pegmatites about which little data is available.

(iii) Rhodesia

Cassiterite occurs in pegmatites, pegmatitic quartz veins and lepidolite greisens, mainly at the extremities of greenstone belts (Macgregor, 1947) as at Bikita, east of Salisbury, south of Shamva and west of Umtali. Tantalum ores and cassiterite may be intimately associated. At Bikita, the cassiterite occurs disseminated in the marginal parts of certain quartz-muscovite greisens and as pockets in quartz zones in large masses of lepidolite greisen. The Bikita pegmatites are now primarily worked as a source of lithium and beryllium.

Rhodesian pegmatites of this age have been studied primarily with respect to beryl mineralization. Such pegmatites show a general tendency to be zoned if they are lenticular in shape. Unzoned and weakly-zoned pegmatites are usually sheet-like in form. Amphibolite is the most common wall rock but biotitization up to three metres from the contact of the pegmatites is reported. However, pegmatites also occur in foliated biotite granite. No clear genetic relationship has been established between the pegmatites and any particular granite.

Geochronological studies on the Swaziland and Rhodesian pegmatites indicate an age of around 3000 m.y., although in the case of certain Swaziland mineralized pegmatites there is some evidence to suggest that a thermal event occurred at about 2000 m.y.

Of interest in the distribution of pegmatites in the greenstone belts is the fact that large pegmatites are more common in those greenstone belts which lie near the craton edge, or where a younger thermo-tectonic event has taken place.

(b) <u>2000 m.y. Deposits</u>

Tin deposits of this age are related, in the Republic, exclusively to the acid phase of the Bushveld Complex. In Rhodesia, the Wankie tin-field north of Tshontanda siding is the most important tin-bearing area in that country. Geochronological studies on pegmatite minerals indicate ages of between 1650 and 2000 m.y.

(i) <u>Bushveld Complex</u>

Ancient tin workings were discovered near Rooiberg in 1905. The start of mining is estimated to have been 300 to 5,000 years ago, but most recent research tends to disprove any ideas of great antiquity (McDermott and Oxley-Oxland, 1961). It has been calculated that about 2000 tons of metallic tin were produced from 30,000 tons of ore having a grade of about 7 per cent Sn. On a small hill about one kilometre from the present Rooiberg mine, an ancient smelting site was discovered. This site (known today as Smelter's Kop) was probably the most important of the ancient smelting sites. Since 1905 the tin mines exploiting deposits genetically related to the acid phase of the Bushveld Complex have been responsible for all but a small proportion of the tin production of the Republic. (Figure 6).

The deposits may be broadly classified as follows :

1. Syngenetic deposits as pipes and disseminations in granite
2. Epigenetic deposits as fissure veins, fault breccias and replacement bodies in
   - (a) granites
   - (b) granophyres
   - (c) felsites
   - (d) sedimentary rocks.

In view of the importance of these deposits their geological setting will be described in a later section.

(ii) <u>Rhodesia</u>

Tin mineralization is associated with the circum-cratonic gneiss belt which is located around the western and northwestern edge of the Rhodesian craton. This period of Rhodesian tin mineralization is included in this section, but it is recognized that the true age is subject to debate. The deposits are located in pegmatites emplaced in pelitic schists and gneisses. The most important tin-field is that at Kamativi in the Wankie district. A belt of tin-bearing pegmatites occurs in garnet-mica schists some 40 km long and 1.5 to 3 km wide. The pegmatites strike westwards but at the western end the strike swings round southwestwards, at which point tin mineralization dies out and wolfram mineralization takes its place. The tin-bearing pegmatites occur both as steeply dipping bodies and as extensive, flat-lying sheet-like bodies. Tourmaline-rich pegmatites devoid of tin are also present in the area but these are older than the stanniferous pegmatites. In the flat-lying pegmatites tin shows a preferential concentration near the floor (Fick, 1960). There is an antipathetic relation between tin and lithium in the younger generation of pegmatites.

(c) <u>1000 m.y. Deposits</u>

(i) <u>Orange River Belt</u>

Mineralized pegmatites having isotopic ages between 900 and 1050 m.y. are located in a belt 16 km wide along the contact of the Namaqualand Granite-Gneiss and the Kheis metarocks intruded by the Grey Gneiss. The pegmatite area has been described by Gevers, Partridge and Joubert (1937). Further information has been provided by Poldervaart and von Backström (1949), von Backström (1961) and de Villiers and Söhnge (1959). Gevers et al (1937) recognized an association between the pegmatites and the Namaqualand Granite Gneiss. The same authors found that internal pegmatites are small and barren, and that marginal pegmatites are frequently big, zoned and mineralized forming with the roof or exterior pegmatites the pegmatite belt. Roering (1963) reports a private communication from P.G. Hugo who found a dome of Grey Gneiss surrounded by a radial array of pegmatite dykes in the Kenhardt district. It is possible that the Grey Gneiss dome forms the roof over a cupola of Namaqualand Granite Gneiss.

Interior pegmatites, in the Springbok area, have a general northerly trend (i.e. more or less parallel to the regional strike of the gneisses). The exterior pegmatites have a northwesterly strike, oblique to the regional strike. Refoliation in a northwest direction has affected the roof zone in the southern Richtersveld.

Cassiterite mineralization is rare in this zone of pegmatites occurring only at the outer margins of the Orange River belt, as at Ankam in the Bethanie district at the northwestern end of the belt and near Upington at the eastern termination. Other occurrences of tin are reported from Rhenosterkop, Kalksluit, McTaggart's Camp in Gordonia and Tweedam near Springbok, Namaqualand. Cassiterite together with wolframite, scheelite, haematite, magnetite, arsenopyrite, galena, pyrite and molybdenite are found in quartz-tourmaline veins striking eastwards with a prominent shear zone which has been traced for 500 metres along strike near Upington. Traces of tin are reported from a pegmatite at Jackalswater.

(ii) Natal

In Natal cassiterite was reported from pegmatites at Umfuli, 15 km north of Eshowe. These pegmatites have not been investigated in detail but they are reported to have a simple mineralogy. Recent age determinations suggest that the 1000 m.y. thermal event affected Natal as well as Namaqualand.

(iii) Richtersveld Igneous Complex

The Richtersveld Igneous Complex consists of plutons occupying a northerly aligned belt in the eastern Richtersveld. North of the Orange River other plutons occur which Martin (1965) suggests may be related to the Richtersveld Complex, particularly in view of the persistence in that direction of the quartz bostonite and hornblende diorite dyke swarms which are assigned to the Complex.

The age of the Complex has been subject to debate. De Villiers and Söhnge (1959) regarded the Orange River pegmatites as being genetically related to the Complex but Middlemost (1965) considered, from chemical similarities between the intercalated tuffs and lavas in the Stinkfontein Formation on the one hand and the Richtersveld rocks on the other, that the Richtersveld igneous activity is in part contemporaneous with the deposition of the Stinkfontein Formation.

The intrusions of the Richtersveld Igneous Complex have the form of ring complexes and well-defined, steep-sided plutons, which consist of alaskitic granite, porphyritic microgranite, porphyritic syenite, granular syenite and local veins of rhyolite (de Villiers and Söhnge, 1959,and Middlemost, 1963). Granite porphyry and quartz porphyry are also present.

De Villiers and Söhnge (1959) report that just west of Rooiberg II beacon granite with a "rudimentary graphic texture" crops out. Fluorspar is abnormally abundant, constituting as much as 25 per cent of the rock. Accessory minerals include zircon, rutile and cassiterite. Assay indicated that 0.35 per cent metallic tin is present. Other samples of granite from the Complex were tested spectrographically but the maximum content was 0.06 per cent Sn.

There is a possibility that stanniferous lodes occur in association with the Richtersveld Complex for a specimen of high grade cassiterite ore is reported to have been picked up in the vicinity of Klein Helskoof.

(d) 500 m.y. Deposits

Tin deposits of this age occur :

1. in the Damara geosyncline and
2. in association with the plutons of Cape granite.

(i) Damaran Pegmatites

In the Damara pegmatite belt the two economic minerals with the widest distribution are beryl and cassiterite, but the two are hardly ever found in economic concentrations in one pegmatite. Beryl occurs in economic quantities in large, complex, zoned pegmatites. Tin on the other hand is confined essentially to unzoned pegmatites. Mineralization in the Damara pegmatites seems to show some dependence on their stratigraphic position or environment (Martin, 1965). Thus copper-bearing pegmatites are confined to the Nosib Formation; lithium- and beryllium-bearing pegmatites are large and cross-cutting; uraniferous minerals are located in pegmatites confined to a particular biotite-schist horizon of the Lower Hakos Stage; and tin is found (with the exception of the Arandis mine) in pegmatites emplaced in the Khomas schists.

Cassiterite-bearing pegmatites are concentrated into four distinct belts lying parallel to the regional strike but within these belts cassiterite is found in only a very small percentage of the host of pegmatites. Within the pegmatites cassiterite concentrations are dependent on structural features such as pinches and swells, saddles in undulating pegmatite sheets, and intersections of pegmatite dykes. Cassiterite normally occurs in preferred loci in greisenized areas characterized by muscovitization, albitization and kaolinization. Cassiterite-bearing pegmatite dykes are reported to be usually free or nearly free of black tourmaline and of garnet (Martin, 1965).

The Uis mine is exploiting the largest pegmatites in the Damara belt, the biggest individual pegmatite being 1,200 m. long and from 60 to 90 m. thick. The pegmatites are cross-cutting bodies which usually have sharp contacts with the country rocks. The only zoning which is noted is the presence of quartz cores with minor beryl and amblygonite. Wolframite is a rare associate except at Brandberg West mine, where it occurs in association with cassiterite in a stockwork of quartz-feldspar veins, of two ages, only the younger set being stanniferous.

The Arandis mine, southwest of Karibib, is unusual, firstly, because of the presence of the tin silicate mineral, arandisite, and, secondly, the nature of the tabular ore-bodies in marble country rock. The cassiterite pipes are located at the nose of a complex anticline which plunges at between 15° and 30° to the southwest. Towards the northeast, some 3 km from the mine, pegmatitic granite occupies the core of the anticlinal structure.

The pipes which range in diameter from 30 or 60 cm to 5 m. are located in or near the crests of minor drag folds in the marble. In some cases the pipes have lateral extensions along bedding planes, thereby linking adjacent pipes. Pipes have been traced for 75 m. down the plunge. The cassiterite occurs with vein quartz, arsenopyrite, pyrrhotite, chalcopyrite and pyrite (Gevers, 1929). Ramdohr (1935) reported that several of the ore-bodies were contained in quartz-feldspar-muscovite pegmatite. Söhnge (1963) has calculated that the projection of the granite mass observed on surface down the gentle plunge would place it about 750 m. below the Arandis mine. He suggests that the more intense deformation of the marble at this point provided a better channelway for solutions expelled from the granite body postulated at depth.

(ii) Cape Plutons

Cassiterite deposits are associated with the emplacement of the granite plutons in the southwestern area of the Cape Province. Occurrences are known at Kuils River, Helderberg, Koeberg, Vredehoek in the immediate vicinity of Cape Town and at Kanonkop. With the exception of the Kanonkop and Vredehoek deposits, the remainder lie along a significant northwest trending line (Krige, 1921). Scholtz (1946) found traces of mineralization at Ysterfontein 65 km northwest of Koeberg hill. The presence of veins of massive granular pyrite, pyritic quartz-tourmaline veins and pegmatitic quartz syenites with disseminated chalcopyrite and pyrite traversing hybrid dioritic rocks is taken by Scholtz as evidence for an underlying granite cupola.

The stanniferous lodes are restricted to zones 200 to 300 m. wide, which may be traced along strike for 3 km in a northerly or north-northwesterly direction. At Helderberg the lodes striking in this direction crop out on the western side of a group of barren quartz veins striking northeast. Most extensive development has taken place at Kuils River where the lodes, up to 1.5 m. wide, dip eastwards at between 15° and 50°. Krige (1921) concluded that the lodes are located within a zone of fissuring in the granite. He considers that some shearing sufficient to cause re-crystallization has affected the mineralized lodes. The cassiterite occurs in a gangue of white quartz and grey micaceous rock (the mica being a lithium-bearing variety). Tourmaline is also present, but fluorite is notably absent. Mineral zoning is recognized which suggests that the granite lies at progressively greater depths beneath the Malmesbury cover in a northwesterly direction.

III. THE BUSHVELD IGNEOUS COMPLEX

It is generally recognized that the Bushveld Complex is the largest mafic and ultramafic complex of its kind in the world. Attention has largely been focused on the economic minerals occurring in these phases, so that the significance of the acid phase of the Complex tends to be overlooked. The total value of minerals produced from the Complex in 1961 amounted to more than R20 million, to which total the value of tin contributed R2.37 million (Willemse, 1964).

The Bushveld Complex has a general basin-like form, its east-west axis being 460 km and the north-south 245 km long. Large portions are covered by younger formations, and much of the Complex beneath this younger cover is inferred. Before the economic geology of the Complex can be discussed, it is necessary to review the geology of the Bushveld Complex as a whole as well as the problems which it poses.

(a) Components of the Complex

Willemse (1964) has summarized the events leading up to and those actually constituting the emplacement of the Complex as follows :

1. Deposition of the Transvaal System including contemporaneous volcanicity which heralds the magmatic event.
2. Sill phase of diabase sheets injected into the Pretoria Series of the Transvaal System.
3. Epicrustal phase represented by the Rooiberg Series (felsites, granophyre, interbedded sedimentary rocks).
4. Main plutonic phase which produced granodioritic, dioritic, mafic and ultramafic rocks.
5. Late plutonic phase represented by the Bushveld granites.

(i) Transvaal System, Sill Phase and Epicrustal Phase

The Transvaal System consists of :

3. Pretoria Series - shales, quartzites and andesitic lavas. The Ongeluk lava half way up the Pretoria Series represents a period of widespread volcanism. More local volcanic activity is marked by the Machadodorp agglomerate higher in the Pretoria Series. The presence of scattered occurrences of andesitic lavas, tuffs and agglomerates at the top of the Pretoria Series is evidence of more widespread volcanicity.

2. Dolomite Series - dolomitic limestones and cherts.

1. Black Reef Series - thin band of quartzite and shale with conglomerates at base.

The sill phase is represented by diabase sheets up to 300 m. thick. The sheets are generally conformable but locally transgress the bedding.

Willemse (1964) includes in the epicrustal phase the Rooiberg felsites, leptites and granophyres. Leptite is the name given to certain quartz-feldspar rocks of medium grain size and uncertain parentage, which, however, in some localities, are reported to grade into granophyres. Gradations from leptite into quartzite are also seen. The term, granophyre, is applied to rocks in which the characteristic intergrowth between quartz and feldspar is developed, and recent work has led to the conclusion that granophyres of more than one origin are present. Strauss and Truter (1944) applied the term pseudogranophyre to certain metasomatically reconstituted sedimentary rocks. Granophyres are reported as a chill phase of the Bushveld granite and are also developed between the granite and the roof rocks. Bushveld granite is also known to be intrusive into these granophyric rocks. Certain granophyres and felsites, such as those occurring at Tauteshoogte and Bothasberg are regarded as the most acid differentiates of the basic phase of the Bushveld Complex (Boshoff, 1942, and van der Westhuizen, 1945).

The felsites are cryptocrystalline rocks with a reddish-brown hue. Lombaard (1932) suggested that typical extrusive felsites carry albite phenocrysts, and that the microperthite-bearing felsites represent the fine-grained or chilled facies of the granophyre. The felsites usually overlie either leptite and granophyre or Bushveld granite, but at a few localities the felsites rest on rocks which are ascribed to the Smelterskop Stage of the Pretoria Series. Argillaceous and tuffaceous sedimentary beds are interbedded with the felsites, particularly towards the top of the succession. Both van Gruenewaldt (1966) and Coetzee (1970) report thicknesses of between 3500 and 5000 m. for the felsites.

(ii) Main Plutonic Phase

The geology of the Main Plutonic Phase has been summarized by Willemse (1964) as follows :

Rock Types	Thickness	
Granodiorite Olivine diorite Gabbro (anorthosite) Magnetite bands at different horizons	2,300 m.	Upper Zone
	Main Magnetite Band	
Gabbro (anorthosite) Thin magnetite band near top Norite (subordinate)	6,250 m.	Main Zone
	Merensky Reef	
Norite (anorthosite) Pyroxenite (subordinate) Chromitite bands at different horizons	1,280 m.	Critical Zone
	Main Chromitite Band	
Pyroxenite Norite (subordinate) Peridotite Chromitite bands mostly near top of zone	1,800 m.	Basal Zone
Norite	erratic	Chill Zone

Mention must be made of the pegmatitic phase related to the Main Plutonic Phase. Two categories are recognized, namely (i) granite pegmatites and (ii) ultramafic pegmatoid.

The granite pegmatites consist of quartz and alkali feldspar sometimes with minor hornblende, muscovite or tourmaline. They are found in the contact metamorphic zone and in all the rock types of the Main Plutonic Phase. Willemse (1964) regards these pegmatites as originating by *in situ* exudation from cordierite-sillimanite gneiss or local melting of semi-pelitic fragments, the palingenetic magma so formed persisting after the consolidation of the main igneous mass.

Included with the ultramafic pegmatoid are pipe-like and irregularly shaped bodies consisting of (i) hortonolite dunite and/or dunite, (ii) (olivine) diallagite pegmatoid, (iii) magnetic iron ore, (iv) bronzite pegmatoid and (v) vermiculite pegmatoid. Usually these bodies have discordant relationships to the normal igneous layering. In the Eastern Transvaal they are especially abundant just above the Main Chromitite Band, but others are present in the Basal Zone. North of Pretoria there are considerable numbers in the lower portion of the Main Zone.

The three best known hortonolite dunite pipes are those which are platinum-bearing in the Steelpoort area. The Driekop pipe consists of a cylindrical ore-body 20 to 30 metres in diameter contained in a dunite pipe 450 m. in diameter dipping steeply across the general layered structure of the Bushveld Complex. At Mooihoek a core of platiniferous hortonolite dunite up to 20 m. in diameter is surrounded by a cylinder of olivine dunite and wehrlite 30 to 100 m. in outside diameter, which is enclosed in an outer shell of pegmatitic pyroxenite with a maximum overall diameter of 300 m.

The Onverwacht pipe is distinguished by the presence of a zone of chromitite xenoliths which can be traced across the pipe, at a depth of 80 m., from the enclosing layered mafic sequence.

The olivine diallagite pegmatoid displays a wide range in shape and mineral composition. The bodies are essentially pipe-like but their outlines are often very irregular. Iron oxide minerals are common in the diallagite pegmatoid : certain pipes consist almost exclusively of magnetite. Vanadium content varies widely from pipe to pipe.

The bronzitite pegmatoid pipes are located mainly to the west of Pilanesberg. More than 60 such occurrences are known. They are of interest because of their content of nickeliferous sulphides but only at Vlakfontein has their pipe-like shape been established and it has been suggested that some may have different shapes and attitudes (Coertze, 1960, 1962). Söhnge (1963) considers that an average diameter of 5 m. would be reasonable for the pipes at Vlakfontein. Coertze (1962) has suggested the Rustenburg fault initiated a broad zone of weakness along which pipes of dunite, magnetite, diallagite pegmatoid and bronzitite pegmatoid were intruded.

Willemse (1964) reports a limited number of occurrences of vermiculite in the vicinity of Roosenkal which have similarities with the preceeding types by virtue of their irregularity in form and pipe-like shape transgressive to the general layering.

The presence of these pipe-like bodies is mentioned to emphasize the fact that it is not only the acid rocks which have such features. The genesis of these deposits has given rise to some debate. Many writers support the view that the dunitic pipes represent local residual pockets of magma or that they represent direct injections from depth. A metasomatic origin has also been postulated.

(iii) Late Plutonic Phase

Although the Late Plutonic Phase underlies the largest area of any of the components of the Complex, it has received the least attention. The Bushveld granite has been generally regarded as a sheet-like layer overlying the Main Plutonic Phase. Such areas of granite which have been studied are mainly those within the vicinity of tin mining centres, where several phases of emplacement have been recognized, but there has not been general agreement as to the time sequence of the different phases. Nowhere is the contact between the main body of granite and the Main Plutonic Phase clearly exposed. Daly (1928) suggested that the main mass of granite could pre-date the Main Plutonic Phase and that only the granites exposed at Magnet Heights, Steelpoort Park etc., are younger. Strauss (1954) has, however, stated that the Magnet Heights granite can be correlated with the first phase of emplacement recognized in the Zaaiplaats area. This granite is concluded to be younger than the Main Plutonic Phase on the grounds that a second phase of granitic activity cuts both this granite and the underlying noritic rocks.

Strauss and Truter (1944) recognized three phases of emplacement at Zaaiplaats, namely

3. Bobbejaankop granite with a hood of Lease microgranite
2. Foothills granite
1. Main granite

The Main granite is considered to be a crudely stratiform sheet, 2750 m. thick, intruded more or less concordantly between overlying Rooiberg felsites and underlying highly metamorphosed sedimentary rocks. Lithologically distinct varieties grade into one another almost imperceptibly, resulting in a pseudostratification which conforms to the floor and roof of the sheet. In general the granites are chemically and mineralogically uniform. They are composed of quartz, perthitic feldspar (often red in colour), hornblende and biotite, the last two named usually being altered to chlorite and generally being subordinate. Texturally, however, the granites display a wide range from those in which the grain size is nearly as fine as that of the felsites to those which are coarse-grained and porphyritic. Granophyric textures are also found.

Wagner (1921) recognized at Stavoren :

1. Red granite
2. Red granophyric granite
3. Granophyre
4. A narrow zone of medium-grained granite occurring between the granophyre and the overlying Rooiberg sedimentary rocks.

Dykes of quartz porphyry cut the granites and variously shaped bodies of pegmatite generally lying horizontally are found in the granite, granophyric granite and granophyre. Although Wagner finds most of the granite to be red in colour, he does report areas of grey granite. The granitic and granophyric rocks are considered to form a stratiform sheet dipping to the south. Wagner (1927) subsequently recognized a dome-shaped pluton of miarolitic granite at Mutue Fides which intrudes the composite sheet.

In both the Zaaiplaats and Stavoren areas tin mineralization is associated with the youngest granites.

At Rooiberg, Boardman (1946) mapped a small area of granite, which contains fragments of the pink, finer grained granite which borders the Rooiberg "triangle" in the north.

(b) Some Problems of the Epicrustal and Late Plutonic Phases

(i) Relation of Bushveld Granite to Norite

At no place has the contact between the main mass of the Bushveld granites and the underlying Main Plutonic Phase been observed although dykes and stocks of granite can be seen cutting the mafic rocks (e.g. Magnet Heights). Daly (1928) considered that a distinct difference existed between the granites intrusive into the mafic rocks and the main body of the Bushveld granites. Daly believed the latter to be *older* than the Main Plutonic Phase. He regarded the granites, granophyres and felsites as forming a compound salic layer, the roof of the granite being "its own chilled surface material". Daly considered it unlikely that the Rooiberg felsites, confined to the central area of the Bushveld Complex, could have formed a stable roof over such an extensive sheet of magma. He points to the absence of granophyre and felsite where granite bodies occur as separate intrusions outside the confines of the Complex. The possibility is not excluded that eruptions of felsite and intrusions of granite of distinctly later vintage, contemporaneous with the Magnet Heights granite, may occur within the salic layer. Conversely some of the felsite flows may be older. Daly envisaged the development of "cracks developed in the central part of a dimple basin". Such cracks tapped a magma chamber in which differentiation by gravity and assimilation had been operating. "The output of magma at the surface was comparatively small at first". Finally as further down-buckling of the basin continued, "the central vents to the surface were well opened and the main body of the salic magma (felsite-granophyre-red granite magma) was poured out, to be followed immediately by the heavier differentiate, the noritic magma". Daly regarded the salic magma as a huge lava flow "having one or more magma filled vents". The diabase sills in the Transvaal System are considered to represent direct emanations from the basaltic substratum.

Hall (1932) expressed the view that Daly's hypothesis had some merit but he preferred to keep an open mind although the tone of his discussion suggests that he inclined towards the more commonly accepted age relationships.

Strauss (1954) is unequivocal in regarding all the Bushveld granites as younger than the Main Plutonic Phase on the grounds that the Magnet Heights granite corresponds to the oldest of the three Bushveld granites recognized at Zaaiplaats.

(ii) Relation of the Bushveld Granites to the Felsites and Granophyres

It is well established that the Bushveld granites are intrusive into the Rooiberg felsites. Relationships between the granites and the granophyres, and between the granophyres and the felsites are less firmly based. Apparently contradictory evidence has been reported and much of the difficulty in interpreting age relations between these rock groups stems from the fact that the granophyres have been formed within the Bushveld Complex by a variety of processes. Van Gruenewaldt

(1966) found that north of Middelburg granophyric rocks are developed along the contact of the Rooiberg felsites with the mafic rocks of the Main Plutonic Phase. Kuschke (1950) reported a close association between granophyric rocks and metamorphosed sedimentary rafts northwest of Brits, as did Strauss and Truter (1944) who found that metasomatically altered sedimentary rocks developed granophyric intergrowths. These latter authors proposed the term pseudogranophyre to describe these rocks. Both Hall (1932) and Lombaard (1932) regarded granophyre as the lower portion of a felsite flow. Where granophyre intrudes felsites it is considered by Hall to represent either an intrusion of granophyre into its own roof or the intrusion of granophyre related to a later flow. Lombaard (1932) recognized the possibility that granophyre may be also the marginal facies of the granite. These conclusions were propounded to explain (i) the intrusive nature of granophyre into felsite, (ii) the gradation from granophyre to felsite and (iii) the gradation from granite through granophyric granite into granophyre. Van Gruenewaldt (1966), reviewing some of the opinions expressed regarding the derivation of the granophyres, concluded that granophyric rocks may be (i) palingenetic products of Rooiberg felsite, (ii) a chill-phase of the Bushveld granites, or (iii) metasomatically altered sedimentary rocks.

Granophyres are reported in some cases to be closely associated with the so-called leptites, a name applied in the Bushveld Complex to metamorphosed and metasomatized, originally sedimentary or volcanic rocks. There is some evidence to suggest that the leptites represent a first step in the generation of granophyre, before mobility and homogeneization was achieved. The leptites occur as rafts, often associated with recognizable sedimentary relicts in granophyre, and also overlying the Main Plutonic Phase as more continuous bodies underlying the Rooiberg felsite succession. This relationship suggests that the source of heat and metasomatizing fluids lay in the Main Plutonic Phase, but northwest of Potgietersrus the leptites lie between the Main Plutonic Phase and the Bushveld granite. Thus, here, the source of the metasomatizing agents could lie in either the acid or the mafic rocks.

Boshoff (1942) and van der Westhuizen (1945) concluded that fine-grained, acid rocks overlying the dioritic layers of the Upper Zone of the Main Plutonic Phase represent the final differentiation product of the basic magma. Boshoff considered that Bushveld granophyre at Tauteshoogte was emplaced after differentiation in depth had resulted in the attainment of the composition of the postulated residual magma. Boshoff further concluded that the granitic veinlets traversing the dioritic layer at Tauteshoogte crystallized from a residual magma developed by differentiation *in situ* and intruded along joint planes in the partially or wholly solidified dioritic rocks.

Van der Westhuizen (1945) regarded the base of the Rooiberg felsites along the Bothasberg to be an amygdaloidal black felsite, the acid rocks below this horizon being the most acid differentiates of the Upper Zone. Both this author and Boshoff report the presence of clinopyroxenes in these acid rocks, while Boshoff found olivine (fayalite) in a specimen of felsite on Tauteshoogte.

Van Gruenewaldt (1966) considered that, on the farm Droogehoek 882-K.S., Lydenburg District, there is clear evidence to show that micrograniti c veinlets are derived from leptite. These microgranitic rocks, reported by Lombaard (1932), Boshoff (1966) and Groeneveld (1968) are found frequently in the acid rocks overlying the Main Plutonic Phase.

Studies on zircons in granite, granophyre and leptite have been made by, among others, Kuschke (1950), Steyn (1962) and Wolhuter (1954). The former finds that the zircons from the granophyre northwest of Brits are turbid and, for the greater part, show no euhedral forms, although there are signs of secondary overgrowths. On the other hand the zircons in the granites are fresh, clear and euhedral, while those in the leptites are rounded. Elongation frequency curves for the zircons obtained from the granites plot in the igneous field.

Steyn (1962) found that the characteristics of the zircons from the granite, granophyric granite and granophyre at Stavoren differed from those obtained from the overlying quartzites. The majority of the zircon grains from the granitic rocks are coated with iron oxides which can be leached with hydrochloric acid, revealing an inherent grey colouration. The zircons from the quartzites are clear. Elongation frequency curves for the three varieties of acid rock are similar suggesting that they are co-genetic, but the curves have maxima at elongation ratios of less than 2. According to Poldervaart (1955a and b) this is not normal for rocks of magmatic origin. Steyn concluded that the high content of malacon in the zircon concentrates confirms a magmatic origin for these rocks, malacon being more unstable than zircon and hence rare in sedimentary rocks.

Wolhuter (1954) examined zircons from the Rooiberg felsites from the vicinity of Loskop Dam. He found that the majority of the zircons had breath:length ratios of between 1:1 and 1:2, and that zircon grains from the overlying Loskop sandstones plotted in the same field. Wolhuter concluded that this method did not provide an infallible guide to enable a distinction to be drawn between rocks of igneous and sedimentary parentage.

(iii) Nature and Distribution of the Felsites

The considerable thickness of felsite reported by Mellor (1907), Daly (1928), van Gruenewaldt (1966) and Coetzee (1970) ranging from 2440 to 5000 m. and the distribution of the felsites within the confines of the area of the Bushveld Complex call for comment.

Recent vulcanological studies have produced evidence to show that acid effusives of the volume reported from the Bushveld Complex are not lava flows. Such rocks are regarded as either ignimbrites or tuff-lavas. Menge (1963) has advanced evidence to support an ignimbrite origin for the agglomerate interlayered with the felsites north of Nylstroom, a view which has been challenged by Coetzee (1970). This author can find no evidence to support the view that the felsites of the Swaershoek Mountains had either an ignimbrite or a tuff-lava origin. The interfingering of two felsite types is considered to represent extrusion from different sources at nearly the same time. Coetzee finds evidence for a cyclic pattern beginning with massive lava succeeded by "the appearance of parallel flow-banding, followed by volcanic flow top horizons, agglomerate and finally subaquaeously deposited sediments". Coetzee concludes that the felsites were extruded as thick flows. He finds, however, quartzite xenoliths in the felsites, having similarities to the Doornpoort metamorphic type. No other xenoliths are found. The tentative suggestion is made that the quartzites represent resistant and unassimilated remnants of the Pretoria Series, and the felsites are "fused and remobilized 'Pretoria' Series sedimentary rocks". The reported presence of perlitic textures suggests that some, at least, of the felsites crystallized from flows.

Willemse (1964) has drawn attention to the fact that the felsite is "confined to the basin-structure of the Complex". The stratigraphic status of the Rooiberg felsites is not clearly defined. Originally regarded as forming part of the Waterberg System, the felsites together with certain underlying sedimentary rocks were separated from this system to form the Rooiberg Series, following the discovery that the Bushveld granites did not intrude the upper, arenaceous portion of the Waterberg System. More recently the sedimentary members of the Rooiberg Series have been reclassified as the Smelterskop Stage of the Pretoria Series, leaving the felsites in limbo. If the felsites are not the final term of the Pretoria Series, then it must be assumed that they represent an effusive phase laid down on the older strata but pre-dating the Main Plutonic Phase of the Bushveld Complex. The petrogenetic implications of this view are far-reaching. A period of acid volcanism of such dimensions preceeding the plutonic Bushveld Complex leads back to Daly's hypothesis that the acid phase is older than the ultramafic and mafic phase. Evidence has been presented by Strauss (1954) that the Bushveld granites are younger than the basic rocks. It is difficult to envisage the basic phase of the Bushveld Complex being sandwiched between acid effusive and acid plutonic phases. The evidence presented by van Gruenewaldt supports the view that the felsites are older than the Bushveld Complex but there is little evidence to substantiate the view that the felsites are genetically related to the Bushveld Complex.

It has been suggested by Hall (1932) and Daly (1928) that the andesitic volcanism of the Pretoria Series and the diabase sheets which intrude this system herald the plutonic event which culminated in the emplacement of the Bushveld Complex. It can be argued that the felsites could represent the acid differentiate of this period of volcanism but the disproportionate ratios of felsite to andesite implies that differentiation was not a simple process, if it operated at all.

If one concludes that the andesitic and felsitic volcanism is unrelated to the Bushveld Complex the areal content of the felsites in particular is remarkable in that they are confined to the area of the Complex, which appears to have exercised a controlling influence over their distribution, whereas andesitic volcanism is associated with the Transvaal rocks well beyond the confines of the Bushveld Complex.

(iv) Origin of the Bushveld Granites

The volume of the Bushveld granites as compared to that of the mafic and ultramafic portions militates against any origin for the Bushveld granites based solely on simple differentiation. It has been suggested that the sedimentary rocks of the Pretoria Series particularly, but others as well, were involved in the genesis of the acidic magma through assimilation, anataxis and granitization.

The remarkable layered structure reported notably by Strauss and Truter (1944), Strauss (1954), Wagner (1921) and Kynaston (1908) requires explanation and this fact must be taken into account in considering the origin of the granites. Daly (1929) regards this layered arrangement as being due to the fact that the Bushveld granites represent the deeper, and more slowly cooled portion of an enormous lava field. He derives the magma by a process of differentiation by gravity in, and assimilation of wall-rocks by, a mafic magma. Suggestions (albeit not widely accepted) have been made, notably by van Biljon (1949), that the noritic portion of the Bushveld Complex has resulted from transformation *in situ* of the Pretoria Series. If this is a possibility it could equally, and probably with more general acceptance, be suggested that certain of the Bushveld granites represent the granitization of felsitic and sedimentary rocks. The layered structure would then represent a ghost stratigraphy.

Söhnge (1963) has suggested that the layered structure discernible in the granophyre, granophyric and later granites may indeed have been inherited from original bedded formations. He proposed that cross-cutting contacts may represent "more or less sharply defined fronts of recrystallization and possibly of melting". Söhnge further envisaged the possibility that the tabular, low-grade disseminated ore-bodies of the Zaaiplaats type may represent granitized equivalents of the Rooiberg replacement type, while the pipes may have been originally mineralized fractures and fissures which, on granitization, were reconstituted to form the more or less integrated pipe systems. Söhnge did not offer any views on the source of the original tin mineralization which must have taken place ahead of the front of granitization.

On the other hand Liebenberg (1961) has concluded from trace element studies that the Bushveld granites plot on curves which support the view that an original magma differentiated to give the various fractions seen today. However the number of his analyses in respect of the acid phase is limited, and he admits that certain inconsistencies were apparent, particularly in respect of Zr, Mn, La, Sr and Ba.

Fourie (1969) undertook a widespread chemical study of the content of major oxides and trace elements in the acid rocks of the Bushveld Complex, from which he concluded that the granites could be distinguished from the granophyres, felsites and leptites. Fourie's sampling reveals a marked bias towards acid rocks collected from the Zaaiplaats and Bronkhorstspruit areas. The non-systematic sampling by Jedwab (1956) has been criticized, and the same reservation must be expressed about Fourie's results. Another factor which requires to be taken into account concerns the relation, if any, between the reported layering in the acid rocks and variations in chemistry. This aspect has not been considered. In spite of these criticisms Fourie's results are important in that they indicate that such studies may well prove to be fruitful and provide important clues to the evolution of the acid phase of the Bushveld Complex.

Attention has already been drawn to the results of zircon studies in discussing the relationship between the granites and granophyres. Not only are there instances where the characteristics of zircons from the granites and granophyres are reported to be either similar or different but certain zircon populations from the granitic rocks have maxima for elongation frequency ratios falling within the non-igneous field. The importance of this last observation depends entirely on the validity of Poldervaart's (1955a and b) conclusions in this connection.

Davies et al (1970) have carried out Sr-isotopic studies of various layered basic complexes. These authors find that the primary Sr^{87}/Sr^{86} ratio of the acid rocks of the Bushveld Complex is unusually high. If the acid and mafic rocks of the Complex were derived from the same magma their respective R_o values should be equal. In the case of the Bushveld Complex these values overlap to a lesser extent than in other southern African complexes, and at the 68 per cent confidence level the values are distinctly different. Davies et al (1970) consider three alternative explanations for the presumed R_o differences in the Bushveld Complex. They consider that differentiation would be acceptable under conditions where the acid differentiate was isolated for some time prior to its intrusion. In the Bushveld Complex this period of isolation would have to be 50 m.y., a not unlikely interval. However, the authors find it difficult to reconcile the large volume of acid rocks with the differentiation hypothesis.

The second alternative suggested by Davies et al envisages that the acid rocks "may have been derived by the assimilation of crustal material by the mafic magma, followed by geochemical differentiation". A mafic magma having an R_o value of 0.7065 (i.e. the value determined for the Bushveld Complex mafic rocks) would have to assimilate 30 per cent crustal material with $R_o = 0.740$ in order to raise the R_o value to that reported in the acid rocks. The authors consider this unlikely because such a ratio is much higher than expected for average crustal rocks at that point in time. The possibility is not excluded that this process could have operated on a smaller scale.

Finally the authors consider that the acid rocks could have been formed by the remelting of crustal rock in isolation from the mafic magma. This would require the R_0 value of the remelted material to be 0.715, a condition which is regarded to be feasible.

Strauss and Truter (1944) and Wagner (1927) have demonstrated the existence of granites intrusive into the layered Bushveld granites. Hence it is apparent that two granite groups are present, at least in the Zaaiplaats area, namely (i) layered conformable or semi-conformable granite bodies, and (ii) intrusive granites. The postulate that the acid members of the Bushveld Complex form a sheet-like body extending over the greater part of the Bushveld Complex must be reviewed in the light of new data. When originally propounded, it was believed that the felsites, granophyres and granites formed a composite unit, but more recent work suggests that a more complex relationship exists between these rocks particularly in respect of the granophyres which appear to have originated by a number of different processes and of the granites which are now not regarded as being part of such a composite. Clearly no attempt to locate new or extensions of existing, mineral deposits in the acid phases can be successful until the geometry and origin of the granitic rocks in particular have been studied.

(iv) The Nature of the Pipe Systems

Within the Lease and Bobbejaankop granites pipe systems are worked for cassiterite. Pipe-like bodies carrying fluorspar are also known within the Bushveld granites (e.g. the Gilspar mine on Ruigtepoort 1373 and the Big Ben mine on Slipfontein 528). These pipes occur in what is described as uniform red granite.

The presence of pipes within the Main Plutonic Phase has been mentioned. On a much grander scale are the pipes of volcanic origin such as Spitskop. Although these later pipes are probably much younger than the Bushveld Complex they together with other pipe-like bodies such as kimberlites constitute prime prospecting targets for a wide range of metals. It is relevant to inquire therefore whether any connection exists between the many pipes in spite of their differing sizes, shapes, geological settings and mineralization. Certainly some pipe-like bodies appear to be aligned along recognizable, structurally controlled directions. If it is valid to make this deduction in respect of some pipes is it equally valid to apply the same principle to the distribution of other pipes?

(v) Chemistry of the Bushveld Granites

Except for the work of Fourie (1969) and Liebenberg (1960), detailed chemical studies on the Bushveld granites have not been undertaken, particularly in regard to trace elements. Analytical data from the Zaaiplaats area given by Fourie (1969), Strauss (1954) and Lombaard (1932) illustrate the difficulty of determining the applicability of conclusions drawn from other tin-bearing granites.

A fair comparison between the results of Fourie on the one hand and Strauss and Lombaard on the other is not possible as the later authors had available only one analysis of each granite type with the exception however of the Main Granite. Most notable is the generally lower values of MgO and the higher values for SiO_2 obtained by Fourie and Lombaard but all analyses indicate an increase of CaO in the mineralized granites. This is reflected in the values for the ratio $K_2O + Na_2O:CaO + MgO$ based on the above averages :

	Main Granite	Bobbejaankop Granite	Lease Granite
Strauss	4.5	3.7	2.6
Fourie	9.9	6.4	6.0

This is in contrast to the results quoted by Rattigan (1960) in Australia where the value for the ratio $K_2O + Na_2O:CaO + MgO$ increases to about 15 in stanniferous granites.

In Table I the analyses from the above mentioned three sources are compared :

	Main Granite		Bobbejaankop Granite		Lease Granite		Lombaard
	A	B	A	B	A	B	
SiO_2	76.000	73.48	76.400	72.56	76.060	72.67	76.69
TiO_2	0.190	0.22	0.085	tr	0.050	tr	0.17
Al_2O_3	11.900	12.48	12.000	13.36	12.820	13.16	10.75
Fe_2O_3	2.040	1.67	1.530	0.95	1.270	0.80	1.31
FeO	1.120	1.63	1.150	1.87	0.800	1.44	1.54
MgO	0.190	0.59	0.180	0.61	0.190	0.79	0.20
CaO	0.600	1.22	1.070	1.63	1.090	2.13	1.25
Na_2O	2.830	3.12	3.000	3.22	2.810	3.09	3.55
K_2O	4.980	5.03	4.960	5.05	4.810	4.37	5.12
P_2O_5	0.023	0.01	0.012	tr	0.011	tr	0.12
Totals	99.873	99.45	100.387	99.25	99.911	98.45	100.70

N.B. The analyses quoted from Strauss (1954) and Lombaard (1932) are more complete than indicated above where only the ten major oxides are compared with Fourie's analyses.

Main Granite

A. Average of 7 analyses. Fourie, 1969.

B. Average of 3 analyses. Strauss, 1954.

Bobbejaankop Granite

A. Average of 5 analyses. Fourie, 1969.

B. Bobbejaankop granite. Strauss, 1954.

Lease Granite

A. Average of 12 analyses. Fourie, 1969.

B. Lease granite. Strauss, 1954.

Lombaard

Analyses of granite Zaaiplaats tin mine. Type not specified.

All the analyses indicate that the red colour of the Bobbejaankop and Lease granites is not caused by an increase in iron content. In fact these granites have generally lower contents of iron. Although Strauss (1954) regards the mineralized granites as being the youngest and most acid, study of the analytical data suggests that the Bobbejaankop granite is not more acid than the Main granite. The value of the modified Larson Index and the Niggli values si and qz are lower in the Bobbejaankop granite suggesting that this granite did not arise from a residuum of the Main granite. However the analytical data for the Lease granite suggests that this granite may have originated from the Bobbejaankop magma as a more acid residuum.

(vi) Morphology of the Bushveld Complex

The disposition of the granitic rocks cannot be considered in isolation from the general morphology of the Complex as a whole. There is, by no means, general agreement on this subject. The existence of a rim of Transvaal System rocks forming a floor with centripetal dips overlain by the pseudostratified mafic members of the Complex having a similar attitude and capped by the Rooiberg felsites was taken as evidence that the Complex had the form of a lopolith. This concept implies that magma was intruded between floor and roof from a central feeder tapping an underlying magma chamber in which differentiation proceeded.

Willemse (1959) has drawn attention to the fact that the relationship between the mafic rocks of the Bushveld Complex and the floor rocks is more involved, particularly in regard to the transgression of the Complex across the members of the Pretoria Series. Willemse considered that the mechanism of emplacement of the Main Plutonic Phase as being similar to that of cone-sheets and postulated a number of centres of intrusion. The folded blocks of Transvaal System rocks known as the Crocodile River and Marble Hall fragments are regarded as the cores of cone-sheet structures. The truncation of various layers by the sedimentary rocks is veiwed as a response to the original disposition of the igneous layering in the funnel-shaped intrusions and the attitude of the cone-sheets. Peripheral faulting, intrusive transgression, thinning of members of the Main Plutonic Phase and slumping during accumulation of the Complex have all been proposed to explain this truncation. Van Biljon (1949) sought to explain the fact that certain bands of mafic rock when followed along strike disappear and their place taken by members of the Pretoria Series as evidence for the metasomatic origin of the mafic rocks.

Truter (1955) suggested that the Complex was intruded from five centres, four of which lay along the main axis of the Complex and the fifth located near Potgietersrus. Cousins (1959) considered that the gravity data over the Complex was inconsistent with a lopolithic form. He visualized the Complex as having been intruded from elongate fissures filling two major troughs, one in the east and one in the west. A third feeder was envisaged at the far western end of the Complex, linked to the western trough by a sheet-like body.

Ferguson and Botha (1964) have drawn attention to the fact that, if several feeders do in fact exist, they "must have a common source at depth" and the individual intrusions "subjected to similar physicochemical conditions to produce the similar rock assemblages", which are consistently developed throughout the Complex.

The origin of the layering in the Main Plutonic Phase is regarded by some students of the Complex as resulting from crystal settling after emplacement of a limited number of surges of magma. Opposed to this view are those who consider that almost each layer represents a separate intrusion, and thus explain the transgression of certain layers on to lower layers.

(vii) Rocks of Uncertain Correlation

Both within and beyond the confines of the Complex rocks of uncertain correlation are found.

South of Marble Hall and forming the core of the Dennilton anticline are acid rocks which Lombaard (1931) mapped as granophyre and Rooiberg felsite. Subsequently Snyman (1958) re-examined the area and concluded that the rocks should be correlated with the Archaean granite and possibly the Onverwacht volcanics. On the proof copy of the 1:1,000,000 geological map of the Republic the original classification of granophyre has been used, while the felsites are correlated with the Dominion Reef System.

Gabbroic rocks are poorly exposed near Argent station, east of Pretoria, which have been classed as post-Waterberg. Willemse (1964) considered that they may be part of the Bushveld Complex forming a southern lobe extending under the Karroo cover, the presence of which is indicated by gravity surveys. Recently isotopic ages have been determined on minerals from granitic and felsitic rocks in this area, which indicate a Bushveld age (Burger et al, 1967).

North of Potgietersrus there is an outcrop of pyroxenite which may be a satellite of the Complex. In the same area coarse-grained granite, known as the Uitloop granite, crops out. It is not certain whether this granite is of Bushveld age.

(c) Cassiterite Deposits

Tin deposits within the Bushveld Complex have been classified (Strauss, 1954) as :

1. Syngenetic deposits as pipes and disseminations in granite, and
2. Epigenetic deposits as fissure veins, faults breccias and replacement bodies in

    (a) granites
    (b) granophyres
    (c) felsites, and
    (d) sedimentary rocks.

(i) Syngenetic Deposits

1. Dissemination Type

The most important dissemination deposits occur in the upper parts of the Bobbejaankop granite at Zaaiplaats mine. The ore consists of normal granite with disseminated grains of cassiterite, individual grains attaining a length of 6 mm. A feature of the mineralized granite is reported to be the "prevalence of scattered patches of dark, intensely altered granite and large irregular flat vugs", (Strauss, 1954). The dark colour is due to intense chloritization. Scheelite is also present in the ore zone, usually preferentially concentrated at the top. Three gently dipping ore zones are known. They have the following characteristics according to Strauss (1954) :

(a) lower zone, 35 feet (11 m.) thick, anticlinal in structure, evenly mineralized with a concentration of scheelite at its upper surface.

(b) middle zone, 20 feet (6.3 m.) thick, dips gently northwards, and also has a scheelite-rich upper contact.

(c) upper zone, irregular in thickness and carries more scheelite than the lower zone.

The lower zone lies 120 m. below the roof of the granite, the dips of the ore zone being parallel to the roof. Root-like apophyses of the roof facies (Lease microgranite) extend down to the disseminated ore zone. Elsewhere in the Zaaiplaats mine mineralized pegmatite pipes intersect the zone. Although these zones of disseminated cassiterite differ in some important respects from the floor deposits at the Anchor mine, Tasmania, there is a marked similarity in that they alternate with sheets of poorly mineralized granite. No greisenization associated with flat-lying fractures has controlled the localization of the Zaaiplaats mineralization as has been the case at the Anchor mine.

At the Groenfontein mine disseminated ore occurs in the Lease microgranite. Here the cassiterite is unevenly distributed with the result that the mineral occurs in small clusters, stringers or in small patches of impregnated granite. The disseminated ore lies between 3 and 10 m. below the roof pegmatite, the ore zone being approximately concordant with the roof. The ore zone varies between 3 and 10 m. in thickness but it is erratically mineralized. The mineralized granite is similar to the unmineralized Lease microgranite but Strauss (1954) observed that the cassiterite and feldspar are intergrown, with the former having replaced quartz. Scheelite is also present. Where the cassiterite is concentrated into clusters and stringers it is accompanied by pyrite, fluorspar, sericite, scheelite and chlorite.

Disseminated cassiterite was reported from the farms Zwartkloof (Elands Tin-field) and Enkeldoorn (Moloto Tin-field). At the former locality Recknagel (1909) describes the cassiterite as being disseminated through the granite and in miarolitic cavities with feldspar. On the farm Enkeldoorn cassiterite is disseminated in ore bodies 4 m. thick at surface thinning to 2 m. at a depth of 84 m. The ore-bearing zone dips at 84° east (Hall, 1904). At Vlaklaagte (Moloto Tin-field) tin occurs in sericitized granite.

In the Olifants Tin-field Wagner (1921) regarded fissuring in the granite to have controlled the presence of disseminated ore-bodies. At the Mutue Fides mine most tin was won from two tabular flat bodies, one dipping 15° WSW beneath a pegmatite sheet, and the other, lower body dipping 20° WNW. Wagner regarded the ore-bodies as replacements of granite about flat lying joints. The stanniferous granite has been intensely altered to sericitic granite over widths up to 1.5 m. Scheelite, wolframite, chalcopyrite, pyrite, arsenopyrite, molybdenite and specularite are associated with the cassiterite in the sericitized granite. The richest ore is reported to have been located where vertical joints intersect the flat fissures. The vertical fissures striking NNE and NE are not mineralized but are regarded by Wagner (1921) as the channels through which the mineralizing solutions passed. Vertical fissures striking WNW are mineralized but only to an economic grade where they intersect one of the other vertical fissures.

Lenticular replacement type ore-bodies occur in Lease microgranite within 2.5 m. of the contact pegmatite in the Zaaiplaats area. Strauss (1954) considers that flat-lying fissures have had some effect on localizing the ore-bodies, and regards the Groenfontein and Zaaiplaats mines deposits as being similar to those at Mutue Fides mine. Some cassiterite may be disseminated in the granite adjacent to the replacement bodies.

2. Pipe Type

The pipe deposits of the Potgietersrust Tin-field have been studied by Strauss (1954), Söhnge (1944), Wagner (1927), and Kynaston, Mellor, and Hall (1911), Kynaston and Mellor (1909) and Recknagel (1909). The pipe deposits were the main source of production of cassiterite until 1926, after which date they were largely exhausted. Pipes barren of tin are also known.

The pipes are long, roughly cylindrical bodies varying in diameter from 10 m. to 12 m., with a mean between 1 and 2 m. Lengths vary from 7 m. to 1000 m. Their attitude may vary from horizontal to vertical. The most striking feature of the pipes is their annular structure and their sharp contact with the enclosing granite. When the pipes were mined the material of the pipe came away cleanly from the granite leaving smooth-sided chimneys.

The pipes are located within the granite from a few metres to 275 m. below the pegmatite lying at the upper contact or roof, the majority having a general trend towards the northwest. An individual pipe displays a bewildering complexity of shape and attitude. It may branch or unite with other pipes, exhibit pinching and swelling, rise and fall or twist and turn in any direction. Strauss (1954) considers that fissures in the granite have exercised no control on the shape or trend of the pipes.

Strauss (1954) describes the typical structure of a pipe as follows :

Rim	White quartz	3-4 mm.
Tourmaline Ring	(Spherulitic tourmaline (Luxullianite (tourmaline and quartz)	10 mm. to 1 m.
Core	Massive sericite or sericitized feldspar with disseminated cassiterite	0-1 m.

Pipes in the Bobbejaankop granite may also have a ring of bright red feldspar inside the tourmaline ring. Some pipes have a ring of silicified, bright red granite around the outer quartz rim.

Not all the rings are present in every pipe and the size of an individual ring may vary along a pipe. Pipes may have an increasingly larger tourmaline ring developed in depth so that the pipe grades into a barren, luxullianite body or a barren pipe with a tourmaline ring surrounding silicified granite.

The core of a pipe is usually composed of granite in various stages of alteration. All the quartz may be replaced by cassiterite and fluorite. Feldspar may be replaced by sericite and chlorite. The ultimate alteration product is a mass of sericite with disseminated cassiterite, pyrite, fluorite and scheelite. Pipes resembling the cassiterite-bearing pipes have been located in Lease microgranite containing high grade copper and zinc ore.

Wagner (1921) describes pipe-like bodies from the Mutue Fides mine in the Olifants Tin-field. He regarded the pipes as being located preferentially at or near the intersections of steeply dipping fissures. A zonal arrangement is observed in these pipes. Preceeding from the centre to the margin, there is a gradation from a sericitized core through stanniferous sericitized granite, followed by silicified granite into unaltered granite. Cassiterite accompanied by scheelite, arsenopyrite, chalcopyrite, pyrite, and fluorite occurs in the sericitized core.

Flat-lying pegmatite pipes also occur at Mutue Fides mine. These bodies have an outer selvedge composed of chlorite and sericite surrounding a rim of red feldspar which encloses a core of quartz-sericite rock with cassiterite and sulphides.

At the neighbouring Oliphants mine so-called ore boulders are found. Although these cannot be regarded as true pipes they can be conveniently described here. The ore boulders are spherical or elliptical in shape and reach a maximum diameter of 1 m. The "boulders" are scattered through the granite from which they are separated by a zone of sericitized granite. The "boulders" consist either of an aggregate of cassiterite, quartz and sericite or of cassiterite crystals. Some "boulders" display an annular structure with an outer rim of cassiterite enclosing a core of cassiterite, quartz and sericite.

In the Elands Tin-field pipe-like bodies have been reported from the farm Zwartkloof. The pipes are regarded as replacement bodies located at or near the intersection of fissures. Intense chloritization occurs in the cores in which the cassiterite is located and gradually decreases outwards into unaltered granite. Pyrite, galena, molybdenite, chalcopyrite and fluorite are present. Irregular pegmatitic bodies carry tin on the farm Quaggasfontein (Moloto Tin-field). Recknagel (1909) records the presence of stanniferous quartz bodies on the farm Enkeldoorn (Moloto Tin-fields) which he regards as marking an incipient stage in the formation of quartz pegmatite lodes. Whether these occurrences at Zwartkloof, Quaggasfontein and Enkeldoorn can be regarded as belonging to the pipe class of deposit is debatable.

(ii) Epigenetic Deposits

In the Potgietersrust Tin-field fracturing of the country rocks is regarded by Strauss (1954) to have taken place at different times. In the Zaaiplaats area he considers that fracturing took place after the epithermal or post-cassiterite stage and consequently the mineralizing solutions where trapped within the Bobbejaankop granite. To the north of Zaaiplaats fissures formed during the pegmatitic stage thus enabling mineralizing solutions to pass into the country rocks. South of Zaaiplaats the granite has not been exposed by erosion and epigenetic deposits are located in the country rocks. Strauss (1954) also regards the contact pegmatite in the hood of Lease microgranite to have acted as an impermeable layer. Thus when it is absent mineralizing solutions have been able to escape into the country rocks.

Epigenetic deposits of economic significance are uncommon in the Zaaiplaats area but the Main granite is in places highly altered and carries disseminated tin. Cassiterite is found in a zone of shearing in the Main granite. Post-Waterberg diabase is associated with the zone of shearing and it has been suggested that movement along the shear, post-dating the emplacement of the dyke, has also taken place.

North of Zaaiplaats cassiterite-bearing lodes are believed to have extended up into the Main granite and the Rooiberg felsites. Strauss (1954) considers that the richest parts of these lodes have been eroded away as only the quartz-tourmaline roots can now be observed.

South of Zaaiplaats mineralized, brecciated fissures occur in the Rooiberg felsites, the brecciation being regarded as a result of the intrusion of the granite. Breccias of four types are recognized namely tourmaline breccia, quartz breccia, siliceous breccia and fluorspar breccia. Sporadic cassiterite occurs in all four breccia types, which dip closely parallel to the felsites except where the latter are steeply dipping. The siliceous breccia carries sericite, tourmaline, chlorite, and sulphides as well as ferruginous and manganiferous material. Scheelite, calcite, chlorite, and sulphides are present in the fluorspar breccias which are the most abundant breccia type.

In the Olifants Tin-field epigenetic tin deposits are known in granophyre and quartzite. In the former the deposits are located in pipes, the most prominent forming a series aligned in a northwesterly direction. The pipes are roughly cylindrical or funnel shaped, ranging in diameter from 30 cm. to 5 m. Near surface the pipes are vertical but at depth many flatten to dip towards the northwest. An annular structure is observed in these pipes. The core consists of calcite or fluorspar often containing patches of arsenopyrite or a vug lined by quartz. A ring of tin-scheelite-arsenopyrite ore surrounds the core and is itself surrounded by feldspar-rich pegmatite. An outermost selvedge of black mica may be separated from the granophyre by a further selvedge of chlorite. Within the pipes there are rapid variations in mineralogy. Tin ore may be replaced by chalcopyrite-fluorspar or scheelite-arsenopyrite ore.

The pipe-like bodies in granophyre on the farm Stavoren in the Olifants Tin-field have been studied in detail by Steyn (1962). He finds evidence for albitization followed by chloritization. The outer zone of a pipe is a quartz-rich, albitized granophyre, in which the typical granophyric texture is absent. The inner zone of the pipe consists of de-silicified granophyre. Chloritization was largely a post-mineralization phenomenon. Steyn does not support Wagner's view that the pipes are located preferentially along joints and fissures.

Fissures striking WNW, NW, NNE and NE are mineralized in the quartzites. Wolframite, chalcopyrite, pyrite and abundant specularite are associated with the cassiterite. No galena nor arsenopyrite is reported to be present, and tourmaline was reported in only one occurrence. The fissure deposits are highly irregular in shape, and are generally of low grade. The quartzite wall rocks have suffered intense alteration by specularite and chlorite, the latter being particularly prominent adjacent to cuprous ores. Some replacement of the quartzites has taken place along flat-lying fractures to give ore-bodies.

The Nylstroom and Rooiberg Tin-fields are wholly epigenetic deposits. At the former locality the tin is located in fissures in felsites and an interlayered sedimentary horizon - the Union Tin shale - which in the vicinity of the main producing mine is siliceous. The economically exploitable ore-bodies are located as a stockwork within the sedimentary bed. The deposits are replacement bodies located close to fractures although not actually filling them (Menge, 1963). The cassiterite grains are extremely fine and are associated with an abundance of haematite and magnetite. Chalcopyrite, arsenopyrite, and galena are also present. Chloritization of the country rock is prominent although the degree of chlorization is not necessarily indicative of the grade of cassiterite mineralization.

To the east of the Union tin mine, cassiterite occurrences are located on the northern limb of a westerly plunging anticline of felsites and interlayered sedimentary beds. A small boss of very weathered granite is exposed in the core of the anticline on the farm Doornkom.

The Rooiberg Tin-field deposits are located in a shaly quartzite underlying a thick shale bed known locally as the Main shale, above which is a thick succession of volcanics with interlayers of sedimentary beds. Ore-bodies are located along a major thrust fault in the Rooiberg sedimentary rocks and in the central area of the Rooiberg outcrop. The thrust plane dips at 25° in the south-west but becomes steeper towards the northeast where dips of 65° are recorded. Dips are directed towards the southeast. On the western side of the thrust the Rooiberg rocks are folded about northwesterly directed axes, but on the eastern side they strike northeastwards and form a limb of the Rooiberg syncline.

Ore-bodies located along the Rooiberg thrust are fissure lodes in cross-bedded quartzites and brecciated fractures in shaly quartzite. Branching from the main thrust are subsidiary fractures which turn to dip parallel to the main thrust after branching off. Where a number of branches are closely spaced, mineralized breccias or irregular impregnations of large size (up to 12 m. in diameter) occur. These constitute main ore-bodies at Nieuwpoort mine. At the Leeuwpoort mine steeply dipping fractures which strike northwestwards displace the ore-bodies associated with the thrust plane which here dips at 30° to the southeast.

Replacement bodies at Rooiberg are confined within a zone approximately 30 metres thick. Discontinuous lenses of replacement ore lie parallel to the bedding. The replacement is thought to have been effected by fissures striking N70°.

Mineralization, which is restricted to the proximity of fractures and fissures and ranges in thickness from 0.5 to 3 m., is accompanied by intense wall rock chloritization, and also sericitization. In addition to cassiterite, scheelite, pyrite, haematite, pyrrhotite, chalcopyrite and sphalerite have been recognized. Gangue minerals include chlorite, sericite and tourmaline.

In the Elands Tin-field mineralization is located in fissures in felsite overlying granite and underlying a shale bed. The felsites are chloritized adjacent to fissures, and cassiterite is finely disseminated in the chloritized felsite. No cassiterite is reported from the fissures themselves. Associated with the cassiterite are minor amounts of magnetite, haematite, pyrite and chalcopyrite. Gangue minerals include quartz, tourmaline and carbonates.

(iii) Theories of Origin of the Deposits

According to Strauss (1954) disseminations of tin appear to be direct crystallization products from the magma only in the Bobbejaankop granite of the Zaaiplaats area. In other deposits disseminations are related to alteration of granite by either sericitization or chloritization, the localization of which was apparently controlled by fissures, either vertical or flatly inclined, in the granite. No evidence has been found to explain the presence of cassiterite as an accessory mineral in the Bobbejaankop granite. Recknagel (1909) considered that tin was a constituent of both the granite and felsite magmas.

Strauss (1954) has suggested that in the Zaaiplaats area there is a genetic connection between the tourmaline nodules found in the Lease microgranite and the pipes, a possibility which Recknagel proposed in 1909. Strauss considers that the nodules probably mark the transition between the pegmatite phase (during which he believes the Lease granite to have been formed) and the hydro-thermal stage when the pipes formed. Strauss envisages the nodules as being the first segregations from the hydrothermal solutions of the granite. As these solutions became more abundant the nodules developed to larger and larger sizes, which if they coalesced in chain fashion would result in an intricate network of pipes. In this way a large volume of volatile matter would be created which would migrate upwards. Strauss does not accept the postulation that the pipes occupy cavities but considers that they were formed by metasomatic replacement of solid or partly solid rock.

Wagner (1921) found cavities 1 m. in length and 40 cm. in diameter in the granite at Mutue Fides mine. Except for a veneer of sericite and some small fragments of granite and sericitized granite scaled off the wall, the cavities were empty. No fissures connect with the cavities. Wagner regards this as significant and suggests that where such cavities are connected to fissures bearing mineralizing solutions, the cavities would provide sites for the crystallization of pegmatitic material and of cassiterite. Wagner (1921) envisaged the origin of the tin in the Mutue Fides-Stavoran area to be derived from a granitic residuum which streamed through fissures which extended to this residuum. Crystallization of the mineralized residuum took place where favourable loci for deposition were encountered.

Recknagel (1909) considered that the tin was a primary constituent of the granites and that concentration was achieved by magmatic differentiation.

Steyn (1962) envisaged that the tin deposits in granophyre on the farm Stavoren were not localized along fissure systems. He proposed that ore-bearing solutions moved upward from the source area through the solidified or partly solidified acid rocks. It must be remembered that Steyn has presented evidence to support the view that the granophyre, at least in this area, is the roof phase of the granite. As the ore-solutions migrated, they would react with the wall-rocks resulting in the formation of silicified and tourmalinized granite. This alteration would be accompanied by strong leaching of K and Na from the wall-rocks, which would lead to an increase in the alkalinity of the ore-solutions. As the solutions migrated further up into lower temperature zones, the alkalis would be returned to the wall rock. This commenced with the albitization and desilication of the granophyre. The K and Si in the solutions supplied the source of the red feldspar (andularia) and quartz which are typical gangue minerals. Chloritization is in part earlier than the deposition of cassiterite but extensive post-mineralization metasomatism of this kind also took place.

Steyn (1962) considers that at Zaaiplaats conditions favoured ore deposition at or shortly above horizons where tourmalinization was active. Consequently the ore solutions had not been enriched to any great extent by Na and K leached from the wall-rocks, and hence only relatively small quantities of Na- and K-rich feldspars could form in the ore-bodies. At Stavoren the ore solutions were able to migrate to higher levels into the granophyre so that the K- and Na-rich feldspars were formed from an ore-solution which had become increasingly alkaline as a result of leaching at greater depth.

Most writers ascribe the origin of the tin deposits to the Bushveld granites. Recknagel (1909) however considered that the felsites themselves were stanniferous and that deposits of cassiterite within these bodies were subsequently concentrated. He further considered that the deposits which occur in sedimentary rocks on the farm Doornhoek were derived from the felsites.

Epigenetic deposits in the Nylstroom, Olifants, and Elands Tin-fields are located in anticlinal structures, in all of which areas granite appears in the core of the anticlinal structure. However, in the Olifants Tin-field mineralization is located in the crest, but at Nylstroom and Elands the mineralization is on the limbs of the anticlinal structures.

Labuschagne (1970) concluded that in the Rooiberg area tin was deposited from alkaline solutions as a result of his study of the deposits at the Blaauwbank and Nieuwpoort mines. Leube and Stumpfl (1963) found that the orthoclase-rich, impure quartzite beds at Rooiberg were preferentially replaced by the ore fluids, a view Labuschagne supports. In contradistinction to the Zaaiplaats area, where quartz is replaced by cassiterite, the feldspar in the Rooiberg quartzites is attacked by cassiterite. The latter author also concludes from a study of the iron content in tourmaline associated with the mineralization that the ore-liquid became impoverished with respect to iron as crystallization proceeded. Cassiterite was deposited in an iron-poor environment and thereafter the iron content of the post-cassiterite tourmaline increased. Boardman (1944), Leube and Stumpfl (1963), and Labuschagne (1970) are agreed that the passage of the mineralizing solutions was controlled by faults and fractures.

IV. SUMMARY

In attempting to synthesize the data which has been accumulated in connection with tin mineralization and to establish parameters to guide further exploration, difficulty is experienced in resolving apparent contradictions. In spite of the conclusions of Pereira and Dixon (1965) that tin deposits are more common in younger rocks, it is suggested that this is a reflection of the greater probability of such deposits being preserved in younger rocks and is not evidence for supporting the view that there has been a significantly greater addition of tin to the crust in more recent geological times. Tin deposits are typically located in the roof zones of granitic intrusives or immediately adjacent to them. It follows, therefore, that these parts of the intrusives, particularly if they are affected by greisenization or a similar process, are more readily subjected to erosion unless some subsequent event has prevented erosion.

If Hosking's (1970) provisional model for Malayan deposits has a wider application, younger granitic rocks may be enriched with respect to tin as a result of assimilation of lower grade deposits in older granites. This factor may influence the apparent increase in economic importance of tin in younger granites.

The Bushveld granites provide suitable exploration targets in that their roof is preserved over wide areas. The Cape granites have, however, been subjected to erosion prior to the deposition of the Table Mountain Sandstone and consequently the search for mineralization should be confined to domes in the Malmesbury rocks. It seems probable that the highest, and, hence the most favourable, apices have been removed by erosion.

Although acidic intrusives and extrusives are widespread in the crust, only a very small percentage of these rocks are associated with economic concentrations of tin. The gross characters of stanniferous granites do not differ, if at all, from barren granites. There is some evidence to suggest that high silica granites deficient in Ca and Mg are potentially richer in tin than other granites, but exceptions are known. The stanniferous granites in eastern Australia are the late stage intrusives of a composite suite of acid rocks and are more acid differentiates. It may well be that this sets them apart from other high silica granites and they may be enriched with respect to tin by a process similar to that envisaged by Hosking for the Malayan granites. The Bushveld granites provide a parallel in that they too are part of a composite suite of intrusives, with the younger Bobbejaankop granite being stanniferous as a result of differention and/or assimilation of lower grade tin mineralization in the Main granite. This concept would be in accord with views expressed by Tauson et al (1968) and Hosking (1970) in respect of deposits in Siberia and Malaya.

Geochemical studies indicate that all acid rocks contain tin, albeit in very small amounts. It has been suggested by Sullivan (1948) that concentration of tin is unlikely in granites rich in mafic minerals due to the similar ionic radii of iron and magnesium to tin, and the relatively low valency of iron and magnesium, which would enable tin to enter the lattice of the mafic minerals. This is supported by the results of Tauson et al (1968) who found tin in hornblende and sphene occurring in barren granites in Siberia. Sullivan (1948) considered that rocks rich in quartz are the most likely to reject many metallic ions because quartz has a closed lattice due to the small size and high valence of the Si ion, making solid solution difficult. However, lead can replace potassium in feldspars and biotite and it could reasonably be deduced that lead would be impoverished in a granitic residuum. Lead is on the contrary a common associate of tin in stanniferous lodes.

Tauson et al (1968) find that late acid differentiates of abyssal batholiths are impoverished with respect to elements such as Zn, Cu, Ni, Co, etc., related to magnesium and iron but show an increase in the content of rare elements related to potassium (Rb, Tl, Pb, etc.) and to the volatile components (U, Th, Sn, Be, Nb, Ta, etc.). In this connection it is worth noting that Fourie (1969) found the Bobbejaankop granite to have lower contents of Zn and higher contents of Rb, Nb, and Th than the Main granite in the Zaaiplaats area.

Hosking (1965) considers that tin is deposited in lodes partly as a result of the alteration of biotite to muscovite and the subsequent silicification of the later mineral, and partly as a result of direct addition from the granitic residuum. This process is seemingly inadequate to account for the dispersed cassiterite grains found in the Bobbejaankop granite. Here the cassiterite appears to be a primary constituent, nor was it derived by ex-solution from magnetite in a manner similar to that found at the Lost River mine, Alaska. The Bobbejaankop is not distinctly more siliceous than the other Bushveld granites. The dispersed cassiterite is, therefore, unlikely to result from rejection in a manner envisaged by Sullivan (1948).

In attempting to synthesize the previous discussion, it would appear that tin deposition of an economic grade is more likely in granitic bodies which have solidified from a magma in which differentiation was permitted to proceed. By this means, a silicic granitic residuum developed, which fed lodes in the apices of the roof of the intrusive. The volatile components need also to be concentrated to provide not only direct additions of tin but also to react with the already wholly or partially crystallized granite, thereby releasing tin contained in the lattice of minerals such as biotite (greisenization and silicification).

There is a difference of opinion as to the ultimate source of tin. It is seemingly implicit in the view of Tauson et al (1968) that all granitoids are stanniferous, special physico-chemical environments being necessary during consolidation to give rise to economic deposits of tin. On the other hand Schuiling (1967) tends towards the view that there was an original inhomogeneous distribution of tin in the crust and that portion of the upper mantle which is likely to adhere to it during continental drift. Subsequent geological events which involve parts of the geochemical "culminations" will lead to the re-activation and generation of tin deposits of economic significance. Darnley (1965) envisages the fractionation of an ore-liquid which is likely to have a variable composition reflecting original mantle inhomogeneities. The ore-liquid reaches the surface in the wake of silicate magmas (particularly viscous acid magma) along fractures and zones of weakness produced in the crust in response to the disturbance caused by the upward migration of the silicate magma. Major tin deposits are preferentially located in linear belts coincide in many cases with orogenic zones (e.g. Andean, Hercynian, Malayan, Tasman). However tin mineralization in Nigeria (the Younger Granites) and the Bushveld Complex is located in anorogenic environments. In Nigeria Wright (1970) has proposed that the Younger Granite tin mineralization is located at the intersection of two lineaments. The tin mineralization associated with the Cape granites (Scholtz, 1946), the Damaran orogen (Martin, 1965) and the Swaziland biotite granites (Davies, 1964) are all reported to be located in defined linear zones. In the latter case, particularly, the tin mineralization is confined to a belt trending northwest across the grain of the country. In the Bushveld Complex tin deposits are more diffusely distributed but a case could be made for postulating their localization along the flanks of the graben-like structure in which the Karroo Sequence is preserved, or alternatively along northwest trending directions. Some of the problems posed by the Bushveld Complex in general and the acid rocks in particular have been mentioned. Solution of these problems together with a re-construction of the original geometry of the Complex in its wider tectonic setting is necessary in order to search for tin and other mineralization associated with the acid phase.

From the foregoing it seems reasonable to suggest that granitic intrusives displaying evidence of (i) differentiation, (the individual products of this process being separately emplaced), (ii) location at intersecting lineaments or within orogenic belts, and (iii) preservation of their original roof will provide potential exploration targets.

Local concentrations, particularly in exogranitic deposits, are located in faults and fractures, and may be preferentially enriched where favourable host rocks are adjacent to these structural disturbances. The fact that tin mineralization occurs late in the intrusive history implies that there will be a complex relation between the tin lodes and their structural controls, because of the differential response of the fracture and fault systems to stress fields operative during the various stages of emplacement of the granitic mass.

Sophisticated geochemical and geophysical tools can be used once the exploration target has been selected. It is clear that all granitoids contain greater or lesser amounts of cassiterite and hence tin by itself is unlikely to prove to be a suitable geochemical pathfinder, either in soils or hard rock. The choice of elements to be used will be largely influenced by the anticipated position of the stanniferous lodes. Endogranitic deposits usually have a relatively simple mineralogy, and the exogranitic lodes are more complex. In the later case Steyn (1962) has found that, at Stavoren, B, Li, Ga and Mo are more abundant in the albitized and chloritized granophyres surrounding tin lodes than in the unaltered portions. In hard rock samples, Zn is reported to be impoverished in the mineralized granites. The development of geochemical techniques, particularly in respect to soil sampling, is necessary to define the best pathfinder elements. In spite of the assertions of Beus and Sitnin (1968) hard rock analysis is fraught with problems which only detailed and systematic sampling can overcome.

Sulphides are reported from many tin deposits in the Bushveld Complex. Geophysical methods for detecting disseminated sulphides suffer from the disadvantage that they are both time-consuming and expensive. However, employment of self-potential techniques should not be overlooked as a follow-up tool in areas where other methods indicate the possible existence of mineralized pipes.

At this stage it would be premature to define an exploration model for tin. Some guide-lines have been indicated as a first step in erecting a model. That greater emphasis has been placed on the deposits associated with the Bushveld Complex should not be construed to imply that this area constitutes the only exploration target in Southern Africa. Tin production in South Africa has come almost exclusively from deposits located within the Complex, consequently the available fundamental data is in the main confined to those deposits. It may be argued that the Bushveld Complex is in many respects, unique and that the tin deposits contained within it are themselves unlikely to provide data which could be applied elsewhere. The basic parameters which define the local concentration of tin in the Bushveld Complex are, however, not unique. Tin is associated with granitic rocks, local structural controls are present and in exogranitic deposits the nature of the host rock has determined the sites of preferential replacement. All these are factors observed and reported from tin-fields around the world.

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LIST OF REFERENCES

Agassiz, J., 1954, Gêologie et pegmatites stannifères de la region Mumba-Numbi, Kivu (Congo Belge) : Comité National du Kivu, Bruxelles.

Barsukov, V.L., 1957, The Geochemistry of Tin : Geochemistry Vol. 1, pp. 41-45.

Beus, A.A. and Sitnin, A.A., 1968, Geochemical Specialization of Magmatic Complexes as a Criteria for the Exploration of Hidden Deposits : XXIII Int. Geol. Cong., Prague, Section 6, pp. 101-105.

Bilibin, Y.A., 1955, Metallogenetic Provinces and Metallogenetic Epochs : (Gosgeoltekhizdat : Moscow, trans. Canad. Geol. Surv.)

Blanchard, R., 1947, Some Pipe Deposits of Eastern Australia : Econ. Geol. Vol. 42, pp. 265-304.

Boardman, L.G., 1946, The Geology of a Portion of the Rooiberg Tin-fields : Trans. geol. Soc. S. Afr., Vol. 49, pp. 103-132.

Boshoff, J.C., 1942, The Upper Zone of the Bushveld Complex at Tauteshoogte : Unpub. D.Sc. Thesis, Univ. Pretoria.

Burger, A.J., Oosthuyzen, E.J. and van Niekerk, C.B., 1967, New Lead Isotopic Ages for Minerals from Granitic Rocks, Northern and Central Transvaal : Ann. Geol. Surv. S. Afr., Vol. 6, pp. 85-89.

Burnham, C. Wayne, 1959, Metallogenic Provinces of the South-Western United States and Northern Mexico : State Bureau of Mines and Mineral Resources, Bull. 65, New Mexico.

Campbell, D.F., 1947, Geology of the Colquiri Tin Mine, Bolivia : Econ. Geol., Vol. 42, pp. 1-21.

Cannon, R.S., Pierce, A.P., Antweiler, J.C. and Buck, K.L., 1961, The Data of Lead Isotope Geology Related to Problems of Ore Genesis : Econ. Geol., Vol. 56, pp. 1-38.

Chase, F.M., 1948, Tin-Silver Veins of Oruro, Bolivia : Econ. Geol., Vol. 43, pp. 333-383, 435-470.

Coertze, F.J., 1960, Anorthosite Emplaced in a Shear-Zone in Gabbro of the Bushveld Igneous Complex : Trans. geol. Soc. S. Afr., Vol. 63, pp. 75-81.

Coertze, F.J., 1962, The Rustenberg Fault as a Controlling Factor of Ore-Deposition in the Northwest of Pilanesberg : Trans. geol. Soc. S. Afr., Vol. 65, pp. 253-257.

Coetzee, G.L., 1970, The Rooiberg Felsite Series North of Nylstroom : Spec. Pub. No. 1, Geol. Soc. S. Afr., pp. 312-325.

Cousins, C.A., 1959, The Structure of the Mafic Portion of the Bushveld Igneous Complex : Trans. geol. Soc. S. Afr., Vol. 62, pp. 179-202.

Daly, R.A., 1928, The Bushveld Igneous Complex of the Transvaal : Bull. geol. Soc. Amer., Vol. 34, pp. 703-748.

Daly, R.A. and Molengraaff, G.A.F., 1924, Structural Relations of the Bushveld Igneous Complex, Transvaal : J. Geol., Vol. 32, pp. 1-35.

Darnley, A.G., 1965, Ore Genesis and Mantle Convection in Some Guides to Mineral Exploration : Geol. Surv. Canad. Paper 65-6, pp. 108-123.

Davies, D.N., 1964, The Tin Deposits of Swaziland in Some Ore Deposits of Southern Africa : Vol II, Geol. Soc. S. Afr., pp. 535-541.

Davies, R.D., Allsopp, H.L., Erlank, A.J. and Manton, W.I., 1970, Sr-Isotopic Studies on Various Layered Mafic Intrusions in Southern Africa : Spec. Pub. No. 1, Geol. Soc. S. Afr., pp. 576-593.

Dennis, J.G., 1959, Note on Some Cassiterite Bearing Pegmatites Near Brandberg, South West Africa : Econ. Geol., Vol. 54, pp. 1115-1121.

Desborough, George A. and Sainsbury, C.L., 1970, Cassiterite as an Exsolution Product in Magnetite, Lost River Tin Mine, Alaska : Econ. Geol., Vol. 65, pp. 1004-1006.

de Villiers, J. and Sõhnge, P.G., 1959, The Geology of the Richtersveld : Mem. geol. Surv. S. Afr., No. 48.

Dewey, H., 1925, The Mineral Zones of Cornwall : Proc. Geol. Ass., Vol. 36, pp. 107-135.

Douglas, G.V., 1957, Pipe-Like Ore Bodies in Plutonic Rocks : Econ. Geol., Vol. 52, pp. 578-581.

Edwards, A.B. and Gaskin, A.J., 1949, Ore and Granitization : Econ. Geol., Vol. 44, pp. 234-241.

Emmons, W.H., 1940, Principles of Economic Geology : McGraw Hill Book Co., Inc., New York.

Ferguson, J. and Botha, E., 1964, Some Aspects of Igneous Layering in the Basic Zones of the Bushveld Complex : Trans. geol. Soc. S. Afr., Vol. 66, pp. 259-282.

Fick, L.J., 1960, The Geology of the Tin Pegmatites at Kamativi : Geologie en Mijnbouw, 39c Jaargang, pp. 472-491.

Fockema, R.A.P., 1952, The Geology of the Area Around the Confluence of the Elands and Crocodile Rivers : Trans. geol. Soc. S. Afr., Vol. 55, pp. 155-174.

Fourie, P.J., 1969, Die Geochemie van Granitiese Gesteentes van die Bosveldstollingskompleks : Unpub. D.Sc. Thesis, Univ. Pretoria.

Garnett, R.H.T., 1961, Structural Control of Mineralization in South-West England : Mining Mag., Vol. 105, pp. 329-337.

Gevers, T.W., 1929, A Hydrothermal Deposit of Cassiterite Near Arandis, South West Africa : Trans. geol. Soc. S. Afr., Vol. 32, pp. 165-170.

Gevers, T.W. and Frommurze, H.F., 1929, The Tin-Bearing Pegmatites of Erongo Area, South West Africa : Trans. geol. Soc. S. Afr., Vol. 32, pp. 111-149.

Gevers, T.W., Partridge, F.C. and Joubert, G.K., 1937, The Pegmatite Area South of the Orange River in Namaqualand : Mem. geol. Surv. S. Afr., No. 31.

Ghosh, P.K., 1934, The Carnmenellis Granite : Its Petrology, Metamorphism, and Tectonics : Quart. J. Geol. Soc. Lond., Vol. 90, pp. 240-276.

Groeneveld, D., 1968, The Bushveld Igneous Complex in the Stoffberg Area, Eastern Transvaal, with Special Reference to the Magnetite Seams : Unpub. D.Sc. Thesis, Univ. Pretoria.

Hall, A.L., 1904, The Geological Survey of the North-Eastern Portions of the Pretoria District, Including the Tin-Fields : Ann. Rep. for 1904, Geol. Surv. Transvaal, pp. 37-45.

Hall, A.L., 1905, Geological Notes on the Bushveld Tin-Fields and Surrounding Area : Trans. geol. Soc. S. Afr., Vol. 8, pp. 47-56.

Hall, A.L., 1913, Notes on the Tin Deposits of Embabaan and Forbes Reef, Swaziland : Trans. geol. Soc. S. Afr., Vol. 16, pp. 142-146.

Hall, A.L., 1932, The Bushveld Igneous Complex of the Central Transvaal : Mem. geol. Surv. S. Afr., No. 28.

Hammerbeck, E.C.I., 1970, The Steelpoort Park Granite, Eastern Part of the Bushveld Complex and Magnetites in the Gabbroic Country Rock : Spec. Pub. geol. Soc. S. Afr., No. 1, pp. 299-311.

Hawkes, H.E. and Webb, J.S., 1962, Geochemistry in Mineral Exploration : Harper and Rowe, New York.

Hiemstra, S.A. and van Biljon, W.J., 1959, The Geology of the Upper Magaliesberg Stage and the Lower Bushveld Complex in the Vicinity of Steelpoort : Trans. geol. Soc. S. Afr., Vol. 62, pp. 239-256.

Hornung, G., 1962, Wall Rock Composition as a Guide to Pegmatite Mineralization : Econ. Geol., Vol. 57, pp. 1127-1130.

Hosking, K.F.G., 1965, The Search for Tin : Mining Mag., Vol. 109, pp. 261-273, 368-383.

Hosking, K.F.G., 1970, Primary Tin Deposits of South-East Asia : Min. Sci. and Eng., Vol. 2, No. 4, pp. 24-50.

Jack, R., 1965, Tin Ore Deposits of North-East Tasmania : in Geology of Australian Ore Deposits, Vol. 1, pp. 497-500.

Jedwab, J., 1956, Caractérisation Spectrochimique des Granites : Bull. Soc. belge Geologie, Vol. 64, pp. 526-534.

Jensen, M.L., 1959, Sulphur Isotopes and Hydrothermal Mineral Deposits : Econ. Geol., Vol. 54, pp. 374-394.

Johnson, J.P., 1907, The Tin, Molybdenum and Lead Occurrences Near Potgietersrust : Trans. geol. Soc. S. Afr., Vol. 10, pp. 115-119.

Jones, W.R., 1925, Tin-Fields of the World : Mining Publications Ltd., London.

Krige, A.V., 1921, The Nature of the Tin Deposits Near Kuils River, Stellenbosch District, and Their Relationship to Other Occurrences in the Neighbourhood : Trans. geol. Soc. S. Afr., Vol. 24, pp. 53-70.

Kuschke, O.H., 1960, Granitic Rocks of the Bushveld North-West of Brits : Unpub. M.Sc. Thesis, Univ. Pretoria.

Kynaston, H., 1907, The Geology of the Country Around Pretoria : Explanation Sheet 1, Geol. Surv. S. Afr.,

Kynaston, H., 1908, The Geology of the Country North and North-West of Potgietersrust : Ann. Rep. geol. Surv. Transv. for 1908.

Kynaston, H., 1910, The Red Granite of the Transvaal Bushveld and Its Relation to Ore Deposits : Proc. geol. Soc. S. Afr., Vol. 12, pp. xxi-xxx.

Kynaston, H., Mellor, E.T. and Swinburne, V.P., 1909, The Geology of the Waterberg Tin-Fields : Mem. geol. Surv. Transv. No. 4.

Kynaston, H., Mellor, E.T. and Hall, A.L., 1911, The Geology of the Country Around Potgietersrust : Explanation Sheet 7, Geol. Surv. S. Afr.

Kynaston, H., Mellor, E.T. and Humphrey, W.A., 1912, The Geology of the Country Around Warmbaths and Nylstroom : Explanation Sheet 10, Geol. Surv. S. Afr.

Labuschagne, L.S., 1970, The Structure and the Mineralization of the Ore-Bodies at Blaauwbank and Nieuwpoort, Rooiberg Tin-Field, Transvaal : Unpub. M.Sc. Thesis, Univ. Pretoria.

Landwehr, W.R., 1967, Belts of Major Mineralization in Western United States : Econ. Geol., Vol. 62, pp. 494-501.

Leube, A., 1960, Structural Control in the Rooiberg Tin-Fields (South Africa) : Trans. geol. Soc. S. Afr., Vol. 63, pp. 265-282.

Leube, A. and Stumpfl, E.F., 1963, The Rooiberg and Leeuwpoort Tin Mines, Transvaal, South Africa : Econ. Geol., Vol. 58, pp. 391-418, 527-557.

Liebenberg, C.J., 1960, Trace Elements of the Rocks of the Bushveld Igneous Complex : Univ. Pretoria Publications Nos. 12 and 13.

Lombaard, B.V., 1931, The Geology of the North-Eastern Pretoria District and Adjoining Country : Explanation Sheet 18, Geol. Surv. S. Afr.

Lombaard, B.V., 1932, The Felsites and Their Relation in the Bushveld Complex : Trans. geol. Soc. S. Afr., Vol. 35, pp. 125-190.

Lombaard, B.V., 1934, On the Differentiation and Relationship of the Rocks of the Bushveld Igneous Complex : Trans. geol. Soc. S. Afr., Vol. 37, pp. 5-52.

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

Macgregor, A.M., 1947, An Outline of the Geological History of Southern Rhodesia : Bull. geol. Surv. S. Rhod., No. 38.

McCartney, W.D., 1965, Metallogeny of post-Precambrian Geosynclines, pp. 33-42 : in Some Guides to Mineral Exploration, Geol. Surv. Canad. Paper 65-6.

McDermott, E.K. and Oxley-Oxland, G. St. J., 1961, Tin Mining in South Africa : Trans. VII Common. Mining and Metall. Cong., Vol. 1, pp. 145-157.

McDonald, D.P., 1913, The Cassiterite Deposits of Leeuwpoort No. 938 : Trans. geol. Soc. S. Afr., Vol. 16, pp. 107-159.

Menge, G.F.W., 1963, The Cassiterite Deposits on Doornhoek 342KR and Vicinity, West of Naboomspruit, Transvaal : Unpub. M.Sc. Thesis, Univ. Pretoria.

Merensky, H., 1908, The Rocks Belonging to the Area of the Bushveld Granite Complex in which Tin may be Expected, with Descriptions of the Deposits Actually Found : Trans. geol. Soc. S. Afr., Vol. 11, pp. 25-42.

Middlemost, E., 1963, Geology of the South-Eastern Richtersveld : Unpub. Ph.D. Thesis, Univ. Cape Town.

Middlemost, E., 1966, The Genesis of the Stinkfontein Formation : Trans. geol. Soc. S. Afr., Vol. 64, pp. 87-98.

Partridge, F.C., 1936, A Contribution to the Mineralogy of the Potgietersrust Tin-Field : Trans. geol. Soc. S. Afr., Vol. 39, pp. 461-464.

Pereira, J. and Dixon, C.J., 1965, Evolutionary Trends in Ore Deposition : Inst. Mining and Metallurgy, Vol. 74, pp. 505-527.

Poldervaart, A. and von Backström, J.N., 1949, A Study of an Area at Kakamas : Trans. geol. Soc. S. Afr., Vol. 52, pp. 433-493.

Poldervaart, A., 1955a, Zircons in Rocks. I. Sedimentary Rocks : Amer. J. Sci., Vol. 253, pp. 433-461.

Poldervaart, A., 1955b, Growth Phenomena in Zircons of Autochthonous Granites : Bull. geol. Soc. Amer., Vol. 66, pp. 947-948.

Rattigan, J.H., 1960, Residual Characteristics of Crystallates Genetically Associated with Ore Deposits : Econ. Geol., Vol. 55, pp. 1272-1284.

Ramdohr, P., 1935, Ein Zinnvorkommen in Marmor bei Arandis, Deutsch-Südwest-Afrika : N. Jahrb. Min. Geol. Paläont. Beil. Bd. 70.

Read, H.H., 1949, A Contemplation of Time in Plutonism : Quart. J. Geol. Soc. Lond., Vol. 105, pp. 101-156.

Recknagel, R., 1908, On Some Mineral Deposits of the Rooiberg District : Trans. geol. Soc. S. Afr., Vol. 11, pp. 83-106.

Recknagel, R., 1909, On the Origin of the South African Tin Deposits : Trans. geol. Soc. S. Afr., Vol. 12, pp. 168-202.

Roering, C., 1963, Pegmatite Investigations in the Karibib District, South West Africa : Unpub. Ph.D. Thesis, Univ. of the Witwatersrand.

Sainsbury, C.L., 1969, Tin Resources of the World : U.S. Geol. Surv. Bull. 1301.

Scholtz, D.L., 1946, On the Younger Precambrian Granite Plutons of the Cape Province : Proc. geol. Soc. S. Afr., Vol. 49, pp. xxxv-lxxxii.

Schuiling, R.D., 1967, Tin Belts on the Continents Around the Atlantic Ocean : Econ. Geol., Vol. 62, pp. 540-550.

Snyman, C.P., 1958, 'n Gneiss, 'n Koepelstruktuur en die Metamorfose van die Sisteem Transvaal Suid van Marble Hall, Transvaal : Trans. geol. Soc. S. Afr., Vol. 61, pp. 225-262.

Söhnge, P.G., 1944, The Structure, Ore Genesis and Mineral Sequence of the Cassiterite Deposits in the Zaaiplaats Tin Mine, Potgietersrust District, Transvaal : Trans. geol. Soc. S. Afr., Vol. 47, pp. 157-182.

Söhnge, P.G., 1963, Genetic Problems of Pipe Deposits in South Africa : Proc. geol. Soc. S. Afr., Vol. 66, pp. xix-lxxii.

Steyn, J.G.D., 1962, The Mineralogy of the More Important Tin-Bearing Pipes on Stavoren : Mem. geol. Surv. S. Afr., No. 51.

Strauss, C.A., 1943, Notes on Rheomorphic Breccias North of Potgietersrust : Trans. geol. Soc. S. Afr., Vol. 46, pp. 39-45.

Strauss, C.A., 1947, Granitization and Rheomorphism Associated with the Granite Near the Leeuwpoort Tin Mine : Trans. geol. Soc. S. Afr., Vol. 50, pp. 161-170.

Strauss, C.A., 1954, The Geology and Mineral Deposits of the Potgietersrus Tin-Fields : Mem. geol. Surv. S. Afr., No. 46.

Strauss, C.A. and Truter, F.C., 1944, The Bushveld Granites of the Zaaiplaats Tin Mining Area : Trans. geol. Soc. S. Afr., Vol. 47, pp. 47-78.

Sullivan, C.J., 1948, Ore and Granitization : Econ. Geol., Vol. 43, pp. 471-498.

Tauson, L.V., Kozlov, V.D. and Kuz'mon, M.I., 1968, Potential Ore-Bearing Granite Intrusions : XXIII Int. Geol. Cong., Prague, Section 6, pp. 123-129.

Taylor, H.P., 1963, Evolution of Chemical Composition of Ore-Bearing Solutions Dependent on the Same Source : Symposium "Problems of Post-Magmatic Ore Deposition", Vol. I, pp. 307-311. Geol. Surv. Czechoslavakia.

Truter, F.C., 1955, Modern Concepts of the Bushveld Complex : C.C.T.A., South. reg. Comm. Geol., Vol. 1, pp. 77-92.

Turneaure, F.C., 1960, A Comparative Study of Major Ore Deposits of Central Bolivia : Econ. Geol., Vol. 55, pp. 217-254, 574-606.

van Biljon, S., 1949, The Transformation of the Pretoria Series in the Bushveld Complex : Trans. geol. Soc. S. Afr., Vol. 52, pp. 1-198.

van der Westhuizen, J.M., 1945, Die Geologie van Bothasberg, Bosveldkompleks : Unpub. M.Sc. Thesis, Univ. Pretoria.

von Backström, J.W., 1950, Notes on a Tungsten-Tin Deposit near Upington, Gordonia District : Trans. geol. Soc. S. Afr., Vol. 53, pp. 35-51.

von Gruenewaldt, G., 1966, The Geology of the Bushveld Igneous Complex East of the Kruis River Cobalt Occurrence, North of Middelburg, Transvaal : Unpub. M.Sc. Thesis, Univ. Pretoria.

Wagner, P.A., 1909, Notes on the Tin Deposits in the Vicinity of Cape Town : Trans. geol. Soc. S. Afr., Vol. 12, pp. 102-111.

Wagner, P.A., 1921, The Mutue-Fides-Stavoren Tin-Fields : Mem. geol. Surv. S. Afr., No. 16.

Wagner, P.A., 1927, The Geology of the North-Eastern Part of the Springbok Flats and Surrounding Country : Explanation Sheet 17, Geol. Surv. S. Afr.

Watson, R.L.A., 1962, The Geology of the Kamativi and Lubimbi Areas : Bull. geol. Surv. S. Rhod., No. 57.

Westerveld, J., 1936, The Granites of the Malayan Tin-Belt Compared with Tin-Granites from other Regions : Proc. kon. Akad. Wet., Vol. 34.

Wiles, J.W., 1961, The Geology of the Miami Mica Field (Urungwe District) : Bull. geol. Surv. S. Rhod., No. 51.

Willemse, J., 1959, The Floor of the Bushveld Igneous Complex and Its Relationships with Special Reference to the Eastern Transvaal : Proc. geol. Soc. S. Afr., Vol. 62, pp. xxi-lxxx.

Willemse, J., 1964, A Brief Outline of the Geology of the Bushveld Igneous Complex : in Some Ore Deposits in Southern Africa, Vol. II, pp. 91-130, Geol. Soc. S. Afr.

Wolhuter, L.E., 1954, The Geology of the Country Surrounding Loskop Dam, Transvaal : Unpub. M.Sc. Thesis, Univ. Pretoria.

Wright, J.B., 1970, Controls of Mineralization in the Older and Younger Tin Fields of Nigeria : Econ. Geol., Vol. 65, pp. 945-951.

Zimmerman, D.O., 1965, Tin Ore Deposits of Australia in Geology of Australian Ore Deposits, pp. 39-45 : Eighth Common. Mining and Metall. Congr.

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APPENDIX I

SOUTH AFRICAN TIN PRODUCTION FOR THE PERIOD 1908 TO 1968

Year	Tons (Metallic Tin)	Year	Tons (Metallic Tin)
1908	1426	1939	796
1909	2647	1940	1005
1910	3383	1941	865
1911	3526	1942	609
1912	2932	1943	515
1913	3600	1944	544
1914	3386	1945	544
1915	3402	1946	513
1916	3235	1947	531
1917	2640	1948	497
1918	2190	1949	497
1919	1598	1950	645
1920	2452	1951	808
1921	1416	1952	997
1922	612	1953	927
1923	1421	1954	842
1924	2051	1955	1438
1925	1939	1956	847
1926	1785	1957	942
1927	1928	1958	1009
1928	1989	1959	-
1929	1996	1960	697
1930	1277	1961	974
1931	681	1962	920
1932	963	1963	1050
1933	1241	1964	1138
1934	967	1965	1077
1935	1026	1966	921
1936	1052	1967	737
1937	948	1968	768
1938	1142		

APPENDIX II

SOUTH WEST AFRICAN TIN PRODUCTION FOR THE PERIOD 1954 TO 1966

Year	Tons (Metallic Tin)	Year	Tons (Metallic Tin)
1954	Not available	1961	649
1955	449	1962	644
1956	649	1963	843
1957	809	1964	740
1958	113	1965	659
1959	4	1966	680
1960	541		

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KEY TO FIGURES

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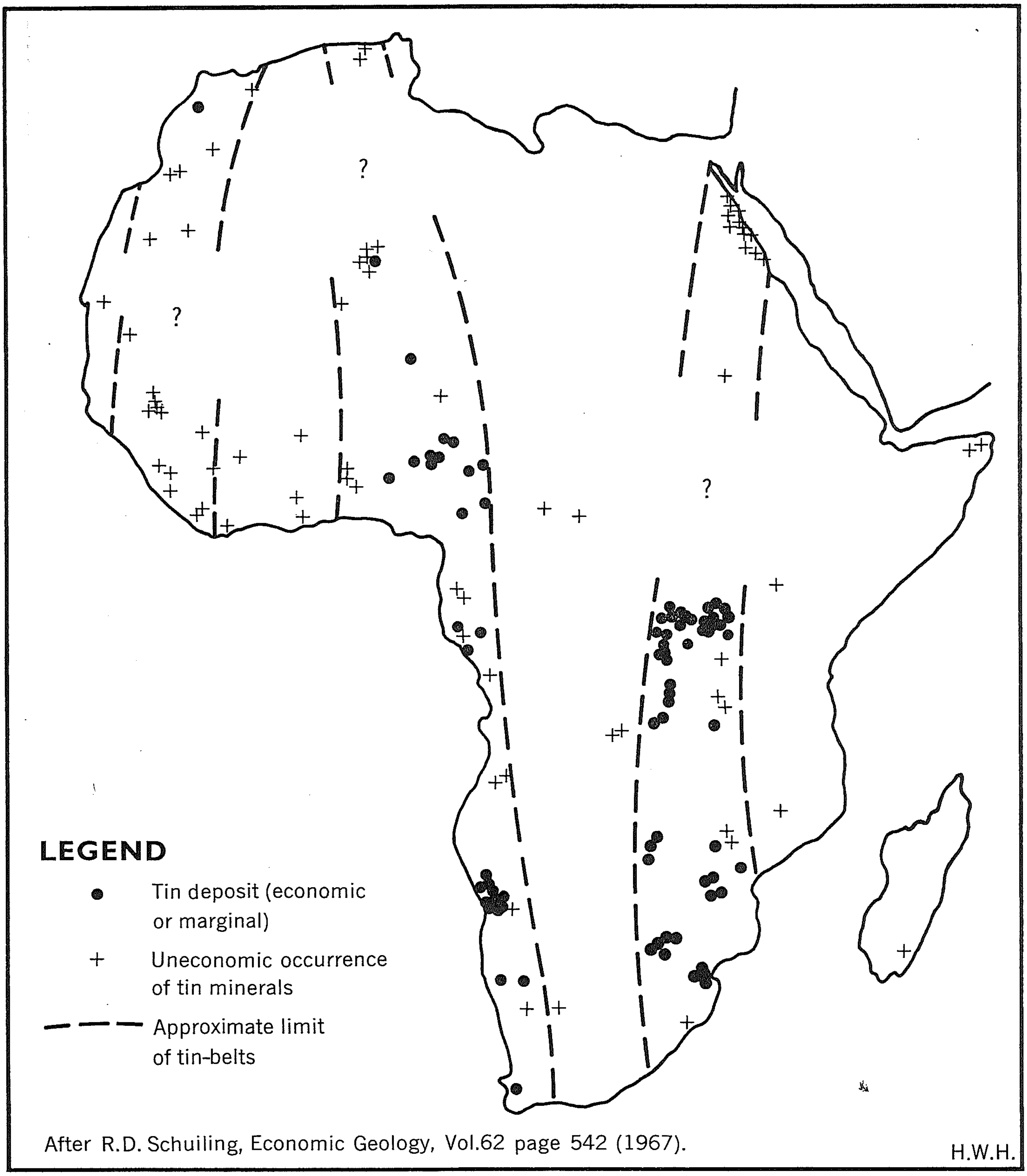
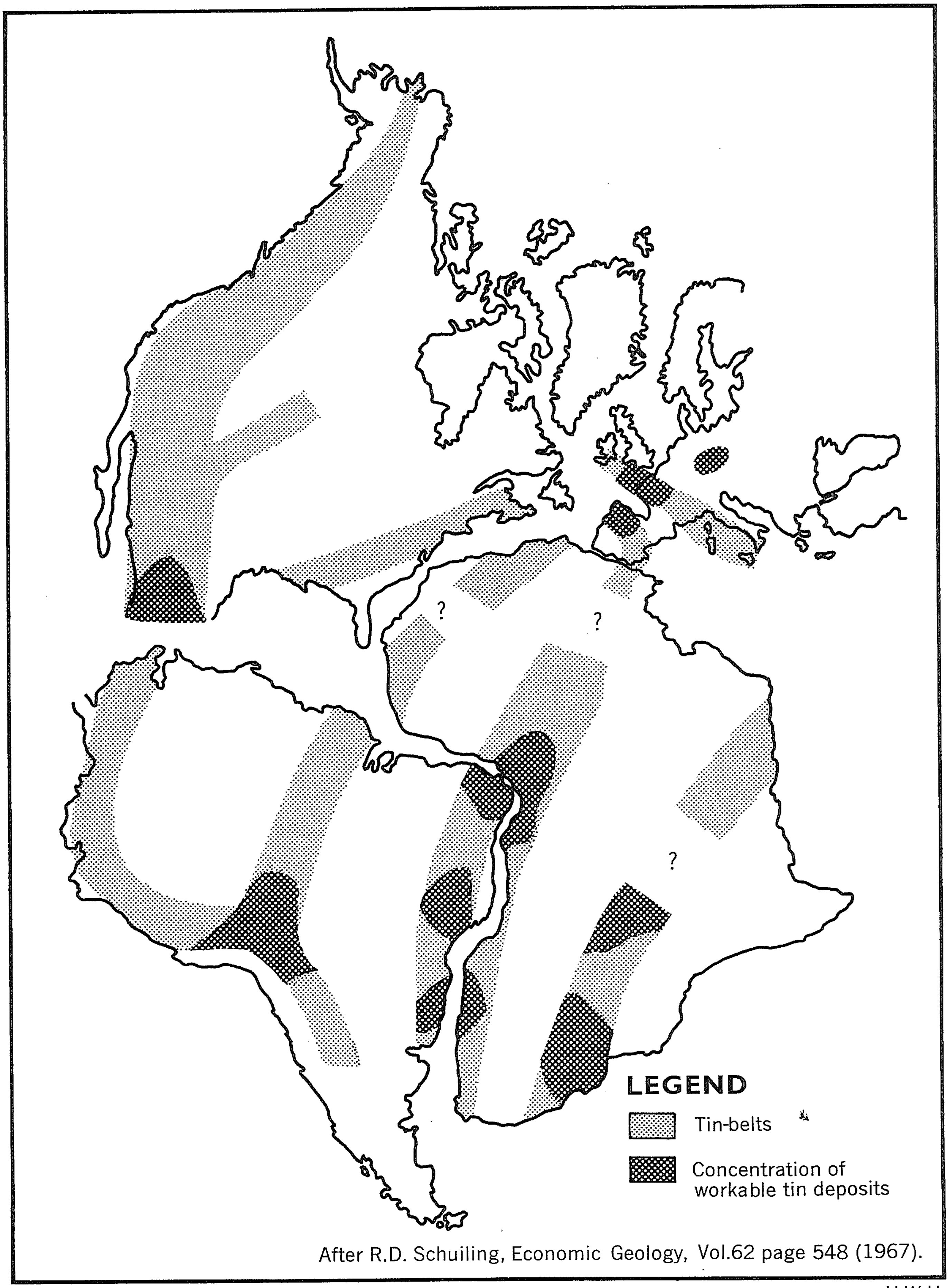


Figure 1. Distribution of tin mineralization on the African continent



H.W.H.

Figure 2. Position of tin-belts on a reconstruction of the continents

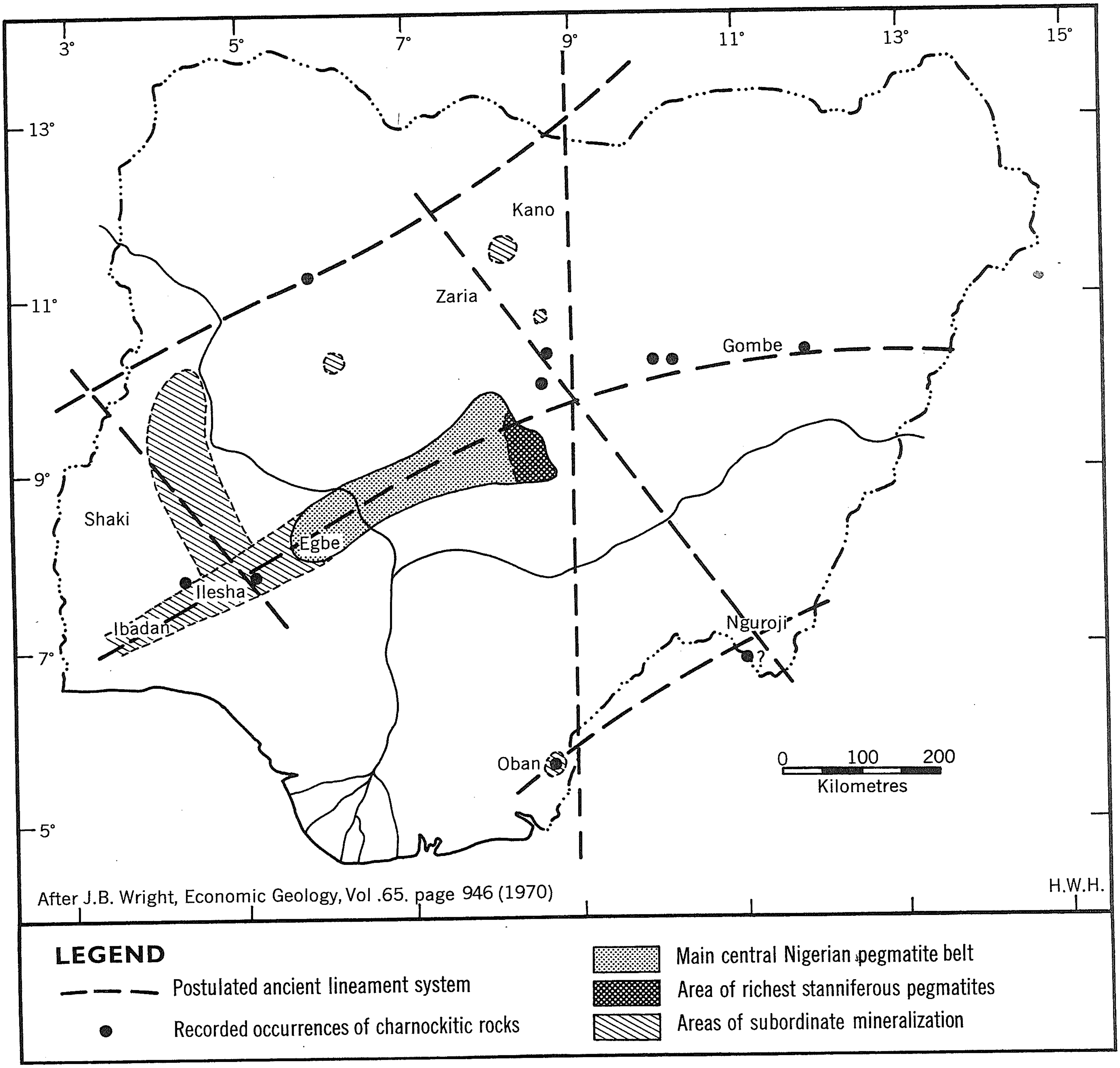


Figure 3. Distribution of tin mineralization associated with Older Granites in Nigeria

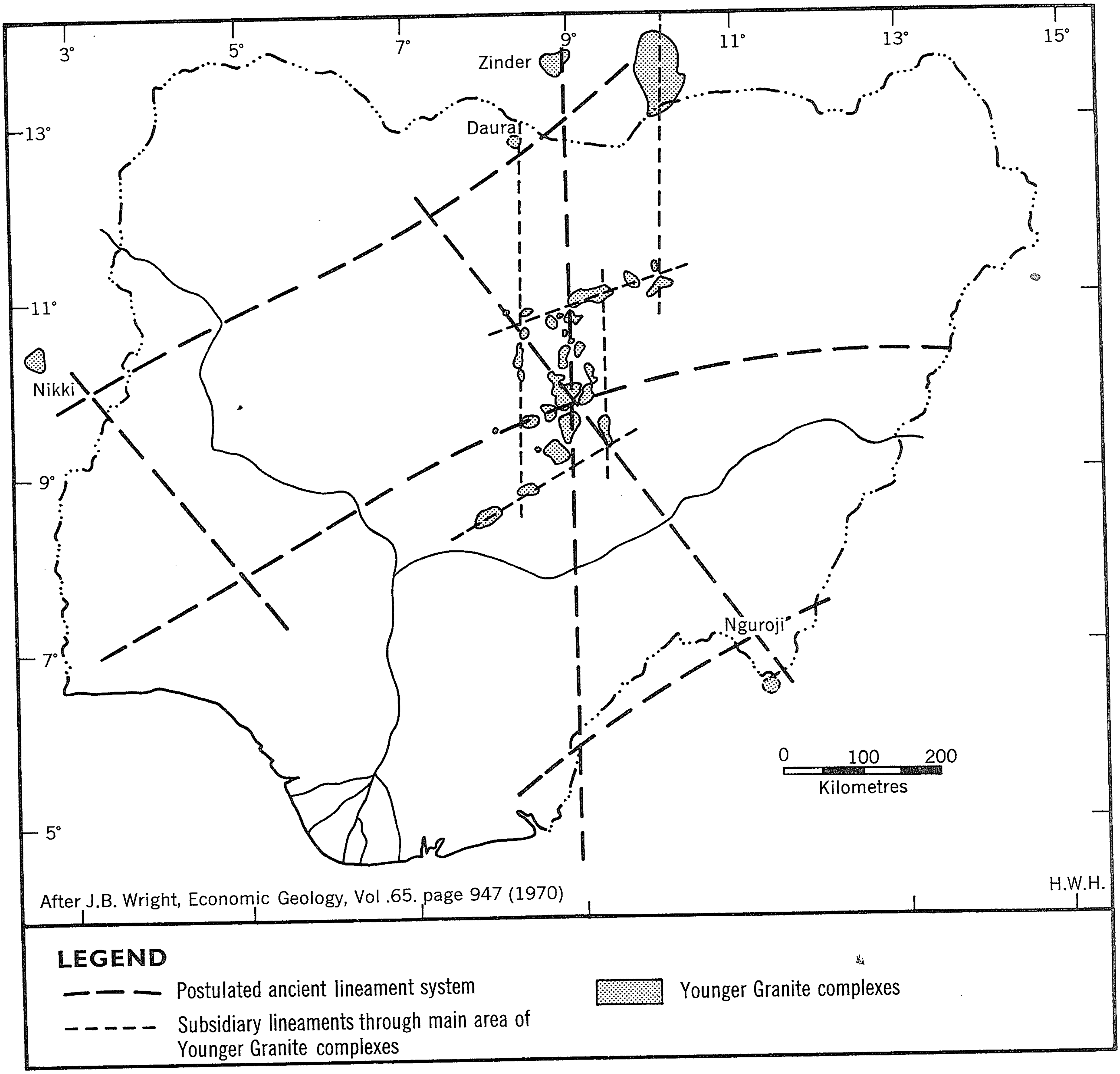


Figure 4. Distribution of Younger Granite complexes in Nigeria

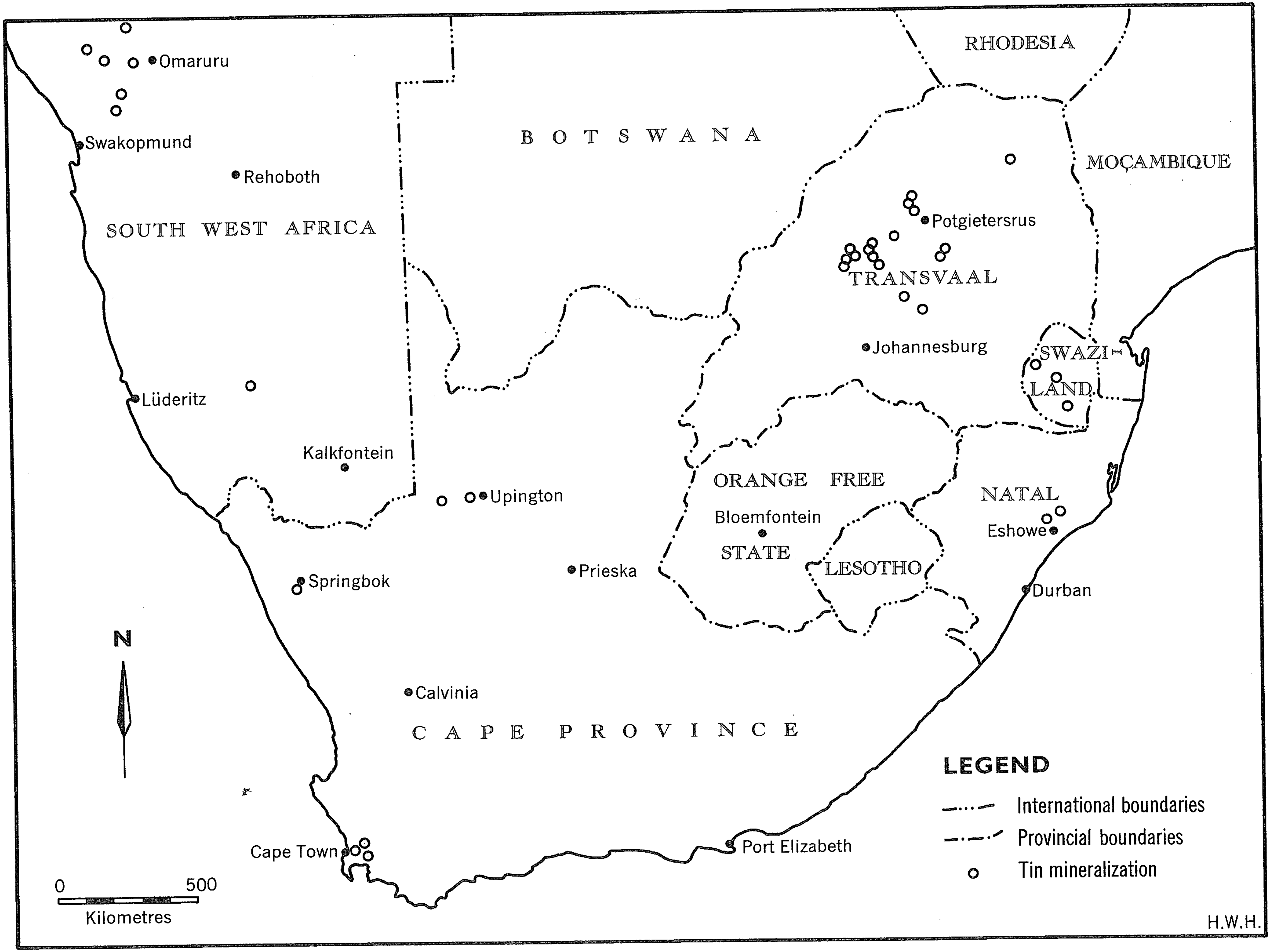


Figure 5. Generalized map showing the distribution of occurrences of tin mineralization in South Africa, South West Africa and Swaziland

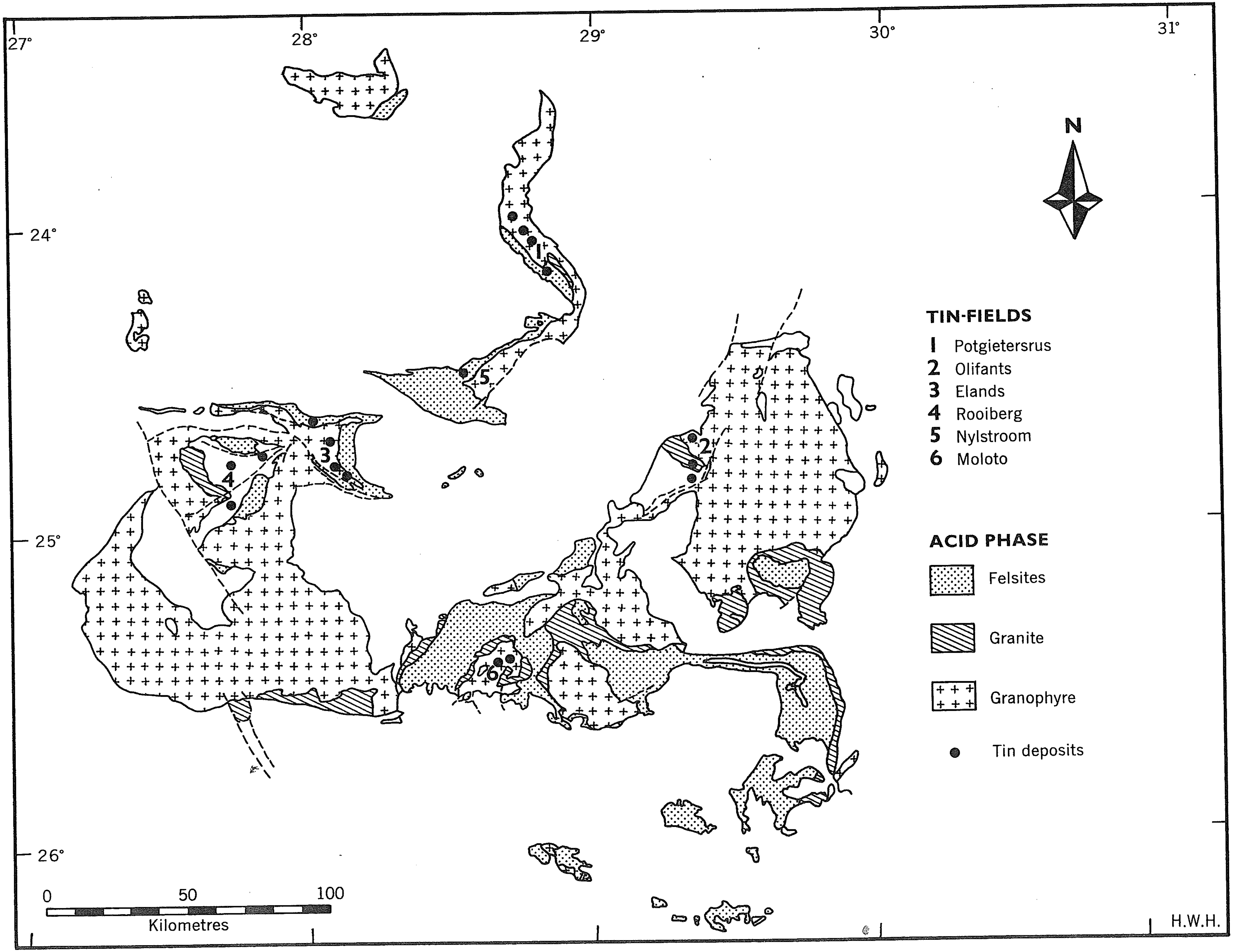


Figure 6. The distribution of tin-fields in the acid phase of the Bushveld Igneous Complex