A GEOCHEMICAL AND PETROGRAPHICAL INVESTIGATION OF THE LOW-GRADE TIN DEPOSITS IN THE BOBBEJAANKOP GRANITE AT THE ZAAIPLAATS TIN MINE

by

JAPIE COETZEE

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ABSTRACT

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JAPIE COETZEE

SUPERVISOR: PROF. DR. G. VON GRUENEWALDT
CO-SUPERVISOR: DR. D. TWIST

DEPARTMENT: GEOLOGY

DEGREE: M.Sc.

Low-grade tin deposits occur within the apex of the Bobbejaankop Granite intrusion at the Zaaiplaats Tin Mine. The fine-grained hood-facies of the Bobbejaankop Granite, called the Lease Granite, seems to be intrusive into granophyric granite of the Rashoop Granophyre Suite. However no clear evidence could be found to support the general view that the Bobbejaankop Granite itself is intrusive into the granophyric granite. Tin mineralization is confined to the Bobbejaankop and Lease granites, where the following types of mineralization are developed: low-grade disseminated orebodies in both granites; highly enriched pipe-like metasomatic orebodies in both granites; high grade greisenized orebodies in the Lease Granite.

The area was geologically mapped on a 1:1 000 scale. A series of 5 boreholes was drilled on a straight line across the intrusion. The borehole core was logged, continuously sampled and analysed for Sn, W, Cu, Pb, Zn, Mo, As, Sb, Th, U, Rb, Sr, Y, Ba, Zr, Nb, Ti, P, Mn, Fe, S, CO_2 and F. Selected samples from the different granites and low-grade ore in Bobbejaankop Granite were also analysed for major elements.

The analytical results indicate that the orebodies occur within a definite zone conformable with the outlines of the intrusion and characterized by anomalously high Sn values ($>$ 35 p.p.m.). Distribution patterns of major elements show no drastic variations in the tin-rich zone. However, a significant increase in Na and a decrease in K is present. The Na and K

variations together with petrographic evidence indicate that albitization has occurred. W, As, S, and F are usually enriched within the tin-rich zone. There are no geochemical haloes and no mineralogical or chemical zonations associated with the tin-rich zone. Cassiterite is disseminated through the tin-rich zone and occurs interstitially. These observations indicate that the cassiterite of the low-grade tin deposits has a primary magmatic origin. The orebodies are further considered as locally enriched portions of the tin-rich zone.

Geochemically the Bobbejaankop and Lease granites are almost identical, although the latter is slightly depleted in F and slightly enriched in Nb. Their similarity indicates that they probably crystallized from the same magma. Compared to both these rocks, the granophyric granite is enriched in Ti, Fe, Mn, P, Ba, Zn and Zr and depleted in Rb, Y, Nb, Th, U and F, which indicates that the granophyric granite is less differentiated than the Bobbejaankop and Lease granites. These sharp changes, occurring exactly on the contact of the granophyric and Lease granites, unquestionably indicate that the latter has not originated through metasomatism of the granophyric granite. The relatively high Nb, Y, W, Mo, Sn, Pb and Zn contents of the Bobbejaankop and Lease granites indicate that they should be classified as A-type granites.

The abundance of incompatible elements, volatiles and metasomatic minerals together with the occurrence of vugs and miarolitic cavities, suggest that the Bobbejaankop and Lease granites are late differentiates that crystallized from a fluid and volatile-enriched magma that intruded at a high level. The Lease granite probably represents a quenched product of fluids and volatiles that was concentrated at the top of the Bobbejaankop Granite magma. The low-grade orebodies probably originated through simple crystallization of a cooling magma which was locally more highly enriched in fluids and volatiles, due to the concentration of the latter beneath an impermeable roof of crystallized granite.

SAMEVATTENDE OORSIG

'N GEOCHEMIESE EN PETROGRAFIESE ONDERSOEK NA DIE LAEGRAADSE TINAFSETTINGS IN DIE BOBBEJAANKOPGRANIET BY DIE ZAAIPLAATS TINMYN

JAPIE COETZEE

STUDIELEIER: PROF.DR. G. VON GRUENEWALDT
MEDE-STUDIELEIER: DR. D. TWIST

DEPARTEMENT: GEOLOGIE
GRAAD: M.Sc.

Laegraadse tinafsettings kom voor in die boonste gedeelte van die Bobbejaankopgranietintrusie by die Zaaiplaats tinmyn. Die fyne-korrelrige dakfase van die Bobbejaankopgraniet, die Leasegraniet, blyk intrusief te wees in die granofiriese graniet van die Suite Rashoopgranofier. Daar is geen getuienis wat daarop dui dat die Bobbejaankopgraniet wel intrusief in die granofiriese graniet is nie. Tinmineralisasie is beperk tot die Bobbejaankop- en Lease graniete waar die volgende tipes mineralisasie voorkom: laegraadse gedissemineerde ertsliggame in beide graniete; hoogsverrykte metasomatiese, pypagtige ertsliggame in beide graniete; hoëgraadse greisenagtige ertsliggame in Leasegraniet.

Die gebied is geologies op 'n 1:1 000 skaal gekarteer. 'n Reeks van 5 boorgate is op 'n reguit lyn dwarsoor die intrusie geboor. Die boorgatkern is beskryf, ononderbroke bemonster en geanaliseer vir Sn, W, Cu, Pb, Zn, Mo, As, Sb, Th, U, Rb, Sr, Y, Ba, Zr, Nb, Ti, P, Fe, Mn, S, CO_2 en F. Geselekteerde monsters van Bobbejaankopgraniet is geanaliseer vir die volle reeks hoofelemente.

Heelrotsanalises dui daarop dat die laegraadse ertsliggame voorkom in 'n bepaalde sone parallel aan die buitelyne van die intrusie en gekarakteriseer deur anomaal hoë Sn waardes (> 35 d.p.m.). Verspreidingspatrone van hoofelemente toon geen drastiese variasies in die tinryke sone nie, alhoewel 'n kleiner maar tog betekenisvolle toename in Na en 'n afname in K voorkom. Die Na en K variasies, tesame met petrografiese getuienis,

dui daarop dat albitisasie voorkom. W, As, S en F is gewoonlik verryk in die tinryke sone. Geen geochemiese halos en geen mineralogiese of chemiese sonering word in assosiasie met die tinryke sone aangetref nie. Kassiteriet kom gedissemineerd en interstisieel voor in die tinryke sone. Hierdie waarnemings dui daarop dat die laegraadse Sn-afsettings 'n primêr-magmatiese oorsprong het. Hulle word verder beskou as lokaal verrykte gedeeltes van die tinryke sone.

Geochemies is die Bobbejaankop- en Lease graniete feitlik identies, alhoewel laasgenoemde effens verarm is in F en effens verryk is in Nb. Dit dui daarop dat die Bobbejaankop- en Lease graniete waarskynlik vanuit dieselfde magma gevorm het. In vergelyking met beide hierdie graniete, is die granofiriese graniet merkbaar verryk in Ti, Fe, Mn, P, Ba, Zn en Zr en verarm in Rb, Y, Nb, Th, U en F, wat daarop dui dat die granofiriese graniet minder gedifferensieerd as die Bobbejaankop- en Lease graniete is. Hierdie skerp veranderinge kom presies op die kontak van die Leasegraniet met die granofiriese graniet voor en dui onteenseglik daarop dat die Leasegraniet nie gevorm het deur metasomatose van die granofiriese graniet nie. Die relatief hoë Nb, Y, W, Mo, Sn, Pb en Zn inhoud van die Bobbejaankop- en Leasegraniete dui daarop dat hulle as A-tipe graniete geklassifiseer behoort te word.

Die hoë konsentrasie van onversoenbare elemente, vlugtige bestanddele en metasomatiese minerale, asook die voorkoms van kristal- en miarolitiese holtes, dui daarop dat die Bobbejaankop- en Leasegraniete laat differensiate voorstel en gekristalliseer het vanaf magma, lokaal verryk in vlugtige bestanddele. Hierdie magma het waarskynlik ook vlak ingedring. Die Leasegraniet verteenwoordig waarskynlik 'n kil-produk van vloeistowwe en vlugtige bestanddele wat gekonsentreer is in die top van die Bobbejaankopgranietmagma. Die laegraadse ertsliggame het waarskynlik ontstaan d.m.v. kristallisasie volgens die gewone kristallisasie volgorde van 'n afkoelende magma, wat in hierdie geval lokaal verryk in vloeistowwe en vlugtige bestanddele a.g.v. die konsentrasie van laasgenoemde onder 'n ondeurlatende dak van gekristalliseerde graniet.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 GENERAL

The Zaaiplaats Tin Mine, is situated on the farm Zaaiplaats 223KR, approximately 35 kilometres northwest of Potgietersrus (Fig. 1). The area, comprising mainly granites of the northern limb of the Bushveld Complex, has been well known for its tin deposits from the beginning of this century. Shortly after the discovery of cassiterite deposits on Zaaiplaats 223KR, in 1906, several additional deposits were located through prospecting on the nearby farms Roodepoort 222KR, Salomon's Temple 230KR, Groenvlei 224KR, Groenfontein 227KR and Appingendam 805LR. Since then the area has generally been referred to as the Potgietersrus tin field. Several small mines were established on some of the farms mentioned above. Prior to 1926 the bulk of ore mined was derived from very rich outcropping pipe-like and lenticular orebodies. An appreciable amount of ore also originated from alluvial workings.
In the post 1930's, the massive low-grade ore of the Bobbejaankop Granite became of major importance as the number of unworked pipes decreased rapidly. Occurrences of low-grade ore in Bobbejaankop Granite are only known from Zaaiplaats and Roodepoort. Because of these the Zaaiplaats mine proved to be the most continuous producer of tin in the area and is presently the only producer; it has an average production of 18 metric tons of metallic tin per month.

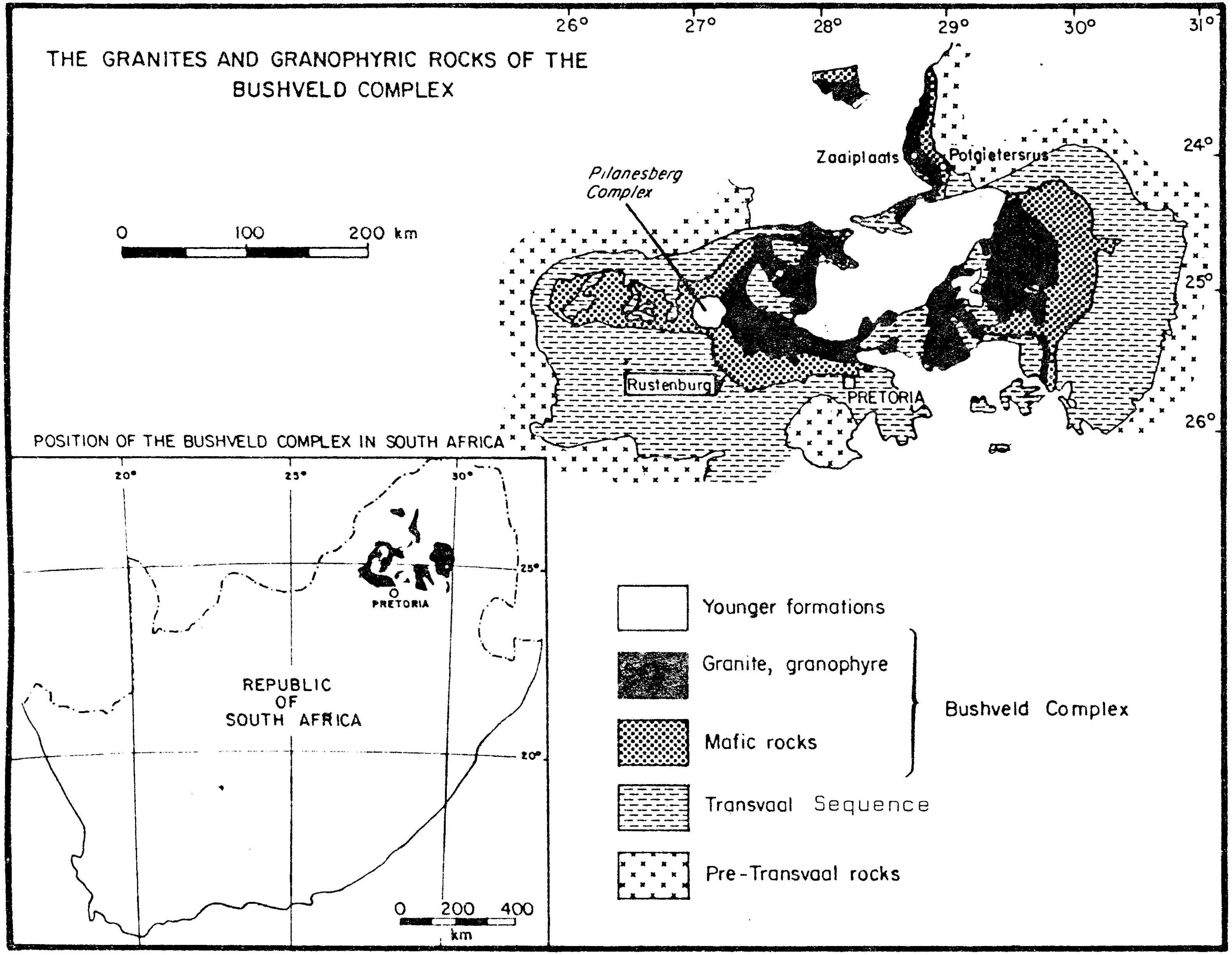


Fig. 1: Map showing the location of Zaaiplaats in relation to the Bushveld Complex.

1.2 PREVIOUS INVESTIGATIONS

The Zaaiplaats area has been the subject of numerous investigations in the past. Four distinct periods of intensive investigation can be identified, namely, 1906 to 1912, 1924 to 1932, 1940 to 1954 and 1970 to the present.

The first publication on tin deposits of the Potgietersrus area was written by Johnson (1907) shortly after the discovery of tin on Zaaiplaats and the nearby farms. This work, as well as the other early publications (e.g. Kynaston, 1908, 1909; Merensky, 1908; Kynaston and Mellor, 1909), rendered broad descriptions of the ore deposits and their associated granites, and contained only limited speculation on the origin of the tin mineralization. Early summaries of all the available geological information were presented by Kynaston, Mellor and Hall (1911) and by Hall (1932).

In the following period (1940 - 1954) investigations became more specialized and descriptions more detailed, such as the description and classification of the granites by Strauss and Truter (1944). A mineralogical investigation of the Zaaiplaats tin deposits, the only one up to date, was provided by Söhnge (1944), who concentrated mainly on the lenticular and pipe-like orebodies. The most comprehensive description of the ore deposits and their associated granites is undoubtedly that by Strauss (1954).

Publications since the late 1960's have mainly been concerned with intensive geochemical investigations of the granites. Earlier work of this nature was carried out by Fourie (1969) and Lenthall (1972), but the most comprehensive geochemical investigation was made by Lenthall and Hunter (1977), who managed to discriminate between the granites on the basis of trace element contents. However, in all these studies the economically important Bobbejaankop and Lease granites received subordinate attention.

The origin of the Bushveld granites and to a lesser extent the tin-bearing granites, was considered on geochemical grounds by various investigators. Genetic models proposed by McCarthy and Hasty (1976), Groves and McCarthy (1978) and McCarthy and Fripp (1980) suggest that the various granites originated through differentiation of a single parent magma by a process of in situ fractional crystallization; the Bobbejaankop Granite representing a late differentiate. The views of these authors and those of Strauss (1954), De Waal (1972) and Crocker (1981) illustrate the intense debate that has surrounded the origin of all these granites, and particularly the Lease and granophyric granites.

The only geochemical investigation of the tin deposits themselves was performed by Strydom (1983), who examined the pipe-like orebodies at Zaaiplaats and identified distinct wall-rock zonation of trace elements around them.

Wall-rock alteration had first been documented by Söhnge (1944).

As indicated by the works of Strauss (1954) and Crocker (1979, 1981) there have been no major controvercies concerning the classification of the ore deposits.

The pipe-like and lenticular orebodies have been described and discussed in much detail. Intensive geochemical and mineralogical studies were made on the pipe-like orebodies. However, the zone of low-grade disseminated mineralization has received little attention by researchers in the past.

1.3 REGIONAL GEOLOGY AND PHYSIOGRAPHY

The formations occurring in the Zaaiplaats district (Fig. 2) are indicated below in chronological order:

Recent Deposits	Sand, soil, ferricrete, etc.
Post-Karoo Intrusions	Dolerite
Post-Waterberg Intrusions	Diabase
Waterberg Group	Sandstone, grit, conglomerate
Bushveld Complex:	
Lebowa Granite Suite	Granite
Rashoop Granophyre Suite	Granophyre, granophyric granite.
Rustenburg Layered Suite	Norite, gabbro, anorthosite, diorite, etc.
Transvaal Sequence:	
Rooiberg Group	Felsite with intercalated shales and breccia
Unclassified (Pretoria Group?)	Quarzite, hornfels, leptite, pseudogranophyre, rheomorphic breccia

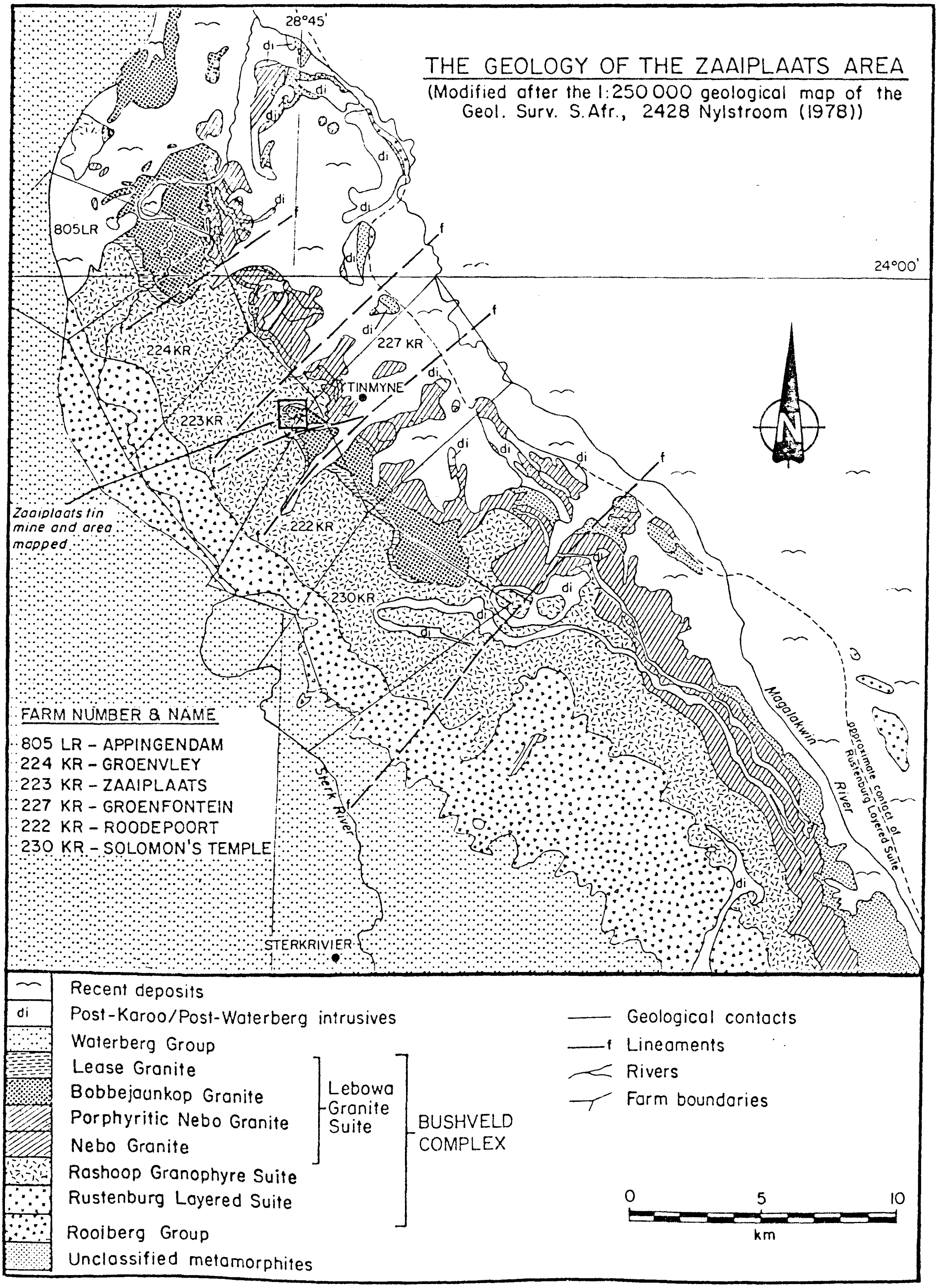


Fig.2: A regional geological map of the Zaaiplaats district showing the area investigated.

The stratigraphic nomenclature used is that proposed by SACS (1980).

A very close relation between physiography and geology exists in this area. The prominent mountain range, the Makapaansberg, trends in a roughly northwesterly direction from Potgietersrus, and comprises acid rocks, mainly granites of the Bushveld Complex and felsites of the Rooiberg Group. Immediately below the steep northern flanks prominent foothills are developed that consist of a porphyritic variety of Nebo Granite, previously known as the Foothills Granite (Strauss, 1954). The broad valley north of the mountain range is occupied by the layered mafic rocks of the Bushveld Complex. The Magalakwin River, that drains this area, approximately follows the contact between the acid and mafic rocks of the Bushveld Complex. A thin discontinuous outcrop of highly metamorphosed sediments, probably belonging to the upper Pretoria Group, occurs along this contact. The gently dipping southwestern slopes of the Makapaansberg are bordered by the valley of the Sterk River, which is responsible for the drainage of this area. Immediately to the west of the river the felsites of the Rooiberg Group are overlain by sediments of the Waterberg Group, which give rise to a prominent escarpment further to the west. The negative erosion of younger mafic sills and dykes gives rise to prominent linear features.

Structurally, the area lies within the northeastern flank of a regional basin structure of Post-Waterberg age. The general strike of the formations is roughly northwest-southeast and the dip varies between 10° to 20° south-west. Tilting of the rocks of the Bushveld Complex and Rooiberg Group commenced before the deposition of Waterberg sediments in this area, causing an angular dis-cordance between them.

Several Post-Karoo faults, trending southwest-northeast occur. Most of them are normal faults with small down-throws to the southeast.

The Rooiberg felsites overlie a composite granite sheet and contain a band of intercalated shales and breccias that is conformable to a pseudo-layering present in the rocks of the Rashoop Granophyre Suite.

The thin sequence of highly metamorphosed rocks that out-crop along the contact of the mafic and acid phases of the Bushveld Complex shows vertical and lateral variations in lithology, and in places one rock type grades into a-nother (Strauss, 1954). To date, no typical stratigra-phic succession has been suggested. The extensive me-tamorphism of these rocks was probably caused by the in-trusion of the mafic phase of the Bushveld Complex (De Waal, 1972).

The mafic layered rocks of the Bushveld Complex, mainly represented by gabbros and olivine diorites, are not well exposed. A thin persistent magnetite layer of the upper zone of the Rustenburg Layered Suite is developed near the contact with the metamorphic sequence.

The upper portion of the composite granite sheet is represented by granophyric granite and granophyre of the Rashoop Granophyre Suite. Previously it has been classified as part of the Main Granite (Strauss and Truter, 1944), or Main Suite (De Waal, 1972). Walraven (1982) considers the granophyric granite as a granophyric facies of the Nebo Granite, confined to the immediate vicinity of the Bobbejaankop Granite domes. A prominent layered structure is exhibited by the granophyric rocks in this area, which in the past has been explained as pseudo-layering caused by "distinct variational facies" (Strauss, 1954) or different degrees of metamorphism of porphyritic rocks (De Waal, 1972). This layering is parallel to the sides of the sheet, which in turn is approximately parallel to the bedding of the metamorphosed upper Pretoria Group (?) and to the contact of the mafic rocks of the Bushveld Complex. Age dating by Faurie and Von Gruenewaldt (1979) indicates that the rocks of the Rashoop Granophyre Suite in this area (2 000 ± 24 Ma), are definately younger than the Rustenburg Layered Suite (2 095 ± 24 Ma.; Hamilton, 1977). Lenthall and Hunter (1977) name the granophyric rocks in contact with Bobbejaankop Granite the "Groenfontein Granophyre".

The Lebowa Granite Suite in this area is represented by the Lease Granite, Bobbejaankop Granite and the Nebo Granite. The Bobbejaankop and Lease granites are classified under the Nebo Granite on the most recent 1 : 250 000 geological map, 2428 Nylstroom. However, they are lithologically acknowledged as individual granites by SACS (1980), and will be referred to as such in this investigation.

According to map sheet 2428 Nylstroom, the Nebo Granite includes coarse-grained, leucocratic and mesocratic granites, previously named the Main Granite by Strauss (1954) or the Main Suite by De Waal (1972), as well as a fine-grained porphyritic variety previously known as the Foothills Granite (Strauss, 1954).

The granites occur at the base of a sheet-like intrusion approximately 2 700 meters in thickness, developed between the overlying felsites and underlying metamorphosed Transvaal (?) rocks. According to Strauss (1954) the Nebo Granite is intruded by the Bobbejaankop and Lease granites. A fine-grained porphyritic granite is also intrusive into both the Nebo Granite and the Rustenburg Layered Suite as numerous sills and dykes. This granite, previously known as the Foothills Granite (Strauss, 1954), is classified under the Nebo Granite on the Nylstroom map. The name "Foothills Granite" is not acknowledged by SACS (1980). Walraven (1982) states that it should be correlated with the Klipkloof Granite. It is best exposed northeast of the Makapaansberg, where it forms the prominent foothills after which it was previously named. De Waal (1972) states that the porphyric granite originated through palingenesis, when some Transvaal sediments were highly metamorphosed by the intrusion of the mafic phase of the Bushveld Complex. Crocker (1981) considers the Lease and porphyritic Nebo granites as one and the same granite. However, during fieldwork in the Zaaiplaats area, the author found no evidence in support of Crocker's claim. The porphyritic granite could never be followed through to the Lease Granite in spite of abundant outcrop. Moreover microscopic investigations have revealed that the typical granophyric textures of the Lease Granite are absent from the porphyritic granite and the porphyritic textures of the latter are not found in the Lease Granite. Therefore the author considers them as different granites.

The Bobbejaankop Granite is economically the most important granite of the Bushveld Complex because of its genetic association with cassiterite, scheelite, molybdenite, bastnaesite and sphalerite deposits. The relation between this red, highly metasomatised granite and the cassiterite deposits, was noted and emphasized by various authors in the past (Merensky, 1908; Söhnge, 1943; Strauss, 1954). The Bobbejaankop Granite mainly occurs as flat-topped domes which were, according to Strauss (1954) intruded into the Nebo Granite as well as into the granophyric granite and granophyre of the Rashoop Granophyre Suite. To the northeast of the Zaaiplaats mine it also intrudes the porphyritic variety of Nebo Granite. The domes of Bobbejaankop Granite are invariably accompanied by a cap of a fine-grained granite, the Lease Granite. The origin of the Bobbejaankop Granite is still debatable. De Waal (1972) suggest that it was intruded under truly plutonic conditions, but Crocker (1981) regards it as a highly metasomatised facies of the upper portion of the Nebo Granite, represented by a coarse-grained gray leucocratic variety that also intruded under truly plutonic conditions.

The fine-grained, highly metasomatised Lease Granite is economically of great importance because of its associated cassiterite and scheelite deposits. It has invariably been found in association with the Bobbejaankop Granite, where it occurs predominantly as lenticular, sheet-like masses in the roof arches. A pegmatite zone is normally developed in the upper portion of Lease Granite, on or near its contact with the overlying granophyric granite. For many years the Lease Granite was considered as a chilled phase of the Bobbejaankop Granite (Wagner, 1929), because of its restriction to the upper portion of the latter, and its intrusive relationship with the granophyric rocks. Strauss and Truter (1944), however, found the Lease Granite to be intrusive into the Bobbejaankop Granite and therefore considered it to be either an in situ reaction product of the latter with rising fluids, or a separate later intrusion. A model in which the Lease Granite represents a highly metamorphosed and metasomatised product of the granophyric granite of the Rashoop Granophyre Suite was proposed by De Waal (1972).

The rocks of the Waterberg Group that unconformably overlie the Rooiberg felsites, are represented in this area mainly by a very coarse-grained, massively bedded conglomerate. A pronounced erosional unconformity exists between these sediments and the underlying formations.

Intrusive into all the rocks described thus far are Post-Waterberg sills and dykes of medium-grained, grey diabase, and dolerite dykes of Post-Karoo age.

In summary, the sequence of geological events that occurred in the area as proposed by Strauss (1954) and De Waal (1972) is presented in Table 1.

Table 1: A summary of the sequence of geological events in the Zaaiplaats area.

Strauss (1954)	De Waal (1972)
1) Deposition of the Transvaal sediments.	1) Deposition of the Transvaal sediments.
2) Extrusion of the Rooiberg felsites.	2) Extrusion of the Rooiberg felsites.
3) Intrusion of the Main Granite as a sheet between the upper Transvaal (?) sediments and the felsites.	3) Multiple intrusions of granite porphyry sheets into the lower portions of the felsite pile.
4) Intrusion of the layered mafic rocks of the Bushveld Complex with extensive metamorphism of the upper Transvaal (?) sediments.	4) Intrusion of the layered mafic rocks of the Bushveld Complex causing various degrees of metamorphism of the porphyry sheets giving rise to a pseudo-layered granite sheet (Main Suite) and causing severe metamorphism of the upper Transvaal (?) sediments, which were partly melted and intruded to form the Foothills Granite.
5) Intrusion of the Foothills Granite.	5) Intrusion of the Bobbejaankop Granite with consequent metamorphism of granophyric granite to produce the Lease Granite.
6) Intrusion of the Bobbekaankop Granite.	
7) Formation or intrusion of the Lease Granite.	
8) Tilting of formations.	
9) Deposition of the Waterberg sediments	
10) Post-Waterberg tilting and intrusion of diabase dykes and sills.	("Main Granite" includes Nebo Granite)
11) Post-Karoo deformation and intrusion of dolerite dykes.	("Main Suite" includes Nebo Granite)

1.4 THE PRESENT INVESTIGATION - AIMS AND APPROACH

Through a study of previous investigations, the low-grade tin ore of the Bobbejaankop Granite was identified as one of the gaps in present knowledge of tin deposits in the area. No specialized research work has ever been done on this type of ore, although it has proved to be the most reliable source of tin in the Potgietersrus district for the past 50 years. Because this type of deposit is very well developed at Zaaiplaats, the Zaaiplaats Tin Mine was chosen as the most suitable area for this investigation.

The aim of this study was to contribute to the present knowledge and understanding of the low-grade tin deposits of the Bobbejaankop Granite by making a geochemical and petrographical study of the ore and related granite in the hope of determining distinguishing criteria that may be useful in future exploration for such orebodies. The following aspects therefore received major attention during this investigation:

i) Field relations and structure of the ore deposit.
ii) Petrographic and geochemical characteristics of mineralized and unmineralized Bobbejaankop Granite.
iii) Petrographic and geochemical characteristics of the different granites.
iv) Petrogenetic aspects of the ore deposit.

In order to achieve the above-mentioned aims, the author spent the second semester of 1982 at the Zaaiplaats Tin Mine. During this period a geological map of the area on a scale of 1:1 000 was constructed by plane table mapping (Folder 1; Back cover).

A series of 5 boreholes, more or less evenly spaced over a stretch of approximately 1 kilometer, were drilled on a straight line perpendicular to the local strike of the formations. The locations of the boreholes were chosen in such a way as to exclude as many geological disturbances as possible e.g. faults and joints (Fig. 3; Folder 1).

The most northern borehole, GS74, is shallow and was drilled in order to determine the dip of the northern contact of the Bobbejaankop and Lease granites with the surrounding rocks. The remaining boreholes penetrated a zone of tin enrichment in Bobbejaankop Granite - a zone that clearly encloses all the economical low-grade orebodies. An additional borehole, GS72 (Folder 1), was drilled in the middle of an area where the low-grade deposits were very well developed and large amounts of ore already extracted. Each of the boreholes was geologically logged in detail and sampled continuously over their whole length for whole-rock analyses. The average core recovery was better than 95 per cent.

All the data obtained were statistically processed and are graphically presented. Thin sections of the ore, gangue and host rocks were prepared from borehole core for petrographic investigation.

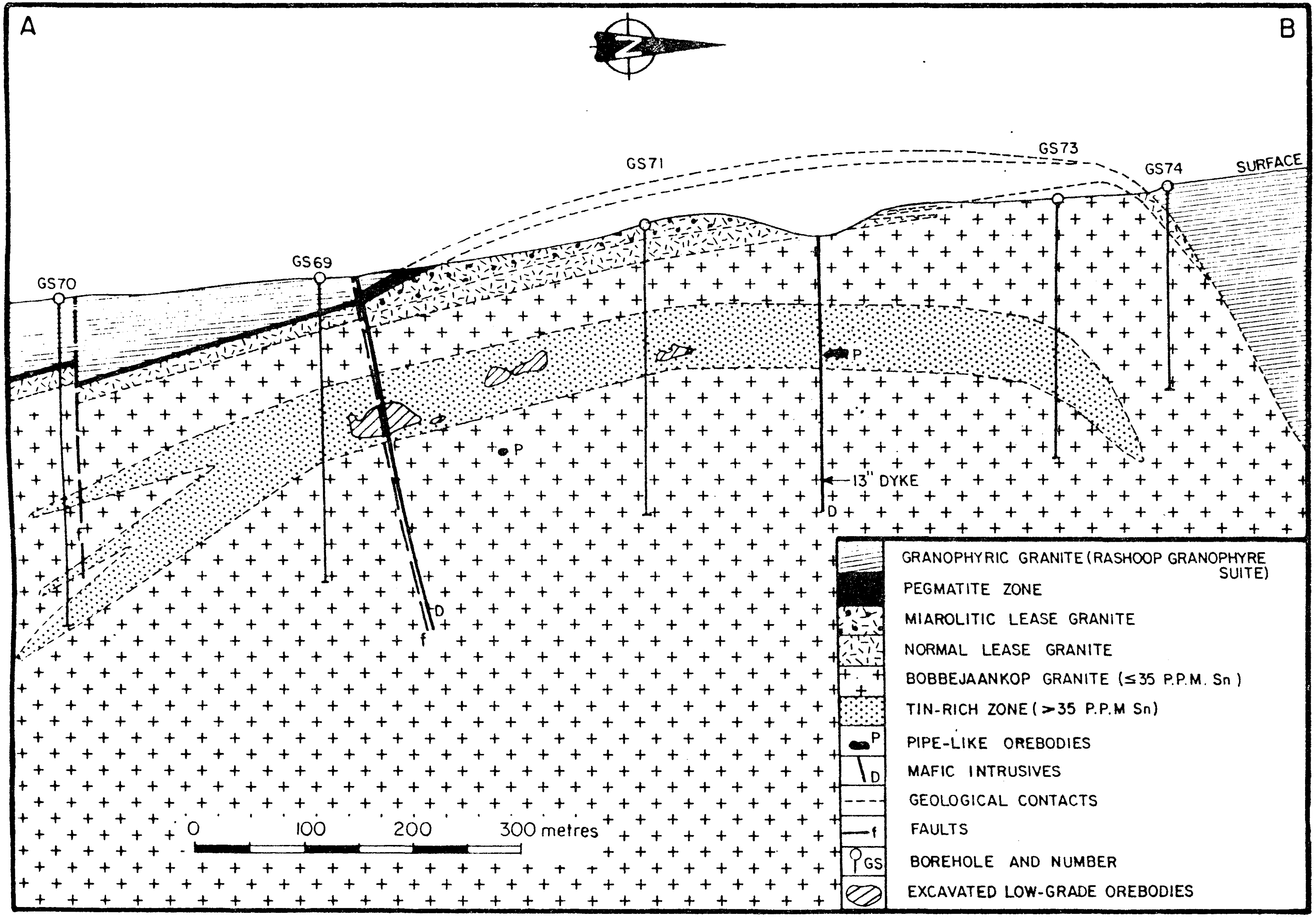


Fig. 3: Geological section (AB) of the accompanying map (Folder 1, back cover) showing the tin-rich zone and locations of the boreholes. (Vertical scale = horizontal scale)

2. STRUCTURE AND FIELD RELATIONS AT ZAAIPLAATS

2.1 HOST ROCKS

The Zaaiplaats Tin Mine is situated on the north-western apex of an approximately flat-topped, oblong intrusion of Bobbejaankop Granite, which extends southeasterly as far as Solomon's Temple 230 KR (Fig. 2). The Bobbejaankop Granite has intruded into the granophyric granite (Rashoop Granophyre Suite) and on the southwestern flank of the intrusion the contact strikes northwest-southeast and dips to the southwest at 10^{o} - 15^{o}. This conforms with the regional strike and dip of the formations in the area. On the northeastern flank of the intrusion the contact dips sharply at 70^{o} to the northeast. When the rocks are tilted back to their Pre-Waterberg position this northeastern contact is near vertical, suggesting that it represents the truncation of a sheet-like intrusion (Strauss, 1954).

The rocks of the Zaaiplaats mine, arranged in chronological order, comprise the following:

Mafic sills and dykes
Lease Granite (with associated pegmatite)
Bobbejaankop Granite
Granophyric granite (Rashoop Granophyre Suite)

Except for the mafic intrusion, all the rocks are very well exposed.

The granophyric granite, unrelated to the local cassiterite deposits, forms part of a thick sheet-like intrusion that strikes roughly northwest-southeast and dips between 10° - 15° to the southwest. The structure conforms to that of the region and is locally further accentuated by jointing parallel to the dip of the rocks. This must not be confused with the pseudo-layering described by Strauss (1954), which is a regional feature. At Zaaiplaats only the granophyric granite facies of the composite granite sheet described by Strauss (1954) is encountered. The granophyric granite in the vicinity of the younger granites has a reddish-brown colour and is often highly granophyric. The area mapped extended only slightly into the outcrop area of the granophyric granite (Folder). The granophyric granite tends to weather into small, smooth, rounded boulders which are thickly scattered about. It is characteristically overgrown with grass, interspersed with proteas and small trees. These features make the granophyric granite easily recognizable from a distance.

The Bobbejaankop Granite is very well exposed at the Zaaiplaats Mine. It typically weathers into prominent, bald dome-like structures causing its outcrops to be recognizable from a distance. The bare, rocky outcrops are usually strewn with huge, spherical boulders. The granite is named after a typical domical outcrop, called Bobbejaankop, situated opposite the mine on the farm Roodepoort 222KR.

The most characteristic feature of the Bobbejaankop Granite is its homogeneity, shown by its uniform colour, texture, mineralogy and composition. This possibly indicates that the original Bobbejaankop Granite magma itself was homogeneous. Groups of quartz crystals stand out conspiciously on weathered surfaces. This feature, together with a prominent red colour makes the Bobbejaankop Granite easily recognizable in the field. At Zaaiplaats the Bobbejaankop Granite has a constant grain size, but according to Crocker (1981) there is a gradual increase in grain size with depth. The small spherulitic clusters of tourmaline and miarolitic cavities which have been recognized elsewhere (Strauss, 1954) are not present in the Bobbejaankop Granite at Zaaiplaats.

According to Strauss and Truter (1944), the Bobbejaankop Granite intrudes the granophyric granite; however, during this investigation, no tongues, dykes or sills of Bobbejaankop Granite could be found within the granophyric granite to support their claim.

The contact of the Bobbejaankop Granite with the granophyric granite is only developed along the northern flank where the Lease Granite is absent. The exact contact is usually sharply defined. However, the actual contact is difficult to distinguish if the granophyric granite is reddish and coarse-grained and the Bobbejaankop Granite slightly chilled. Generally the latter does not exhibit any noticeable chilling along the contact. Chilled Bobbejaankop Granite is finer-grained and porphyritic. The contact is sometimes indicated by the development of pegmatite, quartz-specularite or quartz-tourmaline lenses in the Bobbejaankop Granite.

The Lease Granite is well developed at the Zaaiplaats mine. It occurs predominantly as a thin, sheet-like body, which caps the Bobbejaankop Granite pluton. The Lease Granite gradually pinches out towards the northern flank of the Bobbejaankop Granite pluton where the granophyric granite comes into direct contact with the Bobbejaankop Granite (Folder 1). It is not known whether the Lease Granite pinches out in a southwesterly direction. In the boreholes the Lease Granite sheet varies in thickness between 18 to 75 metres. In a southeasterly direction (along strike) the thickness gradually increases to attain a maximum of ± 122 metres at the centre of the Bobbejaankop Granite pluton , located at Groenfontein 227 KR (Strauss, 1954). Changes in thickness of the Lease Granite were always considered to be gradual. However, borehole information, combined with underground mapping, proved that rapid changes also occur. The Lease Granite also occurs as sills, dykes and veins in Bobbejaankop Granite up to a depth of approximately 145 metres below the main body of Lease Granite. Their thicknesses vary between 5 cm to 2.5 metres and decrease in abundance with depth in the Bobbejaankop Granite. The sills are linked by dykes and veins to the main mass of Lease Granite. The occurrence of the Lease Granite in the roof of the Bobbejaankop Granite is of much interest, because fine-grained greissenized hood facies are very often associated with tin-bearing granites e.g. Chiu Lung Nao in S.E. China, and Storey's Creek and Aberfoyle in Australia (Taylor, 1979).

Various thin (0,5 - 15 cm) tongues, dykes and sills of a very fine-grained variety of Lease Granite intrude the granophyric granite. These are often enriched in calcite, fluorite, scheelite and cassiterite. The dykes and sills occur up to approximately 32 metres above the main Lease-granophyric granite contact. In some cases they are also accompanied by pegmatite.

The Lease Granite normally has a reddish-brown colour, but it may be grey in mineralized areas. Strauss (1954) stated that grain size gradually decreases towards the top of the sheet. The author, however, found differences in grain-size but no systematic change from the bottom upwards. The Lease Granite is often very fine-grained near its upper contact, whilst a coarser variety is often present in the vicinity of its lower contact. Between these zones grain size varies unsystematically.

Miarolitic cavities are scattered through the higher horizons of the Lease Granite, defining a mappable zone (Folder 1). The cavities, varying in size from 1 mm to about 3 cm, contain inward projecting euhedral crystals of quartz and feldspar and are often filled with sericite, fluorite, calcite, cassiterite, scheelite, quartz and tourmaline. The occurrence of these cavities indicates that the Lease Granite must have crystallized from a shallow intrusion of a fluid-enriched magma.

A pegmatite zone, composed of lenticular, laterally-discontinuous, flat bodies of pegmatite is developed within the upper portion of the Lease Granite on or near its contact with the granophyric granite (Folder 1). Several distinct layers of pegmatite, interspersed with Lease Granite, sometimes occur above each other. The intimate relationship between the Lease Granite and pegmatite is shown by their constant association and sympathetic variation. Both thin towards the northern flank of the intrusion. Pegmatite occasionally accompanies dykes and sills of Lease Granite. Individual pegmatite bodies often reveal a layering parallel to their upper and lower contacts, which is normally sharply defined. The layering, due to alternating layers of quartz and red feldspar, is also conformable to the geological structure of the region. The orientation of elongated quartz and feldspar crystals perpendicular to the layering is characteristic of the pegmatite zone. In contrast to the economically important Lease Granite, very little cassiterite is found within the pegmatite zone.

Due to the vast difference in grain size and texture between the Bobbejaankop and Lease granites, their contact is normally sharply defined. This might be explained by chilling caused by a sudden loss of volatiles from the Lease Granite magma. In the first metre or two from the contact the Bobbejaankop Granite is slightly porphyritic and finer grained. This can make it difficult to pinpoint the exact contact, especially if the Lease Granite is coarser-grained than usual. Sometimes a thin (1 cm) layer of pegmatite is developed in the Lease Granite almost on the contact. Sharply defined contacts are also developed between the Bobbejaankop and Lease granites in Lease sills and dykes. A further characteristic of the sills is the development of a zone, 5 to 10 cm thick, that consists of one or more alternating layers of orientated, elongate feldspar crystals. If the crystals are orientated parallel to each other, their long axis are perpendicular to the contact.

The contact of the Lease Granite with the granophyric granite has a very constant dip. It can be projected accurately for several hundred metres down the flanks of the Bobbejaankop Granite pluton. Furthermore it is very smooth and flat, not undulating as one might expect of an intrusive contact between two granites. The contact has a marked topographic signature. The granophyric granite, being more resistant to erosion than the Bobbejaankop and Lease granites, forms the higher ground. The contact is often marked by the development of a thin pegmatite layer (2 cm or more). In such cases the contact is sharply defined and easily recognizable in the field. However, if the pegmatite layer is absent and the Lease Granite is not very fine-grained and granophyric, it may be difficult to pin-point the exact contact. Chemically the contact always shows up clearly.

All the rocks described so far are intruded by dark coloured mafic dykes and sills of post-Waterberg age (Strauss 1954). However, the granophyric granite is not intruded to the extent to which the Bobbejaankop Granite is intruded. This suggests that the granophyric granite is a relatively stronger rocktype, in which joints and fissures are not well developed. The mafic rocks exhibit an aphanitic texture with small elongated feldspars. No noticeable contact metamorphism of host rocks is visible.

Several faults of post-Waterberg age are present at the Zaaiplaats Mine. The major one, trending roughly northeast-southwest, is a normal fault with a downthrow of approximately 33 metres to the southeast. It is occupied by a large diabase dyke which has been eroded to form a deep valley along the southeastern border of Zaaiplaats. During this investigation it became clear that several pipe-like orebodies, believed to be mined out in the past, were actually truncated and displaced by smaller oblique faults.

Three sets of joints trending N30°W, N30°E and N20°E respectively are distinguished. None of these show any movement along their surfaces. The first two sets are very well developed and include locally well known fissures such as the Adit and Mud fissures (Set 1) and Dam fissure (Set 2). Fillings consisting of quartz, calcite, fluorite, chlorite, galena and chalcopyrite are a common feature in the joint set trending N30°W. Fillings in joints of the second set occur sporadically. The third set of joints, being the subsidiary set, is fairly widely spaced and is according to Söhnge (1944) the oldest of the three. The time relation between the first two joint sets could not be determined.

2.2 ORE DEPOSITS

2.2.1 CLASSIFICATION AND DESCRIPTION

The following types of tin deposit are found at the Zaaiplaats Tin Mine:

a) Alluvial and eluvial deposits.
b) Lenticular orebodies in Lease Granite
c) Disseminated orebodies in Lease Granite.
d) Pipe-like orebodies in the Lease and Bobbejaankop granites.
e) Disseminated low-grade orebodies in Bobbejaankop Granite.
f) Orebodies related to faults and fractures.

The modes of occurrence of the different types of primary tin deposit are described in detail by Strauss (1954) and the more important ones are illustrated in Figure 4.

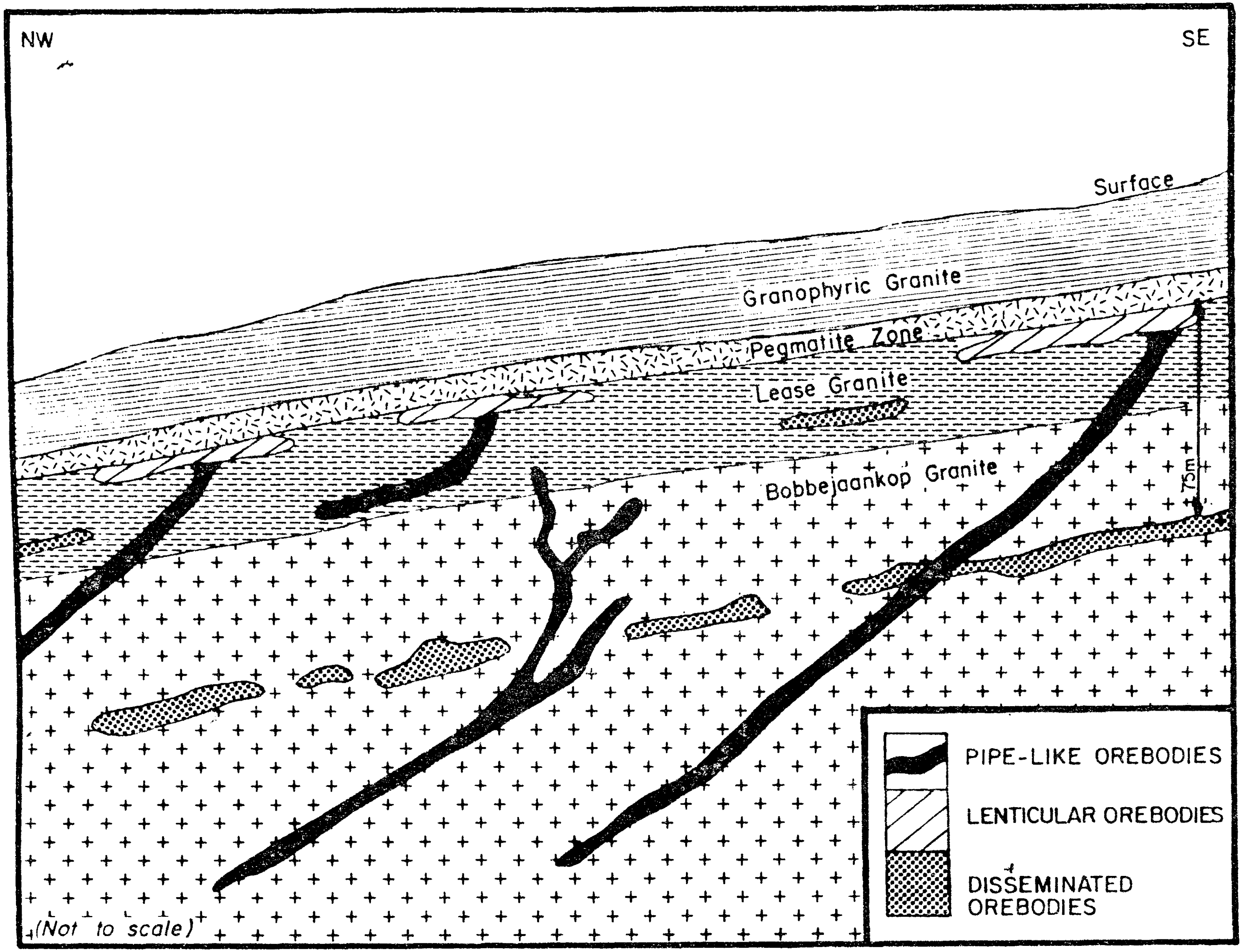


Fig. 4: A generalized section showing the mode of occurrence of the different types of tin deposit .

Alluvial and eluvial tin deposits were abundant when the first mining operation began. Vast amounts of alluvial cassiterite occurred in the valleys, whereas eluvial cassiterite deposits were mainly confined to holes and fissures on the surface of the Lease and Bobbejaankop Granite outcrops. Grades of up to 0,35 per cent were common. However all alluvial and eluvial cassiterite deposits have now been exhausted.

Small, isolated, irregular tin deposits occur within faults or fractures. Because of their size and scarcity they are normally not of economic importance. The so called Christmas Patch (Strauss, 1954) is believed to be one of this type of deposit.

The lenticular orebodies are restricted to the Lease Granite. They mainly occur as flat, elongated, lenticular masses in the upper portions of the Lease Granite immediately below the pegmatite zone. These orebodies are usually concordant with the lower contact of the pegmatite zone. Along dip and strike they may attain thicknesses of up to approximately 1 to 5 metres. The orebodies are typical replacement deposits. Intensive sericitization and chloritization are diagnostic of these ores. Typical minerals include sericite, cassiterite, fluorite, pyrite, chert, scheelite, wolframite, chalcopyrite, calcite, bornite, arsenopyrite and occasionally sphalerite and galena. The grade of the ore varies between 0,2 and 70 per cent with an average concentration of approximately 3 per cent.

Little is known about the disseminated low-grade tin deposits of the Lease Granite. Although this type of deposit is fairly abundant at the Groenfontein mine (Strauss, 1954), mineralization of this kind was only recently intersected by two boreholes at Zaaiplaats. The cassiterite of these deposits seems to be an original constituent of the granite because there is no evidence of cassiterite replacing other minerals. The average ore grade is approximately 0,8 per cent. No information is available on the mode of occurrence of these deposits.

The most spectacular and fascinating type of tin deposit are the pipe-like orebodies that occur within the Lease and Bobbejaankop Granites. These deposits have been described by Strauss (1954) in detail. In general they are long, roughly cylindrical bodies of variable dimensions that range in diameter from 5 cm to 13 metres and vary in length from 6 metres to well over 900 metres. In cross section the shape of the orebodies range between perfectly circular and very irregular, and their attitude varies between vertical and horizontal. Normally the pipes plunge towards the northwest at an angle slightly greater than the dip of the sheet of Lease Granite. The pipes branch and merge, pinch and swell, rise fall and twist and turn in every direction. The pipes are definitely replacement deposits as revealed by the euhedral cassiterite embedded in a matrix of soft sericite. Their cassiterite content varies between 0 and approximately 70 per cent. Strydom (1983) indicated that geochemical haloes exist around these pipe-like orebodies.

2.2.2 LOW-GRADE OREBODIES IN BOBBEJAANKOP GRANITE

In order to obtain a better understanding of the structure of these deposits, various geological sections were constructed in different directions through the mine. The information obtained, combined with underground observations and borehole data, indicates that the low-grade orebodies occur within a sheet-like zone of tin enrichment situated in the upper portion of the Bobbejaankop Granite intrusion (Fig. 3). This zone will be referred to as the tin-rich zone. The zone tends to be conformable to the outlines of the intrusion (Fig. 3). The top of the zone is situated approximately 66 to 83 metres below the contact with the granophyric granites (Fig. 3). The true thickness of the zone varies between 55 and 66 metres, and local pinching and swelling may occur. Down dip the zone continues for well over 1 050 metres and gradually interfingers with barren granite in that direction (Fig. 3). Towards the steep northeastern contact between the Bobbejaankop Granite and the granophyric granite the zone gradually thins out. Along strike in a northwesterly direction the zone thins out as the steep northwestern contact is approached. Along strike in a southeasterly direction the zone continues for several hundred metres up to the farm Roodepoort 222 KR. Whether it extends further in that direction has not yet been established. The tin-rich zone is frequently intersected by the pipe-like orebodies.

The Sn values in the tin-rich zone vary between 35 and 10 000 p.p.m. (The lower limit of 35 p.p.m. was obtained from a calculated threshold value explained in section 4.4.1). The Sn values are irregularly distributed, but a tendency exists for the values to decrease gradually towards the edges of the zone (Figs. 8A, 11A, 12A).

With the present cut-off value of 1 500 p.p.m. it is evident that the whole tin-rich zone cannot be mined economically. The portions with a higher Sn content than 1 500 p.p.m. (orebodies) are irregularly distributed through the tin-rich zone. However, Strauss (1954) stated that ore shoots pitch in more or less the same direction as the pipe-like orebodies.

It is difficult to distinguish between low-grade Sn ore and unmineralized Bobbejaankop Granite in handspecimen. Consequently, orebodies and the tin-rich zone cannot be mapped, but have to be defined through whole rock analyses. Flat, elongated vugs occur sparsely distributed in the tin-rich zone which suggests that the low-grade tin ore crystallized from Bobbejaankop magma locally slightly enriched in fluids and volatiles. The vugs contain variable amounts of coarse euhedral to subhedral quartz, feldspar, calcite, fluorite, allanite, chlorite, arsenopyrite, chalcopyrite, scheelite, molybdenite, pyrite and cassiterite crystals. The vugs are typically associated with locally developed fine grained granite resembling the Lease Granite. The Bobbejaankop Granite in such areas has a darker colour due to an increased amount of chlorite. There is no obvious genetic relation between the low-grade orebodies and the pipe-like orebodies and as noted earlier, the latter frequently cut the former. Because there is no visual difference between the low-grade ore and unmineralized Bobbejaankop Granite, it seems unlikely that the low-grade ore formed from a magma other than the Bobbejaankop Granite magma.

3. PETROGRAPHY

3.1 BOBBEJAANKOP GRANITE

3.1.1 Unmineralized Bobbejaankop Granite

It is leucocratic and is generally red in colour but can vary from brick-red to whitish-pink. The darker shades of red represent the normal case, whereas the very light colours are exceptional. The red colour is probably derived from the oxidation of exsolved iron in orthoclase (Strauss, 1954). Thus the colour variations are probably caused by different amounts of exsolved iron. In addition, there is a tendency for the granite to adopt a lighter colour with an increase in the amount of antiperthite.

The Bobbejaankop Granite is medium to coarse-grained and inequigranular, with grain-sizes varying between 2 and 7 mm. According to grain-shapes the granite can be described as allotriomorphic to hypidiomorphic granular.

Applying the method described by Hutchison (1974) 20 000 point counts, distributed over 20 thin sections, were used to determine the modal composition of this granite, which is as follows:

feldspar	58,0 %	32 % perthite; 26 % antiperthite
quartz	38,7 %	
chlorite	1,1 %	

given by Stemprok and Skvor (1974). There is good correspondence between the modal and normative compositions of the Bobbejaankop Granite with respect to quartz, feldspar and fluorite.

The norm of the Bobbejaankop Granite indicates slightly higher proportions of K-feldspar than plagioclase. This corresponds to the modal composition which indicates slightly higher proportions of perthite than antiperthite.

A photomicrograph of typical unmineralized Bobbejaankop Granite is given in Figure 5A.

Two types of perthite occur, namely mosaic and patch perthite. Mosaic perthite consists of structurally oriented plagioclase patches in a K-feldspar host, whereas patch perthite is characterized by irregular patches of plagioclase (Fig. 5B) irregularly distributed in a K-feldspar host. In the latter the contacts between the feldspars are diffuse (Fig. 5B) which, according to R.G. Taylor (personal communication, 1983), is possibly due to K-metasomatism of plagioclase.

The antiperthite crystals normally consist of irregular patches of K-feldspar in a plagioclase host. The patches often occur near the edges of antiperthite crystals (Fig. 5C), but are also irregularly scattered through the host (Fig. 5C). An increase in the plagioclase proportion of antiperthite occasionally occurs immediately below the tin-rich zone. The contacts between the feldspars are diffuse and, according to R.G. Taylor (personal communication, 1983), this could possibly be the result of Na metasomatism of K-feldspar. Na metasomatism (albitization) often leaves relics of K-feldspar on the edges of the original crystals so that a chopped-off-edge texture results, a feature frequently observed in Bobbejaankop Granite. Albitization is a process commonly associated with numerous Sn deposits in the world (Taylor, 1979). Antiperthite in which K-feldspar patches are more or less structurally controlled is less common in the Bobbejaankop Granite.

Plagioclase in perthite and antiperthite was determined through electron microprobe analysis and proved to be albite with an average Ab:An:Or ratio of 96,4:2,5:1,1. Polysynthetic twinning of albite is common and is often developed in more than one direction in a single crystal. Albite normally has a fresh appearance, although slight saussuritization may occur in isolated cases. "Pure" plagioclase crystals do not occur in unmineralized Bobbejaankop Granite.

K-feldspar only occurs in perthite and antiperthite and characteristically has a deep red colour. Lenthall and Hunter (1977) determined the K-feldspar as intermediate to maximum microcline. Feldspar mainly occurs as subhedral to euhedral crystals, although anhedral crystals between quartz crystals are also encountered. This indicates that feldspar started crystallizing before and continued well after the crystallization of quartz.

Quartz grains are normally transparent, anhedral and virtually free of mineral inclusions. It is well segregated from feldspar grains and forms prominent chains and clusters. The clustered quartz is also a feature of tin-bearing Nigerian granites (Olade, 1980) that are associated with primary tin deposits. Small euhedral quartz crystals now and then occur within chlorite and sericite. Quartz occasionally replaces sericite as well as chlorite (Fig. 5D).

Chlorite is the only dark mineral present in the Bobbejaankop Granite. It is anhedral and occurs interstitially between quartz and feldspar (Figs. 5A, 5D). It is dark green, sometimes brownish in colour and contains small inclusions of quartz, feldspar, fluorite and magnetite (Fig. 5D). The average of 4 probe analyses proved the chlorite to be an iron-rich thuringite with an average Fe:Mg:Mn ratio of 89,7:7,1:3,2. The original mica of the granite was probably an iron-rich biotite. Its alteration to thuringite was accompanied by the exsolution of iron from the biotite lattice resulting in the formation of magnetite lamellae within cleavage planes of chlorite after biotite (Fig. 5D). Chlorite commonly occurs with magnetite, fluorite, and quartz (Fig. 5D).

Sericite is a common accessory mineral of the Bobbejaankop Granite. It invariably has a greenish colour and normally occurs interstitially between quartz and feldspar grains. Probe analyses of sericite gave a K:Fe:Mg ratio of 70,4:24,6:5,0. Sericite sometimes replaces feldspar, chlorite and occasionally calcite and quartz.

Fluorite is an accessory mineral evenly dispersed through the Bobbejaankop Granite. It occurs as anhedral crystals and is strongly associated with chlorite in which it often forms inclusions (Fig. 5D). Fluorite normally has a purple colour, although green and colourless varieties are often seen. Minute inclusions of sulphides and thorite, frequently arranged along cleavage planes, are scattered through the crystals. Sometimes fluorite apparently replaces feldspar.

Calcite is a less common accessory mineral. It occurs as anhedral crystals interstitial between quartz and feldspar. It never exhibits any visible cleavage and is always colourless. Occasionally calcite appears to replace feldspar and is itself replaced by sericite.

Zircon frequently occurs as an accessory mineral. It exhibits a subhedral to euhedral form which indicates that it crystallized quite early. It is brownish in colour and frequently strongly zoned. Zircon usually occurs in association with chlorite (Fig. 5D). It is always strongly altered, mainly to malacon, but also to thorite in some cases.

Monazite, allanite, tourmaline and apatite are very rare accessory minerals of the Bobbejaankop Granite.

Chemical analyses indicate that some scheelite may be present in minor quantities. It was, however, not observed in thin section.

Cassiterite is a very rare accessory mineral that is virtually absent in unmineralized Bobbejaankop Granite. The cassiterite crystals occur interstitially between quartz and feldspar and have a brownish colour.

Sulphides are rare accessory minerals except in some areas immediately below mineralized zones. The most common sulphide is pyrite which normally occurs as disseminated euhedral crystals. Anhedral crystals of chalcopyrite contain relics of pyrite and definitely replace arsenopyrite in some cases. Bornite occurs with chalcopyrite in very small quantities and is partly replaced by chalcocite. Small plates of molybdenite may be present. Sphalerite and galena are rare accessory minerals, usually occurring together.

3.1.2 Bobbejaankop Granite in the tin-rich zone

The modal composition of Bobbejaankop Granite from the tin-rich zone, as determined by 20 000 point counts distributed over 20 thin sections, is as follows:

feldspar	57 %	perthite = 28,6 % antiperthite = 28,4 %
quartz	38,5 %	
chlorite	1,4 %	
sericite	0,8 %	
fluorite	1,2 %	
apatite zircon thorite allanite monazite sulphides calcite	1,1 %	

Compared to the modal composition of unmineralized Bobbejaankop Granite, granite from the tin-rich zone has higher proportions of antiperthite, chlorite, fluorite and the accessory minerals.

The CIPW normative composition of the Bobbejaankop Granite is as follows: (weight %)

quartz	(33,7 - 37,4)
orthoclase	(29,4 - 31,4)
albite	(24,6 - 28,5)
anorthite	(1,2 - 3,4)
diopside	(1,1 - 3,7)
hypersthene	(1,9 - 4,1)
magnetite	(0,6 - 0,9)
ilmenite	(0,1 - 0,2)
apatite	(0,02 - 0,09)
fluorite	(0,27 - 0,72)

There is good correspondence between the modal and normative compositions of granite from the tin-rich zone with respect to quartz, feldspar and fluorite.

The normative composition of the Bobbejaankop Granite from the tin-rich zone differs from that of unmineralized Bobbejaankop Granite with respect to albite and fluorite in that both are more abundant in granite from the tin-rich zone. Although there are no obvious differences in hand specimen between unmineralized Bobbejaankop Granite and Bobbejaankop Granite of the tin-rich zone with respect to colour, grain-size, texture or minerals present, thin section investigation revealed several petrographic differences.

There is a definite increase in the proportion of plagioclase in antiperthite in the tin-rich zone (Fig. 5F). Thus, if it is assumed that albitization occurred in the Bobbejaankop Granite, it was certainly more intense in the tin-rich zone. Small interstitial albite crystals are scattered throughout the tin-rich granite. Large perthite and antiperthite crystals often contain inclusions of subhedral to euhedral quartz. Inclusions of albite frequently occur within chlorite (Fig. 5G).

Small anhedral and more often subhedral to euhedral quartz crystals are scattered through granite of the tin-rich zone (Figs. 5E, 5F). This is a very characteristic feature that may be explained by crystallization from residual siliceous liquids in interstitial spaces. The crystals are found in contact with any mineral. Very small inclusions of quartz also occur within perthite, antiperthite and chlorite (Fig. 5G).

Chlorite is more prominent in the tin-rich zone, where it is often more coarsely developed, has a deeper green colour and is more strongly pleochroic. This mode of occurrence can possibly be ascribed partly to an increased amount of late metasomatizing fluids in the tin-rich zone. Chlorite also contains numerous inclusions of quartz, albite, calcite and fluorite. Fine chlorite flakes within some feldspar crystals indicate that the latter are weakly altered to chlorite in some cases. The amount of sericite seems to be less within the tin-rich zone compared to unmineralized granite.

There is a definite increase in the amount of fluorite within the tin-rich zone. Replacement of fluorite by calcite (or calcite by fluorite?) often occurs (Fig. 5G).

Calcite is often more abundant in the tin-rich zone. It has a good cleavage in contrast to calcite in unmineralized Bobbejaankop Granite. Furthermore, it is often present as inclusions within chlorite where it is frequently related to fluorite.

The economic tin-bearing mineral of the tin-rich zone is cassiterite, which is an abundant accessory constituent. Cassiterite occurs disseminated through the granite. The crystals are typically anhedral and occur interstitially mainly between quartz and feldspar (Figs. 5F, 5H) which suggests that cassiterite crystallized at a very late stage directly from the original melt. Its occurrence strongly contrasts with the euhedral cassiterite crystals that characterize the metasomatic lenticular and pipe-like orebodies. The cassiterite crystals have a reddish-brown colour, show moderate pleochroism and no zoning. Twinning occurs occasionally (Fig. 5F). Cassiterite is virtually free of any mineral inclusions. The most common sulphide mineral associated with cassiterite is arsenopyrite.

Scheelite is a common accessory mineral in the tin-rich zone. The crystals are typically anhedral and occur intersticial to quartz and feldspar (Fig. 6A). The replacement of scheelite by wolframite in the pipe-like and lenticular orebodies as described by Söhnge (1944) has not been found in the orebodies of the tin-rich zone.

From thin section investigations it appears that zircon might be slightly more abundant in the tin-rich zone. Thorite, allanite, monazite and tourmaline are rare accessory constituents, although apatite occasionally seems to be present in slightly higher quantities. Although there is not always an increase in the individual sulphides, the total amount of sulphides, especially arsenopyrite, chalcopyrite and sphalerite, is higher than in unmineralized granite.

In summary, the most important features of granite from the tin-rich zone relative to unmineralized Bobbejaankop Granite are:

a) the increase in the proportion of plagioclase in antiperthite;
b) the presence of small interstitial albite crystals;
c) the occurrence of numerous small subhedral to euhedral quartz crystals;
d) the abundance of albite and quartz inclusions within chlorite;
e) the deep green colour and coarser development of chlorite;
f) the increase in the amount of fluorite;
g) the increase in the amounts of cassiterite and scheelite;
h) the increase in the total amount of sulphides.

A photomicrograph of typical Bobbejaankop Granite from the tin-rich zone is given in Fig. 5E.

3.1.3 Bobbejaankop Granite near Lease Granite contact

The Bobbejaankop Granite within approximately 1 to 2

Fig. 5: Photomicrographs of unmineralized and mineralized Bobbejaankop Granite.

A. Typical Bobbejaankop Granite with quartz (Q) clearly segregated from perthite (PE). Chlorite (C) occurs interstitially. Cross-polarized light. (Magnification = 10x)

B. Patch perthite in Bobbejaankop Granite. Patches of plagioclase (P) in K-feldspar (K). Cross-polarized light. (Magnification = 25x)

C. Antiperthite in Bobbejaankop Granite. K-feldspar (K) in a plagioclase (P) host. Q = Quartz. Cross-polarized light. (Magnification = 25x)

D. The typical chlorite (C)-magnetite(M)-fluorite(F)-zircon(Z) association in Bobbejaankop Granite. Quartz (Q) replacing chlorite is indicated by an arrow. Polarized light (Magnification = 25x)

E. Typical granite of the tin-rich zone. Note the subhedral and euhedral quartz (Q) crystals, large chlorite (C) and euhedral perthite (PE) crystal. Cross-polarized light. (Magnification = 10x)

F. Interstitial cassiterite (C) surrounded by perthite (PE), antiperthite (A) and euhedral quartz of the tin-rich zone. Cross-polarized light (Magnification = 25x)

G. Chlorite (C) with inclusions of quartz (Q), plagioclase (P) and calcite (CA) replacing fluorite (F) in the tin-rich zone. Cross-polarized light. (Magnification = 25x)

H. Interstitial cassiterite (C) between quartz (Q) and perthite (PE) in the tin-rich zone. Cross-polarized light (Magnification = 25x)

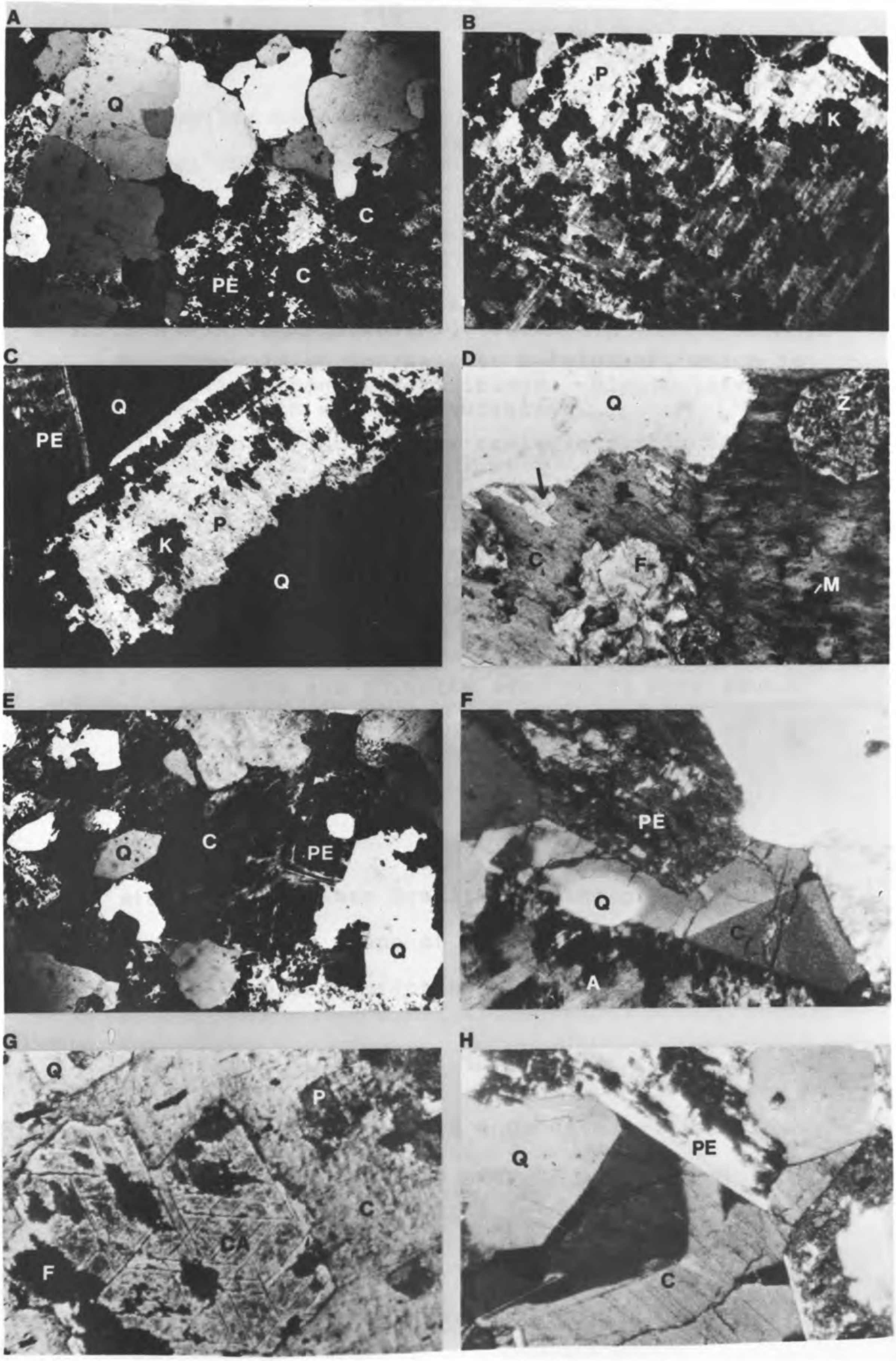


Fig. 5: Photomicrographs of unmineralized and mineralized Bobbejaankop Granite.

metres from its contact with the Lease Granite differs from normal Bobbejaankop Granite in the following respects:

a) The quartz and feldspar crystals are not as well segregated (Fig. 6B).

b) There is an increase in K-feldspar, which is often strongly sericitized. Plagioclase is also much more saussuritized.

c) Feldspar undoubtedly replaces quartz to some extent.

d) Small anhedral quartz crystals are scattered throughout the granite.

e) Quartz in granophyric intergrowth with feldspar is frequently developed (Fig. 6B), especially on the margins of big subhedral to euhedral feldspars. This feature is also common in the Lease Granite.

f) Fluorite and chlorite seem to be more abundant.

3.2 LEASE GRANITE

Since a study of the Lease Granite and the granophyric granite is beyond the scope of this investigation, less detailed petrographic descriptions of these granites are given.

The Lease Granite is leucocratic and has a reddish-brown colour that normally changes to grey or green in mineralized patches. It is medium- to fine-grained and inequigranular with grain-sizes varying between 0,5 and 2 mm. The granite can be described as allotriomorphic to hypidiomorphic granular.

The modal composition of the Lease Granite, as determined by 20 000 point counts distributed over 10 thin sections, is as follows:

perthite + antiperthite	= 59,2 %	
free quartz	= 19,4 %	36,5 %
bonded quartz	= 17,1 %	
chlorite	= 3,0 %	
sericite	= 0,4 %	
fluorite	= 0,7 %	
muscovite	trace	
zircon	trace	
thorite	trace	
tourmaline	= 0,2 %	
calcite	trace	
sulphides	trace	

The CIPW normative composition of the Lease Granite is as follows: (weight %)

quartz	(33,7 - 36,4)
orthoclase	(30,5 - 33,5)
albite	(24,2 - 27,5)
anorthite	(2,0 - 3,7)
diopside	(0,0 - 3,9)
hypersthene	(0,6 - 2,6)
magnetite	(0,44 - 0,7)
ilmenite	(0,12 - 0,14)
apatite	(0,01 - 0,06)
fluorite	(0,23 - 0,3)

There is good correspondence between the modal and normative compositions of the Lease Granite. The modal amounts of quartz, K-feldspar and plagioclase of the Lease Granite plot within the granite field of the revised Streckeisen classification (Streckeisen, 1973; Streckeisen and Le Maitre, 1979) for igneous rocks. Plots on an Ab-Or-Q diagram further show that the norms of the Lease granite fall within the field of averange tin-bearing granites. (Stemprok and Skvor, 1974).

The feldspars of the Lease Granite are mainly perthite, although antiperthite also occurs in some cases. The perthites are typical string or rod perthites (Fig. 6C), but patch perthite is often present. Crystals are subhedral to euhedral (Fig. 6C).

The composition of plagioclase in the perthites and antiperthites lies between albite and oligoclase (Strydom, 1983). It is occasionally saussuritized. Almost no individual plagioclase crystals occur.

Granophyric and graphic intergrowths of feldspar and quartz are common (Figs. 6D, 6E). Feldspar seems to replace quartz where these minerals are not intergrown.

Quartz is present as relics of original free quartz or as bonded quartz in granophyric or graphic intergrowth with feldspar. The free quartz occurs as irregularly shaped grains of various sizes. The grains sometimes form groups characterized by their simultaneous extinction in cross-polarized light. Such a group of grains probably represents a large relict quartz crystal that has been replaced by feldspar. Granophyric intergrowth of quartz and feldspar often occurs on the edges of large feldspar crystals.

Chlorite occurs interstitially between quartz and feldspar and has a typical dark green colour. It is occasionally altered to sericite and seldom contains inclusions. Chlorite tends to be more abundant in the miarolitic Lease Granite.

Sericite is an abundant accessory mineral of the Lease Granite. It mainly occurs interstitially and has a typical light green colour. Occasionally it replaces feldspar. Coarse sericite is present in very small quantities and seems to be more abundant near mineralized patches.

Fluorite is a common accessory mineral of the Lease Granite. It normally has a purple colour, but in massive fluorite, as in the pegmatite zone, individual crystals often show colour variations ranging from deep purple to green to colourless.

Calcite occurs interstitially. It replaces perthite and possibly quartz in a few cases. Zircon and apatite are accessory minerals. Tourmaline is much more abundant in the Lease Granite than in the Bobbejaankop Granite, especially within the miarolitic zone. It has a deep green colour in thin sections and is probably the iron-rich tourmaline, schorl.

The sulphides pyrite, chalcopyrite, bornite, covelite, chalcocite, molybdenite, arsenopyrite, galena and sphalerite are rare accessory minerals in unmineralized Lease Granite. The most common sulphide is pyrite. Arsenopyrite is abundant in and near mineralized patches.

The Lease and Bobbejaankop granites are very similar with respect to their mineralogy and both apparently represent metasomatized granites. However, petrographic differences do exist, as listed in Table 2.

3.3 GRANOPHYRIC GRANITE (RASHOOP GRANOPHYRE SUITE)

The granophyric granite is leucocratic and has a brick-red colour. Occasionally a greyish variety is found, normally some distance away from its contact with the intrusive younger granites.

The granophyric granite is medium to fine-grained and inequigranular with grain sizes varying between 1 and 4 mm. The granite can be described as allotriomorphic to hypidiomorphic granular.

TABLE 2: A petrographic comparison of the Bobbejaankop and Lease granites.

	BOBBEJAANKOP GRANITE	LEASE GRANITE
1.	Medium to coarse-grained.	Fine to medium grained.
2.	Quartz and feldspar well segregated.	Not segregated.
3.	Conspicuous clusters and chains of quartz.	Not present.
4.	Granophyric and graphic textures not present, only present near Lease contact.	Granophyric and graphic textures common.
5.	All quartz is free quartz.	Some quartz is granophyric intergrowth with feldspar.
6.	Antiperthite abundant.	Antiperthite less common.
7.	Mainly patch perthite.	Mainly string and rod perthite.
8.	Plagioclase feldspar is albite.	Plagioclase feldspar is oligoclase.
9.	Small interstitial plagioclase crystals.	Absent.
10.	Euhedral feldspars rare.	Euhedral feldspars common.
11.	Chlorite abundant, never sericitized.	Chlorite less abundant and often sericitized.
12.	Fluorite abundant.	Less abundant.
13.	Tourmaline scarce.	Tourmaline abundant.

The estimated modal composition of the granophyric granite is as follows:

perthite, albite, K-feldspar	± 60 %
quartz	± 35 %
biotite	± 4 %
accessory minerals	± 1 %

The modal amounts of quartz, K-feldspar and plagioclase plot within the granite field of Streckeisen's revised classification of igneous rocks (Streckeisen, 1973; Streckeisen and Le Maitre, 1979)

The CIPW normative composition of the granophyric granite is as follows: (Weight %)

quartz	(31,9 - 35,7)	hypersthene	(3.2 - 4,9)
orthoclase	(32,9 - 32,4)	magnetite	(0,86 - 1,92)
albite	(24,7 - 32,7)	ilmenite	(0,37 - 0,38)
anorthite	(0,4 - 3,2)	apatite	(0,01 - 0,13)
diopside	(0 - 1,6)	fluorite	(0,08 - 0,15)

The normative composition of the granophyric granite differs from the Bobbejaankop and Lease granites in the following respects:

a) It contains less orthoclase and fluorite.
b) It contains more albite, hypersthene, magnetite, ilmenite and apatite.

The feldspars of the granophyric granite are mainly represented by perthite although individual plagioclase and K-feldspar crystals occur in small quantities. Most of the perthites are mosaic perthites, but string or rod perthites do occur in some cases. The perthite crystals have a subhedral form, which is often difficult to distinguish because of intensive overgrowths of quartz. The plagioclase feldspar is albite (Strauss and Truter, 1944) and the K-feldspar is red orthoclase. Most feldspars are in granophyric or graphic intergrowth with quartz (Fig. 6F-H). Feldspar clearly replaces quartz. Sericitisation and saussuritisation of feldspar do occur to a small extent. Antiperthite is present in small quantities near the granophyric granite Lease Granite contact.

Quartz is present as free quartz and as granophyric or sometimes graphic intergrowths with feldspar. The amount of free quartz is estimated at approximately 30 per cent of the total quartz content of the granite. Relics of quartz crystals similar to those found in the Lease Granite are also present in the granophyric granite (Fig. 6G). Granophyric intergrowths of quartz and feldspar are always present. Very typical of the granophyric granite is the development of granophyric textures on the edges of large feldspar crystals (Fig. 6H).

Flakes of dark brown biotite are scattered throughout the granophyric granite. There is a definite increase in the amount of this mineral with increasing distance away from the granophyric granite-Lease Granite contact. Quartz often replaces biotite to varying degrees.

Fluorite occurs in very small amounts and is not typically associated with biotite as found in the Bobbejaankop and Lease granites. The occurrence of antiperthite and chlorite, and the increases in fluorite towards the Lease Granite - granophyric granite contact, can possibly be attributed to metasomatic alteration by Bobbejaankop Granite fluids adjacent to this contact.

Sulphides are present in small amounts and are mainly represented by pyrite, chalcopyrite and arsenopyrite. Hematite is occasionally found in small cracks and veins. Zircon is abundant and usually occurs as euhedral crystals.

The most obvious petrographic differences between the granophyric granite and the Lease Granite, based on observations of 30 thin sections of the Lease Granite and 10 thin sections of the granophyric granite, are listed in Table 3.

TABLE 3: A petrographic comparison of the Lease and granophyric granites.

	LEASE GRANITE	GRANOPHYRIC GRANITE (Rashoop Granophyre Suite)
1.	Feldspar crystal boundaries easily distinguishable.	Very difficult to distinguish because of scattered relics of quartz.
2.	Most feldspar crystals are euhedral.	Feldspars normally subhedral.
3.	String or rod perthites common.	Mosaic perthites common.
4.	Plagioclase is oligoclase.	Plagioclase is albite.
5.	Granophyric and graphic textures not always present	Granophyric and graphic textures always present.
6.	Graphic textures more common than granophyric textures.	Granophyric textures more common than graphic textures.
7.	Little free quartz.	Less free quartz.
8.	No biotite present.	Biotite is abundant.
9.	Sericite is abundant.	Sericite scarce.
10.	Fluorite abundant.	Fluorite scarce.
11.	Sulphides abundant.	Sulphides rare.
12.	Sphene absent.	Sphene present.
13.	Apatite scarce.	Apatite more abundant.

3.4 SUMMARY, DISCUSSION AND CONCLUSIONS

Normative plots of the Bobbejaankop Granite, Lease Granite and granophyric granite (Rashoop Granophyre Suite) on a ternary Ab-Or-Pl diagram indicate that these granites fall within the range of average tin-bearing granites.

Macroscopically, no obvious distinction can be made between unmineralized Bobbejaankop Granite and granite of the tin-rich zone. However, several petrographic differences were revealed through a thin section investigation which are listed in section 3.1.2.

The economic tin-bearing mineral in the tin-rich zone is cassiterite. The mode of occurrence of this mineral indicates that its origin is not metasomatic, but that it apparently formed in the natural course of crystallization of the cooling Bobbejaankop Granite magma.

The Bobbejaankop Granite and Lease Granite is homogeneously metasomatized by the processes of sericitisation and chloritisation. K-metasomatism and albitization also seem to have occurred. Petrographic evidence suggests that albitization was more intense within the tin-rich zone. Metasomatism of the Bobbejaankop Granite probably post-dated the formation of the tin-rich zone. The granophyric granite (Rashoop Granophyre Suite) is slightly metasomatized near its contact with the

Bobbejaankop and Lease granites.

The abundance of minerals such as cassiterite and scheelite in the Bobbejaankop and Lease granites indicates that these granites, in contrast to the granophyric granite (Rashoop Granophyre Suite), represent late differentiates.

Fig. 6: Photomicrographs of mineralized Bobbejaankop Granite, Lease Granite and granophyric granite (Rashoop Granophyre Suite).

A. Interstitial scheelite (s) between perthite (PE) and quartz (Q) in mineralized Bobbejaankop Granite. Polarized light. (Magnification = 25x).

B. Granophyric intergrowth of quartz (Q) and perthite (PE) in Bobbejaankop Granite near its contact with the Lease Granite. Cross-polarized light. (Magnification = 10x).

C. Typical subhedral string perthite (PE) and anhedral quartz (Q) in Lease Granite. Cross-polarized light. (Magnification = 25x)

D. Granophyric intergrowth of quartz (white) and feldspar in granophyric Lease Granite. Note the quartz relics after replacement by feldspar. Cross-polarized light. (Magnification = 10x).

E. Granophyric intergrowth of perthite (PE) and quartz(Q) in Lease Granite. Cross-polarized light. (Magnification = 25x)

F. Granophyric intergrowth of perthite (PE) and quartz (Q) in typical granophyric granite of the Rashoop Granophyre Suite. Chlorite (c) Cross-polarized light. (Magnification = 10x).

G. Feldspar replacing quartz in granophyric granite of the Rashoop Granophyre Suite. Note the relics of quartz (Q) in perthite (PE). Cross-polarized light. (Magnification = 10x).

H. Granophyric intergrowth of quartz (Q) and feldspar on the edges of a large perthite (PE) crystal in granophyric granite of the Rashoop Granophyre Suite. Cross-polarized light. (Magnification = 25x).

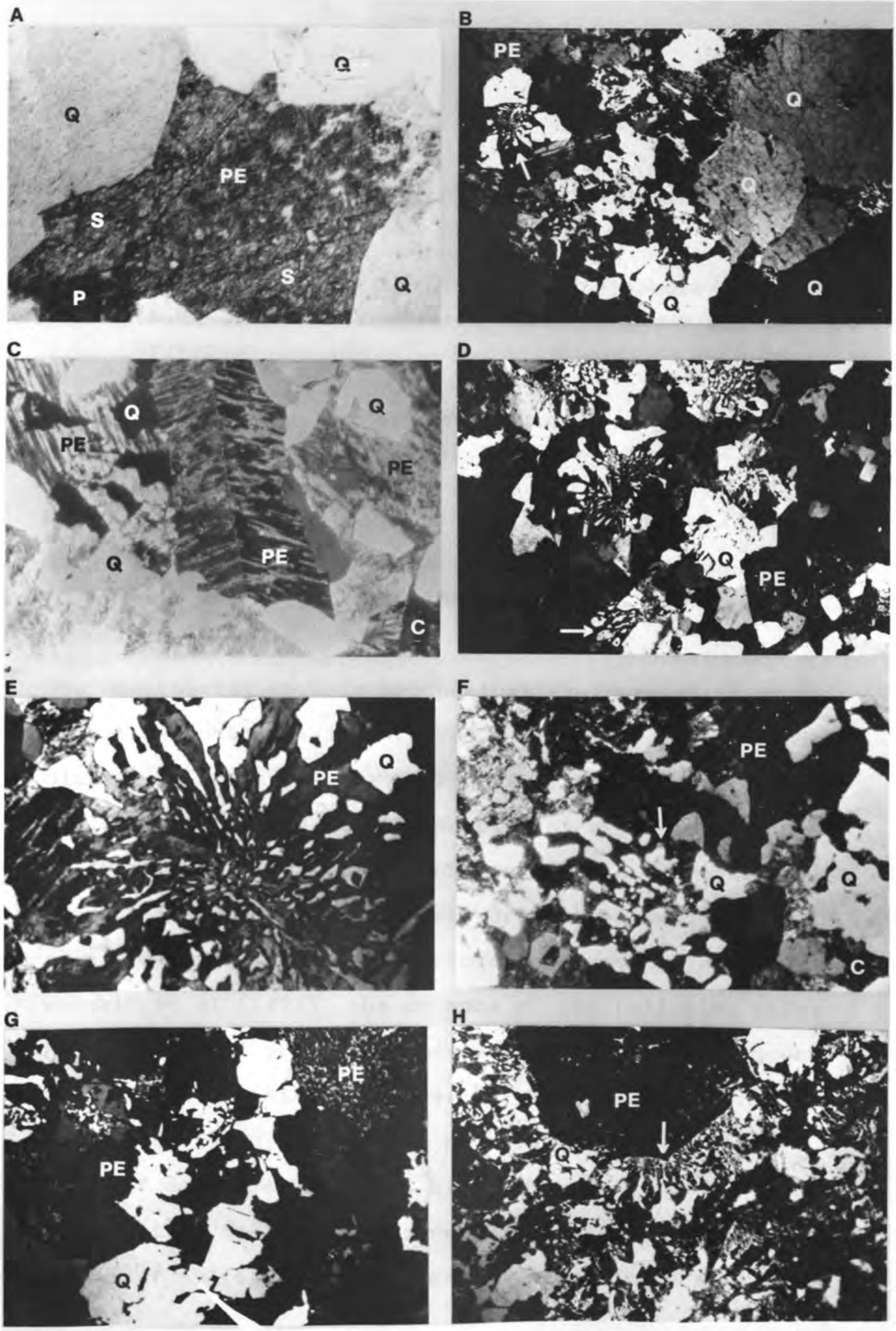


Fig. 6: Photomicrographs of mineralized Boboejaankop Granite, Lease Granite and granophyric granite (Rashoop Granophyre Suite).

4. GEOCHEMISTRY

4.1 GENERAL

The geochemical investigation had the following objectives:

i) To determine the distribution of elements in and around the disseminated low-grade ore in Bobbejaankop Granite.

ii) To establish geochemical criteria, if possible, that could be applied in future exploration for such ore deposits.

iii) To make a contribution to the understanding of the mode of formation of the deposits.

The most useful tool in geochemical exploration is pathfinder elements (Levinson, 1980), also referred to as indicator elements (Beus and Grigorion, 1977). The characteristics of a good pathfinder element are described by Graff and Kerr (1950). The choice of such elements depends mainly on the type of ore deposit as well as on economical and analytical factors. According to Kvyatkovskii et al (1972), one or more of the following pathfinder elements are always present in appreciable amounts in most ore deposits: Cu, As, Mo, Pb, Hg, S, Sn, Ni, V, Cr, U, Be and F. Because other types of ore deposits (e.g. W, Cu, Mo etc.) may occur within the tin-rich zone (with consequent superimposition of multi-element haloes, if present), a wide range of potential pathfinder elements were analysed. Because of the extremely large number of analyses, the data are not presented here but a permanent copy has been lodged with the Institute for Geological Research on the Bushveld Complex at the University of Pretoria, which may be inspected on request.

4.2 SAMPLING AND SAMPLE PREPARATION

Five boreholes, GS69, GS70, GS71, GS72 and GS73, were drilled in the Zaaiplaats area (Folder 1, Fig. 3) specifically for the purpose of this study. Each of these was cut in half with a diamond saw. One half was logged and kept for reference purposes, whereas the other was sampled continuously in 2 metre intervals. This resulted in an average sample weight of approximately 2 kg. The core recovery was well in excess of 95 per cent for all boreholes. All samples were fresh and an individual sample never extended over a lithological contact. Consequently a continuous set of representative, dependable samples was obtained for each borehole.

In order to prevent contamination of W, Zn and Cu, all remnants of the matrix of the drill crowns on the core were removed with sand paper. Primary crushing was done by means of a jaw crusher. Through cone crushing the grain sizes were reduced to approximately 2 mm . The samples were finally powdered to -200 mesh, using a vibrating steel case with concentric hardened chrome steel rings. Throughout, all possible precautions were taken to prevent contamination.

4.3 ANALYTICAL PROCEDURES

4.3.1 Trace elements

Approximately 12 grams of all sample powders (668 samples) were mixed with a binder (Moviol) and pelletized in aluminium cups under a pressure of 20 metric tons. The pellets were analyzed for 15 trace elements (Cu, Pb, Zn, Mo, Sb, Th, U, Rb, Sr, Y, Ba, Zr, Nb, W, Sn) by means of a multichannel Phillips PW1600 simultaneous X-ray fluorescence spectrometer. A rhodium X-ray tube and LiF200 analytical crystal were used. The lower limit of detection (L.L.D.) for this apparatus is about 5 p.p.m. for all elements.

All the samples were additionally analyzed for As on a single channel Rigaku Denki X-ray fluorescence spectrometer. A rhodium X-ray tube and LiF200 analytical crystal were used. The L.L.D. of these analyses is in the order of 2 p.p.m.

The NIM-P standard was used as reference for all analyses. Calibration curves were obtained by the application of international standards.

4.3.2 Major Elements

Because of limited time all samples could not be analyzed for the full range of major elements and only thirty representative samples were therefore selected for analysis. These comprised:

5 specimens of granophyric granite of the Rashoop Granophyre Suite.

5 specimens of Lease Granite.

10 specimens of unmineralized Bobbejaankop Granite.

10 specimens of Bobbejaankop Granite from the tin-rich-zone.

Glass discs were prepared according to the method of Norrish and Hutton (1969) and analyzed for Ti, Ca, K, P, Si, Al, Mg, Fe, Mn and Ni on a single channel Siemens sequential X-ray fluorescence spectrometer. Na analyses were done on pellets. Technical data concerning the major element analyses are listed in Table 4. Calibration curves were constructed using 45 international standards.

H_2O^- and ignition loss were determined for all samples by weighing and heating to 130^o and 930^oC respectively.

Additional analyses for Fe, Mn, Ti and P were obtained as part of the trace element run on the simultaneous XRF spectrometer for all 668 pellets. Na and K were also determined for all pellets of borehole GS72, because this borehole clearly penetrated a low-grade orebody in the tin-rich zone.

4.3.3 Sulphur and total carbon (CO_2)

Analyses for these elements were done by infrared ra-

Table 4: Analytical parameters for XRF-determinations of major elements.

ELEMENT	X-RAY TUBE	ANALYTICAL CRYSTAL	COUNTING TIMES (Sec)	LOWEST LIMIT OF DETECTION (L.L.D.)
Na	Chrome	TLAP	200	0,08000
Ti	Chrome	LiF200	20	0,00784
Ca	Chrome	LiF200	20	0,00857
K	Chrome	LiF200	20	0,00385
Si	Chrome	PET	100	0,05437
Al	Chrome	PET	100	0,03310
Mg	Chrome	TLAP	200	0,11018
P	Tungsten	Germanium	100	0,02624
Fe	Tungsten	LiF220	20	0,02390
Mn	Tungsten	LiF220	40	0,01153
Cr	Tungsten	LiF220	40	0,01485
Ni	Tungsten	LiF220	40	0,01463

diation absorption detection on all sample powders of boreholes GS69 and GS72. The instrument used was the LECO CS244 machine housed at the Geological Survey of South Africa.

The L.L.D. for the elements is as follows:

S = approximately 10 p.p.m.

CO_2 = approximately 6 p.p.m.

CO_2 includes all carbon.

4.3.4 Fluorine

Fluorine was determined wet chemically by the method of standard addition using a fluoride ion selective electrode. These analyses were carried out on all the samples of borehole GS69.

4.4 DISTRIBUTION PATTERNS OF MAJOR AND TRACE ELEMENTS IN AND ADJACENT TO THE TIN-RICH ZONE OF THE BOBBEJAANKOP GRANITE

4.4.1 Statistical treatment and presentation of geochemical data

The effective interpretation of geochemical data of ore deposits involves the consideration of multiple populations of data. Typically, two distinct populations can be distinguished, namely a background population consisting of low values which show a normal distribution, and an anomalous population consisting of anomalously high values related to the ore and having an approximately normal distribution. The latter always has a higher mean and larger standard deviation than the background population. Samples related to unusual aspects of the environment may define additional populations. Background and anomalous populations commonly overlap so that a completely satisfactory separation of their members is impossible. Consequently there exists a problem in selecting an effective threshold value.

In order to separate anomalous samples from background samples a number of methods, all based on the determination of a threshold value, and depending on various factors such as the amount of data, the purpose of the survey, the knowledge of the area surveyed and economic considerations can be used. The different methods are summarized by Rose, Hawkes and Webb (1979).

Statistical tests prove a bimodal distribution of tin in the Bobbejaankop Granite. This indicates that two tin populations are present. Because of the large number of samples available for this investigation, an effective separation of these populations can be accomplished through the application of several methods. Those used are the following:

i) The construction of a histogram clearly revealed overlapping background and anomalous populations (Fig. 7). A threshold value of 35 p.p.m. Sn effectively separates the two populations.

ii) To test the validity of the threshold value obtained, a method, based on a cumulative probability plot of data (Sinclair , 1974) was applied, that gave a threshold value of 38 p.p.m. Sn.

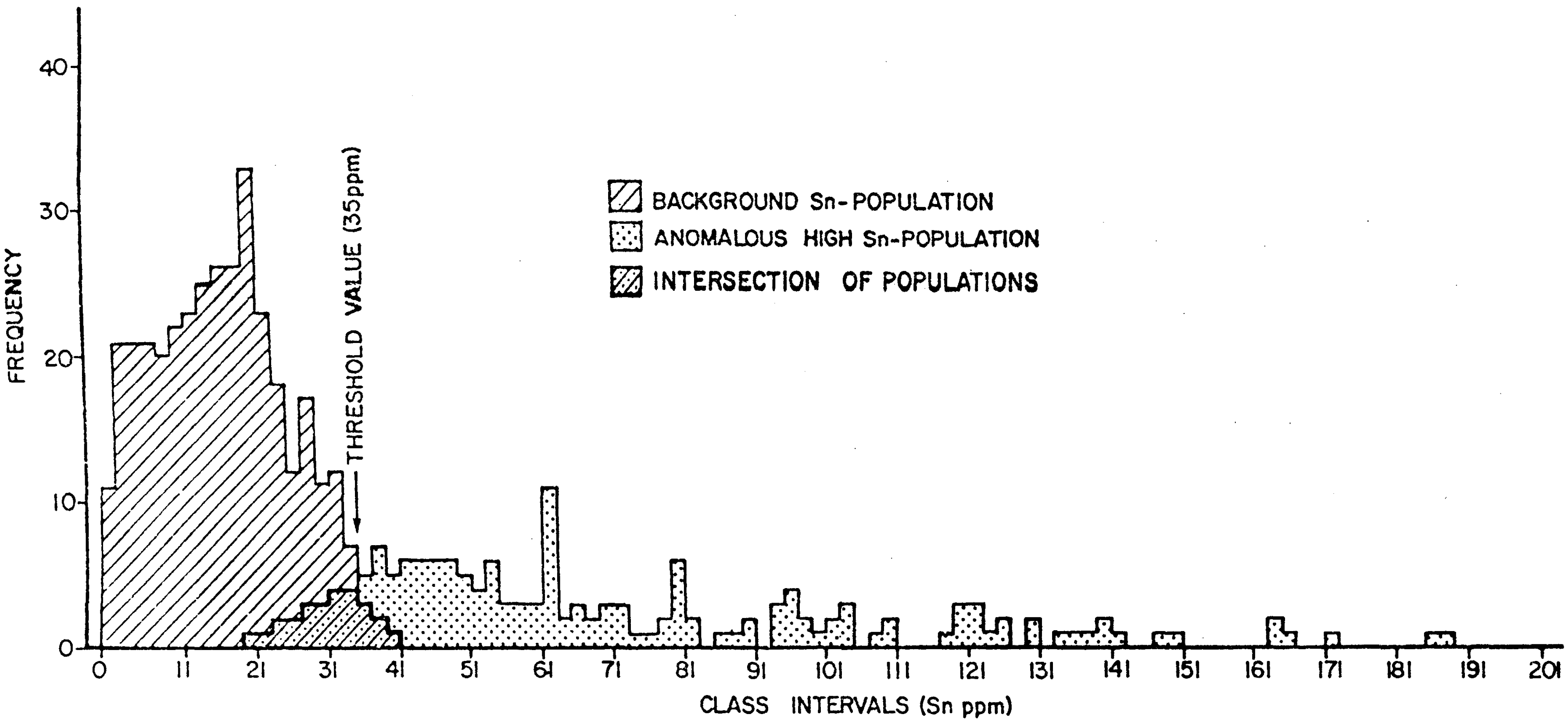
iii) A discriminant analysis was done on the Bobbejaankop Granite data set. This method requires that as many samples as possible that definitely belong to one of the two populations must be separated These are read into a computer programme which then takes all discriminating factors (caused by any element) into account to classify the remaining samples between the two populations. Through inspection of the range of values in the two sample sets, a threshold value, which separates the two populations best, can be determined In this investigation samples were separated on the basis of their tin content. The discriminating elements chosen by the computer with the weight they counted (in brackets) are the following: Sn (86.3 %), W (4.1%), As (4.1%), S (4.1 %), Mo (1.4 %). The threshold value determined for Sn was 35 p.p.m.

Relatively good correspondence of results was obtained through all 3 methods. Consequently, because the threshold values obtained through a discriminant analysis and histogram were both 35 p.p.m., threshold values for other elements were calculated where possible through the discriminant analysis method (Table 5), because this is more valid than visual inspection of a histogram.

Table 5: Threshold values for selected minor and trace elements in Bobbejaankop Granite.

ELEMENT	THRESHOLD VALUE (p.p.m.)
As	40
CO_2	0,19 %
Cu	20
F	4600
Fe_2O_3	3,25 %
Mo	9
P_2O_5	0,003 %
Pb	27
S	0,019 %
Sn	35
Th	53
W	12
Zn	88

Fig. 7: Histogram showing the distribution of Sn values in Bobbejaankop Granite.



In order to reveal possible differences between unmineralized Bobbejaankop Granite, granite from the tin-rich zone, Lease Granite and granophyric granite, means and other statistics were calculated for all major (Tables 7, 13) and trace elements (Tables 10, 15). Discrimination tests were used to compare the means of the different granites. The choice of a discrimination test depends mainly on the size of the populations and on the distribution of the data in the respective populations. Because of the large difference in the numbers of samples analysed for major and trace elements, and because of the different sample sizes of each granite population, no single statistical test could be applied in every case, and the statistical treatment therefore varied depending upon the data sets under consideration.

The number of samples analyzed for major elements is small ($\leq$10 samples) for each rock type and the distribution of the elements in each rock type (population) is unknown. Consequently the major element data required a discrimination test that is not dependant on the distribution of data and is also applicable to populations with a very small number of samples. Neave and Granger (1968) and Ramsey (1971) proved the Tukey test to be one of the most powerful tests of this type. The Tukey test compares the whole distribution of one population (each member) with that of another. The test is based on the number of values (T) in the two series of data that do not overlap (Neave, 1979). The T-values obtained are compared with critical values which are dependant on the number of samples in each population (n), as well as on the confidence level required. Detailed tables with critical values were published by Neave (1978). Critical values required for discussions in this chapter are given in Table 6. T-value determinations for the major elements are presented in Tables 8 and 14.

Because the number of samples analysed for trace elements in the Lease and granophyric granites is small and of comparable size, the Tukey test was also suitable to discriminate between their means. The results are presented in Table 16.

The Kolmogorov-Smirnov test (Miller and Kahn, 1965) was used to compare trace element means of the Bobbejaankop Granite with those of the Lease and granophyric granites, because the samples comprise less than 100 individuals, differ notably in size and the individuals are not normally distributed as proved through normality tests (skewness, kurtosis). The results are presented in Table 16.

Because of the large number of samples analyzed for trace elements in Bobbejaankop Granite, their division into anomalous and background Sn populations resulted in a large number of individuals for each population (n_1 = 406, n_2 = 216). However, although a normal distribution of data was

As an additional aid in studying element distribution patterns, correlation coefficients were calculated for selected major elements (Table 9) and trace elements (Table 12) with Sn in unmineralized and mineralized Bobbejaankop Granite. Because tin is not normally distributed in these rocks, the non-parametric Spearman correlation coefficient is used.

In order to present element distribution patterns in a practical form, graphs were constructed of concentration versus depth, using a five point running mean to smooth the curves. The distribution curves of the major element oxides (TiO_2, Fe_2O_3, MnO_2, P_2O_5) for the different boreholes are given in Figures 8 to 12, while those of the trace elements are presented in Figures 13 to 17. Additional plots were made for Na_2O and K_2O (Fig. 11) and F (Fig. 16) in borehole GS72,and S and CO_2 in boreholes GS69 (Fig. 13) and GS72 (Fig. 16).

Because the samples, analyzed for the full range of major elements, were taken at too wide intervals, graphs similar to those previously described could not be constructed. Consequently discussions on the distribution of these elements in the different granite populations is mainly based on the discrimination of means and the correlations of these elements with tin.

4.4.2 Major element distribution patterns

Statistical results (Tables 7, 8) indicate no significant differences in the distribution of SiO_2, Al_2O_3, MgO, CaO, TiO_2, Fe_2O_3, MnO and P_2O_5 in unmineralized Bobbejaankop Granite and granite from the tin-rich zone (mineralized Bobbejaankop Granite). There is also no meaningful correlation between Sn and these elements (Table 9). However, the distribution patterns of Fe_2O_3, MnO and P_2O_5 (Figs. 8 - 12C, D, E) do show local, subordinate sympathetic variations with Sn in some boreholes. Increases in P_2O_5 (Figs. 10, 11) and decreases in MnO (Fig. 8) are occasionally present immediately below the tin-rich zone. However, because of the erratic behaviour of Fe_2O_3, MnO and P_2O_5, no generalizations concerning their distributions can be made.

Statistical results (Tables 7, 8) indicate a significant increase in Na within the tin-rich zone. The distribution pattern of Na (Fig. 11F) indicates that Na-increases may also occur immediately below the tin-rich zone. A possible explanation for Na increases could be Na-metasomatism (albitization). This supports petrographic evidence, which indicates increases in the plagioclase proportion of antiperthite, mainly within, and occasionally below, the tin-rich zone. The insignificant correlation between Na and Sn (Fig. 9) can be explained by the large number of Na-analyses of borehole GS72 (Fig. 11F) that show an increase below the tin-rich zone and has been used in the calculation of a correlation coefficient.

Statistical results (Tables 7, 8, 9; Fig. 11A, G) indicate a significant decrease in K within the tin-rich zone. The most probable explanation for the loss of K in the tin-rich zone is perhaps the removal of K ions, released through substitution by Na, during albitization.

Although none of the major elements investigated comply with all the requirements of a good indicator element, some of them do show minor variations that may, if used in combination, be an aid in exploration for the low-grade disseminated type of tin deposit in Bobbejaankop Granite. The variations are summarized below:

i) Local Mn increases sometimes occur within, and local decreases may occur below tin-rich zones.

ii) Anomalously high P values occasionally occur within and or below tin-rich zones.

iii) Slight increases in Fe sometimes occur within tin-rich zones.

iv) Na usually increases slightly within or below tin-rich zones.

v) K usually decreases slightly within tin-rich zones.

Table 7: Population statistics of the major element contents of un-mineralized and mineralized Bobbejaankop Granite (Analyses recalculated)

ELEMENT	UNMINERALIZED BOBBEJAANKOP GRANITE (n = 10)				MINERALIZED BOBBEJAANKOP GRANITE (n = 10)			
	$\bar{x}$ (%)	σ	Range of Values		$\bar{x}$ (%)	σ	Range of Values	
			Min (%)	Max (%)			Min (%)	Max (%)
SiO_2	74,923	0,695	73,727	75,921	74,885	0,781	74,101	76,506
TiO_2	0,081*	0,006	0,068	0,088	0,075x	0,005	0,065	0,084
Al_2O_3	11,265	0,118	11,004	11,397	11,294	0,172	11,043	11,523
Fe_2O_3	1,581*	0,006	1,568	1,588	1,575x	0,005	1,565	1,584
MnO	0,030*	0,009	0,014	0,047	0,036x	0,006	0,021	0,042
MgO	0,132	0,047	0,069	0,206	0,137	0,039	0,082	0,209
CaO	0,878	0,201	0,519	1,148	0,989	0,178	0,736	1,360
Na_2O	2,908	0,209	2,547	3,115	3,174	0,125	2,847	3,309
K_2O	5,212	0,184	4,963	5,567	5,041	0,116	4,849	5,213
P_2O_5	0,014*	0,008	0,003	0,029	0,020x	0,008	0,007	0,036

* n = 406

x n = 216

Table 8: Tukey's T-values for discriminating between major element means of unmineralized and mineralized Bobbejaankop Granite.

ELEMENT	T
SiO_2	2
TiO_2	5
Al_2O_3	3
Fe_2O_3	5
MnO	2
MgO	3
CaO	4
Na_2O	8*
K_2O	8*
P_2O_5	4

* = Significant difference at a 95 % confidence level.

Table 9: Spearman correlation coefficients for Sn with selected major elements in Bobbejaankop Granite.

ELEMENT	UNMINERALIZED BOBBEJAANKOP GRANITE	MINERALIZED BOBBEJAANKOP GRANITE
K	-0,1777	-0,6915
Fe	0,1088	0,1327
P	0,2984	0,0942
Na	-0,1751	0,0877
Mn	0,0698	0,0786

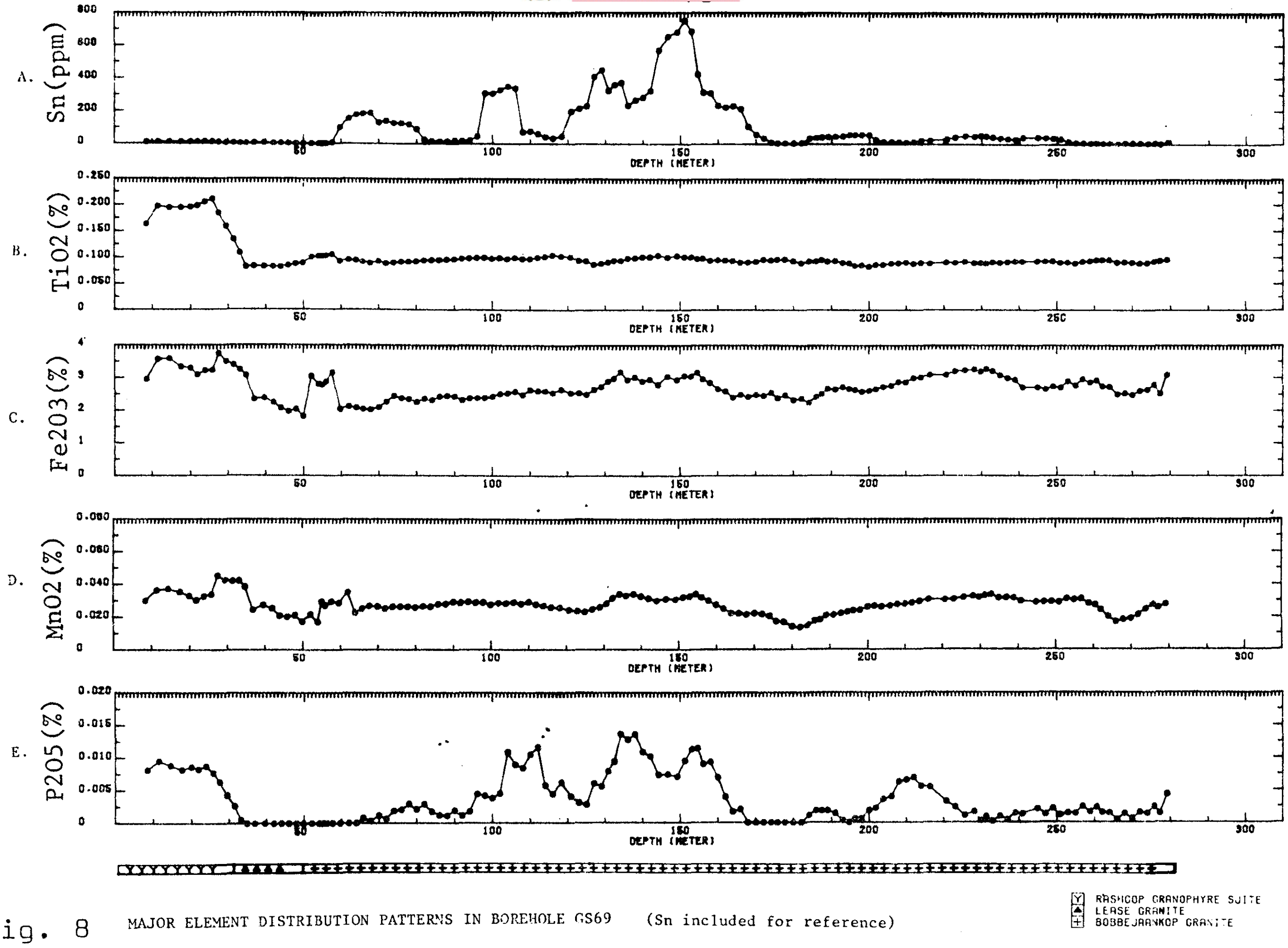


Fig. 8 MAJOR ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS69 (Sn included for reference)

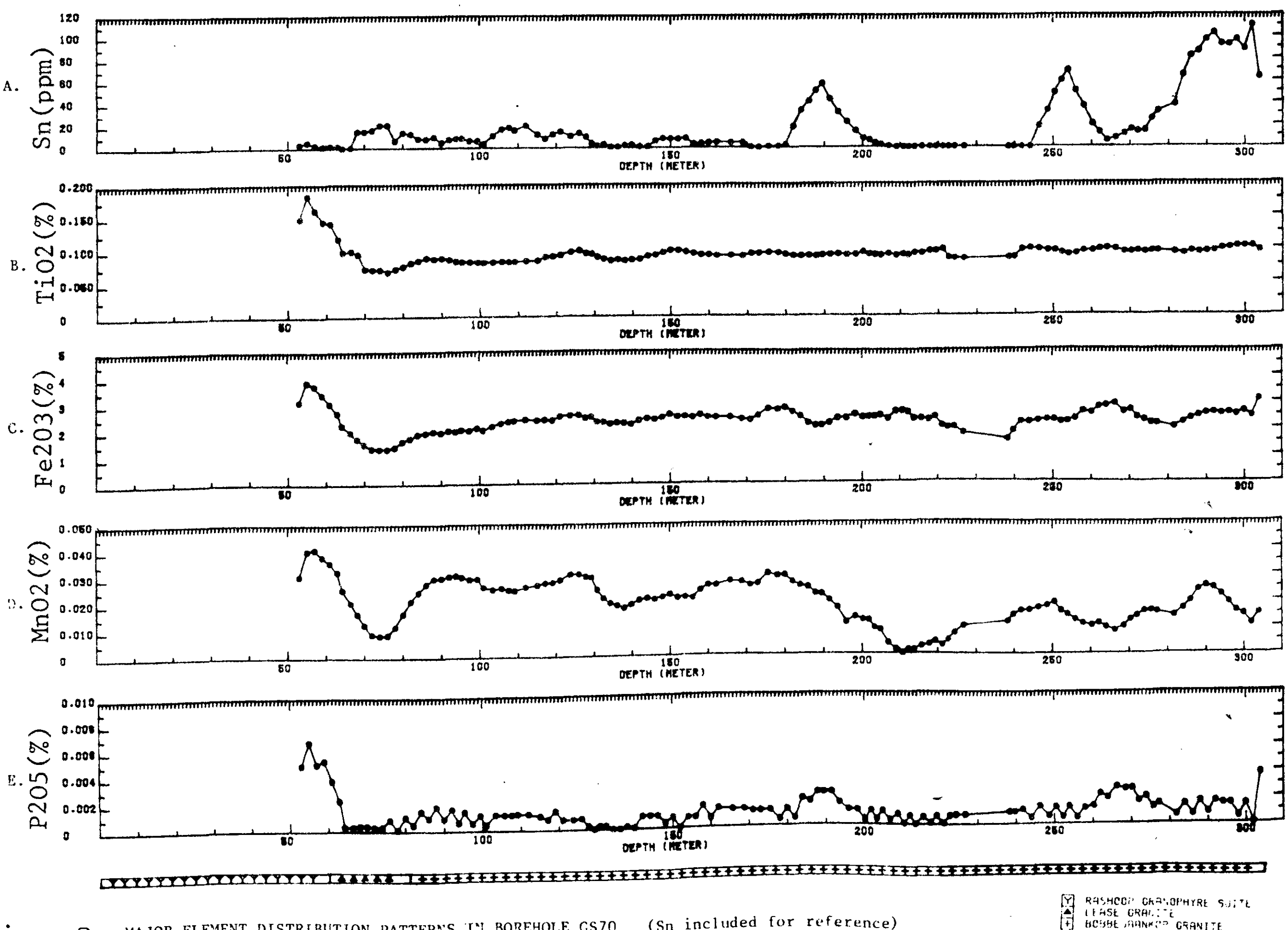


Fig. 9 MAJOR ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS70 (Sn included for reference)

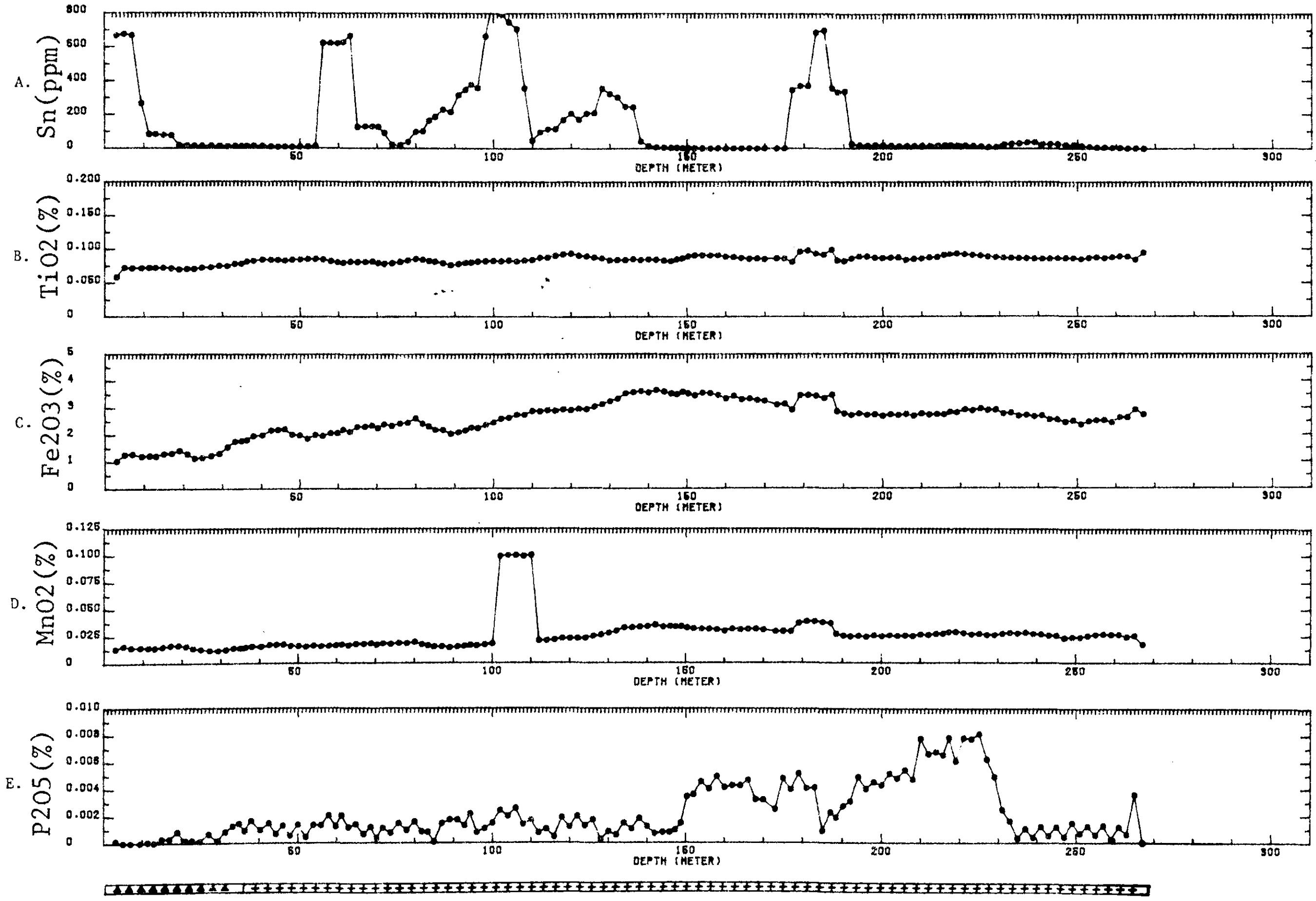


Fig. 10 MAJOR ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS71 (Sn included for reference)

RASHOOP GRANOPHYRE SUITE
LEBOE GRANITE
BOBBEJAANKOP GRANITE

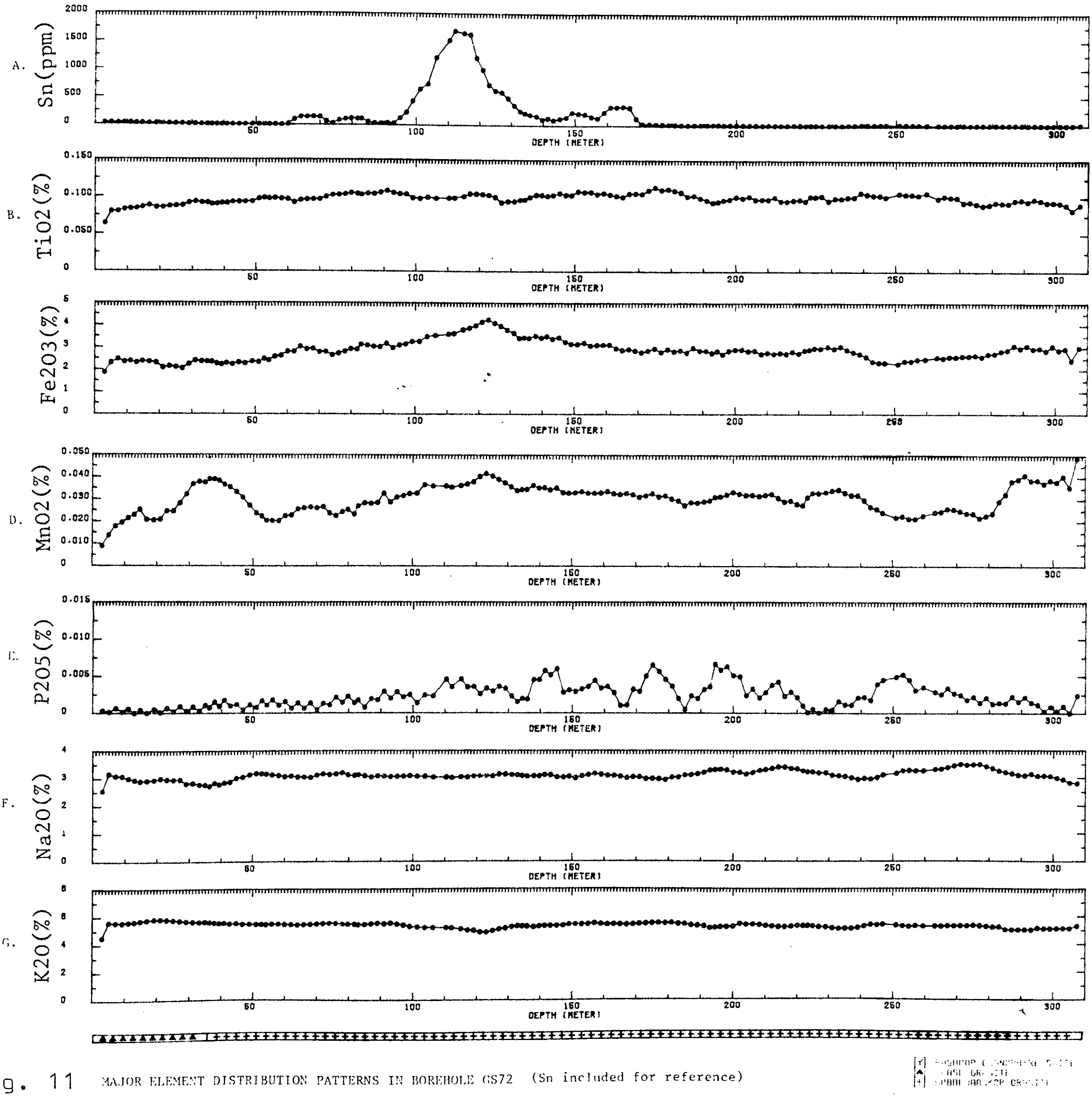


Fig. 11 MAJOR ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS72 (Sn included for reference)

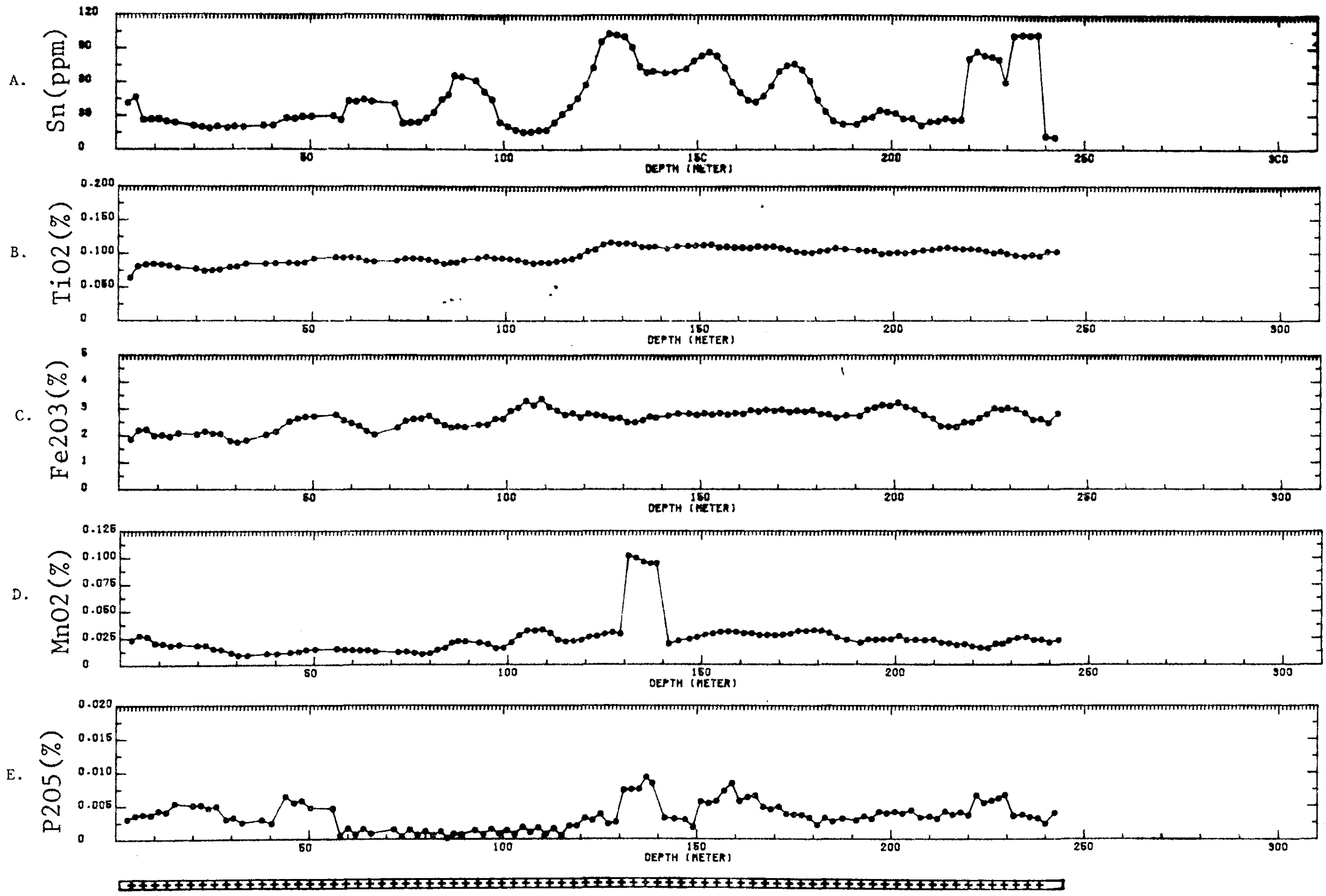


Fig. 12 MAJOR ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS73 (Sn included for reference)

Y RASHOOP GRANOPHYRE SUITE
▲ LEASL GRANITE
+ BOB3LJAANKOP GRANITE

4.4.3 Trace element distribution patterns

Distribution patterns of Sn against borehole depth (Figs. 13A - 16A) indicate that high Sn values alternate with occasional low values in the tin-rich zone. From these figures it is also clear that the tin content of the tin-rich zone gradually decreases towards its upper and lower boundaries. There is no consistency concerning the depths of the richest Sn portions of the tin-rich zone as indicated by the positions of the maxima of Sn peaks in Figures 13A to 16A. The distribution of Sn within the tin-rich zone (Figs. 13A - 16A) further indicates that anomalously high Sn values ($>$ 35 p.p.m.) should be a good indicator of tin ore ($Sn \geq$ 1 500 p.p.m.). For example in Figure 16A such values are present up to a distance of 30 - 50 metres away from the tin ore. Thus Sn is also a good pathfinder element for this type of deposit and could be successfully used in exploration.

Statistical results (Tables 10, 11, 12) and distribution patterns (Figs. 13B - 17B) indicate a small but significant decrease in Rb within the tin-rich zone. The negative correlation of Rb with Sn (Table 12) would not be expected if the present chemistry is purely the result of fractional crystallization of the Bobbejaankop Granite magma. The drop in Rb probably reflects the increase in the plagioclase proportion of antiperthite(albitization) in the tin-rich zone, because albitization is at the expense of K-feldspar, the mineral that probably hosts most of the Rb. The graphs (Figs. 13B - 17B) indicate that Rb values lower than approximately 410 p.p.m. in Bobbejaankop Granite can be an indication of the presence or proximity of anomalously high Sn concentrations in that both can result from late-stage metasomatism.

Statistical results (Tables 10, 11, 12) indicate significant increases in W, As, S and F within the tin-rich zone. This is clearly reflected in the distribution patterns of these elements (Figs. 13 L, P and R to 16 L, P and R, as well as Fig. 13 T). All the evidence corresponds to the general geochemical behaviour of tin deposits, which are typically characterized by W and F enrichment. At Zaaiplaats the W-bearing mineral is mainly scheelite and the F-bearing mineral, fluorite, both of which are more abundant in the tin-rich zone than in the unmineralized granite.

The distribution patterns of the chalcophile elements Cu, Pb, Zn and Mo (Figs. 13 M, N, O and Q to 17 M, N, O and Q) together with statistical results (Tables 10, 11, 12) indicate that increases of these elements are not only confined to the tin-rich zone, but may occur immediately above or below it. It is thus justifiable to draw the conclusion that Cu, Pb, Zn and Mo enrichments occur in association with the tin-rich zone. Enrichment of sulphur and the chalcophile elements in the tin-rich zone can be explained by the fact that S is normally concentrated in the vapour phase, which probably exsolved shortly before and during crystallization of the tin-rich zone.

Statistical results (Tables 10, 11, 12) and distribution patterns (Figs. 13S to 16S) indicate that CO_2 (total carbon) is occasionally enriched within the tin-rich zone. The mineral mainly responsible for CO_2 variations is calcite.

All evidence indicates that there is no systematic variation of Sr, Ba, Y, Zr, Nb, Th, U and Sb with Sn. (Figs. 13 D, E, F, G, H, I and J to Figs. 17 D, E, F, G, H, I and J, as well as Tables 10, 11, 12). According to statistical results (Tables 10 and 11) Nb and Th are significantly depleted within the tin-rich zone. However the differences are within the limits of analytical error of the XRF apparatus and therefore inconsequential.

The present geochemical investigation proved that no zonation of major or trace elements occurs within the tin-rich zone and no primary geochemical haloes surrounds this zone. The lack of geochemical haloes add weight to the proposed mode of formation of the tin-rich zone, because such features are characteristic of metasomatic deposits.

The absence of geochemical haloes and a distinct zonation pattern preclude the possibility of finding real pathfinder elements for the low-grade deposits. The fact that only borehole GS72 intersected low-grade ore (Sn≥1 500 p.p.m.), does not throw any light on this problem, because no generalizations can be made from the distribution patterns of only one borehole. However, in spite of the absence of pathfinder elements, the following criteria may be useful in locating similar disseminated deposits in the Bushveld granites:

i) The occurrence of anomalously high Sn values (Sn> 35 p.p.m.).

ii) Rb decreases locally in a continuous series of samples taken along a line in a specific granite. The Rb values should be lower than approximately 410 p.p.m. This probably indicates albitization associated with tin-rich zone.

iii) A continuous series of anomalously high W, As, S and F values (Table 5) are normally indicative of tin-rich zones.

iv) Anomalously high Cu, Pb, Zn and Mo values (Table 5) occur within or immediately above or below tin-rich zones.

Table 10: Population statistics of the trace element contents of unmineralized and mineralized Bobbejaankop Granite.

Element	(n = 406) Bobbejaankop Granite (Unmineralized)				(n = 216) Bobbejaankop Granite (Mineralized)			
	$\bar{x}$(ppm)	σ(ppm)	Range of Values Min(ppm)	Range of Values Max(ppm)	$\bar{x}$(ppm)	σ(ppm)	Range of Values Min(ppm)	Range of Values Max(ppm)
Cu	39	303	< 5	276	58	90	< 5	484
Y	158	36	49	351	162	41	39	339
Ba	180	110	100	548	178	39	101	345
Pb	23	80	< 5	1027	27	78	5	832
Zn	65	67	< 5	970	88	210	3	3085
Zr	285	29	213	390	278	25	201	382
Sn	14	9	< 5	35	267	447	36	3056
Th	44	7	27	95	43	9	19	127
Rb	443	52	352	939	419	39	253	630
Nb	35	5	19	63	32	5	14	67
Sb	19	14	< 5	53	20	12	< 5	51
U	12	5	< 5	50	11	6	< 5	46
Sr	14	6	6	35	14	5	6	30
Mo	3	4	< 5	67	4	7	< 5	51
W	7	55	< 5	1075	24	68	< 5	719
As	15	13	< 5	96	24	39	< 5	353
CO_2*	0,128	0,069	0,03	0,400	0,142	0,091	0,040	0,730
S*^{2}	0,016	0,062	0	2,013	0,027	0,016	0,006	0,074
F	3674	1592	700	11 600	4600	1277	750	7150

* Percentage

Table 11: Z-values for discriminating between trace element means of unmineralized and mineralized Bobbejaankop Granite.

Element	z	Element	z
Sn	8,314 x	W	3,025 x
Rb	6,471 x	Cu	1,168
Sr	0,798	Rb	0,674
Ba	0,328	Zn	1,556
Y	1,389	As	3,330 x
Zr	3,425	Mo	1,659
Nb	4,375 x	S	3,370 x
Th	2,316 *	CO_2	1,330
U	0,977	F	3,720 x
Sb	0,266		

* Significant difference at 95 % confidence level

x Significant difference at 99 % confidence level

Table 12: Spearman correlation coefficients for Sn with selected trace elements in Bobbejaankop Granite.

ELEMENT	UNMINERALIZED BOBBEJAANKOP GRANITE	MINERALIZED BOBBEJAANKOP GRANITE
Rb	0,0015	-0,5338
Nb	0,1511	-0,1559
Zr	-0,0313	-0,1552
Th	-0,1676	-0,1547
Ti	0,0472	-0,1256
Sb	0,0249	-0,0986
Y	0,0573	-0,0432
F	-0,1290	0,6426
S	-0,0443	0,5606
As	-0,1492	0,5421
Pb	0,1118	0,4890
Cu	0,1715	0,2805
W	0,0237	0,2473
Zn	0,0240	0,2424
Mo	-0,0006	0,2321
Sr	-0,3552	0,2124
CO_2	-0,0702	0,1140
Ba	0,2568	0,1068

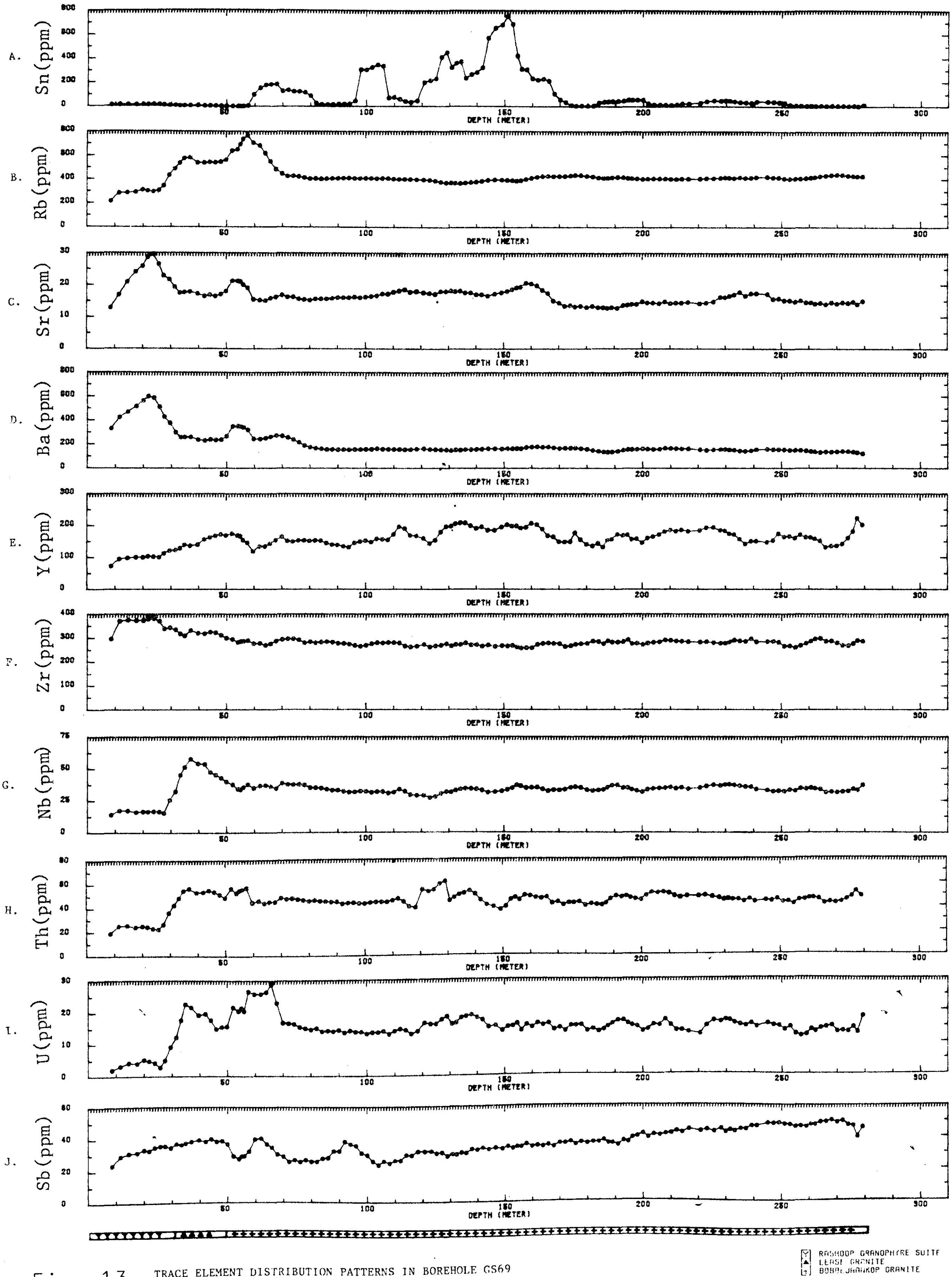


Fig. 13 TRACE ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS69

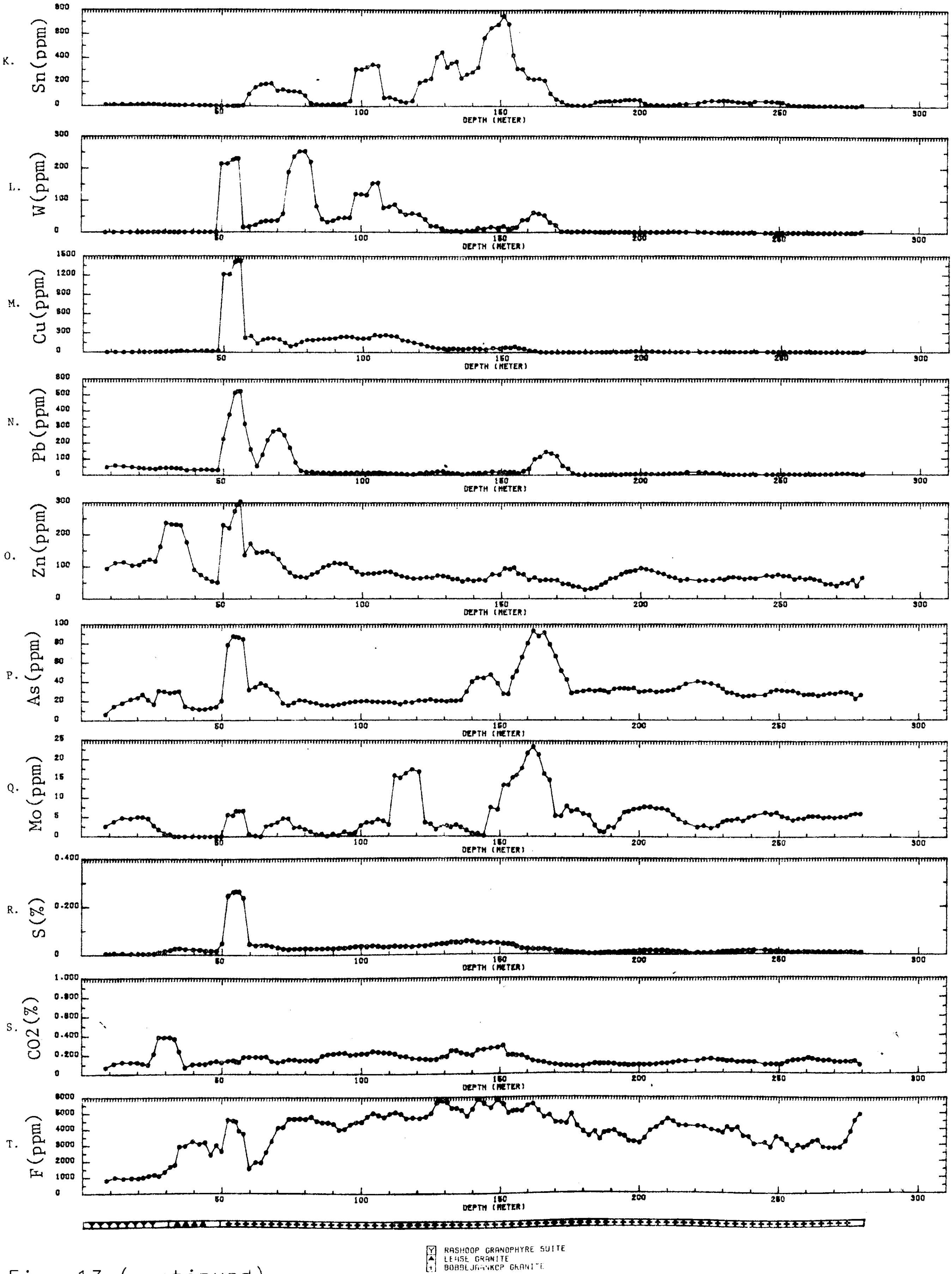


Fig. 13 (continued)

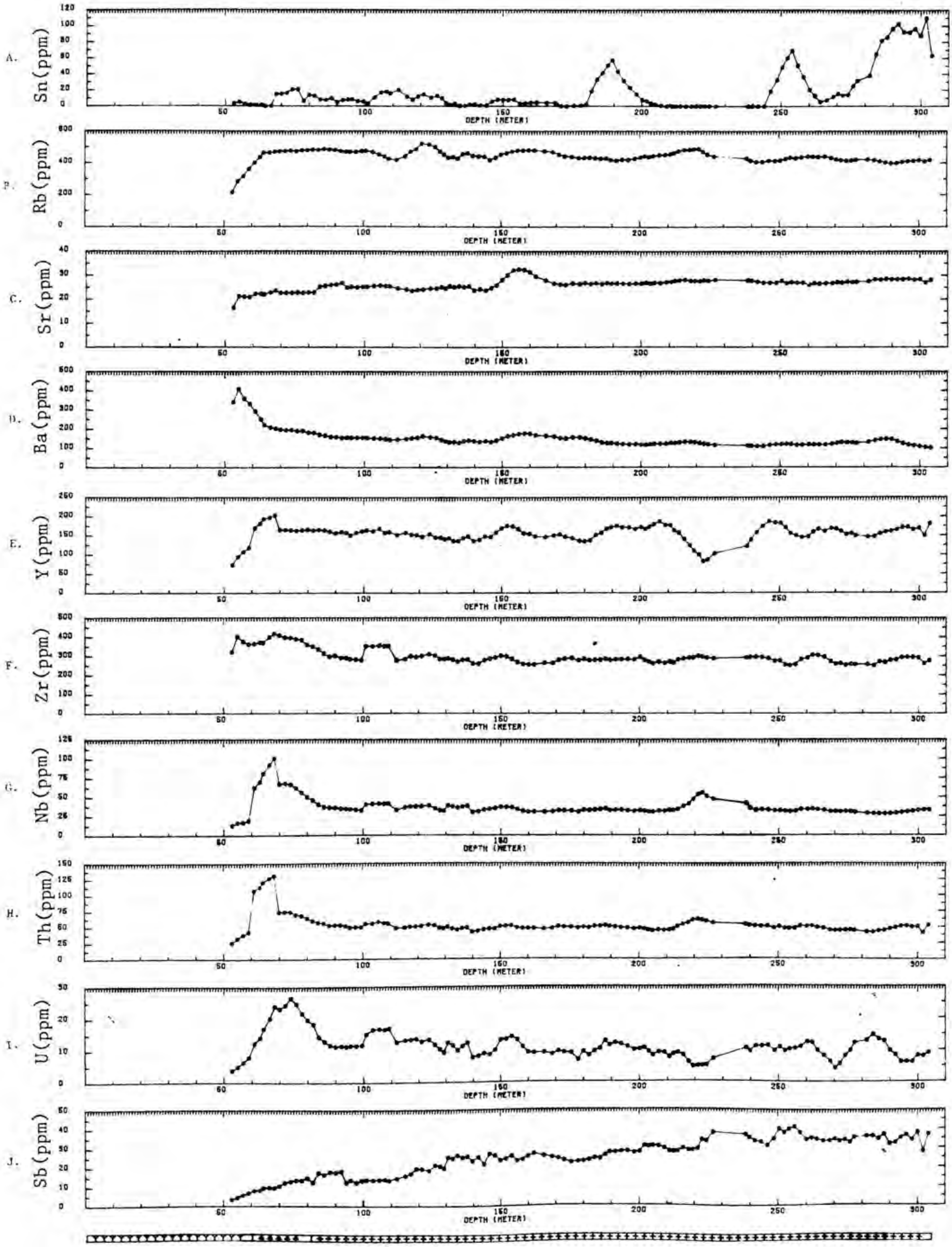


Fig. 14 TRACE ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS79

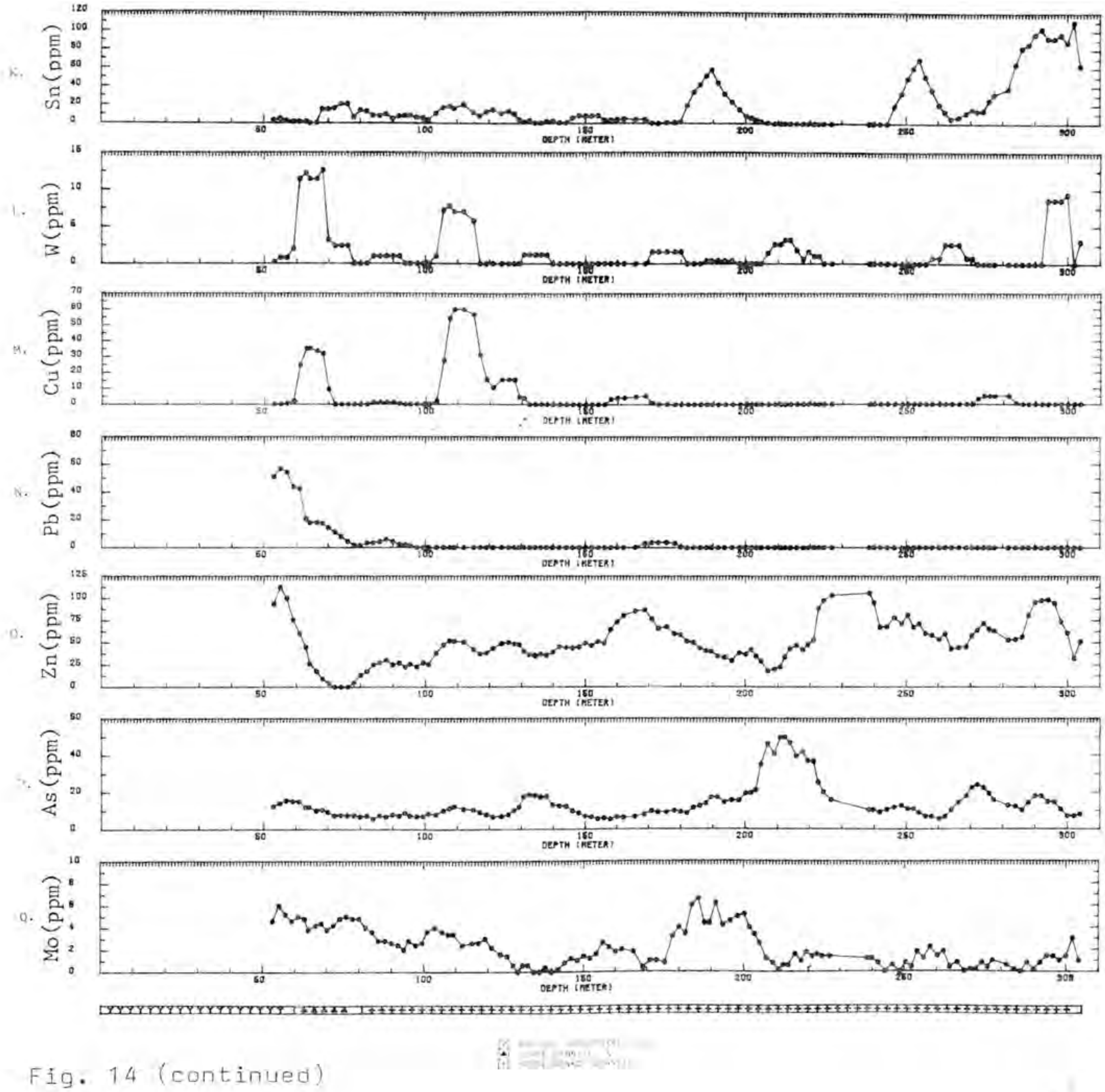


Fig. 14 (continued)

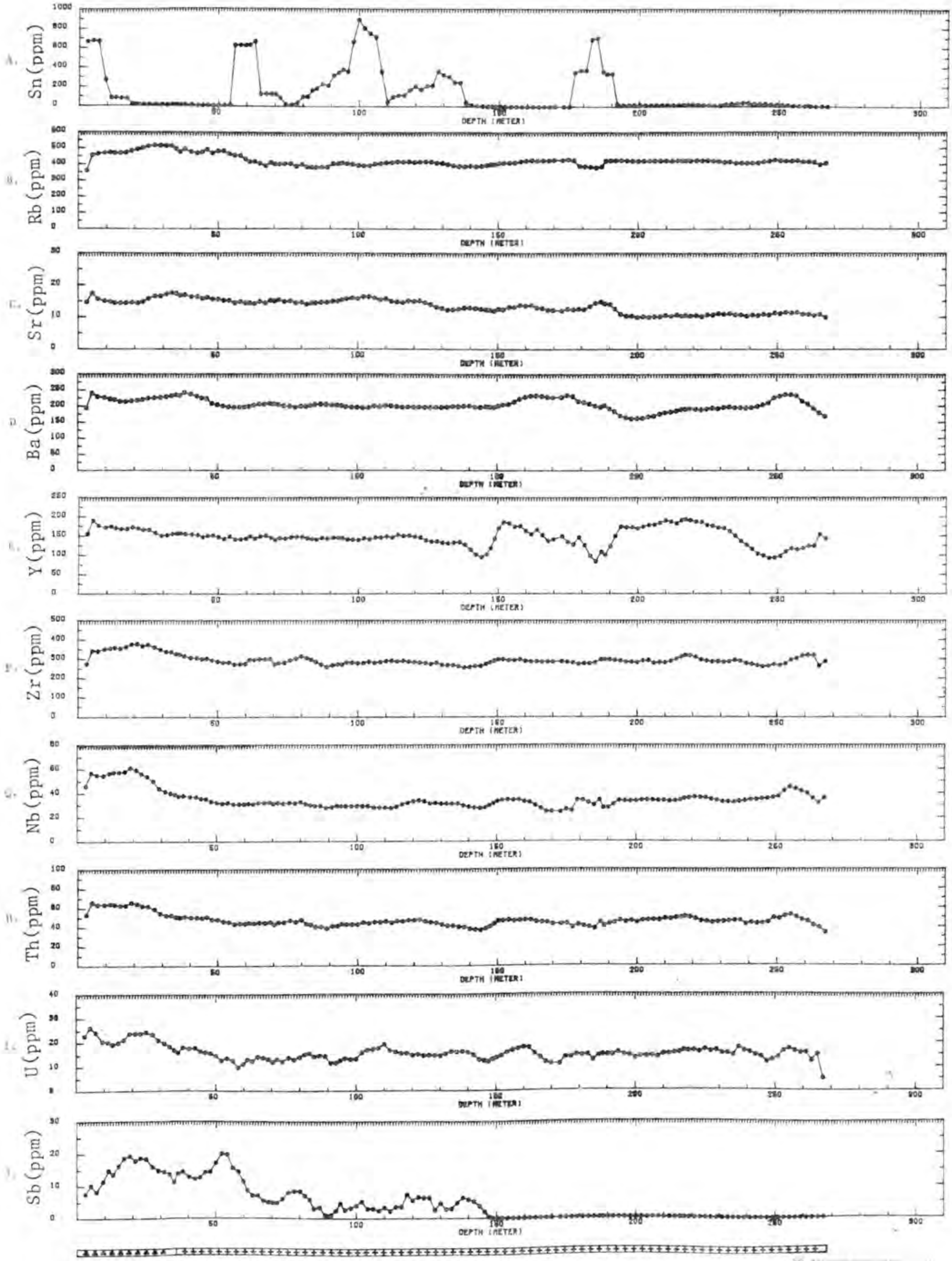


Fig. 15 TRACE ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE CS21

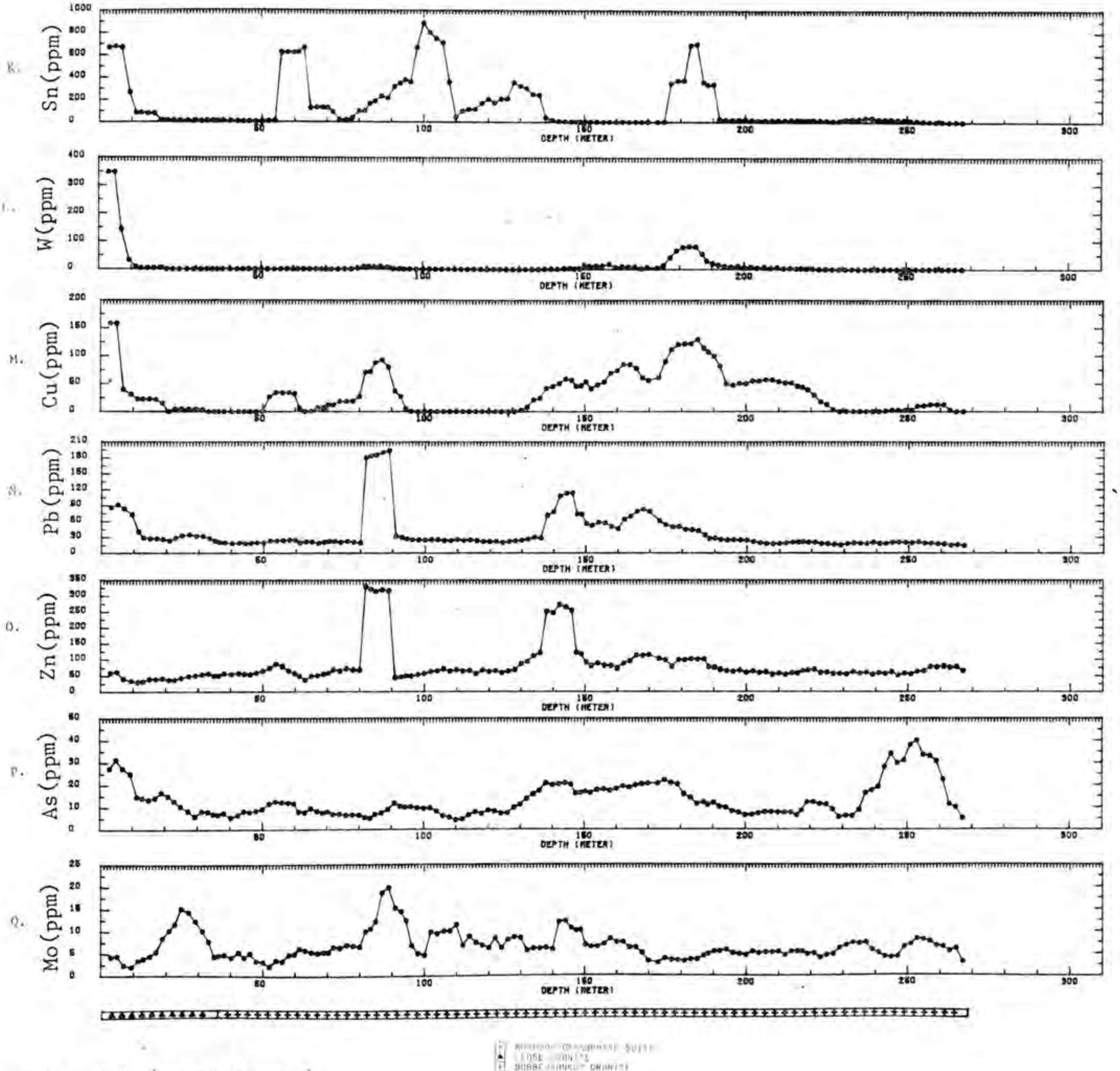


Fig. 15 (continued)

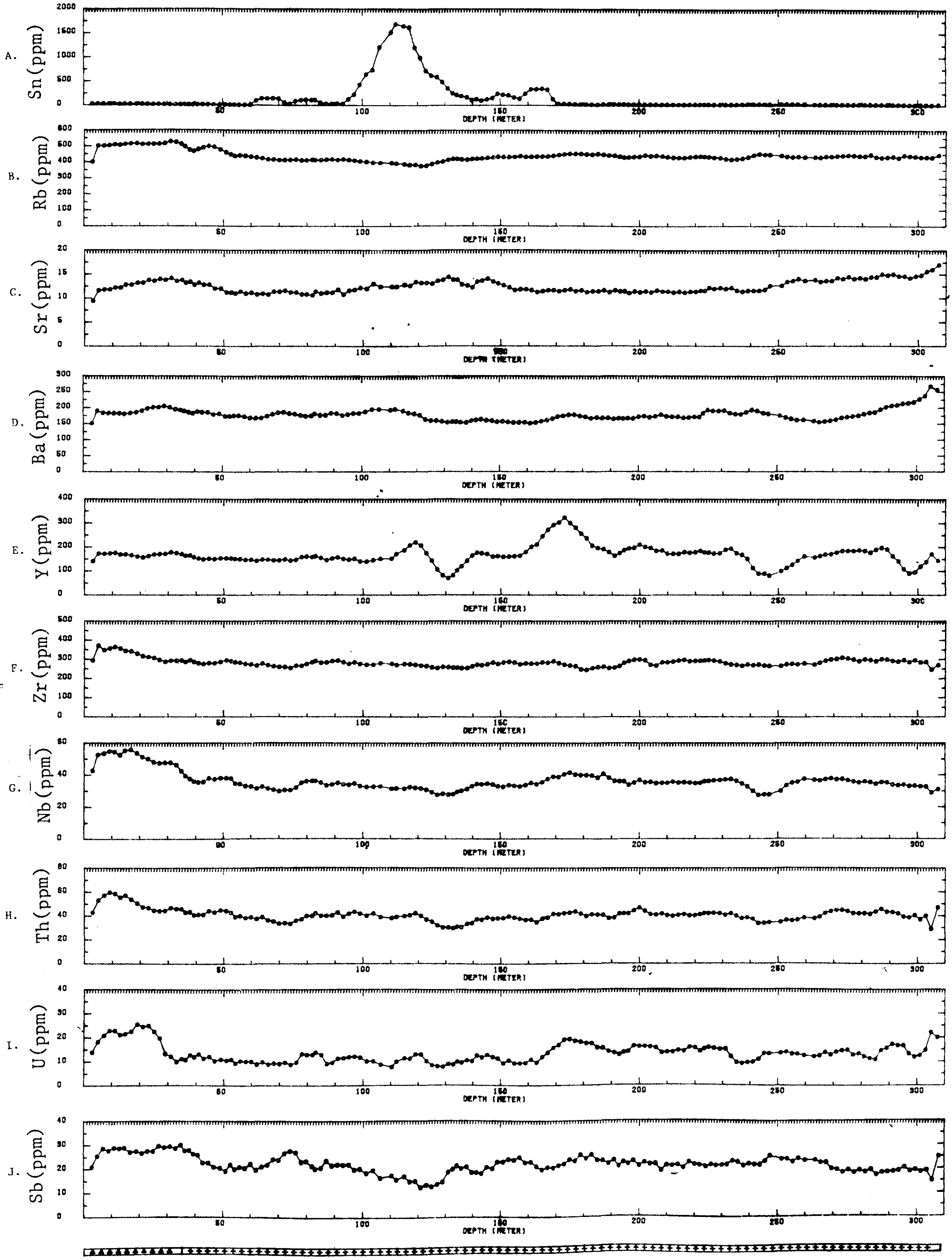


Fig. 16 TRACE ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS72

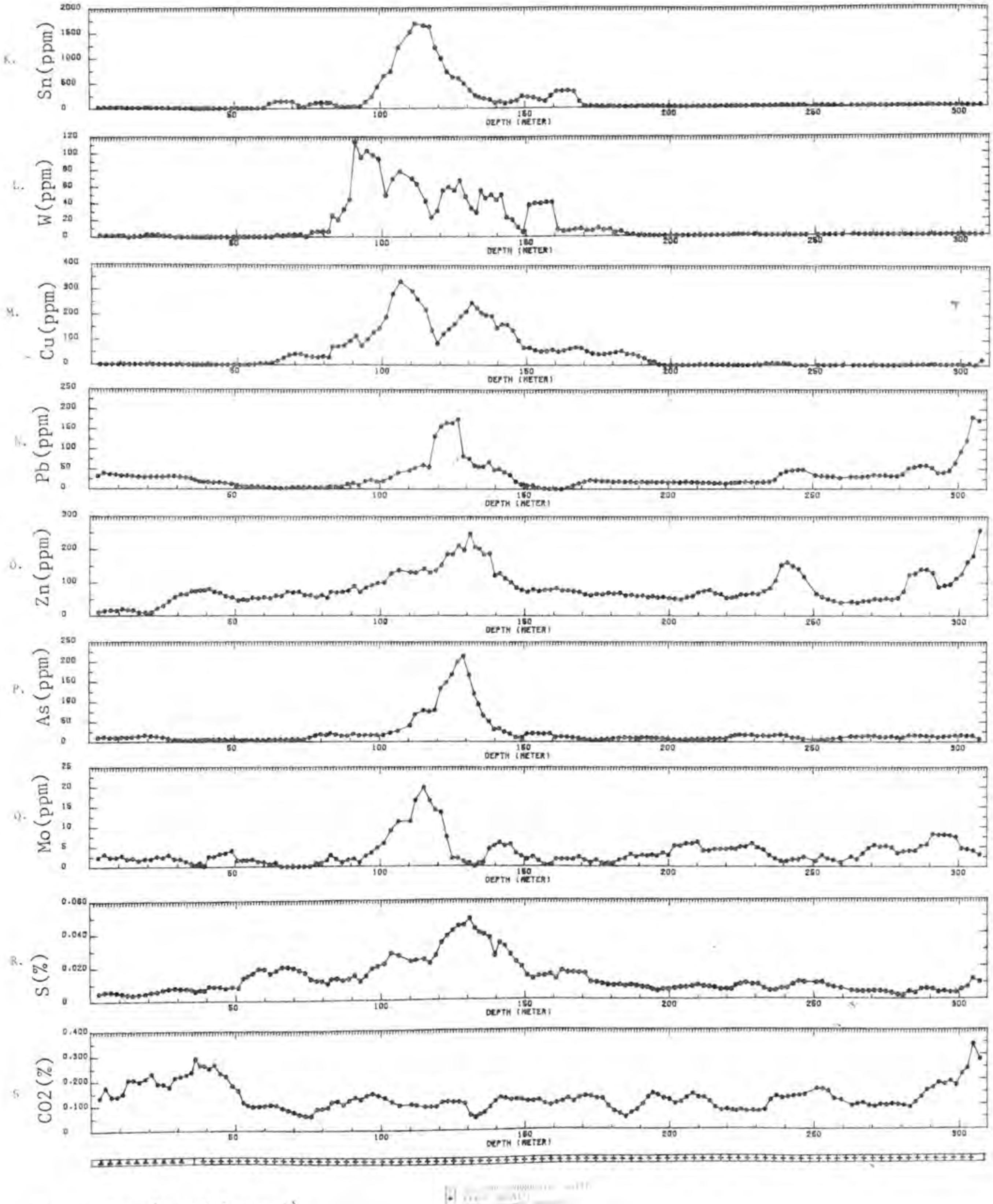


Fig. 16 (continued)

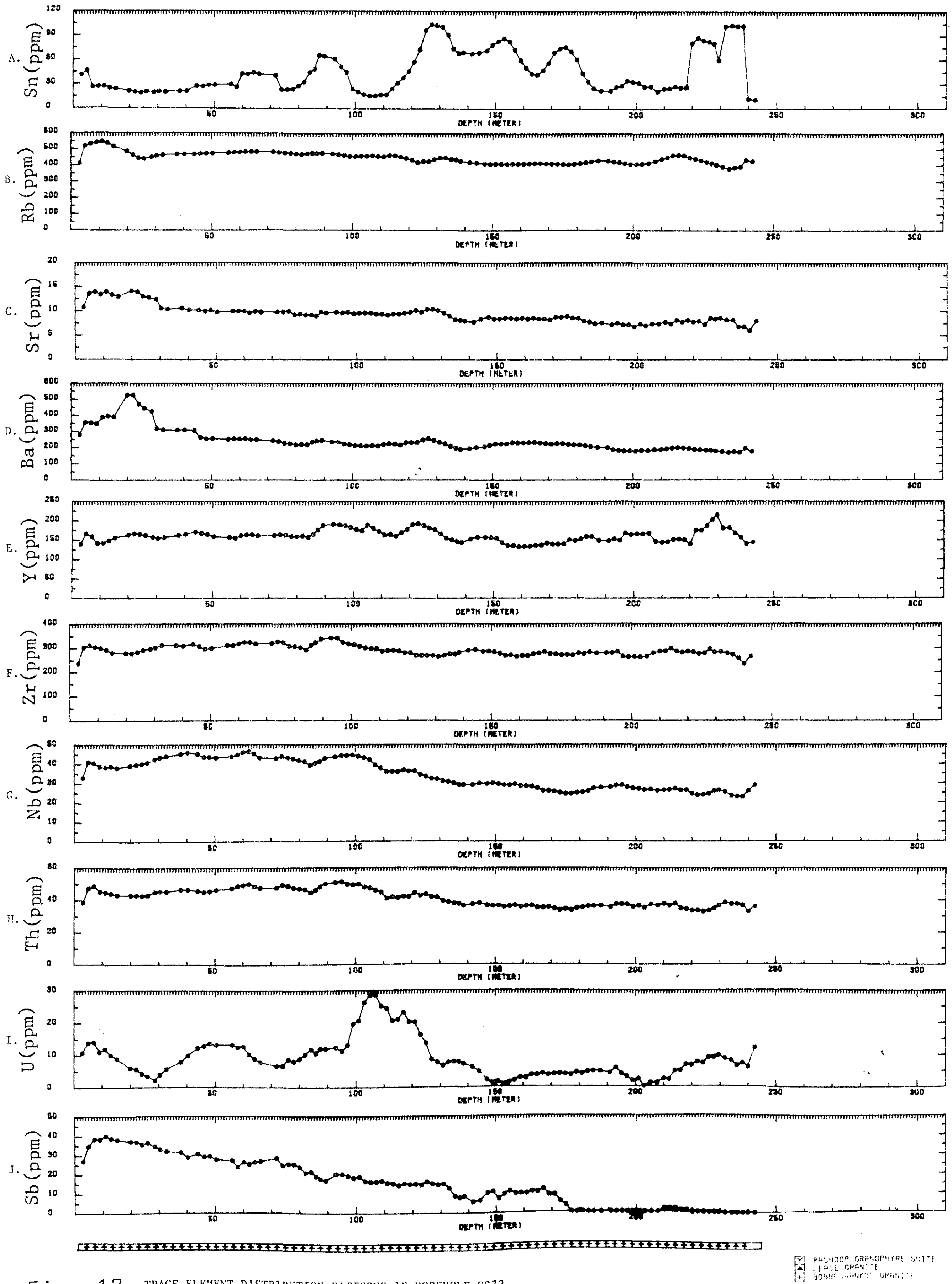


Fig. 17 TRACE ELEMENT DISTRIBUTION PATTERNS IN BOREHOLE GS73

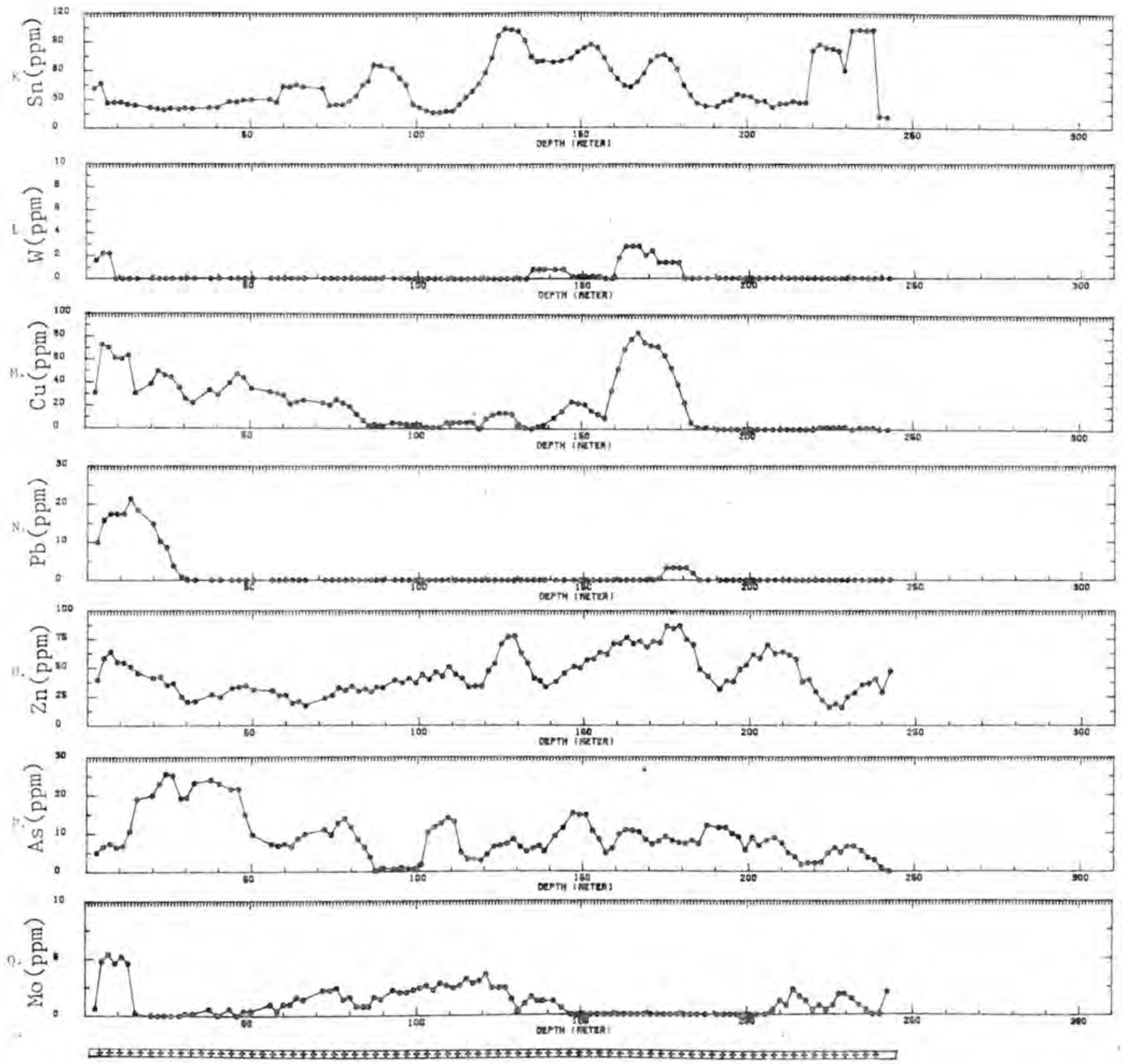


Fig. 17 (continued)

4.5 A GEOCHEMICAL COMPARISON OF THE DISTRIBUTION OF MAJOR AND TRACE ELEMENTS IN THE DIFFERENT GRANITES.

4.5.1 Granophyric granite (Rashoop Granophyre Suite) vs. Lease Granite.

Statistical results (Tables 13, 14) as well as distribution patterns (Figs. 8 B, C, D and E to 9 B, C, D and E) indicate that the granophyric granite, is significantly enriched in the major elements Ti, Fe, Mn and P. The sharp Ti increase confirms the results of Lenthall and Hunter (1977) and Strydom (1983) (Table 17).

Concerning the trace elements, the granophyric granite is significantly enriched in Ba, Zr and Zn (Tables 15 and 16; Figs. 13 D, F and O to 14 D, F and O) and depleted in Rb, Y, Nb, Th, U and F (Tables 15 and 16; Figs. 13 B, E, G, H, I and T to 14 B, E, G, H, I and T). The results confirm those of Fourie (1969) and Lenthall and Hunter (1977) (Table 17). However, no definite increase in Sr within the granophyric granite, as recognized by these workers, and by Strydom (1983), could be identified (Tables 15 and 16; Figs. 13 C and 14 C).

This evidence, taken together with the field relations described earlier, strongly suggests that the granophyric granite is less differentiated than the Lease Granite.

4.5.2 Granophyric granite (Rashoop Granophyre Suite) vs. unmineralized Bobbejaankop Granite.

Statistical results (Tables 13, 14, 15, 16) as well as distribution patterns (Figs. 8 B to E and 9 B to E ; Figs. 13 B, D, F, G, H, I, O and T as well as Figs. 14 B, D, F, G, H, I, O and T) indicate that the same differences that exist between the major and trace element distributions in Lease Granite and granophyric granite, are also present between the latter and the Bobbejaankop Granite. This implies that the Bobbejaankop Granite is more differentiated than the granophyric granite.

4.5.3 Unmineralized Bobbejaankop Granite vs. Lease Granite.

All the evidence (Tables 13, 14; Figs. 8 B and E to 12 B and E) indicates that there is no significant difference between the major element contents of the Bobbejaankop and Lease granites. However, statistical tests (Tables 15 and 16) and distribution patterns (Figs. 13 G to 16 G and 13 T) show that the Lease Granite is significantly enriched in Nb and depleted in F. Lenthall and Hunter (1977) suggested that the Bobbejaankop Granite is also relatively enriched in Zn (Table 17), but in the present study differences in Zn contents are statistically insignificant. Thus, except for the differences in the F and Nb contents of the granites, they are virtually the same. The geochemical and mineralogical similarity of the granites suggests that they most probably have crystallized from the same magma. The higher Nb contents of the Lease Granite probably represents the composition of the top of the Bobbejaankop Granite intrusion, because the roof zones of silicic magma chambers are usually enriched in Nb (Hildreth, 1979). The F enrichment of the Bobbejaankop Granite is possibly due to the concentration of rising volatiles when crystallization was almost complete.

Collins et al.(1982) stated that A-type granites are characterized particularly by their high Nb, Y, W, Mo, Ga and Sn contents. Pb and Zn are also relatively abundant and F is normally present in amounts in excess of 1 000 p.p.m. They further mentioned that A-type magmas are characterized by their homogeneity, the development of a late fluid phase and their association with rare metal deposits associated with F. Consequently, on this basis, the Bobbejaankop and Lease granites should be classified as A-type granites.

4.6 SUMMARY, DISCUSSION AND CONCLUSIONS

The only major elements that show significant variation within the tin-rich zone are Na and K. Their distribution patterns, together with petrographic evidence, indicate that albitization has occurred and was probably most intense within and immediately below the tin-rich zone. Rb depletion of the tin-rich zone is also ascribed to albitization.

The trace elements W, As, S and F are significantly enriched within the tin-rich zone and Cu, Pb, Zn and Mo enrichments often occur within and adjacent to this zone.

There is neither an internal zonation of elements within nor geochemical haloes around, the tin-rich zone. The latter observation precludes the possibility of a metasomatic origin for the tin-rich zone.

Geochemically the Bobbejaankop and Lease granites differ from the granophyric granite in exactly the same respects. The lower Ti, Fe, Mn, P, Ba, Zr, Zn and higher Rb, Nb, Th, U and F contents of the Bobbejaankop and Lease granites indicate that these granites are more differentiated than the granophyric granite. The similarity of the Bobbejaankop and Lease granites suggests that they probably have crystallized from the same magma.

The distribution of Nb in the Lease Granite may suggest that its parent magma originally resided in the roof of the Bobbejaankop Granite magma chamber.

The geochemical composition of the Bobbejaankop and Lease granites indicate that they should be regarded as A-type granites.

Table 13: Population statistics of the major element contents of unmineralized Bobbejaankop Granite, Lease Granite and granophyric granite (Rashoop Granophyre Suite). Analyses are recalculated.

ELEMENTS	GRANOPHYRIC GRANITE (n = 5)				LEASE GRANITE (n = 5)				UNMINERALIZED BOBBEJAANKOP GRANITE (n = 10)			
	$\bar{x}$ (%)	σ	Range of values		$\bar{x}$ (%)	σ	Range of values		$\bar{x}$ (%)	σ	Range of values	
			Min (%)	Max (%)			Min (%)	Max (%)			Min (%)	Max (%)
SiO	73,828	0,599	73,364	74,735	74,407	1,447	72,054	75,919	74,923	0,695	73,727	75,921
TiO_2	0,185•	0,009	0,175	0,193	0,064×	0,005	0,058	0,070	0,081*	0,006	0,068	0,088
Al_2O_3	11,430	0,118	11,308	11,619	11,719	0,352	11,172	12,156	11,265	0,118	11,004	11,397
Fe_2O_3	1,685•	0,009	1,675	1,693	1,564×	0,005	1,558	1,570	1,581*	0,006	1,568	1,588
MnO	0,047•	0,005	0,041	0,054	0,025×	0,009	0,012	0,037	0,030*	0,009	0,014	0,047
MgO	0,141	0,043	0,077	0,185	0,104	0,031	0,077	0,154	0,132	0,047	0,069	0,206
CaO	0,590	0,182	0,363	0,841	1,065	0,479	0,417	1,551	0,878	0,201	0,519	1,148
Na_2O	3,375	0,400	2,849	3,808	2,920	0,172	2,760	3,182	2,908	0,209	2,547	3,115
K_2O	4,661	0,613	3,912	5,332	5,175	0,253	4,963	5,608	5,212	0,184	4,963	5,567
P_2O_5	0,025•	0,016	0,015	0,053	0,013×	0,008	0,005	0,026	0,014*	0,008	0,003	0,029

• (n = 34)

× (n = 50)

* (n = 406)

Table 14: Tukey's T-values and Kolmogorov-Smirnov d-values (where indicated) for discriminating between the major element means of unmineralized Bobbejaankop Granite, Lease Granite and granophyric granite (Rashoop Granophyre Suite).

Granites compared / Element	R.G.G./L.G.	R.G.G/B.K.G(U)	L.G/B.K.G(U)
SiO_2	3	7	2
TiO_2	> 17x	d > 0,46*	d < 0,46
Al_2O_3	5	7	6
Fe_2O_3	> 17x	d > 0,46*	d < 0,46
MnO	> 17x	d > 0,46*	d < 0,46
MgO	2	3	5
CaO	6	8*	3
Na_2O	4	8*	4
K_2O	5	5	1
P_2O_5	> 17x	d > 0,46*	d < 0,46

B.K.G(U) = Unmineralized Bobbejaankop Granite
R.G.G. = Granophyric granite (Rashoop Granophyre Suite)
L.G. = Lease granite
x = Significant difference at 99 % confidence level
* = Significant difference at 95 % confidence level

(d = 0,46 at a 95 % confidence level)

Table 15: Trace element means for the granophyric granite (Rashoop Granophyre Suite), Lease Granite and unmineralized Bobbejaankop Granite.

Element	$\bar{x}$ Unmineralized Bobbejaankop Granite (n = 406)	$\bar{x}$ Lease Granite (n = 50)	$\bar{x}$ Granophyric granite (Rashoop Granophyre Suite) (n = 34)
Cu	39,8	14,5	5,0
Y	158,1	164,5	107,6
Ba	180,8	199,3	442,8
Pb	23,2	25,4	34,7
Zn	65,99	36,3	101,7
Zr	258,7	343,7	383,8
Sn	14,1	12,32	16,6
Th	44,9	59,9	28,1
Rb	443,2	513,6	316,4
Nb	34,3	54,6	18,0
Sb	19,8	23,0	23,8
U	12,4	20,2	5,2
Sr	14,9	15,5	16,9
Mo	3,8	4,5	4,3
W	7,6	3,9	1,2
As	15,38	10,8	16,0
CO_2	0,128%(154)	0,166%(21)	0,160%(11)
S	0,026%(154)	0,011%(21)	0,005%(11)
F	3674,9 (68)	2875 (8)	1070,9 (11)

'n' in brackets where different.

Table 16: Tukey's T-values and Kolmogorov-Smirnov d-values for discriminating between trace-element means of granophyric granite, Lease Granite and unmineralized Bobbejaankop Granite.

Element	R.G.G./L.G.	R.G.G./B.K.G	L.G./B.K.G.
	T	d	d
Cu	< 8	< 0,46	< 0,46
Y	> 17*	> 0,46x	< 0,46
Ba	> 17*	> 0,46x	< 0,46
Pb	< 8	< 0,46	< 0,46
Zn	> 17*	> 0,46x	< 0,46
Zr	> 17*	> 0,46x	< 0,46
Sn	< 8	< 0,46	< 0,46
Th	> 17*	> 0,46x	< 0,46
Rb	> 17*	> 0,46x	< 0,46
Nb	> 17*	> 0,46x	> 0,46x
Sb	< 8	< 0,46	< 0,46
U	> 17*	> 0,46x	< 0,46
Sr	< 8	< 0,46	< 0,46
Mo	< 8	< 0,46	< 0,46
W	< 8	< 0,46	< 0,46
As	< 8	< 0,46	< 0,46
CO_2	< 8	< 0,46	< 0,46
S	< 8	< 0,46	< 0,46
F	> 11*	> 0,46x	> 0,46x

R.G.G. = granophyric granite (Rashoop Granophyre Suite)

L.G. = Lease Granite

B.K.G. = Bobbejaankop Granite (unmineralized)

x = Significant difference at a 95 % confidence level

* = Significant difference at a 99 % confidence level

(d = 0,46 at a 95 % confidence level)

Table 17: A comparison of element means of unmineralized Bobbejaankop Granite, Lease Granite and granophyric granite (Rashoop Granophyre Suite) of this investigation, with those determined by Fourie (1969) and Lenthall and Hunter (1977).

		Ba	Sr	Zn	Zr	Nb	Rb	Th	Ti
Granophyric granite	1	707	19	103	347	23	290	22,5	1900
(Rashoop Granophyre	2	922,6	22,1	80,7	448,9	-	246,14	-	1208,1
Suite)	3	442,8	16,9	101,7	383,8	18,0	316,4	28,1	1850
	1	317	6	61	286	53	537	53,2	-
Lease Granite	2	211	10	14	376	112	485	-	196
	3	199,3	15,5	36,3	343,7	54,6	513,6	59,9	640
	1	391	6	65	210	35	489	40.7	850
Bobbejaankop	2	238	6	31	303	61	385	-	441
Granite	3	180,8	14,9	66	285,7	34,4	443,2	44,9	810

1 = Fourie (1969)

2 = Lenthall and Hunter (1977)

3 = Present investigation

5. PETROGENETIC ASPECTS

5.1 THE GRANITIC ROCKS

The origin of the Zaaiplaats granites and their associated mineralization has always attracted the interest of investigators and various ideas or models have been proposed over the years. For a long period it was accepted that the Bobbejaankop and Lease granites represent younger intrusives (Strauss and Truter, 1944; Strauss, 1954). However, particularly the formation of the Lease Granite and rocks of the Rashoop Granophyric Suite has been widely debated (Strauss, 1954; De Waal, 1972; Crocker, 1981).

Because of its fine-grained texture and the fact that its main occurrence is along the upper contact of the Bobbejaankop Granite, Wagner (1929) considered the Lease Granite to be a chilled phase of the Bobbejaankop Granite. This notion was accepted for many years, although the occurrence of numerous veins, dykes and sills of Lease Granite in Bobbejaankop Granite could not be explained by this model.

Söhnge (1944) stated that the Lease Granite formed through the reaction of late magmatic fluids, rising from the crystallizing Bobbejaankop Granite magma, with crystallized granite. Strauss (1954) supported this idea by suggesting that the Lease Granite might be a late stage reaction product formed in situ. He considered the roots, dykes and sills of Lease Granite in Bobbejaankop Granite to have formed by downward movement of volatiles that collected underneath a solid roof of Main Granite (Rashoop Granophyric Suite). As temperatures decreased the volatiles partly replaced earlier formed Lease Granite to form pegmatite. The volatiles also partly transformed the granophyric granite. Strauss (1954) also considered an alternative model, that the dykes, sills and roots of Lease Granite might represent a separate intrusion, younger than the Bobbejaankop Granite.

De Waal (1972) claimed that the Lease Granite represents a highly metamorphosed and metasomatised granophyre of the 'Main Suite' (Rashoop Granophyre Suite). He further indicated that the latter originated through metamorphism of the basal portion of the Epicrustal Phase of the Bushveld Complex with the intrusion of the mafic phase. Geochemical results (Tables 15, 16) of the present investigation indicate that the Lease Granite probably represents the composition of the top of the Bobbejaankop magma chamber.

McCarthy and Hasty (1976) studied the distribution of Ba, Rb and Sr in the Bushveld granites and proposed a model in which the "Main", Bobbejaankop and Lease granites formed by in situ fractional crystallization of a single parent magma. The Lease Granite, more specifically, developed through quenching of late-stage granitic liquids. The Bobbejaankop Granite started crystallizing from the main mass of magma after at least 85 per cent of the original magma mass had separated as cumulus minerals and intercumulus melt.

Lenthall and Hunter (1977) supported the idea of McCarthy and Hasty (1976) and suggested that the magma was generated at relatively shallow depths because of its apparently low K/Rb and Sr/Ba ratios.

The abundance of metasomatic minerals such as chlorite, sericite and fluorite leaves no doubt that the Bobbejaankop Granite is a highly metasomatised granite. Petrographic evidence indicates that metasomatism probably occurred in a volatile-rich, residual system after the precipitation of Sn in the tin-rich zone. Geochemical results prove that it is highly differentiated. According to McCarthy and Hasty (1976) the differentiation mechanism of the Bushveld Granite magma has been in-situ fractional crystallization. The Bobbejaankop Granite magma thus separated and intruded towards the end stage of crystallization of the parent magma.

The elements enriched within the Bobbejaankop and Lease granites (Tables 13, 14, 15, 16) are essentially identical to the list of elements concentrated in granites associated with tin deposits (Tischendorf, 1974). These elements are probably easily concentrated by thermogravitational diffusion (Ludington, 1981; Whalen, 1983). This implies that differentiation of the Bushveld granites could be caused by this liquid state fractionation mechanism. However, many elements that are believed to centrate through thermogravitational diffusion can also be concentrated through fractional crystallization. The Bobbejaankop Granite is further highly metasomatized and thus obscures zonation patterns. Consequently no conclusion is made concerning a possible differentiation mechanism for the Bushveld granites.

Hildreth (1979) indicated that zoned granitic magma chambers have differentiated silicic tops. The Bobbejaankop Granite most probably represent such a differentiated top to the Nebo Granite. This supports Crocker's (1981) suggestion, that the Bobbejaankop Granite is nothing else but a variation of the grey Nebo Granite.

Distribution patterns indicate very sharp geochemical breaks across the contact of the Lease and Bobbejaankop granites with the granophyric granite (Rashoop Granophyre Suite). These changes, as described in section 4.5.1 and 4.5.2, occur at exactly the same point and include variations in the concentration of elements with contrasting geochemical properties. Seeing that the geochemical behaviour, e.g. the mobility of an element, is greatly influenced by its ionic size, the sharp variations in the concentrations of elements with contrasting mobilities (e.g. P, Ti, Th, Rb) at the same contact can only be explained by two separate intrusions, although these need not necessarily be derived from different parent reservoirs. This observation also precludes the proposal of De Waal (1972), who considers the Lease Granite as a highly metasomatised granophyre of the Rashoop Granopyre Suite. Metasomatism would be expected to produce gradational contacts.

The origin of the Lease Granite is still the topic of much debate. An attempt by Faurie and Von Gruenewaldt (1979) to date this granite, as well as the Bobbejaankop Granite, failed because it was impossssible to extract suitable, unaltered zircon fractions. The intrusive relationship of the Lease Granite to the Bobbejaankop Granite, the absence of a gradational contact between the two, as well as the occurrence of Lease Granite only along the upper contacts of Bobbejaankop Granite imply that the Lease Granite is probably not a chilled phase of the latter, as proposed by Wagner (1929).

The model of in situ replacement of Bobbejaankop Granite by rising volatiles to form Lease Granite as postulated by Söhnge (1944) and Strauss (1954) can also be criticized in that a process of replacement should cause a gradational contact between the Lease and Bobbejaankop granites. Accordingly, on the basis of the information available, this model must also be regarded as rather implausible.

Taking into consideration the abundance of miarolitic cavities, the development of pegmatite and the particular distribution of Lease Granite, it is evident that the latter must have formed from a fluid-rich phase.

5.2 THE MINERALIZATION

The origin and characterization of Sn-bearing granites is a problem that has always attracted wide interest. Various investigations e.g. Flinter, Hesp and Rigby (1972), Hesp and Rigby (1974), Smith and Turek (1976), Taylor (1979), Juniper and Kleeman (1979), Stemprok (1979), Olade (1980), Ishihara (1981), Van de Pijpekamp (1982), Bowden (1982), Saavedra (1982), Imeokparia (1981), etc. attempted to distinguish between Sn-bearing and Sn-barren granites on geochemical, petrographical and petrological grounds, and to explain the genetic aspects of Sn mineralization. The following generalizations concerning Sn mineralization have been made:

i) Sn deposits are normally located within or adjacent to granitic bodies - a well established spatial association.

ii) However, it is clear that all granites are not Sn-bearing.

iii) Except for a slight excess of SiO_2 and K_2O, the distribution of major elements in Sn-bearing and Sn-barren granite are very much the same. Juniper and Kleeman (1979) showed that such granites can be distinguished through the following ternary plots:

SiO_2 - CaO + MgO + FeO - Na_2O + K_2O + Al_2O_3 and Na + K - Fe - Mg. Because albitization has occurred, similar plots of the Bobbejaankop Granite would be meaningless.

iv) Sn-bearing granites contain anomalously high amounts of one or more of the following trace elements: Sn, F, Cl, Li, B and Rb (Taylor, 1979) and are normally enriched in K, Nb and Th (Olade, 1980).

v) Sn-bearing granites are normally depleted in Sr and Ba (Olade, 1980).

vi) They are also characterized by low K/Rb and Ba/Rb ratio's and high Rb/Zr ratio's (Olade, 1980).

vii) The Sn-content of biotite is indicative of the Sn potential of a granite (Imeokparia, 1982).

viii) Sn-bearing granites are normally biotite-bearing and often albitized (Taylor, 1979).

ix) The more metasomatically altered, the higher the Sn-bearing potential of the granite (Van de Pijpekamp, 1982).

According to the above-mentioned criteria the Bobbejaankop and Lease granites are undoubtedly Sn-bearing granites.

A broad investigation of the genesis of Sn-bearing Bushveld granites was made by McCarthy and Hasty (1976), as well as by Crocker (1979), who postulated the development of a Sn-enriched late stage magma through progressive centripetal magmatic cooling. Groves and McCarthy (1978) explained the development of such a magma through fractional crystallization. Views on the origin of the low-grade deposits of the Bobbejaankop Granite were only expressed by Söhnge (1944) and Strauss (1954). Söhnge (1944) postulated that these deposits are primary magmatic and explained their sharp upper contact as being the contact between crystallized granite and magma. However, results of the present study prove that no sharp contact exists.

Strauss (1954) considered the cassiterite of the low-grade tin deposits as an abundant primary accessory mineral. He further discussed the possible relations between the pipe-like and low-grade orebodies and concluded that no direct genetic link exists.

Petrographical evidence from the present study (Chapter 3) clearly indicates that the cassiterite of the tin-rich zone represents an original constituent of the granite and crystallized at a late stage from the interstitial liquid. The presence of vugs in these deposits is an indication that it must have formed from Bobbejaankop magma enriched in volatiles. This is further emphasized by an increase in F and chlorite within the ore zone. The gradational upper and lower contacts of the tin-rich zone indicate that no separate magmatic intrusion can be linked with it. The fact that enrichments of different elements with different geochemical properties occur approximately within the same zone, as well as the lack of geochemical haloes, precludes a metasomatic origin for tin in the tin-rich zone, although petrographic evidence indicates that the Bobbejaankop Granite is more or less homogeneously metasomatised, probably by late interstitial rest liquids. The structure of the tin-rich zone seems to be largely conformable to the edges of the intrusion (Fig. 3), and this may indicate that progressive inward cooling of the magma mass played an important role in the formation of the deposits.

5.3 SUGGESTED MODEL FOR THE TIN MINERALIZATION AT ZAAIPLAATS

Taking all available knowledge on the granitic rocks and mineralization into account, the following model is regarded as the most convincing explanation for the Zaaiplaats situation:

On rotation of the rocks back to their position prior to deformation the upper contact of the intrusive granite mass becomes horizontal and the northern contact almost vertical (Fig. 18a). The highly differentiated and volatile-rich Bobbejaankop magma, most probably representing the top of the Nebo Granite, intrudes and the accompanying volatile fraction collects underneath a solid impermeable roof of rocks from the Rashoop Granophyre Suite (Fig. 18a). Rising volatiles gradually concentrate beneath the impermeable rocks. The very high concentration of volatiles lowers the crystallization temperature of the granite in this zone. The result is that Bobbejaankop Granite underneath the volatile-enriched granite starts crystallizing first (Fig. 19b). With progressive cooling from the sides of the intrusion, fracturing of the crystallized granite may occur. Volatiles under high pressure now intrude these cracks. Fracturing of the roof rocks under pressure of the volatiles causes some of the latter to escape. This results in quenching of the highly volatile enriched magma to form the main mass, dykes, sills and veins of Lease Granite (Fig. 19c). Quenching can also be caused by the separation of a fluid phase from the melt with retrograde boiling. With further cooling trapped fluids in the Lease Granite give rise to the formation of miarolitic cavities and formation of pegmatite. The Lease Granite consequently represents the composition of the top of the Bobbejaankop magma intrusion.

With the quenching of the volatile enriched magma fraction, Sn in solution crystallised interstitially to form the regularly distributed primary magmatic, disseminated tin deposits in Lease Granite (Fig. 18c). Progressive inward crystallization of Bobbejaankop magma continued. The crystallized rock reached a stage where it became impermeable for volatiles. The decreasing amount of rising volatiles concentrated underneath this impermeable roof to produce a volatile enriched Bobbejaankop magma layer conformable to the top of the intrusion and

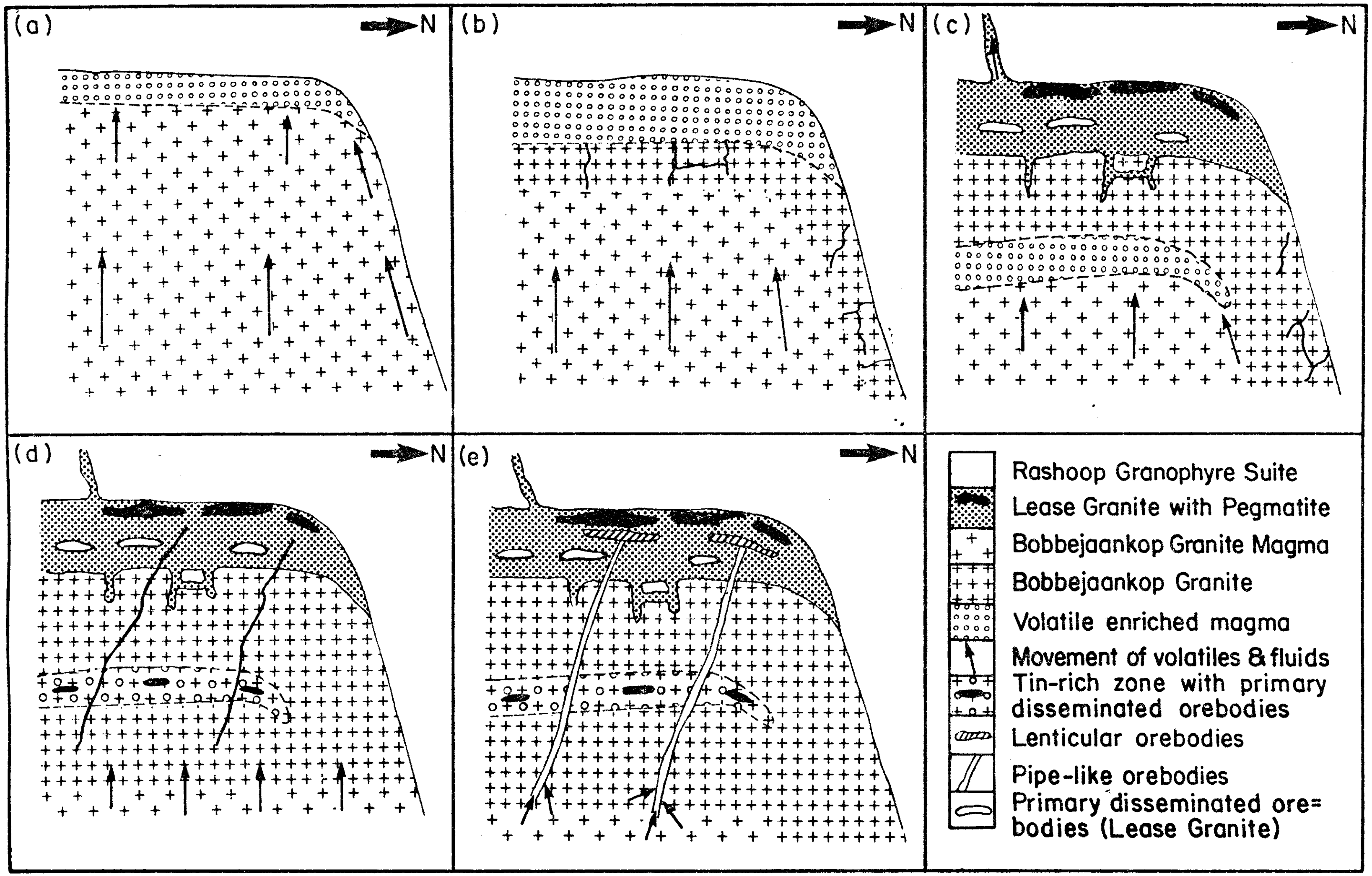


Fig. 18: A schematic presentation of a genetic model for the ore deposits and Lease Granite.

enriched in Sn and other incompatible elements (Fig. 18c). Inward crystallization continued and this layer crystallized to form the primary disseminated tin-rich zone (Fig. 18d). Cracks and joints now developed through cooling of crystallized Bobbejaankop and Lease granites (Fig. 18d). Rising Sn-enriched fluids and volatiles from lower parts of the intrusion escaped upwards along these joints and especially along joint intersections which are clearly recognizable in the field. These fluids became blocked beneath the pegmatite zone, spread out laterally and produced the greissenized, metasomatic lenticular orebodies in Lease Granite (Fig. 18e). Sn-enriched fluids in joint intersections crystallized to form the metasomatic pipe-like orebodies in the Bobbejaankop and Lease granites (Fig. 18e).

In addition to the fact that the Bobbejaankop magma is a late differentiate and should therefore be enriched in Sn, a possible additional source of Sn could be the release of Sn from the biotite lattice with chloritzation (Taylor, 1979) - especially in the later stages of cooling with the formation of the pipe-like orebodies. Whether biotite of the Bushveld granite contains significant amounts of tin has not yet been established.

To conclude, various types of tin deposit occur within the Bobbejaankop and Lease granites. These granites most probably represent the highly differentiated, apical portions of the Nebo Granite magma chamber. The cassiterite of the tin-rich zone, that contains the low-grade disseminated orebodies, seems to be an original constituent of the Bobbejaankop Granite.

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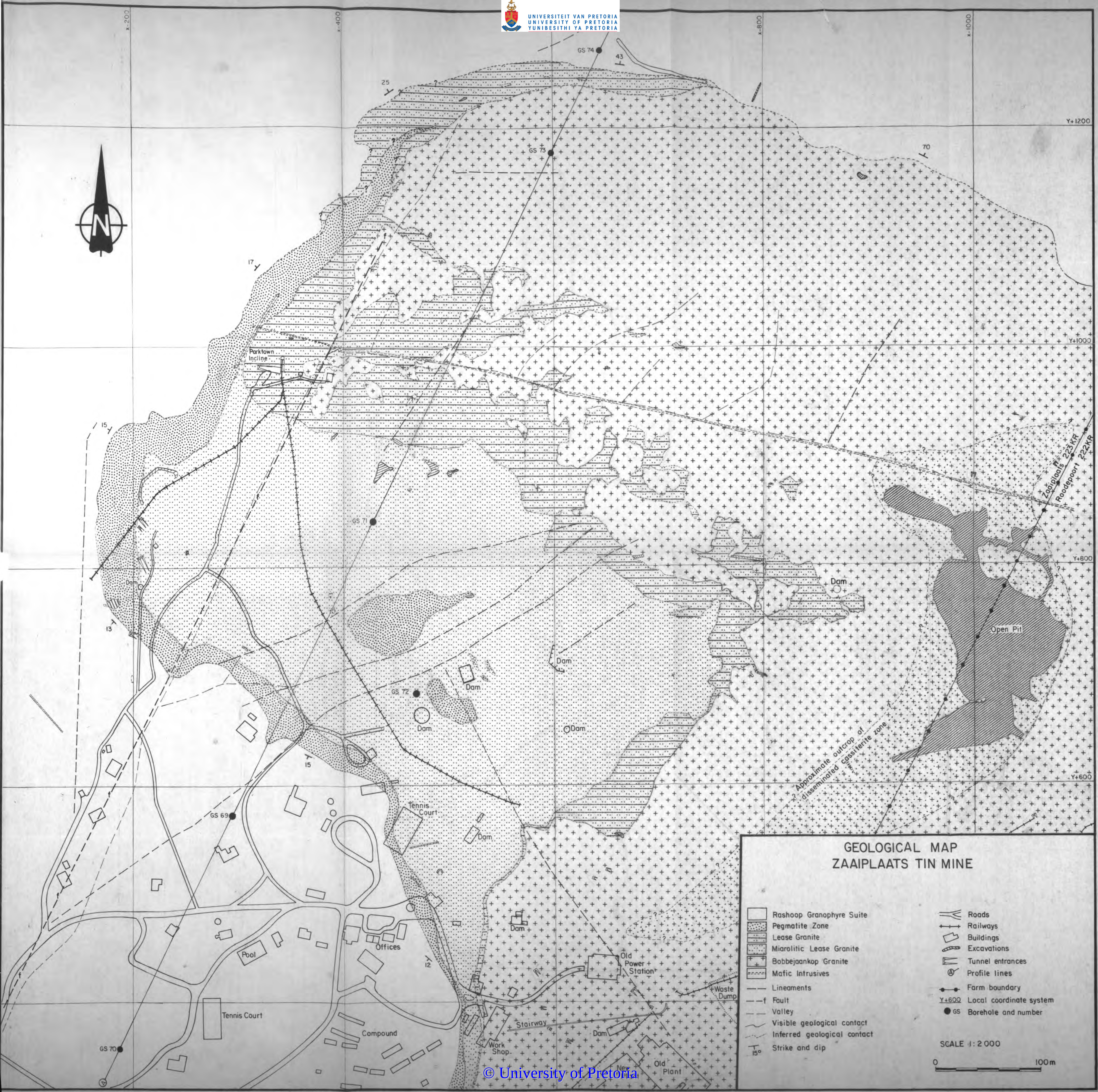
GEOLOGICAL MAP
ZAAIPLAATS TIN MINE
Rashoop Granophyre Suite
Pegmatite Zone
Lease Granite
Miarolitic Lease Granite
Bobbejaankop Granite
Mafic Intrusives
Lineaments
Fault
Valley
Visible geological contact
Inferred geological contact
Strike and dip
Roads
Railways
Buildings
Excavations
Tunnel entrances
Profile lines
Farm boundary
Local coordinate system
Borehole and number
SCALE 1:2 000
100m
Parktown Incline
Open Pit
Zaaiplaats 223KR
Roodepoort 222KR
Approximate outcrop of disseminated cassiterite zone
Tennis Court
Offices
Pool
Compound
Work Shop
Stairway
Old Power Station
Waste Dump
Old Plant
Dam
GS 74
GS 73
GS 71
GS 72
GS 69
GS 70
Y+1200
Y+1000
Y+800
Y+600
x-200
x-400
x-800
x-1000