THE PETROLOGY, GEOCHEMISTRY AND CLASSIFICATION OF THE BIEN VENUE MASSIVE SULPHIDE DEPOSIT, BARBERTON MOUNTAIN LAND

by

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PREFACE

This thesis represents original work by the author and has not been submitted in any form to another university. Where use has been made of the work of others it has been duly acknowledged in the text.

The research was carried out in the Department of Geology and Applied Geology at the University of Natal, Durban during the period October 1987 to March 1989 and completed at the Geological Survey of South Africa, Pretoria. The project was initially supervised by Doctor A. Harwood until his resignation from the Geology Department, whereupon Doctor A. Kerr was appointed as a replacement supervisor.

ABSTRACT

The Bien Venue massive sulphide deposit is associated with a felsic volcanic succession developed in the north-eastern part of the Barberton Greenstone Belt, Eastern Transvaal. The deposit is situated 8km east-north-east of Louw's Creek between the Lily Syncline to the south and the Stentor Pluton to the north. The stratigraphy of the Onverwacht, Fig Tree and Moodies Groups in the vicinity of the deposit is poorly documented, and the exact stratigraphic position of the host felsic volcanics is not known. They are tentatively correlated with the felsic volcanics from the Theespruit Formation, Onverwacht Group.

The felsic volcanics have undergone low-grade greenschist facies metamorphism and occur as quartz-sericite schists. Detailed petrography enables sub-division of the volcanic succession into distinct units. A lapilli metatuff unit hosts the base metal and precious metal mineralisation. The sulphides are best developed in the upper part of this unit, together with intercalated barite-rich horizons and cherts. A series of structural events have modified the attitude of the lithological units and disrupted the continuity of the orebody.

The orebody comprises stratabound lenses of massive to semi-massive and often banded sulphides, as well as disseminated sulphide mineralisation. The dominant base metal mineralogy consists of pyrite, sphalerite, chalcopyrite, galena and tennantite. Native silver and various copper-silver sulphides are also associated with the base metal sulphides. A vertical zonation of the mineralisation exists, from pyrite-chalcopyrite-rich ore in the footwall, to pyrite - chalcopyrite-sphalerite-galena-barite-rich ore towards the hanging wall.

Geochemical studies indicate that the Bien Venue lithologies are rhyolitic to rhyodacitic in composition and show a calc-alkaline affinity. The mobility of some elements at Bien Venue has been clearly demonstrated. This is believed to be associated with hydrothermal alteration that has led to SiO_2 and MgO enrichment, as well as K_2O depletion, in the wall rocks of the deposit.

The geological setting and nature of the mineralisation at Bien Venue suggest that it is an example of a volcanogenic exhalative sulphide deposit. In terms of the classification scheme suggested by Hutchinson (1973, 1980), Bien Venue would best be described as a Primitive type deposit that contains barite.

ACKNOWLEDGEMENTS

Valuable assistance was provided by the following persons and organisations to whom I extend my sincere thanks : the Anglo American Corporation and Anglo American Prospecting Services, for permission to carry out the project and for access to selected data on the Bien Venue deposit; the Geological Survey of South Africa for permission to use various analytical equipment at their laboratories; Mr D. de Bruin of the Geological Survey, for his help with electron microprobe analyses; Dr. D. Bühmann of the Geological Survey, for his assistance with the X-ray Diffraction unit and interpretation of the data.

Thanks are also extended to the technical staff members of the Geology Department and to my fellow research students for their assistance and useful discussion.

I am especially grateful to my supervisor, Dr. A. Kerr, and my former supervisor, Dr. A. Harwood, for their time, patience and guidance during the course of my research.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO PRESENT STUDY

Mineralisation on the farm Bien Venue JU 255, Barberton District, was first recognised by the early prospectors in the area, who excavated pits in the surface gossan, but did not exploit the orebody. The deposit, subsequently referred to as Bien Venue, was fully investigated by Anglo American Prospecting Services during the period 1978-1986. This involved surface mapping, extensive drilling and trenching programs, and an underground exploration adit that intersected the main orebody. The results of these investigations, however, remain confidential, and the deposit is unknown in the geological literature.

In view of the work already completed on the deposit, the objectives of the present study were to investigate the possible volcanogenic exhalative nature of the deposit, and to categorise it in terms of existing classification schemes.

Attempts by the author to map the surface geology in the vicinity of the deposit were unsuccessful due to the poor surface exposures and only limited access to borehole core, on which most of the current geological data is based. The entrance to the underground adit was also closed during the course of the present study. An agreement was therefore reached with Anglo American Prospecting Services personnel that selected data, namely the geological map and cross-section of the deposit, would be made available to the author for use in the present study. The use of this data was on condition that a confidentiality clause be placed on the thesis for a period of two years from the date of submission.

The findings presented in this thesis are therefore based on the following work :

- geological mapping, represented by the geological map and cross-section of the deposit as originally compiled by Anglo American Prospecting Services, but with modifications based on the lithological descriptions and field data introduced by the author.

- petrographic studies, involving 42 thin-sections and 48 polished-sections produced from both surface and underground samples collected during the course of the study.

- geochemical studies, involving 28 XRF (X-ray fluorescence) whole rock analyses.

1.2 REGIONAL GEOLOGY OF THE BARBERTON GREENSTONE BELT

1.2.1 Introduction

The area known as the Barberton Mountain Land comprises a rugged tract of country exposed in the the Lowveld of the Eastern Transvaal and Swaziland, and displays an unrivalled succession of some of the oldest rocks on the planet. The Barberton greenstone belt (see figure 1.1) which forms part of this mountainous terrain, consists of a wide variety of volcanic, igneous and sedimentary rock types, belonging to Swaziland Supergroup that are surrounded and intruded by granitic rocks of widely divergent textures, compositions and ages (Anhaeusser, 1986). Within this greenstone belt, the volcano-sedimentary assemblages of the Onverwacht, Fig Tree and Moodies Groups constitute a distinctive and well-defined major entity, the Barberton Sequence (SACS, 1980).

1.2.2 Lithostratigraphy

The Barberton Sequence (the base of which is nowhere exposed) has been divided into a dominantly volcanic lower assemblage, the Onverwacht Group, and a dominantly sedimentary upper assemblage comprising the Fig Tree (largely argillaceous) and the Moodies (largely arenaceous) Groups. Although disconformable/unconformable relationships exist locally, the succession as a whole is conformable (Viljoen and Viljoen, 1969a). However, it has been suggested (De Wit et al., 1983) that thrusting and nappe tectonics within the greenstone belt have created a complex stratigraphy (i.e. tectonic repetition) invalidating the existing stratigraphic succession.

1.2.2.1 The Onverwacht Group

Viljoen and Viljoen (1969a) divided the Onverwacht Group into a Lower Ultramafic Unit and an overlying Mafic-to-Felsic Unit which have subsequently been formalised as the Tjakastad and Geluk Subgroups respectively (Anhaeusser, 1975). A persistent sedimentary horizon, termed

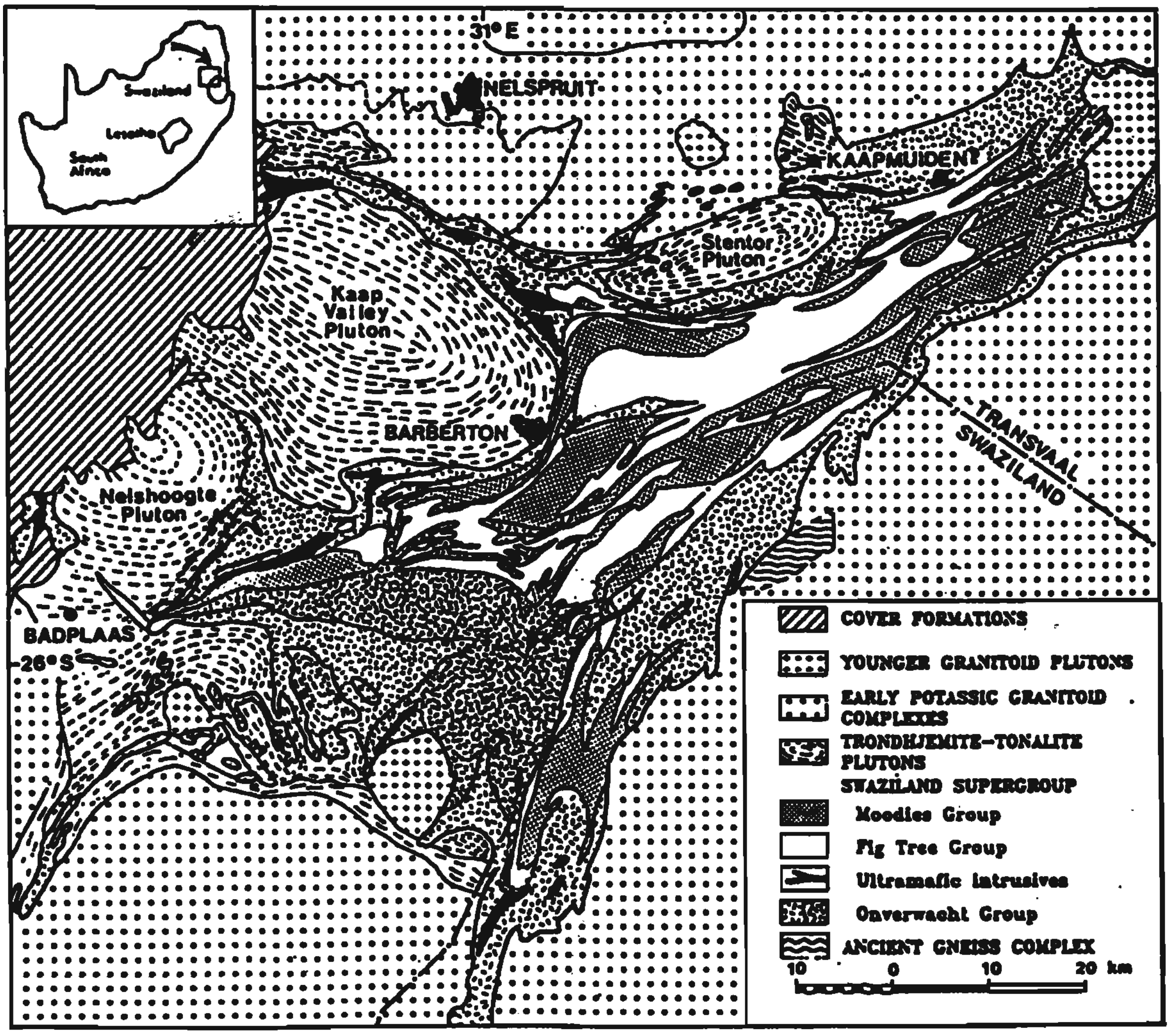


Figure 1.1 Simplified geological map of the Barberton Greenstone Belt.
(from Tegtmeyer and Kröner, 1987)

the Middle Marker (Viljoen and Viljoen, 1969b) separates the two subgroups and heralds an abrupt change in the nature of the volcanic assemblages within the Onverwacht succession.

The Tjakastad Subgroup consists of a predominantly magnesium-rich mafic to ultramafic assemblage of metavolcanics now known universally as komatiites (Viljoen and Viljoen, 1969a). In addition to the pillowed and massive lava flows and sills of komatiite, magnesium basalt and tholeiite, there are significant, but subordinate layers of felsic pyroclastics (tuffs and agglomerates, often aluminous), discontinuous bands and lenses of chert, banded-iron formation and calc-silicate rocks (Anhaeusser, 1986).

The Geluk Subgroup is represented by a typically calc-alkaline series of lavas consisting of cyclically alternating mafic and intermediate to felsic volcanic rocks, together with a wide variety of pyroclastic and chemical sedimentary lithologies (Anhauesser and Viljoen, 1986).

Further details of the geology of the Onverwacht Group are documented in Anhaeusser et al., 1968; Viljoen and Viljoen, 1969a, b; Williams and Furnell, 1979.

1.2.2.2 The Fig Tree Group

The Onverwacht sequence is overlain, apparently conformably, by the sedimentary Fig Tree Group that is composed of greywacke, sandstone, shale, chert and banded-iron formation with minor interlayered conglomerate, barytes, dolomite and tuff (Condie et al., 1970; Heinricks and Reimer, 1977; Eriksson, 1979). The Fig Tree depositional characteristics are similar to those prevailing on modern steep continental margins and suggest a braided alluvial to submarine fan environment (Eriksson, 1980). Further descriptions of the Fig Tree Group can be found in Visser et. al. (1956) and Condie et. al.(1970).

1.2.2.3 The Moodies Group

The Moodies Group, which shows disconformable as well as unconformable relations with the two underlying groups, consists of quartzites, conglomerates and shales, together with minor volcanics and banded-iron formation (Visser et al., 1956; Anhaeusser, 1976). The various sedimentary facies of the Moodies succession have been interpreted palaeo-environmentally in terms of interacting alluvial, estuarine-deltaic, beach-offshore, and tidal flat depositional systems (Eriksson, 1977).

Further descriptions of the geology of the Moodies Group are given in Visser et al., (1956) and Eriksson (1978, 1979).

1.2.3 Structure

The broad-scale structure of the Barberton greenstone belt is that of a regional synform with a pronounced east-north-east to west-south-west trend characterised by dominantly gravity-induced deformation styles that accompanied the emplacement of granitic magmas and diapiric plutons. Within the broad synform there exist a number of tight synclinal folds with steeply-dipping, and often overturned, limbs separated by major strike faults or local thrust faults or nappes (Anhaeusser, 1986). These regional faults effectively divide the Barberton greenstone belt into a number of narrow east-north-east trending segments.

Intrusive tonalitic diapirs of various sizes, particularly evident on the north-west flank of the Barberton greenstone belt as well as in the south-west, were responsible for disrupting the broad regional pattern. This resulted in numerous narrow arcuate zones of intensely deformed greenstones wedged between granite domes.

1.2.4 Metamorphism

The Barberton greenstone belt has undergone only greenschist facies regional metamorphism. However, the Onverwacht volcanic assemblages, particularly along contacts with granitoids have been upgraded to the upper greenschist facies and locally to the amphibolite and granulite facies (SACS, 1980). This aureole of higher-grade metamorphism is, however, very narrow, and a metamorphic zonation occurs grading away from the contacts into various subfacies of greenschist metamorphism.

1.2.5 Geochronology

Isotopic age determinations carried out in the Barberton Mountain Land have confirmed that the majority of rock types in the area exceed 3000 Ma in age. Among the oldest rocks are the komatiite-dominant lower formations of the Onverwacht succession, for which Hamilton et al., (1979) reported a whole-rock Sm-Nd isochron age of 3530±50 Ma. This is in close agreement with those ages obtained by Jahn et al., (1982), Lopez-Martinez et al., (1984), and Brevart et al., (1986). Thus, on the basis of the available age data, the Onverwacht Group is certainly older than 3.4 Ga (Tegtmcyer and Kroner, 1987).

The depositional age of the Fig Tree sediments is unknown but must predate that of the overlying Moodies Group and that of cross-cutting granites in N.W. Swaziland, dated at 3028 ±14 Ma (Rb-Sr whole-rock isochron, Barton et al., 1983).

Work carried out on gneissic and granitic clasts from the Moodies conglomerate by Tegtmeyer and Kroner (1987) suggests a maximum age of 3.3 Ga for the Moodies Group.

CHAPTER 2

GEOLOGY OF THE BIEN VENUE DEPOSIT

2.1 GEOLOGICAL SETTING

The Bien Venue massive sulphide deposit is associated with a felsic volcanic succession developed in the north-eastern part of the Barberton greenstone belt, Eastern Transvaal. The deposit is situated 8km east-north-east of Louw's Creek, between the Lily Syncline to the south and the Stentor Pluton to the north (see figure 2.1).

The host lithologies to the deposit would appear to conform with the felsic zone of the Theespruit Formation, Onverwacht Group, as delineated on the 1:250 000 Geological Survey map sheet 2530 - Barberton 1986 (see figure 2.1), and on the basis of the similarities of the host lithologies to those descriptions of the Theespruit Formation given by Viljoen and Viljoen (1969a). However, the relationships between the stratigraphy in the north-eastern part of the Barberton greenstone belt, and that of the Onverwacht, Fig Tree and Moodies Groups, which are best described from the southern and central parts of the greenstone belt, are not well documented and still require further attention.

The stratigraphic relationship between the Onverwacht and the Moodies Groups in the vicinity of the deposit still has to be resolved. The volcanics of the Theespruit Formation, Onverwacht Group, would appear to conformably overlie the conglomerates of the Moodies Group, which would indicate an inverted / overturned stratigraphy. However, way-up criteria in the form of a stratigraphic ore zonation within the ore body (see section 4.1, p.42) suggests that this is not the case.

This leaves two possibilities. Firstly, that the host lithologies to the deposit do not conform with the Theespruit Formation, or secondly, that the relationship is a tectonic one, with the Onverwacht volcanics having been thrust over the Moodies conglomerates. The first possibility seems unlikely on the basis of comparisons with known Theespruit Formation lithologies in other areas of the greenstone belt. The second possibility is favoured by the author, although evidence to substantiate this "tectonic relationship" has not yet been found.

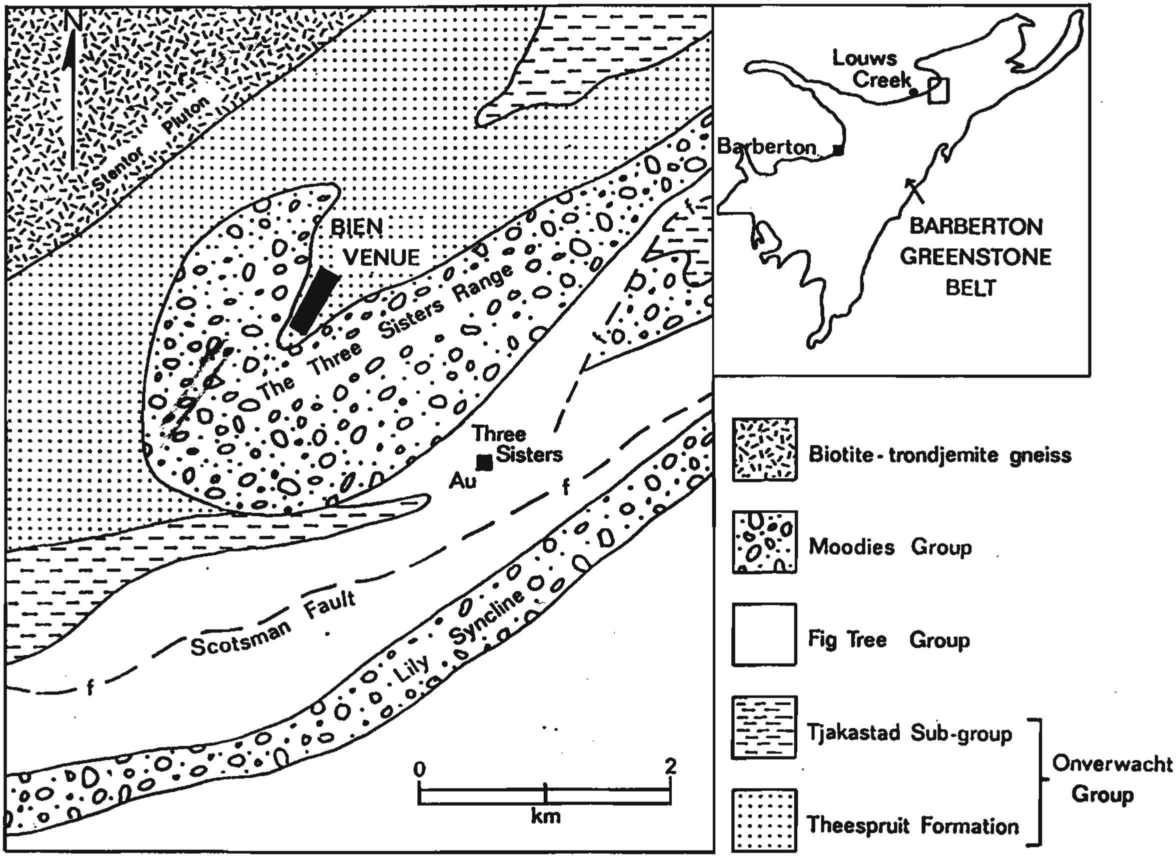


Figure 2.1 Geological map of the area surrounding the Bien Venue deposit.
(after 1:250 000 Geological Survey map sheet 2530 - Barberton, 1986)

2.2 LITHOLOGY

2.2.1 Introduction

The lithology in the immediate vicinity of the Bien Venue deposit consists of a lower sedimentary unit and an upper mixed volcanic sequence as outlined in the stratigraphic column below. Thicknesses of the individual units were not calculated due to the complex structural features in the study area.

FELDSPATHIC INTRUSIVE

METARHYOLITE

CRYSTAL METATUFF
POLYMICT METATUFF AND META-AGGLOMERATE
QUARTZ-AUGEN METATUFF
LAPILLI METATUFF

CONGLOMERATE

The Lapilli Metatuff unit is host to the base metal mineralisation. The sulphides are best developed in the upper part of this unit, together with intercalated barite-rich horizons. The Lapilli Metatuff unit is overlain by the Quartz-Augen Metatuff unit, which is in turn overlain by the mixed Polymict Metatuff and Meta-agglomerate unit. In the immediate vicinity of the deposit the volcanic succession is terminated by the Crystal Metatuff unit. Intrusive Metarhyolites and a Feldspathic Intrusive (Quartz-Diorite) are also found within the succession. The Feldspathic Intrusive appears to post-date the Metarhyolite intrusions and is preferentially sited close to the contact between the Polymict Metatuff and Meta-agglomerate unit and the Crystal Metatuff unit.

The distribution and spatial relationships of these units are shown in the geological map and cross-section, figures 2.2 and 2.3 respectively.

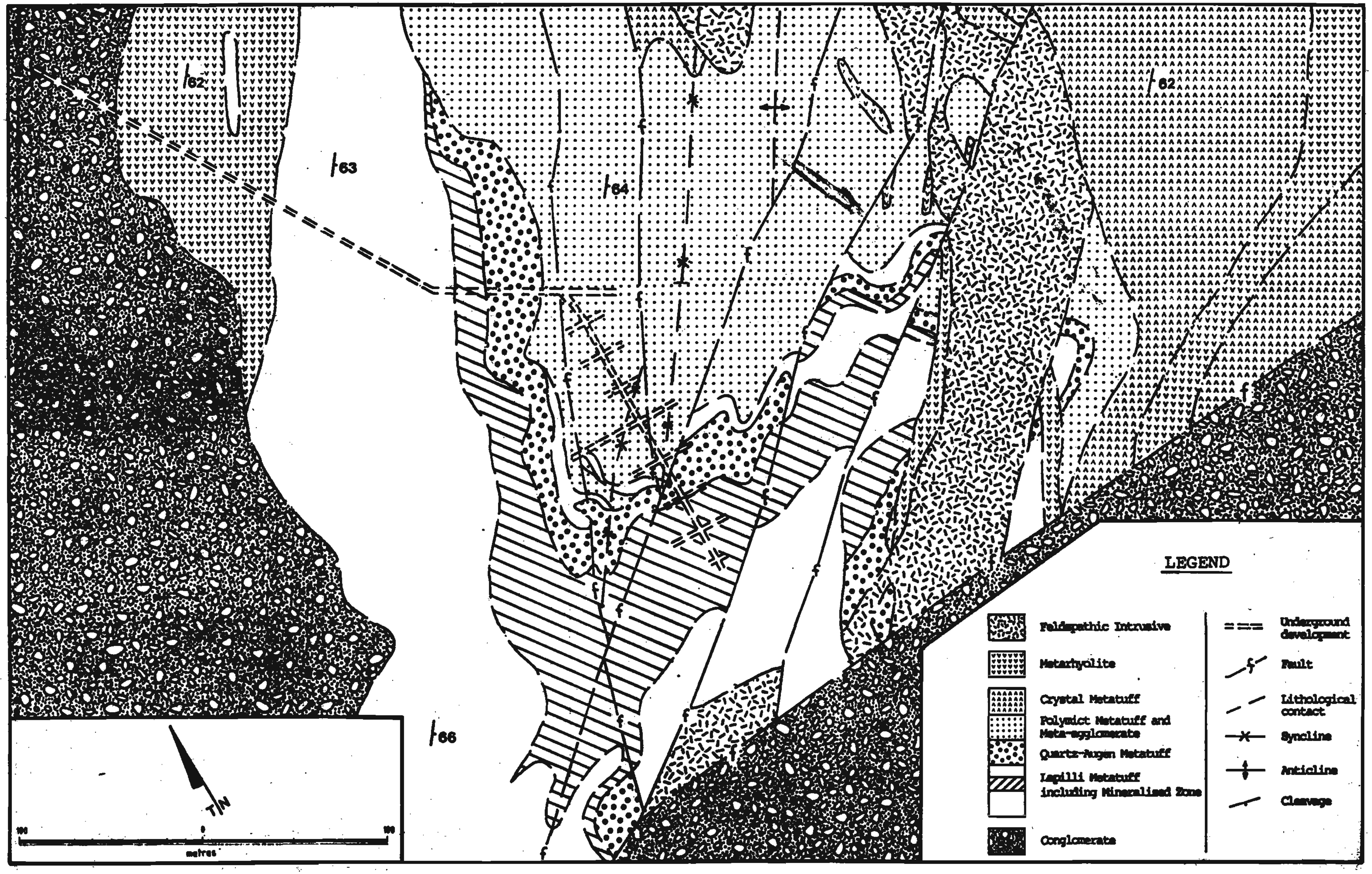


Figure 2.2 Geological map of the Bien Venue massive sulphide deposit. (modified after Anglo American Prospecting Services, 1986)

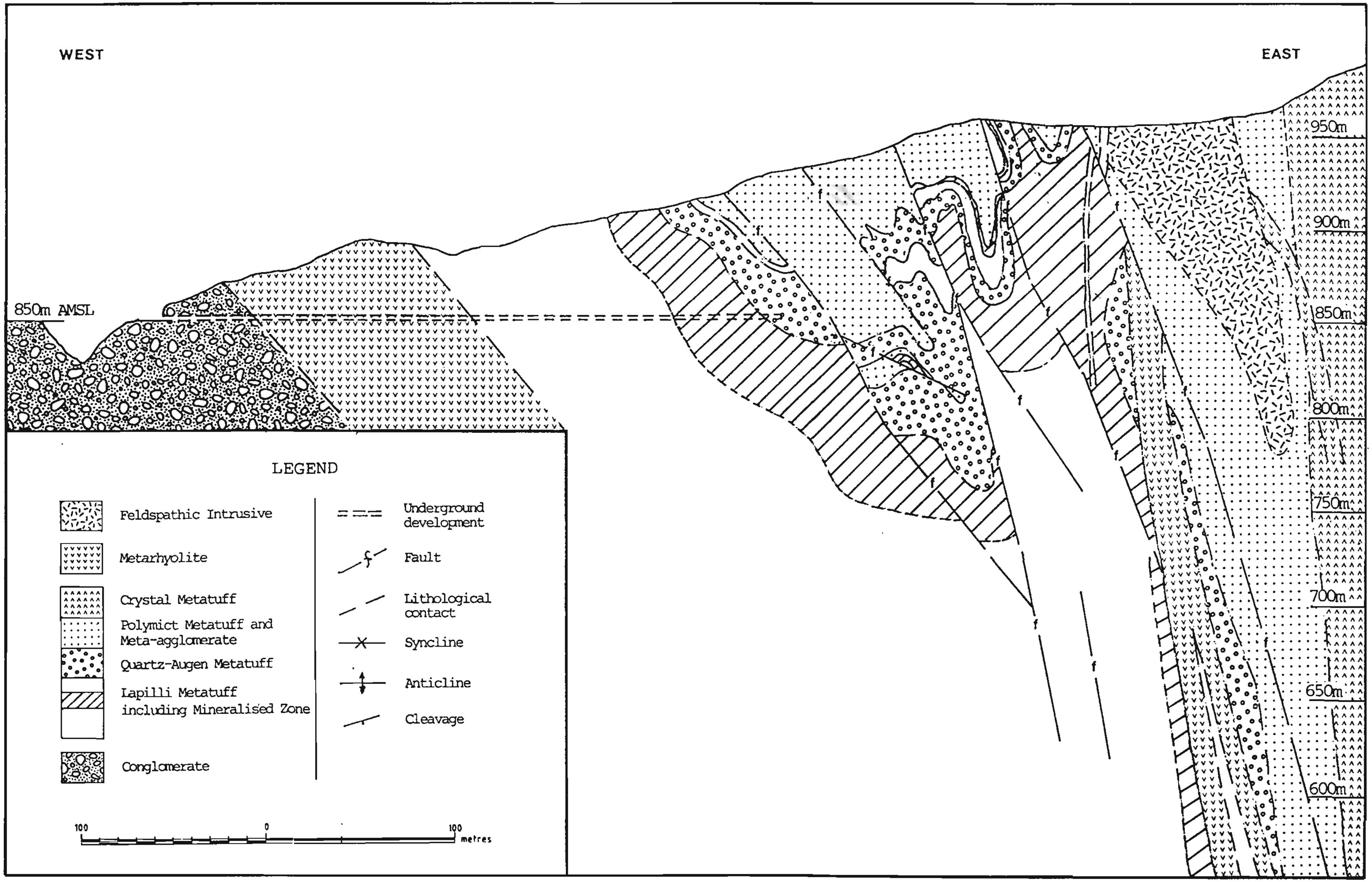


Figure 2.3 Approximate west - east (non-linear) cross-section of the Bien Venue massive sulphide deposit. (modified after Anglo American Prospecting Services, 1986)

2.2.2 Conglomerate

The conglomerates are highly varied, and consist of interbedded clast- and matrix-supported conglomerate, conglomeratic sandstone and quartzitic sandstone units that form the topographically elevated areas to the west and south of the deposit.

The clast assemblage is distincly oligomictic, consisting almost wholly of quartzite, with minor amounts of chert and ultramafic clasts. The clasts are generally rounded and are elongate in the direction of the dominant foliation, giving rise to a shape fabric striking approximately 063° and dipping steeply (68°) to the south (see figure 2.4). The clasts are poorly sorted and have a large size variation. Clast dimensions range from small pebbles (2 x 1cm), through cobble-size, up to boulders (90 x 40 cm), as shown in figure 2.5.

The matrix of the conglomerate is medium- to coarse-grained and even gritty in places, and is essentially quartzitic, having small quartz grains set in a finer-grained quartz-chlorite-sericite groundmass. The matrix is also intensely chloritised and epidotised in places.

2.2.3 Lapilli Metatuff

This is a highly varied and complex unit, ranging from densely-packed "lapillistone" horizons with abundant silicic and sericitic lapilli-sized clasts, to more homogeneous horizons with little or no clasts. Fresh outcrop has a typical pale grey to greenish grey colouration that weathers dirty brown to buff and maroon.

The matrix consists of a fine-grained inhomogeneous assemblage of quartz, sericite and chlorite. Fine orientated sericite interlayed with fine granular quartz defines a well-developed foliation.

The clast assemblage consists predominantly of rounded to sub-rounded and elongated grey - dark grey siliceous clasts that are randomly distributed within the matrix, but are generally orientated with their long axes parallel/sub-parallel to the foliation. Irregularly-shaped and elongate clasts/aggregates of sericite also occur. Clast sizes range between 1,5 x 1cm to 6 x 3cm with rare siliceous clasts of up to 10cm in length.

Packing density is also highly variable, ranging from densely-packed "lapillistone" zones having

Figure 2.4 Conglomerate outcrop showing rounded and elongate clasts (note the clast to the left of the geological hammer) that define a shape fabric approximately parallel to the long axis of the geological hammer in the photograph.

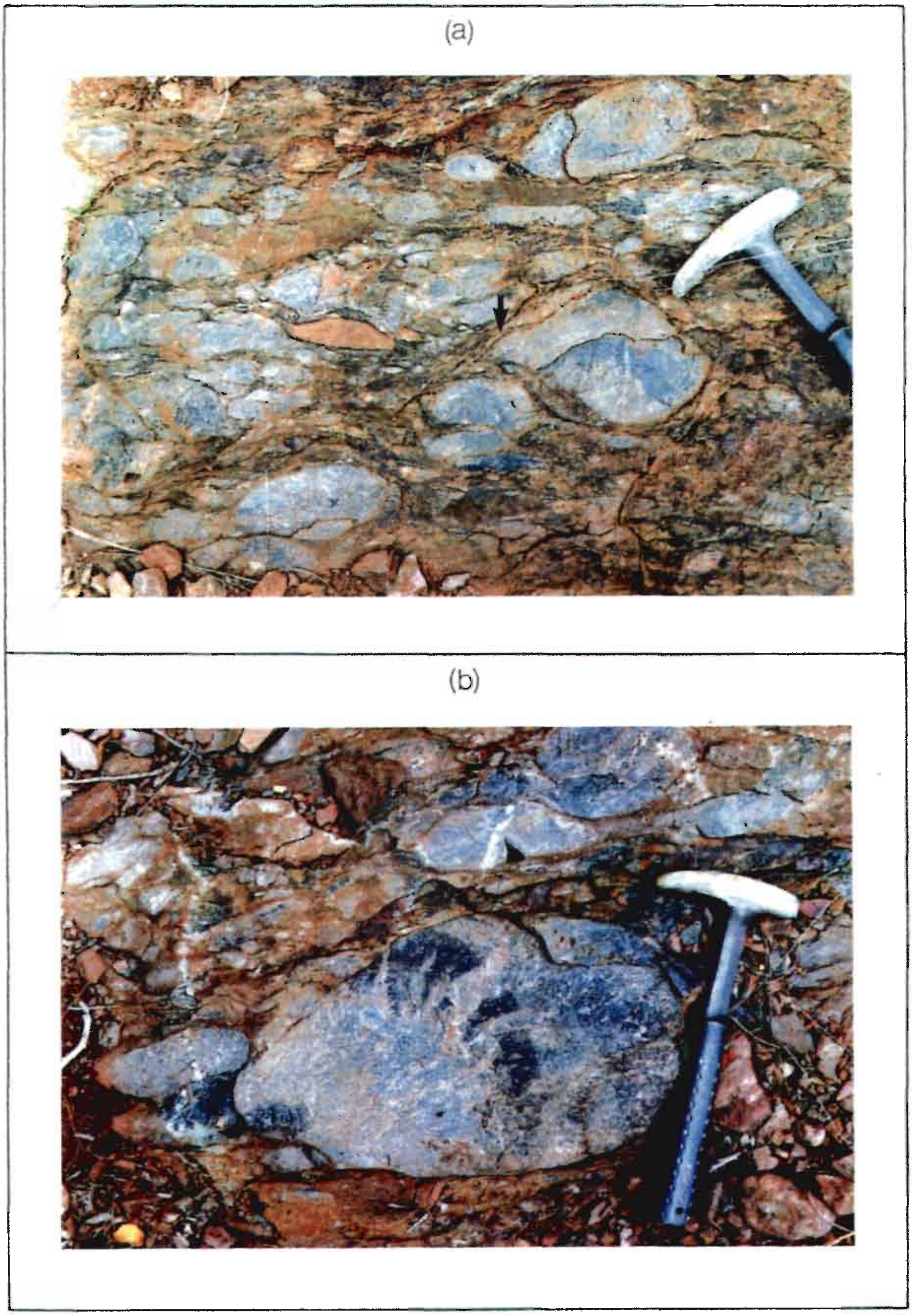


Figure 2.5 (a) and (b) Poorly-sorted conglomerate displaying rounded quartzitic clasts of variable sizes. Some of the clasts (arrowed) have distinct "tails".

high clast : matrix ratios, to horizons having minor isolated small clasts.

In some areas, the unit has an irregular banded appearance that appears to be associated with sericitisation, with the development of narrow (<1cm) bands/lenses of fine-grained sericite interbedded with fine siliceous layers and small silicic clasts.

The sericite to quartz ratio is also highly variable giving rise to distinct zones of (a) predominantly sericite-rich compositional domains, (b) alternating bands of sericitic and siliceous material, and (c) predominantly siliceous material.

The upper part of the Lapilli Metatuff unit is host to the base metal mineralisation, and this zone is known in mine parlance as the "multi-metal" zone. This "multi-metal" zone is approximately 50m in thickness and comprises a variable assemblage of fine-grained highly siliceous and sericitised tuff interbedded with disseminated to semi-massive and massive sulphide mineralisation, massive and disseminated barite, and chert/ultra siliceous horizons.

2.2.4 Quartz-Augen Metatuff

This highly variable unit is characterised by the presence of abundant and randomly distributed "quartz-eyes" (see section 3.4) within a fine-grained pale grey - greenish grey, inhomogenous quartz-sericite (± chlorite) matrix (see figure 2.6). There is a distinct variation in the distribution, size and abundance of quartz-eyes within this unit, ranging from horizons of densely packed quartz-eyes (generally 0,5mm, but up to 10mm in diameter) having high clast : matrix ratios, to zones containing small (<2mm) randomly distributed quartz-eyes of minor abundance. Other clasts present include fine-grained elongate aggregates of sericite (up to 10mm in size), and much larger but rare siliceous clasts up to 80mm in diameter.

2.2.5 Polymict Metatuff and Meta-agglomerate

The term "polymict" is used to describe the different types of clast found within this unit. The Polymict Meta-agglomerate is a coarser-grained variety (clasts generally > 50mm) of the Polymict Tuff, into which it appears to grade both laterally and vertically.

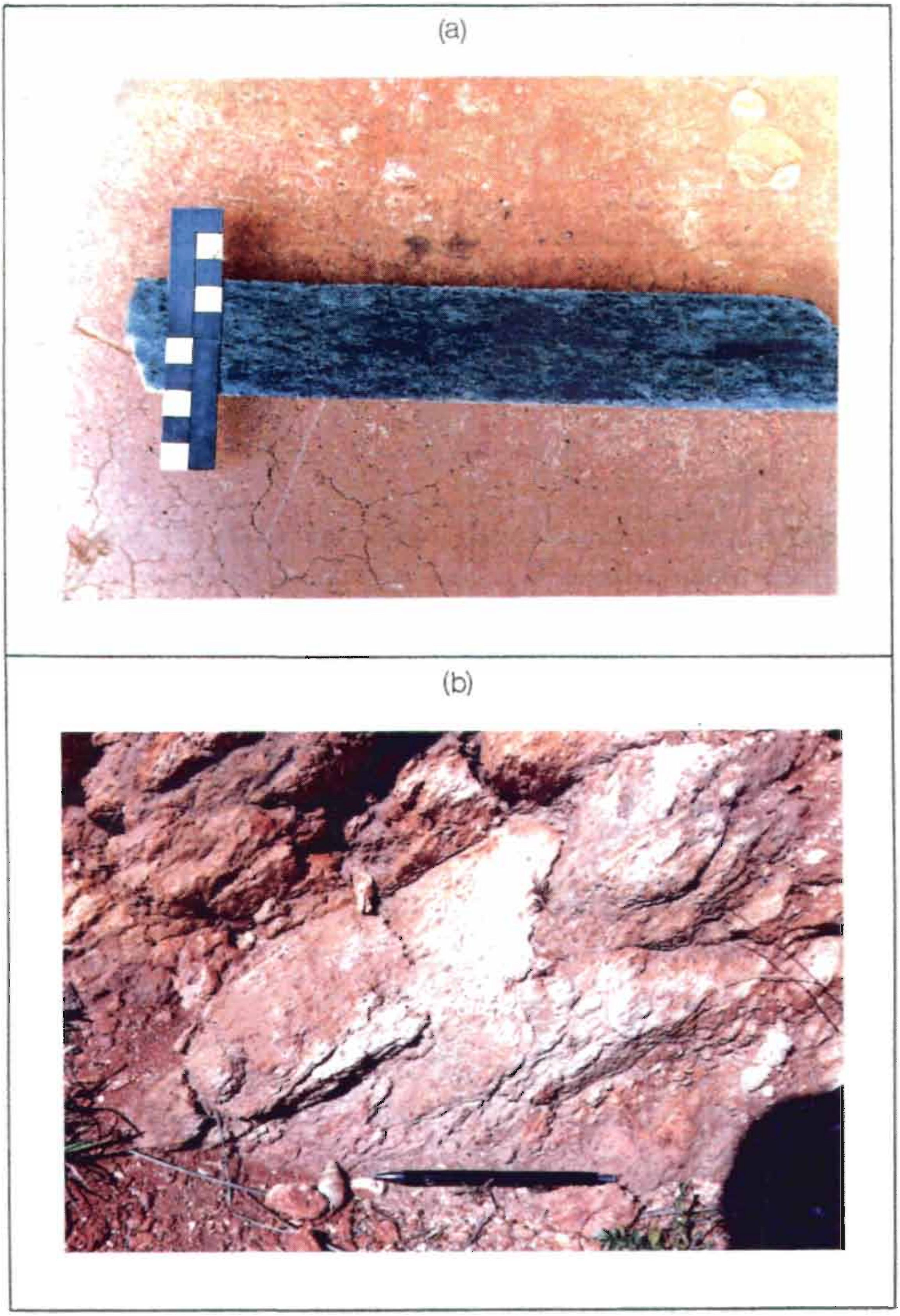


Figure 2.6 (a) Sectioned core sample of quartz-augen metatuff showing abundant "quartz-eyes" in a greenish grey quartz-sericite matrix.

(b) Typically weathered quartz-augen metatuff is still characterised by abundant and randomly distributed "quartz-eyes".

This unit consists of a fine-grained well-foliated inhomogeneous matrix assemblage of quartz, sericite and chlorite that encloses a variety of clasts. Depending on the clast assemblage and the amount of chlorite in the matrix, the colour varies from greyish green to dark greenish grey in borehole core, to pinkish and light grey-creamy white when weathered.

The clast assemblage is varied in composition, size, shape and abundance. The clasts consist predominantly of sericite, chlorite, chert/ultra-silicic material, and lesser, but often significant amounts of feldspar porphyry. The clasts are sub-rounded to irregular in shape and are generally elongated in the plane of the dominant schistosity. Size varies from several mm's to 5cm in the tuff, and generally 5-15cm in the agglomerate. Lenticular and often irregular aggregates of carbonate also occur within the matrix. The carbonates weather easily to form brownish aggregates or "limonitic vugs" that often have chloritic rims.

The overall texture of the unit is highly variable from light greenish-grey, fine-grained, more homogeneous zones with abundant small clasts/aggregates of sericite and chlorite, to distincly coarser and darker coloured zones having a higher clast to matrix ratio, and consisting of abundant larger clasts, including feldspar porphyry clasts as well as dark green chloritic aggregates and lenses.

2.2.6 Crystal Metatuff

This unit consists of abundant quartz-eyes and small sericite and siliceous clasts, together with microcline feldspar crystals, within a fine-grained inhomogeneous quartz-sericite matrix (see figure 2.7). Chlorite is noticeably absent, hence the characteristic light grey to buff and creamy white colour. This unit is similar to the Quartz-Augen Metatuff, although colour and the occurrence of feldspar are distinguishing features. The small (<3mm) subhedral microcline feldspars are commonly corroded and extensively sericitised, a feature that has produced dense sericitic aggregates within the matrix.

The overall texture of the unit varies from dense concentrations of clasts in narrow (<30cm) horizons, to zones where clasts are almost completely absent. The Crystal Metatuff unit is also highly silicified and carbonated in places.

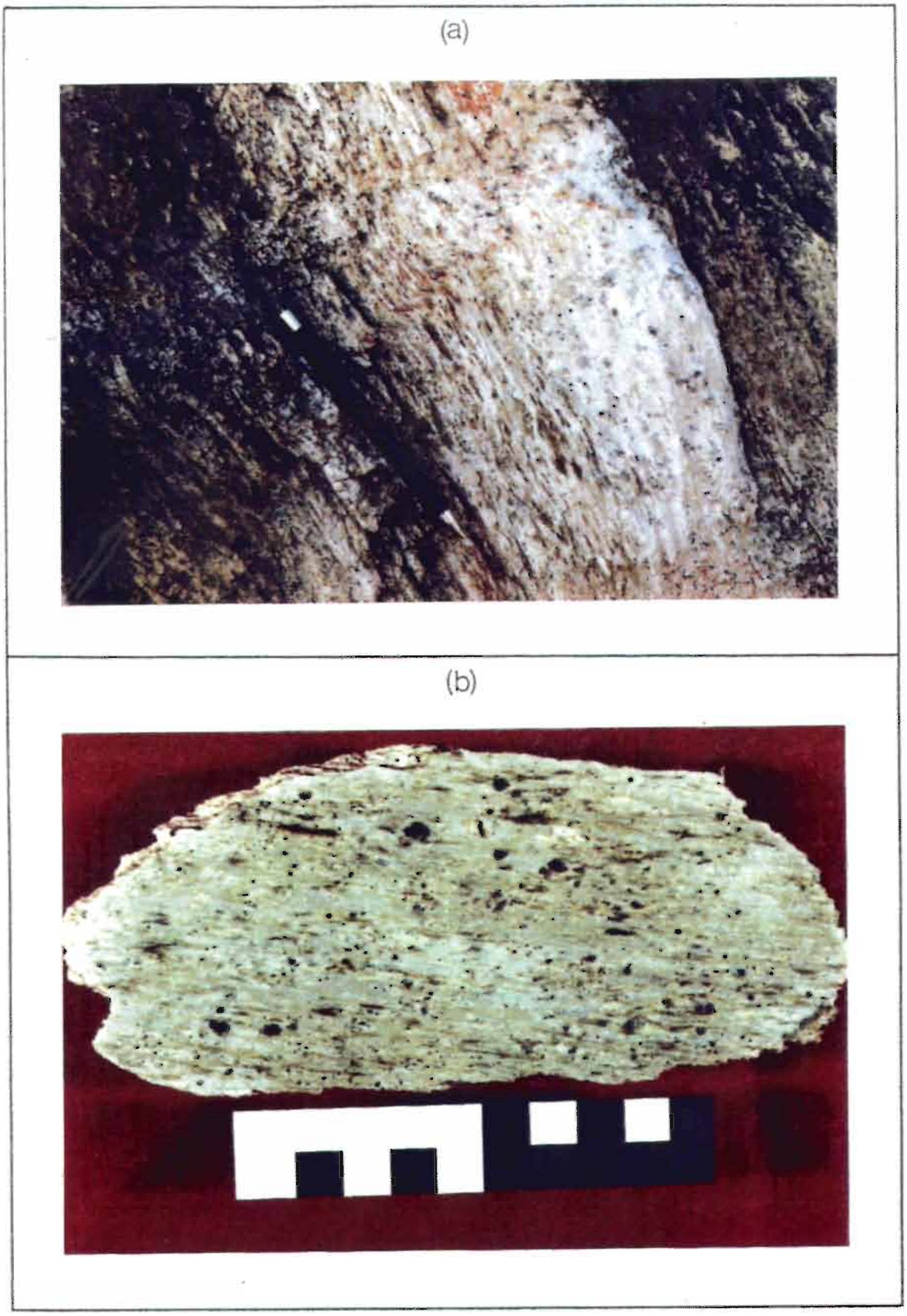


Figure 2.7 (a) Crystal metatuff in outcrop, characterised by its light grey - white colour and abundant "quartz-eyes".

(b) Sectioned crystal metatuff hand specimen showing the distribution of sericite aggregates and "quartz-eyes" within a fine-grained quartz-sericite matrix.

2.2.7 Metarhyolite

This unit is characterised by abundant and evenly-distributed quartz-eyes that are enclosed within a grey to dark grey, fine-grained, well-foliated and homogeneous quartz-sericite matrix. The packing density of the quartz-eyes within the matrix remains high throughout the unit, and this, together with the small size of the quartz-eyes (<2mm), distinquishes the metarhyolites from the metatuffs. Minor amounts of small sericite clasts accompany the quartz-eyes within the matrix. In outcrop, the rhyolites are typically pale grey to cream in colour, and vary from highly weathered friable quartz-sericite schists that retain abundant fine quartz-eyes, to zones that are highly siliceous and resistant to weathering (see figure 2.8).

2.2.8 Feldspathic Intrusive

The Feldspathic Intrusive is a highly weathered, fine-grained, pale brown to khaki coloured, granular rock having a schistose texture defined by parallel mineral alignment. The fine-grained matrix has a fairly homogeneous appearance in weathered form and consists essentially of quartz, sericite, chlorite and feldspar (highly sericitised). The rock is also highly carbonated in places with the resultant development of dolomitic aggregates. This lithology was only observed in a highly weathered and altered state, making an interpretation of the original rock type difficult . Anglo American geologists have, however, referred to the Feldspathic Intrusive as a Leuco-Quartz Diorite.

2.3 STRUCTURE

The attitude of the lithologies at Bien Venue has been modified by a series of structural events. The stratigraphy has been subjected to at least two major folding events and later faulting.

A penetrative cleavage, defined by strong platy mineral alignment, transgresses the lithologies with a consistent north-easterly strike and steep (63 - 70°) south-easterly dip. A mineral lineation, that is well developed within the Crystal Metatuff unit, plunges at approximately 68° to the south-east within the plane of the cleavage. A weak fracture cleavage striking north

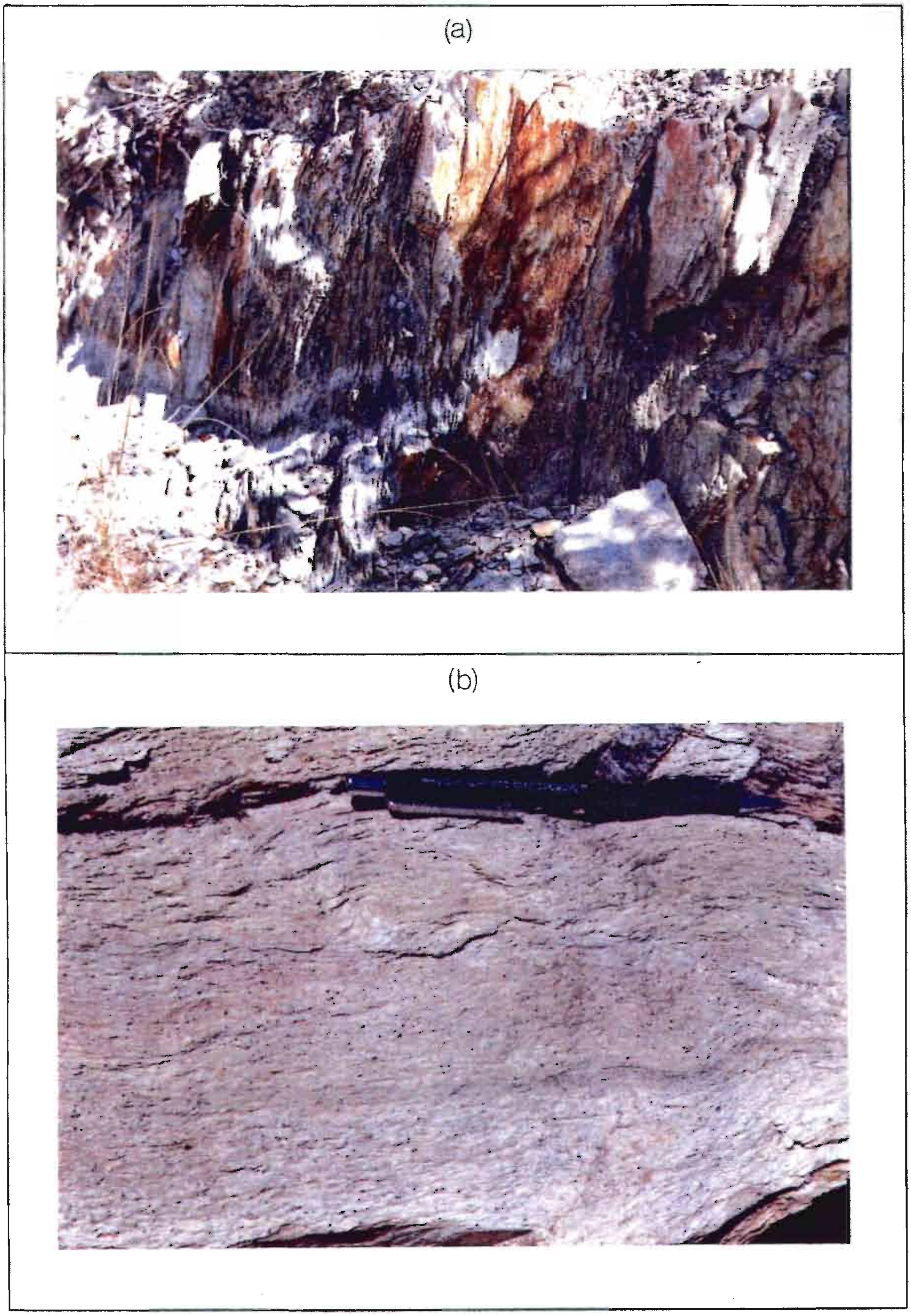


Figure 2.8 (a) Metarhyolites are well-foliated and weather to extremely friable quartz-sericite schists.

(b) Siliceous metarhyolite. Note the occurrence of fine evenly distributed "quartz-eyes" (grey specks in photograph) within the quartz-sericite matrix.

north-east and dipping south-east at 70°, truncates the earlier penetrative cleavage with an angular difference of approximately 15°. The intersection of the two cleavages has produced micro-kinking which defines a crenulation lineation that plunges steeply to the south-east.

The lithological succession has been folded into an "S" - shaped minor fold, as shown in the surface outcrop pattern, and best defined by the synformal and antiformal repetition of the Quartz-Augen Metatuff unit. On a regional scale this fold pattern is found to be a subsidiary fold on the eastern flank of the regional antiform, defined by the refolded conglomerate unit to the west of the Bien Venue deposit.

Late faulting, in the form of a series of north north-east and north-east striking faults dipping to the south at between 60 - 70°, has further modified the attitude of the folded lithological succession, by disrupting the local continuity of the different lithological units and the mineralised zone. The southern limit of the volcanic succession has also been terminated by a major fault. The originally linear shape of the mineralised zone has been divided into two major sections by reverse faulting. The orientation and juxtaposition of these two sections give the erroneous appearance of two limbs of a synform. Evidence that these are indeed reverse faulted sections of the same protore is shown by the metal zonation that occurs within the mineralised zone (in both sections, the copper-rich zone is on the western side). The faults are marked by fault gouge zones, narrow ultra-mylonite zones and associated shear zones. The fault zones do not outcrop and the attitude of most of the faults has been derived from correlation and extrapolation of borehole data.

2.4 METAMORPHISM

Mineral assemblages developed in the Bien Venue lithologies are those of the greenschist facies of low-grade regional metamorphism. The co-existence of sericite and biotite with chlotite and quartz, and the absence of stilpnomelane, indicates that Barrow's biotite zone of low-grade regional metamorpism has been reached (Winkler, 1974).

The mineralisation at Bien Venue has also been affected by metamorphism. This is indicated by the recrystallisation textures displayed by various ore minerals and described in chapter 4.

CHAPTER 3

PETROLOGY

3.1 INTRODUCTION

The Bien Venue mineralisation occurs within a sequence of felsic volcanic rocks that have undergone regional metamorphism to greenschist facies and could generally be described as quartz-sericite schists. However a more detailed classification of these rocks is required in order to subdivide the sequence into various units, and to determine a genetic origin of the rocks, be it lavas, pyroclastics, or even intercalated sedimentary units.

3.2 PETROLOGY OF THE BIEN VENUE LITHOLOGIES

The following descriptions serve to illustrate the character of the rocks as viewed under the petrographic microscope, and to delineate the subtle differences between some of the rock types.

The felsic volcanics have a well-foliated, fine- to very fine-grained, granoblastic quartz + sericite matrix that displays varying degrees of inhomogeneity with respect to the distribution of quartz-rich and sericite-rich compositional domains (see figure 3.1). The schistosity is defined by the parallel orientation of sericite and the occurrence of narrow elongate compositional domains. Although the lithologies have similar matrices, individual rock types can be recognised, and are characterised by the type, size, predominance and distribution of clasts and/or quartz-eyes within the matrix.

3.2.1 Lapilli Metatuff

The Lapilli Metatuff is a highly varied and complex unit that is host to the Bien Venue mineralisation. The matrix consists of an inhomogeneous assemblage of quartz and sericite, with

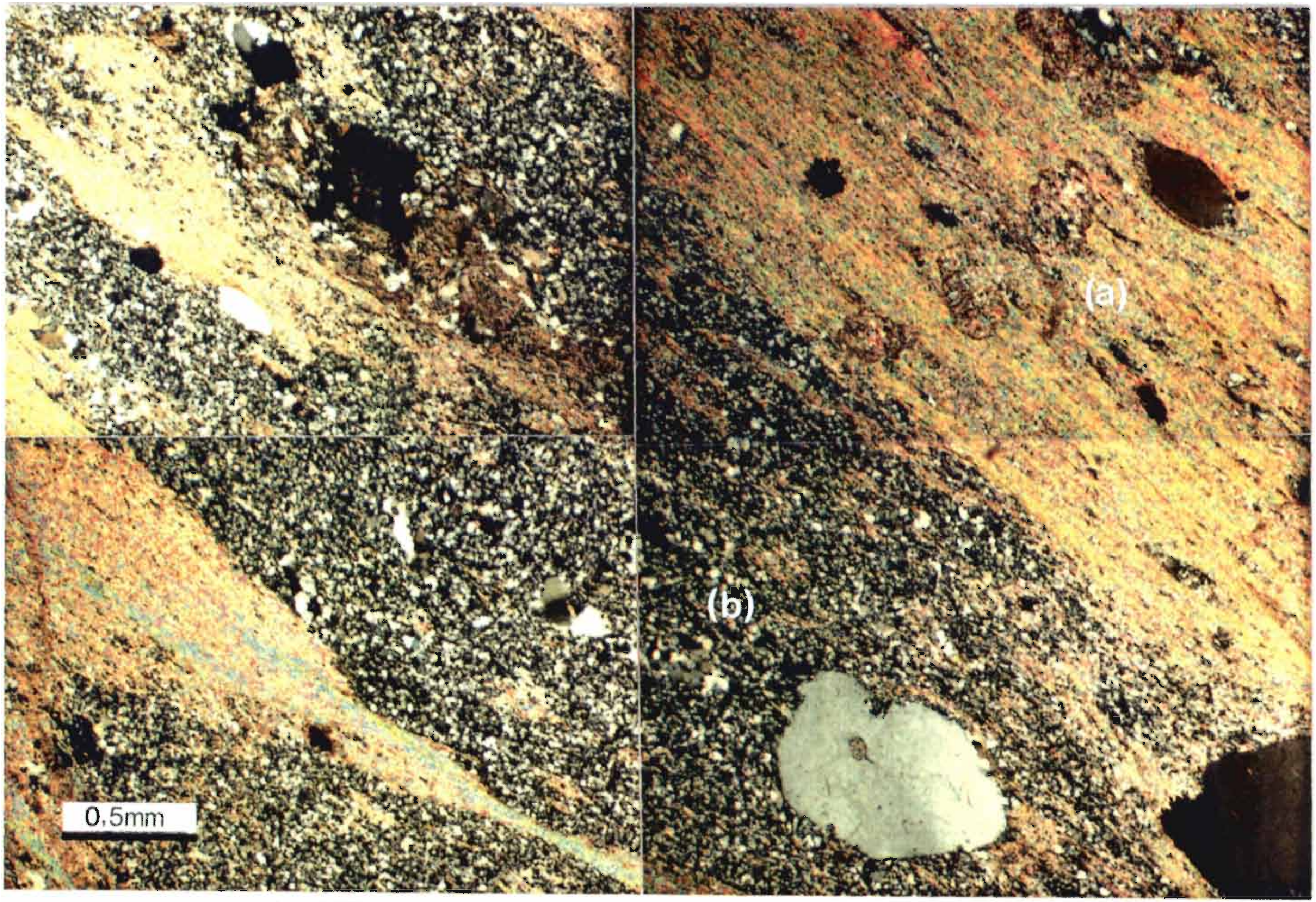


Figure 3.1 Photomicrograph mosaic of a well foliated, fine-grained granoblastic quartz-sericite matrix that displays varying degrees of inhomogeneity with respect to the distribution of sericite-rich (a) and quartz-rich (b) compositional domains.

minor amounts of chlorite. The grain-size of the matrix ranges from a fine-grained type to distinctly coarser varieties. The distribution of quartz-rich and sericite-rich compositional domains is well-defined in many samples and this gives rise to the inhomogeneous nature of the matrix. Sericite-rich domains occur preferentially along cleavage folia and this process is a result of solution cleavage and the preferential dissolution of quartz, as described within the metarhyolite unit (section 3.2.5).

The texture of this unit is also highly variable, from zones with abundant clasts (ie. high clast to matrix ratio) to relatively clast-free zones. The majority of the clasts consist of coarse-grained aggregates of quartz sub-grains that show an increasing degree of recrystallisation from the centre to the margins of the clast. These siliceous clasts have a similar appearance to quartz-filled lithophysae (see figure 3.2a and 3.2b), but are generally considered to be former glassy fragments that have been deformed and altered due to metamorphism. Minor sericitic and chloritic patches/aggregates are also present (see figure 3.2c and 3.2d).

Samples taken from barite-rich horizons in the upper parts of the orebody indicate that barite constitutes approximately 60 - 70% of these horizons, with subordinate amounts of quartz, sericite, albite plagioclase, and minor mineralisation in the form of pyrite and sphalerite.

The barite occurs as coarse anhedral granular aggregates (with individual crystals up to 1,5 mm in size) that often totally enclose crystals of quartz and plagioclase (see figure 3.2e and 3.2f). The barite crystals are anhedral to subhedral in shape, show two distinct cleavage directions and are often fractured. Elongated barite crystals are also observed and are aligned parallel to the foliation, which is defined by the parallel orientation of stringers of mica. However, within the barite-rich horizons the foliation is not as distinct as with the majority of the other Bien Venue lithologies.

Other minerals present in minor to trace amounts include Na-amphibole, biotite and zircon. Intense silicification and carbonatisation (carbonate alteration) occurs in some samples.

3.2.2 Quartz-Augen Metatuff

This porphyritic rock type is characterised by the presence of abundant quartz-eyes that are randomly distributed within a quartz-sericite matrix (see figure 3.3). The essentially

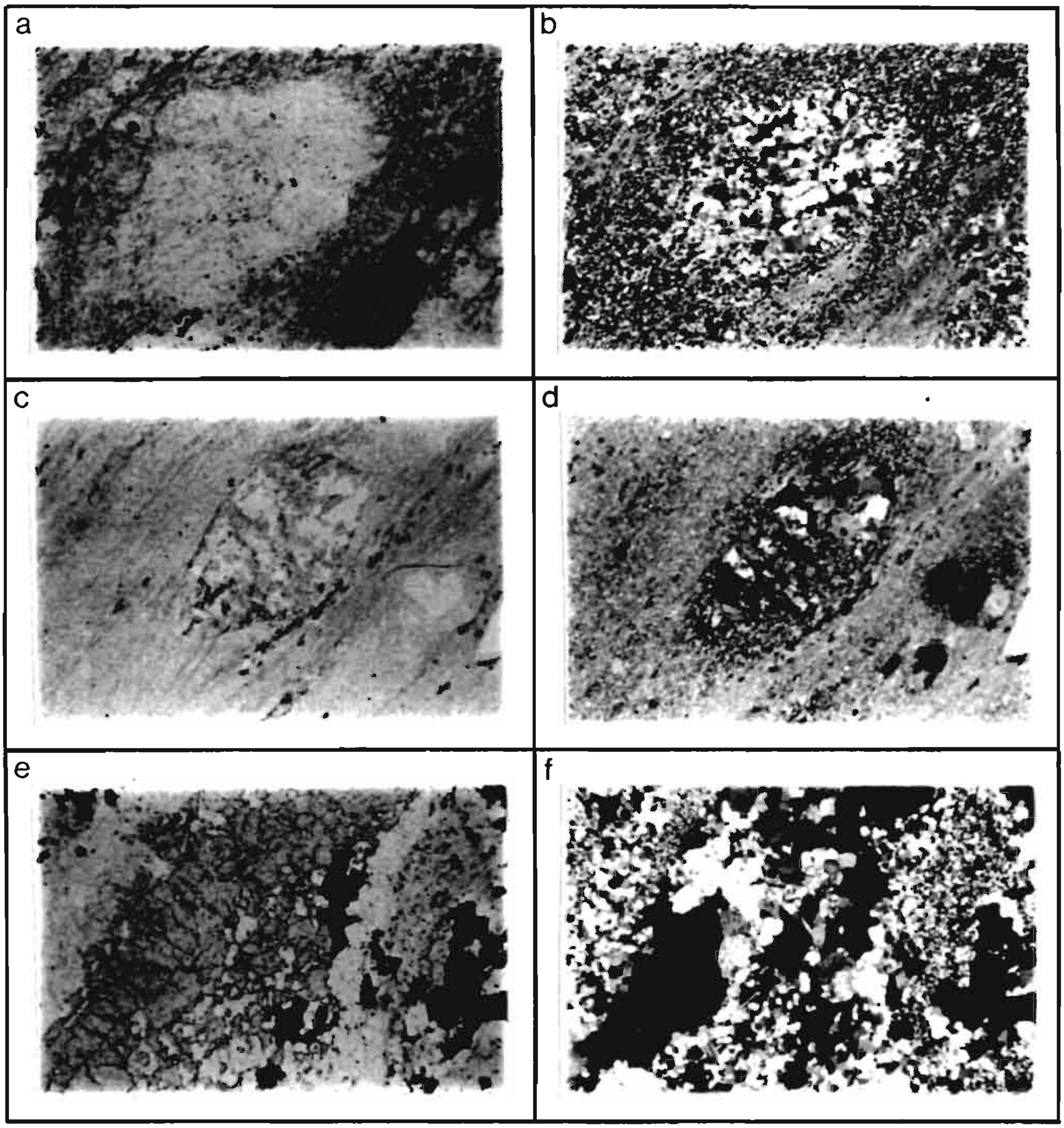


Figure 3.2 Photomicrographs of various lapilli metatuff thin-sections.

(a) Plane-polarised light, and (b) crossed nicols. Siliceous clast in the form of a coarse-grained aggregate of quartz sub-grains. Width of field : 4mm.

(c) Plane-polarised light, and (d) crossed nicols. Chloritic aggregate together with quartz grains in a quartz-sericite matrix. Width of field : 4mm.

(e) Plane-polarised light, and (f) crossed nicols. Coarse anhedral barite aggregate (ba) enclosing quartz and plagioclase crystals, in relation to the much finer-grained quartz-sericite matrix. Width of field : 4mm.

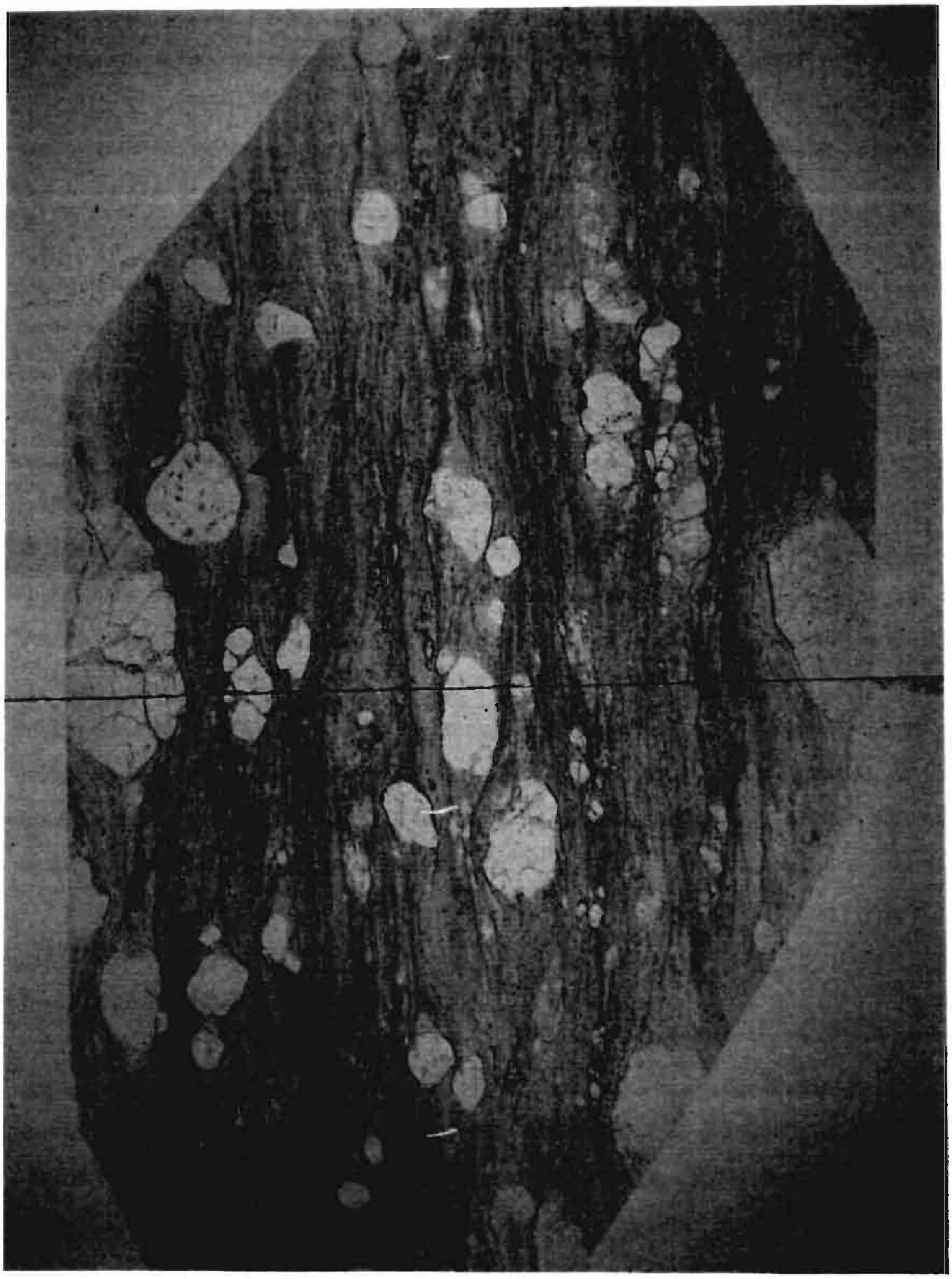


Figure 3.3 Photo-enlargement of a quartz-augen metatuff thin-section. Note the porphyritic nature of this rock type, characterised by the presence of abundant quartz-eyes randomly distributed within the quartz-sericite matrix. Rounded bipyramidal quartz-eyes with embayments (arrowed in photograph) are common in the quartz-augen metatuff unit. Magnification : X4.

microcrystalline quartz-rich matrix is fine-grained, inhomogeneous, displays a granoblastic texture and shows a well developed foliation in the form of fine orientated sericite. Sericite-rich compositional domains are present in the form of lensoidal aggregates or as narrow discontinuous layers intercalated and interfingered with microcrystalline quartz.

The quartz-eyes, which occur in varying amounts throughout the whole volcanic sequence, are best developed in the Quartz-Augen Metatuff unit.

The quartz-eyes of this unit vary in size from less than 1 mm to a maximum of 8 mm, and occur as predominantly sub-rounded to rounded grains, with minor idiomorphic bipyramids, embayed and sub-angular crystals. They are poorly sorted and are randomly distributed within the matrix, generally with their long axes parallel to the foliation, although some examples are seen to transect the sericite mica fabric. Various degrees of strain and deformation are exhibited by the quartz-eyes, even within the confines of a single thin-section. A typical feature of many quartz-eyes is the recrystallisation and sub-grain growth of quartz at low pressure zones, with the resultant development of pressure shadows around which the matrix is bowed. A more detailed discussion of these quartz-eyes can be found later in the text (p.33).

Minor amounts of Mg-rich chlorite , occurring as clasts/aggregates of randomly orientated subhedral flakes, are generally present within sericite-rich compositional domains of the matrix. Other minerals present in minor amounts include chloritoid, zircon, rutile and biotite. Silicification and carbonatisation are notable alteration features in some thin-sections.

3.2.3 Polymict Metatuff and Meta-agglomerate

As with all the Bien Venue volcanic rocks, the matrix consists of a foliated, fine-grained and inhomogeneous assemblage of granoblastic quartz and sericite. The distribution of quartz-rich and sericite-rich compositional domains delineates the inhomogeneity of the matrix. Sericitic compositional domains commonly occur as highly elongated lenticular bodies and stringers that together with fine orientated sericite define the schistosity.

The clasts consist predominantly of fine-grained lensoidal aggregates of either sericite, chlorite or microcrystalline quartz, and lesser but often significant amounts of feldspar porphyry. Quartz-eyes do occur , but only in minor amounts and are generally less than 2 mm in size. The majority of clasts are distorted and elongated, and have their long axes orientated parallel to the foliation.

3.2.4 Crystal Metatuff

This rock consists of a well-foliated, inhomogeneous, fine-grained quartz-sericite matrix containing abundant quartz-eyes and feldspar (microcline) crystals. Quartz predominates within the matrix, occurring as recrystallised grains having a granular mosaic appearance, together with fine orientated sericite that defines the schistosity.

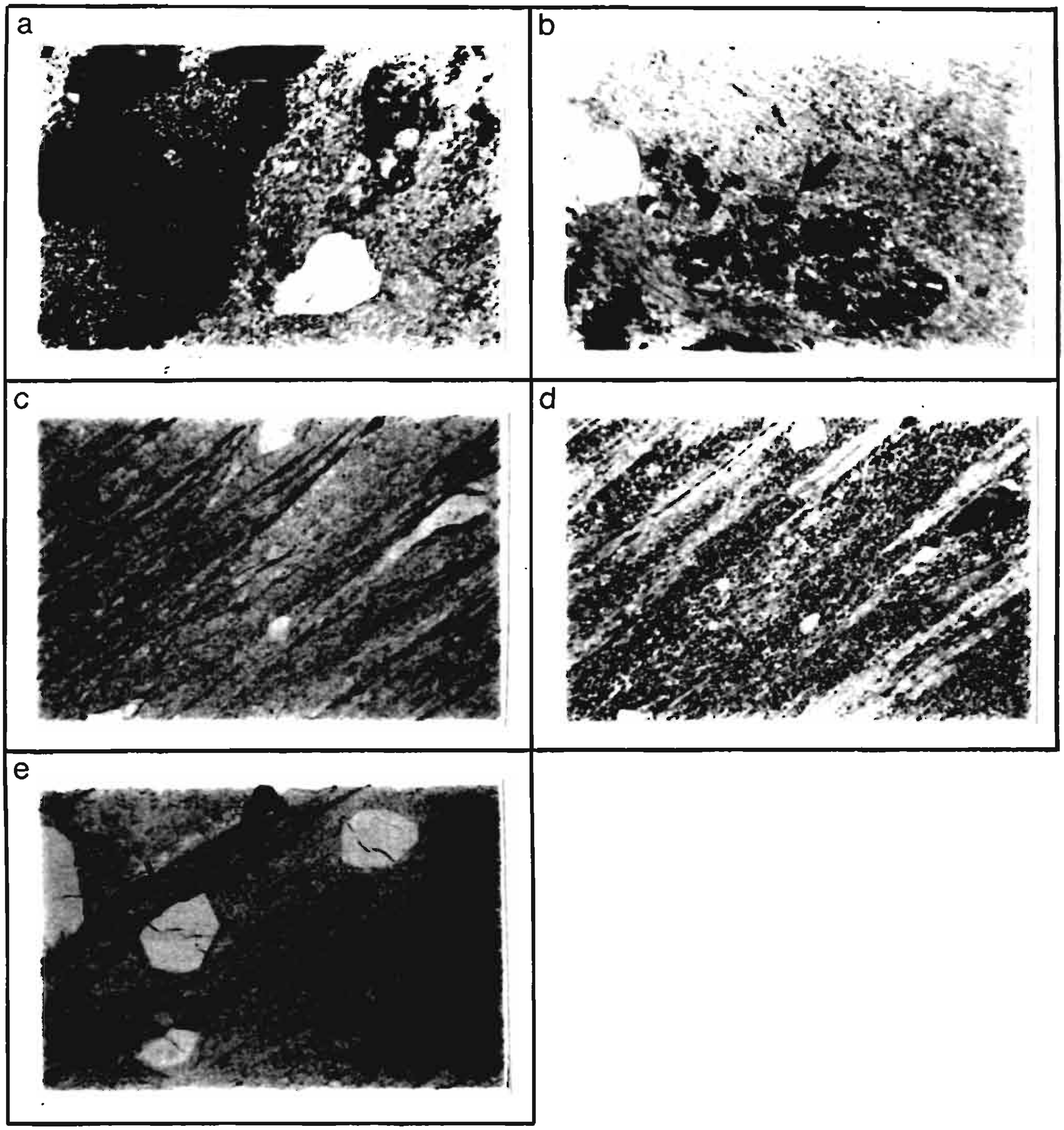
Sericite is also found concentrated in narrow lenticular to stringer-like bodies, in the pressure shadow zones of quartz-eyes and in elongate clast-like masses that are believed to represent deformed and altered former phenocrysts or glassy fragments. The presence of these sericite-rich compositional domains gives rise to the inhomogeneity of the matrix.

The quartz-eyes are generally sub-angular to rounded, between 0,5 - 3 mm in diameter, and have been deformed and elongated so that the majority of the quartz-eyes have their long axes orientated parallel to the schistosity (some examples do however transect the mica s-trains). Idiomorphic bipyramids and embayed crystals were also noted. Strain effects displayed by the quartz-eyes vary from slight undulatory extinction, through local sub-grain growth to major sub-grain growth and associated fragmental texture, and completely recrystallised quartz sub-grain aggregates.

Quartz crystal fragments are also present within the matrix, and they are distinguished from the quartz-eyes by their generally smaller size (0,1 - 1 mm in diameter) and greater degree of angularity.

The microcline feldspars occur as small lath-like crystals less than 0,8 mm in diameter, that display typical cross-hatch and polysynthetic twinning (see figure 3.4a). Most of the feldspar crystals are embayed and corroded, with alteration to sericite occurring in many cases (see figure 3.4b).

Other constituents present in minor amounts within the matrix include biotite, sphene and zircon.



·Figure 3.4 Thin-section photomicrographs.

(a) Microcline feldspars (m) from the crystal metatuff unit. Note the typical cross-hatch twinning. Crossed nicols. Width of field : 1mm.
(b) Sericitised feldspar crystal (arrowed) from the crystal metatuff unit. Crossed nicols. Width of field : 1mm.
(c) Plane-polarised light, and **(d)** crossed nicols. Well developed schistosity, defined by the parallel orientation of sericite which is preferentially concentrated along cleavage folia. Width of field : 4mm.
(e) Quartz-eyes showing development of secondary rims/halos of very fine-grained sericite and microcrystalline quartz. Also note the quartz-eye (arrowed) that is truncated by a cleavage plane, suggesting that solution cleavage has taken place. Plane-polarised light. Width of field : 4mm.

3.2.5 Metarhyolite

This rock type is characterised by a fine-grained, homogeneous quartz-sericite matrix that encloses abundant small quartz-eyes. A well developed schistosity is defined by the parallel orientation of sericite, and the occurrence of cleavage folia along which sericite is often preferentially concentrated (see figure 3.4c and 3.4d).

The quartz-eyes in the Metarhyolite, unlike the Quartz-Augen Metatuff, have a narrow size range, generally 0,3 - 2 mm in diameter, and are evenly distributed within the matrix. They are generally subidiomorphic in outline, often with embayed margins, and occasional angular crystal fragments were also noted. Many quartz-eyes have developed a secondary rim or halo of very fine-grained sericite and microcrystalline quartz, the thickness of which is often varied around the circumference of the crystal (see figure 3.4e).

Most quartz-eyes show evidence of minor strain only, with slight undulatory extinction predominating. Local sub-grain growth, fragmented grains and recrystallised aggregates of quartz sub-grains do occur, but are not common.

Lenticular clasts made up of aggregates of sericite and/or chlorite, are also enclosed within the matrix.

Examples of solution cleavage are observed within the rhyolites. In figure 3.4e a quartz-eye is clearly truncated by a cleavage plane, and this suggests that a portion of the grain has been removed by dissolution, with the resultant concentration of less mobile material such as sericite.

3.2.6 Feldspathic Intrusive

Only highly weathered samples of this rock type could be obtained. Thin-section examination revealed a fine-grained granular rock, consisting of a groundmass of quartz, chlorite, muscovite and dolomite, enclosing laths of albite plagioclase. The original texture of the rock is often totally destroyed by the development of dolomite, which is disseminated throughout the groundmass as irregular aggregates, and by the alteration of feldspars to clays.

3.3 ALTERATION

3.3.1 Introduction

The effects of hydrothermal alteration are evident at Bien Venue, with significant sericitisation, silicification, chloritisation and the introduction of sulphides, as well as the addition and depletion of various elements (see Ch. 5 Geochemistry, section 5.4). Geochemical analysis for chemical additions and depletions of the lithologies provides an excellent means of examining the extent of hydrothermal systems. For example, silica addition is indicated by the presence of quartz-veining and silicification of rock matrices, and magnesium addition is indicated by chloritisation and the dolomitisation of calcite.

Massive sulphide deposits, in general, may be associated with three forms of hydrothermal alteration (Franklin et al., 1981). These are :

1) An alteration pipe or conformable zone in the footwall lithologies that immediately underlie the deposit.
2) A very large, semi-conformable alteration area that is present below the ore horizon, and is either below the alteration pipe or may have the pipe superimposed upon it.
3) A relatively small, transgressive alteration area in hanging wall lithologies.

Some massive sulphide deposits of the proximal type may exhibit all three forms of alteration, whereas distal deposits may show none. In many districts, alteration studies are incomplete and the three forms of alteration are unrecognised. This latter statement holds true for the Bien Venue deposit, as the author could only gain access to 6 of the 27 boreholes drilled in the area, and although several alteration types were recognised, the distribution and attitude/geometry of the alteration zones could not be ascertained.
Alteration associated with the Bien Venue deposit consists of sericitisation, silicification and chloritisation, and with the exception of sericitisation, occurs predominantly in the footwall lithologies. This is not surprising, since Sangster (1972), points out that the most common alterations found in the footwall pipes of Archean massive sulphide deposits are chloritic, sericitic, silicification and carbonate.

3.3.2 Sericitisation

Sericitisation is present in nearly all types of hypogene ore-forming environments in aluminous rocks, as well as in nearly all types of massive sulphide deposits in Precambrian metamorphic terrains (Franklin et al., 1981). At Bien Venue sericitisation is abundant, and is the most widespread of the alteration types, occurring in both the footwall and hanging wall lithologies.

Sericitised metatuffs are grey-white and highly schistose, with sericite and quartz being the dominant minerals, although sericitised feldspar and disseminated pyrite are locally abundant. As sericite is easily confused, both in the field and under the microscope, with paragonite, pyrophyllite and phlogopite, XRD (X-ray Diffraction) analysis was required for positive identification, and the occurrence of the dioctrahedral 2M1 mica, muscovite, was confirmed. Details concerning the XRD analysis, carried out at the laboratories of the Geological Survey of South Africa, Pretoria, are presented in Appendix B.

Other minerals found in sericitised zones adjacent to areas of mineralisation include, albite plagioclase, tourmaline, kaolinite and gibbsite.

3.3.3 Silicification

Silicification at Bien Venue predominates in the footwall lithologies where several highly siliceous zones are encountered, with extensive silicification of rock matrices involving an increase in the proportion of microcrystalline quartz. The silica may have been added hydrothermally, or the quartz content may have increased by selective hydrothermal leaching of bases leaving residual silica as quartz.

3.3.4 Chloritisation

Chloritisation is most intense in the footwall lithologies immediately below areas of mineralisation at Bien Venue. Chloritised metatuffs are typically grey-green in colour, with the dominant mineral assemblage consisting of chlorite, sericite and quartz. The occurrence of the IIb chlorite, clinochlore, was confirmed by XRD analysis.

3.4 THE QUARTZ-EYES : THEIR TERMINOLOGY, NATURE AND POSSIBLE ORIGINS

The term "quartz-eye" is used in preference to genetic terminology such as phenocryst, porphyroblast, porphyroclast or clast, since the long-standing debate in the geological literature on the origins of quartz-eyes, has seen various papers (Hopwood, 1976, 1977; Vernon and Flood, 1977; Vernon, 1986; Williams and Carmichael, 1987) supporting different hypotheses.

The quartz-eyes, which are best developed in the Quartz-Augen Metatuff unit, are present throughout the whole volcanic succession, where they are enclosed in the foliated, fine-grained quartz-sericite matrices of the volcanic lithologies. The quartz-eyes are highly variable in size, shape, abundance and density within the matrices, and the textures and strain effects that they exhibit. Sizes vary from less than 1 mm to a maximum of 8 mm in diameter. Quartz-eye shapes range from the predominant sub-rounded and rounded grains, with minor idiomorphic bipyramids, sub-angular and embayed crystals, to the often lensoidal aggregates of recrystallised quartz sub-grains. The quartz-eyes are generally poorly-sorted and randomly distributed within the matrices of the volcanics. However, in the metarhyolites, it is noted that the quartz-eyes have a more uniform distribution (ie. similar clast : matrix ratios throughout) and a small size range, having diameters generally less than 2 mm. In most cases the quartz-eyes are orientated with their long axes parallel or sub-parallel to the foliation, although some examples are seen to transect the sericite mica s-trains (see figure 3.5a and 3.5b).
The distinctive feature from which the name "quartz-eye" has arisen, is the occurrence of metamorphic or pressure shadows developed at many quartz crystal margins, giving a distinct "augen" appearance. Strain and metamorphism have resulted in the development of granular mosaics of quartz sub-grains (often intergrown with fine sericite) in the low pressure zones of the quartz-eyes. This, together with the bowing of mica s-trains around quartz-eyes, delineates these pressure shadow zones (see figure 3.5a and 3.5b).

Various degrees of strain and deformation are exhibited by the quartz-eyes, even within the confines of a single thin-section. Progressive strain and deformation are demonstrated in a sequence of figures as follows:

- relatively unstrained quartz-eyes, with no or minor development of undulose extinction and no sub-grain growth.
- quartz-eyes showing strong undulose extinction (and often deformation lamellae), with local

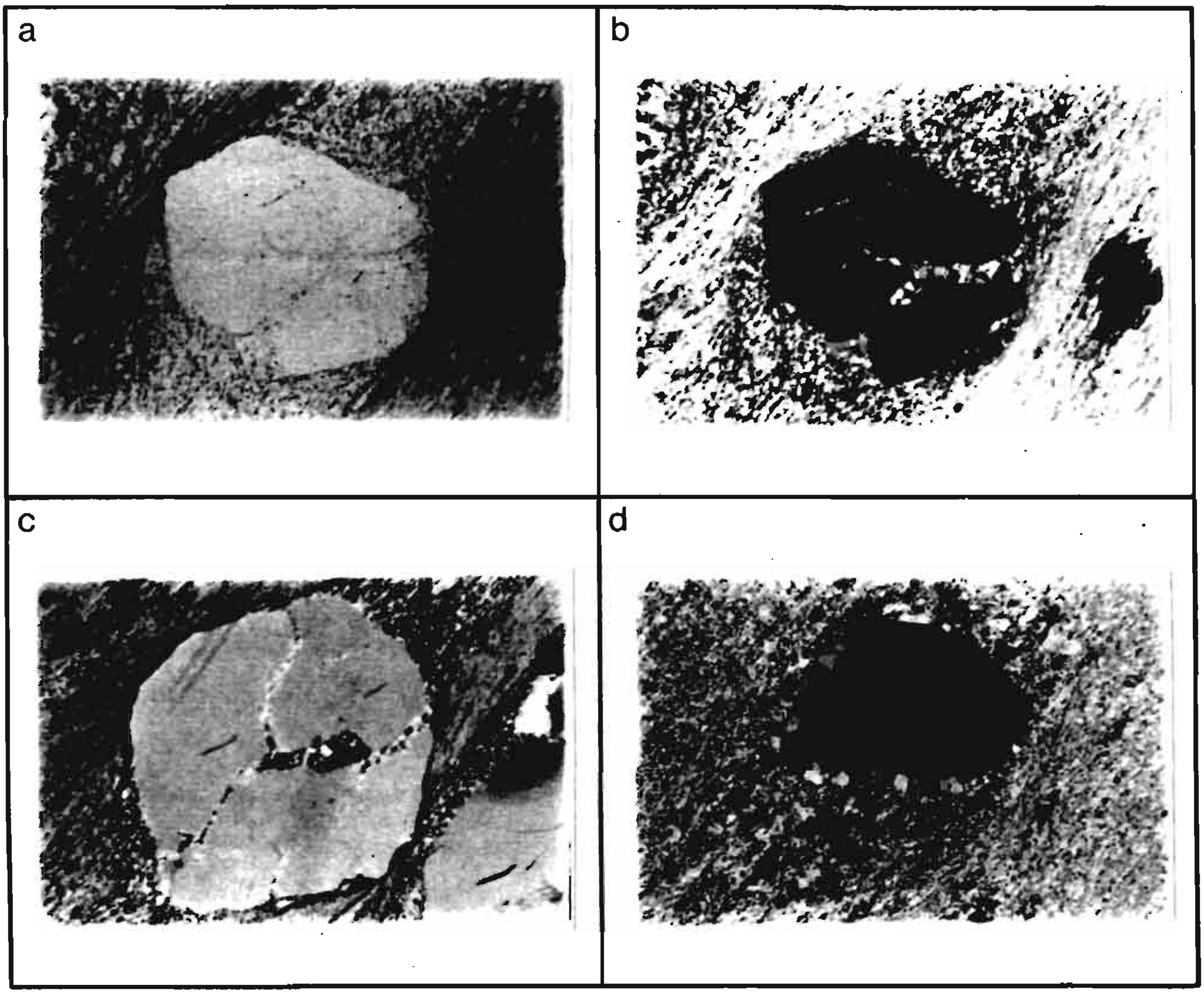


Figure 3.5 Thin-section photomicrographs.

(a) Plane-polarised light, and (b) crossed nicols. An originally bipyramidal shaped quartz-eye transgressive to the foliation. Note the well defined pressure shadow and associated development of a granular mosaic of quartz sub-grains and intergrown fine sericite. Width of field : 2mm.
(c) Local sub-grain growth along fractures within a quartz-eye. Crossed nicols.
Width of field : 2mm.
(d) Local sub-grain growth along the margins of a quartz-eye. Crossed nicols.
Width of field : 2mm.

sub-grain growth along fractures or crystal margins (see figure 3.5c and 3.5d).
- major development of sub-grains within quartz-eyes giving rise to a fragmental texture (see figure 3.6a and 3.6b).
- complete recrystallisation of the quartz-eyes giving rise to lensoidal and often elongated granular mosaic aggregates of quartz sub-grains (see figure 3.6c).

Similar degrees of deformation of quartz-eyes were described by Frater (1983) from felsic volcanoclastic rocks at Golden Grove, Western Australia.

3.4.1 Quartz-eye Textural Implications

Many features of the quartz-eyes of the Bien Venue lithologies have also been observed by Hopwood (1976), in his work on Archean massive sulphide deposits in Canada. Although similarities do exist with the quartz-eye bearing Bien Venue lithologies, there are also some important differences.

Hopwood concluded that the combined association of
(1) pyrite-rich stratigraphic units, and
(2) a characteristic style of quartz-eye porphry
is closely related to the occurrence of volcanogenic massive sulphide deposits. Although this does not hold true for all Canadian massive sulphide deposits, the association is clear when applied to Bien Venue.

Hopwood also concluded that texturally, the quartz-eyes of the Canadian deposits appeared to have been formed by porphyroblastic growth within a matrix that was actively deforming during the development of the regional schistosity. Hopwood's evidence for porphyroblastic growth involves remnant micaceous s-trains that traverse quartz-eyes, and quartz-eyes that overprint and include groundmass s-trains of sphene or groundmass trails of pyrite.

The quartz-eyes of the Bien Venue lithologies do not contain inclusion trails, nor do they display any other evidence conducive with porphyroblastic growth. Textural observations for the Bien Venue quartz-eyes such as rounded to bipyramidal shapes that are often heavily embayed (see figure 3.6d), and the occurrence of unfoliated fine-grained aggregates within such embayments, even though the adjacent matrix is strongly foliated, suggests that the quartz-eyes

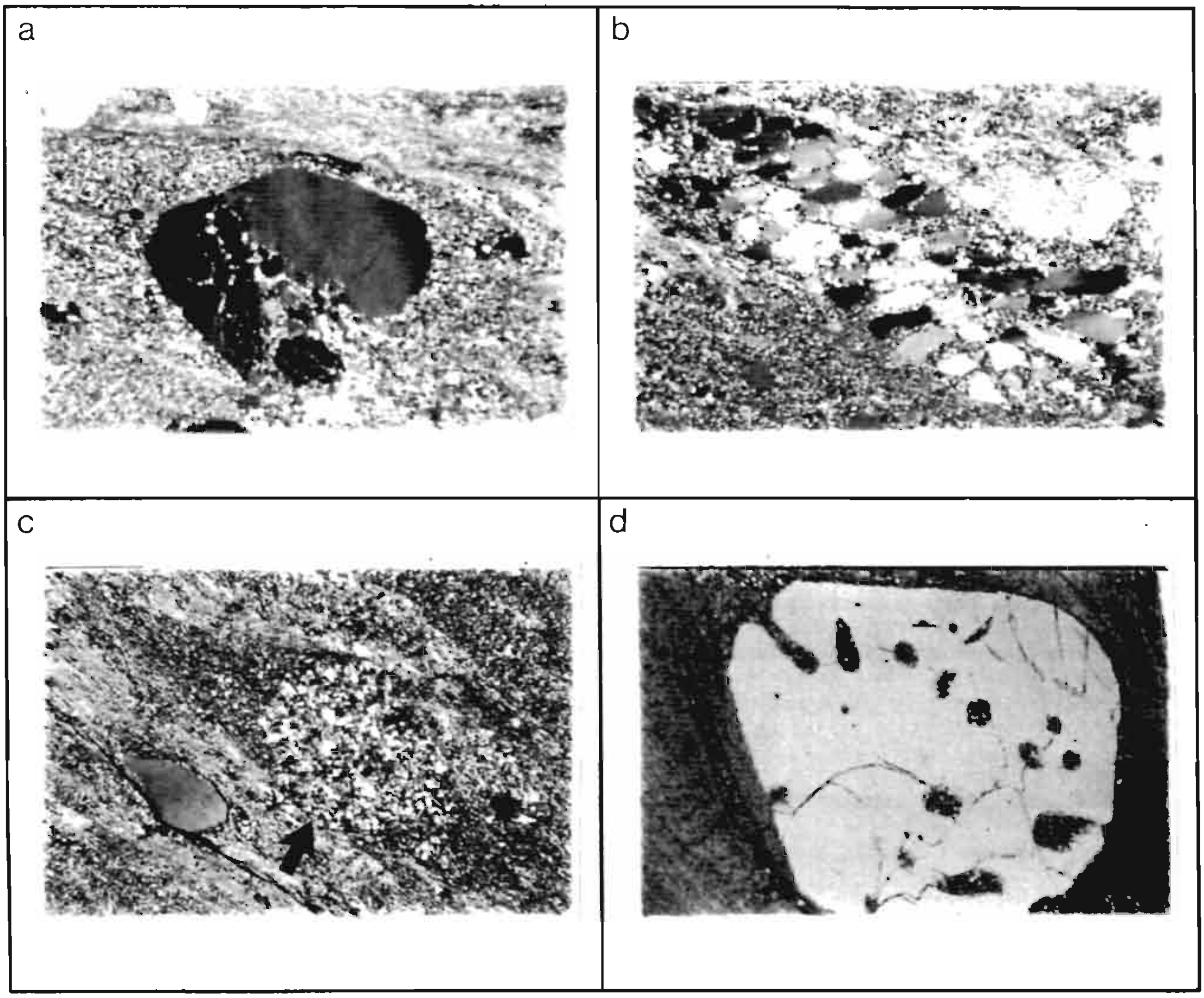


Figure 3.6 Thin-section photomicrographs.

(a) Partial fragmentation of a quartz-eye due to increased sub-grain growth. Crossed nicols. Width of field : 4mm.
(b) Major sub-grain growth resulting in the complete fragmentation of a quartz-eye. Crossed nicols. Width of field : 4mm.
(c) Complete recrystallisation of a quartz-eye resulting in a granular mosaic aggregate of quartz sub-grains (arrowed). Note how such advanced sub-grain formation reduces the contrast between the quartz-eye and the microcrystalline quartz-rich matrix. Crossed nicols. Width of field : 4mm.
(d) Rounded bipyramidal quartz-eye showing distinct embayments. Crossed nicols. Width of field : 4mm.

represent original phenocrysts.

Vernon and Flood (1977) and Vernon (1986) state that rounded to bipyramidal crystal shapes having embayed margins are typical of quartz phenocrysts in silicic volcanic and tuffaceous rocks that have not undergone deformation or metamorphic alteration. In such rocks, the rounded and embayed shapes must have been formed at the magmatic stage, regardless of their exact mechanism of origin (which is usually ascribed to magmatic resorption). Vernon (1986) concluded that embayed quartz-eyes that occur in rocks of felsic bulk composition are best regarded as residual phenocrysts.

Williams and Carmichael (1987) presented a further explanation for the origins of quartz-eyes. Their hypothesis is that quartz-eyes may be fragments derived by disaggregation of early (pre- or early syntectonic) veins or other quartz-rich bodies. However, this hypothesis only holds true for those quartz-eyes that are not embayed and occur in rocks where " there is no suggestion of acidic igneous components to the protoliths ". It is therefore not applicable to the Bien Venue quartz-eye bearing lithologies.

In light of the above evidence it would appear that the quartz-eyes of the Bien Venue lithologies could represent residual phenocrysts of a tuffaceous or intrusive / extrusive igneous volcanic rock.

3.5 CLASSIFICATION OF THE BIEN VENUE LITHOLOGIES

Work carried out by Hopwood (1976) on "quartz - eye" bearing porphyroidal rocks associated with Archaean massive sulphide deposits in Canada, suggested that the quartz-eye porphyroidal rocks may be derived from intrusive quartz-porphyries. He noted 12 examples from various Canadian deposits. However, descriptions of this rock type by various workers from different mines, give alternative interpretations. These include rhyodacite or rhyolite breccia, rhyolite porphyry, crystal tuff and augen schist, all of which are petrographically and chemically similar.

With respect to the Bien Venue quartz-eye bearing lithologies, and in view of their age, petrographic similarities and the degree of alteration/metamorphism to which they have been subjected, it is difficult to classify their protoliths.

The petrographic evidence suggests that the Bien Venue quartz-eye bearing lithologies are of a volcanic nature, in view of the interpretation of the quartz-eyes as representing residual phenocrysts. The inhomogeneous compositional nature of the matrices of these rocks is defined by quartz-rich, sericite-rich and chlorite-rich compositional domains, and suggests a tuffaceous/pyroclastic origin for the Bien Venue lithologies, with the exception of the metarhyolites. This compositional heterogeneity could be explained in terms of an originally fragmental nature, coupled with local metasomatic changes accompanying the low-grade metamorphism of glassy materials (Vernon and Flood, 1977). The sericite-rich and chlorite-rich patches / aggregates present within the matrices could be interpreted as included fragments or alternatively as altered and deformed feldspar phenocrysts. Vernon and Flood (1977) state that such patches are very common in metamorphosed, deformed silicic tuffs, where they represent former glass fragments.

In the deformation of felsic volcanic rocks, the groundmass preferentially deforms relative to the phenocrysts because its fine grain-size and polymineralic composition promote fluid transfer and mineral reactions, with both processes assisting the deformation (Etheridge and Vernon, 1981). Feldspar phenocrysts commonly undergo syndeformational or predeformational hydrothermal alteration or low - medium-grade metamorphism to fine-grained, mechanically weaker micaceous aggregates. These secondary aggregates can deform as readily as the groundmass and so become incorporated in the foliated matrix, thereby leaving the unaltered quartz phenocrysts as relatively undeformed relics in a schistose rock free of feldspar phenocrysts; ie. a typical quartz-eye rock. (Vernon 1986)

The metarhyolites differ from the other lithologies in that they have more homogeneous matrices and are intrusive into the succession. They are therefore not regarded as having a pyroclastic origin, but rather an extrusive igneous origin.

CHAPTER 4

ORE PETROLOGY

4.1 MINERALISATION

The mineralisation at Bien Venue occurs in the upper part of the Lapilli Metatuff unit, and is locally described as the "multi-metal" zone in mine parlance. This "multi-metal" or mineralised zone is approximately 50 - 70 metres in width and comprises highly variable amounts of interbedded fine sericitic to chloritic and siliceous tuff (the host rock), disseminated to semi-massive and massive sulphides, interlayered and disseminated barite, chert/ultra-siliceous horizons, and minor quartz-carbonate veining.

The stratabound sulphide mineralisation is generally distributed along the pervasive north-east trending schistosity, and the massive/semi-massive sulphide bodies are also elongate in this direction. Two types of mineralisation are prominent on a macroscopic scale.

(a) Massive / Semi-massive Sulphides

The massive/semi-massive sulphide zones comprise various bands, layers and discontinuous lenses of sulphides, consisting predominantly of pyrite, with lesser, but still significant amounts of sphalerite, and minor amounts of galena, tennantite and chalcopyrite. A distinctive feature of these sulphides is the occurrence of mineralogical banding, consisting of pyritic sulphide bands alternating with bands of host rock (see figure 4.1). Although the proportions of the individual sulphides vary from band to band, some bands consist solely of pyrite or sphalerite. The bands are laterally discontinuous, locally crenulated and disturbed by microfractures, and generally range in thickness from less than 1cm to 3cm, although individual pyrite bands attain thicknesses of up to 20cm. The massive sulphides are often coarsely recrystallised, producing coarse-grained monomineralic pyrite zones exhibiting distinctive "buckshot" textures characterised by the occurrence of coarse cubic pyrite and pyrite porphyroblasts (see figure 4.2). Remobilisation of sulphides can be seen in the form of irregular veinlets of pyrite transgressing the banding, or occurring along the axial planes of crenulations in the foliation.

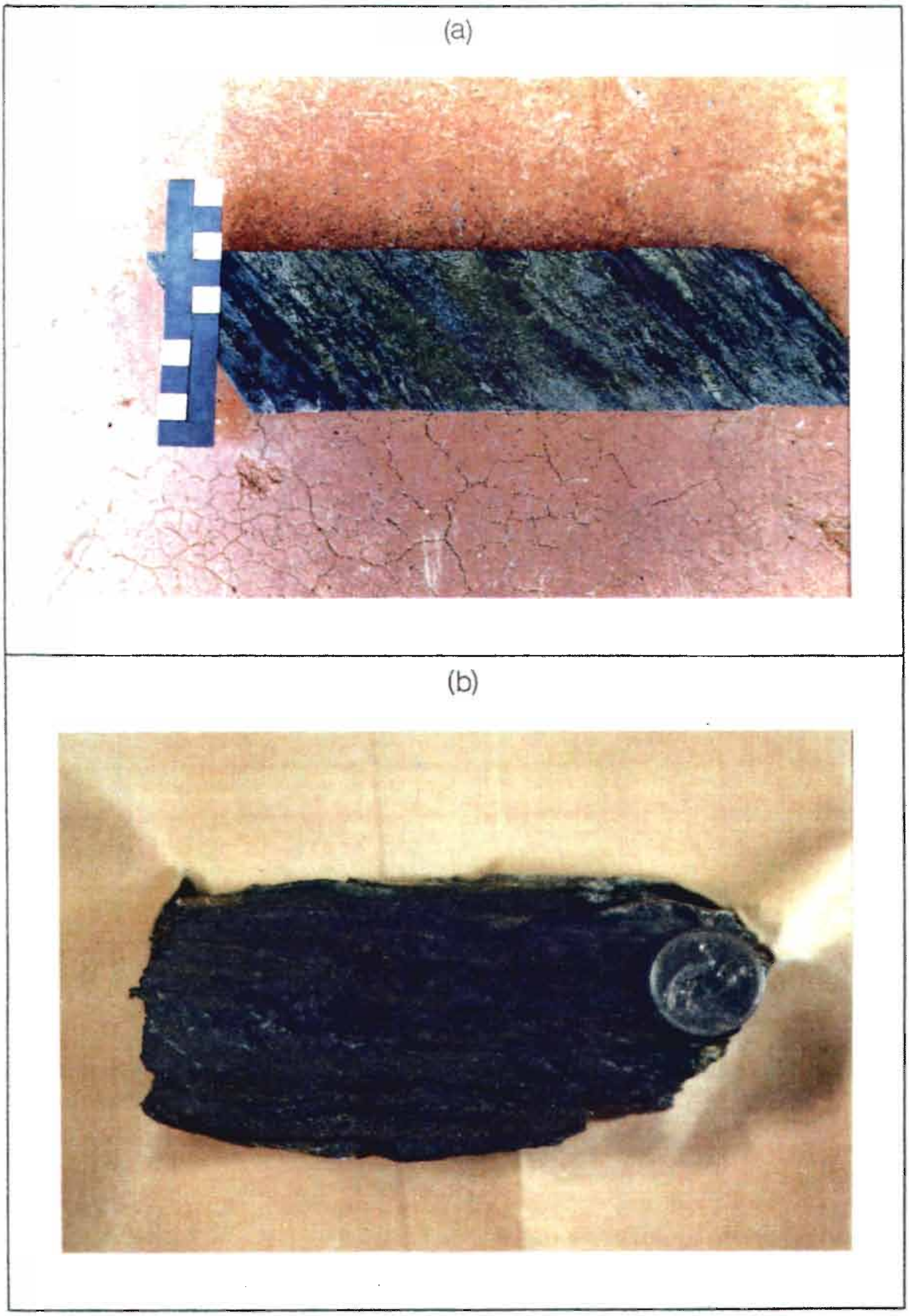


Figure 4.1 (a) Core sample from a massive sulphide zone showing distinct mineralogical banding of pyritic sulphides alternating with siliceous host rock.

(b) Hand specimen of massive sulphide ore showing sulphides distributed along the foliation as narrow bands and lenticular aggregates intercalated with the host rock.

Figure 4.2 Hand specimen taken from a monomineralic pyrite zone. Note the "buckshot" texture and occurrence of pyrite porphyryoblasts.

(b) Disseminated Sulphides

These sulphides occur within fine-grained, highly siliceous lapilli metatuffs, and are found stratigraphically below the massive/semi-massive sulphides, although areas of disseminated sulphides are intercalated within massive sulphide zones. The disseminated sulphides consist predominantly of pyrite, and minor chalcopyrite, in the form of finely disseminated granules and irregular elongate aggregates.

Barite is found in the upper part of the mineralised zone and only several metres below the hanging wall lapilli metatuff/quartz-augen metatuff contact. The barite occurs as massive to semi-massive bands up to 40cm in thickness, interbedded with lapilli metatuff. Intercalated within these barite bands are thin (cm thickness) and often discontinuous layers or lenses of pyritised and siliceous host rock, resulting in in a distinct banded appearance in places (see figure 4.3). When massive, the barite has a coarse-granular appearance.

Cherts are found in the uppermost part of the mineralised zone and are normally stratigraphically higher than the barite horizons. The cherts occur as massive units up to a metre in thickness, that are often difficult to distinguish from zones of silicification, and as banded cherts consisting of alternating layers of quartz and dolomite (see figure 4.4). These banded cherts may in fact represent silicified dolomite horizons.

A vertical zonation of the sulphide mineralisation at Bien Venue exists. The percentage of sphalerite and galena present in the ore increases towards the stratigraphic top of the orebody, and barite is present only in the uppermost part of the orebody. This zonation suggests a simple paragenetic sequence from pyrite-chalcopyrite-rich (Fe-Cu) ore in the footwall, to pyrite-chalcopyrite-sphalerite-galena-barite-rich (Fe-Cu-Zn-Pb-Ba) ore towards the hanging wall.

4.2 BASE METAL MINERALOGY

4.2.1 Introduction

This section is based on extensive microscope studies of 48 polished-sections, supplemented by electron probe microanalysis carried out at the laboratories of the Geological Survey of South Africa, Pretoria. Details concerning the electron probe microanalysis are presented in Appendix C.

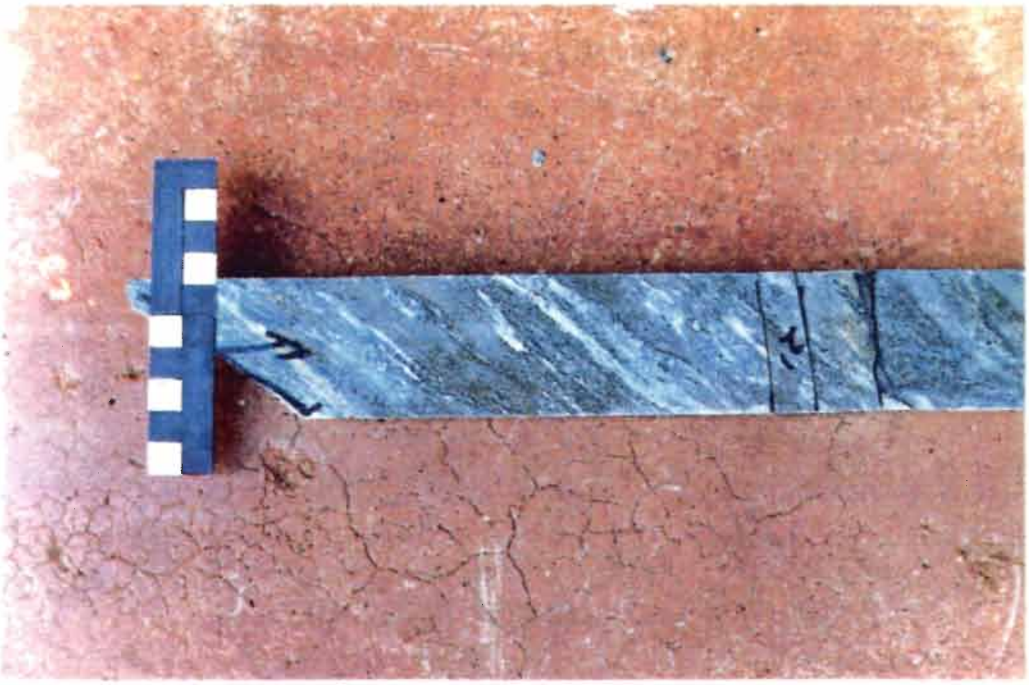


Figure 4.3 Core sample showing thin barite bands intercalated with siliceous host rock.

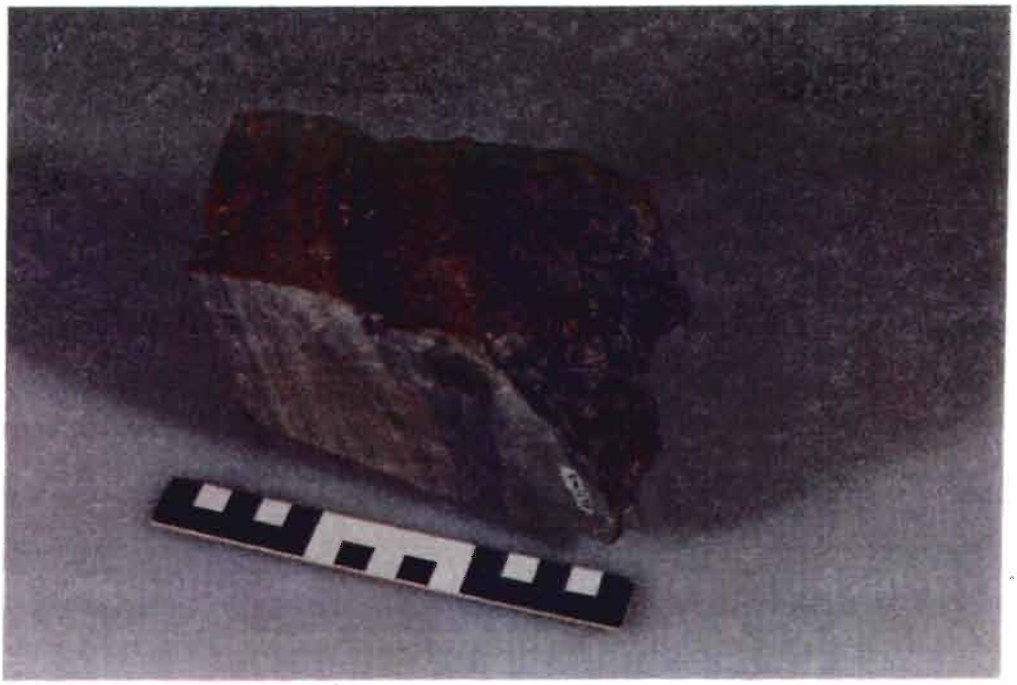


Figure 4.4 Hand specimen of banded chert, consisting of alternating layers of quartz (dark grey) and dolomite.

In general, the base metal mineralogy of the Bien Venue deposit is simple and consists of abundant pyrite and sphalerite, accompanied by variable but subordinate amounts of chalcopyrite, and minor amounts of galena and tennantite. Other minerals present in minor amounts include covellite, pyrrhotite, the copper-silver sulphide minerals jalpaite and mckinstryite, native silver, novakite and a copper-silver-zinc sulphide alteration product. The sulphides are generally distributed along the foliation as narrow bands and lenticular aggregates intercalated with layers of gangue and as disseminations within the gangue, as shown in figure 4.5.

4.2.2 Pyrite (FeS_2)

Pyrite is the most abundant sulphide found at Bien Venue and occurs in variable amounts throughout the orebody. The pyrite most commonly occurs as idiomorphic to hypidiomorphic cubic crystals that form aggregates of between 100 to 400 microns in diameter (see figure 4.6a). However one also finds a distinctly finer-grained size fraction consisting of hypidiomorphic to xenomorphic grains less than 50 microns in size. These fine-grained disseminations are concentrated in thin layers and lenses that are intercalated with gangue and coarse granular sulphides.

The recrystallisation of pyrite is a prominant feature in many samples, and indicates that metamorphism has affected the ore, with the resultant formation of pyrite porphyroblasts up to 3 mm in diameter. The pyrite aggregates also display typical "foam" or annealed textures (normally only revealed after etching) having distinctive triple-point contacts (see figure 4.6b). Remobilisation of pyrite occurs in some samples whereby pyrite fills partings and fractures in the host lithology, and these often transect the mineralogical banding.

Pyrite displays a strong tendency towards idiomorphic crystal growth, and the pyrite euhedra are corroded and partly replaced by the interstitial matrix minerals (ie. sphalerite and tennantite) producing distinctly more xenomorphic shapes that exhibit "caries" texture (see figure 4.6c).

Other significant features of the pyrite include anisotropism, which is an indication of strain effects on these grains, and growth zoning (see figure 4.6d). This type of zoning is most

Figure 4.5 Photo-enlargement of a thin-section showing sulphides distributed along the foliation as narrow bands and lenticular aggregates intercalated with layers of gangue, and as disseminations within the gangue. The sulphides consist of pyrite and sphalerite that are indistinguishable within the black areas of the photograph. Gangue material comprises fine-grained and well-foliated qtz-sericite-chlorite. Also note the crenulated foliation and microfracturing, along which sulphides have been remobilised. Magnification : X10

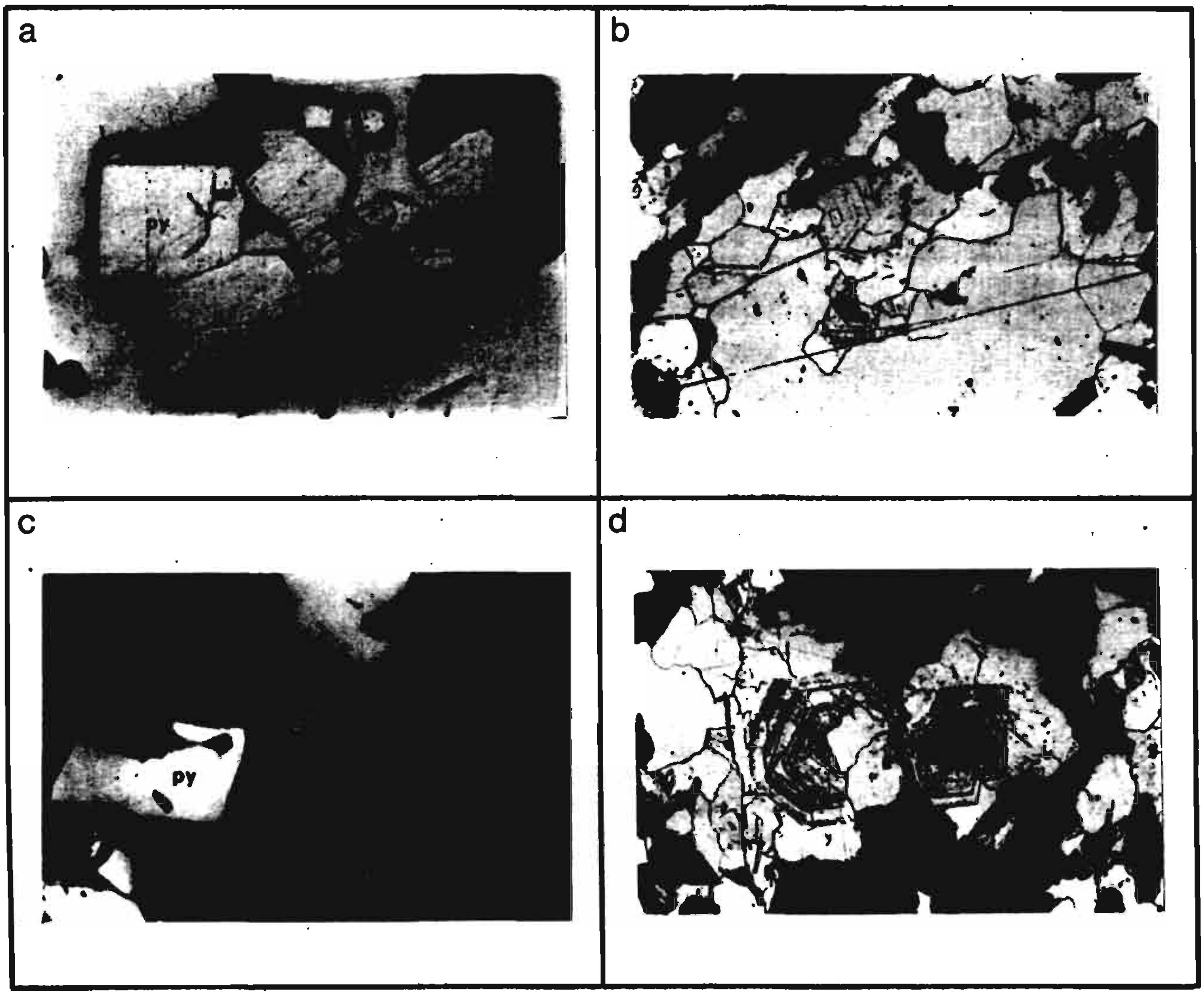


Figure 4.6 Photomicrographs of polished-sections in plane-polarised light and under oil immersion.

(a) Idiomorphic pyrite crystals (py) within a matrix of galena (gl) and sphalerite (sph). Width of field : 1mm.

(b) Pyrite aggregate, after etching with hydrochloric acid, exhibits an annealed texture with triple-point contacts.Remnants of growth zoning can also be observed. Width of field : 0.5mm.

(c) Pyrite crystal (py) that is corroded and partially replaced by tennantite (tn) to produce a typical "caries" texture. Width of field : 0.3mm.

(d) Pyrite aggregates, after etching with hydrochloric acid, exhibit distinct growth zoning. Width of field : 0.5mm.

probably the result of rhythmic interruptions or a slowing down of the growth process because of changes in the saturation of the mineralising solutions. In figure 4.6d, growth zoning having both octahedral and cubic habits can be observed. Ramdohr (1969) notes that zoning in the core of pyrite often corresponds to an octahedral habit, changing increasingly to a cubic habit in the outer zones. Further evidence of metamorphic effects on the ore is shown by the fact that the growth zoning within pyrite is incomplete (see figure 4.6b and 4.6d). Shadlun (1971) has shown that although unmetamorphosed pyrite grains commonly exhibit well-developed growth zoning, metamorphosed pyrite commonly exhibits irregular overgrowths and only incomplete zoning.

Pyrite also contains rounded to irregular-shaped inclusions (10 - 40 microns) of chalcopyrite, galena, sphalerite and pyrrhotite.

4.2.3 Sphalerite (ZnS)

Sphalerite, although less abundant than pyrite, is still a significant constituent of the ore. It occurs predominantly as aggregates of xenomorphic grains that are often intergrown with gangue (ie. mica) or is commonly interstitial to pyrite where it exhibits well-developed "caries" texture. The sphalerite is also observed as dissemminations of small irregular grains and as stringer-like ore.

A significant feature of the sphalerite is that it contains chalcopyrite in the form of randomly dispersed or crystallographically oriented blebs/inclusions less than 5 microns in size (see figure 4.7a). This form of chalcopyrite, appropriately termed "chalcopyrite disease", has commonly been ascribed to exsolution on the cooling of ores after emplacement. The structure of sphalerite is closely related to that of chalcopyrite and oriented intergrowths between these two minerals are common. Solid solution takes place at least to a limited extent at elevated temperatures, and exsolution is therefore possible during falling temperatures (Ramdohr, 1980). However, experimental studies (Wiggins & Craig, 1980; Hutchinson & Scott, 1980) have demonstrated that chalcopyrite will not dissolve in sphalerite in significant amounts unless temperatures are above 500°C. These data and the occurrence of chalcopyrite-bearing sphalerites in Zn-Pb ores in carbonates (which formed at 100 - 150°C) and in unmetamorphosed volcanogenic ores (200 - 300°C) (Craig & Vaughan, 1980), suggest that temperature dependent exsolution is not the means by which these intergrowths have formed. Barton (1978) in describing chalcopyrite

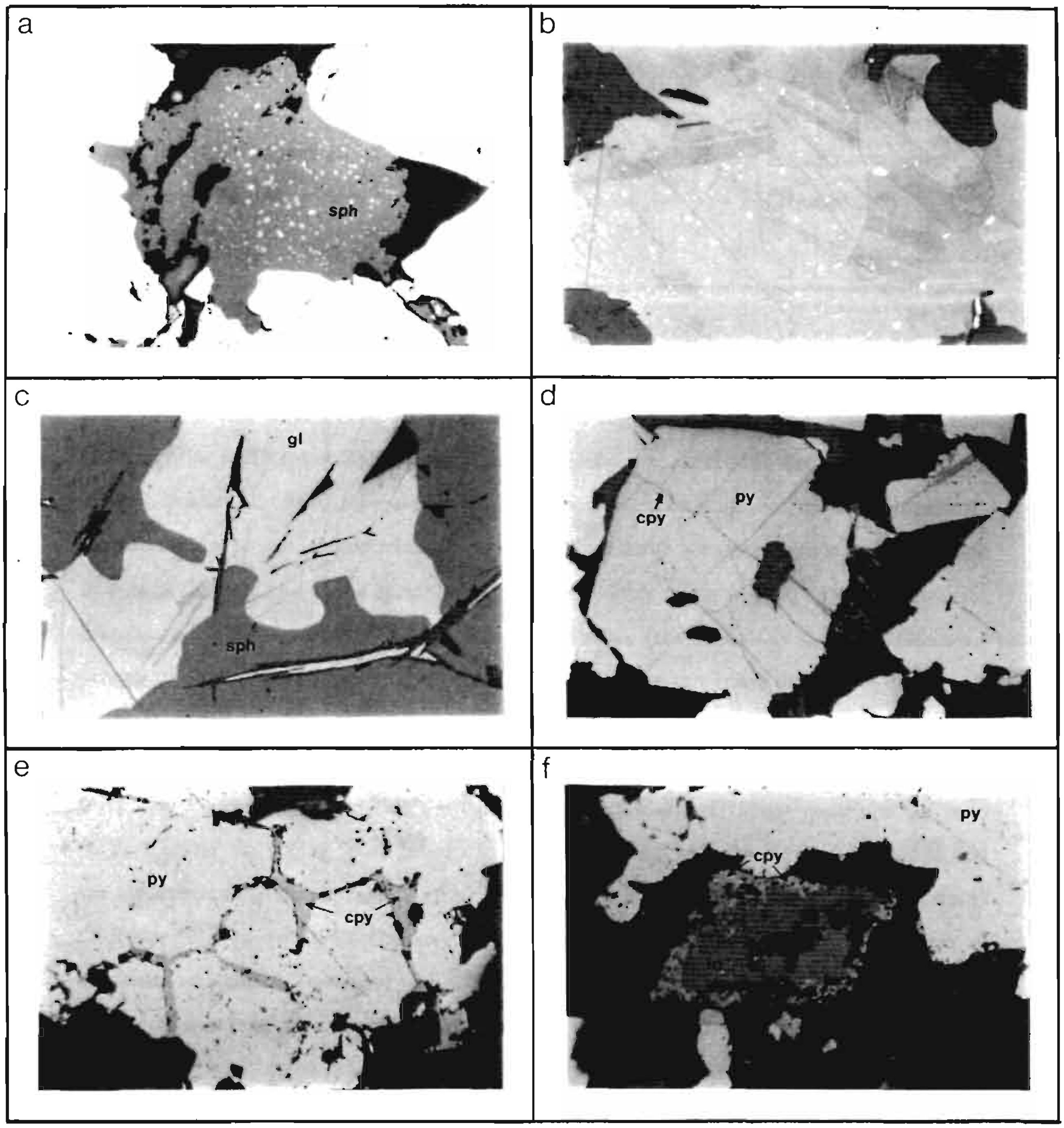


Figure 4.7 Photomicrographs of polished-sections in plane-polarised light and under oil immersion.

(a) Sphalcrite (sph) enclosing tiny blebs of chalcopyrite, a feature commonly termed "chalcopyrite disease". Width of field : 0.5mm.

(b) Twinning and recrystallisation textures within sphalerite after etching with a hypochlorite solution. Polysynthetic twin lamellae are developed in several directions, and recrystallisation has produced aggregates of equigranular grains, with blebs of chalcopyrite occurring along grain boundaries and at triple-point contacts. Width of field : 0.3mm.

(c) "Mutual boundaries" texture developed at galena (gl)/sphalerite (sph) contacts.
Width of field : 0.3mm.

(d) Chalcopyrite developed within fractures in pyrite (py). Width of field : 1mm.

(e) Chalcopyrite (cpy) developed along grain boundaries and triple-point contacts within pyrite (py). Width of field : 0.5mm.

(f) Chalcopyrite (cpy) occurs as a replacement rim around tennantite (tn). Width of field : 0.3mm.

disease concluded that the chalcopyrite results either by epitaxial growth during sphalerite formation or by replacement as copper-rich fluids reacted with the sphalerite after formation. The latter is in agreement with Eldridge et. al. (1983) who suggest that the chalcopyrite disease results from the interaction of copper-bearing fluids and pre-existing sphalerite in which the disease may consume cations such as iron to form chalcopyrite by replacement.

The sphalerite shows a variation in colour from whitish cream to yellow-orange and red, as observed from internal reflections in polished-section. The colouration of sphalerite has long been attributed to iron content, although this is a matter of contention in the geological literature. Palache et. al. (1944) state that with increasing iron content, the colour of sphalerite changes from white (pure ZnS) through yellows, oranges, reds, reddish browns and finally to black. Slack et. al. (1966) have shown that the colour of natural sphalerites is attributable to the substitution of iron and/or cobalt for zinc in the sphalerite structure, with strong absorption of light at the blue end of the spectrum imparting a reddish colour to iron - bearing sphalerite. Electron microprobe analyses of Bien Venue sphalerites (see table 4.1) show that whitish - orange sphalerites have lower iron contents (0.4 wt %) than red sphalerites (2.2 - 3.0 wt %). A direct correlation between colour and iron content is therefore evident for the Bien Venue sphalerites. This is in agreement with Hill et. al. (1985) who studied colour-banded sphalerites from Pine Point. They found that the lighter (light yellow-orange) bands contained 0,5 mole % Fe whereas the darker (dark brown) bands contained 3.2 mole % Fe, and concluded that the absorption of light in sphalerite varies in response to iron content. However, several authors (Roedder & Dwornik, 1968; Graesar, 1969; Nishiyama 1974) claim that the iron content of sphalerite cannot be correlated with the colour of the mineral. Nishiyama (1974) discounted any correlation between colour and iron content in sphalerites from the Shakanai mine, Japan, whereby yellowish-brown sphalerites had higher iron contents (0.31%) than black sphalerites (0.18%).

Structural etching of sphalerite has revealed twinning and recrystallisation textures. Twinning is abundant in sphalerite and polysynthetic twin lamellae are developed in several directions (see fig.4.7b). These twin planes are normally not visible, but are clearly revealed by etching with sodium hypochlorite solution. Etching has also revealed monomineralic aggregates of equigranular grains having typical triple - point junctions, indicating that recrystallisation or annealing has taken place. A common feature of such aggregates is the occurrence of blebs or intergranular films of chalcopyrite along the sphalerite boundaries (see figure 4.7b). This is possibly due to the redistribution of finely dispersed chalcopyrite within the sphalerite when

	WHITE INTERNAL REFLECTIONS					RED INTERNAL REFLECTIONS				
	1	2	3	4	5	6	7	8	9	10
Zn	68.8	68.7	69.4	70.0	68.3	66.3	66.6	66.3	66.0	65.3
Fe	0.4	0.4	0.4	0.4	0.5	2.6	2.3	2.2	3.0	3.0
S	30.6	30.2	30.0	30.1	31.7	30.4	30.5	30.5	31.5	31.5
Tot	99.8	99.3	99.8	100.5	100.5	99.3	99.4	99.0	100.5	99.8

Table 4.1 Electron microprobe analyses of sphalerites from Bien Venue show that a direct correlation exists between colour and iron content.

the sphalerite recrystallises during metamorphism.

4.2.4 Galena (PbS)

Although the galena content may be high in some samples, it remains a relatively minor constituent of the ore. It occurs as coarse - grained (up to 3 mm) matrix aggregates interstitial to pyrite, and in some cases, sphalerite. Galena is also present as smaller (< 200 microns) more xenomorphic grains isolated within gangue, or as thin stringers elongated parallal/sub-parallel to the foliation.
Minor amounts of galena are also seen as small (20 - 80 microns), rounded to irregular inclusions within pyrite and sphalerite.

Distinctive features of the galena include well-developed triangular cleavage pits and a "mutual boundaries" texture on contacts with sphalerite. This texture is often the reverse of "caries" texture as regards the shape of the contacts of the two minerals (see fig. 4.7c).

The distribution of galena and silver within the orebody may be closely related since galena is commonly intergrown with silver minerals.

4.2.5 Fahlore (Tetrahedrite - Tennantite - Freibergite)

Fahlore is a sack-name used to describe the minerals tetrahedrite ($Cu_{12}Sb_4S_{13}$), tennantite ($Cu_{12}As_4S_{13}$) and freibergite ($[Ag,Cu]_{12}[Sb,As]_4S_{13}$) between which a complex solid solution series exists, and whose optical properties are virtually identical. The term fahlore is therefore often used when analyses are not available for the differentiation of individual members of the solid solution series.

There is an extensive compositional range within the fahlore group of minerals and few analyses correspond to the ideal formulas, since the structure is extremely elastic in its ability to accept multiple substitutions, and iron and zinc are almost invariably present (Riley, 1974). This can be seen from electron microprobe analyses of Bien Venue fahlore (see table 4.2), where there are significant amounts of zinc and iron. These analyses indicate the presence of the As - rich member, tennantite, in the orebody.

	1	2	3	4	5	6	7	8
Cu	41.85	42.03	42.11	41.83	41.70	40.82	41.53	35.12
Zn	8.13	6.35	6.77	4.55	4.91	5.86	6.86	5.03
Sb	2.95	4.79	4.72	4.84	4.38	6.43	2.97	11.79
Ag	0.49	0.62	0.64	0.50	0.32	0.78	0.72	7.37
As	17.23	16.65	16.09	17.21	16.90	15.88	17.48	11.80
Fe	1.76	2.39	1.77	3.64	3.48	1.64	2.13	2.94
S	27.69	27.74	28.03	28.22	27.75	27.83	27.58	26.21
Tot	100.10	100.57	100.13	100.79	99.44	99.24	99.27	100.26

Table 4.2 Electron microprobe analyses of Bien Venue fahlore. The high As-content indicates the presence of the As-rich member, tennantite.

Tennantite, like galena, is a relatively minor constituent of the ore, although it can be locally abundant. The tennantite generally occurs as a matrix mineral (often together with sphalerite) interstitial to pyrite aggregates and euhedra. It is also observed as isolated xenomorphic grains within gangue and is commonly intergrown with sphalerite and chalcopyrite. The occurrence of silver mineralisation and copper-silver sulphide minerals is closely associated with tennantite and these minerals are often intergrown.

4.2.6 Chalcopyrite ($CuFeS_2$)

Chalcopyrite is present as a minor constituent but is ubiquitous in the orebody. It occurs primarily as isolated xenomorphic grains less than 300 microns in size, but its most widespread occurrence is as fine inclusions and blebs within sphalerite (ie. the so-called chalcopyrite disease). Chalcopyrite is also observed as an intergranular film developed on sphalerite - tennantite boundaries, in fractures and along triple-point contacts within pyrite (see figures 4.7d and 4.7e) and as a replacement rim around tennantite (see figure 4.7f).

4.2.7 Covellite (CuS)

The leaching and oxidation of primary (hypogene) chalcopyrite has resulted in the formation of the secondary copper mineral, covellite. The covellite is typically associated with chalcopyrite and the copper-silver sulphide minerals, where it is observed as rims or irregular masses suggesting the replacement of these former minerals. This feature is typical of the supergene breakdown of silver minerals. Covellite is also frequently developed on the boundaries between chalcopyrite and sphalerite, where it replaces the chalcopyrite.

4.2.8 Pyrrhotite ($Fe_{1-x}S$)

Pyrrhotite is a very minor constituent of the ore, and was observed only as small (< 20 microns) bleb-like inclusions within sphalerite and pyrite.

4.3 SILVER MINERALOGY

4.3.1 Introduction

The silver mineralisation encountered in the Bien Venue ore is complex. Detailed polished-section examination, supplemented by electron-microprobe analysis and x-ray diffractometry, has revealed the presence of native silver, the copper-silver sulphides jalpaite (Ag_3CuS_2) and mckinstryite ($Cu_{0.8+x}Ag_{1.2-x}S$), a copper-silver-zinc sulphide alteration product, and novakite.

These silver phases occur interstitially to pyrite, together with the matrix minerals, as irregular anhedral grains and aggregates that are generally less than 100 microns in diameter. The silver mineralisation is closely associated with both tennantite and galena. Silver minerals are only observed in samples containing abundant tennantite, where they commonly occur as intergrowths with both galena and tennantite.

4.3.2 Copper-Silver Sulphides

4.3.2.1 Introduction

The copper-silver sulphide minerals stromeyerite (CuAgS), jalpaite (Ag_3CuS_2), and mckinstryite ($Cu_{0.8+x}Ag_{1.2-x}S$) are normally associated with silver deposits, and have been described from the Echo Bay Mine, N.W.T., Canada (Robinson and Morton, 1971; Clark and Rojkovic, 1971) and from the Foster Mine, Cobalt, Ontario (Skinner et. al., 1966; Petruk et. al., 1971). These minerals have also been described from several massive sulphide deposits, although these are regarded as rare occurrences. Examples include the Godejord Deposit, Norway (Bergstol and Vokes, 1974) and the Kosaka Mine of the Kuroko district, Japan (Sato, 1969; Shimazaki, 1972; Matsukuma et. al., 1974).

At Bien Venue, the copper-silver sulphide mineralogy consists of jalpaite, mckinstryite and a copper-silver-zinc sulphide alteration product.

4.3.2.2 Jalpaite (Ag_3CuS_2)

The existence of jalpaite as a distinct mineral species has been doubted in geological literature, where it has often been listed as a variety of argentite (Schwartz, 1935; Palache et. al., 1944). However, Suhr (1955), Djurle (1958) and Skinner(1966), all working with artificial systems, definitely verified the existence of jalpaite. The mineral was first described by Breithaupt (1858), who indicated its formula as Ag_3CuS_2 on the basis of chemical analysis. This is remarkably close to those analyses of Bertrand (1872), Kalb and Bendig (1924), Grybeck and Finney (1968) and the determinations made in the present study (see table 4.3).

Jalpaite is the most abundant copper-silver sulphide phase in the Bien Venue ore and occurs as irregular, anhedral grains, generally less than 100 microns in diameter (see figure 4.8a and 4.8b). In polished-section the jalpaite is light grey in colour and shows weak anisotropism in shades of violet to light tan and pale blue-green. Jalpaite takes a bad polish, due to its softness, indicated by a highly scratched grain surface, which is a distinctive feature when compared to the other matrix minerals. Jalpaite is also light-etched (a roasting effect) when exposed to strong light.

The optical properties documented above are very similar to those of the minerals argentite and polybasite, thus initial identification was problematic. Skinner (1966) remarked that where jalpaite and argentite occur separately, or even when they are found together, they may be difficult to distinguish in polished section. However, the occurrence of jalpaite at Bien Venue has been confirmed by electron microprobe analysis (see table 4.3).

4.3.2.3 Mckinstryite ($Cu_{0.8+x}Ag_{1.2-x}S$)

Mckinstryite is present in trace amounts as fine anhedral grains generally less than 20 microns in size, that show a close association with galena, tennantite and jalpaite (see figure 4.8c and 4.8d). In polished section mckinstryite shows similar optical properties to jalpaite, a feature which initially caused some difficulties in distinguishing between them during observations of their textural relations. The mckinstryite has a slightly lighter grey colour than jalpaite and shows similar anisotropism with pale greyish blue and light brown colours. Electron microprobe analyses of the mckinstryite are shown in table 4.4.

	1	2	3	4	5	6	7	8	9	10
Cu	14.36	14.29	15.72	16.37	13.12	13.06	14.10	14.1	13.8	14.08
Ag	71.40	71.85	72.09	70.93	71.51	71.63	71.73	71.7	71.7	71.71
S	14.27	13.79	13.68	14.37	14.36	14.02	16.33	14.2	14.5	14.21
As	0.53	0.36	0.35	0.56	-	-	-	-	-	-
Zn	0.13	0.05	0.21	0.19	-	-	-	-	-	-
Fe	-	0.03	-	0.11	0.79	0.57	-	-	-	-
Tot	100.69	100.37	102.05	102.53	99.78	99.28	102.16	100.0	100.0	100.00

No. 1 - 4 Bien Venue
5 Jalpa, Mexico (Breithaupt, 1858)
6 Tres Puntas, Chile (Bertrand, 1872)
7 Altai, U.S.S.R. (Kalb and Bendig, 1924)
8 Silver Plume, Colorado (Grybeck and Finney, 1968)
9 Boulder, Colorado (Grybeck and Finney, 1968)
10 Jalpaite (Ag_3CuS_2) - theoretical

Table 4.3 Electron microprobe analyses of jalpaite from Bien Venue (No. 1 - 4) compare favourably with those of jalpaite from various localities throughout the world.

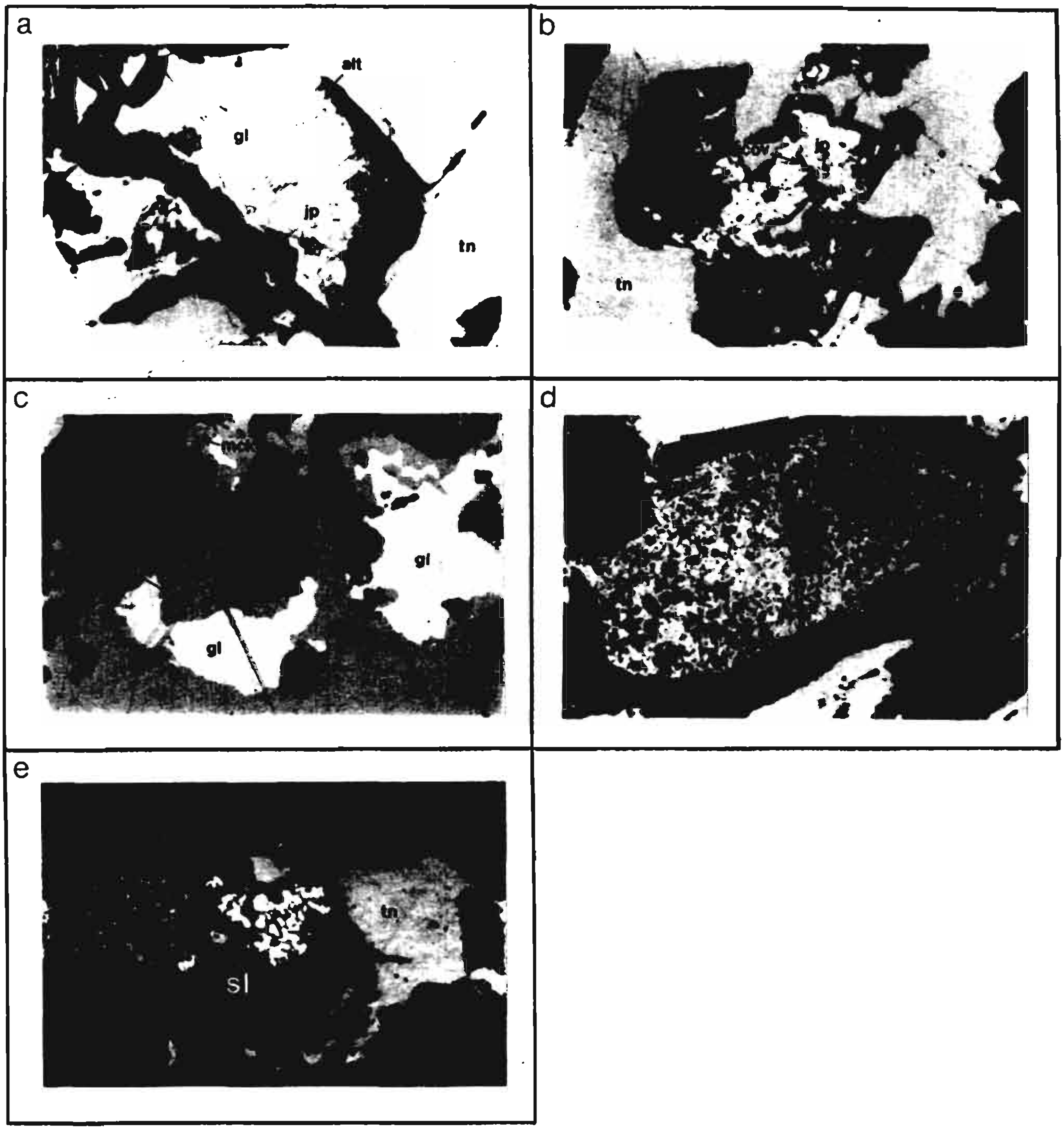


Figure 4.8 Photomicrographs of polished-sections in plane-polarised light and under oil immersion.

(a) Jalpaite (jp) in association with galena (gl), tennantite (tn) and a grey alteration phase (alt). Note the highly scratched and light-etched surface of jalpaite when compared to the surrounding minerals. Width of field : 0.2mm.
(b) Jalpaite (jp) associated with galena (white blebs in photograph), the grey altered phase (alt) and minor covellite (cov). Width of field : 0.2mm.
(c) Fine anhedral grains of mckinstryite (mck) associated with galena (gl) and tennantite (tn). Width of field : 0.2mm.
(d) Copper-silver-zinc sulphide altered grain. Light patches are silver-rich and the dark patches are zinc-rich. Width of field : 0.3mm.
(e) Fine-grained aggregate of native silver (sl) isolated within gangue. Note its high reflectance when compared to the adjacent tennantite (tn). Width of field : 0.2mm.

	1	2	3	4	5	6		8	9	10
Cu	21.19	21.72	19.73	23.5	24.9	23.9	24.63	24.59	21.6	24.5
Ag	57.83	63.83	63.78	61.5	60.0	61.0	60.32	59.95	65.1	61.6
S	15.77	14.72	14.94	15.4	15.1	15.1	15.01	14.86	13.7	14.6
Zn	0.99	0.27	0.26	–	–	–	–	–	–	–
Sb	0.79	0.65	0.46	–	–	–	–	–	–	–
As	3.23	0.36	0.62	–	–	–	–	–	–	–
Fe	0.60	0.17	0.03	–	–	–	–	–	–	–
Tot	100.40	101.72	99.82	100.4	100.0	100.0	99.96	99.40	100.4	100.7

No. 1 – 3 Bien Venue
4. Godejord (av. analysis). Bergstöl and Vokes (1974)
5. Foster Mine, Cobalt, Ontario. Skinner et al. (1966)
6. Synthetic mckinstryite. Skinner (1966)
7. Chanarcillo, Chile (av. analysis). Clark and Rojkovic (1971)
8. Echo Bay, NWT. Clark and Rojkovic (1971)
9. Echo Bay, NWT. Robinson and Morton (1971)
10. Uwamuki No.4 Deposit, Kosaka Mine. Matsukuma et al. (1974)

Table 4.4 Electron microprobe analyses of mckinstryite from Bien Venue (No. 1 – 3), as compared with those analyses of mckinstryite from other localities throughout the world.

The copper-silver sulphide minerals are very sensitive and are etched fairly easily by strong light. They therefore decompose readily under electron bombardment during electron probe microanalysis. A large beam diameter (defocussed beam), low accelerating voltage and short measuring time are therefore required to prevent decomposition. This, however, is done at the expense of consistent and repeatable results. In this regard, particular problems were experienced with mckinstryite analyses, due to the very fine grain size (<20 microns) and the tendency for the electron beam to penetrate through the mckinstryite.

4.3.2.4 Copper-Silver-Zinc Sulphide Alteration Product

Several altered grains were observed in association with the copper-silver sulphides. These altered grains appear to represent copper-silver sulphide minerals that are replaced by a grey Zn-rich phase. The resultant composite grains consist of silver-rich (typically 64% Ag, 22% Cu, 14%S) light-coloured patches and Zn-rich (typically 65%Zn, 17%Ag, 18%S) darker patches, as shown in figure 4.8d.

4.3.2.5 Discussion

It is generally accepted in the geological literature that the copper-silver sulphides, jalpaite and mckinstryite, form under supergene enrichment conditions. Grybeck and Finney (1968) described jalpaite from Silver Plume and Boulder County as probably forming at some temperature below 117°C, as suggested by the size and homogeneity of the material. Skinner (1966) points out that above this temperature jalpaite forms a body centered cubic mineral with a large compositional field. Upon cooling, the higher temperature form decomposes into a mixture of acanthite, mckinstryite and jalpaite. It is probable that the high temperature phase would separate into fairly fine-grained intergrowths. Skinner et al. (1966) in discussing the temperature relations indicated by mckinstryite at the Foster Mine, concluded strongly in favour of crystallisation below 94.4°C, the temperature above which the mineral breaks down to a two phase assemblage of jalpaite and a cation disordered compound of composition $(Cu_{0.96}Ag_{1.04})S$. Both Clark and Rojkovic (1971) and Bergstöl and Vokes (1974), working at the Echo Bay and Godejord deposits respectively, concluded from textural considerations that mckinstryite formed by the replacement of stromeyerite under supergene conditions.

The mode of occurrence and textural relations of the copper-silver sulphide minerals at Bien Venue would also indicate formation under supergene conditions.

4.3.3 Native Silver

Native silver, which is easily distinguished in polished-section by means of its high reflectance, occurs predominantly as fine-grained aggregates and grains having an average size of approximately 50 microns in diameter (see figure 4.8e). The native silver is often intergrown with the copper-silver sulphides, but occurs predominantly as isolated grains within the gangue.

4.3.4 Novakite ($[Cu,Ag]_4As_3$)

The copper arsenide, novakite, was first described by Johan and Hak (1961) from carbonate veins in mica schists and gneisses at Cerny Dul, northern Bohemia, where it forms irregular aggregates within a carbonate gangue, and is closely associated with native arsenic.

Its presence at Bien Venue is therefore not surprising, considering the amount of As-bearing tennantite within the orebody. Although novakite was not observed in polished-section, X-ray Diffractometry has shown it to be present in trace amounts.

4.4 ORE MINERAL PARAGENESIS

The growth habits, textures and associations of the minerals comprising the ore were used to determine the paragenetic sequence at Bien Venue, as described below and illustrated in figure 4.9.

Four paragenetic stages are envisaged as follows :

Stage 1 - Hypogene Ore : exhalations of the various metals and precipitation of sulphides, possibly syndepositional with the host lithology, in a paragenetic sequence indicated by primary textures. This is confirmed by the vertical zonation of sulphides in the orebody.

Stage 2 - Recrystallisation and Remobilisation : produced by metamorphic effects possibly related to shearing. Textures exhibited by sphalerite would indicate a metamorphic event subsequent to the metamorphism which produced the foliation in the host lithology. Brittle sulphides such as pyrite and sphalerite recrystallise, and the more malleable sulphides such as galena, chalcopyrite and tennantite, are remobilised. These remobilised sulphides are interstitial to, and often replace, pyrite and sphalerite.

Stage 3 - Brittle Fracturing : chalcopyrite penetrates fractures within pyrite.

Stage 4 - Supergene Enrichment : formation of the copper-silver sulphides, jalpaite and mckinstryite, which replace chalcopyrite, galena and tennantite. Covellite typically replaces chalcopyrite and the copper-silver sulphides.

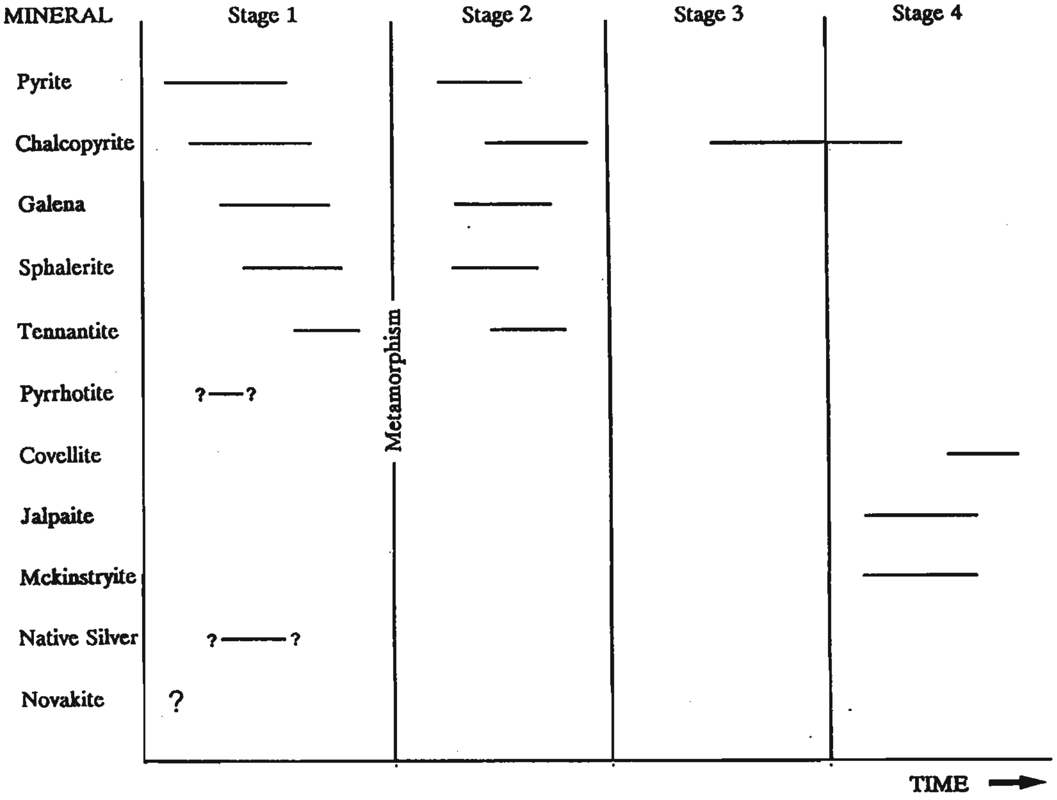


Figure 4.9 Generalised paragenesis of the massive sulphide mineralisation at Bien Venue.

CHAPTER 5

GEOCHEMISTRY

5.1 INTRODUCTION

A geochemical investigation of the metavolcanic rocks associated with the Bien Venue massive sulphide deposit was carried out in an attempt to classify the lithologies, and to define any trends that occur. Petrographic studies (chapter 3) indicate that the Bien Venue lithologies have undergone alteration and low-grade metamorphism, and therefore the chemical data must be interpreted in the context of these processes.

Where tectonism and/or metamorphism have produced a series of schistose or gneissose rocks of variable composition that might represent metamorphosed volcanic products, the magmatic or volcanogenic parentage of the series may need to be demonstrated (Floyd and Winchester, 1978). A sedimentary character or origin for the Bien Venue lithologies cannot be totally discounted, but petrographic evidence seems to indicate a volcanic/magmatic parentage for these rocks (see section 3.5).

Twenty eight whole rock samples were analysed for major, minor and trace elements by X-ray fluorescence spectrometry at the geochemical laboratories of the Geological Survey. The results are summarised in Table 5.1. Detailed information about sample collection, preparation and analytical techniques are presented in Appendix A.

Samples were collected from throughout the study area with the number of samples not necessarily representing the relative proportions of each rock type. Although care was taken to sample fresh and unweathered rocks, subsequent petrographic examination has revealed that all the Bien Venue lithologies have been affected, to a greater or lesser extent, by sericitisation, silicification, chloritisation and minor carbonatisation.

5.2 GEOCHEMICAL TRENDS

Evidence of alteration is widespread at Bien Venue and occurs in both the footwall and hanging wall sequences. Such alteration, commonly associated with massive sulphide

	UND 900	UND 901	UND 902	UND 903	UND 904	UND 905	UND 906	UND 907	UND 908	UND 909	UND 910	UND 911	UND 912
SiO_2	74.92	68.01	73.63	71.67	79.51	71.59	69.47	79.45	64.91	76.84	72.65	76.78	71.92
TiO_2	0.20	0.40	0.24	0.25	0.24	0.51	0.43	0.36	0.65	0.23	0.19	0.25	0.45
Al_2O_3	12.74	18.97	14.74	14.01	10.66	16.23	17.16	11.55	18.10	14.20	13.87	14.89	17.50
Fe_2O_3	2.26	2.03	1.08	0.80	0.89	0.06	0.96	0.69	5.51	1.58	0.83	0.87	0.75
FeO	0.00	0.00	0.74	1.36	0.76	0.84	1.16	0.00	0.00	0.00	1.20	0.00	0.00
MnO	0.06	0.08	0.10	0.12	0.07	0.05	0.04	0.07	0.19	0.04	0.11	0.02	0.06
MgO	4.21	3.57	2.78	3.88	2.79	4.44	3.88	3.58	0.86	0.92	1.89	0.92	3.61
CaO	0.00	0.15	0.31	1.00	0.07	0.00	0.00	0.00	1.22	0.00	2.15	0.00	0.00
Na_2O	0.08	0.09	0.14	0.10	0.10	0.22	0.19	0.20	0.16	0.22	0.05	0.03	0.07
K_2O	3.13	5.02	4.25	3.13	2.60	3.00	3.23	1.86	6.87	3.42	3.88	4.64	4.68
P_2O_5	0.04	0.08	0.05	0.04	0.03	0.05	0.06	0.07	0.19	0.02	0.05	0.01	0.08
Cr_2O_3	0.17	0.11	0.11	0.14	0.17	0.21	0.24	0.25	0.09	0.08	0.17	0.08	0.15
S	0.00	0.05	0.05	0.09	0.14	0.00	0.00	0.00	0.77	0.06	0.00	0.00	0.00
H_2O^+	1.52	1.32	0.93	1.54	1.18	1.98	2.58	1.60	1.32	1.62	0.70	0.73	0.72
H_2O^-	0.03	0.03	0.03	0.07	0.03	0.04	0.20	0.04	0.02	0.05	0.02	0.01	0.07
CO_2	0.47	0.51	0.67	1.24	0.57	0.06	0.11	0.05	0.03	0.05	2.09	0.10	0.09
TOTAL	99.83	100.42	99.85	99.44	99.81	99.28	99.71	99.77	100.89	99.33	99.85	99.33	100.15
Rb	97	140	142	91	75	76	80	45	45	87	98	128	128
Sr	12	24	22	17	10	32	31	19	16	29	48	3	2
Y	29	56	43	44	28	23	27	21	30	29	54	57	51
Zr	198	295	185	194	162	251	218	206	183	269	158	187	183
Nb	15	14	16	12	8	13	12	11	11	15	16	18	17
Ni	5	9	9	10	9	11	17	7	11	9	19	10	11
Zn	300	285	106	340	377	49	61	28	41	46	29	13	15
Cu	5	0	0	8	26	0	0	0	0	36	0	0	0
Pb	14	19	20	20	23	16	16	11	14	14	15	11	13
Ba	642	495	465	1384	671	97	100	35	26	345	570	6	61
Ga	14	19	19	14	12	17	17	12	12	18	16	15	15

Table 5.1 Whole rock chemical analyses for selected Bien Venue lithologies. UND 900-904 Quartz-Augen Metatuff; UND 905-910 Metarhyolite; UND 911-912 Crystal Metatuff.

	UND 913	UND 914	UND 916	UND 917	UND 918	UND 919	UND 920	UND 921	UND 922	UND 923	UND 924	UND 925	UND 926	UND 927
SiO_2	72.71	57.10	53.59	52.67	61.36	76.27	63.06	76.34	72.39	73.10	73.82	71.95	74.15	71.93
TiO_2	0.23	0.63	0.79	0.77	1.03	0.24	0.97	0.23	0.24	0.27	0.21	0.26	0.23	0.22
Al_2O_3	18.03	28.23	21.17	19.46	20.82	14.19	17.51	13.45	14.97	15.42	13.50	15.80	15.71	14.44
Fe_2O_3	1.74	7.19	6.91	6.46	5.56	1.24	4.48	1.39	2.38	1.39	1.83	1.07	2.02	0.96
FeO	0.00	0.00	1.12	1.61	0.76	0.79	1.21	0.79	0.75	0.74	1.26	0.82	0.74	1.24
MnO	0.06	0.26	0.09	0.03	0.20	0.06	0.19	0.08	0.08	0.09	0.02	0.11	0.08	0.08
MgO	1.30	0.67	5.06	6.88	1.32	1.67	1.30	1.93	2.54	2.09	3.13	3.42	1.82	2.71
CaO	0.00	0.38	0.00	0.00	1.74	0.00	1.82	0.00	0.00	0.00	0.00	0.00	0.00	0.69
Na_2O	0.02	0.03	0.00	0.00	0.01	0.04	0.04	0.31	0.02	0.36	0.02	0.17	0.08	0.04
K_2O	5.27	3.64	6.41	6.31	5.81	4.36	5.78	3.62	4.29	4.53	3.15	3.66	3.39	3.88
P_2O_5	0.04	0.25	0.07	0.09	0.44	0.03	0.50	0.04	0.04	0.03	0.03	0.04	0.03	0.05
Cr_2O_3	0.19	0.18	0.30	0.23	0.02	0.15	0.06	0.14	0.17	0.15	0.11	0.19	0.20	0.21
S	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.98	0.59	0.14	0.01
H_2O^+	0.93	0.70	3.23	2.87	0.94	0.68	0.97	0.87	1.38	0.84	1.56	1.58	1.06	1.18
H_2O^-	0.04	0.04	0.63	0.78	0.05	0.05	0.03	0.09	0.09	0.09	0.05	0.03	0.02	0.03
CO_2	0.09	0.05	0.65	1.51	0.35	0.07	1.32	0.14	0.09	0.12	0.08	0.20	0.25	1.47
TOTAL	100.65	99.35	100.02	99.67	100.41	99.84	99.25	99.42	99.43	99.22	99.75	99.89	99.92	99.14
Rb	135	85	173	193	130	154	110	135	171	158	81	109	93	93
Sr	2	0	3	3	10	12	10	7	6	18	8	17	14	17
Y	57	45	28	23	39	49	42	45	53	49	40	41	37	38
Zr	186	142	114	111	286	306	309	280	325	332	221	271	231	289
Nb	18	15	5	5	16	18	17	17	19	21	16	21	17	17
Ni	10	9	331	285	10	21	12	11	14	19	10	9	8	8
Zn	25	22	63	64	237	4313	4485	432	1643	2780	209	101	61	65
Cu	0	0	166	0	0	135	0	1	156	146	23	0	0	0
Pb	13	12	17	15	16	39	14	14	20	33	14	19	16	24
Ba	10	39	33	78	102	141	621	54	157	171	324	298	173	683
Ga	15	13	18	15	14	16	16	14	17	15	13	18	14	14

Table 5.1 continued. UND 913-914 Crystal Metatuff; UND 916-917 Feldspathic Intrusive; UND 918-923 Polymict Metatuff and Meta-agglomerate; UND 924-927 Lapilli Metatuff.

mineralisation, is well documented in the geological literature (see table 5.2, p.77), and is characterised by distinctive geochemical trends that suggest major element mobility. The mobility of elements, co-eval with alteration and metamorphism, has also been assessed by a number of authors (Condie et al, 1977; Hughes, 1982; Hallberg, 1984 and Floyd and Winchester, 1978).

In order to obtain a realistic interpretation of the geochemical data, it is considered important that the various oxide and elemental abundances are plotted against the least mobile element using variation diagrams. High Field Strength elements such as Ti, P, Zr, Y, Nb, and Ga have been considered to be immobile in many studies (Floyd and Winchester, 1978). However, Finlow-Bates and Stumpfl (1981) have shown that while Zr and TiO_2 are mostly immobile during intense hydrothermal alteration, Y, Nb and Sc can be extremely mobile. So, in view of these findings and because of its large compositional range, Zr has been selected as the immobile element best suited for the purposes of this study.

Several major oxide and trace element adundances are plotted against Zr in Figures 5.1 and 5.2. Most of these variation diagrams show a considerable scatter of data points and this can be ascribed to element mobility associated with secondary processes such as hydrothermal alteration and metasomatism. The significant features of these diagrams are described below.

The plot of silica against Zr (Figure 5.1a) shows no discernable trend, although the majority of samples plot between 70-80 % SiO_2. A weak scatter may be due to the addition of silica during silicification, as evidence of this process was noted during the petrographic studies.

Alumina shows minor scatter when plotted against Zr (Figure 5.1b) and some anomalously high values (>20%). The extensive development of sericite commonly observed in petrographic studies may account for this variability and abundance of alumina in some samples.

The plots of Na_2O versus Zr and K_2O versus Zr (Figures 5.1c and 5.1d) show considerable scatter and is interpreted in terms of element mobility. Hughes (1982) found that metasomatism played a major role in the redistribution of alkalies. He showed that the potassium/sodium ratio for unaltered rocks in the range basalt through to rhyolite increases within certain limits which he defined as the Igneous Spectrum. He concluded that samples which plotted outside this spectrum had been affected by alkali metasomatism. Analyses from Bien Venue are plotted

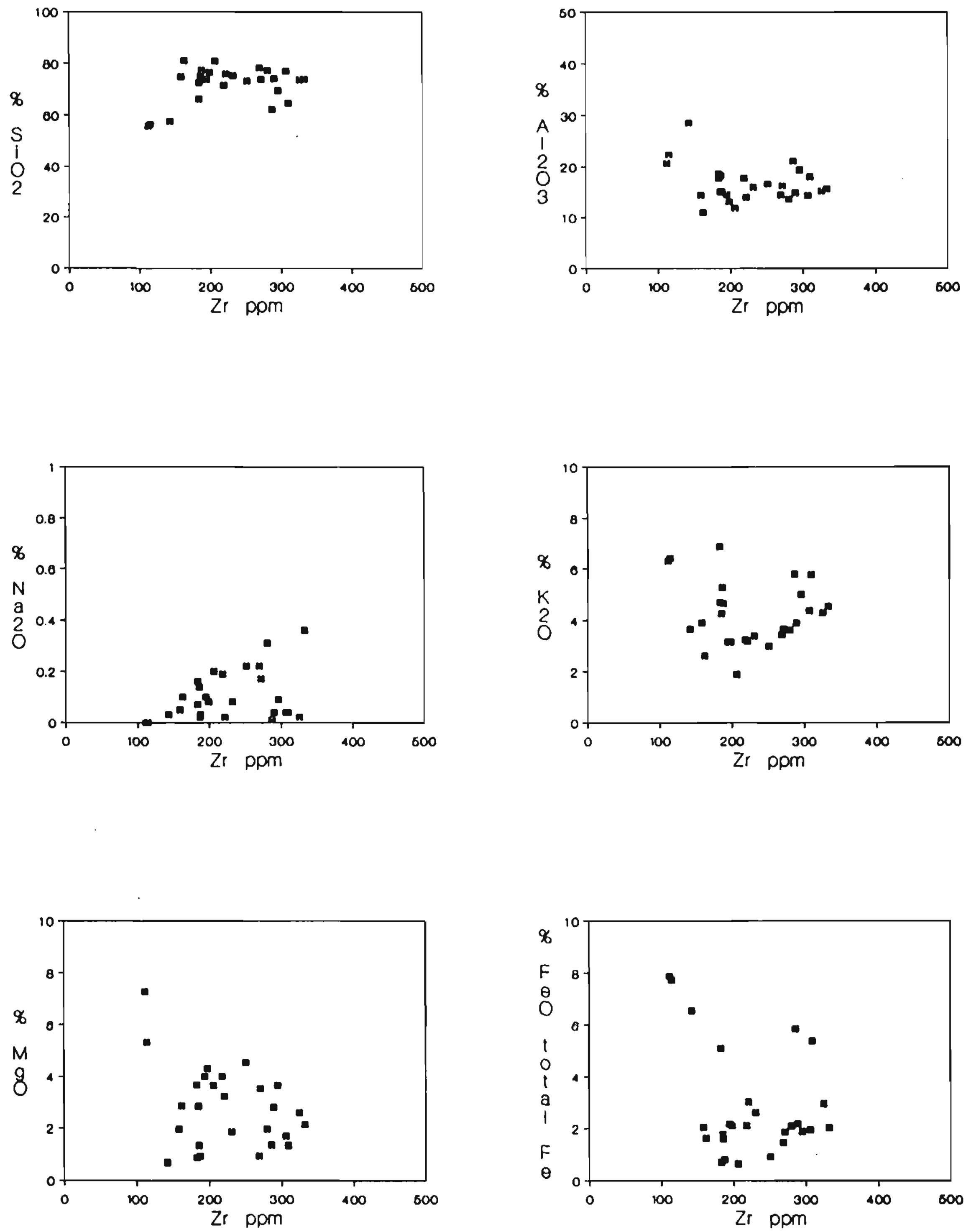


Figure 5.1 Variation diagrams showing Zr plotted against major element oxides for rock samples from the Bien Venue deposit.

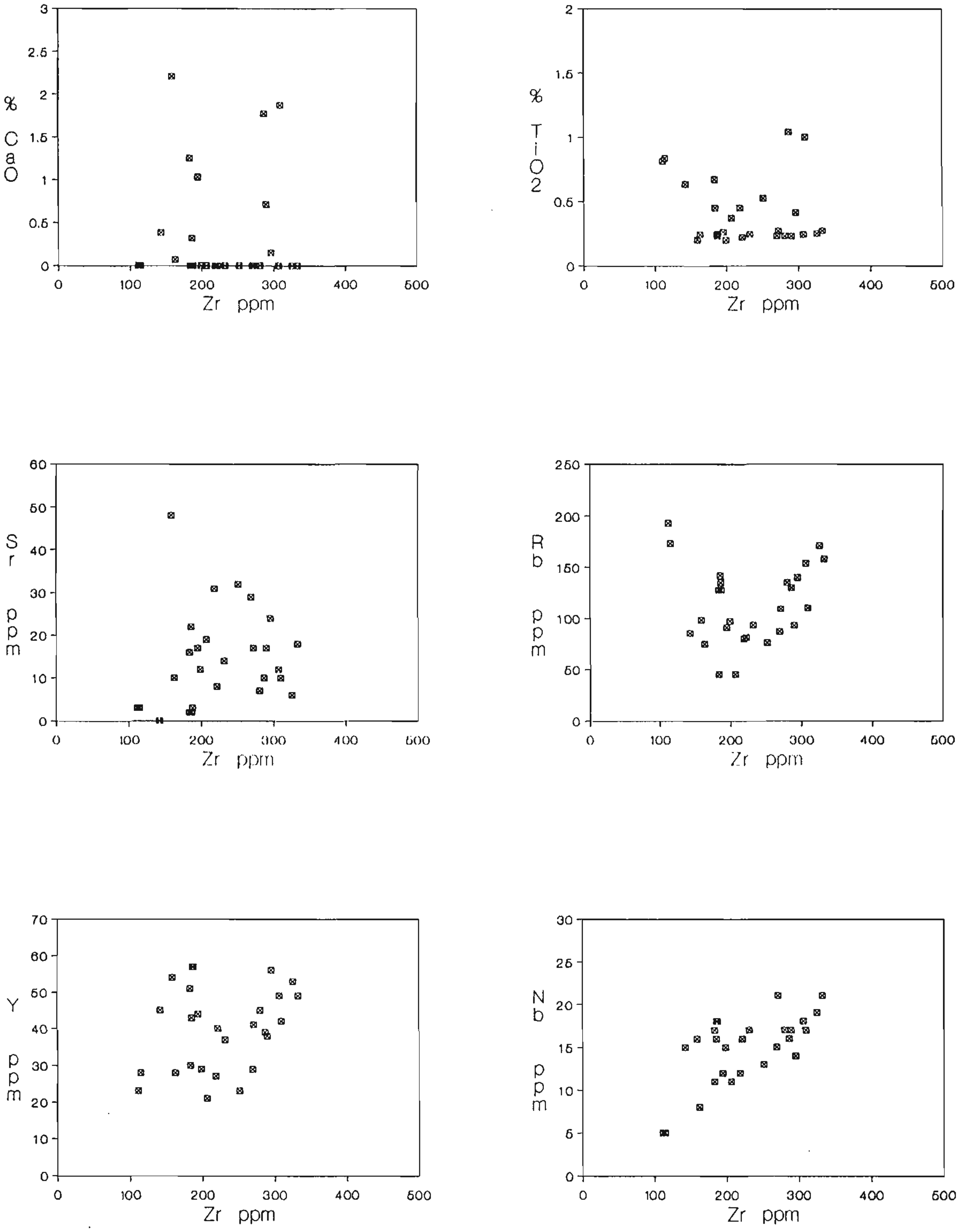


Figure 5.2 Variation diagrams showing Zr plotted against major oxides and trace elements for rock samples from the Bien Venue deposit.

in Figure 5.3, with all the samples plotting outside the Igneous Spectrum as defined by Hughes, thus apparently confirming that alkali metasomatism has played a major role in the redistribution of elements at Bien Venue.

By comparing the geochemical trends of relatively unaltered and variably altered wallrocks, Bubar and Heslop (1985) found evidence of Na_2O depletion and K_2O enrichment in the alteration zone of the Gondor massive sulphide deposit, Canada. On a plot of K_2O vs Na_2O (see Figure 5.4b) their data defined distinct fields for the unaltered and altered wallrocks. In the same figure data for the Bien Venue samples clearly define a field depicting significant sodium-depletion and potassium enrichment.

The plot of magnesium against Zr (Figure 5.1e) shows some scatter and several anomalously high values ($>5\%$). The data are not consistent with primary magmatic processes such as fractionation and the variability of the magnesium content suggests mobility of this element, with enrichment occurring in some samples. Bubar and Heslop (1985) were able to show such Mg enrichment at the Gondor massive sulphide deposit. In a plot of MgO versus SiO_2 (Figure 5.4a) their data for relatively unaltered samples plot in a field reflecting a normal magmatic differentiation trend. However, the more altered samples plot within a larger field displaced upward on the graph, suggesting that the altered rocks have undergone magnesium enrichment. On the same graph the data for the Bien Venue samples define a field that, to some extent, mimics such magnesium enrichment.

Calcium plotted against Zr (Figure 5.2a) displays considerable scatter and in many samples is totally depleted as shown by the large number of zero values. The absence of calcium in these samples may be related to the process of sericitisation. Calcium is released during sericitisation and may also be lost during the breakdown of volcanic glasses to layer silicates (ie. sericite) which do not have sites for Ca (Viereck et. al., 1982). The scatter of samples having higher values is possibly related to the presence of secondary calcium carbonate.

No trend can be observed from the scatter of data in the plot of TiO_2 against Zr (Figure 5.2b). The observed scatter could indicate titanium mobility, which may be related to the presence of sphene (Pearce and Cann, 1973) in many Bien Venue samples.

Strontium plotted against Zr (Figure 5.2c) shows considerable scatter and no discernable trend. Pearce and Cann (1973) concluded that features such as calcium depletion in low-grade

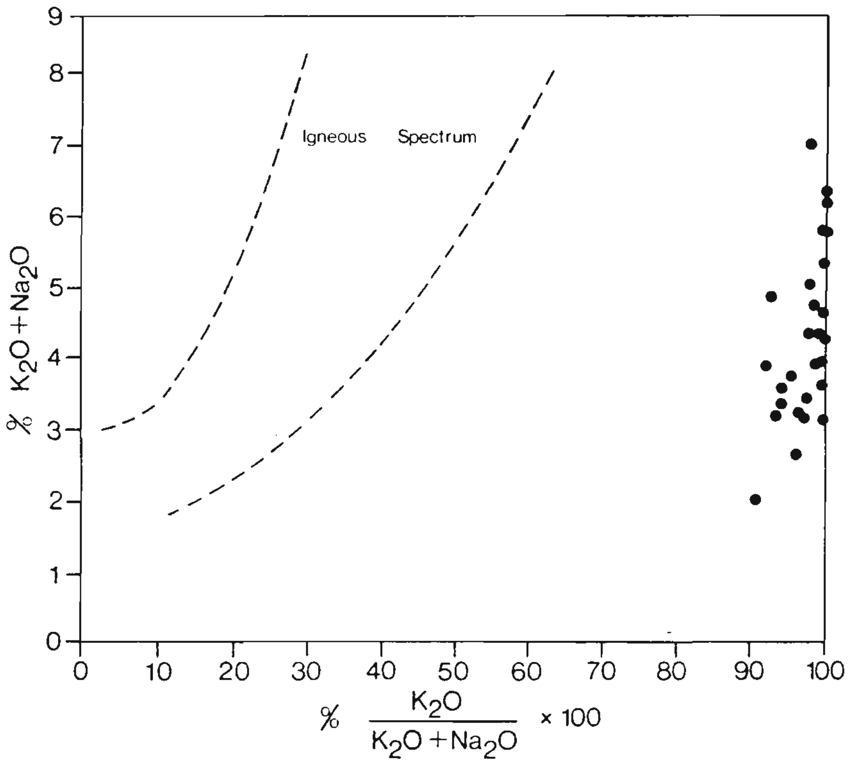


Figure 5.3 Lithologies from the Bien Venue deposit are shown plotted on the Igneous Spectrum diagram (after Hughes, 1982).

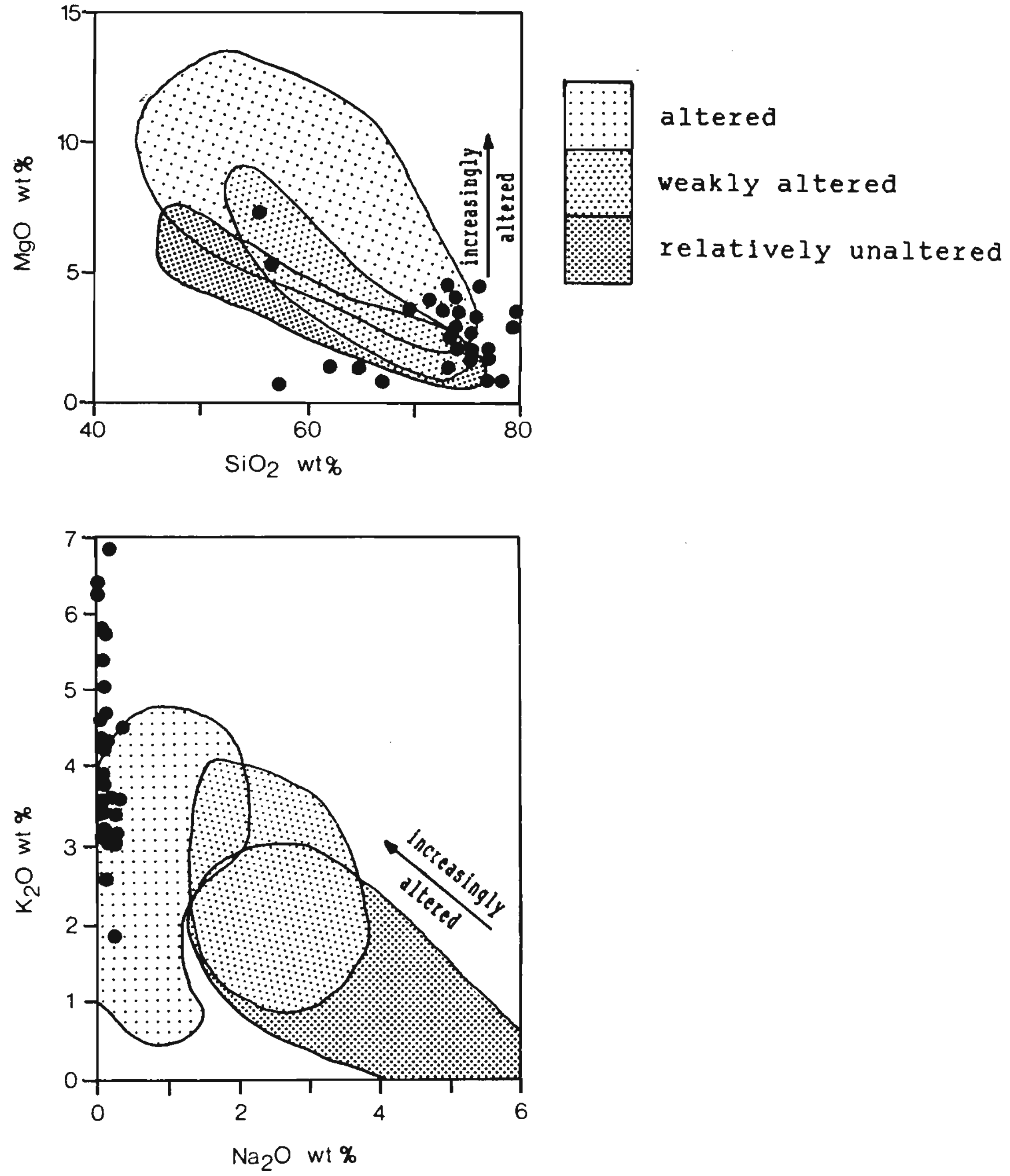


Figure 5.4 (a) Mgo versus SiO_2 diagram.
(b) K_2O versus Na_2O diagram.

Major element plots illustrating the principal geochemical trends in the altered wallrocks of the Gondor deposit (after Bubar and Heslop, 1985), compared to data for the Bien Venue lithologies. Gondor data points define distinct fields indicated by stippled areas. Bien Venue data points are represented by black dots.

metamorphism, as well as fluctuating Sr values in otherwise chemically similar rocks, are good indicators of Sr mobility.

The plot of Rubidium versus Zr (Figure 5.2d) shows some scatter but a weak general increase of Rb with increasing Zr is discernable, possibly suggesting Rb was less mobile than other incompatible elements such as Sr.

Yttrium plotted against Zr (Figure 5.2e) shows wide scatter and this may be interpreted in terms of element mobility associated with hydrothermal alteration. Although yttrium is generally considered to be immobile (Floyd and Winchester, 1978), the mobility of yttrium under conditions of extreme hydrothermal alteration has been shown by Finlow-Bates and Stumpfl (1981).

The plot of Niobium against Zr (Figure 5.2f) shows a clearly discernable concomitant increase in concentration of both elements, with only minor scatter. This is in agreement with known igneous trends and in keeping with their mutual High Field Strength characteristics.

5.3 CLASSIFICATION

The major oxides used to classify volcanic rocks are commonly mobile during hydrothermal alteration and metamorphism and are thus unsuitable for use in the present study. Such mobility for Si, Al, Mg, Ca, Na, and K is evident from the chemical analyses of the Bien Venue samples.

Oxides such as Na_2O, K_2O, MgO and FeO (ie. total iron) are commonly utilised to decide whether a suite of volcanic rocks have a tholeiitic or calc-alkaline affinity. The two broad magmatic types exhibit characteristic trends on an AFM (alkalies, total iron and magnesium respectively) diagram (Irvine and Baragar, 1971). The tholeiites demonstrate extreme iron enrichment in the early stages of fractionation followed by a later enrichment of alkalies. The calc-alkaline series show a gradual increase in alkali content from mafic to acid rocks while maintaining an essentially constant Fe/Mg ratio. The geochemical data for the Bien Venue samples plot in the calc-alkaline field of the AFM diagram (Figure 5.5). However the magmatic affinity suggested by this variation diagram may be regarded as unreliable since the data points are scattered, and in terms of the probable mobility of the elements demonstrated earlier.

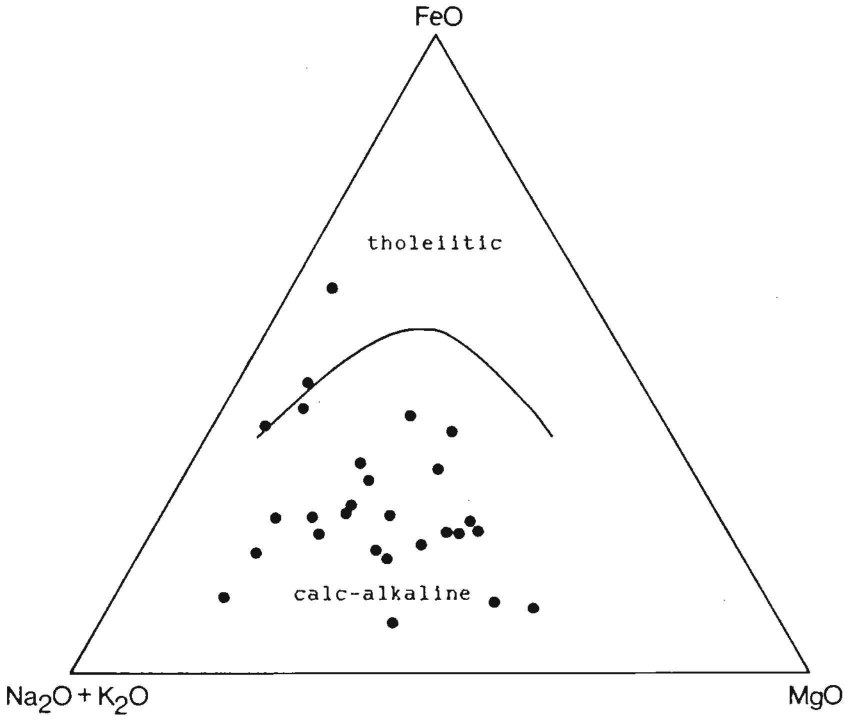


Figure 5.5 AFM diagram (after Irvine and Baragar, 1971), showing data points for the Bien Venue lithologies. Solid line represents the sub-division between tholeiitic and calc-alkaline magmas.

The samples from Bien Venue are plotted on a total alkalies versus silica diagram (Figure 5.6). This plot is commonly used to classify recent and unaltered volcanic rocks but, as can be seen from the diagram, the majority of the Bien Venue samples plot outside the designated fields making it unsuitable for classification purposes in the present study. However, the scatter does again tend to reinforce the probability that extreme element mobility has occurred in these rocks.

An attempt at a chemical classification should therefore be made in terms of High Field Strength (HFS) elements which are considered to be relatively immobile under a wide variety of conditions (Cann, 1970; Field and Elliot, 1974; Winchester and Floyd, 1977; Floyd and Winchester, 1978).

High Field Strength elements such as Ti, P, Zr, Y, Nb and Ga have a high charge : ionic size ratio and are regarded by Winchester and Floyd (1977) to be resistant to the process of alteration and metamorphism. These authors were able to demonstrate that by using these HFS elements, altered and metamorphosed volcanic suites could be characterised in terms of magma series (alkaline, sub-alkaline) and degree of differentiation (basalt - rhyolite). However they caution that differential mobility of HFS elements is possible under conditions of extreme alteration. As mentioned earlier, Finlow-Bates and Stumpfl (1981) have indeed shown that HFS elements can be mobile during extreme hydrothermal alteration associated with massive sulphide deposits.

A plot of immobile element ratios Nb/Y vs Zr/TiO_2 can be used to discriminate altered and metamorphosed volcanic suites in terms of magma series and degree of differentiation (Floyd and Winchester, 1978). Samples from Bien Venue plotted on such a diagram (Figure 5.7) indicate predominantly rhyolitic to rhyodacitic compositions. The Nb/Y ratio for the samples analysed is generally less than 0.5, indicating a sub-alkaline affinity.

5.4 DISCUSSION

The geochemical investigation of the metavolcanic rocks associated with the Bien Venue massive sulphide deposit has revealed several characteristic features that are common to many massive sulphide deposits worldwide, particularly those found in the Abitibi Belt, Canada.

The Bien Venue lithologies are rhyolitic to rhyodacitic in composition and show a calc-alkaline affinity. In this respect, they are similar to those lithologies in other volcanic belts known to

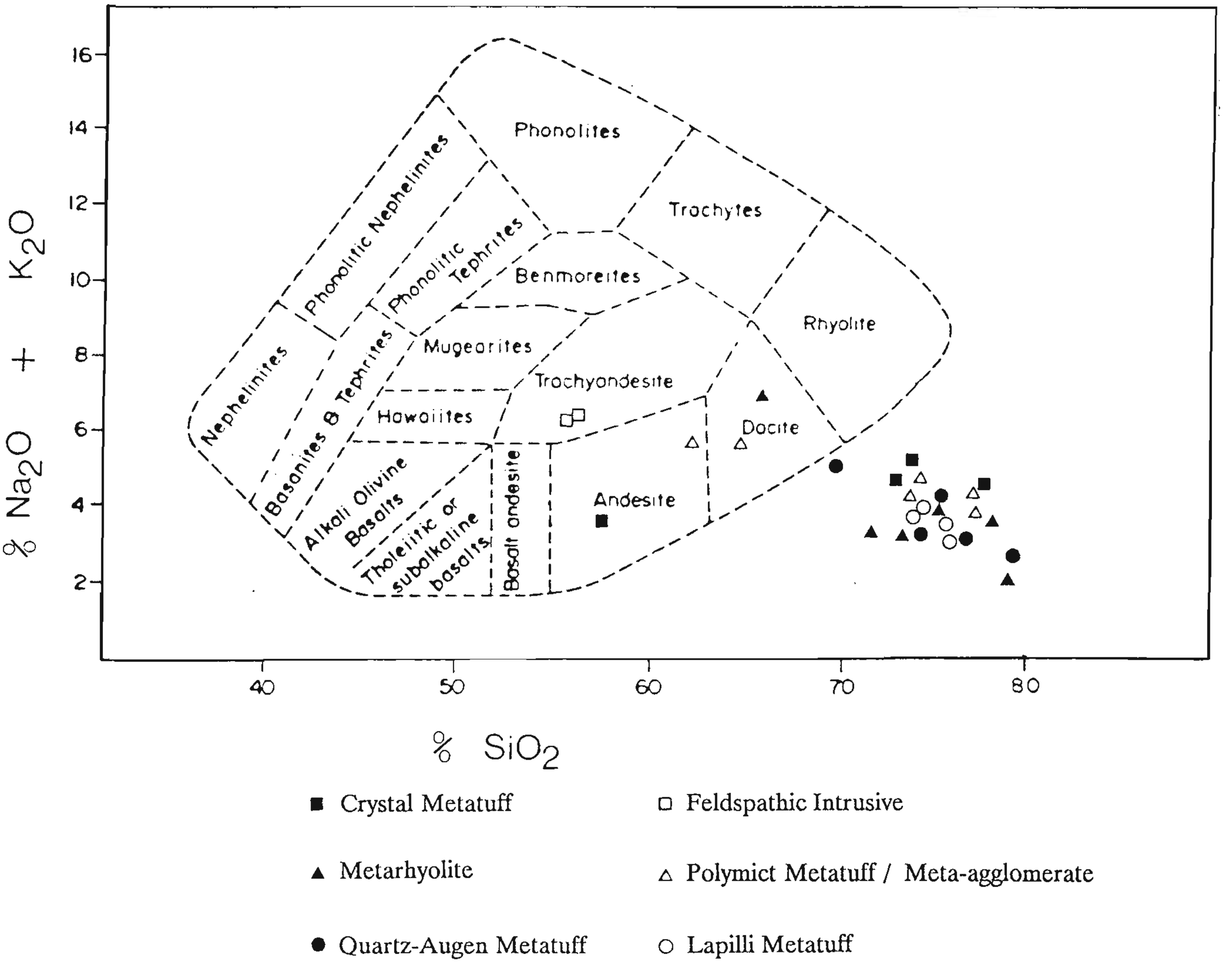


Figure 5.6 Total alkalies - silica diagram showing the delineated fields for common volcanic rocks (after Cox et. al., 1979).

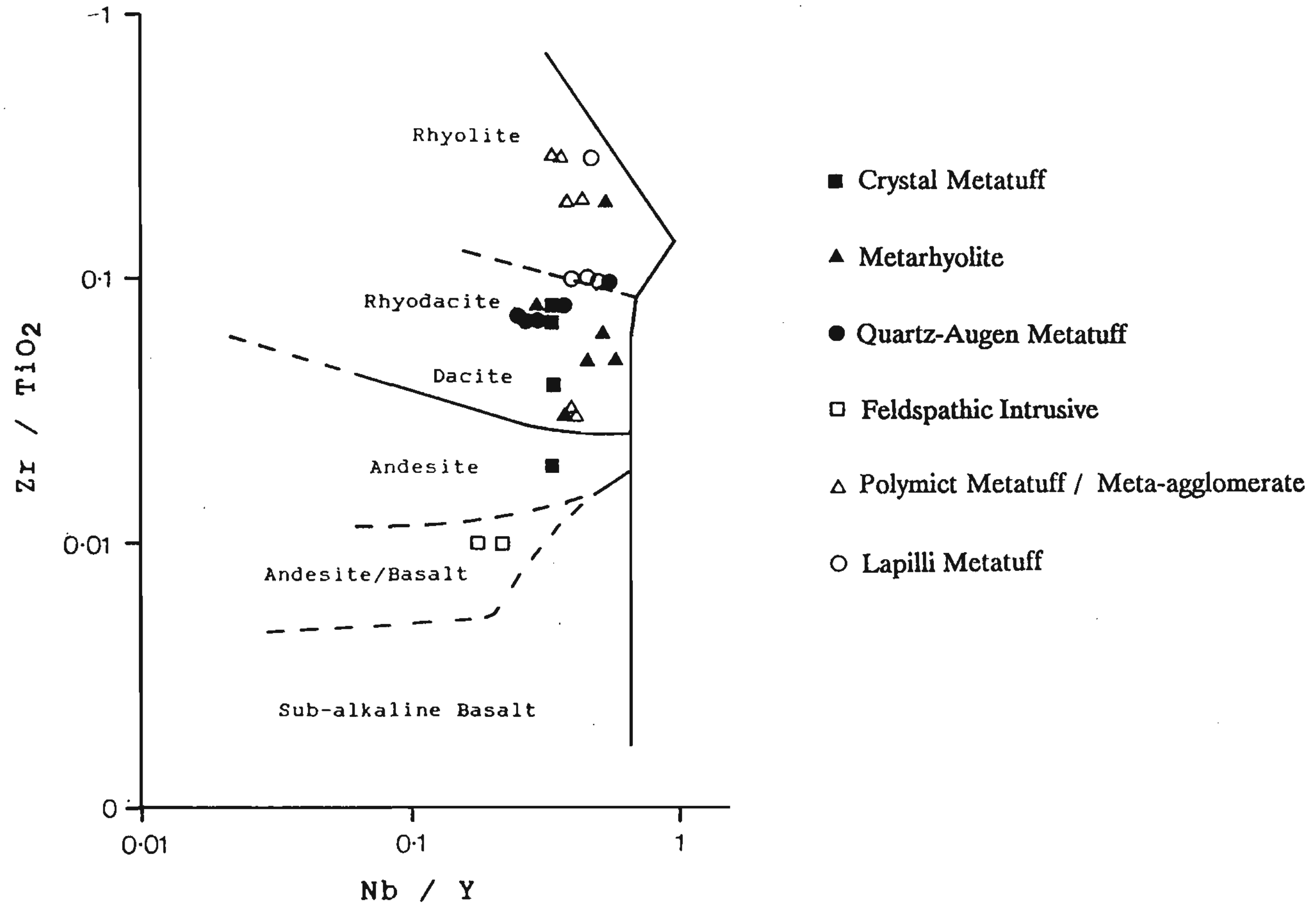


Figure 5.7 Zr/TiO$_2$ versus Nb/Y diagram showing the delineated fields for common volcanic rocks (after Winchester and Floyd, 1977).

host volcanogenic massive sulphide deposits. ie. the Abitibi Belt, Canada, where the volcanogenic massive sulphide deposits are mainly found in rhyolites or acid pyroclastics in the uppermost portion of a calc-alkaline volcanic series (Descarreaux, 1972).

The mobility of elements at Bien Venue has been clearly demonstrated, and is believed to be associated with hydrothermal alteration effects that has led to depletion and enrichment trends of certain elements in the wall-rocks of the deposit. Due to the lack of stratigraphic continuity in the vicinity of the Bien Venue deposit, it is difficult to determine absolute depletion and enrichment trends of elements, because there are no unaltered equivalent lithologies for comparison purposes. However, when compared to the least altered lithology, the crystal metatuff, SiO_2 and MgO enrichment, as well as K_2O depletion is evident. These trends are similar to those found by Bennett and Rose (1973), who studied the geochemistry of Archean felsic volcanic rocks in the Canadian Shield that were associated with massive sulphide deposits, as opposed to unrelated volcanics. These authors concluded that those volcanics most directly associated with massive sulphide deposits show a loss of alkalis and a gain of magnesia, probably related to the process of mineralisation.

These depletion and enrichment trends mentioned above are typical of the alteration zones in the vicinity of many other Archean volcanogenic massive sulphide deposits, as summarised in table 5.2. From table 5.2 it can be seen that the most significant trends are those of Na_2O and CaO depletion, and MgO enrichment. Although MgO enrichment is certainly evident at Bien Venue, Na_2O and CaO depletion is not conclusively demonstrated, in terms of the differences between the Na_2O and CaO contents of the altered wall-rocks and the relatively unaltered lithologies. However, the Bien Venue lithologies are certainly depleted in these elements when compared with Le Maitre's (1977) average unaltered rhyolite and Goodwin's (1972) average Archean rhyolite (see table 5.3), and show the same elemental abundances comparable to similar lithologies that host massive sulphide mineralisation and are known to be depleted in these elements. It is therefore possible that Na_2O and CaO depletion in the Bien Venue lithologies is a primary characteristic, and not related to the process of hydrothermal alteration.

A more intensive geochemical investigation would be required to fully understand the nature of the altered wall-rocks at Bien Venue, and to define an alteration halo around the Bien Venue mineralised zone.

DEPOSIT	ALTERATION	REFERENCE
Gondor	$-Na_2O$, $-CaO$, $+MgO$, $+K_2O$	Bubar and Heslop, (1985)
Buchans	$-Na_2O$, $-CaO$, $-K_2O$, $+MgO$, $+SiO_2$	Thurlow et al., (1975)
Skorovass	$-Na_2O$, $-CaO$, $+MgO$	Gjelsvik, (1968)
United Verde	$-Na_2O$, $-CaO$, $+MgO$, $+Fe$, $+SiO_2$	Vance and Condie, (1987)
Millenbach	$-Na_2O$, $-CaO$, $+MgO$, $+Fe$, $+SiO_2$	Knuckey et al., (1982)
Mattagami	$-Na_2O$, $+MgO$, $+Fe$	Descarreaux, (1972)
Penn	$-Na_2O$, $-CaO$, $+K_2O$, $+SiO_2$	Peterson, (1988)
Louvem	$-Na_2O$, $-CaO$, $+MgO$	Spitz and Darling, (1975)
Lac Dufault	$-Na_2O$, $+MgO$	Sakrison, (1966)
Poirier	$-Na_2O$, $+MgO$	Descarreaux, (1973)
Brunswick No. 12	$-Na_2O$, $-CaO$, $-K_2O$, $+MgO$, $+Fe$	Goodfellow, (1974)
Mattabi	$-Na_2O$, $-CaO$, $+MgO$, $+Fe$	Franklin et al., (1975)
Crandon	$-Na_2O$, $-CaO$, $+Fe$, $+SiO_2$	Lambe and Rowe, (1987)

Table 5.2 Summary of alteration around volcanogenic massive sulphide deposits worldwide, as described in the geological literature.

	LE MAITRE (1977)		GOODWIN (1972)	BIEN VENUE LITHOLOGIES					
	Average Rhyolite	Average Rhyodacite	Average Archean Rhyolite	Average Qtz-Bleb Tuff	Average Rhyolite	Average Crystal Tuff	Average Feldspathic Intrusive	Average Polymict Tuff	Average Lapilli Tuff
SiO_2	72.82	65.55	72.90	75.19	74.21	70.29	56.05	71.44	74.76
TiO_2	0.28	0.60	0.23	0.27	0.41	0.39	0.82	0.51	0.24
Al_2O_3	13.27	15.04	14.50	14.54	15.55	19.84	21.43	16.30	15.23
Fe_2O_3	1.48	2.13	1.20	1.44	1.64	2.66	7.04	2.79	1.51
FeO	1.11	2.03	1.29	0.58	0.55	-	1.45	0.85	1.04
MnO	0.06	0.09	0.07	0.09	0.08	0.10	0.06	0.12	0.07
MgO	0.39	2.09	0.68	3.52	2.66	1.65	6.31	1.83	2.84
CaO	1.14	3.62	1.20	0.31	0.58	0.10	-	0.61	0.18
Na_2O	3.55	3.67	3.80	0.10	0.17	0.04	-	0.13	0.31
K_2O	4.30	3.00	2.10	3.63	3.71	4.56	6.36	4.73	3.52
P_2O_5	0.07	0.25	0.18	0.05	0.07	0.10	0.09	0.18	0.04
Cr_2O_3	N/A	N/A	-	0.14	0.18	0.15	0.28	0.12	0.18
S	N/A	N/A	-	0.06	0.13	-	-	-	0.43
H_2O^+	1.10	1.09	0.71	-	-	-	-	-	-
H_2O^-	0.31	0.42		-	-	-	-	-	-
CO_2	0.08	0.21	0.89	-	-	-	-	-	-
Total	99.96	99.79	99.75	99.92	99.94	99.88	99.89	99.61	100.35

Table 5.3 Comparison between the average analyses of individual Bien Venue lithologies as derived from this study, and those of fresh, unaltered rhyolites and rhyodacites worldwide, as presented by Le Maitre (1977) and Goodwin (1972).

CHAPTER 6

GLOBAL OCCURRENCES OF VOLCANOGENIC EXHALATIVE SULPHIDE DEPOSITS : GENERAL CHARACTERISTICS AND CLASSIFICATION.

6.1 INTRODUCTION

The aims of this chapter are as follows. Firstly, to prove the volcanogenic exhalative nature of the Bien Venue deposit, by showing that the characteristic features common to all volcanogenic exhalative sulphide deposits are present at Bien Venue. Secondly, to classify the deposit in terms of present day classification schemes, by studying these schemes and how they can be applied to Bien Venue.

The terminology "volcanogenic exhalative" is used to describe a particular variety of base metal sulphide deposit. The term "volcanogenic" signifies a volcanic host-rock association and "exhalative" refers to exhalations of hydrothermal solutions, normally under marine conditions. The term "volcanogenic exhalative" therefore refers to those base metal sulphide deposits that are considered to have formed in recurrent episodes of hydrothermal sea-floor activity, during prolonged periods of subaqueous volcanism (Horikoshi, 1969).

6.2 GENERAL CHARACTERISTICS

The volcanogenic exhalative sulphides comprise a major family of ore deposits, the members of which share a set of common identifying characteristics. Although not all of these characteristics are present in each deposit, they are well described in the literature (Sangster, 1972; Hutchinson, 1973, 1980; Sangster and Scott, 1976; Klau and Large, 1980) and are summarised below :

- irregularly shaped but stratabound lenses of massive and often banded sulphide mineralisation.
- relatively simple ore mineralogy dominated by pyrite, sphalerite, chalcopyrite and galena, the relative proportions of which are variable. Gold and silver may also be present.
- beneath the stratabound ore there is often a stockwork zone consisting of cross-cutting mineralisation.

- an extensive alteration zone occurs below the mineralisation. The footwall host rocks are usually Mg-metasomatised (with an inner chlorite and an outer sericite zone) and Na-depleted.
- deposits are commonly zoned, both vertically and laterally, with respect to their metal and barium contents; copper is invariably found at the stratigraphic base in an upward Cu-Zn-Pb-Ba sequence.
- ferruginous (and sometimes manganiferous) cherts commonly overlie the stratabound sulphide mineralisation.
- in felsic terrains, the deposits are spatially related to rhyolitic volcanics that are characteristically brecciated or agglomeratic; these normally form the immediate footwall.

Difficulties in identification may arise if the primary characteristics are disrupted and complicated to varying degrees, or even obliterated, by subsequent metamorphism (Vokes, 1969), thus obscuring evidence of a volcanogenic exhalative origin.

The Bien Venue deposit bears comparison with many deposits of the volcanogenic exhalative type in various parts of the world (see Table 6.1), particularly the Pre-Cambrian deposits of the Canadian Shield and the Kuroko-type deposits in Japan. However, one important feature of volcanogenic exhalative sulphide deposits was not observed at Bien Venue, namely a stockwork zone below the mineralisation. This could be explained in terms of the existing configuration of the orebody (refer to figure 2.3, p.11). It is possible that only a portion of the original orebody has been preserved. The stockwork zone and associated mineralisation could therefore have occurred as an extension to the present orebody, and have either been removed by the present level of erosion or faulted out.

Notwithstanding the stockwork zone problem, the geological setting of the Bien Venue deposit, together with the nature of its mineralisation, suggest that it an example of a volcanogenic exhalative deposit, syndepositional with the host lithology.

6.3 CLASSIFICATION SCHEMES

Despite the unifying similarities amongst volcanogenic exhalative deposits, there are readily recognisable differences between the various deposits, which serve to classify the deposits into

Volcanogenic Exhalative Deposits - General Geolgical Features	Present At Bien Venue?
• stratabound massive & banded/laminated sulphide mineralisation	yes
• dominant sulphides: pyrite, sphalerite, chalcopyrite & galena	yes
• stockwork zone below the ore	?
• alteration zones within host rocks ie. Mg-metasomatism, Na-depletion	yes
• stratigraphic ore zonation : Cu(base)- Zn-Pb-Ba(top)	yes
• cherts overlie the mineralisation	yes
• in felsic terrains, deposits are spatially related to rhyolitic volcanics	yes

Table 6.1. **Summary of the common identifying characteristics of volcanogenic exhalative deposits and whether they are present at Bien Venue.**

distinct types. Historically, the classification of volcanogenic massive sulphide deposits has been approached in several ways by various authors, as summarised in Table 6.2, and outlined below.

Hutchinson (1973) proposed a threefold, compositionally - based classification system, using environmental factors as secondary classification criteria:

1. zinc-copper deposits, which are principally Archean in age and volcanic hosted.
2. lead-zinc-copper-silver deposits, which occur in both volcanic and mixed volcanic/sedimentary strata of predominantly Proterozoic and Phanerozoic age.
3. cupreous-pyrite deposits, which are associated predominantly with mafic and ultramafic volcanic rocks, principally of Phanerozoic age.

Sangster and Scott (1976) proposed a division into three types on the basis of environment of deposition (ie host lithology):

1. volcanic-associated
2. sedimentary-associated
3. mixed volcanic and sedimentary associated

Sawkins (1976) suggested a classification based upon the tectonic setting and associated volcanics:

1. Cyprus type deposits - associated with spreading ocean or back-arc spreading ridges, and with basic volcanics, usually ophiolites.
2. Besshi type deposits - associated with the early part of the main calc-alkaline stage of island arc formation.
3. Kuroko type deposits - associated with the later stages of island arc formation and felsic volcanics.

Solomon (1976) used a compositional approach to classification and divided the volcanic-hosted deposits into three groups according to their ore content:

1. zinc-lead-copper
2. zinc-copper
3. copper

Klau and Large (1980) also used a compositional approach by classifying deposits according to the dominant host lithology, as follows:

1. mafic volcanic-association

Hutchinson (1973)	Zn–Cu (principally Archaean) Pb–Zn–Cu–Ag (predominantly Proterozoic and Phanerozoic) Cupreous pyrite (principally Phanerozoic)
Sangster and Scott (1976)	Predominantly volcanic-associated Predominantly sedimentary-associated Mixed association of above
Sawkins (1976)	Kuroko type Cyprus type Besshi type Sullivan type
Solomon (1976)	Volcanic-hosted divided into: Zn–Pb–Cu Zn–Cu Cu
Klau and Large (1980)	Mafic volcanic-associated Felsic volcanic-associated Sedimentary types
Hutchinson (1980)	Primitive Zn–Cu Polymetallic Zn–Pb–Cu Kieslager Cu–Zn Cupreous Pyrite Cu

Table 6.2. Summary of recent attempts to classify volcanogenic massive sulphide deposits.

2. felsic volcanic-association
3. sedimentary association

Two principal approaches to classification have thus emerged. Firstly, a division based on geological environment, as interpreted through host-rock lithology (Sangster and Scott; Sawkins; Klau and Large), and secondly, an ore composition approach (Hutchinson; Solomon). Each classification method has its advantages. Classification based on host-rock lithology is useful in that the principal stratigraphic elements of any deposit are readily observed and recorded on geological maps. Alternatively, an ore composition classification can be precisely determined since ore compositions are usually well known for any economically significant occurrence.

Hutchinson (1980) combined these two classification methods, and used ore composition, tectonic setting and host rock lithology to divise a fourfold classification for volcanogenic sulphides as follows:

1. Primitive type
2. Polymetallic type (or Kuroko type)
3. Cupreous Pyrite type (or Cyprus type)
4. Kieslager type (or Besshi type)

The essential criteria used in Hutchinsons classification scheme are summarised in Table 6.3. This classification is the most useful currently available and forms the basis for the classification of the Bien Venue deposit.

6.4 GEOLOGY OF THE MAJOR VOLCANOGENIC EXHALATIVE SULPHIDE TYPES

6.4.1 Primitive Type

The base metal mineralisation of this type consists of zinc and/or copper, with only minor amounts of lead. Gold and silver usually accompany zinc-rich sulphides, with gold being relatively more important in copper-rich deposits (Hutchinson, 1973).

The host volcanic rocks include broadly differentiated suites ranging from basalts through andesites and dacites to rhyolites, having both calc-alkaline (Wilson et. al., 1965; Goodwin and Ridler, 1970) and tholeiitic (Baragar, 1968) affinities. Intercalated with the volcanic lithologies

Type	Volcanic rocks	Clastic sedimentary rocks	Depositional environment	General conditions	Plate tectonic setting	Known age range
Besshi (=Kieslager) Cu−Zn±Au±Ag	Within plate (intraplate) basalts	Greywackes and other turbidites	Deep marine sedimentation with basaltic volcanism	Rifting	Epicontinental or back-arc	Early Proterozoic Palaeozoic
Cyprus Cu(±Zn)±Au	Ophiolitic suites, tholeiitic basalts	Minor or absent	Deep marine with tholeiitic volcanism	Tensional, minor subsidence	Oceanic rifting at accreting margin	Phanerozoic
Kuroko Cu−Zn−Pb ±Au±Ag	Bimodal suites, tholeiitic basalts, calc-alkaline lavas and *pyroclastics*	Shallow to medium depth clastics, few carbonates	Explosive volcanism, shallow marine to continental *sedimentation*	Rifting and regional subsidence, caldera formation	Back-arc rifting	Early Proterozoic Phanerozoic
Primitive Cu−Zn±Au±Ag	Fully differentiated suites, basaltic to rhyolitic lavas and pyroclastics	Immature greywackes, shales, mudstones	Marine, < 1 km depth. Mainly developed in greenstone belts	Major subsidence	Much debated: fault-bounded troughs, back-arc basin?	Archaean—early Proterozoic

Table 6.3. Summary of volcanic - associated massive sulphide deposit types. (after Hutchinson, 1980)

are various sedimentary rocks, particularly chemical sediments such as cherts and various facies of iron-formation, and immature greywackes (Goodwin and Ridler, 1970).

The tectonic environment in which these volcanics were deposited is typical of an early eugeosynclinal orogenic event. This clearly involved major subsidence on a very large scale with deposition of two or more cycles of differentiated mafic to felsic subaqueous volcanic rocks (Ridler, 1970).

The best examples of the Primitive type are of Archean age. These include the numerous deposits in the Noranda (Spence and de Rosen-Spence, 1975), Timmins (Walker et. al., 1975) and Matagami Lake (Roberts, 1975) areas of the Keewatin greenstone belts on the Canadian Shield.

6.4.2 Polymetallic Type (Kuroko Type)

This type of volcanogenic sulphide deposit is abundant in both lead and zinc, contains minor copper, and yields important silver rather than gold. Carbonate-rich gangue is often present in older examples of these ore deposits (Bennett, 1965), and sulphate gangues, including both bedded gypsum-anhydrite strata and barite, are often found in younger deposits (Matsukuma and Horikoshi, 1970).

The volcanic rocks associated with this type consist of intermediate and felsic lavas, along with porphyritic subvolcanic intrusions, breccias and pyroclastic rocks. The petrochemical affinities of these volcanic rocks appear to be calc-alkaline (Tatsumi et. al., 1970). The deposits are also closely associated with a particular phase of explosive rhyolitic volcanism and intrusive rhyolitic domes (Horikoshi, 1969). Epiclastic sedimentation was extensive during the deposition of the volcanics. As a result, epiclastic sedimentary rocks predominate over chemically deposited cherts and iron-formations, and volcanoclastic sedimentary rocks, although these are still present (McAllister, 1960).

The oldest Polymetallic type deposits occur in Proterozoic rocks, of which the Errington and Vermilion Lake deposits (Franklin et. al., 1981) within the Sudbury Basin, Ontario, are examples. The Polymetallic type is equally important in earlier Paleozoic time, with the numerous large deposits of the Bathurst District, New Brunswick (Davies and McAllister, 1980) being good examples. However, the best examples of the Polymetallic type are the Tertiary Kuroko deposits from the Kuroko district of Japan.

The Kuroko deposits are undoubtedly among the best examples of volcanogenic exhalative mineralisation since they are well preserved, show little deformation and retain significant primary features. For these reasons, the geology of Kuroko deposits has been frequently reviewed and detailed descriptions can be found in Sato (1977) and Ohmoto and Skinner (1983). The characteristic features of a typical Kuroko deposit are depicted in Figure 6.1 and outlined below:

- a stratabound unit of massive barite commonly overlies the massive sulphide mineralisation.
- notable absence of pyrrhotite from the sulphide mineralisation.
- vertical (upward) zonation of Cu-Zn-Pb-Ba mineralisation.
- an anhydrite-gypsum assemblage may occur beside or beneath the stratiform massive sulphides.
- close spatial relationship to rhyolite/dacite domes.

6.4.3 Cupreous Pyrite Type (Cyprus Type)

This type of volcanogenic sulphide deposit is characterised by copper-rich mineralisation. These deposits contain virtually no lead, only minor zinc, and have significantly higher proportions of gold relative to silver.

The geological setting of the Cupreous Pyrite deposits is directly related to the presence of ophiolites, which are usually interpreted as obducted fragments of oceanic crust (Gass, 1977). The sulphide mineralisation occurs as lenses of massive pyrite-chalcopyrite ore, hosted by spilitised basaltic pillow lavas of mafic-ultramafic composition (Hutchinson, 1973), that resemble modern oceanic tholeiites (Smitheringdale, 1972). Unlike both of the other types of deposit, felsic volcanic rocks are rare or absent, and the associated sedimentary rocks (chemically deposited cherts, ironstones and manganstones) are volumetrically insignificant.

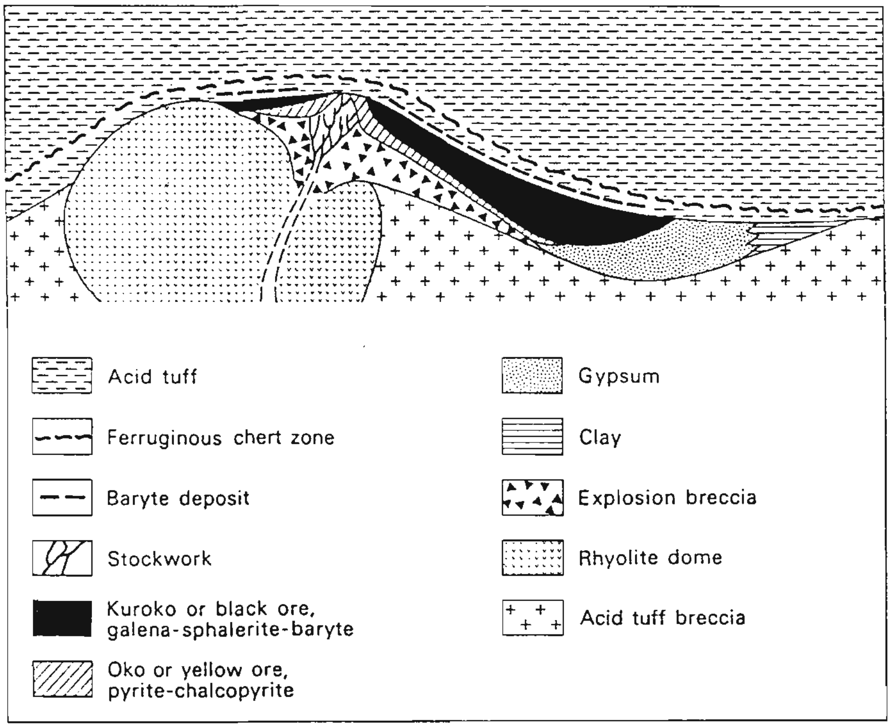


Figure 6.1. Schematic section through a typical Kuroko deposit. (after Sato, 1977)

The tectonic depositional environment of the ophiolitic lava sequence has been interpreted by Gass (1970), to be the product of minor subsidence, probably tension-induced and the result of crustal attenuation and rifting.

The Cupreous Pyrite type deposits are Phanerozoic in age, appearing first in early Paleozoic ophiolite complexes such as in the Notre Dame Bay and Bay of Islands areas in Newfoundland (Upadhyay and Strong, 1973). However, the best examples are Mesozoic in age, and include the numerous deposits of Cyprus (Constantinou and Govett, 1973).

A typical Cyprus deposit (see Figure 6.2) consists of a footwall stringer zone of cross-cutting pyrite and chalcopyrite mineralisation, that extends for hundreds of metres below the deposit. This zone is overlain by massive stratiform sulphides which may be banded and often brecciated. These massive sulphides are overlain by the so-called 'ochre' horizon, a zone of mixed iron sulphide and oxide-rich sediments.

6.4.4 Kieslager Type (Besshi Type)

This type of deposit is abundant in both copper and zinc, and often has associated gold and silver. In many respects, this type is intermediate in geological characteristics to the Primitive and Cupreous Pyrite types (Hutchinson, 1980). The Kieslager or Besshi type is associated with tholeiitic volcanic or plutonic rocks within thick greywacke sequences, and is characterised by its strong sedimentary affinities and the absence of significant differentiated calc - alkaline or felsic lithologies.

Deposits of the Kieslager type appear to be relatively late in geologic time, with good examples known only in rocks of late Precambrian and Paleozoic age. Notable examples occur in the Amphibolite Belt of South West Africa (Goldberg, 1976) and at the Besshi and neighbouring deposits in Japan (Kanehira and Tatsumi, 1970).

6.5 CLASSIFICATION OF THE BIEN VENUE DEPOSIT

The classification of the Bien Venue deposit has been attempted in terms of the classification scheme suggested by Hutchinson (1973, 1980). Hutchinson's classification scheme is based on differences in metal content, associated lithologies, age and depositional environment, and

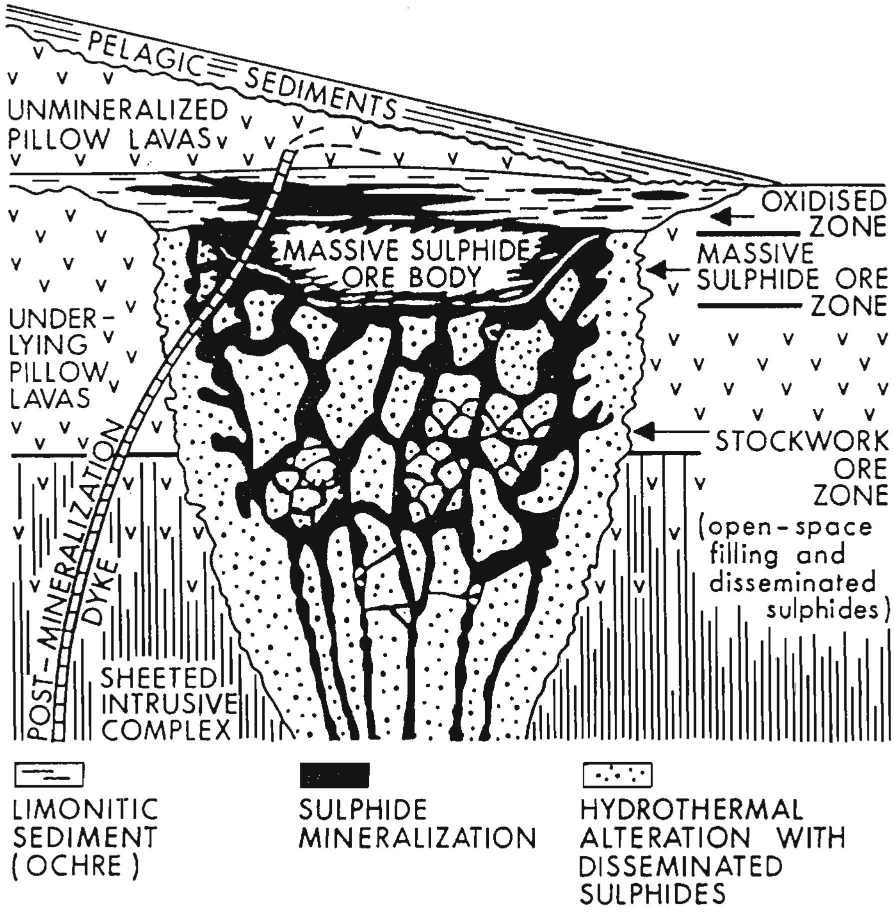


Figure 6.2. Schematic diagram of a Cyprus - type deposit. (after Hutchinson and Searle, 1971)

subdivides the volcanogenic exhalative sulphides into four distinct types (see table 6.3). Hutchinson does however emphasize that there are no sharp boundaries between these types, but instead there is a natural, continuous spectrum of geologic environments.

Hutchinson's classification criteria have been applied to the Bien Venue deposit, and this is compared to the other volcanogenic exhalative types, as shown in figure 6.3 and discussed below.

On the basis of lithology, only the the Kuroko and Primitive types approximate to Bien Venue. The association of the Bien Venue deposit with calc-alkaline felsic volcanics clearly distinguishes the deposit from the Cyprus and Besshi types, both of which are hosted by tholeiitic mafic volcanics. In terms of age, mineralisation and tectonic environment, the Bien Venue deposit approximates the Primitive type rather than the Kuroko type. Bien Venue is Archean in age, as are the majority of Primitive type deposits. On the other hand, Kuroko type deposits occur much later in geological time (Proterozoic to Tertiary) and no Archean Kuroko type deposits have been described in the geological literature. The Zn-Cu mineralisation at Bien Venue conforms to that of the Primitive type, whereas the Kuroko type deposits are distinctly Pb-rich in addition to Zn and Cu, and are thus "polymetallic". Although galena (Pb) is present in the Bien Venue orebody, its abundance does not comply to a "polymetallic" description for the mineralisation. The Barberton greenstone belt succession has been interpreted as displaying remnants of the oldest upper mantle, oceanic crust, and an overlying island-arc like complex, together with later continental sediments (Anhaeusser, 1986). The tectonic environment of the Barberton Mountain Land could therefore be described as a greenstone belt that formed in deep troughs on a relatively thin crust, and this is the type of environment where one would expect to find ores of the Primitive type.

Despite the fact that Bien Venue has many similarities with the Primitive type, there is one important difference ; barite is present in significant amounts in the Bien Venue orebody, a feature characteristic of the Kuroko type and unknown in the Primitive type.

Therefore, in terms of Hutchinson's classification criteria, Bien Venue would best be described as a Primitive type deposit that contains barite.

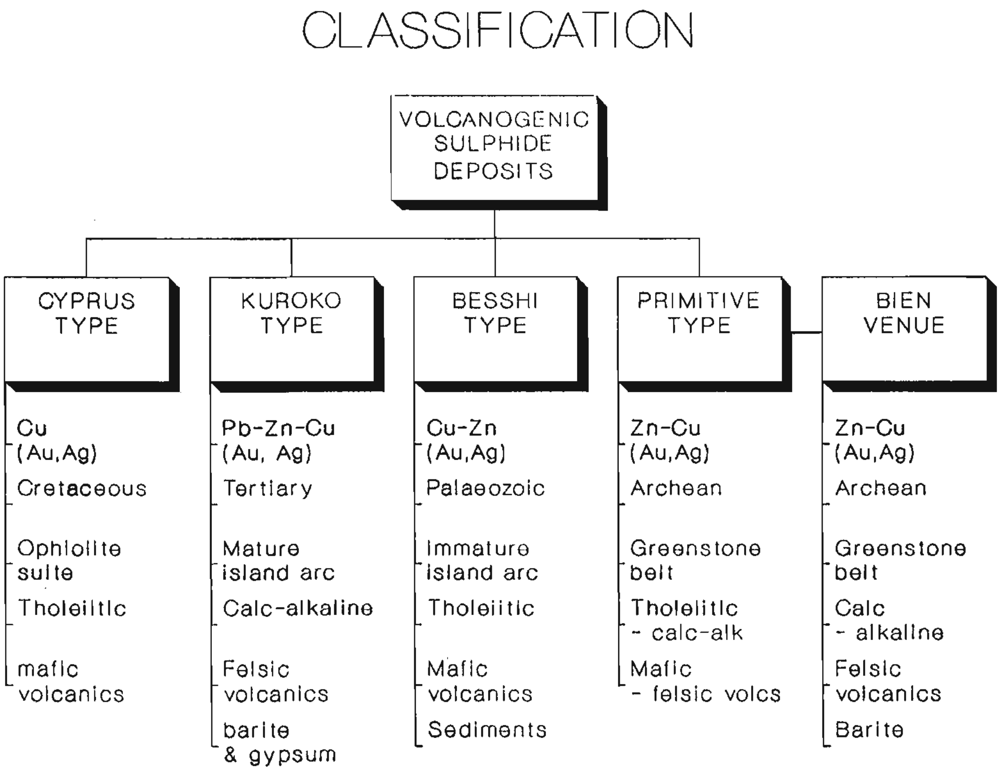


Figure 6.3. Classification of the Bien Venue deposit according to the classification scheme of Hutchinson (1973, 1980).

CHAPTER 7

CONCLUSIONS

The characteristic features of the Bien Venue deposit, as determined during the course of the study, are outlined below :

- the mineralisation is hosted by a metavolcanic/tuffaceous lithology.

- the orebody comprises stratabound lenses of massive to semi-massive and often banded sulphides, as well as disseminated sulphide mineralisation. Barite is an important constituent in the upper parts of the orebody.

- the ore mineralogy is dominated by pyrite, sphalerite and chalcopyrite, with minor galena, tennantite and native silver.

- the orebody exhibits a vertical zonation with respect to its metal and barium contents; copper is found at the stratigraphic base in an upward Cu-Zn-Pb-Ba sequence.

- the Bien Venue lithologies are predominantly rhyolitic to rhyodacitic in composition, and show a calc-alkaline affinity.

- element mobility is clearly evident at Bien Venue and is associated with hydrothermal alteration, resulting in the depletion of K_20 and the addition of MgO and SiO_2 in the wall-rocks of the deposit.

These characteristic features suggest a volcanogenic exhalative origin for the Bien Venue deposit.

The Bien Venue deposit does not conform to any existing category of volcanogenic exhalative massive sulphide deposits, in terms of present classification schemes. However, according to Hutchinson's (1973, 1980) classification criteria, Bien Venue is best described as a Primitive type deposit that contains barite.

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APPENDIX A

X-RAY FLUORESCENCE SPECTOMETRY

Twenty eight samples were collected from the metavolcanic rocks associated with the Bien Venue massive sulphide deposit, and analysed for major, minor and trace elements by x-ray fluorescence spectrometry.

Sample Collection

The sampling programme was undertaken as a reconnaissance survey to establish whether any chemical characteristics could be determined, since all the Bien Venue lithologies have been altered to some extent. Samples weighing approximately two kilograms (considered sufficient due to the fine-grained nature of the lithologies) were selected away from structural features and areas of obvious alteration/weathering, in an attempt to obtain only "fresh" and homogeneous material.

Sample Preparation

The sample was reduced to fragments of 5-10 cm in diameter by using an hydraulic sample splitter. The fragments were washed under running water and dried in an oven at 100°C for one hour. The material was then passed through a jaw crusher with hardened steel jaws and crushed to fragments less than 1 cm in diameter. This crushed sample was then reduced to approximately 100g by the cone and quartering technique, before being milled to a fine powder in a Siebtechnik laboratory disc mill.

Analytical Techniques

All major, minor and trace elements were determined by x-ray fluorescence spectrometry carried out on a Philips PW1400 spectrometer in the laboratories of the Geological Survey of South Africa, Pretoria. Callibrations were controlled using international standards.

All the major elements were analysed using the lithium tetraborate fusion method of Norrish and Hutton (1969), as outlined below.

Approximately 3g of sample was weighed into silica crucibles which had been cleaned in a dilute solution of HCl and dried in a furnace at 100°C. The crucibles with samples, were placed in a furnace at 1000°C for two hours and allowed to cool in a desiccator. The Johnson and Matthey Spectroflux 105 used for the fusion discs was preheated in platinum crucibles at 1000°C, and 1,5g of the ashed sample was added as near as possible to the ratio of weight sample : weight flux = 0,18. Fusion was effected at 1000°C, and the product was cast in a platinum crucible maintained at 250°C. Annealing occurred within ± 3hours on a heated asbestos plate and the samples were then allowed to cool gradually.

The trace elements were analysed using pressed powder pellets following the methods described by Feather and Willis (1976).

Sulphur and CO_2 were analysed by thermal decomposition of samples with an iron catalyst in an induction furnace (oxygen atmosphere), and the infra-red detection of SO_2 and CO_2 gases was undertaken using a Leco CS244 Carbon and Sulphur Determinator.

X-ray fluorescence spectrometry detects total Fe calculated as Fe_2O_3. The ratio FeO : Fe_2O_3 is therefore determined by an acid (HF-H_2SO_4) digestion of approximately 0,5g of sample followed by a redox-titration with a standard $K_2Cr_2O_7$ solution.

Moisture content was determined using a Leco RMC100 Rapid Moisture Analyser. Samples were heated from room temperature to 1200°C under a nitrogen atmosphere, with infra-red detection of the OH^- absorption band at 120°C (H_2O^-) and at between 750-1200°C (H_2O^+), depending on the nature of the sample.

APPENDIX B

X-RAY DIFFRACTOMETRY

X-ray data were obtained from random powder mounts using a Philips X-ray Diffractometer in the laboratories of the Geological Survey of South Africa, Pretoria.

Instrument conditions were as follows :

Instrument : Philips X-ray Diffraction Unit equipped with a Cobalt tube and iron filter, hence producing $Co_{K\alpha}$ radiation.
Divergent slit : 1°
Receiving slit : 0,2mm
Scatter slit : 1°
Take-off angle : 3,5°
Scanning : 2-75° 2O
kV : 40
mA : 40

APPENDIX C

ELECTRON PROBE MICROANALYSIS

Electron microprobe analyses were obtained using a JEOL 733 Electron Microprobe in the laboratories of the Geological Survey of South Africa, Pretoria.

Instrument conditions were as follows :

Instrument	:	JEOL 733 (wavelength spectrometers)
kV	:	20
Beam current	:	20 nA
Peak counting	:	10 seconds
Background counting	:	2 x 5 seconds
Spot size	:	5 x 10^{-6}mm

Elements	X-ray	Analysing Crystal	Counter
Cu, As, Fe, Zn	Kα	LIF	XENON
S	Kα	PET	Gas Flow
Ag, Sb	Lα	PET	XENON

Correction Procedure : An on-line ZAF FORTRAN programme supplied by JEOL (FZAFMC) which uses an absorption correction of Philibert (1963) and Heinrich (1966), an atomic number correction of Duncumb and Reed (1968) and a fluorescence correction of Reed (1965), was used.

Standardisation :

Cu, Fe, S	ASTIMEX Chalcopyrite
Zn	ASTIMEX Sphalerite
As	ASTIMEX Cobaltite
Ag	ASTIMEX Ag metal
Sb	ASTIMEX Sb metal