FIGURE 5.5b
ALTERATION-MINERALIZATION
of the FRIEDA RIVER
PORPHYRY COPPER DEPOSITS,
PAPUA NEW GUINEA
(400 METER LEVEL)

LEGEND

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Argillic</td>
<td>Carbonate-Clay</td>
</tr>
<tr>
<td>Karstite</td>
<td>Carbonates</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>Fault zone</td>
</tr>
<tr>
<td>Diaspore</td>
<td>Fault positive</td>
</tr>
<tr>
<td>Pyrophylite</td>
<td>Fault assumed</td>
</tr>
<tr>
<td>Biotite</td>
<td>Alteration contact</td>
</tr>
<tr>
<td>Propylitic</td>
<td>Stockwork</td>
</tr>
<tr>
<td>Transitional</td>
<td>Diamond drill</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>Section 11</td>
</tr>
<tr>
<td>Chloritic</td>
<td></td>
</tr>
<tr>
<td>Sericitic</td>
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</tbody>
</table>

NOTE: Effects of Flentem trachyandesite dykes are omitted.
The alteration-mineralization assemblages will be discussed in the order of their spatial relationships, from the inner, relatively unaltered core and biotitic zone through the transitional, chloritic and sericitic zones, to the outer advanced argillic or propylitic alteration assemblages. Formation temperatures of the alteration assemblages and descriptions of supergene alteration and structure are then presented and are followed by discussion and interpretations which conclude this Chapter. Detailed results of the alteration study are presented on the diamond drill sections of Maps 8 and 9 and are summarized in Figures 5.5a and 5.5b.

Geochemical analyses of the alteration minerals were obtained by electron microprobe. The procedure used and tabulated results are contained in Appendix 3. Although certain minerals occur in several alteration zones, for comparative purposes their chemistry is discussed in the section in which they are the dominant or characteristic mineral.

5.4.1 Unaltered Zones in Horse Microdiorite

Patches of relatively unaltered zones have textures that are similar to aplitic Horse microdiorite (Fig. 5.6a) and are characterized by the presence of fresh hornblende. As discussed previously (see section 5.3.4) these unaltered patches may represent late pulses of Horse microdiorite, although in the Koki deposit, the central nature and apparent gradational change from biotite-altered to relatively fresh rock suggests that this is an unaltered core zone.

The presence of abundant K-feldspar in the groundmass of rocks from unaltered zones distinctly contrasts with biotite-altered Horse microdiorite which does not contain groundmass K-feldspar. The possibly gradational verses abrupt intrusive nature of contacts
Figure 5.6

Photomicrographs of features in unaltered and biotitic alteration zones

(a) A sample of Horse microdiorite from the central unaltered zone in the Koki deposit. It contains twinned and commonly zoned hornblende (H) phenocrysts which, with biotite and plagioclase, are set in a groundmass typical of aplitic Horse microdiorite (cross-polarized light, scale = .4 mm, sample #D56 282.3).

(b) Matt texture of secondary biotite and rutile after hornblende. Rutile occurs as reticulated crystals in the secondary biotite and as coarser, subrounded, bead-like grains at the crystal boundaries of the biotite blades (plane-polarized light, scale = 50 microns, sample #D92 405.2).

(c) Matted clot of secondary biotite in an intensely biotite-altered rock (cross-polarized light, scale = .5 mm, sample #D40 221.4).

(d) Sutured soda-rich feldspar rims on glomeroporphyrritic plagioclase phenocrysts (cross-polarized light, scale = .5 mm, sample #D90 324.9).

(e) Plagioclase phenocryst crosscut by soda-rich veins and vein selvages (cross-polarized light, scale = .5 mm, sample #D14 51.1).

(f) Magnetite grain altered to hematite at its rim (reflected light, scale = 50 microns, sample #D56 362.8).
associated with these unaltered zones, therefore, might best be
determined by extensive staining for K-feldspar.

Although plagioclase is dusted with sericite and although selected
ferromagnesian phenocrysts, mainly hornblende are completely altered to
chlorite, epidote, albite or quartz and rare carbonates, most hornblende
and biotite phenocrysts are completely fresh; and overall alteration is
incipient.

5.4.2 Biotitic Alteration

The term potassic alteration of Asami and Britten (1980) is replaced
in this study with biotitic alteration because potassic alteration generally
refers to a K-feldspar-biotite-dominated equilibrium assemblage (Creasy,
1959). In the porphyry-copper systems at the Frieda River Prospect, K-
feldspar is not found in the biotitic zone, but is found in vein selvages
associated with transitional alteration which clearly overprint biotitic
alteration.

The inner limit to biotitic alteration, which is the outer limit to the
unaltered core zones, is defined where about 50% of the primary mafic
minerals are not altered. The outer boundary is marked by overprinting
veins and selvages of transitional alteration that occupy about 50% of the
rock.

Biotitic alteration is most common near the center of the Koki
deposit (Figs. 5.5a and 5.5b). Another relatively large patch is located
south of the Koki deposit but is poorly mineralized and contains chlorite
and quartz. Numerous other biotitic zones are located within the
mineralized regions of the Koki and Horse/Ivaal deposits as disconnected
patches that are normally bordered by transitional alteration-
mineralization. It should be noted that the outer boundary of biotitic
altered zones in the Horse/Ivaal deposit is highly erratic and is only approximated in Figures 5.5a and 5.5b.

Characteristic minerals of this alteration are biotite, soda-rich feldspar, magnetite, hematite, rutile, and, less commonly, chalcopyrite and bornite. Shreddy, .01 to .20 mm biotite flakes are diagnostic and most commonly pseudomorph mafic minerals as matted aggregates with rutile (Fig. 5.6b), or, less commonly, with magnetite or chalcopyrite. Biotite also occurs as discrete flakes in the matrix and rarely as discontinuous microveinlets. Some units are altered to such a degree that secondary biotite constitutes more than 25% of the rock and replaces most phenocryst phases (Fig. 5.6c). Hornblende is normally completely biotitized in moderately altered zones, although grains' included in feldspar are generally preserved. Primary biotite books in Horse microdiorite are not affected except where alteration is intense, in which case, rims are ragged.

Biotites are generally brown in colour, although green flakes are rarely noted in widely scattered localities and might reflect a higher Fe/Mg ratio compared to the brown biotites (Meyer and Hemley, 1967). Lighter reddish-brown colours were also noted in moderately biotitized rocks south of the Koki deposit but do not reflect a major change in chemistry according to electron microprobe analyses.

The chemical characteristics of primary (~1 mm size) and various secondary biotites (~.01 to .1 mm size) in Horse microdiorite from the Horse/Ivaal and Koki deposits were analysed by electron microprobe (see Appendix 3). One hundred and one analyses of primary biotite grains were obtained from 10 samples. Each grain was analysed between 2 and 4 times and the results were averaged and plotted on a ternary diagram (Fig. 5.7a). Except for three analyses on sample D29 137:2 from the
transitional alteration zone of the Hose/Ivaal deposit, all other analyses of primary biotite from the unaltered, biotitic, transitional and propylitic zones plotted in the range proton-deficient oxyannite\textsuperscript{9-14} annite\textsuperscript{25-30} phlogopite\textsuperscript{59-65}. This tight clustering suggests that the chemistry of primary biotites was not markedly changed by the processes that caused the various types of alteration but preserved primary biotites.

Analyses of secondary biotites were obtained in a manner similar to that for primary biotites except analyses on separate grains within a single aggregate of secondary biotite were averaged. At least two sets of averaged analyses were obtained for each sample to investigate the 'within-sample' chemical homogeneity. A total of 106 analyses on 15 samples yielded 36 averaged analyses which are plotted on Figure 5.7b. In this figure secondary biotites from the biotitic and transitional alteration zones are classified according to whether they replace hornblende, occur in indistinct clots of uncertain nature, or are groundmass constituents. Secondary biotites that replace hornblende in the biotitic alteration zone cluster tightly and correlated well with primary biotites of Horse microdiorite. Those from the transitional alteration zone that occur in indistinct clots are more widely scattered and generally lie above the field of primary biotites. This probably reflects more oxidized conditions associated with transitional alteration. There are not sufficient data to comment on other categories of secondary biotite although they all occur within similar compositional limits.

The 'within-sample' chemical homogeneity is greater for secondary biotites from the transitional zone than those from the biotitic altered zone. This is demonstrated in Figure 5.7, where 15 analyses of secondary biotites from the transitional zone plotted as 7 points whereas
Figure 5.7 Compositions determined by electron microprobe of primary and secondary biotites in Horse microdiorite plotted on a proton-deficient oxyannite-annite-phlogopite ternary diagram.

(a) Primary biotites are plotted according to location in unaltered, biotitic, transitional or propylitic altered zones.

(b) Secondary biotites from the biotitic and transitional alteration zones are plotted according to their habit or occurrence. Compositional fields for primary biotite of Horse microdiorite, secondary biotites of other porphyry copper deposits (Beane, 1974) and primary biotites from rocks of granitic-granodioritic composition (Heinrich, 1946; Foster, 1960) are shown for comparison.

Values of FeO and Fe₂O₃ for primary and secondary biotites are, respectively, 12.96 and 0.72 wt % and 12.06 and 1.30 wt %; these were determined on mineral separates (see Appendix 3 for analytical techniques). The brackets contain the number of analyses plotted for each category of primary or secondary biotite.
21 analyses from the biotitic zone plotted as 21 relatively distinct points. The relations between secondary biotites from the two alteration zones indicate relatively heterogeneous 'within-sample' compositions but relatively tight or homogeneous chemistry between samples from the biotitic alteration zone. The reverse is true for the transitional alteration zone where 'within-sample' compositions are homogeneous and those between samples are scattered. This indicates poor local equilibration during processes causing biotitic alteration but good local re-equilibration of secondary biotite in transitional altered zones.

Unlike primary biotites, the chemistry of secondary biotites therefore is markedly different in different alteration zones, although the biotites do have Fe/Fe+Mg ratios that overlap in range between .20 and .37 (see Fig. 5.14). In addition, TiO$_2$ content increases in secondary biotite from the transitional zone (average $\approx$ 2.5 wt %) to the biotitic zone (average $\approx$ 3.1 wt %) which are both lower than primary biotites (average $\approx$ 3.6 wt %). Similar relations between primary and secondary biotites for TiO$_2$ have been noted in porphyry copper deposits at Bingham, Utah (Moore and Czamanske, 1973), Santa Rita, New Mexico (Jacobs and Perry, 1979), Babine Lake, British Columbia (Carson and Jambor, 1974), Butte, Montana (Brimhall, 1977), and Panguna, Papua New Guinea (Ford, 1978). Overall, primary and secondary biotites lie closer to the alteration biotites of Beane (1974) rather than the igneous biotite compositions of Heinrich (1946) and Foster (1960).

Plagioclase in the biotitic zone is generally unaltered, although dustings of sericite and, less commonly, clay minerals or carbonates are observed in some phenocrysts. Soda-rich feldspar occurs as sutured rims on plagioclase (Fig. 5.6d) or as micro selvages in plagioclase (Fig. 5.6e). Single microprobe analyses of these habits are plotted in Figure
5.8. Plagioclase phenocrysts and rims normally range An_{24-37} Ab_{61-73} Or_{1-3} and An_{7-17} Ab_{80-90} Or_{1-6}, respectively, whereas micro selvages in plagioclase have compositions in both of these fields. Also plotted for comparison are analyses of feldspar alteration products that occur as grains in vein selvages, in biotite-quartz-rutile aggregates that pseudomorph hornblende, and in the groundmass. They generally lie within An_{1-9} Ab_{89-99} Or_{1-6} and are distinctly, albexitic in comparison to the interiors and sutured rims of plagioclase phenocrysts.

The most common opaque mineral in the biotitic zone is magnetite, which, like biotite, has a bimodal habit. Equant or euhedral, .1 to 1.0 mm magnetite cubes that are disseminated in the matrix are probably primary. Finer-grained, .01 to 0.1 mm, subhedral and euhedral secondary magnetite is found disseminated in the matrix and in clots with other alteration minerals. A feature commonly noted on magnetite grains are hematite rims of .01 to .2 mm width (Fig. 5.6f) that reflect the original composition of the magnetite (Table 5.1) and indicate oxidation associated perhaps with incipient transitional alteration. Rutile is normally found in biotite clots where it has a number of habits, but occurs most commonly at grain boundaries as anhedral bead-like grains generally less than .01 mm in diameter or as reticulated clusters in biotites (Fig. 5.6b).

Disseminated bornite, chalcopyrite, pyrite, and rare chalcocite normally have grainsizes similar to secondary magnetite but are typically anhedral. In many samples a definite increase in sulphide abundance is noted toward fractures lined with sulphides and chlorite or, in some cases, pink K-feldspar. The sulphides appear to form selvages to these fractures, although silicate alteration that overprints biotitic alteration is generally lacking. This suggests that much of the
Table 5.1  Electron microprobe analyses of a magnetite grain that is oxidized to hematite at its rim. (Sample #D56 362.8; see Fig. 5.6f).

<table>
<thead>
<tr>
<th>Magnetite</th>
<th>Hematite rim on Magnetite grain</th>
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<tr>
<td>SiO2</td>
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<td>TiO2</td>
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<tr>
<td>Al2O3</td>
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<td>Fe2O3</td>
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<td>MgO</td>
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<td>V</td>
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</tr>
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</tr>
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<td>Total</td>
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<td>No. Analyses</td>
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</tr>
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</table>
Figure 5.8 Compositions determined by electron microprobe of plagioclase feldspar from the biotic alteration zone plotted on an anorthite (An)-albite (Ab)-orthoclase (Or) ternary diagram; feldspar alteration products are shown for comparison. Brackets enclose the number of analyses plotted for each category.
copper and gold mineralization formerly thought temporally associated with biotitic alteration is, in fact, mostly later.

Interstitial anhydrite, epidote, and chlorite are other minor constituents of this alteration. Whereas epidote occurs with biotite in mafic pseudomorphs, chlorite is almost always a retrograde alteration product of biotite and, in most cases, is related to incipient transitional alteration.

5.4.3 Transitional Alteration

Transitional alteration is the most complex category of alteration. It is characterized by fracture-controlled mineral assemblages which generally mark a change from inner pervasive biotitic alteration to outer pervasive chloritic or sericitic alteration. It includes a very unusual K-feldspar-bearing assemblage. This style of this structurally-controlled alteration that contrasts with the pervasive nature of adjacent alterations, the width of this zone, presence of distinct vein assemblages, and the exploration potential of these characteristics, justifies distinction of these features as transitional alteration.

The outer boundary of transitional alteration is located by the near-complete eradication of secondary biotite, by overprinting sericitic or chloritic alteration, or, in other areas, by the presence of minerals associated with propylitic alteration. The inner limit is placed where overprinting by transitional alteration has affected about 50% of the normally biotite-altered rock. These boundaries however are relatively arbitrary due to the erratic nature of the alteration.

Stockworks associated with transitional alteration are characterized and located on the diamond drill sections in Maps 8 and 9. These stockworks and other types of transitional alteration generally border
biotitic altered zones in the deposits except the eastern periphery of the Koki deposit (Figs. 5.5a and 5.5b). Some stockworks, however, do crosscut the biotitic zone, but unlike those at the Yandera (Tilley et al., 1978; Watmuff, 1978) and the Ok Tedi (Bamford, 1972) deposits, they do not constitute a major central core zone. Mineralized patches of transitional alteration also occur in the Upper Prospect Creek area, where they are sometimes difficult to distinguish from vein-controlled propylitic assemblages.

Except for quartz veins which are resistant to leaching and weathering (see Fig. 5.22b), few other primary vein minerals that are associated with transitional alteration are observed in surface exposure. Consequently, this zone was primarily studied through extensive examination of drill core. Representative drill-core samples were slabbased, polished, stained for K-feldspar, observed through a binocular microscope, and described; some were observed in thin section or X-ray diffracted.

Employing these techniques, compositions, characteristics, and paragenesis of vein assemblages are relatively easily established in each slabbased sample from a drill hole, but correlation of vein relationships between samples of any one drill hole is commonly more difficult. Correlation of vein relationships between different drill holes is even more difficult due to a number of factors. Core size and intensity of fracturing are two obvious problems, while the nature and number of vein episodes present more subtle problems. The difficulty in establishing paragenesis increases disproportionately to the increase in number of vein episodes. Problems are compounded where vein mineral assemblages of different episodes are similar and differ only in relative proportions and habits, such as vein width, presence or absence of selvages, cockscomb, crustiform or other textures (see Fig. 5.10a).
Remobilization, hypogene leaching, or re healing of early open veins or fracture linings by later alteration episodes are additional complicating factors. For example, supergene gypsum commonly heals recent fractures as well as older fractures that are lined with other alteration minerals and is easily recognized as later. Carbonate or quartz that heal open fractures lined with earlier K-feldspar may be incorrectly associated with the K-feldspar as a single vein assemblage rather than two separate vein episodes. K-feldspar and chalcopyrite, that are both concordant and discordant to porous quartz vein stockworks in the Koki deposit, present a similar problem. They could be associated with late-stage development of the quartz stockwork, or alternatively, postdate the stockwork.

In spite of these problems a preliminary assessment of vein relationships is established. Minerals noted in veins, their relative abundance, and general paragenetic relationships are illustrated in Figure 5.9a; temporal and spatial relationships of vein assemblages are schematically represented in Figure 5.9b for transitional alteration and other alteration zones that contain vein and fracture fillings. Although the relative abundance of minerals in veins is probably representative within the broad limits set, temporal vein relationships are less certain for the reasons stated above. Temporal relationships will be more confidently established when characteristics of veins can be traced over longer distances following development of adits or open pits.

The most common vein mineral is quartz, although anhydrite is as abundant as quartz beneath the zone of deepest supergene leaching (Fig. 5.9a). The sulphides, chalcopyrite and pyrite, although widespread, are volumetrically much less abundant than quartz and anhydrite. K-feldspar and chlorite, in addition to sericite, are not as
(a) Major vein episodes

<table>
<thead>
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<th>Early</th>
<th>Main Stage</th>
<th>Late</th>
<th>Supergene</th>
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</thead>
<tbody>
<tr>
<td>Secondary Biotite</td>
<td>Bi</td>
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<td></td>
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</tr>
<tr>
<td>K-Feldspar (K-spar)</td>
<td></td>
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<td></td>
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<tr>
<td>Chlorite (Chl)</td>
<td></td>
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<tr>
<td>Pyrite (Py)</td>
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<td></td>
<td></td>
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<tr>
<td>Chalcopyrite (Cpy)</td>
<td></td>
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<td></td>
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<tr>
<td>Bornite (Bn)</td>
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</tr>
<tr>
<td>Quartz (Qt)</td>
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<td>Hematite (Ht)</td>
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<tr>
<td>Gypsum (Gyp)</td>
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</table>

Figures 5.9 (a) Minerals noted in veins but not selvages, their relative abundance, and general paragenetic relationships.

(b) Generalized temporal and spatial relationships of vein assemblages in various alteration zones. Unless stated otherwise, the listed mineral assemblages occur in partially or completely healed veins; square brackets enclose assemblages that occur in selvages whereas, parentheses enclose minerals of relatively minor abundance in either veins or selvages.
(b) Generalized temporal-spatial relations of vein assemblages

| Early (inner): Mainly occur in the Biotitic zone | Intrusion of Horse microdiorite |
| Bi (rare) | Microfracture |
| K-spar ± Cpy | Fracture |
| Chl-Qt±Cpy=[Cpy] | Fracture |
| Cpy-Py | Fracture |
| Py-Qt | Crustiform |
| Py-[Qt] | |
| Main Stage: Abundant in the Transitional Alteration Zone as stockworks; Qt and An assemblages also noted in the Sericitic and Propylitic Zones |
| Mt-(Py,Cpy)[Qt-Ser±K-spar] | |
| An&Mt±Cpy±Py±Ht | Crustiform or banded |
| An-Qt×Mts±Cpy±Py±[K-spar±Ser-Chl-Qt-An-(Py,Cpy)] | |
| or [Chl-An] | |
| Qt-Cpy±K-spar±[K-spar±Ser] | - at least 2, possibly 3 episodes |
| An-Cpy-K-spar | |
| Qt-Chl-Cpy | |
| Emplacement of Ivaal andesite porphyry and biotite-bearing Flintem trachyandesite dikes (Fta I) |
| Qt | Barren stockwork |
| Py-Qt±Cpy | Crustiform |
| Carbs? | Graphic |
| K-spar | Fracture |
| Py [Ser±Chl] | Fracture |
| Cpy | |
| Intrusion of non biotite-bearing Flintem trachyandesite dikes (Fta II) |
| Carbs? | |
| Gyp | |
| Fe-oxides | |
| Late: Found below the Advanced Argillic Zone | |
| Supergene: Widespread Gypsum in nearly all alteration zones at deep levels | |
common in veins as the previous minerals, but are more abundant than the sulphides in vein envelopes. Envelopes, however, are not included in the abundance estimation because they commonly overlap in or near the pervasive chloritic and sericitic alteration zones and their characteristics are difficult to assess. Of the remaining hypogene oxide and sulphide minerals, magnetite is most common, followed by bornite, molybdenite, hematite and rutile. Although carbonate is locally abundant, it is not widespread, unlike gypsum, which is a widespread but less abundant supergene product.

Both the vein abundance and assemblages have been categorized into major episodes of early, main stage, late and supergene veins (Figs. 5.9a and b). The early episode consists of rare biotite microfractures and K-feldspar, chlorite and chalcopyrite-dominated assemblages that line walls of open fractures. Except for biotite, various combinations of these minerals, completely heal fractures in some areas. Early-episode veins occur mainly in the biotite zone and are commonly overprinted or obliterated in the transitional zone. They may be temporally related to some main stage veins in the transitional zone.

Main stage veins consist of a variety of assemblages dominated by quartz, anhydrite, pyrite, and, less commonly, magnetite. Many of these are enveloped by assemblages consisting of variable combinations of K-feldspar, quartz, sericite, chlorite, anhydrite and relatively minor sulphides. The paragenetic sequence presented in Figure 5.9b is considered only a first approximation of the vein sequence which is probably more complex (cf. Fig. 5.10a). These relationships were primarily established on samples collected from the transitional zone. Complex vein relationships do occur in the chloritic and sericitic alteration zones, but because of intense pervasive overprinting
Representative features of transitional alteration

(a) This rock slab of intensely biotite-altered hornfels has been fractured and healed by at least three episodes of quartz-chalcopyrite veins. An early, thick, faintly crustiform vein (1) is offset by a similar set (2). Both of these are crosscut by a third (3), thinner, less regular vein. The myriad of other thin veins may be related to episodes (2) or (3) although at least one (?) may predate all previously mentioned episodes (scale = 2 cm, sample #R1911).

(b) Overprinting fracture-controlled sericite and chlorite alteration episodes have introduced an indistinct pseudobreccia texture to this rock slab (scale = 2 cm, sample #D72 225.5).

(c) A polished slab of Horse microdiorite from the transitional alteration zone in the Horse area. The anhydrite-quartz-chalcopyrite-molybdenite vein (1) which is bordered by a narrow, irregular bleached zone is clearly truncated on the right side of the photograph by a thin chalcopyrite-anhydrite-quartz-carbonate fracture filling (2) which has .3 cm selvage of sericite, K-feldspar, anhydrite, and chlorite. At the left side of the photograph the reverse appears to be true because the selvage appears to be truncated. Careful examination, however, reveals a thin fracture filling without a selvage that intrudes into, but does not entirely crosscut the anhydrite-quartz vein (scale = 2 cm, sample #D30 308.2).

(d) Photograph of a rock slab of Horse microdiorite from the Ivaal area in which there are two vein episodes. A thick quartz-chalcopyrite vein (1) which has irregular walls and a 2 cm selvage that is composed of K-feldspar, sericite, chlorite and chalcopyrite is offset and crosscut by a second set of veins (2). This second set is also quartz-chalcopyrite but is relatively porous and much thinner. It also has a selvage which is about .5 cm wide and composed of K-feldspar, sericite, chalcopyrite and minor chlorite (scale = 2 cm, sample #D79 246.5).

(e) Photomicrograph of the turbid, perthitic twinning evident in coarse-grained K-feldspar alteration products (plane-polarized light, scale = 150 microns, sample #D9 164.6).
(f) Photomicrograph of an albited plagioclase in which faint twinning remains. The dusting is mainly anhydrite and sericite (cross-polarized light, scale = .5 mm, sample #D36 437.5).

(g & h) Photomicrographs illustrating the textural destruction of fresh biotite-altered Horse microdiorite (g in cross-polarized light) to a sericite-quartz-sulphide assemblage (h in plane-polarized light) at the inner portion of a crosscutting vein selvage (scale = 2 mm, sample #D12 347.8).
alteration, they commonly impart a pseudobreccia texture to the rock (Fig. 5.10b) and have uncertain characteristics and relationships.

Later stage veins probably followed the emplacement of intermineralization intrusion breccia (Iap) and Flittem trachyandesite dikes (Fta I). These veins consist of barren quartz stockworks, crustiform pyrite-quartz ± chalcopyrite veins, carbonate and graphic K-feldspar-quartz veins which commonly occur in the propylitic zone and are possibly late stage, and fracture fillings of chalcopyrite or pyrite with sericite envelopes. Total copper sulphides in these veins is low. Rare occurrences of late-stage veins that crosscut Flittem trachyandesite (Fta II) dikes have been noted, but intrusion of these dikes postdates most late stage veins.

Gypsum that fills a late set of fractures is almost certainly the hydrated and commonly remobilized supergene alteration product of anhydrite (see Asami and Britten, 1980, p. 129); a supergene origin for late carbonate veins is less certain. Remobilized supergene gypsum is characterized by soft fibrous crystals that have grown perpendicular to very distinct, generally parallel, vein walls. Optically this gypsum has low order interference colours or is semi-isotropic. Gypsum that directly replaces anhydrite is generally less isotropic.

A feature of main-stage transitional alteration atypical of most porphyry copper deposits are veins of quartz, sulphide or K-feldspar that commonly have envelopes which contain sericite-K-feldspar ± chlorite assemblages (Figs. 5.10c and 5.10d). Sericite is abundant nearest the vein or on the inside of the envelope where it replaces phenocryst and groundmass constituents with K-feldspar. Toward the outer margin of the selvage, K-feldspar content increases and largely replaces groundmass constituents. The K-feldspar is normally white or
pink orthoclase and generally ranges $\text{An}_{0-1} \text{Ab}_{0-54} \text{Or}_{46-100}$ in composition according to electron microprobe analyses (Fig. 5.11). Coarse-grained K-feldspar commonly exhibits a turbid perthite twinning (Fig. 5.10e). Accompanying K-feldspar in the outer part of the envelope are chlorite after secondary biotite and partially albitized-sericitized plagioclase in which faint twinning is preserved (Fig. 5.10f).

K-feldspar-bearing vein assemblages that postdate biotitization may prove to be a feature that is common in porphyry copper systems of the Southwest Pacific because similar assemblages have been noted at the Panguna (Ford, 1978) and the Yandera (Titeley et al., 1978) porphyry copper systems in Papua New Guinea.

Features of transitional alteration are variable on a larger scale and to illustrate, major variations and approximate size ranges observed in one drill hole (DDH 79, Section I5, Map 9) are summarized below:

1) patchy coatings of chlorite-pyrite that line fractures and microfractures which are .01 to .10 mm or more in width;

2) a variety of complex overprinting vein assemblages composed of quartz, pyrite, chalcopyrite, anhydrite and other minerals, with selvages of sericite, chlorite; K-feldspar, and sulphides are 2 to 10 mm and 1 to 3 cm in width for veins and selvages, respectively;

3) quartz-pyrite veins that are 2 to 6 mm wide;

4) irregular patches of sulphide-poor quartz flooding that are roughly 1 to 5 cm wide;

5) crushed, texture destroyed, sericite-kaolinite zones which are 1 to 3 m in width;
Figure 5.11 Compositions determined by electron microprobe of K-feldspar in selvages of transitional altered zones and K-feldspar in the groundmass of altered and unaltered rock plotted on an anorthite (An)-albite (Ab)-orthoclase (Or) ternary. Brackets enclose the number of analyses plotted.
cream-coloured pervasive sericite-kaolinite alteration in which textures are preserved and are 1 to 10 m wide.

* Indicates features that normally contain significant copper mineralization.

A subclass of transitional alteration, chlori-biotitic, is typified by biotitized rocks that are partially altered to chlorite. The alteration is pervasive with no obvious fracture control and may be a relatively weak phase that is marginal to chloritic alteration. Chlorite commonly pseudomorphs the shreedy texture of secondary biotite and, in many cases, has produced intermediate products that have similar optical properties to chlorite or biotite, but are semi-isotropic and appear to be amorphous. A single grain of biotite that was partially pseudomorphed by chlorite has an alteration front composed of this intermediate product. Microprobe analyses across this front indicate that the intermediate product has a composition that is between that of biotite and chlorite (Fig. 5.12).

Page and Wenk (1979) who worked on a vein envelope from Butte found that hydrothermal alteration of plagioclase progressed from montmorillonite through intermediate products to 2M₁ sericite toward the vein. They discovered the intermediate products were interlayered phyllosilicates that included smectite, sericite, kaolinite, sepecholorite, and chlorite. An analogous situation of interlayered phyllosilicates is envisaged for the intermediate chlorite-biotite alteration products.
Figure 5.12 Variation in composition across a partially chloritized secondary biotite grain is illustrated in this photomicrograph and figure. An alteration front which is about 25 microns wide has a composition that is intermediate to the chlorite and biotite end-members; n = number of analyses from other chlorites and biotites in the same sample that are shown for comparison (plane-polarized light, scale 100 microns, sample #D29 137.2).
5.4.4 Chloritic Alteration

This type of alteration is defined by conversion of all mafics and feldspars to a pervasive chlorite-sericite-quartz-sulphide assemblage in which chlorites generally have low grey interference colours. Although the shreedy-matt to fine-grained bladed texture of secondary biotite is sometimes preserved (Fig. 5.13a to d) the pseudomorphic outlines of formerly biotitized hornblende do not normally survive. Feldspar is generally converted to sericite or, in the most intensely altered areas, chlorite. Unlike the transitional alteration zone, K-feldspar is only rarely noted in the chloritic zone.

The inner boundary is marked by the complete alteration of biotite to chlorite, and the outer and upper limits are defined by the disappearance of chlorite normally in the sericitic zone. A lower boundary with propylitic alteration is arbitrarily located where chloritic alteration was not of sufficient intensity to completely alter feldspars or where typical propylitic assemblages are present.

Chloritic alteration bounds the transitional zone on all sides except at the southeast margin of the Horse/Ivaal deposit (Fig. 5.5a and 5.5b). In the Koki deposit it covers the western periphery in a wide zone and grades with depth to propylitic alteration. Scattered patches occur in the Upper Prospect Creek area and northwest of the Koki deposit. A large patch of chloritic alteration occurs southwest of the porphyry copper systems (Map 3) where it is associated with sericitic alteration but is not mineralized.

Chlorites in the porphyry copper systems range between epidolite to pycnochlorite according to the classification of Hey (1954) and assuming they are unoxidized; intermediate chlorite-biotite products are commonly diabantite. Those from the transitional zone (Figs. 5.13a and 5.13b) and chloritic zone (Figs. 5.13c and 5.13d) generally pseudomorph
**Figure 5.13**

Photomicrographs of chlorite from various alteration zones

(a & b) Chlorite and rutile replace a clot of secondary biotite in a vein selvage that overprints an intensely biotitized porphyritic rock in the transitional alteration zone of the Horse/Ivaal deposit. The matted texture of secondary biotite is clearly pseudomorphed (a in plane-polarized light, b in cross-polarized light, sample #D40 221.4).

(c & d) A matted aggregate of chlorite and rutile that probably replaced secondary biotite in the chloritic alteration zone (c in plane-polarized light). The rim has been altered to sericite (see d in cross-polarized light) (sample #D96 89.3).

(e & f) The fan-shaped to spherulitic texture of chlorite after hornblende in propylitic altered rocks is distinct from the matted texture of chlorite after secondary biotite (a in plane-polarized light, b in cross-polarized light, sample #D59 143.2).

All scale bars = 0.5 mm.
secondary biotite and commonly have low first-order grey and brown interference colors, respectively. In the propylitic zone chlorite commonly pseudomorphs hornblende (Figs. 5.13e and 5.13f) and has strong green pleochroism, and anomalous brown to purple interference colours.

Ninety-one geochemical analyses on 15 samples obtained in the same manner as those for secondary biotites were averaged to give 34 analyses representing chlorites from three alteration zones; these are plotted on Figure 5.14. Intermediate chlorite-biotite alteration products which are characterized in Figure 5.12 are plotted for comparison but such products were generally avoided in this study. The compositional range for chlorites from the transitional alteration zone lies within the fields of primary and secondary biotites, whereas those from the chloritic alteration zone generally lie outside these fields. These relations indicate that the relative amounts of total Al, total Fe and Mg between biotites and chlorites of the biotitic and transitional alteration zones are preserved, but relative to these zones, chlorites in the chloritic zone are enriched in total Al and Mg.

The most common opaques in the chloritic zone are pyrite, chalcopyrite, and rutile. The sulphides vary from .01 to .3 mm although chalcopyrite is smaller on the average. Pyrite is generally rounded and embayed, whereas chalcopyrite is typically equant-angular and sometimes exhibits a graphic texture similar to chalcopyrite in the sericitic zone (see Fig. 5.15a). Rutile is normally bead or rod-like, averages .02 mm, and occurs in clots with chlorite and chalcopyrite. Hematite and magnetite are similar in grain size to the sulphides and magnetite is relatively rare in the chloritic zone compared to the transitional and biotitic zones. However, hematite is locally abundant as euhedral rod-like grains disseminated throughout the rock (Fig. 5.15e).
Figure 5.14 Chemical variation determined by electron microprobe of chlorites from various alteration zones and intermediate chlorite-biotite products illustrated on a total Al-total Fe-Mg ternary plot. The fields for primary biotites (solid line) and secondary biotites (broken line) in Horse microdiorite are also plotted.
5.4.5 Sericitic Alteration

The sericitic zone is characterized by ubiquitous alteration assemblages that are dominated by sericite and quartz, less abundant sulphide, less widespread andalusite, and minor rutile. All primary minerals except quartz are converted to a very fine-grained (.001 to .01 mm) mosaic and textures are commonly obscured (see Figs. 5.10g and 5.10h). The inner or lower limits to sericitic alteration are located where chlorite is first recognized, whereas pyrophyllite or propylitic assemblages mark the outer boundary.

Sericitic alteration surrounds the northwestern two-thirds of the Horse/Ivaal deposit and the western periphery of the Koki deposit (Fig. 5.5a). These areas are significantly smaller or disappear altogether at depth (Fig. 5.5b, section I5). Remnant patches occur at the southeast end of the Horse/Ivaal and are scattered in the general area of Upper Prospect Creek. Nearly all of these sericites are the $2M_1$ polymorph. Three other major occurrences of sericitic alteration have been noted. Those located about 2 km west-northwest of the Koki deposit and scattered patches within a band that is located 1 to 2 km south and extends to 3 km southwest of the Horse/Ivaal deposit are composed of $1M$ or $1M_d$ sericites and, are barren (Map 3). A third occurrence is located southwest of the Nena mineralization where chlorite and limited secondary biotite alteration are also present. This sericite is $2M_1$, is commonly weakly mineralized, and is associated with a chalcopyrite-covellite-bornite mineral assemblage.

One hundred and twenty four analyses on 17 samples were averaged to give 31 analyses of sericites from the transitional, chloritic, sericitic, and propylitic alteration zones. The analyses reveal the overall phengitic nature of the sericites and a ternary plot of octahedral Al-total
Figure 5.15

Photomicrographs of sericitic alteration assemblages and associated oxides and sulphides

(a) Chalcopyrite (Cp) and sericite (S) have a graphic boundary intergrowth. Andalusite (A) which is separated from the chalcopyrite by sericite occurs as granular aggregates its most common habit (plane-polarized light, scale = 0.5 mm, sample #D102 52.6).

(b) This classic rosette of andalusite is set in a groundmass of sericite, quartz and minor opaques (plane-polarized light, scale = 200 microns, sample #S159 27.8).

(c) An uncommon feature noted in a single sample from the Koki deposit is bladed andalusite (A) that has grown in a plagioclase phenocryst (cross-polarized light, scale = 0.5 mm, sample #D31 34.1).

(d) Hematite (H) which fills the central portion of a vein is bounded by pyrite (P) that in turn is bordered by quartz (Q) (reflected light, scale = 0.5 mm, sample #D100 236.2).

(e) Hematite blades (H) are enclosed by and border chalcopyrite (Cp) and are irregularly disseminated throughout a matrix completely altered to sericite, quartz and chlorite (reflected light, scale = 200 microns, sample #D77 159.2).

(f) Supergene chalcocite (Cc) has replaced rims of irregular chalcopyrite grains. Boundaries between the unreplace chalcopyrite cores (Cp) and the chalcocite are commonly of an angular embayed or splintery nature. Pyrite (P) is unaffected by enrichment processes (reflected light, scale = 200 microns, sample #R1987).
Fe-Mg (Fig. 5.16) shows an increase in Al\textsuperscript{V1} and Fe/Fe+Mg from the transitional to the chloritic and sericitic alteration zones. This trend parallels an increase in the total amount of sericite and probably reflects increasing hydrogen metasomatism from inner to outer zones of alteration. Other components in sericites do not vary significantly between alteration zones; however, compared to muscovite, sericites appear high in H\textsubscript{2}O and phengitic components but are slightly low in K\textsubscript{2}O (average \( \approx 10.3 \) wt %).

Andalusite is normally classified with advanced argillic alteration in other porphyry copper systems. But, because andalusite is intimately associated with sericite, overlaps the outer .3% copper contour in the Horse/Ivaal deposit, and does not normally occur with other advanced argillic assemblages, it is considered a subclass of sericitic alteration. Andalusite has a granular, bladed, or less common rosette habit (Fig. 5.15a, b and c) that ranges from less than .1 to greater than .5 mm. It is commonly enclosed by sericite, which, in turn, is surrounded by a sericite-quartz matrix. Andalusite has also been noted in weak chloritic alteration, and in one sample from the transitional alteration zone of the Koki deposit, it partially replaced a plagioclase phenocryst (Fig. 5.15c) and may represent a high-temperature analogue of sericite alteration (Gustafson and Hunt, 1975). Alternatively, in the Horse/Ivaal deposit, it probably marks the inner boundary of relatively lower temperature advanced argillic alteration assemblages (Hemley et al., 1980).

Kaolinite is generally found in the upper sections of the sericitic zone in the Horse/Ivaal deposit where its origin is uncertain, but might be supergene. Kaolinite, however, is also found at deeper levels in the advanced argillic alteration zone near the southwest periphery of the Horse/Ivaal deposit where it is most likely hypogene.
Figure 5.16 An octahedral Al-total Fe-Mg ternary diagram illustrating the chemical variation determined by electron microprobe of sericites in the transitional, chloritic, sericitic, and propylitic alteration zones.
Opaques in the sericitic zone include pyrite which is subangular to rounded, .01 to .5 mm, and contains rounded inclusions of chalcopyrite, silicates and minor pyrrhotite. Irregular, skeletal or graphic chalcopyrite grains that are commonly intergrown with sericite are about half the size of pyrite (Fig. 5.15a and 5.15b) while bead-like rutile is an order of magnitude smaller. Bladed hematite in a pyrite-quartz vein was also noted in the sericitic zone (Fig. 5.15d) and nearly completely resorbed hematite grains were sometimes observed in disseminated chalcopyrite grains.

5.4.6 Carbonate-Kaolinite Alteration

Carbonate-kaolinite alteration is composed principally of cream-coloured calcite-dolomite-kaolinite assemblages that, in some areas, contain lesser amounts of quartz, anhydrite and rare siderite. These assemblages are structurally controlled and occur as stockworks or veins with wide selvages (Fig. 5.17a). Vein material is generally coarse-grained relative to grains in selvages and in some drusy veins reaches 2 to 3 mm in size.

Supergene processes have removed carbonates near the surface; consequently, this alteration is recognized only in drill core. A major stockwork zone parallels the intrusive-lower Wogamush sediment contact at the eastern margin of the Koki deposit (Fig. 5.5b). Isolated stockworks are located in the southeastern half of the Horse/Ivaal deposit, and with other veins and selvages of carbonates that are found throughout the deposit, are probably related to biotitic, propylitic and, less commonly, chloritic alteration.

Copper sulphides are very rarely noted with carbonate-clay assemblages and this type of alteration is primarily post-mineral. In the
Figure 5.17

Features of carbonate-kaolinite and propylitic alteration assemblages

(a) Strong biotitization (B) is overprinted by thin quartz-feldspar-chalcopyrite-molybdenite veins (Q) which have envelopes of K-feldspar-chalcopyrite in Horse microdiorite. These are crosscut by crustiform and porous dolomite-calcite veins (D). The remainder of the rock consists of feldspars that are pseudomorphed by carbonates and a quartz-kaolinite groundmass (scale = 2 cm, sample #D15 130.7).

(b) A dolomite vein selvage (left side of the photograph) in which plagioclase is altered to well-ordered kaolinite (K), apatite is unaltered and the groundmass is composed of dolomite-quartz-kaolinite. This is overprinted by a sericite-quartz selvage to a pyrite-quartz fracture filling (right side of the photograph) which is bounded by a reaction front composed of pyrite, carbonate, and siderite (S) (cross-polarized light, scale = 0.5 mm, sample #D42 146.3).

(c) Zoned crystals in a dolomite vein (D) which truncates an early quartz-pyrite stringer (Q) in the same sample as (b) (plane-polarized light, scale 0.5 mm, sample #D42 146.3).

(d) The soda-rich rim is preserved although the interior of this plagioclase phenocryst is pseudomorphed by kaolinite (K), carbonate (C) and minor anhydrite. A similar assemblage occurs in veins that have thin chlorite selvages which are crosscut by quartz stringers that have sericite selvages (cross-polarized light, scale = 150 microns, sample #D94 400.2).

(e) Chlorite (C), rutile (R), and epidote (E) replace a ferromagnesian mineral in a sample from the propylitic zone of the Koki deposit (plane-polarized light, scale = 100 microns, sample #D8 208.5).

(f) An actinolite (A), quartz, and pyrite vein crosscuts biotite hornfels and is bordered by an envelope leached of biotite (plane-polarized light, scale = 0.5 mm, sample #S154 90.0).

Except for (a) which is a photograph of a rock slab, all others are photomicrographs.
Koki deposit however, these stockworks and veins merge with anhydrite-quartz stockworks. The lack of well-defined crosscutting relations suggest that these stockworks may be contemporaneous. In the Horse/Ivaal deposit, zoned dolomite crystals occur in a vein that has a selvage in which feldspars and groundmass are, respectively, replaced by kaolinite and dolomite (Fig. 5.17b). This vein and selvage is crosscut by a pyrite-quartz fracture filling that has a sericite envelope (Fig. 5.17c).

Carbonate and kaolinite assemblages also occur in transitional alteration zones where they replace plagioclase-phenocrysts (Fig. 5.17d). Vein control in this case, while suspected, cannot be firmly established.

5.4.7 Propylitic Alteration

Propylitic alteration is generally characterized by aggregates of chlorite, carbonate, epidote, rutile, and other finer-grained alteration products that pseudomorph mafic sites (Fig. 5.17e), and sericite and carbonates that replace plagioclase. This alteration fringes the western boundary of alteration-mineralization in the Koki deposit and the southeastern periphery of the Horse/Ivaal deposit. The areal extent increases at the 400 m level (Fig. 5.5b) and virtually surrounds the Koki deposit. This expansion indicates a vertical zonation from upper chloritic and sericitic alteration to deeper propylitic assemblages.

The groundmass of most rock types contains variable proportions of turbid plagioclase, albite, quartz, and K-feldspar which generally occur as very fine-grained mosaics that, in many cases, have an uncertain primary or secondary origin. It also contains many of the alteration minerals previously mentioned in addition to biotite, magnetite, hematite,
pyrite and chalcopyrite. Secondary biotite is locally abundant and presents difficulty in classification. This is especially true where overprinted by vein networks which produce assemblages similar to those of transitional and chloritic alteration. Criteria that are not infallible, but which help distinguish propylitic from other types of alteration assemblages, are the weaker degree of alteration and mineralization and more coarse-grained (commonly ranging up to 1 mm) and euhedral mineral constituents in propylitic altered zones. In addition, chlorite in the propylitic assemblages commonly has anomalous blue-purple-brown interference colors whereas chlorite from other zones normally has first order grey or brown interference colors.

5.4.8 Hornfels and Skarn Zone

Hornfelsed lower Wogamush sediment and a skarn zone that are located at the outer margins of the propylitic zone in the Pish area (Fig. 5.1a) are features that are spatially and probably temporally related to propylitic alteration (Map 3). Hornfelsing of lower Wogamush sediments in this area is dominantly a product of hydrothermal alteration and not a contact metasomatic effect, because other fresh Knob diorite plutons that intrude lower Wogamush sediments at the periphery of the Complex do not have significant contact breccias.

Hornfels is typically composed of submicroscopic (<1μ) minerals that may, or may not, preserve sedimentary features. Within mineralized and intensely altered zones hornfelsed xenoliths generally reflect the alteration zone in which they are located. For example, in the biotitic zone, the rock is normally biotite hornfels. Beyond the 3% copper contour, however, in the propylitic zone, a variety of assemblages occur, and in addition to biotite hornfels, chloritized and silicified
hornfels can be found. The latter two are hard, fine-grained, green and black rocks, respectively, in which the original carbonate content of the host rock is commonly leached out. A less common feldspar assemblage is also noted and occurs as bands that conform to bedding. Microfractures filled with quartz, pyrite or actinolite (Fig. 5.17f) that are commonly enclosed by a leached envelope are also characteristic of hornfels in the propylitic zone.

The skarn zone was not studied in detail and much of the brief description that follows was communicated to the author by A. Takigawa. The skarn zone is located in the Pish area (Fig. 5.1a) at the southwest periphery of the Complex within limy horizons near the Salumei metamorphic and lower Wogamush sediment contact. The zone is a 1600 m by 500 m, irregular, elongate body that strikes north-northwest and dips southsouthwest. Koki diorite porphyry and Horse microdiorite intrusions that contain weak porphyry copper alteration-mineralization are spatially related, but temporal relationships are not clear.

Common irregular pyrrhotite aggregates and minor chalcopyrite and pyrite in blue-black, fine-grained massive magnetite constitutes one skarn assemblage. Another, is a calc-silicate assemblage that is generally peripheral to the massive magnetite and consists of medium to fine-grained epidote, chlorite, quartz, diopside, actinolite, garnet, pyrite, or magnetite. Whereas this assemblage is reasonably stable, the massive magnetite skarn assemblage is highly reactive in the surface environment and quickly decomposes when fresh surfaces are exposed.

5.4.9 Advanced Argillic Alteration

Advanced argillic alteration assemblages have pervasively altered pyroclastic and porphyrytic rocks in the area of the porphyry copper
systems. They have similar petrography to district-scale advanced argillic assemblages which, except for locally distinct features, will not be reiterated here (see Chapter 3, section 3.5.3). The assemblages primarily occur in a series of overlapping zones that erratically fringe the northwest upper and outer end of the Horse/Ivaal deposit (Fig. 5.5a reduced scale inset; Map 8, sections 13 and 17). They are bounded on the inside by the sericite ± andalusite, or chloritic zones and progress outward and upward to the diaspore through the prophylilitie-diaspore and on to an alunite-dominated zone. Although kaolinite-dominated assemblages similar to those of district-scale advanced argillic alteration are not present, kaolinite is associated with these assemblages in lesser amounts (Fig. 5.18c and 5.18d).

Textural features indicate that paragenetic relations between these mineral assemblages are complex and commonly ambiguous at the scale of the microenvironment (Fig. 5.18a to e). Diaspore or related amorphous material generally appears to replace andalusite and alunite and commonly occurs as aggregates in matted or felted patches of pyrophyllite. In other samples, diaspore is crosscut by kaolinite or accompanies alunite, zunyite (Fig. 5.18e) and pyrite in stringers.

There is a striking relationship between alunite and sericite, which have not been observed in contact or crosscutting one another. These minerals are almost always mutually exclusive in X-ray diffraction results of samples from all areas of the Frieda River Prospect except for abnormally large sample splits taken over a 3 m interval from recent shallow drill holes. Even in these large splits both minerals were noted in only rare or trace amounts (see Appendix 2) and could represent mutually exclusive patches in the 3 m interval. The change from sericite to alunite in the advanced argillic alteration zone generally occurs in the
Figure 5.18

Photomicrographs of textural features in the advanced argillic alteration zone

(a) A clot of andalusite (A), pyrite (P), diaspore (D) and minor sericite is set in a matrix of sericite, quartz and opaques. The diaspore appears to be replacing the andalusite (plane-polarized light, scale = 0.5 mm, sample #S162 98.9).

(b) The diaspore (D) replaces alunite (A) in a clot which also consists of pyrite (P) and is enclosed by a matrix of quartz and alunite (plane-polarized light, scale = 150 microns, sample #S202 86.1).

(c & d) Turbid diaspore (D) is more crystalline at its ragged edges. Kaolinite (K) fills a fracture that crosscuts the diaspore and occurs as a matt-texture with pyrophyllite (P). A high-relief, transparent unknown (?) occurs in the kaolinite-pyrophyllite. It was noted in other diaspore-rich samples and may be an intermediate alteration product (c in plane-polarized light, d in cross-polarized light, scale = 0.5 mm, sample #S161 101.0).

(e) Zunyite (Z) is a rare mineral and in this photomicrograph occurs with alunite (A) and Diaspore (D) in a narrow vein. The mineral is characterized by its isotropic property and triangular-shaped inclusions or voids. A vapour phase was noted in one inclusion. Growth bands are apparent at the left side of the photomicrograph (plane-polarized light, scale = 50 microns, sample #S202 86.1).
pyrophyllite-diaspore assemblage where the sericite content is much less than in the inner sericitic alteration zone.

5.4.10 Temperatures of Formation

The temperatures of formation of the porphyry copper alteration zones at the Frieda River Prospect have been investigated through fluid inclusion work (Eastoe, 1976, 1979), mineral-equilibrium relationships and mineral-chemical equilibrium data.

Fluid inclusion work: A reconnaissance fluid inclusion study of the porphyry copper systems undertaken by Eastoe (1976) indicates that the copper mineralization occurred at temperatures ranging from over 600° to as low as 400°C. Eastoe found that later quartz-sulphide, sulphide and sulphate mineralization occurred between 450° and 300°C, whereas white anhydrite was deposited between 150° and 100°C. Characteristics of the inclusions indicate that the fluids boiled and contained 40% or less water and 60% or more ionic salts composed of NaCl, KCl and in certain fluids possibly CaSO₄. In addition to halite, sylvite and possibly anhydrite, hematite, chalcopyrite and three other anisotropic salts were also noted.

According to Eastoe, data from these chemically and physically complex fluids were difficult to interpret because of several factors. Some fluids were heterogeneous when trapped, other inclusions had necked or were contaminated by subsequent cooler, less saline fluids, and still others exhibited a metastability phenomenon that increased the gas homogenization temperature.

Eastoe (1978) completed a much more detailed fluid inclusion study of the Panguna deposit which is located on the island of Bougainville and found that the study emphasized the problems of interpretation of complex fluids, and the complexity of the deposit itself. In contrast to
the Panguna deposit, which has been well exposed by open-pit mining and for which the geology and alteration (Bäumer and Fraser, 1975; Baldwin et al., 1978), alteration geochemistry (Ford, 1978) and stable isotopes (Ford and Green, 1977) was subsequently studied in detail, studies of the Frieda River porphyry copper deposits rely on weathered outcrops and sampling of diamond drill core. Eastoe's work on the Frieda River ore deposits was primarily based on drill core sampling of the Horse and Koki deposit areas that was completed prior to drilling of the Ivaal area and prior to any detailed alteration study (Asami and Britten, 1980; this study). Even so, Eastoe concluded that "although lacking in detail, the fluid inclusion work at Frieda indicates that fluid phenomena similar to those inferred at Panguna took place at Frieda, and that the evolution of fluid compositions may have been more complicated at Frieda." This statement is supported by a long 2 m.y. cooling history, and a series of alteration episodes that are indicated by the complex vein paragenesis in the porphyry copper systems.

Locations and descriptions of samples studied by Eastoe (1979) indicate that most are from the transitional alteration zone and are probably main stage vein episodes. Therefore, based on Eastoe's work, a range between less than 300° and about 600°C is estimated, although because of the problems cited by Eastoe this range is uncertain and possibly too broad.

Mineral Equilibrium Relationships: There are several mineral equilibrium relationships that have been recently established which constrain temperatures in various alteration zones. At the Santa Rita deposit, New Mexico, Beane (1974) has determined a 350° to 550°C temperature range from a biotite-K-feldspar-magnetite assemblage. At El Salvador
(Gustafson and Hunt, 1975) and Butte (Brimhall, 1977) temperatures above 550°C are indicated in the potassic zone by an andalusite-K-feldspar assemblage. Although all of these minerals have been noted at the Frieda River Prospect, they rarely, if at all, form equilibrium assemblages and cannot be used to determine temperatures of formation of the biotite alteration zone.

Constraints on the temperature of formation of the advanced argillic assemblages that are peripheral to the northwest end of the Horse/Ivaal deposit however, can be established through mineral equilibrium relationships. Hemley et al., (1980) have calculated pressure-temperature curves in the system $\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ at low water pressures (Fig. 5.19). The estimated depth of emplacement of the Frieda porphyry copper systems is between about 1.0 to 2.0 Km. If a maximum $P_{\text{H}_2\text{O}}$ equal to about 4 Kb is assumed, then according to Figure 5.19 the assemblages kaolinite-pyrophyllite-diaspore and pyrophyllite-diaspore-andalusite fix temperatures at about 290°C and 320°C, respectively, at the later stages of development of the porphyry copper system. The presence of sericite and alunite in these assemblages indicate high $\text{aK}^{+2}$ and $\text{SO}_4^{2-}$ and could also be produced within this temperature range (Hemley et al., 1969). In addition, the appearance and disappearance of andalusite, diaspore and pyrophyllite indicates a decreasing temperature gradient from inner to outer zones.

Mineral-Chemical Equilibrium Data: Work by Brimhall (1977) has resulted in a model for the partitioning of potassium and sodium between muscovite and alkali feldspar at quartz saturation (Fig. 5.20). His application of this model to the early, pre-Main stage veins at Butte, Montana, imply temperatures in the range 600°C to 700°C for early
(Gustafson and Hunt, 1975) and Butte (Brimhall, 1977) temperatures above 550°C are indicated in the potassic zone by an andalusite-K-feldspar assemblage. Although all of these minerals have been noted at the Frieda River Prospect, they rarely, if at all, form equilibrium assemblages and cannot be used to determine temperatures of formation of the biotite alteration zone.

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Figure 5.19 Calculated pressure-temperature curves in the system Al₂O₃-SiO₂-H₂O at low water pressures (Hemley et al., 1980). An estimated P(H₂O) = .4 Kb gives temperatures of 292°C and 325°C for kaolinite-pyrophyllite-diaspore and pyrophyllite-diaspore-andalusite assemblages. Abbreviations: Kaolinite (K); Quartz (Q); Pyrophyllite (P); Water (W); Diaspore (D); Andalusite (A); Corundum (C).
alteration and mineralization. Brimhall found that phase equilibria applied to the early quartz-alkali feldspar + muscovite + andalusite assemblages at Butte are consistent with this temperature range and imply conditions near the triple point andalusite-alkali feldspar-muscovite in the presence of quartz.

In the porphyry copper systems at the Frieda River Prospect, assemblages that contain variable proportions of quartz, K-feldspar, sericite (or muscovite), and andalusite are common except for those that contain coexisting K-feldspar and andalusite, which are rare. The assemblage quartz-K-feldspar-sericite is common in envelopes to veins from the transitional alteration zone and, as used to investigate the potential application of Brimhall's model at the Frieda Complex.

Of many samples examined, only five proved suitable for microprobe analysis of coexisting sericite and K-feldspar because of the small size and generally turbid nature of the constituents or because of overprinting vein assemblages. Ranges in K/K+Na atomic ratios for minerals from these samples are plotted on Figure 5.20 and individual ratios are listed in Table 5.2. These results show a wide scatter both between and within samples. The scatter might reflect a widely fluctuating temperature environment from much less than 500°C to more than 700°C. There does appear to be a decrease in scatter of K/K+Na ratio for K-feldspar from lower to higher temperatures although this trend is uncertain because of the small sample population. A more likely alternative is that the results indicate a lack of equilibrium between sericites and K-feldspar within individual vein selvages, and that Brimhall's method cannot be applied at the Frieda Complex.
Figure 5.20 Binary (K-Na) compositions of secondary K-feldspar and sericites in transitional alteration vein selvages from the Horse/Ivaal and Koki deposits. Compositions were determined using the electron microprobe and individual analyses are listed in Table 5.2. Theoretical exchange isotherms derived by Brimhall (1977) at $P = 1.0$ Kb are also shown.
Table 5.2  K/K + Na (atomic proportions) for sericites (Ser) and K-feldspar (K) coexisting in transitional alteration vein selvages.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Ser</th>
<th>K</th>
<th>Sample #</th>
<th>Ser</th>
<th>K</th>
<th>Sample #</th>
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<th>K</th>
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<tr>
<td>D9 164.6</td>
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<td>D30 308.2</td>
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5.4.11 Supergene Alteration

To confidently determine alteration zonation it is necessary to understand the characteristic changes of hypogene mineral assemblages through the supergene profile. These changes occur in several horizons which are tabulated and illustrated in an idealized supergene alteration profile through the Horse/Ivaal deposit (Fig. 5.21) and are discussed below in relation to this figure; features of some horizons are shown in Figure 5.22.

Horizons A and A' are SI scree and reworked scree and alluvium, respectively. A small patch of horizon A that caps a ridge-line in this deposit in notable because it is one of the few locations where the chalcocite blanket (horizon E) occurs at a ridge top (Fig. 5.21). Most other ridges are deeply weathered. Preservation of the chalcocite blanket in this area is probably due to the nature of the clayey matrix in SI scree which is impervious to leaching agents.

Textures of hypogene altered rocks are not preserved in soils (horizon B), but are generally preserved in saprolites (horizon C). Deep soil and saprolite horizons are developed in areas of transitional and biotitic alteration, but are poorly or erratically developed in areas of sericitic and advanced argillic alteration due to a number of factors. The high quartz content in these assemblages is a major factor because quartz-rich rocks are more resistant to mechanical processes of weathering. Consequently, differential erosion causes softer saprolites to erode more quickly and leave behind ridges that consist of quartz-rich alteration assemblages (Fig. 5.22a). If soil and saprolite horizons were able to develop the material would tend to slump off of these steep unstable slopes. Attesting to this is slide rubble that consists of soil, saprolite and leached cap fragments which are erratically distributed in
<table>
<thead>
<tr>
<th>Horizon</th>
<th>Range in Depth (Meters)</th>
<th>Average Depth (Meters)</th>
<th>Sulphide, Oxide and Supergene Minerals</th>
<th>Range Major</th>
<th>Avg. % Cu</th>
<th>Range Minor</th>
<th>Avg. % Cu</th>
<th>Au g/t</th>
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<td>A, Alluvium</td>
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<td></td>
<td>Kaol</td>
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<td>2</td>
<td></td>
<td>Kaol</td>
<td>&lt;.01-.1</td>
<td>.02</td>
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<td>C, Saprolite</td>
<td>0-20</td>
<td>5?</td>
<td></td>
<td>Kaol, Ht, Goet</td>
<td>&lt;.01-.1</td>
<td>&lt;.05</td>
<td>0.50</td>
<td>.26</td>
</tr>
<tr>
<td>D, Capping</td>
<td>0-70</td>
<td>30</td>
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<td>Kaol, Ht, Ant, Bro, Cup, Goet, Mal, Neot</td>
<td>.04-.3</td>
<td>1</td>
<td>0.13</td>
<td>.26</td>
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<td>E, Enriched</td>
<td>&lt;20-75</td>
<td>35</td>
<td></td>
<td>Cc, Cov, Caol, Py, Cpy</td>
<td>.5-&gt;2.0</td>
<td>9</td>
<td>1.8 2</td>
<td>.263</td>
</tr>
<tr>
<td>F, Sulphates, Leached</td>
<td>100-300</td>
<td>200</td>
<td></td>
<td>Py, Cpy, Bn, Mo, Au</td>
<td>.3-.7</td>
<td>5</td>
<td></td>
<td>.26</td>
</tr>
<tr>
<td>G, Sulphates, PR, Reserved</td>
<td>&gt;100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.26</td>
</tr>
</tbody>
</table>

1 Enrichment or depletion factor relative to immediate subjacent zone.
2 Minimum estimate.
3 Apparent enrichment of Au in horizon E (M. Eyal, 1983).
creek beds and at fringing break-in-slopes of the ridges. In the biotitic
zone, saprite generally grades into weakly leached but otherwise
relatively well preserved cap rocks of horizon D. Exturc fracture
controlled, rust oxides or copper oxides, such as malachite or azurite,
have been noted but are not economically significant.

Surface exposures of transitional alteration (Fig. 5.22b) are
commonly obscured due to dissolution of sulphides and anhydrite-
minerals that are common at depth, in the transitional alteration zone and
the adjacent sericitic and chloritic alteration zones. Breakdown of these
minerals produces acid waters that cause pervasive leaching and
bleaching, a feature that is uncharacteristic of the transitional alteration
zone. Even where abundant quartz veins remain, classification of
pervasively weathered exposure as transitional as opposed to sericitic or
chloritic alteration can be difficult because quartz stockworks are locally
found in all of these alteration types.

Intensely leached and bleached cap rocks of horizon D are exposed
over wide areas in advanced argillic and sericitic altered zones (Fig.
5.22). Exturc iron oxides, mainly hematite and geothite, are locally
common and form a crust on the surface of outcrops or fill fractures.

Cuprite, although common, although brochantite and malachite
are noted in a small zone at the leached cap-enriched blanket (horizon D
and E interface. Otherwise, these rocks are normally cream-white in
color; are completely leached of sulphides or iron oxides, and contain
what is probably supergene kaolinite in addition to the typical hypogene
minerals. Sericite (M. polymorph) generally retains its ordering, but
in the leached cap and saprolitic horizons, however, ordering in
chlorite is not as well preserved.
Figure 5.22

Representative outcrop in the Ivaal area showing features of the supergene profile

(a) This view looks north-northwest toward the Ivaal area in the middle foreground and the ridge-line of Ekwai Debom in the background. The arrow marks a location on Kosaka Ridge that corresponds to the same point on Figure 5.21. Landslide scars which emphasize the steeply incised nature of the area mark the location of diamond drill sites which are located on commonly deeply weathered ridge lines. The ridge-line of Ekwai Debom is at about 1350 m, the arrow points to 730 m, and the ridge in the foreground is about 700 m.

(b) An outcrop of transitional alteration in which two generations of veins with quartz selvages (a wide selvage parallels the pen) crosscut biotite-chlorite altered Horse microdiorite that has been partially weathered to saprolite (horizon C).

(c) A leached and bleached ridge-top outcrop of sericite-quartz kaolinite cap rock (horizon D) which shows the random blocky type of fracturing that is commonly observed in this type of alteration.

(d) A highly friable texture that parallels the pen in this photograph is a structural feature that aids enrichment but is very susceptible to erosion.
Similar features characterize advanced argillic assemblages, although less work was done on this type of alteration. It is likely that severe leaching and bleaching of alunite-dominated assemblages would eventually destroy any trace of alunite or related sulphides.

Underlying the leached cap is a chalcocite-enriched blanket (horizon E) that is best developed in the Ivaal area of the Horse/Ivaal deposit (see Asami and Britten, 1980). This blanket contains approximately 40 million tonnes that grade 0.85 to 0.90% copper and 0.3g/t gold. It averages roughly 35 m thick and is characterized by chalcocite or digenite and minor covellite that replace mainly chalcopyrite. In the upper sections of the blanket supergene copper sulphides generally completely replace primary copper sulphides but, at deeper levels, only rims and fractures in chalcopyrite are replaced.

Below the enriched blanket is a sulphate-leached zone (horizon F); pristine hypogene altered rocks (horizon G) that are unaffected by supergene processes occur at a deeper level. These zones are described by Asami and Britten (1980, p. 129) and will not be discussed here.

5.5 **STRUCTURE**

Structural features that include fault trends, major strikes to intrusion, and major and local alteration trends have been noted in the area of the porphyry copper systems and are summarized with regional trends in Figure 5.23. Correlation of these structural features between drill holes and surface exposure is generally difficult; this is especially true of fault patterns.

Northeast fault trends dominate structure in the area of the porphyry copper deposits (Fig. 5.1a). These trends roughly parallel the intrusive trend of Flintem trachyandesite dikes that are locally fault-
Figure 5.23 Summary of structural features in the porphyry copper deposits.
bounded and which heal an earlier set of fractures. Because fault zones are easily eroded they are likely to be covered by valley-fill such as scree or alluvium. Two examples are the north-trending fault in central Koki Creek and the northwest fault zone that coincides with Ok Ekwai in the Horse/Ivaal deposit. Both of these fault zones were intersected in drill holes on several sections and, no doubt exerted strong control on the style of erosion in the two areas.

Friable zones which consist of finely-laminated wafers occur in and peripheral to the area of the porphyry copper deposits (Fig. 5.22d). This feature, which is most common in sericitic altered zones, is probably a product of fault displacement. It may be characteristic of blocks located between fault zones or fault surfaces that were subjected to excessive pressure during movement and subsequently crushed.

Major alteration patterns that have been disturbed by fault offsets, trend northwest in the Horse/Ivaal deposit and roughly north-south in the Koki deposit. Mineralization in peripheral areas is also dominated by northwest-striking patterns, although weaker northeast and north-south trends are also apparent. More local alteration trends include structurally controlled veins and relatively narrow pervasively altered zones that crosscut variously altered rocks. These features have not been studied in detail mainly due to poor exposure but also because qualification and quantification of vein trends in strongly weathered outcrops is time consuming. A patch of northeast-trending, sericitic altered zones, that range 1 to 3 m in width are exposed in trenches. They are located between the southeast end of the Horse/Ivaal deposit and the Ekwai area and roughly parallel a weak alteration trend in the area.
Trends to veins mapped within and peripheral to the Horse/Ivaal deposit are subvertical and appear to range 020° to 115°. This range may not be very meaningful because of the small amount of data collected, in relation to a very complex and poorly understood vein paragenesis.

Dolomite-calcite-kaolinite stockworks and pervasive alteration is located in a north-south-trending zone at the eastern margin of the Koki deposit (Fig. 5.5b). It parallels the main axis of the Koki alteration-mineralization and is probably a late feature that was controlled by structural disruption along the Koki diorite porphyry-lower Wogamush sediment contact.

Except for Flintem trachyandesite dikes and Horse microdiorite in the Koki deposit which trends north-south and has been fault offset to unknown magnitudes, most intrusions located in the area of the porphyry copper deposits are oriented northwest. Although the intrusive trend to Ivaal andesite porphyry depends entirely on drill data, it was intersected by at least two drill sections in both the Horse/Ivaal and Koki deposits.

Other structural features of interest that are somewhat enigmatic are the relation between intrusive contacts and between intrusive and lower Wogamush sediment contacts in the porphyry copper systems (Maps 6 and 7). The Koki diorite porphyry-lower Wogamush sediment contact at the eastern edge of the Koki deposit is concordant to bedding attitudes in this area (Fig. 5.1a; Map 2). The massive nature of Koki diorite porphyry suggests that intrusion as a sill is unlikely to account for this concordancy. An alternative is downwarping of lower Wogamush sediments caused by subsidence, followed by later buckling of the more ductile sediments during a later period of folding against the relatively
massive Koki diorite porphyry intrusion. The attitudes of lower Wogamush sediments that dip southwest near the Salumeei contact but dip north near the Koki deposit indicates that the deposit may be located near but lie at an oblique angle to the trough of a syncline.

In contrast to westerly dips to contacts in the Koki area, those at the southeast margin of the Horse/Ivaal deposit dip easterly and are discordant to the relatively steeper southwest dip of the lower Wogamush sediments. This trend suggests that the deposit has been tilted to the northwest. Alteration patterns and stratigraphic relations support northwest tilt of this deposit. Where the Horse/Ivaal deposit lies in relation to the fold pattern is uncertain. The subvertical contacts to the northeast and southwest Horse microdiorite contact in the Horse/Ivaal deposit suggest that either the intrusion was not rotated during folding or that the deposit is located in the hinge zone of a fold.

5.6 DISCUSSION AND INTERPRETATIONS

5.6.1 Geologic History

Development of the porphyry copper systems at the Frieda River Prospect involved a number of major interpreted events which are briefly outlined below and examined in detail in the discussion that follows. Many of the events, but notably episodes of alteration-mineralization, are refined and revised interpretations of Asami and Britten (1980), although most of the theoretical interpretations depend on analogy with other, better exposed and more thoroughly studied deposits. Asami and Britten (Appendix 4, Fig. 9, page 137), schematically illustrate the geologic history of these systems.

Emplacement of premineralization host rocks, the lower Wogamush sediments, Koki diorite porphyry, Debom pyroclastics and Frieda diorite
porphyry was followed by the structurally-controlled intrusion of Horse microdiorite stocks. This intrusion was multi-phase and involved at least two major variants which are individually variable in texture. Alteration zonation is centered on the cupola zones of these stocks (Figs. 5.5a and 5.5b).

Both primary and secondary biotites are found in Horse microdiorite and reflect evolution from late magmatic, to subsequent, related hydrothermal processes. Ivaal andesite porphyry intrusion breccias, which are normally strongly biotitized, followed Horse microdiorite intrusion but post-dated early sericitic and anhydrite alteration-mineralization. Major transitional, chloritic, and sericitic alterations overprint most biotite-altered rocks and at least some followed intrusion of Ivaal andesite porphyry which has characteristics of an intermineralization breccia. Over-printing was controlled by two major events; extensive fracturing or crackle brecciation of wall-rocks near the contacts of Horse microdiorite intrusions which was then followed by mixing of meteoric and magmatic waters and collapse of the system. The subsequent influx of meteoric fluids caused transitional, chloritic, and sericitic alteration and a complex vein paragenesis and emplaced much of the copper, gold, and molybdenum mineralization. Development of the sericitic and propylitic zones beyond significant copper-gold mineralization largely depended on local structure and wall-rock chemistry, in addition to suitable physio-chemical conditions.

Advanced argillic alteration that is marginal to upper sericitic alteration zones was developed concurrently and represents higher-level convection of meteoric waters through units that were previously altered by district-scale advanced argillic alteration.
Biotite-bearing Flimtem trachyandesite dikes (Fta I) are probably closely related to Horse microdiorite intrusion. They are generally more altered and crosscut by a greater abundance and variety of veins than non-biotite-bearing Flimtem trachyandesite dikes (Fta II) which are probably post-mineralization.

5.6.2 Intrusion and Biotitic Alteration

The close spatial relationship between Horse microdiorite intrusions and biotitic alteration assemblages suggests a close genetic link between magmatic and secondary processes. This link will be examined in relation to level, style, and history of intrusion, chemistry of host rocks, and the source and physico-chemical conditions of altering fluids. Many of these features are detailed in Chapters 3 and 4 and will be briefly reviewed here.

The geochemistry of intrusive rock types indicates an andesitic composition that had intrusive-eruptive temperatures between 900°C to 1100°C. An increase in SiO₂ content from earliest Koki diorite porphyry to later Horse microdiorite and Flimtem trachyandesite intrusion and petrographic features suggest that magmas were cumulate-melt mixtures and, therefore, fractional crystallization was the evolving process. Biotite and Fe-Ti oxide compositions indicate oxygen fugacity was high, with conditions lying between the nickel-nickel oxide buffer and below the magnetite-hematite buffer. Increasing Mg/Mg + Fe in amphibole suggests a progressive increase in f₀₂ from early Koki diorite porphyry to Horse microdiorite intrusion.

Reconstruction of the volcanic pile indicates the cupola zones of Horse microdiorite intrusions reached to within 0.5 to 2 km of the surface and, therefore, P_total = 0.1 to 0.5 kb. Emplacement of the intrusions, especially in the Horse/Ivaal deposit, was structurally controlled and was
followed by a cooling period of about 2 m.y. During the cooling or crystallization period, biotitic alteration occurred and was probably related to the evolution and concentration of a magmatic vapour phase toward the end of crystallization in the cupola zones of the Horse microdiorite intrusions. This is a favoured process in the development of porphyry copper systems (Burnham, 1967, 1979; Lowell and Guilbert, 1970; Whitney, 1975) and is thought to be caused by crystal settling which results in a marked increase in the H₂O or volatile content of the melt. A reduction in pressure causes bubbles to form which rise at a relatively rapid rate. Burnham (1979) has further suggested that for rocks of granodiorite to diorite composition, evolution of a vapour phase in which chlorine is strongly partitioned (Kılınc and Burnham, 1972) could maintain \( X^V_{KCl}/X^V_{KCl} + X^V_{NaCl} \) (\( X_\text{v} \) = mole fraction, \( v \) = vapour) at relatively low levels of about 2 and cause Na-metasomatism in the subsolidus regions of the intrusion. As the melt continues to cool and hornblende becomes stable the ratio increases dramatically to about 0.75 and fluids have the potential of extensive K-metasomatism.

Evidence of cumulative-melt mixtures and crystal fractionation suggests a similar process operated at the Frieda River Prospect. Na-metasomatism and K-metasomatism are, respectively, reflected in the soda-rich rims and envelopes to microfractures in plagioclase and the secondary biotite that largely replaces hornblende. Because they affect different phenocryst phases, the temporal relationship between these metasomatic events is not known, but it is clear that they reflect a change in physico-chemical conditions. A sudden change from almost contemporaneous crystallization of primary biotite and hornblende to complete replacement of hornblende by secondary biotite is probably related to the sudden evolution of an alkali-chloride-rich vapour phase.
The similarity in compositions of primary and secondary biotites suggests that the change, although rapid, was an extension of the crystallization of primary biotite or an extension of magmatic processes. It is interesting to note, however, that the TiO$_2$ content of secondary biotite (averages $\pm 3.1$ wt.%) is much higher than that of the hornblende being replaced (1 to 2 wt.%). Although some of the increase may be due to a change in specific gravity from hornblende to secondary biotite, Ti, which is generally considered a relatively immobile element, must have been added.

Burnham (1979) regards the evolution of a subsolidus carapace and vapour phase as a recurring process with concurrent development of dikes and breccia dikes. This carapace is repeatedly breached between episodes which causes a drop in pressure and subsequent evolution of the alkali-chloride-rich vapour phase that causes Na and K-metasomatism. Following each successive breaching of the carapace, outer, cooler fluids flow inward, react with the heated environment and magmatic fluids or vapour, and cause hydrolytic alteration that overprints earlier pervasive biotitic alteration. Although all stages of each episode cannot be defined, the variability in texture of Horse microdiorite, the presence of a fresh core zone, the generally biotitized intermineralization Ivaal andesite porphyry intrusion breccias, texturally and compositionally similar Flin TEM trachyandesite dikes, and a complex series of vein, fracture, and selvage-controlled alteration-mineralization suggest episodic development of a similar system at the Frieda River porphyry copper deposits. However, if biotitization altered successive subsolidus carapaç es, then fracture-controlled and overprinting biotitic alteration episodes, in addition to the pervasive alteration, might be expected. This is not the case at Frieda, where biotitization is always
pervasive and only rare discontinuous lacy microveinlets have been noted. A possible explanation is that biotitization took place above the solidus following crystallization of hornblende but before quenching of the groundmass and was therefore caused by diffusional rather than infiltrational alteration processes.

5.6.3 Transitional, Chloritic, and Sericitic Alteration

Breaching or crackling of the cupola zone of intrusion because of overpressures caused by retrograde boiling (Phillips, 1973) and the successive influx of meteoric-dominated waters was probably responsible for the development of the well-mineralized transitional, chloritic, and sericitic alteration zones. This sequence of events is conjectural as the role of magmatic and meteoric fluids in the development of the Frieda River Prospect porphyry copper deposits has not been investigated through isotopic work. The source of fluids responsible for porphyry alteration and mineralization has been investigated, however, in several other deposits through oxygen and hydrogen isotope studies (Sheppard et al., 1969, 1971; Taylor, 1974; Sheppard and Taylor, 1974; Sheppard and Gustafson, 1976; Ford and Green, 1977). These studies indicate that the porphyry copper systems are generally dominated by magmatic water during the early potassic alteration stages and meteoric water during the latter, and generally outer development of the sericitic or advanced argillic alteration zones. Spatial and temporal alteration-mineralization features that are similar to the isotopically studied deposits suggest an analogous role of magmatic and meteoric waters at the Frieda River deposits.

Mineralogic changes indicate that the $\text{Al}^+/\text{H}^+$ and $\text{Mg}^{2+}/\text{H}^+$ were controlling factors in the development of the transitional, chloritic and
sericitic alteration zones at the northwest end of the Horse Tvaal deposit and at the eastern side of the Koki deposit. According to diagrams plotted by Garrels and Christ (1965) and Parry et al. (1960) at temperatures of 100°C or less (for which thermodynamic data is available), phlogopite, chlorite, K-feldspar, and muscovite are stable within a range of $aK^+$ and $pH$ at a given activity of $Mg^{2+}$ at quartz saturation. Phlogopite, however, is generally not in equilibrium with the other minerals at the Frieda River Prospect which probably reflects high aqueous Mg concentration (Hemley and Montoya, 1971).

Various K-feldspar-sericite-chlorite assemblages that occur in vein selvages of the transitional alteration zone were probably produced by the following reactions:

$$3 \text{Andesine} + 1\frac{1}{2} H_2O + H^+ + 2K^+ \rightarrow$$

$$2 \text{Sericite} + 3(\text{Na, Ca})^+ + \frac{3}{4} O_2$$ \hspace{1cm} (5.1)

$$2 \text{Biotite} + 4H^+ + 2 \text{Chlorite} + 3 \text{Quartz}$$

$$+ (\text{Mg, Fe})^{2+} + 2K^+$$ \hspace{1cm} (5.2)

$$\text{Albite} + K^+ \rightarrow \text{Orthoclase} + Na^+$$ \hspace{1cm} (5.3)

Rutile, which commonly accompanies these assemblages, is not included for simplicity and because it is probably less mobile compared to other elements. In some vein selvages an inner sericite-rich zone (reaction 5.1) is bordered by a chlorite-rich zone (reaction 5.2) and probably reflects an increasing $aMg^{2+}/aH^+$ ratio from inner to outer parts of the selvage. K-feldspar replaces mainly groundmass constituents by simple cation exchange (reaction 5.3) which probably consumed $K^+$ that was liberated by chloritization of biotite (reaction 5.2).
The components released by these reactions, Mg$^{+2}$, Fe$^{+2}$, Na$^{+}$, and Ca$^{+}$, have been redistributed throughout the alteration zones. Ca$^{+}$ liberated by reaction 5.1 later combined with sulphate to produce the abundant anhydrite found in the porphyry systems and, to a lesser extent, carbonates. Assuming adequate sulphur activity the Fe$^{+2}$ was primarily fixed as pyrite, or depending on the Cu$^{+2}$ activity of the hydrothermal solution, was fixed as chalcopyrite or bornite. Excess Mg$^{+2}$ was probably transported into the chloritic alteration zone as indicated by the higher Mg/Fe ratio in the chlorites and sericites, or alternatively, was fixed in later carbonate stockworks as dolomite. Therefore, a change from transitional alteration, in which K-feldspar is a common constituent, to the chloritic and then sericitic alteration zones indicates that the aK$^{+}$/aH$^{+}$ decreased from inner to outer zones (Hemley et al., 1969) and that aMg$^{+2}$/aH$^{+}$ probably peaked in the chloritic alteration zone. The mineralogy and size of these alteration zones were also strongly influenced by the dioritic composition of the progenitor and the bulk chemistry of hosts to intrusions (see Asami and Britten, 1980, p. 135).

The extent to which H$^{+}$ was produced during the evolution of magmatic vapour or during the interaction of the hot magmatic environment with inflowing groundwater also exerted strong control on the development of these alteration zones. Production of H$^{+}$ was probably controlled by interaction of magmatic H$_2$S with oxygenated groundwaters as expressed in the following reaction:

$$\text{H}_2\text{S} + 2\text{O}_2 \rightarrow 2\text{H}^{+} + \text{SO}_4^{-2} \quad (5.4)$$

Early pyrite-quartz veins in the transitional alteration zone and large, rounded and embayed, disseminated crystals indicate the early development of pyrite.
Early pyrite probably closely followed a change in oxidation state from between the magnetite-hematite and nickel-nickel oxide buffers in the magmatic environment to above the magnetite-hematite buffer in some areas of transitional, chloritic and sericitic alteration zones. This increase in oxidation is first noted in areas of incipient transitional alteration where hematite rims magnetite in patches of relatively weakly overprinted biotite alteration. Abundant anhydrite and less abundant hematite that are noted in veins and disseminated in these alterations also indicate high oxidation state. At a microscopic scale, both solid inclusions of red euhedral hematite flakes and hematite and possible anhydrite daughter products in fluid inclusions of quartz veins also attest to a more oxidized environment.

Attempts at determining temperatures of formation in the transitional alteration zone using the method of Brimhall (1977) and K and Na compositions in coexisting sericites and K-feldspars were largely unsuccessful. Preliminary work by Hemley and Montoya (1971) suggests that the K-feldspar-chlorite assemblage which is also commonly found in those vein selvages is stable between 300° and 500°C. This range is similar to the 300° to about 600°C temperature range determined on fluid inclusions by Eastoe (1976, 1979), although the upper temperature of this range may be too high because of metastability effects. Some early main-stage veins and their selvages in the transition alteration zone were probably produced by saline fluids in the upper part of this temperature range. Alteration in the outer, pervasive chloritic and sericitic zones which are commonly bordered by advanced argillic assemblages was probably caused by less saline fluids in the lower end of this temperature range; this is discussed further in the section that follows.
5.6.4 Advanced Argillic Alteration

Development of the advanced argillic alteration assemblages beyond the zone of sericite-andalusite alteration was, in part, controlled by a temperature gradient that decreased from a minimum possible value of 310°C for an andalusite-bearing assemblage to a maximum possible value of 290°C for a kaolinite-bearing assemblage. The complex and commonly ambiguous textural features of the advanced argillic assemblages suggest that conditions fluctuated in time and space over at least this temperature range although the general area of these assemblages is probably a reasonable estimate of the 300°C isograd during the later stages of the development of the porphyry copper systems. Characteristics of this isograd region have important economic and exploration implications because it is in the sericite-andalusite zone that copper and gold grades abruptly drop below .3% and .1 g/t, respectively.

The major chemical control on the development of these assemblages are the activities of $K^+$, $H^+$, and $SO_4^{2-}$. Hemley et al. (1969) have studied the stability relations of alunite at 200, 300 and 380°C with quartz in excess and at about 1 Kb (Fig. 5.24). Pressure has little effect on equilibrium relations of these assemblages except at very low values (see Fig. 5.19), and recently published work by Hemley et al. (1980) indicates that near 300°C the kaolinite stability field changes to pyrophyllite which, like kaolinite, separates the muscovite and alunite fields. The separation of muscovite and alunite-bearing assemblages at the Frieda River Prospect in the region of the 300°C isograd indicates that the fluid flow path passed below the alunite-muscovite-pyrophyllite (or kaolinite)-quartz assemblage invariant point (Fig. 5.24).
Figure 5.24 Stability relations in the system K$_2$O-Al$_2$O$_3$-SiO$_2$-H$_2$O-SO$_3$ with quartz present and at about 1 Kb and temperatures of 300° and 380°C (Hemley et al., 1969). The arrow marks a possible fluid flow path from outer, lower temperature (<300°C) alunite associated with advanced argillic alteration to inner, higher-temperature, K-feldspar assemblages associated with transitional alteration.
5.6.5 Summary of Porphyry Copper Development and Movements of Chemical Components

Various features of spatially and temporally related alteration-mineralization events have been previously discussed. In this section the temperature regimes, oxidation states and movement of chemical components are summarized and integrated on an idealized model of the Frieda River porphyry copper deposits (Fig. 5.25).

Biotitic alteration is an extension of magmatic processes. It was caused by an alkali-chloride-rich fluid/vapour phase that evolved from a hydrated and oxidized cumulate-melt mixture. Temperatures probably dropped rapidly from magmatic (about 900°C) during intrusion to about 500 to 600°C following biotitic alteration.

The influx of oxidized and cooler meteoric water, following sequential breaching of the biotitized carapace and subsequent collapse of a magmatic-dominated fluid system caused transitional, chloritic, sericitic and advanced argillic alteration. Fluids that caused the inner transitional alteration probably had a high magmatic component and fluctuated about the hematite-magnetite buffer and caused K-feldspar associated alteration between about 400 and 600°C. Mineralogic characteristics indicate that temperature and $\text{aK}^+ / \text{aH}^+$ decreased from the transitional to the outer advanced argillic and propylitic zones, although the decrease is not smooth because of the repeated influx of meteoric waters. In both the chloritic and diaspore-pyrophyllite assemblages, the ratio probably increased because $K^+$ was not being consumed and may even have been liberated, whereas $H^+$ was consumed in the formation of chlorite and pyrophyllite. The position of the 300°C isograd fluctuated with time but in the waning stages of the system's evolution was roughly located between the sericite-andalusite and advanced argillic assemblages.
which lie a short distance beyond the outer limit of significant copper-gold mineralization.

Observation of mineral assemblages and fluid inclusions and microprobe analyses allow a first approximation of the movements of other chemical components. MgO is enriched in the chloritic zone relative to inner transitional alteration zone and may be slightly enriched relative to the biotitic zone. It decreases in sericitic alteration and occurs in only trace amounts in the advanced argillic assemblages but, with MnO, increases once again in the deeper-level propylitic alteration zone. CaO in anhydrite and feldspars is abundant in the transitional alteration zones. Decreases in the chloritic and sericitic and increases in the propylitic but is very low in the advanced argillic assemblages. NaO is high in the biotitic and transitional alteration zones but is low in most other zones except alunite-dominated advanced argillic assemblages and propylitic alteration. Sodium as NaCl daughter products in fluid inclusions was noted throughout the alteration zones and was a major constituent of the hydrothermal fluid. The sulphur component is high throughout all alteration zones relative to the central biotitic and fresh core zones. A more quantitative estimate of the distribution, movements, and enrichments of major and trace elements is reserved for Chapter 7.

5.6.6 Comparison With Other Models

The characteristics summarized in the previous section and the geometry of alteration zones help constrain the nature and dynamics of the hydrothermal system which caused porphyry copper alteration-mineralization at the Frieda River Prospect and allow comparison with other proposed models. Recent theoretical studies on the nature of fluid flow and heat transfer in hydrothermal systems with applications to
porphyry copper deposits have been modelled by many authors. One that has received major attention involves convection of groundwater around and through a cooling subsolidus pluton (Norton, 1972, 1978, 1979; Norton and Knapp, 1977; Norton and Knight, 1977; Villas and Norton, 1977; Norton and Cathles, 1979; Cathles, 1977) which leads to ore formation. An alternative is the orthomagmatic model which involves transport of ore components in a magmatic vapour phase to a site of deposition (Burnham, 1967, 1979; Neilsen, 1968; Rose, 1970; Fournier, 1972; Phillips, 1973; Whitney, 1975, 1977). Evolution of magmatic vapour phase during the emplacement and crystallization of calc-alkaline magmas is petrologically possible (Burnham, 1967, 1979; Holland, 1972). Another model involves a plume of low-salinity magmatic gas which is exsolved from a crystallizing pluton and penetrates and interacts with a pre-existing groundwater convection system (Henley and McNabb, 1978). This model has many similarities with that postulated for El Salvador (Gustafson and Hunt, 1975) which involves an evolving early magmatic system that is overprinted by a late groundwater hydrothermal system. It is this latter model that has the most similarities with the history of the porphyry copper deposits at the Frieda River Prospect.

A comparison of features between Horse microdiorite and Knob diorite stocks (both biotite and non-biotite-bearing) which are summarized in Table 5.3 may provide further clues as to which model is most likely to have produced the porphyry copper mineralization at the Frieda River Prospect. A major difference between these rock types, in addition to those associated with alteration-mineralization, is the lack of a substantial metasomatic aureole in either lower Wogamush sediments or volcanics surrounding Knob diorite stocks. If a heat source and subsequent groundwater convection is all that is required to produce
Table 5.3 Comparison of features between Horse microdiorite and Knob diorite

<table>
<thead>
<tr>
<th>Horse microdiorite</th>
<th>Knob diorite</th>
</tr>
</thead>
<tbody>
<tr>
<td>- elongate (100 to 600 m wide, 1000 to 1600 m long), strong structural control, uncertain contacts</td>
<td>- conical-shaped, 200 to 1000 m diameter, regular contacts</td>
</tr>
<tr>
<td>- multi-phase, variable groundmass textures</td>
<td>- possibly multi-phase within individual intrusions; certainly between individual stocks</td>
</tr>
<tr>
<td>- associated with dykes and intrusion breccias</td>
<td>- no associated dykes or intrusion breccias noted</td>
</tr>
<tr>
<td>- partially exposed cupola, deeper level of intrusion</td>
<td>- range from partially exposed, to fully exposed or eroded cupola</td>
</tr>
<tr>
<td>- wide metasomatic aureole of hornfels (50 to 200 m)</td>
<td>- narrow aureoles of hornfels (or volcanics) (1 to 10 m)</td>
</tr>
<tr>
<td>- progenitor to porphyry copper alteration and mineralization</td>
<td>- unaltered or barren</td>
</tr>
<tr>
<td>- saline, multi-phase fluid inclusions</td>
<td>- no multi-phase fluid inclusions noted</td>
</tr>
</tbody>
</table>

Other similarities include: major element chemistry, cooling history, time of intrusion and location in relation to the Frieda Complex.
alteration or mineralization, then at least some of these Knob diorite stocks should have more substantial alteration haloes because in terms of chemistry, time of intrusion, size, and location in the Frieda Complex these rock types are closely related. There is no doubt, however, that local structure played a greater role during intrusion of Horse microdiorite. Local structural control is reflected in the relatively irregular, elongate pattern of Horse microdiorite intrusions, presence of intrusion breccias and Flinnes trachyandesite dikes. The various vein and fracture fillings of transitional and other alteration zones which perhaps evolved in response to retrograde boiling (Burnham, 1967, 1979; Phillips, 1973) during alteration-mineralization events, are additional structural features that are peculiar to Horse microdiorite and not Knob diorite stocks.

These structural features indicate high permeability which probably enhanced groundwater convection and subsequent alteration of areas peripheral to the intruding Horse microdiorite stocks. This is essentially the model of Norton and other workers, and has application not only to the porphyry copper systems but also to district-scale advanced argillic alteration which was probably generated by Frieda diorite porphyry plugs. However, magmas from which these altered intrusions evolved must have had intrinsic properties which were absent in magmas from which the unaltered Knob diorite stocks evolved. A high-sulphur-chloride-water volatile content in the parent melts of Horse microdiorite and Frieda diorite porphyry is a plausible explanation.

It is postulated that the Frieda River Prospect porphyry copper deposits were produced by magmatic vapour separation from a crystallizing magma in the manner described by Burnham (1979) that was previously discussed. Interaction between this vapour, which may have
had the form of a plume (Henley and McNabb, 1978), and cooler convecting groundwater followed shattering of the carapace and host rocks which led to collapse of the system that caused overprinting hydrolytic alteration, deposited mineralization, and effectively resealed the system. This process repeatedly occurred until evolved volatiles could no longer overcome the confining pressure of the rehealed and recently crystallized carapace. Why Horse microdiorite was endowed with characteristics necessary to form the porphyry copper deposits whereas other Knob diorite stocks were not, is enigmatic. The fact that the porphyry copper systems are located at the southeast end of the district-scale advanced argillic alteration suggests related structural control of both events which are perhaps related by processes of volatile concentration at the early stages of magma crystallization in a deeper magma chamber.

5.6.7 Comparison of the Porphyry Copper Deposits at the Frieda River Prospect

The principal features of the porphyry copper deposits are compared and interpreted by Asami and Britten (1980, p. 135). This paper treats the Horse/Ivaal deposit as two separate areas - the Horse area in the southeast, and the Ivaal area in the northwest, because each has distinctive characteristics; the same distinction is used in this discussion.

According to Asami and Britten, a major difference between the deposits was caused by overprinting of early district-scale advanced argillic alteration by later porphyry copper alteration-mineralization. This interpretation was based on variations of host rock chemistry and on the gross geometric relationships of the porphyry copper alteration
assemblages that appear to crosscut the alteration front of the district-scale advanced argillic alteration assemblages (see Asami and Britten, 1980, Fig. 9, p. 137). Although confirmation of this interpretation received particular attention in this study, alternative explanations were also considered.

Variations in chemistry of the progenitor and mineral-forming fluids between the deposits is an unlikely alternative because petrographic features, fluid inclusions and timing of events are similar. Variation in depth of emplacement or post-alteration-mineralization structural disruption are more likely possibilities. To aid the investigation of these possibilities approximate alteration-mineralization zonation from along a line that is central to each of the deposits at the 400 m level (see Fig. 5.5b) is plotted on Figure 5.25. The level for the Upper Prospect area is based on interpretation of surface exposure that is extrapolated to the 400 m level. The location of these lines on Figure 5.25 suggests a higher level of emplacement from the Upper Prospect area to the Horse and Koki areas to the Ivaal area. The tilt to the line representing the Koki deposit pattern may reflect a distortion caused by the host rock's chemistry or a fold disrupted pattern as discussed in section 5.5. The relative levels of the other areas must partially reflect the 15 to 20° northwest district-scale tilt indicated by the plunge to fold axes in other areas of the Frieda River Prospect. A 15° to 20° plunge to the central northwest-striking axis of the Horse/Ivaal deposit would cause 250 to 350 m downward displacement of the Ivaal area relative to the Horse area. There is a 300 m difference between the lines representing the Horse and Ivaal areas on Figure 5.25 which indicates that the district tilt can account for the variation in alteration patterns between or within the deposits rather than, or, in addition to host rock chemistry.
Figure 5.25 Idealized alteration-mineralization model of the porphyry copper deposits at the Frieda River Prospect. The straight lines represent the intersection of a southwest-northeast section and the 400 meter level of the central zone of each mineralized area.
CHAPTER 6

GEOLGY OF THE NENA MINERALIZATION

6.1 INTRODUCTION

The Nena mineralization is located in the central region of the Frieda Complex about 7 km northwest of the porphyry copper deposits. The mineralized zone occupies the northeast facing slope of the main northwest-trending axial ridge of the Frieda Complex. A major water course, the Nena River, has deeply incised and exposed a large section of this ridge at the southern end of the Nena mineralization. Topography, therefore, is very steep and slopes of 30 to 40° or greater are common (see Fig. 6.1).

Investigation of a relatively subtle stream-sediment geochemical anomaly (see Britten, 1977) resulted in the discovery of the Nena mineralization in 1975. Detailed mapping by the author and Ryo Yamada and a 3-hole diamond drill program followed in 1976 and 1977; mapping by Fred Rykema since 1978 and a more extensive drill program are currently underway. The author examined and sampled drill core of the earlier 3 holes and first 8 holes of the current drill program. Representative samples from 7 later holes were provided by Frieda Copper Pty Ltd.; locations of all samples studied are noted on Figure 6.2 and Map 10.

Except for a brief description by Asami and Britten (1980) little has been published on the Nena mineralization although the opaque mineralogy of drill core from several holes has been investigated (Ogushi, 1977; Croxford, 1980).
6.2 GEOLOGY

6.2.1 Volcanics

A volcanic pile that is intruded by Frieda diorite porphyry and Knob diorite stocks is host to the Nena mineralization (Fig. 6.1). The extrusives are generally intensely altered and structurally disrupted, which are features that hamper differentiation of a volcanic pile that is already inherently complex. The volcanics are differentiated as lava and agglomerates, pyroclastics, and silicified tuff-breccia—a classification that is rather loose because some units are difficult or impossible to distinguish, for example, altered crystal tuff and porphyritic lavas. However, characteristic features of this classification are generally discernible in strongly weathered outcrops and therefore the classification is practical for broader-scale field mapping. In addition, it roughly categorizes the volcanic units according to their history and response to alteration processes.

Lava and agglomerate: Massive or brecciated porphyries are characteristic of this unit which trends northwest and occurs stratigraphically above and below the Nena mineralized zone (Fig. 6.1). Mottled colors of purplish-brown are noted in the unit below the mineralization although, in and near a major northwest-trending fault, overprinting hydrothermal alteration has caused greenish-grey sericite-chlorite-montmorillonite-gypsum-dominated alteration; the upper unit is altered to similar assemblages.

The lavas and agglomerates are of andesitic to trachyandesitic composition and have characteristics that are similar to Debom andesite; indeed, the lower unit is interpreted as Debom andesite in Figure 3.1 and in Map 2.
Pyroclastics: Lapilli tuff, crystal tuff, and fine tuff that occasionally contain a muddy or sedimentary component comprise the pyroclastic unit. They are generally intensely altered to advanced argillic assemblages and are the major host to the Nena mineralization. The pyroclastics trend northwest and generally dip southwest; textural characteristics are highly variable over short distances. A reliable marker horizon has not been found although an altered tuff-breccia that consists of unusual white fragments and a black matrix was investigated (Fred Bykema, pers. comm.). Lapilli tuff which contains rounded fragments that may be chalazoidites (Fig. 6.3a) is another possible marker horizon; its predicted attitude has not been investigated by a second drill hole.

Silicified breccia: This breccia could be regarded as a member of the pyroclastic unit because it primarily consists of tuff-breccia and is mainly found in the pyroclastics near the mineralized zone. The unit has been differentiated, however, because it retains relatively distinct characteristics in weathered outcrops caused by intense silicification and because it commonly contains accessory pyroclastic fragments and accidental lithic fragments some of which are structurally disrupted (Fig. 6.3b). Samples of drill core that have not been leached and bleached to variable, light cream-colors normally contain minor quantities of pyrite, alunite, or native sulphur and are richer or darker in color.

6.2.2 Scree and Alluvium

Areas peripheral to the Nena mineralized zone are commonly obscured by typical scree (SI), boulder scree (SII), or alluvium (see Map 2 for distribution). Descriptions of these units are in Chapter 3, section 3.8.1.
6.2.3 Intrusions

Frieda diorite porphyry: Small bodies of altered, subcrowded, hornblende feldspar porphyry that outcrop northeast and southwest of the Nena mineralization are tentatively identified as Frieda diorite porphyry. A similar porphyry that is in fault contact with pyroclastics occurs at the bottom of two diamond drill holes (Fig. 6.1). These intersections suggest that the porphyry expands at depth as interpreted on Section BB', Map 4.

Knob diorite: Both hornblende-bearing (Kd I) and biotite-(pyroxene?)-hornblende (Kd II) Knob diorite variants are located northeast of the Nena mineralized zone. Kd II, like Frieda diorite porphyry, also occurs in fault contact with pyroclastics at depth (Fig. 6.1) where it is generally moderately altered. Texturally and compositionally the unit is similar to the Knob diorite that is described in Chapter 3, section 3.4.2.

6.3 STRUCTURE

Structural disruption of the Nena mineralized zone is clearly indicated by the stratigraphic attitudes and numerous fault planes that have been mapped. From these data faults have been interpreted and are shown bounding major blocks of stratigraphy in the Nena area (Fig. 6.1).

6.3.1 Bedding Attitudes

Most attitudes were obtained from intensely weathered pyroclastic outcrops in the Nena mineralized zone and, in some cases, may be of dubious quality. In addition, shallow-dipping, relatively local faults might reflect slumping of near-surface blocks. Mapping by three geologists, however, indicates an overall southwesterly dip to
stratigraphy; an attitude that was confirmed at depth in oriented drill core (Fred Rykema, pers. comm.).

Geology at the Frieda Complex scale (Map 2) suggests that the Nena is located on the northeast limb of a fault-disrupted northwest-trending syncline. Stratigraphic attitudes are generally consistent within individual fault-bounded blocks but, as indicated beyond the southeast end of the Nena mineralized zone, attitudes can vary considerably between blocks.

6.3.2 Faults

Three major generations of faults have been noted in the area. Northeast-trending faults offset subvertical northwest-trending faults and a shallow, northeast dipping fault which is located at the contact between intrusions and the volcanic pile at the bottom of most drill holes. Offsetting of the shallow dipping fault is based on the assumption that it is constant in attitude (Fred Rykema, pers. comm.). This shallow fault lends support to possible thrust activity in the Frieda Complex area (Davies, 1979) that predates at least northeast fault activity, and perhaps left-lateral wrench displacement along a northwest-trending principal displacement zone; an interpretation that is discussed in Chapter 3, section 3.7.1.

The three generations of faults completely bound a block that contains the major 'know' portion of the Nena mineralization. Within this block strata have vertical or subvertical attitudes in a broad zone of northwest-trending anastomizing faults that together constitute part of a major displacement zone at the northeast margin of the block (Fig. 6.1, section SE3). Attitudes are less steep (55 to 70°) at the southwest margin of the block.
6.4 ALTERATION-MINERALIZATION

The three major types of alteration which are described as oxidized volcanics, district-scale advanced argillic alteration and porphyry copper alteration in Chapter 3 are observed in the area of the Nena mineralization. Oxidized volcanics primarily occur northwest of the mineralized zone and are overprinted by assemblages associated with advanced argillic alteration; they will not be discussed further. Porphyry copper alteration assemblages that are located southwest of the Nena mineralization are associated with Friđa diorite porphyry and appear to crosscut advanced argillic alteration. Within and peripheral to the Nena mineralized zone alteration assemblages are similar to district-scale advanced argillic assemblages, but in addition to quartz, alunite, clay minerals, and pyrophyllite-diaspore dominated assemblages, massive pyrite, native sulphur, anhydrite-gypsum, and other peripheral assemblages are also noted. Except for silification, assemblages are discussed in relation to the Nena mineralization from inner to outer zones in the order pyrite, alunite-native sulphur, and outer alteration assemblages. These are followed by descriptions of porphyry copper-related alteration, the Nena copper-gold mineralization, rutile, and similar mineral occurrences in other areas of the prospect. A description and discussion of supergene alteration concludes this section.

6.4.1 Quartz Ridges and Silification

The ridge and slope in which the Nena mineralization is found (Fig. 6.2) have features of the 'quartz ridges' and silification which are described in Chapter 3, section 3.5.3; briefly they are defined as assemblages that contain between 50 and 90% and, greater than 90% quartz, respectively. Although not differentiated on Figure 6.2, intense silification is commonly associated with silicified breccia (Fig. 6.1) or
native sulphur (Fig. 6.3c) or relatively minor alunite at depth. Except for zones of silicified breccia most of the area designated quartz ridges and silicification on Figure 6.2 probably represents outcrop that has been leached of major amounts of alunite, native sulphur, or, less commonly, pyrite. This outcrop is gritty and porous relative to areas of intense silicification and at lower elevations is generally stained by iron oxides. Supergene processes have commonly obscured textures of finer-grained volcanics.

Quartz veins or stringers, although not a major feature of this type of alteration, occur in drill core from section SE3. Thick (~5 cm), dull, translucent veins have an opaline appearance, whereas thin stringers (Fig. 6.3b) occur with barite which have quartz-rich selvages that are depleted of rutile (Fig. 6.3d).

Cavities lined with quartz crystals (Fig. 6.3e) are a more common feature that is noted in zones of more intense silicification. Below the leached cap these cavities commonly contain crystalline native sulphur (Fig. 6.3c), alunite, or, less commonly, barite.

6.4.2 Pyrite

Three major types of pyrite that have a variety of habits are noted in the area of the Nena mineralization; these are massive (Fig. 6.3f), disseminated (Fig. 6.3g), and fracture-controlled (Fig. 6.3h) pyrite.

Areas that are composed of more than about 30% iron sulphide are defined as massive pyrite zones. They are found within the copper-gold mineralization and outcrop near drill section SE3 (Fig. 6.2). Rich, ocherous-red limonites that are located in the oxide zone northwest and in scattered patches southeast of drill section SE3 are probably the supergene altered products of massive pyrite. In one patch at the base of the slope near SE13 boulders, that consist of laminated crusts of
Figure 6.3

Features of advanced argillic alteration associated with the Nena mineralization

(a) Lapilli-tuff completely altered to quartz-alunite and lesser native sulphur-pyrite-rutile. A friable pyrite vein (P) has a wide selvage in which native sulphur has been converted to a unknown 'sooty' mineral (perhaps pyrite or hydrated iron sulphide?). Black rounded fragments may be altered chalazoidites (cf. Fig. 3.3d) (scale = 2 cm)

(b) Thinly laminated, angular, intensely silicified, tuff fragments and rare enargite-luzonite-barite fragments (E) are cemented by finer clastic material that is altered to pyrite. Irregular, hairline fractures are filled with quartz-barite or later pyrite (scale = 0.2 mm, sample #D89 200.6).

(c) Tuff completely altered to quartz-native sulphur-rutile in the light area is leached to a porous, iron oxide-stained siliceous rock in the darker area of the photograph (scale = 2 cm, sample #D164 63.8).

(d) Photomicrograph of a fragment in a strongly silicified brecciated tuff (see b) that is crosscut by a thin barite (B) vein. The selvage has been completely leached of reticulated rutile (or anatase?) clusters (plane-polarized, scale = 0.2 mm, sample #D89 200.6).

(e) Drusy quartz-lined cavities in an intensely silicified tuff that also contains pyrite and enargite (scale = 0.5 mm, sample #D87 104.0).

(f) Very fine-grained massive pyrite has a 'muddy' appearance and a relatively rare, contorted, thinly laminated texture in this otherwise quartz-bearing rock (scale = 2 cm, sample #R1824).

(g) Photomicrograph of a tuff in which fragments, phenocysts, and groundmass are altered to alunite (A), pyrite (P) and quartz-rutile. Relatively coarse-grained pyrite in the groundmass which commonly has anisotropic overgrowth rims is probably early relative to the finer-grained pyrite (reflected light, scale = 0.5 cm, sample #D87 216.0).

(h) A fine tuff to lapilli tuff completely altered to quartz-alunite and lesser native sulphur-pyrite-rutile is cut by parallel pyrite veins that have selvages in which groundmass-native sulphur has been altered to pyrite. A volcanic fragment (F), in which phenocrysts have been altered to relatively coarse-grained native sulphur and pink alunite is cut by a
thin pyrite vein and selvage; it illustrates the reactive nature of the
groundmass relative to fragments. There appears to be several diffusion
gradients associated with the formation of pyrite across these selvages
(scale = 2 cm, sample #D110 119.0).
limonite with cemented leaves and twigs, represent exotic limonite derived by subsurface leaching of a massive pyrite zone followed by spring deposition at the surface.

Massive pyrite consists of dense, very fine-grained sulphides that are commonly less than 10 microns in size. Closely packed generally isotropic pyritehedrons or faceted growth-zoned crystals commonly have overgrowths of anisotropic pyrite and are cemented by finer-grained interstitial sulphides and quartz. Thinly laminated (Fig. 6.3f), flow laminated or multi-brecciated fragments in massive pyrite (see Fig. 3B, Appendix 4, p. 133) suggest a near surface or syngenetic origin for at least some massive pyrite although replacement textures are more common. The most important feature of the massive sulphide zone is its close association with the copper-gold mineralization; this relation is discussed in a later section.

Disseminated pyrite is a common constituent in parts of the alunite-native sulphur assemblages which fringe the massive pyrite zone. Of two major size populations those between .001 and .01 mm are abundant and those between 0.5 and .2 mm are less common (Fig. 6.3g). They occur as individual cubes, pyritehedrons, or anhedral crystals that are commonly growth zoned and have overgrowth rims. Pyrite also replaces fragments and aggregates that consist of crystals cemented by interstitial iron sulphides (Fig. 6.3g). Larger-grained (up to .5 mm) striated cubes of pyrite are commonly disseminated through outer alteration zone assemblages.

Fracture-controlled pyrite is a feature of diamond drill hole #110. It occurs in parallel fracture fillings and related vein selvages that are nearly perpendicular to the drill core axis (Fig. 6.3h), is very fine-grained, and clearly post-dates alunite-native sulphur alteration.
6.4.3 Alunite and Native Sulphur

These minerals are widespread in the immediate area of the Nena mineralized zone where they are peripheral to the massive sulphides and except for isolated veins are not found in the massive sulphide zone. In this area native sulphur is easily identified by its vitreous yellow color. In contrast, alunite which has a variety of habits and colors can be difficult to recognize. This is especially true of mixtures of cryptocrystalline (about .001 mm or less) quartz and alunite which together with minor rutile can impart dull cream-white, grey-brown, brown, or pink colors to the rock. However, patches of larger grains (<.05 to .2 mm) intergrown with pyrite and quartz, or subhedral blades or equant crystal aggregates of mainly alunite that replace phenocrysts (Fig. 6.3g) or fragments (Fig. 6.3h) also occur in most samples.

Vein-controlled alunite is not visible in surface exposures but is found in drill core from the northwest area. The veins are from .5 to 1 cm wide and are filled with chalk or milky white, dark brown, or grey-brown, very fine-grained, porcelain-like alunite of variable hardness depending on quartz content. A translucent, milky-white coarsely crystalline (1 to 3 mm) variety of alunite that fills an open space associated with copper minerals and native sulphur was originally identified as barite.

According to the method of Cunningham and Hall (1976) (see Chapter 3; section 3.5.3) alunites range from .3 to .7 in K/K+Na (atomic proportions) and average about .6 in the area that borders and overlaps the mineralized zone (Fig. 6.2).

Orthorhombic, granular or crystalline native sulphur most commonly replaces phenocrysts or fragments, with or without alunite (Fig. 6.4a) or fills interstices in the groundmass. The sulphur is generally very
Figure 6.4

Alunite-native sulphur, pyrophyllite-diaspore and anhydrite

gypsum-native sulphur alteration assemblages

(a) Bedded tuff-breccia completely altered to alunite-quartz and lesser native sulphur and pyrite. Some fragments are selectively replaced by pyrite-quartz (1), native sulphur-quartz (2), or alunite-native sulphur-quartz. Abundant, thin discontinuous filaments (F) are filled with native sulphur or alunite (scale = 2 cm, sample #D105A 262.7).

(b & c) Kaolinite(K)-diaspore(D) and pyrophyllite(P)-kaolinite replace feldspar at the inner (b) and outer (c) portions, respectively, of a selvage to a gypsum-anhydrite-native sulphur vein (plane-light, scales = 250 microns, sample #D106 218.2).

(d) Tuff breccia altered to quartz-gypsum-pyrite-anhydrite is crosscut by an irregular stockwork of gypsum-native sulphur-anhydrite veins (scale = 2 cm, sample #D104 44.0).