CHAPTER 6

METAL DISTRIBUTION, ZONING AND RATIOS
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METAL DISTRIBUTION, ZONATION AND RATIOS

6.1 Introduction

In this chapter, the distribution of precious and base metals in the PBH and Kerikil deposits are documented. The distribution and zoning of metals in ore deposits can help to delineate fluid pathways and the physio-chemical conditions of metal transport and precipitation (e.g., Broderick, 1929, Cu districts of Upper Michigan; Brown, 1935, Austinville District, Virginia; Goodell and Petersen, 1974, Julcani Mining District, Peru; Gemmell et al., 1988, Fresnillo, Mexico).

Geochemical data for the Mt Muro deposits were compiled from exploration and mining metal assays. These assays included Au, Ag, Cu, Pb and Zn from surface samples and diamond drill core samples that were recorded in the Mt Muro database and historical logs. Cu, Pb and Zn assays had to be manually entered into the IMK database from historical logs, since only Au and Ag assays had previously been used during mine planning and development. Only sparse assays for antimony and arsenic were available, and were not used in this study. All IMK assays were determined by conventional methods using an Australian commercial laboratory and are based on 1 m core sample splits. In this study, selected cross-sections were examined that span the vertical and lateral extent of the deposits. At PBH, these sections comprise 50 drill holes and 2625 assays, and at Kerikil, 55 drill holes and 4645 assays.

6.2 District metal distribution

The distribution of metals on a district-scale at Mt Muro can be determined from exploration assays on surface samples (taken from top of bedrock and soils). Two large magnetite destruction halos (from aeromagnetics) correlate roughly with Au values greater than 20 ppb in soils (Fig. 6.1). Cu, Pb and Zn values in excess of 100 ppb are coincident with the silicified peaks of Mt Muro and Ganung Baruh and are enclosed by the magnetite destruction haloes associated with the PBH and Kerikil deposits (Fig. 6.1). Patchy higher
Figure 6.1 Mt Muro CoW gold and base metal surface anomalies

Areas of low level gold (> 20 ppb) and base metals (> 100 ppb) on the Mt Muro CoW, showing the strong correlation with areas of magnetic destruction (outlined in orange) and dominant structural directions deduced from SAR and magnetic imagery. Metal values are from the JMK exploration database and represent assays of samples collected from soils and at the top of bedrock.
Au values define broadly northwest and north-south trends that may correspond to confinement of mineralizing fluids along northwest and north-south trending structures. Areas of base metal anomalism, coincident with the silicified Mt Muro and Ganung Baruh peaks, may correspond to higher temperature areas at the centre of the original PBH and Kerikil hydrothermal systems.

6.3 PBH metal distribution

The PBH deposit is represented by several north-south to north-northwest striking, 2200 m long, mineralized structures (see Chapter 4, Fig. 4.9). Metals are hosted by veins and breccias and are present in stage 3 microcrystalline quartz + sulfide + sulfosalt and stage 4 crystalline quartz + sulfide (see Chapter 5).

6.3.1 Vertical metal distribution at PBH

Precious and base metal assays were averaged across mineralized deposit intersections through the main PBH structure. The database of intersection assays used in this study comprised 385 points across the length, width and depth of PBH. Averaged metal values were plotted with respect to upper, middle and lower zones to determine metal variation with respect to depth (Fig. 6.2 and Table 6.1). Precious and base metals were also plotted on a representative cross section to show the distribution of metal values within the main PBH structure (Fig. 6.3). RL refers to relative level and corresponds to the height in meters above sea level.

In general, Au and Ag values at PBH increase with increasing RL from an average 0.76 g/t Au and 31.4 g/t Ag below 100 RL, to 2.3 g/t Au and 85.4 g/t Ag above 100 RL (Fig. 6.1 A and Table 6.1). Cu values appear to increase slightly at 150 RL (Fig. 6.2 A and Table 6.1). Pb and Zn values increase with depth from an average of 486 ppm Pb and 569 ppm Zn above 150 RL, to 963 ppm Pb and 1732 ppm Zn below 150 RL (Fig. 6.2 A and Table 6.1).

A drill hole cross section along line 12000 N at Hulubai was selected as a representative section to examine the distribution and zoning of precious and base metals with respect to the main PBH structure (Fig. 6.3). This section was also used in the detailed examination of volcanic architecture and alteration, and therefore has the most
Figure 6.2 PBH mean metal values vs. relative level (RL)

<table>
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<th>Level System (RL)</th>
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</table>

Table 6.1 Summary of PBH metal values vs. relative level (RL)
Figure 6.3 Contoured metal grades on cross section 12000N, PBH

Metal grades taken from diamond drilling on section 12 000N. Metal grade contours intervals used in this figure are the same as for Fig. 6.8. Geological and alteration cross sections are provided in Figs. 3.15B and 7.2B, respectively.

A  Gold: grades increase above 145 RL in the main mineralized structure and the hanging-wall structures.

B  Silver: grades increase above 145 RL in the main mineralized structure and there are low silver grades in the hanging-wall structures.

C  Lead: grades increase below 145 RL in the main mineralized structure.

D  Zinc: grades increase below 125 RL in the main mineralized structure.
geological constraint (see Fig. 3.15 B and Fig. 7.2 B). As shown in Figure 6.3, precious and base metals are confined to the main PBH structure and hanging wall split vein. Au and Ag values increase in the main structure and hanging wall split vein at Hulubai at 125 RL, while Pb and Zn values increase below 125 RL (Fig. 6.3 A, B, C and D). Cu values are elevated across the whole structure and increase above 125 RL (Fig. 6.3 E). In general, metal distribution on the 12000 N section is consistent with the pattern observed for averaged data plotted against RL for the whole PBH deposit (Fig. 6.2 A and B compared with Fig. 6.3).

6.3.2 Lateral metal distribution at PBH

Au and Ag values at PBH are highest in the main PBH north-northwest to northsouth striking structure and also at the intersection of the north-south and northwest striking structures at Permata and Hulubai. Au and Ag values are generally low in the northwest trending structures.

Base metal values are elevated along the main PBH structure and increase at the intersection of a northwest structure at Permata. This is consistent with geological observations of coarse chalcopyrite associated with stage 4 infill in this region of the deposit (Chapter 5). Highest base metal values occur in the southwestern portions of the northwest striking structures. Elevated base metal values define the northwest striking structures and northwest orientated veins, such as Maantung and Julaan Bukit (Fig 6.5 A). Zn and Pb values are also elevated in northwest, and to a much lesser extent, northeast striking structures.

North-northwest striking structures at PBH are defined by Au, Ag and Cu, and to a lesser extent, Zn and Pb. Northwest striking structures are defined by base metals. Since the base metal values generally increase towards the south, a source for base metals is implied to be to the south of PBH. This trend in base metal values is coincident with base metal anomalism south of the PBH deposit that is shown on the CoW anomalism map (Fig. 6.1).

Precious metal values were plotted on long sections to determine their lateral and vertical distribution along the main Permata and Permata North deposit (Fig 6.4 A and B). The distribution of metals illustrated in this section highlight the lithological and structural
Figure 6.4 Permata long section of contoured precious metal grades

A. Gold grades display a long section of contoured precious metal grades at Permata. Higher gold values are generally associated with the northwest striking basaltic andesite dyke and the intersection of northwest striking structures.

B. Silver grades display a long section along the same Permata and Permata North dyke at Permata. A high grade of the northwest striking structures. High grade silver values are generally associated with the northwest striking basaltic andesite dyke and the intersection of northwest striking structures. Lower grade silver values are generally associated with the northwest trending Long section (RL).

Key

- >5 ppm Au
- >1 ppm Au
- >0.5 ppm Au
- <0.5 ppm Au
- >50 ppm Ag
- >5 ppm Ag
- >1 ppm Ag
- <1 ppm Ag
controls to PBH Au and Ag values. Low Au and Ag values shallow (above 130 RL) towards the northern and southern extremities of the structure, and deepen (below 50 RL) at the intersection of cross cutting northwest striking structures at 30300 N, Perronata. High Au and Ag grades are irregular with most occurring between the 100 and 150 RL level (Fig. 6.4 A and B). The plunge on some of the ore shoots is consistent with the plunge on the host volcanics, indicating a lithological control to mineralization.

High Au values at the 150 RL level are coincident with other geological evidence for boiling (Chapters 5 and 8). Bonanza Au and Ag values extend below 150 RL at the intersection of the northwest and north-northwest striking structures, which may suggest telescoping of mineralization or a zone of higher permeability (Fig. 6.4 A and B).

6.4 PBH metal ratio studies

Metal ratios were used to determine possible fluid flow vectors along the PBH deposit. Representative intersections distributed along and through the main PBH structure were chosen and averaged to produce single point values for Au, Ag, Cu, Pb and Zn. In all, 41 intersections along the length and depth of the deposit, both within and below the ore zone, were examined. Metal ratios were plotted (as opposed to metal values) because using metal values on vein long sections is often indicative of ore shoot geometry, such as width and permeability, rather than physiochemical changes along the structure. In contrast, metal ratios reflect the change of the chemical character of the material deposited, are independent of the amount of material deposited, and are more indicative of the physiochemical character of the mineralized fluid (Goodell and Petersen, 1974). A metal ratio is determined by taking the value of one metal for a given point or intersection and dividing it by the value of another metal for the same intersection, therefore making the number independent of the amount of metal present. By using metals that precipitate from the fluid under different physiochemical conditions, it is possible to map gradients such as temperature, salinity and/or dilution (Goodell and Petersen, 1974). For example, by using an element that reflects a low temperature depositional environment and dividing it by an element which represents a high temperature depositional environment, it is possible to predict high and low temperature areas of ore deposition. Generally, fluid will flow from the high temperature to the lower temperature regions and vectors can then be
Figure 6.5: PBH hand contoured metal ratio long sections.

A. Map of the PBH deposit showing the surface expression of the PBH vein and pattern of important structural features and long section trace. This shows the problems of Fig. 6.3 and Fig. 6.4 deposit. The location of the long sections is depicted in Fig. 6.5 C, D, and E, represented by the line "X." -

B. Hand contoured Cu/Pb ratio for PBH showing the major crosscutting sheet from the northwest and southeast trending, in Permata and Hulubai. Contours are depicted for the 1.5, 1.0, and 0.5 main values. Black areas represent fluid flow directions.

C. Hand contoured Ag/Pb ratio for PBH showing the minor crosscutting sheet from the northwest and southeast trending, in Permata and Hulubai. Contours are depicted for the 0.5 main value. Black areas represent fluid flow directions.

D. Hand contoured Au/Pb ratio for PBH showing the major crosscutting sheet from the northwest and southeast trending, in Permata and Hulubai. Contours are depicted for the 0.1 main value. Black areas represent fluid flow directions.

E. Hand contoured [Bi, Pd] x 1000 ratio for PBH showing the major crosscutting sheet from the northwest and southeast trending, in Permata and Hulubai. Contours are depicted for the 5.0 and 0.1 main values. Black areas represent fluid flow directions.
determined for fluid flow.

In this study, metal ratios (including Cu/Pb, Ag/Pb, Ag/Cu, and [Au/Pb] x 1000) were used to determine possible fluid flow directions at PBH (Fig 6.5). These ratios, with the exception of [Au/Pb] x 1000, are similar to those used by Goodell and Petersen (1974) to imply fluid movement direction in veins of the Julcani District, Peru. The [Au/Pb] x 1000 ratio was postulated and tested at PBH and Kerikil based on previous investigations into metal zonation in this study. In particular, the fact that Pb is in higher concentrations in deeper, and possibly hotter, parts of the system and Au in the shallower, possibly cooler, parts of the system, suggests that this ratio would be useful to highlight physiochemical gradients in these deposits. The Au/Pb ratio was typically very small (generally $10^{-3}$), due to the large difference in Au to Pb abundance in the deposit. Therefore, the ratio was multiplied by 1000 ([Au/Pb] x 1000) for ease of use in contouring and presentation.

All the metal ratios determined at PBH, including Cu/Pb, Ag/Pb, Cu/Pb and [Au/Pb] x 1000, show that there is a general movement of fluid from deep to shallow levels (Fig. 6.5 B, C, D and E). In addition, plotting the Cu/Pb, Ag/Cu and [Au/Pb] x 1000 ratios give larger values to the north and south away from intersecting northwest striking structures (Fig. 6.5 B, D and E). The [Au/Pb] x 1000 ratio locates the intersection of the northwest striking structures as areas of low [Au/Pb] x 1000 values, and consequently high temperature. Above 125 RL, the north-northwest structure has high [Au/Pb] x 1000 (Fig. 6.5 A and E). An increase in the [Au/Pb] x 1000 upwards and outwards (hence indicating a decrease in temperature) occurs to the north and south away from the intersection of the northwest striking structures (Fig. 6.5 E).

### 6.5 Kerikil metal distribution

The Kerikil deposit consists of three main north-south to north-northwest striking mineralized structures; Kerikil 1, 2 and 3, totaling 1000 m in length. (Chapter 4, Fig. 4.13). Metals are hosted by breccias and, to a lesser extent, veins. Metals are present in stages 2 microcrystalline quartz + sulfide + sulfosalt, stage 5 rhodochrosite + sulfide + sulfosalt and stage 8 crystalline quartz + sulfide (Chapter 5).
6.5.1 Vertical metal distribution at Kerikil

Precious and base metal assays were averaged across mineralized deposit intersections through the Kerikil 1, 2 and 3 structures. The database of intersection assays consisted of 928 points across the length of Kerikil 1, 2 and 3. Averaged metal values were plotted against RL at 50 m intervals across the deposit to represent upper, middle and lower zones and to determine metal variations with respect to depth. Unaveraged precious and base metal values were also plotted on a representative cross section (line 6700 N) to show the distribution of metal values within the main Kerikil 2 structure. This section was chosen because it was also used in the examination of volcanic architecture and alteration and therefore has the most geological constraints (see Figs. 3.17 B and 7.9 B).

At Kerikil, maximum precious and base metal values occur at roughly the same level. The highest Au, Ag, Cu, and Pb values occur between 100 and 150 RL (Fig. 6.6 A and B and Table 6.2), with maximum Au and Ag values of 403 g/t and 12566 g/t, respectively. All metals decrease above 200 RL, and also decrease sharply below 100 RL (Fig. 6.6 A and B). The abrupt decrease in Au and Ag below 100 RL and increase above 100 RL is the most prevalent feature of vertical metal distribution at Kerikil. In contrast to PBH, zoning of base and precious metal values with respect to elevation is not as evident at Kerikil. However, a subtle increase in base metals in the deepest portions of the Kerikil deposit is similar to that seen at PBH.

As shown in section 6700 N (Fig. 6.7), precious and base metals are confined in stockwork veins and breccias at the margins and within the main Kerikil structure. Au, Ag, Cu, Pb and Zn values peak between 125 RL and 200 RL (Fig 6.7). There is an increase in Pb and Zn below 50 RL. The metal distribution pattern is consistent with averaged metal data plotted against RL determined for the whole Kerikil 1, 2 and 3 deposits (Fig. 6.6 A and B and Fig. 6.7).

6.5.2 Lateral metal distribution at Kerikil

Elevated Au and Ag values occur along north-northwest striking structures at Kerikil and increase at the intersection of these structures with north-south striking structures. Cu, Pb and Zn values are highest at the intersection of northwest striking structures and north-south striking structures and are lower along late northeast striking
Table 6.2 Summary of Kerikil metal values vs. relative level (RL).

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<th>SD</th>
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<td>164</td>
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Figure 6.6 Kerikil mean metal values vs. relative level (RL).
Figure 6.7 Hand-contoured metal grades on cross-section 6700N, Kerikil 2

Nb. Equivalent geological and alteration cross-sections are provided in Figs 3.17 B and 7.9 B, respectively.

A Hand-contoured gold grades taken from diamond drilling on cross section 6700 N.
B Hand-contoured silver grades taken from diamond drilling on cross section 6700 N.
C Hand-contoured lead grades taken from diamond drilling on cross section 6700 N.
D Hand-contoured zinc grades taken from diamond drilling on cross section 6700 N.
E Hand-contoured copper grades taken from diamond drilling on cross section 6700 N.
Figure 6.8 Kerikol hand-contoured gold grade long sections.

A: Kerikol 2 long section with hand-contoured gold grades, showing trend of north-northwest structures and volcanic layer on shallow dipping high grade shoot. Gold grade shoots shown be controlled by volcanic layering. INSET shows intersection.

B: Kerikol 3 long section with hand-contoured gold grades, showing trend of north-northwest structures and volcanic layer on shallow dipping high grade shoot. INSET shows intersection.

C: Kerikol 1 long section with hand-contoured gold grades, showing trend of north-northwest structures and volcanic layer on shallow dipping high grade shoot. INSET shows intersection of north-northwest structures.
Figure 6.9 Kerlkit hand contoured silver grade long sections.

A: Kerlkit Z-long section with hand contoured silver grade, showing potential northwest mining envelopes and volcanic layering indicating high grade shoots. Silver grade appears to be associated with volcanic layering. (Inset) shows the plan view A.

B: Kerlkit Z-long section with hand contoured silver grade, showing potential northwest mining envelopes and volcanic layering indicating high grade shoots. INSET shows the plan view B.

C: Kerlkit Z-long section with hand contoured silver grade, showing potential northwest mining envelopes and volcanic layering indicating high grade shoots. INSET shows the plan view C.
structures. Pb has very weak values associated with the north-south striking structure and weak values associated with the northwest striking structure and intersection of northwest and north-south striking structures.

Lithological and structural controls to Kerikil Au and Ag grades are apparent in long section (Figs. 6.8 and 6.9) and maximum metal values are associated with the intersection of north-south striking structures. Ore shoot plunges at Kerikil 1, 2 and 3 are consistent with the 50° dip on volcanic layering, implying a lithological control to precious metal distribution and possibly the paleo-hydrology of the hydrothermal system. High precious metal values occur in the deeper parts of the deposit (below 130 RL), where northwest striking structures intersect the north-south striking Kerikil deposit. This relationship suggests that the northwest striking structures are an important focus for fluid flow, while outflow may be constrained by volcanic layering. Elevated Au and Ag grades (>5 ppm Au and >100 ppm Ag) occur between 100 and 225 RL at Kerikil 1; between 75 and 225 RL at Kerikil 2; and between 125 and 175 RL at Kerikil 3 (Figs. 6.8 and 6.9). Consistently high Au and Ag values above 100 RL at Kerikil 1, 2 and 3 suggests a physical link to metal precipitation across the three deposits.

6.6 Kerikil metal ratios

Metal ratios, including Cu/Pb, Ag/Pb, Ag/Cu, and [Au/Pb] x 1000, were used to delineate physiochemical gradients and fluid flow directions along the main mineralized, north-south striking structures at Kerikil 1, 2 and 3 (Fig. 6.10). Metal ratios were determined by using representative intersections distributed through the main Kerikil structures. These intersections were averaged to produce point values for Au, Ag, Cu, Pb and Zn. In all, 119 intersections along the length, width and depth of the deposit, including the ore zone and deeper elevations, were examined.

All metal ratios at Kerikil (including Cu/Pb, Ag/Pb, Cu/Pb and [Au/Pb] x 1000) indicate that there is a general movement of fluid from depth to shallow elevations (Fig. 6.10 B, C, D and E). At Kerikil 2 and 3, Cu/Pb, Ag/Cu and [Au/Pb] x 1000 ratios all increase to the north and south away from the intersection of northwest striking structures (Fig. 6.10 A, B, D and E). Low values of the [Au/Pb] x 1000 ratio accurately locate the intersection of the northwest structures at Kerikil 2 and 3, suggesting higher depositional
Figure 6.10 Kerikil hand contoured metal values long sections.

A. Map of the Kerikil deposits showing the surface expression of the mineralisation and prominent structural and mineral alteration trends. Insets show isopach maps of the Kerikil deposits. The location of isopach sections through Kerikil 1, 2 and 3 is displayed in Figure 6.10A. B and C is isopach map of the Kerikil 1, 2 and 3 deposits.

B. Hand contoured Cu/Pb values for Kerikil 1, 2 and 3 at 10 m above the surface in the Cu/Pb ratio.

C. Hand contoured Ag/Pb values for Kerikil 1, 2 and 3 at 10 m above the surface in the Ag/Pb ratio.
Figure 0.1: (Cont.) Kerikil hand contoured metal long sections.

E. Heli-coil counterbored at 0.1 in.

F. Copper clips on 0.2 in. wide. Heli-coil (0.1 in. - 0.002 in.)

G. Copper clips on 0.2 in. wide. Heli-coil (0.1 in. - 0.002 in.)

H. Copper clips on 0.2 in. wide. Heli-coil (0.1 in. - 0.002 in.)
temperatures (Fig 6.10 E). The \[\text{Au/Pb} \times 1000\] ratio also indicates a decrease in
temperature upwards and outwards to the north and the south away from the intersection
of the northwest striking structures. At Kerikil 1, \[\text{Au/Pb} \times 1000\] values increase with
elevation above 125 RL, suggesting a decrease in temperature with elevation and minimal
lateral fluid flow.

6.7 Summary

On a district-scale, surficial Au and base metal anomalism correlate with major
structural trends and alteration zones delineated from geophysical radiometric and
magnetic imagery.

A distinct vertical metal zonation is recognized at PBH (Fig. 6.11). Au and Ag values
decrease with depth, while Pb and Zn values increase with depth. Cu values increase at a
specific height in the system (above 125 RL). In contrast, vertical zonation of metals at
Kerikil is not well developed. Au, Ag, Cu, Pb, and Zn all exhibit high values at
approximately the same elevation (between 125 and 200 RL). High Pb and Zn values do,
however, occur at depth (Fig. 6.11). Precious metal deposition between 100 RL to 200 RL
at both PBH and Kerikil may indicate that both systems were formed at a similar paleo-
level, in response to boiling at hydrostatic pressures.

Lateral distribution of metals at PBH and Kerikil exhibit a similar relationship to
faulting. Elevated Au and Ag values occur in the north-south and north-northwest
trending dilational structures, and high Cu, Pb and Zn values in northwest striking
structures. Long-section projections provide additional information on ore shoot
geometry. Variation in elevated Au and Ag grades at both PBH and Kerikil correlate well
with primary host rock layering, as well as intersections of the deposits with northwest
striking structures. Metal distribution and metal ratios suggest that northwest striking
structures were an important conduit and focus for hydrothermal fluids, which migrated
along dilational north-south and north-northwest trending structures from the intersection
of the northwest-striking structures at both PBH and Kerikil. It is likely that dilation of the
north-south and north-northwest striking structures created open space and pressure
release conducive to boiling and/or mixing, leading to precious metal deposition.
**Figure 6.11 PBH and Kerikil vertical metal distribution and relative metal abundances**

Vertical distribution of metals at PBH and Kerikil. The figure shows zonation of precious metals above 150 RL and base metals below 150 RL at PBH, and a lack of systematic metal zonation at Kerikil. The elevations which exhibit evidence of boiling are shaded. The base of oxidation is included to demonstrate that zonation effects are not a result of supergene processes.
CHAPTER 7
ALTERATION FACIES, DISTRIBUTION AND
GEOCHEMISTRY
7.1 Introduction

Hydrothermal alteration is the result of the interaction of a hot mineralizing fluid with the host country rock (Simmons and Browne, 1990). The mineralizing fluids responsible for alteration within an epithermal system can vary both laterally and vertically along a vein, in response to changes in pressure and temperature, fluid composition and wallrock interaction. The alteration of the host rock often reflects changes in response to these variables (e.g., Browne and Ellis, 1970; Hedenquist, 1990; Reyes, 1990; Corbett and Leach, 1996).

Previously, Simmons and Browne (1990) carried out preliminary investigations on the rank, intensity and character of alteration associated with the Kerikil deposit (using thin sections and XRD). In this study, alteration mineralogy at both PBH and Kerikil was determined with the aid of field, hand specimen and thin section observations, as well as SWIR spectral analysis, XRD analysis and feldspar staining. Detailed transects were completed across the deposits at a mine-face level and using DDH sections to determine the distribution of alteration assemblages. Alteration facies are defined by the dominant alteration minerals present within the alteration assemblage. Six alteration facies were assigned at PBH and five at Kerikil. The distribution of alteration facies at PBH and Kerikil were mapped using samples selected both laterally and vertically away from mineralization.

Representative samples selected from each alteration facies were analyzed for their whole rock geochemistry to determine major and trace element compositions. Whole rock oxygen isotopes were also determined for each of the alteration facies and are discussed in Chapter 8. A comparison between alteration facies characteristics and distribution at both PBH and Kerikil is addressed at the end of this chapter.
7.2 District scale alteration

Hydrothermal alteration is responsible for at least some of the topographic features in the Mt Muro CoW, with clay alteration producing topographic lows and silicification creating resistant peaks. The PBH and Bantian Batu Tembak (BBT) structures are both associated with coincident linear topographic highs related to weathering-resistant silicification of the volcanic host rocks along the structure. Clay alteration on the flanks of the deposit structure weathers and erodes to form steeply incised valleys. Mt Muro and Gunung Baruh are the result of extensive silicification of the host rocks, which are related to central portions of the PBH and Kerikil hydrothermal systems, respectively.

Radiometric potassium-thorium surveys show two circular regions of potassium anomalousism (approximately 5km diameter and 2km diameter) centered on the Mt Muro and Gunung Baruh peaks, respectively. These anomalies represent patches of clay alteration (Fig. 7.1). The areas of clay alteration are controlled by northwest and northeast trending lineaments and are defined by a roughly northeast trend from the southwest to the northeast of the CoW. A large region of clay alteration encloses the PBH, BBT, Serujan and Tengkanong deposits and a smaller region of clay alteration encloses the Kerikil deposit.

Two large circular halos of magnetite destruction are also seen on the regional CoW aeromagnetic image (Figs. 3.16 B, 4.2 B and C). These two areas enclose the Permata, Hulubai, Batu Badinding, Bantian, Batu Tembak, Serujan and Tengkanong deposits, centered on Mt Muro, and the Kerikil deposit, centered on Gunung Baruh (Fig. 7.1).

7.3 PBH alteration facies

Six main alteration facies are recognized at PBH and are distinguished by the dominant alteration minerals present. Alteration minerals identified include quartz, chlorite, illite, sericite, phengite, carbonate, pyrite, adularia, albite, kaolinite, silica, halloysite and epidote. In general, quartz is the most abundant alteration mineral and is common to all alteration facies. Pyrite, although not an abundant mineral, is the most widespread and occurs in all alteration facies except the halloysite alteration facies. The nature, distribution and timing of all six alteration facies are described in the following sections.
Figure 7.1 District scale alteration as determined from aeromagnetic and radiometric potassium-thorium data

The PWH and Kerikil deposits can be seen within the margins of the two magnetic destruction halos, as discussed in Chapter 4. Patches of clay alteration, as defined by potassium anomalies, have a rough north-south trend with the main clay alteration encompassing the PWH, BML, Sengar and Tengkaiang deposits. A smaller area of clay alteration surrounds the Kerikil deposit. Clay alteration is defined using PSH airborne radiometric data.
7.3.1 Chlorite + carbonate + albite + epidote + pyrite (CCA) alteration facies

*Description, distribution and timing relationships:* Chlorite + carbonate + albite + epidote + pyrite (CCA) altered rocks are generally relatively soft and dark to pale green (Fig 7.2). CCA alteration can be pervasive but is typically selective or fracture associated and is not generally destructive of primary volcanic textures. The CCA is dominated by chlorite and carbonate, with lesser amounts of albite, pyrite, quartz, adularia, epidote, sericite and illite. Plagioclase phenocryst boundaries are still preserved, despite being partially or totally replaced by albite, epidote, chlorite, adularia and/or sericite and/or illite, within coherent andesites. The groundmass of coherent volcanics is completely chlorite and quartz altered. Chlorite and carbonate fill vesicles, cavities, and veins within the coherent volcanics. Cubic pyrite (generally less than 2%) is present as disseminations replacing plagioclase, homblende, mafic minerals and the groundmass.

CCA alteration affects all lithologies at PBH, but is best developed in the coherent andesite lavas and coherent breccias (Fig 7.2 B). CCA altered rocks are observed in contact with PBH infill stages 5 and 6. Coherent basaltic andesite and basalt dykes at Permata exhibit weak fracture and vein associated CCA facies alteration. The CCA facies extends for hundreds of meters away from the deposit in both the footwall and hanging-wall, and typically occurs from 170 down to 0 RL. Areas of CCA alteration form topographic lows and are generally oxidized to supergene iron oxides and secondary clays at surface. Secondary clays are readily detected on radiometric imagery as potassium and thorium highs (Fig. 7.1).

7.3.2 Quartz + sericite ± phengite + adularia + pyrite (SPA) alteration facies

*Description, distribution and timing relationships:* The SPA facies is dominated by phengite, sericite, quartz, adularia and pyrite. SPA altered rocks are soft and friable and can be white and grey to green (Fig 7.3 A and B). Alteration is pervasive and can be destructive of primary volcanic textures (Fig 7.3 B).

SPA alteration is best developed along tuff and lapilli tuffs layers in the Batu Badinding and Hulubai hanging-walls and occurs marginal to illite facies alteration (Fig. 7.3)
Figure 7.2 (cont.) PBH chlorite + carbonate + albite + epidote + pyrite (CCA) alteration facies


I Photomicrograph of cubic pyrite crystals in CCA facies altered coherent andesite (Same sample as Fig 7.2 H). Reflected light, Permata (AWP 0017). (Scale = 2000 µm).

J Photomicrograph of chlorite altered plagioclase phenocryst (top right of photomicrograph) and chlorite-lined, calcite-filled cavity in CCA altered coherent basaltic andesite. Cross-polarized light, Permata (AWP 0013). (Scale = 1000 µm).

K Photomicrograph of chlorite altered plagioclase phenocrysts and chlorite (chl) lined and calcite (cal) filled cavity in CCA facies altered coherent basaltic andesite. Plagioclase phenocrysts are altered to sericite in the top left of the photomicrograph. Cross-polarized light, Permata (AWP 0013). (Scale = 1000 µm).
Figure 7.3  PBH quartz + sericite ± phengite + adularia + pyrite (SPA) alteration facies

A  View of Hulubat vein at 12 000N and 145 RL showing illite alteration in the hanging-wall, chlorite alteration in the footwall, and kaolinite alteration which extends down the footwall contact (cf., 12 000N section on Fig. 7.2).

B  Pervasive SPA facies alteration in lapilli tuff. Lapilli are preserved. Hulubat (AWH 0039).

C  Photomicrograph of pervasive SPA facies alteration in lapilli tuff (same sample as Fig. 7.3 B). Cross-polarized light. Hulubat (AWH 0039). (Scale = 2000 µm).

D  Pervasive SPA alteration in lapilli tuff. Lapilli are preserved. Hulubat (AWH 0080).

E  Photomicrograph of pervasive SPA facies alteration in lapilli tuff (same sample as Fig. 7.3 E). Cross-polarized light. Hulubat (AWH 0080). (Scale = 2000 µm).
A). The SPA assemblage is recognized from 170 to 100 RL, an interval which corresponds to the distribution of tuff and lapilli tuff and also boiling evidence, based on the occurrence of bladed quartz after calcite and adularia (Chapter 5), and fluid inclusions (Chapter 8.2.1). SPA alteration is cross-cut by PBH infill stages 5 and 6.

7.3.3 Quartz + illite + pyrite (QIP) alteration facies

*Description, distribution and timing relationships:* QIP alteration facies is dominated by quartz, illite and pyrite with smaller amounts of adularia and chlorite. QIP altered rocks are soft and friable and can be grey, to white and pale green (Fig. 7.4). QIP alteration can be selective but is typically pervasive and can be destructive of primary volcanic textures. However, textural outlines and phenocryst boundaries are typically still preserved within coherent andesite lavas and breccias (Fig. 7.4 B and C). Feldspar phenocrysts in coherent andesites and basaltic andesites exhibit adularia + illite + pyrite alteration, while the groundmass may be completely illite + pyrite altered (Fig 7.4 E). Clusters of pyrite locally reflect the relict boundaries of precursor mafic phenocrysts, (e.g., hornblende and augite).

The QIP facies affects all lithologies at PBH except for the youngest coherent basalt dykes. Coherent basaltic andesite is generally less altered than the other volcanic facies. QIP alteration is best developed at the hanging-wall margins to the steeply dipping PBH deposit and intensifies towards the deposit. The facies is observed in contact with wall rocks of infill stages 1, 2, 3 and 4, from 170 to 0 RL. Areas affected by QIP alteration generally form topographic lows and weather to form secondary clays and iron oxides at surface.

7.3.4 Kaolinite alteration facies

*Description, distribution and timing relationships:* The kaolinite facies is largely composed of kaolinite and quartz with local pyrite, or (more commonly) iron oxides. Alteration is pervasive and destructive of primary textures, generally making it difficult and frequently impossible to discern the primary rock type from hand specimen observations. (In such cases, only geochemical characteristics, such as the Ti/Zr ratio, may be used to suggest the primary rock type, as discussed in Chapter 3.9.6 and Fig. 3.26). Kaolinite altered rocks can be very soft and friable and white or may be indurated when associated with silicification.
Figure 7.4  PBH quartz + illite + pyrite (QIP) alteration facies
F  Photomicrograph of CCA facies altered coherent andesite with chlorite altered plagioclase feldspar being replaced by illite and adula. Plane-polared light. Hubub (AHP 0017). (Scale = 2000 }{m}.
G  Photomicrograph of CCA facies altered coherent andesite with chlorite altered plagioclase feldspar being replaced by illite and adula. Cross-polared light. Hubub (AHP 0087). (Scale = 2000 }{m}.
H  Photomicrograph of QIP facies alteration coherent breccia. Cross-polared light. Hubub (AHP 0050) (Scale = 2000 }{m}.
I  Photomicrograph of kaolinite altered adula crystals in pervasive destructive QIP facies alteration that is being replaced by kaolinite. Host rock was coherent andesite lava. (Volcanic precursor; coherent andesite was determined by Ti/Zr ratios of 27 and mapping relationships). Cross-polared light. Hubub (AHP 0038) (Scale = 2000 }{m}.
J  Photomicrograph of pervasive, destructive QIP facies alteration in ruff. Plane-polared light Hubub (AHP 0031) (Scale = 2000 }{m}.
K  Photomicrograph of pervasive, destructive QIP facies alteration in ruff. Cross-polared light. Hubub (AHP 0031) (Scale = 2000 }{m}.
Figure 7.5 PBH kaolinite alteration facies

A View of Permata vein at 10400 N and 145 RL showing that alteration in the hanging-wall, chlorite alteration in the footwall and kaolinite alteration which extends down the footwall contact.

B White, destructive, pervasive kaolinite facies alteration of coherent andesite lava, Permata (AWP 0029B).

C Grey, destructive, pervasive kaolinite + silica alteration, Hulubai (AWH 0018).

D Photomicrograph of pervasive lithology destructive Kaolinite facies alteration and silicification. Cross-polarized light Hulubai (AWH 0018). (Scale = 2000 μm).

E Photomicrograph of pervasive lithology destructive Kaolinite facies alteration and silicification. Cross-polarized light Hulubai (AWH 0018). (Scale = 2000 μm).
Kaolinite alteration occurs in all lithological units and overprints all earlier alteration facies. At PBH, the kaolinite facies occurs in the footwall contact to the steeply dipping deposits and in footwall fault gouge (Fig. 7.5). Alteration is recognized from 170 down to 130 RL.

7.3.5 Silica alteration facies

Description, distribution and timing relationships: The silica facies is dominated by quartz and secondary iron oxides. Rutile is also present in trace amounts. Alteration is pervasive, but can enhance and preserve primary textures in tuffs and phenocryst boundaries within andesite autobreccias and lavas. Silica altered rocks are hard and can be brown to white (the brown color typically results from iron staining; Fig 7.6).

Silica alteration generally affects lithologies at higher elevations (forming ridges and knobs which are readily detected on SAR as topographic highs and ridges; Fig. 4.1 A). At PBH, silica alteration parallels the vein structure, forming north-south ridges that lead up to Mt Muro (which in itself is a silicified knob of fragmental tuff). The silicified area at the top of Mt Muro forms a flat lying zone which is at least 20 m thick. Silicification is not observed associated with any particular infill stage but is an incipient deposit scale feature. Silica alteration occurs from 428 to 400 RL at the summit of Mt Muro, and also from 200 to 170 RL associated with the deposit structure.

7.3.6 Halloysite alteration facies

Description, distribution and timing relationships: Halloysite altered rocks are extremely soft, friable and white with red and orange iron oxide staining (Fig 7.7 A). Alteration is pervasive and destructive of primary textures making it difficult to identify the original rock type.

Halloysite alteration affects surficial exposures of all lithologies (within the top 3 to 4 m of host rock). It also overprints the CCA, SPA, QIP, and kaolinite alteration facies.

7.3.7 PBH alteration facies paragenesis

The paragenesis of alteration facies at PBH is summarized in Figure 7.8. The CCA facies is selective in coherent andesite, basaltic andesite and basalt and breccias and is
A View down the Pennata pit towards the silicified Mt Muro Summit (428 RL). The remaining footwall and hanging-wall rocks are chlorite altered andesite lavas, autobreccias and tuffs. Excavation in the bottom of the pit is moving the Pennata vein at 365 RL. The base of the pit is predominantly QIP facies altered. The pit walls exhibit CCA facies alteration. (Bench height = 15 m).

B View from the Mt Muro Summit (428 m) looking north along the PBH pit. Silica facies altered fragmental volcanics can be seen in the lower right hand corner of the photograph Mt Muro Summit (AWR.0017).

C Silicified fragmental volcanic and pervasive destructive silicification Mt Muro Summit (AWR.0017).


overprinted by all later alteration facies. The SPA facies is pervasive in lapilli tuff, tuff, coherent breccias and stratified volcanic mudstone at Hulubai. QIP alteration occurs as selective alteration distal to the deposit, but becomes progressively more pervasive and texturally destructive proximal to the deposit. The chlorite-altered groundmass of the coherent andesite, basaltic andesites and breccias is replaced by illite. Relic albite altered plagioclase phenocrysts are replaced in succession by adularia and later illite. The kaolinite and silica facies are pervasive and can be destructive, overprinting the CCA and QIP facies. Kaolinite alteration is restricted to footwall fault gauge. The silica facies is pervasive at higher levels in the deposit, replacing all earlier minerals. However, this generally has the effect of preserving macro-scale volcanic textures (such as volcanic clast outlines), but also makes it difficult to identify the primary lithology or any earlier alteration type. Halloysite alteration affects surficial exposures of all lithologies and overprints all alteration facies on the flanks of the silicified ridges. Although a hydrothermal origin cannot be ruled out for the halloysite alteration, surface distribution suggests it is most likely the product of
CHAPTER 7 ALTERATION FACES, DISTRIBUTION AND GOCHEMISTRY

Relative mineral abundances

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Figure 7.8 PBH alteration paragenesis

PBH alteration paragenesis showing the relative abundance of alteration minerals in each alteration facies and location, relative to mineralization. The paragenetic sequence can be read from left to right, earliest to latest, respectively. Chlorite + carbonate + albite + pyrite (CCA) facies and quartz + phengite + sericite + adularia + pyrite (SPA) are overprinted by quartz + illite + pyrite (QIP) facies, kaolinite facies, silica facies and halloysite facies. QIP facies is overprinted by kaolinite, silica and halloysite facies. Halloysite overprints kaolinite facies.

weathering processes (Fig. 7.8).

7.4 Kerikil alteration facies

Five main alteration facies are recognized at Kerikil. Alteration minerals include quartz, chlorite, illite, sericite, albite, kaolinite, halloysite, pyrite, carbonate, adularia, and epidote. In general, quartz is the most abundant and is common to all facies. Pyrite, although not an abundant mineral, is the most widespread and is common to all facies except the halloysite alteration facies. The nature, distribution, and timing of the five
alteration facies are described in the following section.

7.4.1 Chlorite + carbonate + albite + adularia (CCA) alteration facies

Description, distribution and timing relationships: Chlorite + carbonate + albite + adularia (CCA) alteration facies rocks are either hard and dark green in coherent basaltic andesite, or soft and pale green in coherent andesite (Fig. 7.9). CCA alteration facies is widespread at Kerikil and is well developed as selective alteration of coherent andesite lavas and fracture-related alteration of the basaltic andesite intrusion. Within this intrusion, chlorite alteration is confined to the immediate selvages of minute fractures. Microscopically, plagioclase crystals are replaced by albite + adularia ± epidote ± sericite. The presence of albite is distinguished by its turbid extinction in cross polarized light and quantitative XRD studies that show up to 15 wt % albite (e.g., AWK 0408; Table 7.1). Adularia generally replaces albite that is later replaced by sericite along fractures within relic plagioclase phenocrysts. Mafic andesite is commonly altered to chlorite and pyrite.

CCA alteration borders QIP alteration and extends for hundreds of meters away from the Kerikil deposit. CCA alteration occurs from 270 RL down to -25 RL. The CCA facies is associated with infill stages 3, 4 and 7. At higher elevations, CCA alteration is overprinted kaolinite and halloysite alteration facies.

7.4.2 Quartz + illite + pyrite (QIP) alteration facies

Description, distribution and timing relationships: Quartz + illite + pyrite (QIP) altered rocks are soft and can be grey to white to pale green (Fig. 7.10). Alteration is pervasive within coherent andesite lavas and is generally only developed along fractures in the coherent basaltic andesite intrusion (Fig. 7.10). In coherent andesite, plagioclase phenocrysts are replaced by illite and/or adularia and pyrite with crystal outlines still preserved. Mafic deposit, QIP alteration intensifies and is texturally destructive (Fig. 7.9 D and E).

QIP alteration occurs from 310 RL down to -25 RL. The alteration envelopes the Kerikil deposit and is typically associated with infill stages 1, 2, 5, 6 and 7. In the upper sections of Kerikil 1, 2 and 3, the QIP facies is overprinted by later kaolinite and halloysite
Figure 7.9  Kerikil chlorite + carbonate + albite + adularia (CCA) alteration facies
A View looking north of the northern pit wall of Kerikil 2, showing the juxtaposition of CCA, QJP and kaolinite facies alteration with respect to the northern section of the Kerikil 2 deposit (short dashed line). On the western side of the deposit the dark green area represents weak CCA facies alteration in coherent basaltic andesite and on the eastern side the pale green area represents pervasive CCA facies alteration in coherent andesite lavas. QJP facies alteration envelopes the Kerikil 2 deposit and kaolinite alteration can be seen on top of both the CCA and QJP facies alteration. (Bench height is 15 m).
B Pale green, intensely altered, CCA facies coherent andesite lava with Stage 3 infill of vein stockwork and crackle breccia 165 RL southern pit wall, Kerikil 1
C Dark green, weakly altered CCA facies coherent basaltic andesite intrusion with thin Stage 4 calcite veins. 170 RL southern eastern pit wall, Kerikil 2.
Figure 7.9 (cont.) Kerikil chlorite + carbonate + albite + adularia (CCA) alteration facies


F  Photomicrograph of albite altered plagioclase phenocryst with albite alteration along fractures. Plane-polarized light Kerikil 2 (AWK 0408) (Scale = 500 μm).


H  CCA faces coherent basaltic andesite intrusion unifill stage 3 martian vein. Wet cut slab. Kerikil 2 (AWK 0481).


K  Same view as Figure 7.9 J, showing adularia and sericite alteration at Stage 3 vein boundary. Cross-polarized light. Kerikil (AWP 0481) (Scale = 2000 μm).
Figure 7.10 Kerikil quartz + illite + pyrite (QIP) alteration facies

A View of Kerikil I structure developed at boundary between andesite lavas showing illite alteration in hanging wall and enveloping chlorite alteration. There is an overprint of kaolinite and halloysite alteration along the within the vein.

B Pale green, pervasive QIP alteration facies in coherent andesite lava, Kerikil 1 (AMK 0455).


Figure 7.10 (cont.) Kerikil quartz + illite + pyrite (QIP) alteration facies

F Bleached, pervasive lithology: destructive QIP alteration facies in coherent andesite lava. Kerikal 2 (AWK 0140).

G Bleached, pervasive lithology: destructive QIP alteration of coherent andesite clasts in Kerikal infill stage 1 matrix supported breccia. Pervasive QIP alteration of clasts have illite and pyrite altered groundmass. Kerikal 2 (AWK 0465).


I Same view as Figure 7.4 H showing photomicrograph of illite altered zetaic plagioclase phenocryst and pervasively altered andesite groundmass. Cross-polarized light. Kerikal 2 (AWK 0465). (Scale = 2000 μm).


alteration. QIP altered rocks form topographic lows, as seen on radar imagery, and are expressed as areas of magnetite destruction on aerial magnetic imagery.

7.4.4 Kaolinite alteration facies

Description, distribution and timing relationships: The kaolinite facies consists of kaolinite + pyrite + quartz and overprints all earlier alteration minerals, except for halloysite. Kaolinite altered rocks are extremely soft and friable and bleached to white. Alteration is pervasive and destructive of primary textures, making it difficult to identify the primary rock type (Fig. 7.11). Kaolinite altered regions of vein breccias are characterized by etched-out clasts of volcanic rock and carbonate. Simmons and Browne (1990) tentatively identified alunite in one sample from their advanced argillic alteration assemblage (which is correlated with kaolinite alteration facies of this study), but this was not confirmed. Alunite was not observed in this study, although some sulfate was detected in SWIR spectra.

Kaolinite alteration affects all lithological units and overprints all earlier alteration facies. Kaolinite alteration occurs from 310 RL down to 90 RL. Alteration is best developed within northwest striking faults and down the footwall contact to the steeply dipping Kerikil 1 and Kerikil 2 deposits. Kaolinite alteration is typically associated with pyrite veins of Kerikil infill stage 9. Within the oxide zone, pyrite veins are oxidized to gossanous hematite which fills fractures within the kaolinite facies (Fig. 7.11 A). Kaolinite alteration is overprinted by, and has a gradational contact with the halloysite facies.

7.4.4 Silica alteration facies

Description, distribution and timing relationships: The silica alteration facies largely consists of quartz with minor hematite. Trace rutile is also observed. Microscopically, the hematite has colloform textures when viewed under reflect light. Silica alteration is very hard, white to red and orange, and is pervasive and locally destructive (Fig. 7.12). In some cases, silicification preserves primary rock macro-textures such as phenocryst and breccia clast outlines.

Silicified tuffs and coherent andesite occur in a flat layer, approximately 20 to 60 m thick, which form the resistant peak of Ganung Baruh (390 m) and the ridge flanking the
Figure 7.11 Kerikil kaolinite alteration facies

A View of Kerikil starter pit looking west showing bleached QIF and kaolinite alteration facies in coherent andesite with iron stained and oxidized stockwork veins in the hangingwall to the Kerikil deposit.

B View of Kerikil starter pit looking west showing pale green chlorite and kaolinite altered coherent andesite with iron stained and oxidized stockwork veins in the footwall to the Kerikil deposit.

C Bleached pervasive lithology destructive kaolinite facies altered coherent andesite lava, Kerikil2 (AWK 0436).

D Photomicrograph of pervasive kaolinite facies altered coherent andesite lava showing relic boundaries of plagioclase phenocrysts Kerikil (AWK 0436) (Scale = 1000 µm).

C Bleached kaolinite facies altered coherent andesite lava, Kerikil2 (AWK 0436).

F Photomicrograph of kaolinite facies altered coherent andesite lava, Kerikil2 (AWK 0505) (Scale = 2000 µm).
Figure 7.12 Kenkil silica alteration facies

A View east of the Kenkil 2 deposit footwall showing intense stockwork and brecciation. Silification at the top of the deposit is responsible for the resistant peak of Ganung Baruah (390 m = 390 RL). Beneath the silification coherent andesite lavas are kaolinite and CCA alteration facies altered lower in the pit. The Kenkil 2 deposit is enveloped by these alteration in the pit floor at 200 RL. On the flanks of Ganung Baruah a layer of Halloysite clays can be seen. Blast hole drilling for scale bottom right corner is 3m long, bench height is 15 m.

B View of stockwork and pervasive iron stained silification. 265 RL, Kenkil 2 footwall.

C Clasts of volcanic have been totally replaced by silica and voids are infilled with pyrite (cf., Fig. 5.21 D). Wet cut slab (AK10025)
Kerikil ore bodies to the east (Fig 7.12). Silicification locally also flanks the margins of the deposit where it replaces coherent andesite host rocks and hydrothermal breccia clasts and carbonates of Kerikil infill stages 5 and 6 (Fig 7.12 B and C). The silica facies is observed from the 390 RL down to 330 RL. Patchy silicification is also recognized at the deposit margins, extending downwards along fractures and stockwork veining. Paragenetic relationships suggest silica alteration overprints all other alteration facies, however, earlier alteration minerals are often obliterated by silicification.

7.4.5 Halloysite alteration facies

_Description, distribution and timing relationships:_ Halloysite altered rocks are extremely soft, friable and white, with ubiquitous red and orange iron oxide staining (Fig. 7.13). Alteration is pervasive and generally destructive of primary textures, but primary plagioclase phenocryst outlines are rarely discerned. Halloysite alteration is generally developed at surface (within the top 10 to 15 m of the host rocks) and may extend downwards along the deposit structure to the 90 RL. Halloysite alteration facies has gradational contacts with other alteration types and overprints CCA, QIP, and kaolinite alteration facies.

7.4.6 Kerikil alteration paragenesis

The paragenesis of alteration facies at Kerikil is summarized in Figure 7.14. The CCA facies is selective or pervasive and is overprinted by all later alteration facies. QIP alteration can be selective or pervasive and overprints the CCA facies. The chlorite altered groundmass of coherent andesite and basaltic andesite is overprinted by illite/sericite. Relic albite altered plagioclase phenocrysts are replaced first by adularia and then illite/sericite and pyrite. The kaolinite and silica facies are pervasive and generally destructive, overprinting CCA and QIP alteration. Kaolinite alteration is widespread at higher elevations in the deposit, and is also present along footwall fault gauge and late structures in the deeper portions of the Kerikil deposits. Silica alteration is compositionally destructive at higher levels in the deposits, replacing all earlier alteration facies, thus making it difficult to identify primary lithologies or alteration types. Halloysite alteration affects the surficial exposures of all lithologies and overprints all alteration facies. Although
Figure 7.13 Kerikil halloysite alteration facies

A. View of the upper portions of the Kerikil 2 pit showing halloysite clays developed in the weathering zone at the top of the deposit.

B. View east of the Kerikil 3 deposit footwall showing halloysite facies altered talus breccia (TALBRX). Bench height is 15 m.

C. Halloysite facies altered and iron stained tuff. Kerikil 2 footwall (AWX 0044).
Figure 7.14 Kerikil alteration paragenesis

Kerikil alteration paragenesis showing the relative abundance of alteration minerals in each alteration facies and relative location to mineralization. The paragenetic sequence can be read from left to right, earliest to latest, respectively. Chlorite + carbonate + albite ± pyrite + adularia (CCA) facies are overprinted by quartz ± ilcite ± pyrite (QIP) facies, kaolinite (Kaol) facies, silica facies and halloysite facies. QIP facies is overprinted by kaolinite, silica and halloysite facies. Halloysite facies overprints kaolinite facies.

A hydrothermal origin cannot be ruled out for the halloysite facies, the surficial distribution and presence of secondary iron oxides suggests that it is most likely the product of weathering and oxidation processes in the supergene environment.

### 7.5 Short wave infra-red (SWIR) spectral data

Short wave infra-red (SWIR) spectra were determined for 384 samples from PBH and 1246 samples from Kerikil (Appendix 5). Spectra were analyzed using the Portable Infra-red Mineral Analyzer (PIMA) of Auspec International and interpreted using PIMA View™ and The Spectral Geologist™ software (aided by comparison of mineral spectra with mineral library SWIR profiles). Spectral profiles were generally of better quality and more consistent in samples with intense and pervasive alteration. Least altered samples.
exhibit a mix of alteration minerals, due to selective alteration between clasts, matrix and/or groundmass and phenocrysts. A particular limitation of SWIR studies is the inability to effectively determine alteration mineralogy from dark coloured, infrared absorbent samples. Consequently, alteration in dark samples was determined with the aid of thin sections and XRD studies.

The main alteration minerals, determined by SWIR at PBH are illite, sericite/phengite, chlorite, kaolinite, various carbonates and halloysite. At Kerikil, the dominant alteration minerals identified are kaolinite, illite, sericite, halloysite, chlorite and various carbonates. A minor amount of sulfate was determined from SWIR spectra at PBH and Kerikil, but no sulfates (such as alunite or gypsum) were observed in either thin section or hand specimen. Considerably more sulfates were detected at Kerikil than at PBH.

7.6 X-ray diffraction (XRD) studies

7.6.1 Introduction

Selected representative samples of alteration facies from PBH and Kerikil were analyzed by X-ray diffraction (XRD). The purpose of this study was to compare XRD to SWIR spectral interpretations and obtain semi-qualitative mineralogical data. This study is limited in scope and is not intended as a comprehensive analysis.

7.6.2 Sampling and analytical techniques

Representative samples of each alteration facies at PBH (20 samples) and Kerikil (13 samples) were chosen and submitted for XRD analysis to the University of Ballarat under the supervision of Dr. Stafford McKnight. All sample preparation was carried out at the University of Tasmania. Samples were initially crushed using a steel jaw crusher to produce fragments of 0.5 cm$^3$ or less. They were then ground in a tungsten carbide ring mill for approximately 3 minutes to produce a rock powder of less than 200 μm. The mill was cleaned with 1 to 2 passes of high purity quartz sand between each sample run. The samples were sent to the University of Ballarat, where they were further ground in a swing mill for 3 minutes. X-ray traces were obtained from randomly orientated bulk powders
Table 7.1 Comparison of SWIR to XRD results for selected PBH and Kerikil alteration facies

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Deposit</th>
<th>Lithology</th>
<th>Alteration Facies</th>
<th>SWIR spectra</th>
<th>XRD semi-quantitative analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TSA 1</td>
<td>TSA 1 %</td>
<td>TSA 2</td>
</tr>
<tr>
<td>PBH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWP 0026</td>
<td>Permata</td>
<td>BAS</td>
<td>CCA</td>
<td>chl</td>
<td>65</td>
</tr>
<tr>
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<td>Huluba</td>
<td>AND</td>
<td>CCA</td>
<td>chl</td>
<td>61</td>
</tr>
<tr>
<td>AWH 0039</td>
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<td>SPA</td>
<td>pheng</td>
<td>59</td>
</tr>
<tr>
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<td>Huluba</td>
<td>SED</td>
<td>SPA</td>
<td>pheng</td>
<td>70</td>
</tr>
<tr>
<td>AWH 0013</td>
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<td>AND</td>
<td>QIP</td>
<td>ill</td>
<td>59</td>
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<tr>
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<td>AND</td>
<td>QIP</td>
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<td>66</td>
</tr>
<tr>
<td>AWP 0029B</td>
<td>Permata</td>
<td>AND</td>
<td>Kaolinite</td>
<td>kaol</td>
<td>100</td>
</tr>
</tbody>
</table>

7.7 Alteration distribution and zonation

The following section details the distribution and zonation of alteration facies on a deposit-scale. In general, alteration at PBH is zoned and best developed in the hanging-wall to the steeply dipping planar deposit. Disruption to the vertical and lateral zonation occurs where fluid has exploited more permeable or reactive layers in the volcanic sequence. In contrast, the distribution of alteration at Kerikil is more complex and zoning is less apparent due to a late-stage kaolinite overprint.

7.7.1 PBH vertical distribution of alteration assemblages

At PBH, analysis of the frequency of alteration minerals with respect to depth in altered wall rocks was determined from SWIR spectra and supported by XRD techniques (Fig 7.15). The depth intervals listed in Figure 7.15 include a broad range across 140 m of both the mineralized and un-mineralized portions of the PBH deposit.

![Figure 7.15 PBH alteration facies vs. RL](image)

**Figure 7.15 PBH alteration facies vs. RL**

PBH alteration facies vs. RL expressed as a percentage of the total samples collected at that level. All samples were collected from within 100 meters of the deposit. The plot shows CCA alteration facies increase with depth while QIP alteration facies decrease with depth. SPA alteration facies is seen above 100 RL while carbonate is seen below 100 RL. Kaolinite and halloysite alteration facies are present at shallow levels.
At PBH, halloysite and kaolinite only occur above 150 RL and 130 RL, respectively. Phengite only occurs above 110 RL. Illite is present from 30 RL to 170 RL and decreases in relative abundance below 70 RL. Chlorite increases in abundance below 170 RL. Both Fe-chlorite and Mg-chlorite were recognized in the deposit. SWIR data indicates that chlorite identified below 110 RL is magnesium-rich but, above 110 RL, is iron-rich. However, no microprobe work has been carried out to distinguish between Fe- or Mg-chlorite. Carbonate alteration in the wall rocks (as opposed to carbonate observed as vein infill) only occurs below 110 RL.

### 7.7.2 PBH lateral distribution of alteration assemblages

The QIP facies envelopes the PBH deposit and extends for tens of meters into the hanging-wall, but is hardly developed in the footwall (Fig. 7.16). SPA alteration may extend for several tens of meters along tuff, lapilli tuff, and stratified mudstone layers. The CCA facies is more widespread and is recognized for hundreds of meters distal to the vein and enveloping the QIP facies. The CCA facies is only observed proximal to the deposit at depth and as fracture alteration in less reactive coherent basaltic andesite and basalt facies. Isolated occurrences of CCA and SPA alteration facies can be seen in the hanging-wall of the Hulubai deposit (Fig. 7.16 B). At PBH, the kaolinite facies is confined to the immediate margin of the vein, associated with late stage footwall fault gouge. The silica facies occurs in the uppermost portions of the deposit and is responsible for the steep topographic ridges associated with the PBH deposit and the competent Mt Muro peak. Halloysite alteration blankets the deposit at surface and is probably related to weathering.

### 7.7.3 Kerikil vertical distribution of alteration assemblages

The frequency distribution of the main alteration minerals with respect to depth in altered wall rocks at Kerikil (determined with PIMA and supported by XRD and thin section descriptions) is shown in Figure 7.17. The depth interval shown includes the full vertical extent of the vein and breccia system from 0 to 270 RL.

As shown, halloysite and kaolinite are widespread and occur from 20 to 270 RL. Halloysite gradually increases in frequency from 70 to 200 RL, where there is a sharp decline and then steady increase in abundance to 270 RL. Kaolinite increases in abundance
Figure 7.16 Geological cross sections across the PBH vein showing alteration distribution

A Geological cross section of the Pennata vein across 10 400 N generated from diamond drill core logging and pit mapping. Section shows narrow alteration zone with QIP alteration facies next to the vein and chlorite distal to the vein. There is a late overprint of kaolinite alteration in the footwall of the vein and silicification at surface. Position of 0100 N is marked on Fig 3.3.

B Geological cross section of the Halubai across 12 000 N generated from diamond drill core logging and pit mapping. Section shows narrow alteration zone with QIP alteration facies next to the vein and CCA alteration facies distal to the vein. SPA alteration facies is developed along the tuff and sediment layers in the hanging-wall. There is a late overprint of kaolinite alteration in the footwall of the vein and silicification at surface. Position of 12 000 N is marked on Fig 3.3.

Legend
- Diamond drill hole
- Vein/Breccia
- Weathering
- Silica alteration facies
- CCA alteration facies
- kaolinite alteration facies
- SPA alteration facies
- QIP alteration facies
- Halloysite alteration facies
Figure 7.17  Kerikil alteration facies vs. RL

Kerikil alteration facies vs. RL expressed as a percentage of the total samples collected at that level. All samples were collected from within a 100 meters of the deposit. The plot shows CCA and QIP alteration facies increase with depth. CCA alteration facies (carbonate) is observed below 100 RL. Kaolinite and halloysite alteration facies are occur at shallow levels.
compared to other minerals from 50 to 270 RL, with a sharp increase in frequency at 100 RL. Both halloysite and kaolinite are most abundant above 170 RL. No distinction was made between illite and sericite at Kerikil. Since PIMA has difficulty in distinguishing mica minerals, these results were followed up with microscope and XRD work. Illite is abundant throughout the Kerikil deposit with a minor decrease from 110 to 170 RL. Sericite occurs in a zone between 40 and 210 RL with the most consistent zone occurring from 80 to 200 RL. At Kerikil, there is no zonation of Mg- and Fe-chlorite with respect to depth. Carbonate alteration within the wall rocks (as distinct from carbonate in infill stages) only occurs below 130 RL.

7.7.4 Kerikil lateral distribution of alteration assemblages

Distribution of alteration facies at Kerikil is complex. Cross sections were constructed across representative sections of the Kerikil 1, 2 and 3 deposits (Fig 7.18) in order to clarify the distribution of alteration assemblages. These sections show the alteration facies directly associated with, and peripheral to, the main mineralized zones.

In general, QIP alteration envelopes the deposits and in turn is flanked by the CCA alteration facies and covered by the kaolinite and halloysite assemblages (Fig. 7.18). Zonation is most complex at mid levels in the deposits (approximately 170 RL) due to intermingled zones of QIP, kaolinite, halloysite and CCA alteration facies. This area corresponds to the highest gold and silver grades within the Kerikil 2 deposit. Lateral zoning is more apparent in the deepest portions of the deposits (approximately 120 RL), with QIP alteration occurring proximal to the main Kerikil 2 deposit and CCA alteration enclosing the QIP facies. Kaolinite and halloysite alteration cross-cuts the QIP and CCA alteration facies and are associated northwest striking structures. At higher elevations at Kerikil 2, a shallowly dipping layer of QIP alteration is controlled by volcanic layering in the coherent andesite country rocks (Fig. 7.18 B). The kaolinite alteration facies that overlies QIP alteration is associated with the talus breccia (TALBRX) (cf. Fig. 3.18 B with 7.18 B). Kaolinite alteration also extends down the northwest striking fault at Kerikil 2 (Fig. 7.18 A and B, respectively) and down the main deposit structure at Kerikil 1 (Fig.
Figure 7.18 Alteration cross sections across the Kerikil deposit

A  Cross section 6 750N Kerikil 1 and Kerikil 2 showing QIP alteration facies associated with veins and enveloping CCA alteration facies. There is a late overprint of kaolinite alteration down the vein and fault structures. Constructed from pit mapping and DDH cross sections.

B  Cross section 6 700N Kerikil 2 showing enveloping CCA alteration facies and QIP facies alteration associated with the veins and horizontal alteration zones associated with volcanic layer boundaries. There is a late overprint of kaolinite facies beneath the silicification down the vein and late north west fault structures. Constructed from pit mapping and DDH cross sections.

C  Cross section 6 300N Kerikil 3 showing QIP alteration facies associated with veins at depth and enveloping CCA alteration facies. There is a late overprint of kaolinite facies alteration, blanketing the vein and fault structures and beneath the silicified cap exposed at Ganung Baruh. Constructed from pit mapping and DDH cross sections.
east of the Kerikil 1, 2 and 3 deposits (Fig 7.18). alteration facies, except for the silica alteration facies, and generally parallels surface topography, suggesting that it is a weathering feature.

7.8 Interpretation and discussion alteration mineralogy, alteration facies and distribution at PBH and Kerikil

The production of clay and mica minerals during hydrothermal alteration are strongly influenced by temperature, pH and fluid to rock ratios and are important in determining the physio-chemical environment of ore deposition and characteristics of the altering fluid. In this section, the alteration minerals are discussed in the context of the alteration paragenesis determined at PBH and Kerikil (e.g., Browne and Ellis, 1978; Hedenquist, 1990; Reyes, 1990; Corbett and Leach, 1996).

**Chlorite**: Chlorite in epithermal systems occurs due to interaction of host rocks with a near neutral fluid at temperatures of greater than 180°C (Corbett and Leach, 1995; Fig. 7.19). The large extent of chlorite at PBH and Kerikil may reflect the fluid recharge area and extent of the former hydrothermal system.

**Sericite/phengite**: Sericite is highly ordered form of illite and phengite is a Mg- and Fe-rich member of the illite-sericite group of minerals. Sericite is produced by the interaction of host rocks with a near neutral fluid at temperatures of greater than 200°C (Henley and Ellis 1983; Corbett and Leach, 1995; Fig. 7.19). The presence of adularia associated with sericite in the SPA alteration facies suggests boiling has occurred (Browne and Ellis, 1970; Browne, 1978; Henley, 1985; Hedenquist, 1990; Dong and Morrison, 1995).

**Illite**: Illite is very common in the epithermal environment and can occur both proximal and distal to alteration. Illite alteration occurs due to interaction of host rocks with weakly acidic to near neutral fluids at temperatures of 200 to 250°C (Henley and Ellis 1983; Corbett and Leach, 1995; Thompson and Thompson, 1998; Fig. 7.18). Illite alteration is a common alteration assemblage that occurs both proximally and distal to epithermal mineralization, and reflects high water to rock ratios and interaction of a near neutral to slightly acidic fluid (Thompson and Thompson, 1998). The presence of adularia within this alteration facies indicates boiling has occurred (Browne and Ellis, 1970; Browne, 1978;
Figure 7.19  Relationship of PBH and Kerikil alteration facies to temperature and pH

Alteration facies at PBH and Kerikil have epithermal characteristics and hydrothermal alteration minerals indicative of near neutral, hotter conditions to cooler, more acidic conditions. CCA and SAP facies are found distal and proximal to the deposits, while QIP facies is only found proximally. Kaolinite, silica and halloysite facies are found proximal to the PBH and Kerikil deposits at shallow levels, but the halloysite facies is widespread and may be related to oxidation and weathering processes.

(Facies are displayed on a diagram modified after Corbett and Leach (1996). Greyed-out minerals, mineralogical groups and deposit styles were not observed at PBH and Kerikil. Mineral abbreviations are: Ab: albite; Act: actinolite; Ad: adularia; Al: alunite; And: andalusite; Ch: carbonate; Chl: chlorite; Chd: chaledonite; Ch-Sm: chalcedony/smecite; Cor: corundum; Cpx: clinopside; Cr: cristobalite; Ccr: calcsilicate; Do: dolomite; Dk: dike; Dp: diaspore; Ep: epidote; Fsp: feldspar; Ga: garnet; Hal: halloysite; I: ilite; I-Sm: illite/smectite; K: kaolinite; Mt: magnetite; Op: opaline silica; Py: pyrophyllite; Q: quartz; Ser: sericite; Sld: siderite; Sm: smectite; Stb: solfite; Top: topaz; Tr: tremolite; Trd: tridymite; Ves: vesuvianite; Ws: wollastonite; Zeo: zeolite.)
Henley, 1985; Hedenquist, 1990; Dong and Morrison, 1995). Simmons and Browne (1990) note that adularia and illite are in equilibrium at Kerikil, consistent with formation from host rock reaction with neutral to alkaline chloride waters.

**Silica:** Silica alteration reflects the interaction and replacement of the host rocks by a silica rich-fluid, which is typically developed at the water table above a boiling geothermal system (Thompson and Thompson, 1998; Corbett and Leach, 1995; Fig. 7.19). Areas of silicification thus provide an indicator of the paleo-water table and indicate areas above extinct boiling zones in the hydrothermal system (i.e. steam heated zone). The silicified peaks of Ganung Baruh (390 m) and Mt Muro (428 m) are the highest preserved parts of the extinct hydrothermal system and may reflect the paleo-water table. Marsupa Ria, 30 kilometers from Mt Muro has an expansive associated silica cap that has also been attributed to the position of the paleo-water table (Thompson et al., 1994). At PBH and Kerikil, silicification is also developed at the margins to the veins and breccias and in more permeable units, and may reflect paleo-fluid flow pathways. Generally, the deposition of silica is due directly to cooling of the hydrothermal fluid (Barnes, 1976; Thompson and Thompson, 1998).

**Kaolinite:** Kaolinite occurs due to interaction of the host rocks with an acidic fluid at temperatures of less than 200° C (Thompson and Thompson, 1998; Corbett and Leach, 1995; Fig. 7.19). The presence of pyrite together with kaolinite suggests a reduced, acidic fluid may have been responsible for the alteration. The presence of pyrite in the absence of iron oxides also suggests that at least some of the kaolinite is hypogene rather than supergene in origin. At PBH and Kerikil, kaolinite may have been developed above the hydrothermal system in response to acidic conditions. The acidic environment was likely produced by the dissociation of gases derived by boiling (such as carbon dioxide, sulfur dioxide and hydrogen sulfide) lower in the system and dissolved into groundwater above the water table (i.e. steam heated zone). Downward movement of these cooler acidic fluids occurred after waning of the hydrothermal system. Acidic fluids thus migrated downwards along footwall contacts at PBH and through fractures and brecciation at Kerikil, locally producing kaolinite alteration lower in the deposits. Kaolinite alteration commonly occurs as zones of massive argillic alteration in low sulfidation epithermal environments and can be observed when the upper portions of the hydrothermal system are still preserved (e.g.,
Marsupa Ria, Thompson et al., 1994). Despite the kaolinite alteration being soft and easily eroded, it can be locally preserved by the presence of a silica cap, as is the case at Kerikil.

*Halloysite:* Halloysite is related to the weathering and hydration of clays in the supergene environment (Corbett and Leach, 1995; Fig. 7.19). Halloysite can also form under very low temperature hydrothermal conditions. Harvey and Browne (1991) showed evidence for halloysite formation at the Wairaki Geothermal Field, New Zealand. The distribution of the halloysite assemblage as a blanket paralleling the ground surface and overprinting earlier alteration assemblages indicates that it is most probably a weathering feature (cf., Fig. 7.7 and 7.13 A). However, at Kerikil, the halloysite may locally be hypogene in origin.

### 7.9 Alteration Whole Rock Geochemistry

#### 7.9.1 Introduction

This section describes the geochemistry of the alteration facies and relative enrichments and depletions of mobile elements in the host rocks associated with the PBH and Kerikil deposits. Samples were selected from representative altered rocks and analyzed for a suite of major and trace elements. These data are compared to least altered data from host rocks in Chapter 3 to determine geochemical trends associated with the various alteration facies, their relationship to mineralization, and potential exploration vectors (Chapter 10.3).

#### 7.9.2 Sampling and analytical techniques

A total of 125 samples, representing the principal lithofacies and alteration assemblages, were analyzed for major and trace elements. These samples include least altered through to strongly altered samples selected from drill core and pit exposures at Kerikil and PBH. Prior to this study, limited geochemical studies had been completed on the alteration facies at Mt Muro (Simmons and Brown, 1990). Sampling away from the
deposits was not possible due to the thick jungle and tropical weathering profile, and all samples are at least partially altered for this reason. Least altered samples were therefore used as a reference point for lowest alteration rank, due to the lack of completely unaltered samples. Altered samples in this study were selected from hand specimen, PIMA, XRD and thin section observations, and generally have loss on ignition values (LOI) in excess of 6%.

Major and trace element geochemistry of altered samples were determined using the X-ray fluorescence and ICPMS facility at the School of Earth Sciences in the University of Tasmania and at ANALABS in Perth. Analytical methodology is identical to that for least altered host rocks outlined in Chapter 3.9.2. All altered and least altered whole rock geochemical data are presented in Appendix 3.

7.9.3 Alteration box-plot

The Alteration Index (AI) (determined by $100(MgO + K_2O)/(MgO + K_2O + CaO + Na_2O)$; Ishikawa et al., 1976) is a measure of the intensity of alteration in felsic volcanic rocks. The index is based on the alteration of plagioclase to sericite and illite during hydrothermal alteration and is equally applicable to intermediate and mafic volcanics (Gemmell and Large, 1992). The chlorite-carbonate-pyrite index (CCPI) (defined as $100(MgO + FeO)/(MgO + FeO + K_2O + Na_2O)$; Large et al., 2001) measures the degree of chlorite, (Fe, Mg)-carbonate and/or pyrite alteration (Large et al., 2001). A boxplot that combines these two indices was developed by Large et al. (2001) for use in volcanic-related massive sulfide alteration systems, in order to relate the whole rock geochemistry of a sample to alteration intensity. Within each alteration zone, more intensely altered samples plot toward the end-member alteration mineral that characterize that type of alteration. Fresh or unaltered rocks plot within a specific range of AI and CCPI values that are different from the altered samples. The box plot has previously been shown to be applicable to the low sulfidation epithermal environment at Gosowong, Indonesia (Gemmell, 2001a).

Figure 7.20 shows Mt Muro geochemical data plotted as CCPI and AI boxplots. In general, these data have a significant spread of AI values away from the least altered box towards rocks of sericite/illite + pyrite composition. A suite of data from Indonesian
Figure 7.20 Boxplots showing unaltered Indonesian Arc volcanics and PBH and Kerok least altered and altered lithologies

A Indonesian arc volcanics from Stolz (1995) plotted with respect to the Carbonate-Chlorite-Pyrite Index (CCPI) of Gemmell and Large (1992) and Alteration Index (AI) of Ishikawa et al. (1976). The fields of basalt/andesite and dacite are derived empirically from the plots of the Indonesian arc volcanics (Stolz, 1995). The rhyolite field comes from Large et al. (2001). The end member alteration mineral species plot at the boundaries of the boxplot, and samples with compositions closer to these values will plot towards the end member alteration species PBH and Kerok least coherent volcanics plot within or near the field of least altered basalt and andesite, which is consistent with geochemical determinations for volcanic rock type discussed in Chapter 3.

PBH alteration facies show a spread away from the field of least altered basalt and andesite towards higher AI values and compositions consistent with a chlorite, illite, sericite and pyrite mineralogy. The spread of values for alteration types is due to the large range of precursor rocks at PBH.

C Kerok alteration facies show a spread away from the field of least altered basalt and andesite towards higher AI values and compositions consistent with a chlorite, illite, sericite and pyrite mineralogy. An increase in alteration value with alteration facies rank at
volcanics (Stolz, 1995) represent the field of least altered volcanics. The volcanic data provide the boundaries for basaltic to dacitic compositions, and the boundary for rhyolitic composition is taken from Large et al. (2001). The PBH and Kerikil coherent volcanics generally plot in the basalt to andesite range of the least altered Indonesian volcanics box (Fig. 7.20 A). Although most lithologies sampled at PBH and Kerikil are altered to some degree, the coherent volcanics plot within or close to the least altered box (Fig. 7.20).

CCA, SPA, QIP, silica, kaolinite, halloysite alteration facies all plot with successively higher Alteration Indices (AI) towards geochemical compositions consistent with chlorite ± illite/sericite + pyrite mineralogical composition (Fig 7.20 B and C).

### 7.9.4 Alteration bubble box-plots

The bubble box-plot is a modification to the box plot of Large et al. (2001). It is used to relate alteration intensity (AI and CCPI) and host rock characteristics back to geochemical assay data and to highlight chemical characteristics of different alteration facies (Gemmell, 2001 b). By determining the geochemical characteristics of different alteration facies, it is possible to delineate geochemical vectors towards ore, particularly in alteration systems that have zoned alteration facies such as at Kerikil and PBH (Chapter 10.3).

### 7.9.5 PBH major element variations with respect to alteration facies

Major element alteration bubble box-plots for PBH samples are presented in Figure 7.21. Data for all altered samples are compared to the least altered PBH samples. In general, TiO₂, Al₂O₃ and MgO remain relatively constant with increasing AI values. However, the kaolinite alteration facies does show a decrease in TiO₂, Al₂O₃ and MgO. Both Na₂O and CaO values decrease with increasing AI values, reflecting plagioclase and albite destruction. MnO decreases with increasing AI values but increases relative to the CCPI. K₂O, Fe₂O₃ and S all increase with increasing AI.

### 7.9.6 PBH trace element variations with respect to alteration facies

Trace element alteration bubble box-plots for PBH are presented in Figure 7.22 and 7.23. The mobility of trace elements Nb, Y and V was examined in order to test their
Figure 7.21 PBH alteration facies major element geochemistry with variations in alteration and carbonate-chlorite-pyrite index.

Legend
- Dark grey circles: Al-rich (>15 wt% Al2O3) and Fe-rich (MgO > 5 wt%)
- Medium grey circles: Al-rich (<15 wt% Al2O3) and Fe-rich (MgO > 5 wt%)
- Light grey circles: Al-rich (<15 wt% Al2O3) and Fe-poor (MgO < 5 wt%)
- Transparent circles: Al-poor (>15 wt% Al2O3) and Fe-rich (MgO > 5 wt%)
- White circles: Al-poor (>15 wt% Al2O3) and Fe-poor (MgO < 5 wt%)

Range values: (a) TiO2, (b) Al2O3, (c) MgO, (d) Na2O, (e) CaO, (f) MnO, (g) K2O, (h) Fe2O3, (i) SiO2.
Figure 7.22  PBH alteration facies immobile element geochemistry
Bubble box-plots showing relative immobility of immobile elements with respect to PBH alteration facies.
Figure 7.23 PbH alteration facies trace element geochemistry with variations in alteration and carbonate-chlorite-pyrite index.

Legend:
- CDA (carbonate-chlorite)
- CDA (carbonate-chlorite-pyrite)
- CDA (carbonate-pyrite)
- CDA (pyrite)
- CDA (unidentified)

The black dots represent the concentration ranges within each regional PbH alteration facies. The lines indicate the range of the alteration index (AI) and the element index (X). Ranges are indicated by color-coded bubbles, with the smallest bubble representing the lowest range and the largest bubble representing the highest range.
Figure 7.23 cont. PDBH alteration facies trace element geochemistry with variations in alteration and carbon-chlorite-pyrite index.

Legend:
- Early stage CCA alteration facies
- CCG alteration facies
- Early stage metatexites
- CAA alteration facies
- Late stage metatexites
- Post-metamorphic facies
use as volcanic alteration facies discriminators (Chapter 3.9.6), even in strongly altered rocks. Nb, Y and V all show relatively little change with increasing alteration at PBH, indicating that these elements were relatively immobile during hydrothermal alteration (Fig. 7.22). This supports earlier conclusions in Chapter 3 that were based on the immobile elements in the least altered coherent volcanics, and also indicates that Nb, Y and V could potentially be used to discriminate volcanic alteration facies even in strongly altered rocks at PBH.

Ore-related trace elements were determined from geochemical analyses of PBH infill Stages 3 and 4 (Chapter 5.13) and include Au, Ag, Cu, Pb, Zn, Cd, Sb, As, Tl, Se, Te and Hg all increase with increasing Alteration Index (Fig 7.23). Au, Ag and Cu values are highest in the QIP facies and kaolinite altered host rocks. Pb and Tl have the highest values in SPA altered rocks. However, Tl values are also elevated across CCA, QIP, and kaolinite alteration facies with increasing alteration. Cd values are highest within some, but not all, CCA altered rocks. As and Sb values generally increase with increasing AI and are highest in kaolinite altered rocks. Sb values can be higher in CCA facies. Hg values are highest in the silica and QIP facies and are also elevated in kaolinite altered rocks. Se values do not show any trend with increasing Alteration Index. Te values increase with increasing Alteration Index.

Other elements (including Sn, Mo, Bi, Sr, Rb and Ba) also exhibit trends with increasing AI and CCPI. Sn values remain relatively constant with increasing AI. Mo, Bi, Rb, and Ba values all increase with increasing AI, but Sr decreases. Mo and Bi values are highest in the silica alteration facies.

7.9.7 Kerikil major element variations with respect to alteration facies

Major element alteration bubble box-plots for Kerikil samples are presented in Figure 7.24. Again, all increases and decreases are discussed relevant to the least altered Kerikil samples in the least altered box. At Kerikil, TiO₂ and Al₂O₃ remain relatively constant with increasing Alteration Index, except in the kaolinite facies, which has relatively elevated values of TiO₂ and Al₂O₃. Na₂O and CaO values decrease with increasing alteration, reflecting plagioclase and albite destruction. MgO and MnO values also decrease with increasing alteration index, reflecting the destruction of mafic
Figure 7.24 Kerikil alteration facies major element values with variations in alteration and carbonate-chlorite-pyrite index.
phenocrysts. $K_2O$, $Fe_2O_3$ and $S$ values all increase with increasing Alteration Index.

7.9.6 Kerikil trace element variations with respect to alteration facies

Trace element alteration bubble box-plots for Kerikil samples are presented in Figures 7.25 and 7.26.

The mobility of trace elements Nb, Y and V was examined in order to test their use as volcanic alteration facies discriminators (e.g., Chapter 3.9.6), even in strongly altered rocks. Nb, Y and V all show relatively little change with increasing alteration at Kerikil, indicating that these elements were relatively immobile during hydrothermal alteration (Fig. 7.25). This supports earlier conclusions in Chapter 3, based on the immobile elements in the least altered coherent volcanics, and also indicates that Nb, Y and V could potentially be used to discriminate volcanic alteration facies, even in strongly altered rocks at Kerikil.

Ore-related trace elements were determined from geochemical analyses of infill stages 2, 5 and 8 (Chapter 5.13) and include Au, Ag, Cu, Pb, Zn, Cd, Sb, As, Tl, Se, Te and Hg. In general, these elements all increase with increasing Alteration Index (Fig 7.26). Au and Ag values are highest in QIP and silica altered host rocks. Cu values are highest in the halloysite alteration facies and Pb, Zn, Cd, Tl values are highest in the QIP facies. Levels of As are highest in both the kaolinite and halloysite alteration facies. Sb is highest in the silica alteration facies. Se, Te and Hg values are highest in QIP, kaolinite and halloysite alteration facies, with only trace amounts of these elements present in least altered or CCA altered rocks.

Other elements, including Sn, Mo, Bi, Sr, Rb and Ba, also exhibit trends with increasing AI and CCPI. These elements typically increase with increasing Alteration Index.

7.9.9 Discussion of PBH and Kerikil alteration facies geochemistry

Variations in whole rock geochemical data occur in different alteration facies and with increasing Alteration Index. Both PBH and Kerikil showed depletion of $Na_2O$ and $CaO$, reflecting the destruction of primary plagioclase in the host volcanics. High $K_2O$ values represent potassium metasomatism of the host rocks (reflected by the production of adularia and sericite/illite), and high $Fe_2O_3$ and $S$ values reflect pyrite formation.
Figure 7.25  Kerilik alteration facies immobile element geochemistry
Bubble box plots showing relative immobility of immobile elements with respect to different Kerilik alteration facies.
Figure 7.26: Kerisit alteration facies trace element geochemistry with variations in alteration and carbonate-chlorite-pyrite index.

This is a scatter plot showing the correlation of trace elements with the redox index, carbon content, and alteration index. Each point represents a sample, and the size of the point indicates the variation in the alteration index. The legend explains the different symbols used for different elements, with legend entries for Au, Pb, Sb, Ag, Zn, As, Cu, Cd, and Ti.
Figure 7.26 cont. Kerall alteration facies trace element geochemistry with variations in alteration and carbonate-chlorite-pyrite index.
depletion of MnO and MgO at Kerikil indicates destruction of mafic minerals in the volcanic host rocks. The depletion of Mn with increasing alteration at Kerikil may also provide a clue as to the origin of abundant Mn-carbonates. If MnO was stripped from the coherent volcanics in the steam heated zone at the top of the hydrothermal system, it could have remained in the fluid and would have been deposited as rhodochrosite during the waning of the system. Therefore, Mn required for rhodochrosite in Period 2 stages, may have been derived from altered volcanics in the steam heated. Mn is rare in deep circulating geothermal fluids (e.g., Henley et al., 1986). To test the plausibility of manganese coming solely from the volcanic host rocks, a simple calculation was performed, as to how much andesite would be needed from the host rock and if it would be plausible for the coherent andesite facies to have supplied enough manganese for the Period 2 infill stages at Kerikil. The amount of Mn in least altered coherent andesite was on average 0.5 wt% Mn (Chapter 3). Mn has been totally stripped from altered andesites in the steam heated zone is therefore 0 wt% Mn (Chapter 4). Mn in vein stages from period 2 are on average 10 wt% Mn of the total infill stage (Chapter 5). Using this data, a 1 m$^3$ section of rhodochrosite-bearing infill stages at Kerikil would require 20 m$^3$ of andesite, hence a factor of 20 times as much andesite is needed to make the rhodochrosite-bearing infill stages at Kerikil. The main section of the rhodochrosite-bearing breccia body at Kerikil is 5m wide, 100 m long and 250 m deep. This equates to 125 000 m$^3$ of rhodochrosite-bearing infill stage. Multiplying this by a factor of 20 gives the amount required to be 2500 000 m$^3$ of andesite. The steam heated zone at Kerikil represented by the kaolinite alteration facies alteration and silica facies alteration is approximately 400 m by 600 m in surface area and averages 200 m thick, this equates to 48 000 000 m$^3$ of altered andesite which has been completely stripped of Mn. This implies that the kaolinite and silica facies in the steam heated zone at Kerikil, could supply nineteen times as much Mn as is needed for the production of the rhodochrosite-bearing infill stages in the main Kerikil 2 deposit. It is worth noting that only the kaolinite and silica facies have been included in this scenario and additional manganese is also available from the QIP alteration facies and CCA alteration facies where manganese has been completely or partially stripped, therefore the amount of manganese available could be considerably higher (up to 50% higher and forty times as much as is needed).
At both PBH and Kerikil, ore-related elements all increase with increasing Alteration Index, reflecting greater interaction of the host rocks with the mineralizing fluid. Elevated Te and Se values are associated with the most proximal alteration facies at Kerikil, but are more sporadic at PBH. Te and Se are generally transported in the vapor phase and both elements have been suggested as good evidence for a magmatic source for mineralizing fluids within hydrothermal systems and (e.g., Cooke and Mc Phail, 2001; Cooke and Bloome, 1990). Selenium deposition and substitution in sulfides is also known to be enhanced by oxidizing conditions (e.g., Simon et al., 1997). Elevated Se values in the alteration assemblages at Kerikil may represent the interaction of upflowing mineralized fluids with a downward migrating oxidized fluid (meteoric water and/or steam heated waters). High Hg values are normally associated with the topographically highest expressions of a low sulfidation epithermal systems (e.g., Buchanan, 1981). Relatively elevated Hg values in the silica cap at PBH on the summit of Mt Muro support this as being the topographically highest preserved portion of the hydrothermal system.

7.10 Summary

Alteration assemblages were divided into 6 major alteration facies at PBH and five alteration facies at Kerikil. These alteration facies are defined according to the dominant alteration minerals present, based on thin section, XRD and SWIR analyses.

At PBH, alteration is generally zoned about the steeply dipping deposit, except in the more permeable and/or reactive lithological units. QIP alteration occurs proximal to the vein and is developed extensively in the hanging-wall. The QIP alteration facies is flanked by CCA alteration. The SPA facies occurs in more permeable tuff and lapilli tuff units in the Hulubai hanging-wall. Silica alteration facies form resistant ridges and peaks on top of the deposit. Kaolinite alteration is a late stage overprint which is largely confined to the footwall fault gouge. Halloysite alteration occurs at or near the surface and is most likely a weathering feature.

At Kerikil, alteration is also zoned but is more complex and exhibits a more extensive late stage kaolinite overprint than at PBH. The QIP alteration facies occurs proximal to the veins and is flanked by the CCA alteration facies. Kaolinite alteration overprints both these facies at higher elevations. Silica alteration is responsible for the resistant peak of Ganung Baruh.
At both deposits, illite within the QIP alteration facies is indicative of interaction of host rocks with 200° to 250°C, near neutral fluids, and high water to rock ratios. The QIP facies therefore represents the regions of highest fluid flow closest to the mineralizing, neutral chloride waters. Chlorite and carbonate within the CCA alteration facies represent the former recharge area for the hydrothermal system. Both minerals form from reaction of host rocks with fluids greater than 180°C and neutral pH. These features, and the presence of carbonates observed as vein and vug infill, are consistent with bicarbonate waters produced during boiling at the margins of the system (e.g., Simmons and Browne, 2001). The SPA alteration facies observed at PBH is the result of interaction with 200° to 250°C, near neutral fluids with tuffs and lapilli tuffs. The SPA alteration facies was not observed at Kerikil, due to the absence of precursor porous lithologies such as tuffs and lapilli tuffs. The extra porosity within these units may allow the fluid to boil and deposit adularia. Silicification at the top of the deposits is caused by cooling of a silicassaturated fluid at the outflow zones of the former hydrothermal system. A late-stage kaolinite overprint, which is extensive at Kerikil but confined to the footwall at PBH, indicates the reaction of host rocks with a cooler acidic fluid and represents the migration of steam-heated acid sulfate waters back into the system. Kaolinite facies alteration is well developed at Kerikil since numerous fracture and brecciation zones allow multiple fluid pathways for descending acid sulfate waters. At PBH, acidic fluids were confined to the footwall of the single PBH structure. The halloysite alteration facies is common to both PBH and Kerikil, and appears to be a weathering horizon.

Both PBH and Kerikil show depletion of Na₂O and CaO and increases in K₂O, Fe₂O₃ and S. Depletion of MnO and MgO at Kerikil indicates destruction of mafic minerals in the volcanic host rocks. At both PBH and Kerikil, immobile elements are constant across alteration stages and are inferred to be immobile under the hydrothermal conditions at Mt Muro. Ore-related elements all increase with increasing Alteration Index, reflecting greater interaction of the host rocks with the mineralizing fluid closer to the mineralized zones. Hg and As values are highest in the upper alteration zones of both deposits.

The alteration minerals and features observed at PBH and Kerikil are exemplary of the low sulfidation epithermal class of ore deposit, and have similar features to many other epithermal deposits (e.g., southwest U.S and Mexico, Buchanan, 1981; circum-Pacific deposits, Hedenquists et al., 1990).