CHAPTER 5

MINERALIZATION AND PARAGENESIS
CHAPTER 5

MINERALIZATION AND PARAGENESIS

5.1 Introduction

In low and intermediate sulfidation epithermal deposits, gangue and ore mineralization varies laterally and vertically along the host structure in response to variations in pressure, temperature, fluid composition and wallrock interaction (e.g. Lindgren, 1922; Sillitoe, 1977; Buchanan, 1981; Berger and Henley, 1989; Cooke and Simmons, 2000; Hedenquist et al., 2000; Sillitoe and Hedenquist, 2003; Einaudi et al., 2003 and many other workers). Vein and breccia infill mineralogy as well as textural characteristics provide information on the physico-chemical environment of mineral deposition. At both PBH and Kerikil, the identification of vein and breccia infill paragenesis and distribution has provided an insight into the evolving hydrothermal system through time and space.

Prior to this study, documentation of mineralization at Mt Muro was limited to sparse internal company memos and consultant reports, based largely on paragenetically unconstrained samples collected from mines and drill core. Limited studies of PBH and Kerikil mineralization were carried out previously by Simmons and Browne (1990) using only exploration drill core, as mining had not yet begun. Simmons and Browne (1990) proposed a four stage paragenetic sequence for breccia and vein formation at Kerikil and reported sulfide and gangue mineral assemblages, including electrum fineness, from the primary and oxide ore zones. They state that paragenetic relationships were complex and hard to discern at Kerikil, due to multiple overprinting infill stages. The current study has had the benefit of a structural framework and exposures of vein and breccia relationships due to more recent mining in the PBH and Kerikil pits. The new data collected has led to the refinement of breccia and vein infill relationships.

This chapter documents in detail the vein and breccia infill mineralogy, textures and distribution for the PBH and Kerikil deposits. Infill paragenetic relationships were determined through careful observation of cross-cutting relationships, structural
orientation, internal textures and mineralogy. Representative samples of vein and breccia material were selected for characterization by microscopic, geochemical and isotopic analysis. The paragenetic and mineralogical data are discussed in the context of the structural development and hydrothermal evolution of the two deposits.

5.2 Permata-Batu Bading-Hulubai: Infill stages, description, distribution and timing relationships

The main mineralized structure at PBH is a fault, 2.2 km long and up to 5 m wide, that hosts veins and breccias infilled with jasper, microcrystalline quartz, sulfosalts, sulfides, crystalline quartz, amethyst, calcite and manganoan carbonates.

Six vein and breccia infill stages are recognized at PBH (Fig. 5.1). A stage is defined by compositional, textural and mineralogical relationships and is named for the most important and dominant gangue and ore minerals present. Infill stages at PBH are described (as follows) in chronological order, with stage 1 being the earliest deposited and stage 6 being the latest.

5.2.1 Stage 1 jasper infill

Description: Stage 1 jasper infill occurs as rare lensoid pods and veins from 1 to 20 cm in thickness and up to 3 m in length (Fig. 5.2 A). At Hulubai, stage 1 pods and veins are crimson to deep red and commonly have a brecciated contact with wall rocks (Fig. 5.2 B). Matrix supported wall rock breccia clasts of illite-altered coherent andesite may exhibit jigsaw fit textures with angular, slabby and splintery shapes, which appear to be spalled from the vein wall. Clasts are normally less than 10 cm. The matrix between clasts is infilled by stage 1 jasper. At Permata, stage 1 veins have sharp wall contacts, are very hard and break with a conchoidal fracture (Fig. 5.2 C). These veins are characterized by thin bands of microcrystalline quartz and jasper parallel to the vein wall contact with a non-distinct centerline. Late euhedral cubic pyrite of vein overprints the bands and very fine fractures are coated with stage 6 calcite. Host rocks associated with stage 1 infill are altered to an illite + pyrite + adularia assemblage.

Distribution and timing relationships: Veins and breccias with stage 1 jasper infill occur in the footwall of the Hulubai and Permata structures, strike north-northeast and dip steeply...
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Key

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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<tbody>
<tr>
<td>PBH host rocks</td>
<td>Coherent andesite, basaltic andesite and basalt, tuff, volcanoclastic sediments and volcanic breccias</td>
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<tr>
<td>Stage 1</td>
<td>Jasper infill</td>
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<tr>
<td>Stage 2</td>
<td>Microcrystalline quartz infill</td>
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<tr>
<td>Stage 3</td>
<td>Microcrystalline quartz + sulfide + sulfosalts infill</td>
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<tr>
<td>Stage 4</td>
<td>Crystalline quartz + base metal sulfides infill</td>
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<td>Stage 5</td>
<td>Amethyst infill</td>
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<tr>
<td>Stage 6</td>
<td>Carbonate infill</td>
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<tr>
<td>Open space</td>
<td>Vugs filled with coarse euhedral quartz, amethyst or calcite crystals.</td>
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Figure 5.1 PBH infill stage relationships

A. Schematic diagram showing PBH vein paragenesis in the ore zone and the relationship of various veins and breccia stage infill characteristics. In the ore zone, vein stages 1 to 6 are present. Alteration associated with the vein stages is described in chapter 7.

B. Schematic diagram showing PBH vein paragenesis below the ore zone and the relationship of various veins and breccia stage infill characteristics. Below the ore zone, vein stages 1, 2, 4, 5 and 6 are present but the main precious metal bearing infill (stage 3) is absent. Alteration associated with the vein stages is described in chapter 7.

Inset: Relative location of vein stages on 12:00 NN cross section, Hulubai from Fig 3.15.
to the west. Stage 1 infill is observed at 145 RL at Hulubai and at 165 RL at Permata, and is absent below 145 RL at both deposits. Stage 1 infill is cross-cut by north-northwest striking, stage 2 microcrystalline quartz, stage 3 microcrystalline quartz + sulfide + sulfosalt veins and late northeast striking stage 6 carbonate veins. Stage 1 clasts are locally enclosed by stage 3 vein infill.

5.2.2 Stage 2 microcrystalline quartz infill

Description: Stage 2 microcrystalline quartz infill occurs as lensoid pods and narrow veins up to 10 m long and ranging from 0.5 to 30 cm in thickness. It is also recognized as initial vein infill of the main PBH structure (Fig. 5.3 A). The color of stage 2 infill varies from grey to black (in the earlier deposited microcrystalline quartz) to pale or white (in the later varieties: Fig. 5.3 B, C and D). Stage 2 is very hard and breaks with a conchoidal fracture (Fig. 5.3 F). Pods and veins of stage 2 may have sharp or brecciated wallrock contacts (Fig. 5.3 B and C). The vein textures can be massive or banded with dark and light colored bands alternating on a millimeter to centimeter scale, paralleling the vein wall contact (Fig. 5.3 B, C and F). Matrix supported breccia clasts composed of earlier, dark
Figure 5.3  PBH: Stage 2 microcrystalline quartz infill - ore zone

A  Stage 2 microcrystalline vein with sharp wallrock contact, Hulubai hanging-wall.
B  Breciated and banded stage 2 microcrystalline vein with fragments of earlier stage 2 fine colloform banded infill and later quartz + sulphosalts + sulphides vein. 145RL, Hulubai (AWH 0004).
C  Banded stage 2 microcrystalline vein with adularia + illite + pyrite altered wallrock. 145RL, Hulubai (AWH 0007).
D  Breciated stage 2 microcrystalline vein with fragments of earlier fine colloform banded stage 2 and later quartz-sulphosalts-sulphides vein. 145RL, Hulubai (AWH 0002).
E  Stage 2 white microcrystalline vein with sharp vein wall and adularia + illite + pyrite altered wallrock (stained with cobalt-nitrate to show presence of K-feldspar/adulana). 150 RL, Pennata (AWP0083).
F  Crustiform layers in banded Stage 2 microcrystalline quartz with later Stage 2 microcrystalline quartz cross-cutting layering. 145RL, Hulubai (AWH 0018).
colored banded stage 2 can be entrapped in a matrix of late, white, massive stage 2 infill (Fig. 5.3 C). Breccias may be jigsaw fit or matrix supported (by stage 2 infill) with angular and rotated clasts. Clasts are normally less than 5 cm in diameter. Coherent andesite lavas and tuff wall rocks are altered to an quartz + illite + pyrite assemblage (Fig. 5.3 E). Fine-grained euhedral cubic pyrite crystals are observed throughout stage 2 infill. Staining suggests fine-grained K-feldspar (inferred to be adularia) is present throughout stage 2 (Fig. 5.3 F).

Distribution and timing relationships: Veins and breccias with stage 2 microcrystalline quartz infill strike from north-northwest to north-northeast and dip steeply to moderately to the west. They occur laterally along the entire PBH vein, but are most prevalent at the junction of vein splits and bifurcations. Stage 2 is recognized over the full vertical interval of the PBH deposit, from 225 RL down to 25 RL, a vertical distance of 200 m. Local exposures of stage 2 are also recognized in the deepest explored parts of the deposit (0 RL), in association with stages 5 and 6. At these deep levels, stage 2 is represented by veins and brecciated clasts which are infilled or enclosed by later infill stages 5 and 6 (Fig. 5.4 A and B). At shallower levels, Stage 2 infill is typically deposited at vein wall contacts with later infilling by stages 3, 4, 5 and 6 (Fig. 5.3 F and G). Stage 2 is also cut by late northeast striking stage 6 veins and fractures. Stage 2 often occurs as clasts enclosed by stage 3 and stage 4 infill.

Figure 5.4  PBH: Stage 2 microcrystalline quartz infill - deep zone
A  Brecciated stage 2 microcrystalline quartz clasts enclosed by later stage 2 microcrystalline infill. Sample is cross-cut by later crystalline quartz and amethyst veins from the deep un-mineralized portions of the Permata Vein. DDH 739, 133m, 60 RL, Hubba (AWH 0128).
B  Brecciated stage 2 microcrystalline quartz clasts enclosed by later stage 5 amethyst infill and later bladed stage 6 calcite infill from the deep un-mineralized portions of the Permata Vein. Bladed carbonates is a good indicator of boiling conditions. DDH 794, 154m, 30 RL, Hubba (AWH 0180).
5.2.3 Stage 3 microcrystalline quartz + sulfide + sulfosalt infill (ore)

Description: Stage 3 microcrystalline quartz + sulfide + sulfosalt infill is the main ore hosting stage at PBH. Stage 3 occurs as infill to faults and veins that range in width from 0.5 cm to 3 m, with continuous segments up to 200 m long (Fig. 5.5 A). The veins may have brecciated or sharp wallrock contacts (Fig. 5.5 B and C). Stage 3 is hard, has a brittle fracture, and consists of alternating black to steel grey and white (to buff or cream) colloform bands. The dark bands are composed of pyrite, sphalerite (colorless to honey-colored), galena, chalcopyrite, jalpaite, silver sulfosalts, acanthite and low fineness electrum. The pale-colored bands are composed of microcrystalline quartz and lesser amounts of adularia and clay. Alternating quartz and sulfide + sulfosalt bands, from submillimeter to centimeter in thickness, occur paralleling the vein wall contact or encircling breccia clasts of wall rock and earlier brecciated clasts of stage 2 or 3 (Fig. 5.5 C). Up to eight alternate bands of microcrystalline quartz and black sulfide + sulfosalt and have been noted in stage 3 infill. Wallrock adjacent to stage 3 infill exhibits illite + pyrite + adularia alteration (Fig. 5.5 D). Staining of stage 3 slabs shows that potassium feldspar (inferred to be adularia) is present as bands within the veins and has altered primary plagioclase feldspar crystals in the host coherent andesite.

Distribution and timing relationships: Veins and breccias with stage 3 microcrystalline quartz + sulfide + sulfosalt infill occur sporadically throughout the Hulubai and Permata deposits. Above 75 RL, Stage 3 is recognized throughout the PBH vein but is most prevalent at the junction of vein splits and at bifurcations. Vertically, stage 3 is common from 225 RL down to 75 RL but is not observed in the deepest explored sections (0 RL) of the PBH vein. Stage 3 was deposited after stage 2 but before stages 4, 5 and 6. Stage 3 is also cut by late, northeast striking, stage 6 calcite infill.

5.2.4 Stage 4 crystalline quartz + base metal sulfide infill (ore)

Description: Stage 4 crystalline quartz + base metal sulfide infill consists of coarse-grained, white to clear, crystalline, massive and comb quartz and massive to crystalline sulfide (Fig. 5.6 A and B). Stage 4 quartz crystals and massive clots of chalcopyrite, pyrite, sphalerite and galena (with lesser amounts of fine-grained sulfosalts, acanthite and low fineness electrum) can be up to several centimeters in diameter. In some samples, covellite (after chalcopyrite) was observed. Early pyrite contains small inclusions of cervellite
Figure 5.5 PBH: Stage 3 microcrystalline quartz + sulfide + sulfosalt infill

A. Pennata North vein with sharp vein wall contact cutting across thin (3cm wide) microcrystalline quartz veins. Host rocks are altered to an illite + pyrite + adularia assemblage, Pennata.

B. Stage 3 microcrystalline quartz + sulfide + sulfosalt veins with fine crustiform and colloform banding, Pennata.

C. Stage 2 infill with fine crustiform and colloform banding and later Stage 3 microcrystalline + sulfide + sulfosalt vein with fine crustiform colloform banding. High grade ore, 150 RL, Pennata (AWP 0034A).

D. Stage 3 microcrystalline quartz + sulfide + sulfosalt with fine colloform and cockade banding, enclosing stage 2 pre-mineralization clast. Sample also contains later stage 4 crystalline quartz + sulfide infill. High grade ore, 150 RL, Pennata (AWP 0080).

E. Stage 2 infill with fine crustiform and colloform banding and later Stage 3 mineralized microcrystalline quartz + sulfide + sulfosalt vein with fine crustiform colloform banding. High grade ore, 150 RL, Pennata (AWP 0042).

F. Stage 3 microcrystalline quartz + sulfide + sulfosalt with fine colloform and cockade banding, enclosing coherent adularia clasts that contain stage 2 microcrystalline quartz veins. Also shown in a late stage 4 cross-cutting vein. Wallrock clasts exhibit illite + adularia + pyrite alteration. High grade ore, 165 RL, Pennata (MBM 4).
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Figure 5.6 PBH: Stage 4 coarsely crystalline quartz + base metal sulfide infill

A Fine grained crustiform and colloform stage 3 sulfide + sulfosalt + microcrystalline quartz and later coarse stage 4 sulfide + crystalline quartz infill. 165 RL, Permata (AWP 0040).

B Coarse grained crystalline stage 4 sulfide + quartz infill with chalcopyrite and minor sphalerite and galena. 165 RL, Permata (AWP 0040).

(Ag₄TeS). Stage 4 is always enclosed by stage 3 (Fig. 5.6 A) and rarely occurs in contact with wallrock, so host rock alteration associated with this stage cannot be determined (Fig. 5.3 D).

Distribution and timing relationships: Stage 4 crystalline quartz + base metal sulfide infill occurs as a late stage vein infill at bifurcations and splits in the main Permata vein at 30 300N. Stage 4 is recognized in the ore zone between 225 to 75 RL and locally below the bonanza zone in the deepest explored parts of the PBH vein (0 RL), where it can be associated with stage 6 calcite. Stage 4 was deposited after stages 2 and 3 but before stages 5 and 6 infill.

5.2.5 Stage 5 amethyst infill

Description: Stage 5 amethyst occurs as fault and vein infill throughout the Hulubai and Permata deposits. Veins containing stage 5 range in width from 0.5 cm to 3 m, with continuous segments up to 200 m long. Stage 5 is characterized by coarse-grained, clear and pale lilac to deep purple, euhedral amethyst crystals up to several centimeters in length. The amethyst forms colloform and cockscomb bands and infills vuggy vein cavities (Fig. 5.7). Deep purple varieties occur at shallower levels in the PBH system and are associated with, and deposited after, high grade stage 3 vein infill (Figs. 5.5 F, 5.7 D and E). At deeper levels in the PBH deposit, stage 5 infill is lighter in color (clear to pale lilac) and exhibits colloform, cockade and cockscomb textures which enclose clasts of earlier stage 2 or stage 3 matrix-supported brecciated host rock (Fig. 5.7 F). Amethyst crystals from the
Figure 5.7  PBH: Stage 5 amethyst infill

A  Post-mineralization stage 5 crustiform comb amethyst vein located between the branches of the cymod vein. 165 RL, Central Permata.

B  Post-mineralization stage 5 crustiform comb amethyst vein with several cycles of white to purple amethystine quartz deposition. Vuggy space at vein centerlines which are locally filled by late stage 6 carbonates. 145 RL, Hulubat (AWP 0049).

C  Post-mineralization stage 5 crustiform comb amethyst vein with white to purple amethystine quartz and late stage 6 carbonate infill. 145 RL, Hulubat (AWP 0049).

D  Brecciated stage 2 nucrocrystalline quartz clasts with late stage 5 post-mineralization amethyst infill displaying cockade and crustiform textures. 150 RL, Permata (AWP 0078).

E  Permata high grade ore block with colloform crustiform stage 3 sulfide + sulfosalt + nucrocrystalline quartz vein and stage 4 sulfide + crystalline quartz infill. Also shown are late stage 5 amethystine quartz veins. Permata.

F  Brecciated stage 2 nucrocrystalline quartz clasts with late stage 5 amethystine quartz infill displaying cockade and crustiform textures. Sampled from deep zone at Hulubat DDH 794, 153-4 m, 30 RL, Hulubat (AWP 0091).
deeper parts of the PBH system are locally zoned with clear bases and termination points of pale lilac. Repeated sealing and re-brecciation events are not recognized in stage 5. Chlorite + epidote + carbonate + pyrite alteration occurs at vein margins where stage 5 is in contact with wall rocks. Significant amounts of stage 5 can dilute the overall precious metal grade of ore blocks in the mine.

**Distribution and timing relationships:** Stage 5 amethyst infill occurs throughout the Hulubai and Permata deposits, in north-northwest to north-northeast striking and steeply to moderately west dipping veins. Stage 5 infill was observed laterally and vertically through the entire PBH vein (from 225 RL down to 0 RL), but is most prevalent at the junction of vein splits, bifurcations and at depth. Stage 5 is also common along the northern Permata vein segment and is frequently observed below the bonanza zone in the deepest explored parts of the PBH vein (0 RL). Stage 5 is deposited after stages 2, 3 and 4 and before stage 6.

### 5.2.6 Stage 6 carbonate infill

**Description:** Stage 6 carbonate occurs as fault and vein infill throughout the Hulubai and Permata deposits (Fig. 5.8). Individual veins of stage 6 can be up to 30 cm in width, but generally occur as small fractures and veins up to tens of centimeters wide (Fig. 5.8 A). Stage 6 also occurs infilling voids within the host rock and as late stage vug infill. Stage 6 is characterized by coarse-grained, white to pink, euhedral crystals of carbonate and clear quartz crystals. These crystals can be up to several centimeters long with well formed termination points. The pink carbonate fizzes under dilute warm hydrochloric acid and is implied to be a manganoan calcite species. Manganoan calcite occurs at shallow levels in the PBH deposit infilling faults which cross-cut the main vein. White calcite is more common in the deep sections of the PBH deposit where it is observed infilling after stages 2, 4 and 5 (Figs. 5.4 B, 5.8 A, B and C). Chlorite + epidote + carbonate + pyrite alteration occurs where stage 6 is seen in contact with wall rocks. Significant amounts of stage 6 can dilute the precious metal grade of ore shoots.

**Distribution and timing relationships:** Stage 6 carbonate infill occurs throughout the Hulubai and Permata deposits. It forms in north-northwest to north-northeast striking and steeply to moderately west dipping veins, as well as infill in late northeasterly faults which
offset the north-northwest to north-northeast striking PBH veins. Stage 6 infill is observed laterally and vertically throughout the entire PBH vein (from 225 RL down to 0 RL) but is most prevalent at the junction of vein splits, at bifurcations, at depth and as infill of late northeast trending faults. At Hulubia, stage 6 is represented by pink manganoan calcite at shallow levels. Stage 6 at Permata is largely represented by white calcite; no manganoan carbonate was observed in the deeper parts of the vein. White, fine grained, bladed quartz crystals are assumed to have replaced carbonate below the bonanza zone in the deepest explored parts (0 RL) of the PBH vein. Stage 6 was deposited after stages 1, 2, 3, 4 and 5.

5.3 Interpretation of PBH vein stages

Stage 1 is characterized by narrow dilation structures and hydrothermal brecciation of wallrocks. This stage represents the initiation of the hydrothermal system and is always crosscut by infill stages 2, 3 and 6 or it occurs as clasts enclosed by infill stage 2. Slabby and jigsaw fit brecciation recognized in this stage is caused by rapid de-pressurization and
hydrothermal brecciation at the initiation of fissure formation, when lithostatic pressure exceeds hydrostatic pressure. The fine-grained crystal size indicates a rapid rate of nucleation in response to either cooling or the effects of boiling (Browne and Ellis, 1970).

Stage 2 infill is always observed as the second stage deposited within the main PBH vein and is crosscut by later infill stages or occurs as clasts enclosed by later infill stages. As in Stage 1, narrow dilated structures and hydrothermal brecciation of wallrocks characterize the early stages of the hydrothermal system. The fine-grained crystals and adularia represent rapid rates of deposition in response to either cooling or the physico-chemical effects associated with boiling (Browne and Ellis, 1970; Browne, 1978; Henley, 1985; Hedenquist, 1990a).

Stage 3 infill occurs as the third stage deposited within the main vein stratigraphy and is crosscut or infilled by later stages 4, 5 and 6. Stage 3 marks the start of metal deposition and is the main ore infill stage. Narrow dilated structures with limited hydrothermal brecciation of wallrocks and thin banding suggests incremental opening and pulsing of hydrothermal fluids into the fissure. The fine-grained nature of the crystals and adularia suggest rapid cooling and the physico-chemical effects associated with boiling (Browne and Ellis, 1970; Browne, 1978; Henley, 1985; Hedenquist, 1990a).

Stage 4 infill is observed post stage 3 within the main vein stratigraphy and is crosscut by later infill stages or occurs as clasts enclosed by later infill stages. Thick banding and vuggy cavities suggest open space filling and large dilation of structures. The coarse, well-formed euhedral crystals in this stage indicate slow rates of crystallization in response to cooling of a silica under-saturated fluid and slowly changing conditions (Fournier, 1985a; Saunders, 1994). Stage 4 marks the waning stage of metal deposition and is a minor ore stage. Base metal sulfides of this stage are only observed below the 75 RL and are not associated with precious metals, suggesting a different physico-chemical environment of deposition than stage 3 and conditions not conducive to gold deposition.

Stage 5 infill is deposited after stages 3 and 4 within the main vein stratigraphy and crosscut by later infill stage 6. Stage 5 marks the waning stages of silica deposition. Thick banding and vuggy cavities suggest open space filling and large dilation of structures. Coarse, well-formed euhedral crystals within this stage indicate slow rates of crystallization in response to cooling of a silica under-saturated fluid (Fournier, 1985a; Saunders, 1994). No mineralogical evidence of boiling was observed in this stage. This stage may either
indicate regions low temperature fluids which have previously boiled or the possible telescoping of the barren roots of the epithermal system onto the main zone of ore deposition.

Stage 6 infill is observed post stages 1, 2, 3, 4 and 5 within the main vein stratigraphy or in late faults offsetting the main PBH structure. Thick banding and vuggy cavities suggest open space filling and a large amount of dilation. The coarse, well-formed euhedral crystals indicate slow rates of crystallization in response to heating or carbon dioxide exsolution. Bladed carbonate recognized in the deep parts of the deposit provide evidence for boiling (Simmons and Christenson, 1994). Stage 6 marks the waning stages of the hydrothermal system.

5.4 Kerikil vein and breccia stage infill, description, and distribution

Veins and breccia-filled faults are the main mineralized structures at Kerikil 1, 2 and 3. These structures are typically infilled with microcrystalline quartz, crystalline quartz, amethyst, calcite, rhodochrosite, ankerite, sulfides, sulfosalts, and/or electrum.

The paragenesis of the Kerikil deposit was largely unknown at the start of this study. Simmons and Browne (1990) recognized four infill stages at Kerikil based on observations of drill core in the early stages of exploration. They stated, however, that individual breccia stages were hard to determine due to the high degree of brecciation and overprinting relationships. Although determining the nature and timing of different infill stages at Kerikil is challenging, this study has had the benefit of pit exposures which have helped to refine observations of Simmons and Browne (1990) and develop a new paragenetic sequence.

To further separate overprinting relationships, periods as well as stages have been defined for the Kerikil deposit. A stage is defined by composition, textural and mineralogical characteristics, juxtaposition and relationship to other stages, with stage 1 being the earliest and stage 9 being the latest. A period is defined by the dominant gangue composition (e.g. quartz, carbonate or sulfide) and deposition style, and can be related to other periods.

Nine vein and breccia infill stages were documented at Kerikil in three distinct periods of mineral deposition (period 1 being the earliest and period 3 the latest; Fig. 5.9).
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Key

- Kerikil host rocks: Coherent andesite, basaltic andesite and volcanic breccias.

**Period 1 (silica polymorph dominated veins and breccias)**

- **Stage 1** microcrystalline quartz infill
  - Thinly banded veins and breccia infill with colloform, crustiform and cockade texture
  - Enclosing breccia clasts of host rock
  - Thinly banded veins of microcrystalline quartz with disseminated fine-grained pyrite crystals

- **Stage 2** microcrystalline quartz + sulfide + sulfosalt infill
  - Thinly banded veins and breccia infill with colloform, crustiform and cockade texture
  - Enclosing breccia clasts of host rock and stage 1
  - Thin bands of pyrite, chalcopyrite, sphalerite, galena, Ag-Sb and As sulfosalts, acanthite, silver and electrum

- **Stage 3** amethyst infill
  - Coarsely banded veins and breccia of amethyst infill with colloform, crustiform and cockade texture
  - Enclosing breccia clasts of host rock and stage 1, 2, and 3
  - Coarse bands of crystalline comb amethyst crystals
  - Wug filling

- **Stage 4** carbonate infill
  - Thinly banded veins of carbonate and quartz infill with colloform and crustiform texture

**Period 2 (rhodochrosite bearing veins and breccias)**

- **Stage 5** rhodochrosite + sulfide + sulfosalt infill
  - Coarsely banded breccia infill with colloform and cockade texture
  - Enclosing breccia clasts of host rock and stages 1, 2, 3, and 4
  - Diffuse band margins
  - Thin bands of pyrite, sphalerite, chalcopyrite, galena, Ag-Sb and As sulfosalts, acanthite, silver and electrum
  - Native silver infilling vugs

- **Stage 6** microcrystalline quartz + rhodochrosite infill
  - Thinly banded vein and breccia infill with colloform and cockade texture
  - Enclosing breccia clasts of host rock and stages 1, 2, 3, 4, and 5

- **Stage 7** amethyst + rhodochrosite infill
  - Coarsely banded veins and matrix text pyrite + breccia with colloform, crustiform and cockade texture
  - Enclosing breccia clasts of host rock and crosscutting stages 1, 2, 3, 4, 5, and 6
  - Coarse bands of crystalline comb amethyst crystals
  - Operated by thin bands of rhodochrosite
  - Wug filling

**Period 3 (sulfide veins)**

- **Stage 8** base metal sulfide + quartz infill
  - Coarse veins of pyrite, sphalerite, galena, chalcopyrite, covellite, ruby silver, and electrum

- **Stage 9** pyrite infill
  - Coarse veins of pyrite and marcasite

- **Open space**: Vugs often lined with coarse euhedral quartz, amethyst or calcite crystals or rarely electrum and native silver wires

**Figure 5.9** Kerikil infill stage relationships

Schematic diagram showing Kerikil vein and breccia infill periods and stages.

A. Vein infill relationships in period 1. Breccia clasts of period 1 are enclosed by period 2 breccias.

B. Veins and breccia infill relationships in periods 2 and 3. Breccia clasts of period 1 are enclosed by period 2 breccias, which are in turn cross-cut by veins of period 3.

INSET: Relative location of periods and vein stages on Kerikil section 6.75DU from Fig. 3.17.
Period 1 is dominated by silica polymorphs deposited in colloform, crustiform bands in veins, or as infill to breccias. Infill stages within period 1 are deposited sequentially within a single structure (in the order listed in Fig. 5.9) with no repetition of individual stages. Period 2 is dominated by breccias with rhodochrosite as a primary gangue mineral. In this period, multiple repetition of infill stages (Stages 5, 6 and 7) are recognized within the same structure. Period 3 is represented by two phases of late cross-cutting veins containing coarse-grained base metal sulfides and pyrite, respectively. No repetition of individual stages in period 3 is recognized.

The majority of work in this study has concentrated on the Kerikil 2 veins and breccias, and to a lesser extent on Kerikil 1. Mining was active through the main ore zone at Kerikil 2 during this study but was close to completion at Kerikil 1. Kerikil 3 was only in the early phase of strip-back prior to pit excavation and therefore inaccessible. Due to these constraints, the infill stage paragenesis determined here for the Kerikil deposits is largely based on work at Kerikil 2, but has been tested on archival and drill core samples at Kerikil 1 and is also considered to be valid for that deposit.

5.4.1 Stage 1 microcrystalline quartz infill

*Description:* Period 1 is characterized by microcrystalline and crystalline quartz infill of veins and breccias with crustiform, colloform and cockade bands. Fragments of period 1 frequently occur as rounded to angular and rotated breccia clasts in period 2 and are crosscut by veins of period 3.

Stage 1 is the first stage of period 1 and is characterized by microcrystalline quartz. This quartz is white, buff to dark grey, hard, and breaks with a conchoidal fracture. Stage 1 occurs as thin veins from 2 to 5 cm in width and as the matrix to matrix- and clast-supported jigsaw fit and monomictic breccias. These breccias contain angular to sub-rounded, rotated and unrotated clasts of coherent basaltic andesite and coherent andesite. Clasts and host rocks can be silicified or altered to an illite + pyrite + adularia or chlorite + epidote + albite + pyrite assemblage. (Fig. 5.10). Jigsaw fit brecciation has curvi-planar fracture surfaces (Fig. 5.10 E). Stage 1 locally exhibits a thinly banded texture but is more frequently massive. Staining of stage 1 (using cobalto-nitrate) indicates that disseminations of K-feldspar (inferred to be adularia) are present. Stage 1 microcrystalline quartz is
Figure 5.10  Kerikil Stage 1 microcrystalline quartz infill

A  Stage 1 microcrystalline quartz infill of jigsaw fit breccia at margin to Kerikil 2 breccia body. Coherent basaltic andesites host rock and clasts are illite + pyrite + adularia altered.

B  Stage 1 microcrystalline quartz matrix supported breccia. Rotated angular to sub rounded breccia clasts and host rocks are illite + pyrite + adularia altered. Kerikil 2.

C  Veins with stage 1 infill cross-cut by later stage 3 veins of coarse-grained crystalline amethyst. Host rock is an altered silicified coherent basaltic andesite. Kerikil 2.

D  Stage 1 microcrystalline quartz infill of jigsaw fit breccia at margin to Kerikil 2 breccia body. Coherent andesite host rocks and clasts are illite + pyrite + adularia altered.

E  Breccia vein with white stage 1 infill and curvilinear fractures around breccia vein. Breccia clasts are rotated, angular to sub rounded, slabby and curved and host rocks are coherent andesite which are illite + pyrite + adularia altered. Kerikil 2 footwall.
equivalent to the stage 1 of Simmons and Browne (1990).

Distribution and timing relationships: Stage 1 is cross-cut by all later infill stages. The microcrystalline quartz infill occurs throughout the Kerikil deposit but is more predominant at the margins of vein and breccia bodies and at the widest sections of breccia bodies. Stage 1 occurs along the entire length of the deposit at Kerikil 1 and 2 and over the full vertical extent of the ore body (from 300 to 0 RL).

5.4.2 Stage 2 microcrystalline quartz + sulfide + sulfosalt infill

Description: Stage 2 is the second stage of period 1 and consists of massive white microcrystalline quartz and dark sulfide + sulfosalt banded veins with crustiform, and colloform textures (Fig. 5.11). Breccia clasts of both stage 1 and stage 2 are locally enclosed by later stage 2 infill with cockade banded textures. Wallrock margins to stage 2 veins are either sharp and straight or brecciated (5.11 F). Breccia clasts and wall rocks associated with stage 2 are coherent basaltic andesite or andesite lavas, which can be altered to illite + pyrite + adularia or chlorite + epidote + albite + pyrite assemblages. Jigsaw fit brecciation is common with angular or slabby clasts (5.11 E). Staining of stage 2 shows that fine-grained disseminations of K-feldspar (inferred to be adularia) are present. The thin dark sulfide and sulfosalt bands consist of fine-grained pyrite, chalcopyrite, galena, sphalerite, silver sulfosalts and electrum. Stage 2 was not distinguished in the paragenetic sequence of Simmons and Browne (1990).

Distribution and timing relationships: Complete veins with stage 2 infill are rare in the Kerikil deposit. This stage most commonly occurs as breccia clasts of banded veins within the main breccia body at Kerikil 2. A single, high grade stage 2 vein (100 m long and up to 4 m wide, but averaging only 2 m wide) is observed in the southwest corner of the Kerikil 2 pit (see Fig. 4.19 C). This vein shows jigsaw fit brecciation at the contact with wall rocks and banded stage 1 infill at the margins of the main vein structure. Stage 2 microcrystalline quartz + sulfosalt + sulfide infill is precipitated after stage 1, while stages 3 to 9 cross-cut stage 1. Stage 2 clasts are recognized over a vertical distance of 150 m, from 150 to 300 RL.
Figure 5.11 Kerikil: Stage 2 microcrystalline quartz + sulfide + sulfosalt infill

A. Stage 2 colloform-crustiform banded microcrystalline quartz + sulfide + sulfosalt vein striking 180° and cross-cutting early microcrystalline quartz veins. The cavity is where the vein has been dug out by itinerant miners. High grade vein, Kerikil 2.

B. Stage 2 colloform-crustiform banded microcrystalline quartz + sulfide + sulfosalt vein with stage 1 microcrystalline quartz breccia at the margin. High grade vein, southwest of Kerikil 2.

C. Stage 2 colloform-crustiform banded microcrystalline quartz + sulfide + sulfosalt vein with stage 1 microcrystalline quartz breccia at the margin. High grade vein, southwest of Kerikil 2.

D. Stage 2 colloform-crustiform banded microcrystalline quartz + sulfide + sulfosalt vein. High grade vein, Kerikil 2.

E. Stage 2 cockade banded microcrystalline quartz + sulfide + sulfosalt matrix to breccia of stage 1 microcrystalline quartz clasts. High grade vein, southwest of Kerikil 2.

F. Stage 2 colloform-crustiform banded microcrystalline quartz + sulfide + sulfosalt breccia infill. High grade vein, Kerikil 2.

(Ank 0441)
5.4.3 Stage 3 amethyst infill

*Description:* Stage 3 is the third stage of Period 1. Stage 3 amethyst vein and breccia infill consists of coarse, clear, and pale lilac to deep purple amethyst crystals up to several centimeters long. The crystals form colloform and cockscomb textured infill as well as infill in vugs (Fig. 5.12). Veins containing stage 3 are normally less than 5 cm wide. Stage 3 frequently forms the matrix to jigsaw fit breccia veins that contain slabby and angular breccia clasts of basaltic andesite and andesite. Clasts are not rotated. Stage 3 host rocks of coherent andesite and basaltic andesite are chlorite + epidote + albite + pyrite altered. Significant amounts of stage 3 can dilute the overall gold grade of mining ore blocks.

*Distribution and timing relationships:* Stage 3 amethyst infill occurs throughout the Kerikil deposits. It is recognized laterally and vertically through the entire vein and breccia body (from 0 to 300 RL), but is most common at the junction of vein splits, bifurcations and at depth. Veins are typically from 1 to 3 cm wide and from 2 to 20 m long. Breccia zones up to 3 m wide and 100 m long occur at the margins to the deposit. In the high grade vein seen in the southwestern section of Kerikil 2, amethyst infill is precipitated after stage 2. Stage 3 amethyst can be distinguished from stage 6 by the absence of repeated episodes of rhodochrosite and amethyst infill. Stage 3 is deposited after stages 1 and 2 and before stages 5, 6, 7, 8 and 9.

5.4.4 Stage 4 carbonate vein infill

*Description:* Stage 4 is the fourth and last stage of period 1. Stage 4 infill is rare and consists of alternating crustiform and colloform bands of massive to crystalline calcite and coarse-grained, clear to white, euhedral quartz crystals (Fig. 5.13). Veins containing stage 4 are typically less than 5 cm wide.

*Distribution and timing relationships:* Stage 4 veins occur at the margins to the main Kerikil 2 orebody and are recognized as much as 50 meters away from the main breccia. Isolated stage 4 veins also occur throughout all drill core examined, at both shallow and deep levels. These veins are 1 to 2 cm wide and 2 to 20 m long. Stage 4 carbonate veins appear to be more common in the basaltic andesite intrusion as very fine, wispy, and curved extension veins. Breccia clasts of carbonate veins that occur in later polyolithic breccias may be stage 4 veins, but their origins are uncertain. Stage 4 carbonate infill occurs post stages 1, 2 and 3.
Figure 5.12 Kerikil: Stage 3 amethyst infill

A. Crustiform-colloform vein with stage 2 and late stage 3 infill. Kerikil 2.
B. Crustiform amethyst vein stage 3 infill cross-cutting stage 1 microcrystalline quartz infill. Kerikil 2.
C. Amethyst vein of stage 3 with crustiform and cockscomb textures. Andesite host rocks are silicified pyrite altered. Kerikil 2.
D. Stage 3 amethyst matrix with cockade and cockscomb textures cementing jigsaw fit brecciated basaltic andesite clasts. Kerikil 2.
F. Stage 3 amethyst matrix with cockade and cockscomb textures cementing jigsaw fit brecciated basaltic andesite clasts. Basaltic andesite is chlorite + epidote + albite + pyrite altered. Kerikil 2.
5.4.5  Stage 5 rhodochrosite + sulfosalts + sulfide infill

Description: Period 2 is represented by a wide range of polyolithic, matrix to clast-supported breccias and the presence of manganese carbonate minerals. Rocks of period 2 containing manganese carbonates frequently weather to form black manganese wad in the oxide zone.

Stage 5 is the first stage of period 2. Stage 5 is characterized by an assemblage of rhodochrosite + sulfosalts + sulfide ± microcrystalline quartz infilling veins and enveloping breccia clasts. Textures include crustiform, colloform and cockade banding (Fig. 5.14). Banding is not well developed, however, and edges of the bands are diffuse. Stage 5 polyolithic breccia clasts include coherent andesite, basaltic andesite and clasts of earlier infill stages 1 through 4. These clasts are up to 15 cm across, and can be rotated or unrotated, angular or rounded.

Carbonate infill of stage 5 is pink and fizzes with warm hydrochloric acid.
Psuedomorphs of bladed quartz after carbonate are rare but do occur locally. Sulfides, sulfosalts and electrum are present in diffuse dark bands and clots surrounded by rhodochrosite and quartz. Native silver is present as fine wires in open vugs and as scales on fractures. Stage 5 is an important high grade ore stage, with grades locally exceeding several 1000 g/t Au and several percent Ag. Stage 5, along with stage 6, are equivalent to the second paragenetic stage defined by Simmons and Browne (1990).

Distribution and timing relationships: Stage 5 occurs sporadically throughout Kerikil 2 and is most common at the widest sections of breccia bodies and at bifurcations and junctions of cross-cutting structures. Breccia zones up to 5 m wide and 100 m long that contain stage 5 infill occur in the centre of the main north-south Kerikil structure. Stage 5 is observed over the full vertical interval of the vein from 300 down to 50 RL, a distance of 250 m. Stage 5 infill encloses clasts of veins and breccia infill stages 1 through 4. Clasts of stage 5 rhodochrosite + microcrystalline quartz + sulfide + sulfosalt that occur in later polylithic breccias are enclosed by infill stages 6 and 7. Vein infill stages 8 and 9 cross-cut stage 5.
5.4.6 Stage 6 microcrystalline quartz + rhodochrosite infill

*Description:* Stage 6 is the second stage of period 2 and is characterized by an assemblage of fine grained, grey to white, microcrystalline quartz + pink rhodochrosite + black fine-grained sulfides and sulfosalts. This stage is recognized as banded colloform and cockade infill around breccia clasts (Fig. 5.15). These clasts consist of jigsaw fit, rotated or unrotated, monolithic to polyolithic breccia clasts of coherent andesite, basaltic andesite and/or clasts of earlier vein and breccia stages 1 through 4. Clasts are generally less than 10 cm wide and can be angular to well rounded. Rhodochrosite of stage 6 fizzes with warm hydrochloric acid. Near the surface of the Kerikil2 deposit, rhodochrosite has been weathered to form black manganese wad. Stages 5 and 6 combined are equivalent to stage 2 of Simmons and Browne (1990).

*Distribution and timing relationships:* Stage 6 rhodochrosite + microcrystalline quartz infill is closely associated with stage 5 and occurs throughout the Kerikil2 deposit. It is most common at the widest sections of the breccia body and at bifurcations and junctions of cross-cutting northeast and northwest structures. Breccia zones containing stage 6 infill also occur in the centre of the deposit and are up to 15 m wide and 100 m long. Stage 6 is observed over the full vertical interval of the deposit from 300 down to 0 RL, a distance of 300 m. Stage 6 infill encloses clasts of veins and breccias from stages 1 to 5. Cavities in stage 6 rhodochrosite + microcrystalline quartz are infilled by stage 7 amethyst + rhodochrosite. Several episodes of sealing and brecciation are recognized in stage 6. Vein infill stages 8 and 9 cut across stage 6. A significant amount of stage 6 infill can dilute the grade of mining ore blocks.

5.4.7 Stage 7 amethyst + rhodochrosite infill

*Description:* Stage 7 is the last stage of period 2. Stage 7 is distinguished by an assemblage of colloform and cockade banded amethyst + rhodochrosite infill that surrounds angular breccia clasts and occurs in vein stockwork (Fig. 5.16). The breccia clasts consist of coherent andesite, basaltic andesite or rounded to angular polyolithic breccia clasts of earlier vein stages. Clasts can exhibit jigsaw fit brecciation and the andesite clasts are locally altered to an assemblage of quartz + illite + pyrite to chlorite + pyrite. Stage 7 carbonate is pink and fizzes with warm hydrochloric acid. Amethyst crystals vary
Figure 5.15 Kerik#: Stage 6 microcrystalline quartz + rhodochrosite breccia infill

A PolylnhK breccia with rotated, angular and rounded clasts of earlier infill stages and coherent andesite and basaltic andesite cemented by stage 6 infill.

B PolylnhK breccia with rotated, angular and rounded clasts of earlier infill stages and coherent andesite with stage 1 infill veins. Clasts are cemented by stage 6 rhodochrosite + microcrystalline quartz infill. Kerik# 2 (AWK 0458B).

C PolylnhK breccia with rotated, angular rounded and jigsaw fit clasts of earlier infill stages cemented by cockade banded stage 6 rhodochrosite + microcrystalline quartz infill. Kerik# 2 (AWK 0514).

D PolylnhK breccia with rotated, angular rounded and jigsaw fit clasts of earlier infill stages cemented by crustiform banded stage 6 rhodochrosite + microcrystalline quartz infill. Kerik# 2.

E Breccia with rotated, angular, rounded and jigsaw fit clasts of earlier infill stages and coherent basaltic andesite clasts cemented by stage 6 rhodochrosite + microcrystalline quartz infill. Kerik# 2.

F PolylnhK breccia cemented by infill stage 6 and cross-cut by crustiform banded and vein of infill stage 7. Kerik# 2.

G PolylnhK breccia with rotated, angular, rounded and jigsaw fit clasts with cross-cutting stage 6 veins. Kerik# 2.

H PolylnhK breccia with rotated, angular, rounded and jigsaw fit clasts of earlier infill stages and cockade stage 6. Kerik# 2.
CHAPTER 5 MINERALIZATION

Figure 5.16 Kerikil: Stage 7 amethyst + rhodochrosite infill

A Stage 7 amethyst and rhodochrosite infill of stage 5 breccia. Breccia clasts and wallrock are composed of illite to chlorite altered coherent andesite. Late stage 9 pyrite can be seen filling a vuggy cavity. Rhodochrosite rims the clasts with later pale purple amethyst.

B Stage 7 amethyst and rhodochrosite infill of stockwork and stage 5 breccia. Breccia clasts and wallrock are composed of illite to chlorite altered coherent andesite. Dog-tooth crystals can be seen growing into vuggy open spaces.

C Rhodochrosite rimming a chlorite altered coherent basaltic andesite clast with later, stage 7, coarsely crystalline, pale purple amethyst. Kerikil 2 (AWK 0434).

D Stage 7 amethyst and rhodochrosite vein cross-cutting illite + pyrite altered basaltic andesite. Kerikil 2 (AWK 0126).

E Poorly-sorted rounded polymict breccia facies with late cross-cutting stage 7 amethyst + rhodochrosite vein. Kerikil 2 fonnfall (AWK 0433).

F Comparison of stage 6 rhodochrosite + microcrystalline quartz only infill (top) with stage 6 with stage 7 rhodochrosite + amethyst infill (bottom). Kerikil 2.
from light to dark purple. The light purple variety is associated with rhodochrosite and the
darker amethyst is associated with ankerite. Stage 7 amethyst + rhodochrosite is
distinguished from stage 3 amethyst by the presence of rhodochrosite and their spatial
distribution. Stage 7 amethyst + rhodochrosite can be distinguished from stage 6
rhodochrosite + microcrystalline quartz by the lack of microcrystalline quartz infill and a
lack of evidence of repeated brecciation (Fig. 5.16 F). Stage 7 can dilute the grade of ore
blocks. Stage 7 is equivalent to stage 3 of Simmons and Browne (1990).

Distribution and timing relationships: Stage 7 occurs throughout Kerikil 2, typically at the
margins to the main deposit. Stage 7 infill is also concentrated at the northerly end of the
Kerikil 2 pit, where a late northeast striking structure intersects the main north-south
deposit. Stage 7 infill encloses clasts of veins and breccias from stages 1 through 6. Vein
and vug infill of stages 8 and 9 cross-cut stage 7.

5.4.8 Stage 8, base metal sulfide + quartz infill

Description: Period 3 is represented by late, cross-cutting, coarse crystalline quartz and
base metal sulfide veins and late pyrite vein swarms. This period marks the end of the
hydrothermal system.

Stage 8 is the first stage of period 3. Stage 8 occurs as veins containing crystalline
quartz and discontinuous bands and clots of coarse base metal sulfide (including sphalerite,
chalcopyrite, galena, covellite and the ruby silvers) and rare sulfosalts (Fig. 5.17). Clots of
sphalerite and chalcopyrite can be up to 10 cm with individual sulfide crystals up to 2 cm.
Sphalerite is of the honey colored, iron-poor variety. Wall rocks of coherent andesite and
clasts enclosed by stage 8 are commonly kaolinite altered. Vuggy spaces remaining from
leached, altered volcanic and carbonate clasts are filled with base metal sulfides of stage 8.
Stage 8 is equivalent to stage 4 of Simmons and Browne (1990).

Distribution and timing relationships: Stage 8 veins occur outside the main breccia body
in the footwall of the Kerikil 2 deposit. They form straight, lens-shaped, tension gash veins
up to 20 m long and 50 cm wide which cross-cut the margins of the main Kerikil 2
structure. Stage 8 veins dip steeply and strike northwest at 130°.
5.4.9 Stage 9 pyrite infill

*Description*: Stage 9 is the second stage of period 3. Stage 9 is characterized by crustiform and cockade bands of marcasite, pyrite and crystalline quartz that infill veins and enclose breccia clasts of earlier vein stages (Fig. 5.18). Marcasite occurs at vein margins and rimming clasts, while pyrite occurs in the centre of veins. Linear vein swarms of stage 9 cross-cut earlier brecciation events. Host rocks and clasts of coherent andesite enclosed by stage 9 can be silicified or kaolinite altered. Vuggy space is created after altered and leached volcanics and dissolved carbonate. Stage 9 was not recognized as a separate paragenetic stage by Simmons and Browne (1990).

*Distribution and timing relationships*: Stage 9 veins occur as swarms of parallel vein sets that dip steeply and strike to the northwest at 120°. The veins cross-cut the breccias of the Kerikil 2 deposit. Stage 9 also occurs as infill around breccia clasts of stage 2 microcrystalline quartz + sulfide + sulfosalt and in vugs after stage 3 amethyst.
Figure 5.18 Kerikil: Stage 9 pyrite infill

A  Stage 9 pyrite vein cutting kaolinite altered coherent andesite. Kerikil 2 (AWK 0416).
B  Crystalline quartz vein and stage 9 pyrite, with marcasite along vein boundaries. Kerikil 2 (AWK 0483).
C  Polymer breccia with Stage 6 infill around clasts being cross cut by late stage 9 pyrite vein. Kerikil 2 (AWK 0413).
D  Brecciated with Stage 2 clasts being ringed by late stage 9 pyrite infill. Kerikil 2 (AWK 483 a and b).
E  Stage 3 amethyst infill with late stage 9 pyrite infilling after amethyst. Kerikil 2 (AWK 4836).
F  Stage 9 pyrite and quartz vein in kaolinite altered andesite host rock. Kerikil 2 (AWK 0429).
G  Stage 9 pyrite and quartz veins (with marcasite sun) cross-cutting jigsaw breccia of whitened coherent andesite infilled with stage 3 amethyst. Kerikil 2 (AWK 0421).
H  Stage 9 pyrite and quartz infilling stage after amethyst infill of stage 3 and stage 2 microcrystalline quartz + sulfide + sulfosalt bands. Kerikil 2.
5.5 Interpretation of Kerikil vein and breccia stages and periods

Period 1 at Kerikil is dominated by silica polymorphs and has a similar sequence of infill stages to that at PBH. The 4 stages of period 1 begin with the brecciation of coherent andesite and basaltic andesite host rocks (stage 1). Breccia textures commonly associated with stage 1 indicate rapid pressure release and rock fragmentation. Fine-grained crystals and the occurrence of adularia indicate a rapid rate of crystal nucleation in response to cooling or boiling (Browne and Ellis, 1970; Browne 1978). The recognition of stage 1 clasts in later stages suggests that sealing and re-brecciation was common. In stage 2, the occurrence of fine-grained crystals in thin growth bands suggests a rapid rate of nucleation in a steadily dilating structure. The presence of adularia suggests boiling occurred. Base- and precious-metal deposition is associated with stage 2 and most likely occurred in response to boiling. Coarse-grained stage 3 amethyst crystals occur in thick bands and also line vuggy cavities. The coarse-grained euhedral crystals indicate slow rates of crystallization in response to cooling of a silica under-saturated fluid and slowly changing conditions (Fournier, 1985a; Saunders, 1994). No mineralogical evidence for boiling was recognized in stage 3. This may indicate deposition from lower temperature fluids which have previously boiled. Jigsaw fit brecciation suggests rapid pressure release, possibly due to unloading of the hydrothermal system by tectonic movement or hydraulic release. Stage 4 calcite, recognized at depth and distal to the main Kerikil system, was deposited from bicarbonate fluids. Bicarbonate fluids develop when carbon dioxide (produced by boiling) dissolves in surrounding ground waters (Cooke and Simmons, 2001). These fluids are forced to peripheral regions due to buoyancy and heat effects related to the active hydrothermal system. However, when the hydrothermal system wanes and collapses, bicarbonate fluids flood back into the system filling cavities and late structures. Thick banding and the vuggy cavities recognized in stage 4 suggest open space and dilation. Coarse, euhedral crystals indicate slow rates of crystallization in response to heating or carbon dioxide exsolution (Corbett and Leach, 1996).

Period 2 is characterized by the presence of significant manganan carbonate and a wide range of breccias exhibiting repeated crack/seal brecciation events. These features are consistent with a hydrothermal system that was sealed off in period 1, likely due the high silica content and fine-grained nature of the period 1 assemblages. Sealing of the
system would have eliminated buoyancy effects and allowed the subsequent influx of peripheral bicarbonate fluids above the seal. Due to a combination of brittle and impermeable host rocks, hydraulic overpressurization and/or tectonic brecciation, the seal was broken and manganese-bearing bicarbonate fluids were allowed to mix with the renewed upflow of hydrothermal fluids. A hydrothermal eruption is the favored mechanism of seal breaking, since the sudden pressure release and consequent low pressure void and implosion would have allowed peripheral bicarbonate fluids to flow back into the system. Brecciation in stage 6 was suggested by Simmons and Browne (1990) to be the result of hydrothermal eruption due to a lack of schlickenslides and restricted lateral extent of the breccia (< 600m). This study also favors hydraulic brecciation and proposes that stages 5, 6 and 7 of period 3 all represent the result of crack seal brecciation and lithostatic unloading, which may have been expressed as hydrothermal eruption at surface. Stage 5 represents the initiation of this event and is characterized by jigsaw breccias that are indicative of a rapid pressure release and rock fragmentation, due to lithostatic unloading. Evidence for boiling in stage 5 is recognized by bladed carbonate pseudomorphs. The ill-defined sulfide and sulfosalts bands associated with rhodochrosite in this stage may suggest turbulent mixing, boiling and deposition. Stage 6 is represented by repeated episodes of crack/seal brecciation marked by microcrystalline quartz and rhodochrosite. The fine-grained nature of crystals suggests rapid nucleation in response to boiling or cooling. In stage 7, alternating bands of coarse-grained amethyst and rhodochrosite suggest fluctuating carbonate- and silica-rich fluids. The occurrence of coarse, well-formed euhedral crystals indicate slow rates of crystallization. No mineralogical evidence of boiling is recognized in stage 7. This stage may represent deposition from low temperature fluids that have previously boiled. Jigsaw fit brecciation suggests rapid pressure release, possibly due to unloading of the hydrothermal system by tectonic movement or hydraulic release.

Period 3 is distinguished from period 2 by a change in dilation (from north-south to northwest), structural style (from breccias to veins), and gangue mineralogy (from fine-grained microcrystalline quartz, rhodochrosite, sulfide and sulfosalts to coarse-grained crystalline quartz + sulfides). Stage 8 is the first stage of period 3 and occurs as dilation veins that cross-cut period 1 and 2 infill stages. Thick banding and vuggy cavities suggest open space and large dilation of structures. The occurrence of coarse-grained, euhedral
crystals again indicates slow rates of crystallization. Coarse-grained sulfides likely deposited in response to gradual cooling or dilution. Leaching of volcanic and carbonate clasts and silicification indicate a more acidic fluid. Stage 9 is the last stage of the hydrothermal system. The presence of marcasite is indicative of a cool, low pH fluid (Deer et al., 1992; Saunders et al., 1997). The low temperature, acidic conditions may be related to the collapse of the hydrothermal system and encroachment of reduced, sulfur-rich fluids and iron back into the system via pathways that were opened up by the change in tectonic direction.

### 5.6 PBH ore mineralogy

This section describes in detail the PBH ore mineralogy which is dominated by sulfides and sulfosalts with lesser oxides and rare occurrences of tellurides (Fig. 5.19). Pyrite is the most abundant sulfide and is present in stages 1, 2, 3 and 4. Sphalerite, galena and chalcopyrite are accessory minerals along with trace jalpaite, acanthite, silver sulfosalts, silver tellurides, native silver and electrum in stages 3 and 4.

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*Figure 5.19 PBH infill stage paragenesis detailing gangue and ore mineral occurrences*
5.6.1 Pyrite

Pyrite is the most abundant sulfide phase at PBH. It is ubiquitous in vein stages 1 to 4 and occurs as very fine- to coarse-grained (< 1 mm to 3 cm), pyritohedral, cubic or anhedral grains (Fig. 5.20 A, B and F). Pyritohedral forms are observed in the northern section of the Hulubai vein (Fig. 5.20 B). Microscopically, pyrite is present as light yellow to buff, single crystals or agglomerations of crystals. Stage 2 pyrite is very fine-grained and rarely coarser than 30 \( \mu m \). Pyrite is the earliest sulfide in the mineral paragenesis of stage 3 and 4, and pre-dates sphalerite, galena and chalcopyrite deposition (Fig. 5.20 C). Within the thin, dark sulfide and sulfosalt bands of stage 3 (5.20 F) pyrite is rare, and instead occurs immediately prior to and after sulfide and sulfosalt precipitation. Pyrite from Permata is commonly fractured and infilled by later chalcopyrite (Fig. 5.20 D). Pyrite collected from the vein extremity at North Hulubai contains rare electrum inclusions (Fig. 5.20 A and C). At the bifurcation of the Permata and Permata North veins, pyrite precipitated in the initial bands of stage 4 has inclusions of cervelleite (Ag\(_4\)TeS\(_2\); Fig. 5.20 E).

5.6.2 Sphalerite

Sphalerite in stage 3, the main ore-bearing vein stage, is present in thin sulfide and sulfosalt bands with grain sizes rarely coarser than 1 mm (Fig. 5.20 F). In contrast, stage 4 sphalerite crystals may reach several centimeters in size. Sphalerite occurs as clear to honey colored (iron-poor), fine-grained (< 100 \( \mu m \)), euhedral crystals that frequently exhibit chalcopyrite disease. Sphalerite is abundant within veins and is associated with galena, japaite, silver sulfosalts, chalcopyrite, acanthite, silver and electrum (Figs. 5.19 and 5.21). Sphalerite is more abundant in the late sulfide and sulfosalt bands of stage 3, along with galena and rare chalcopyrite. Sphalerite is generally more abundant in the deeper portions of the PBH deposit (below 100 RL).

5.6.3 Galena

Galena occurs in thin sulfide + sulfosalt bands of stage 3, rarely reaching grain sizes coarser than 1 mm. Stage 4 galena is present as coarse-grained, euhedral crystals up to 1 cm in diameter (Figs. 5.21 and 5.20 F). Galena is typically associated with sphalerite and is
Figure 5.20  PbH sulfides (A)

(All images are photomicrographs, taken under reflected light)

A  Chalcopyrite (cpy), cubic pyrite (py) and electrum (el) of stage 3. Hukubat (AWH0006). Scale = 50 µm.
B  Pyrrhotite-psilite (py) in illite + pyrite + adularia altered coherent andette, stage 3. Hukubat (AWH0006). Scale = 550 µm.
C  Electrum (el) grains enclosed in cubic pyrite (py) with chalcopyrite (cpy), galena (gn), and sphalerite (sph), stage 3. Hukubat (AWH0006). Scale = 50 µm.
D  Fractured cubic pyrite (py) crystals with later chalcopyrite (cpy) unfll, stage 3. Permata (AWP0040A). Scale = 50 µm.
E  Cerneellite (Ag2TeS) in pyrite from stage 4. Central Permata (AWP0040). Scale = 50 µm.
observed syn- and post-deposition of silver sulfosalts, silver and electrum. Galena generally occurs late in vein paragenesis along with sphalerite. Galena is less abundant in vein samples collected from Hulubai at the northern end of the PBH vein system. Galena (like sphalerite) is also more abundant in the deeper portions of the PBH deposit below 100 RL.

5.6.4 Chalcopyrite

Chalcopyrite occurs in both stages 3 and 4, the main ore-bearing vein stages. It is commonly observed in samples collected from central Permata but is rare at the extremities of the vein in southern Permata and at northern Hulubai. Chalcopyrite at PBH is present in either the thin, dark bands of stage 3 (rarely reaching grain sizes coarser than 1 mm) or as massive crystals in stage 4 (Figs. 5.21 and 5.20 F). Chalcopyrite from stage 3 is associated with acanthite, electrum and, to lesser extent, native silver and silver sulfosalts (Figs. 5.19 and 5.21). Coarse chalcopyrite associated with coarsely crystalline quartz is one of the main characteristics of stage 4 (Fig. 5.6 A and B). In this stage, chalcopyrite occurs late in the vein paragenesis and is associated with sphalerite and galena (Fig. 5.21 F).

5.6.5 Covellite

Covellite was only observed in vein stage 3 and 4 within central Permata. Covellite occurs as rims to jalpaite, sphalerite and chalcopyrite grains (Figs. 5.19 and 5.21 D). Covellite is considered a supergene product.

5.6.6 Jalpaite

Jalpaite (Ag₃CuS₂) and possibly mckinstryite ((Ag, Cu)₂S) are important silver ore minerals that occur in thin sulfide and sulfosalts bands of stage 3 (Figs. 5.22 C, D, F and 5.20 F). Jalpaite can only be distinguished microscopically and occurs as pale grey, euhedral crystals exhibiting a poor polish. It is typically confined to particular sulfide and sulfosalts bands. Jalpaite is associated with chalcopyrite, silver sulfosalts, acanthite, native silver, electrum and lesser amounts of galena and sphalerite (Figs. 5.19, 5.21 D and 5.22 A and B).
Figure 5.21 PBH sulfides (B)

(All photomicrographs are taken under reflected light)

A Sphalerite (sph), galena (gn) and chalcopyrite (cpy) of stage 3 infilling bladed texture - possibly after bladed carbonate. Permata (AWP 0043B). Scale = 550 µm.

B Increased magnification of view in 5.21 A showing stage 3 sphalerite (sph), galena (gn) and chalcopyrite (cpy) infilling bladed texture - possibly after bladed carbonate. Permata (AWP 0043B). Scale = 140 µm.

C Coarse-grained sphalerite (sph), galena (gn) and chalcopyrite (cpy), stage 4. Permata (AWP 0040B). Scale = 1800 µm.

D Sphalerite (sph) rimmed by later covellite (cov) with galena (gn), jalpaite (jal) and electrum (el), stage 3. Permata (MM4). Scale = 550 µm.

E Chalcopyrite (cpy) intergrown with sphalerite (sph) and galena (gn), stage 3. Permata (AWP 0042). Scale = 550 µm.

F Sphalerite (sph) with galena (gn) and chalcopyrite (cpy). Permata (AWP 0042). Scale = 50 µm.
5.6.7 Acanthite

Acanthite is also an important silver ore mineral and is present in thin sulfide and sulfosalt bands of stage 3. Acanthite is bright white (in reflected light) and forms fine-grained (100 μm), acicular crystals (Figs. 5.22 C, D, E, F and 5.20 F). Acanthite typically occurs early in the stage 3 band paragenesis (with electrum and silver sulfosalts) and is followed by later chalcopyrite, galena and sphalerite (Fig. 5.22 D).

5.6.8 Silver sulfosalts

A range of silver sulfosalts occur within thin sulfide and sulfosalt bands of stage 3 (Figs. 5.22 C, D, E, F and 5.20 F) and are important silver minerals at PBH. Sulfosalt grains are typically <1mm and are not visible in hand specimen. The most abundant sulfosalt species are the antimony-rich end members, represented by pale grey-green, well polished friebregite (argentian tetrahedrite, (AgCuFe)₁₂(Sb,As)₄S₁₃) and bright whitish green polybasite ((AgCu)₁₆Sb₂S₁₁). The silver sulfosalts are associated with chalcopyrite, jalpaite, native silver, electrum and lesser amounts of galena and sphalerite (Figs. 5.19 and 5.22 B and C).

5.6.9 Unidentified silver sulfides, sulfosalts and tellurides

A range of minor silver sulfides (> 50 wt % Ag), sulfosalts, tellurides and alloys that could not be identified petrographically were analyzed by electron microprobe (Appendix 3). A search of known mineral elemental compositions showed that many of the silver-rich minerals had atypical compositions of silver, copper, iron, zinc, lead, antimony, arsenic, tellurium, and sulfur and could not be identified. A more detailed mineralogical study of the unusual silver minerals was beyond the scope of this project.

5.6.10 Silver

Rare native silver occurs in stage 3, the main ore-bearing vein stage, in thin dark bands (Figs. 5.22 C, D, E, F and 5.20 F ). Silver is bright white (in reflected light) and is present as anhedral grains typically less than 1 mm in diameter. Where present, native silver is associated with chalcopyrite, jalpaite and the silver sulfosalts (Figs. 5.19 and 5.22 C).
Figure 5.22 PBH silver-bearing minerals
(All photomicrographs are taken under reflected light)

A Anhedral friebergite (frieb) grains enclosing tarnished chalcopyrite (cpy) together with minor sphalerite (sph), galena (gn) and electrum (el), stage 3. Hulubas (AWP 0006). Scale = 50 μm.

B Sphalerite (sph) and friebergite (frieb) enclosing galena (gn), which in turn encloses chalcopyrite (cpy), stage 3. Permata, (AWP 0043B). Scale = 50 μm.

C Jalpaite (jal), sphalerite (sph) and chalcopyrite (cpy), stage 3. Hulubas (AWP 0006). Scale = 50 μm.

D Anhedral silver grain enclosed by jalpaite (jal) with chalcopyrite (cpy), stage 3. Permata (AWP 0042A). Scale = 50 μm.

E Acicular acanthite (aca) enclosing electrum (el) with minor pyrite (py), galena (gn) and chalcopyrite (cpy) stage 3. Permata, (AWP 0041B). Scale = 550 μm.

F Anhedral silver grains (Ag), chalcopyrite (cpy) and jalpaite (jal) enclosed by sphalerite (sph). Covellite (cov) is replacing the rims of chalcopyrite (cpy), sphalerite (sph) and jalpaite (jal) grains, stage 3. Permata (MM 4). Scale = 550 μm.
5.6.11 Electrum

Electrum is the primary ore mineral at PBH. It occurs in the thin dark bands of stages 3 and locally interstitial to coarse-grained crystals in stage 4 (Figs. 5.23 and 5.20 F). Electrum ranges from bright canary yellow to pale yellow in color (in reflected light) and is present as fine-grained anhedral grains between 10 to 100 μm. Optical variation between lighter colored, silver-rich and darker colored, gold-rich regions (Fig. 5.23 F) is common. Electrum is associated with sphalerite, galena, chalcopyrite, acanthite, silver sulfosalts (Figs. 5.21 D, F and 5.23 A, B, C, D) and rarely occurs as inclusions in pyrite (e.g. Northern Hulubai: Fig. 5.20 A and C).

5.7 Kerikil ore mineralogy

Ore mineralogy at Kerikil can be distinguished from that at PBH by the greater abundance of chalcopyrite, common inclusions of electrum in pyrite, lack of tellurides, and selenium substitution in jalpaite (and other sulfides). Kerikil ore is dominated by pyrite with lesser amounts of chalcopyrite, sphalerite, galena, covellite, jalpaite, acanthite, silver sulfosalts, native silver and electrum (Fig. 5.24). Ore minerals occur in all three periods but are most abundant in stages 2, 5 and 8.

5.7.1 Pyrite (+ marcasite)

Pyrite occurs in stages 1, 2, 5, 8 and 9 (Fig. 5.25) and is represented as pyritohedral, cubic and anhedral forms. Pyrite in stages 1, 2 and 5 is generally fine-grained (< 1mm) but is coarser grained (> 1cm) in stages 8 and 9. Microscopically, pyrite is present as light yellow to buff colored, fine- to coarse- grained, single crystals or agglomerations. In stage 5, pyrite in sulfosalt bands associated with rhodochrosite contains abundant electrum inclusions. Within this stage, pyrite may occur as rims that overgrow earlier pyrite and chalcopyrite (Fig. 5.25 E and F). In stage 9, marcasite is present as bright yellow, massive bands and is associated with coarsely crystalline quartz in colloform veins and as late stage vug infill. Pyrite always occurs early in the mineral paragenesis of stages 1, 2, 5, 8 and 9 (Fig. 5.24).
Figure 5.23 P8H electrum
(All photomicrographs are taken under reflected light)

A Chalcopyrite (cpy), sphalerite (sph) and electrum (el), stage 3. Hukumi (AWP 0084). Scale = 50 µm.

B Chalcopyrite (cpy), sphalerite (sph), acanthite (aca) needles enclosing electrum (el), stage 3. Penitas (MM 4). Scale = 50 µm.

C Electrum (el) associated with sphalerite (sph) and galena (gn) enclosed by freibergite (free) intergrown with sphalerite (sph), stage 3. Penitas (AWP 0085). Scale = 50 µm.

D Electrum (el) associated with sphalerite intergrown with galena, stage 3. Penitas (AWP 0085). Scale = 50 µm.

E Chalcopyrite (cpy), sphalerite (sph), galena (gn), acanthite (aca) and electrum (el), stage 3. Penitas (AWP 0040B). Scale = 50 µm.

F Electrum (el) grain showing optical variation due to silver- and gold-rich zones. The gold-rich parts have elevated mercury values, stage 3, Penitas (MM 4). Scale = 50 µm.
5.7.2 Chalcopyrite

Chalcopyrite is more common at Kerikil than at PBH and occurs in the main ore-bearing stages (stages 2, 5 and 8; Fig. 5.24). Chalcopyrite from stages 2 and 5 occurs in fine, dark colored bands (with grain sizes rarely coarser than 1 mm) and is associated with sphalerite, galena, silver sulfosalts and electrum (Fig. 5.26 A, B, C and D). Chalcopyrite in stage 8 occurs as massive vein infill with sphalerite, galena and pyrite (Fig. 5.26 E and F). Microscopically, the chalcopyrite is canary yellow and typically forms fine-grained (100 mm) euhedral crystals. Chalcopyrite is also present as “chalcopyrite disease” (Bente and Doering, 1993; 1995) in sphalerite from stage 8.
Figure 5.25 Kerilik sulfides (A)

(A, B, C, D and E are photomicrographs, taken under reflected light)

A Early cubic and pyrohedral pyrite (py) with later sphalerite (sph) and lesser amounts of chalcopyrite (cpy) and trace galena (gn). Pyrite has electrum inclusions. Stage 5, Kerilik 2 (AWK 0447a). Scale = 550 μm.

B Pyrite (py) with later chalcopyrite (cpy) and lesser amounts of sphalerite (sph) and trace galena (gn). Pyrite has electrum inclusions. Stage 5, Kerilik 2 (AWK 0447a). Scale = 550 μm.

C Early cubic and pyrohedral pyrite (py) with later rims of pyrite intergrown with chalcopyrite (cpy) and lesser amounts of ilmenite (il) and trace sphalerite (sph). Stage 5, Kerilik 2 (AWK 0447a). Scale = 140 μm.

D Early pyrohedral pyrite (py) with electrum inclusions enclosed by galena (gn). Stage 5, Kerilik 2 (AWK 0447a). Scale = 50 μm.

E Fractured marcasite (mar) band. Stage 9, Kerilik 2 (AWK 0421). Scale = 2000 μm.

F Fractured marcasite (mar) band between bands of coarsely crystalline quartz. Note: same view as Fig 5.25E under cross-polarized light. Stage 9, Kerilik 2 (AWK 0421). Scale = 2000 μm.
Figure 5.26 Keriitl sulfides (B)

(A,B,D and E are photomicrographs, taken under reflected light)

A Pyrite (py) and ilpilax (ilp) intergrown with sphalene (sph) and surrounded by galena (gn) and chalcopyrite (cpy). Stage 5, Keriitl 2 (AWK 0447a) Scale = 140 μm.

B Pyrite (py) associated with sphalene (sph) and galena (gn) and chalcopyrite (cpy). Stage 5, Keriitl 2 (AWK 0447a) Scale = 140 μm.

C Cavities in quartz after bladed calcite infilled with stage 5 sulfide. Note: same view as Fig. 5.29D under plane-polarized light. Keriitl 2 (AWK 0448). Scale = 550 μm.

D Cavities after bladed calcite infilled with chalcopyrite (cpy), sphalene (sph) and galena (gn). Stage 5, Keriitl 2 (AWK 0448). Scale = 550 μm.


F Prussian blue covellite (cov) after chalcopyrite (cpy) surrounding galena (gn) and sphalene (sph). Sphalene contains a dendron of chalcopyrite as “chalcopyrite disease”. Stage 8, Keriitl 2 (AWK 0447a). Scale = 550 μm.
5.7.3 Sphalerite

Sphalerite is less common at Kerikil compared with PBH and occurs in stages 2, 5 and 8 (Fig. 5.26 A, B, E and F). Fine-grained sphalerite is present as thin, dark bands in stage 2 and as diffuse bands and clots in stage 5, where it is associated with galena and lesser amounts of chalcopyrite, silver sulfosalts, native silver and electrum (Fig. 5.25 A and B). Sphalerite from both these stages occurs as optically clear and honey colored (iron-poor) varieties, typically forming fine-grained (500 μm), euhedral to anhedral crystals. Stage 8 sphalerite occurs as massive, coarse-grained crystals generally greater than 5 mm (Fig. 5.26 E and F). Light brown to red sphalerite from this stage exhibits zoned crystals and chalcopyrite disease (Fig. 26 E and F). Sphalerite commonly occurs infilling lattice work textures, possibly after earlier bladed carbonate. Sphalerite can occur both early and late in the infill stage paragenesis. Sphalerite and galena are abundant in samples collected from deeper (below 50 RL) in the Kerikil system.

5.7.4 Galena

Galena is less common at Kerikil compared with PBH and is observed in stages 2, 5 and 8 (Figs. 5.25 B,C and 5.26 A, B). It is present in thin dark bands of stages 2 and 5, rarely reaching grain sizes coarser than 1 mm, and is frequently associated with chalcopyrite (within ore stages) and lesser amounts of sphalerite, silver sulfosalts and electrum. Stage 8 galena frequently occurs as massive, coarse-grained (> 5mm), cubic crystals associated with coarse chalcopyrite and sphalerite. Finer-grained varieties (100 μm) are recognized microscopically as pale grey, euhedral crystals with pronounced rip up triangles (due to polishing). Galena and sphalerite are common at deep levels in the Kerikil deposit.

5.7.5 Covellite

Covellite at Kerikil occurs rimming stage 8 chalcopyrite, sphalerite and jalpaite (Fig. 5.26 F).

5.7.6 Jalpaite

Jalpaite is recognized in stages 2 and 5 and is one of the main silver ore minerals.
Microscopically, jalpaite (Ag₃Cu(S)₂) occurs as pale grey, poorly polished, euhedral crystals confined to particular sulfide bands within vein stages 2 and 5 (Fig. 5.27 A, B, C and F). Jalpaite is commonly associated with chalcopyrite, native silver, electrum and lesser amounts of galena and sphalerite. Selenian-jalpaite is common and is often associated with electrum.

5.7.7 Acanthite

Acanthite occurs in the main ore-bearing vein stages 2 and 5 and is another main host for silver ore at Kerikil (Fig. 5.27 D). Fine-grained (< 1mm) acanthite is present in thin dark bands, and is associated with chalcopyrite and electrum and lesser amounts of sphalerite, galena and silver sulfosalts. Microscopically, the acanthite is recognized as white, euhedral and anhedral crystals.

5.7.8 Silver sulfosalts

A broad range of silver sulfosalts occur in stages 2 and 5, the main ore-bearing vein stages, but not all the species could be identified. Silver (with antimony and/or arsenic) sulfosalts are present in the thin dark bands, rarely reaching grain sizes greater than 1 mm. The most abundant sulfosalts are pale grey-green friebergite (argentian tetrahedrite, (AgCuFe)₁₂(Sb,As)₄S₁₃) ranging to grey tennantite (AgCuFe)₁₂(As,Sb)₄S₁₃), bright white polybasite (AgCu₁₆Sb₂S₁₁) and the ruby silvers, proustite (Ag₁₃As₅S₉) and pyrargyrite (Ag₃SbS₄). In general, the silver sulfosalts are not associated with chalcopyrite-rich bands. Galena and sphalerite appear both early and late in the paragenesis compared to the silver sulfosalts minerals.

5.7.9 Unidentified Ag sulfides, sulfosalts and tellurides

A range of minor silver sulfides (> 50 wt % Ag), sulfosalts, tellurides and alloys that could not be identified petrographically were analyzed by electron microprobe (Appendix 3). A search of known mineral elemental compositions showed that many of the silver-rich minerals had atypical compositions of silver, copper, iron, zinc, lead, antimony, arsenic, tellurium, selenium and sulfur and could not be identified. A more detailed mineralogical study of the unusual silver minerals was beyond the scope of this project.
Figure 5.27  Kerikil silver-bearing minerals
(All photomicrographs are taken under reflected light)

A  Jalpate (jal) surrounded by sphalente (sph) intergrown with chalcopyrite (cpy) and pyrite (py). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 µm.

B  Pyrite (py) with electrum (el) inclusions surrounded by sphalente (sph), jalpate (jal) and galena (gn). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 µm.

C  Pyrite (py) with electrum (el) inclusions surrounded by jalpate (jal) intergrown with sphalente (sph) and galena (gn). Stage 5, Kerikil 2 (AWK 0446). Scale = 50 µm.

D  Chalcopyrite (cpy) and sphalente (sph) surrounded by acanthite (aca). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 µm.

E  Electrum (el) surrounded by chalcopyrite (cpy) and galena (gn). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 µm.

F  Chalcopyrite (cpy) intergrown with electrum (el) and surrounded by jalpate (jal). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 µm.
Figure 5.28  Kerikil electrum

(All photomicrographs are taken under reflected light)

A  Electrum (el) inclusions in pyrite (py). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 μm.

B  Electrum (el) inclusions in pyrite (py) with later pyrite rims which are intergrown with galena (gal) and chalcopyrite (cpy).

C  Electrum (el) inclusions in pyrite (py), which is in turn surrounded by electrum intergrown with galena (gal), sphalerite (sph), electrum (el) and chalcopyrite (cpy). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 μm.

D  Sphalerite (sph) enclosed by electrum (el) intergrown with galena (gal). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 μm.

E  Electrum (el), sphalerite (sph) and galena (gal) surrounding pyrite (py). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 μm.

F  Chalcopyrite (cpy) surrounded by electrum (el) which is intergrown with sphalerite (sph) and chalcopyrite (cpy). (which encloses pyrite (py) with rims). Stage 5, Kerikil 2 (AWK 0447a). Scale = 50 μm.
5.7.10 Silver

Native silver occurs in stage 5 (a main ore-bearing stage) as fine wires in open vugs and scales plating fractures. Native silver is commonly associated with rhodochrosite-bearing stage 5 infill. Microscopically, the silver forms bright white, anhedral grains that are frequently associated with silver sulfosalts.

5.7.11 Electrum

Electrum occurs in the main ore-bearing vein stages 2, 5 and 8 within the thin dark bands. Microscopically, the electrum ranges from bright canary yellow to pale lemon (in reflected light), and is present as grains ranging from 10 to 500 \( \mu \text{m} \). It is observed as inclusions in pyrite and is associated with chalcopyrite, galena and silver sulfosalts.

5.8 Discussion of PBH and Kerikil ore mineralogy

The following discussion addresses the occurrence of the sulfide ore minerals at PBH and Kerikil and implications for the physico-chemical environment of deposition.

Pyrite is abundant at both PBH and Kerikil, indicating that significant amounts of iron were precipitated under reducing conditions. Pyrite within the early vein stages is assumed to have been deposited from an iron chloride complex, a process which is dependent on the presence of \( \text{H}_2\text{S} \) produced during boiling (e.g., Romberger, 1993). The youngest pyrite and marcasite veins of stage 9 at Kerikil may have been deposited by different processes other than boiling. Late pyrite and marcasite vein stages have been noted in several other epithermal deposits (e.g., Stage E, OH Vein, Creede, Plumlee and Whitehouse-Veaux, 1995). Reed and Plumlee (1992) showed that late vein stages containing pyrite and marcasite, associated with kaolinite are indicative of an acidic, low temperature fluid. Low temperature, acidic conditions are therefore indicated during the closing stages of the hydrothermal system at Kerikil.

At PBH and Kerikil, copper and silver are precipitated as chalcopyrite and acanthite, respectively, or together as jalpaite. Copper and silver can also be precipitated with zinc and antimony in the silver sulfosalts. The close association of copper, silver, zinc and antimony mineralization suggests common depositional controls. These elements are typically
transferred as a chloride complexes in hot saline conditions, but can also be transported as bisulfide complexes in low temperature, epithermal environments under near neutral, dilute conditions (Barnes, 1979; Henley and Brown, 1985; Brown, 1986). It is known that copper, silver and antimony precipitation is controlled by decreases in temperature, salinity and pH and/or increases in H2S concentration (Barnes, 1979). It is likely that the effects of boiling or mixing with a dilute fluid may have been responsible to the mineral assemblages recognized at PBH and Kerikil. Covellite rimming chalcopyrite suggests alteration by a late, acidic fluid.

Electrum at PBH is deposited with a variety of sulfides and sulfosalts, whereas electrum at Kerikil is most abundant as inclusions in pyrite. Studies have shown that gold is preferentially transported as bisulfide complexes in low temperature, epithermal environments and under near neutral, dilute conditions (Seward, 1991). Gold deposition is controlled by pH, oxygen fugacity, activity of sulfur, salinity and temperature (Seward, 1991). The fact that gold and silver are deposited together as electrum and in association with acanthite, jalpaite and silver at PBH and Kerikil suggests that gold precipitated from bisulfide and chloride complexes under similar conditions to silver and copper deposition.

Lead and zinc, precipitated as galena and sphalerite in stage 4, are assumed to have been transported as chloride complexes and their precipitation resulted from decreases in temperature, salinity and pressure (Barnes, 1979; Henley, 1985a, 1985b).

Tellurium is precipitated as gold-silver telluride inclusions in early pyrite from stage 4 at PBH and may be indicative of throttling of the main ore structure. Cooke and Bloom (2001) suggest tellurium will be preferentially transported in the gas phase in boiling epithermal systems, but that throttling of a conduit can be an effective way of maintaining tellurium in the fluid. Subsequent tellurium deposition can occur due to condensation, cooling or mixing (Cooke and Bloom, 2001). The presence of coarse-grained chalcopyrite, sphalerite and galena crystals in stage 4 also suggests a slow, gradual decrease in temperature. This is in contrast to the fine-grained nature of sulfides in stage 3 that were deposited in response to boiling. Stage 4 is also devoid of silver sulfosalts and electrum, suggesting that metal precipitation due to a boiling bisulfide fluid may not have occurred. Instead, deposition of copper, lead and zinc was likely induced by cooling.

5.9 Supergene Mineralization

A detailed characterization of supergene mineralogy was not a primary objective of this study. The supergene sections of PBH and Kerikil 1 and 2 had been mined out before
the initiation of this project and drill core from the supergene zone had deteriorated under
the tropical conditions on-site. In general, the supergene zone is confined to the top 25 m
of deposits where manganese and iron oxides replace manganoan carbonates and sulfides
(Simmons and Browne, 1990) (Fig. 5.29). Copper oxides are rare, suggesting that oxidation
is due to an acid sulfate overprint and the collapse of the hydrothermal system, rather than
oxidizing weathering processes. A review of drill logs and internal company reports
suggests that manganese wad and iron oxides were initially present in the supergene zone
at PBH and extended down for tens of meters along permeable footwall structures. In an
electron microprobe study of electrum fineness, Simmons and Browne (1990)
demonstrated that there was no compositional difference between electrum from the oxide
and sulfide zones at Kerikil.

5.10 PBH gangue mineralogy

This section details the gangue mineralogy at PBH which is dominated by various
silica polymorphs with smaller amounts of carbonate, adularia and clays (Fig. 5.9). The
range of silica polymorphs indicate different depositional environments and physico-
chemical characteristics of the precursor fluid during different paragenetic stages. As
quartz is the only phase deposited through the entire history of the vein, it records vein
growth and evolution before, during, and after precious metal deposition (Dowling and
Morrison, 1989).

5.10.1 PBH silica polymorphs

In this study, epithermal textural classification for silica polymorphs is based on the
work of Dong et al. (1995). Bates and Jackson (1987) subdivide quartz into crystalline,
microcrystalline and cryptocrystalline based on individual grain size. Under this
terminology, chalcedony fits into the cryptocrystalline classification. However,
cryptocrystalline and microcrystalline quartz have not been subdivided in this study and
chalcedony is described under microcrystalline quartz.

Jasper at PBH occurs as veins and infilling brecciated wall rocks, where it exhibits
finely banded, colloform textures (Fig. 5.30 A). The jasper is typically crimson to deep red
in color and very fine-grained. Microscopically, it occurs as extremely fine, intermeshed
and mosaic patterned quartz crystals with hematite inclusions. Jasper is overprinted by late
Figure 5.29 Kerikil supergene mineralization

A Stage 9 veins have oxidized hematite- and goethite-filled fractures in kaolinite altered coherent andesite. 285 RL, Kerikil starter pit. Bench height 2.5 m.

B Oxidized stage 2 and stage 3 vug fill vein with stage 3 amethyst infill. 370 RL, Ganung Benuh.

C Oxidized stage 5 with black manganese wad aftermanganoan carbonate. 285 RL, Kerikil 2. Field of view is 10 cm.

D Hand sample with oxidized stage 6 but late stage 7 amethyst infill is preserved and can be seen on the cut surface. 285 RL, Kerikil 2.

E Oxidized stage 5 with black manganese wad aftermanganoan carbonate. 285 RL, Kerikil 2.
Stage 1, fine-grained cubic pyrite crystals and pyrite veins and is cross-cut by calcite-filled fractures (Fig. 5.30 B and C). Jasper has not been observed at Kerikil.

Microcrystalline quartz is white to grey or buff and brown and very fine-grained in hand specimen (Fig. 5.31 A). As vein infill, microcrystalline quartz may be massive or exhibit fine, rhythmically banded colloform and crustiform textures. Microscopically, the quartz occurs as very fine crystals with long axes perpendicular to one another, creating an unusual cross-hatched or grid pattern (Fig. 5.31 B, C and D). Light and dark bands within the silica are a result of different crystal sizes; fine-grained crystals giving rise to darker bands and coarse crystals giving rise to paler bands (Fig. 5.31 A, B and C). Stage 2 infill, which is composed completely of microcrystalline quartz, is hard and frequently cleaves with a conchoidal fracture, having the appearance of grey-brown flint. Clasts of microcrystalline quartz from vein stage 2 typically occur entrapped in later massive microcrystalline quartz from stage 2 and by infill stages 3, 5 and 6. Microcrystalline quartz also occurs in barren sections of the PBH structure beneath the main ore zone (approximately 25 RL). At these levels, the main structure consists of a thick (4 to 5 m), colloform crustiform vein of microcrystalline quartz with thin quartz stringer veins in the adjacent host rock.

Crystalline quartz is present as massive to coarse, euhedral crystals in comb,
Figure 5.31 PBH microcrystalline quartz

A. Microcrystalline quartz vein showing pale and dark-colored bands which reflect a change in the quartz crystal size. Most quartz is seen along the vein wall. Area of photomicrograph in Fig. 5.31B is marked by the white box. Hulubat (AWH 0041A).

B. Photomicrograph in cross-polarized light of microcrystalline quartz showing cross-hatched grid work texture. A crack across the finer microcrystalline quartz is filled by coarser microcrystalline quartz. Area of photomicrograph in Fig. 5.31C is marked by the white box. Hulubat (AWH 0041A). Scale = 550 μm.

C. Photomicrograph in cross-polarized light of microcrystalline quartz showing cross-hatched grid work texture and varying crystal size of quartz. A crack across the finer microcrystalline quartz is filled by coarser microcrystalline quartz. Hulubat (AWH 0041A). Scale = 140 μm.

D. Photomicrograph in cross-polarized light of microcrystalline quartz showing cross-hatched grid work texture created by alignment of major crystal axes perpendicular to each other. Hulubat (AWH 0008). Scale = 50 μm.

E. Photomicrograph in plane-polarized light of microcrystalline quartz showing cross-hatched grid work texture and variable sizes of quartz crystals. Hulubat (AWH 0004). Scale = 200 μm.

F. Photomicrograph in cross-polarized light of same image as Fig. 5.31E. Photo shows microcrystalline quartz showing cross-hatched grid work texture and variable sizes of quartz crystals. Hulubat (AWH 0004). Scale = 200 μm.
cockade, crustiform and colloform textured bands. Crystals may be clear or milky white in color and either very fine-grained (< 1 mm) or up to several centimeters in length.

Microscopically, the crystalline quartz exhibits well defined growth bands, ghost rings and fluid inclusions trails. Crystalline quartz is the most common gangue mineral by volume and is present in vein stages 4 to 6 (Fig. 5.32). The quartz typically occurs interstitial to sulfide bands within, and after, the main ore-bearing vein stages (Fig. 5.32 C). Locally, crystalline quartz occurs as lattice textures after the replacement of bladed calcite.

Amethyst at PBH occurs as coarse-grained, euhedral crystals that are dark purple to pale lilac to clear. Amethyst exhibits cockade, crustiform, colloform and comb textures with vuggy open space along the centres of veins. Crystals may be up to 10 centimeters in length, but are commonly only several centimeters (Fig. 5.5 B). In the PBH vein, crystals
Figure 5.33 PHH amethyst

A. Crustiform banded amethyst and crystalline quartz vein displaying zoned amethyst crystals with white bases and purple terminations. Late carbonate occurs along the vein centre line. 145 RL, Hulubai (PHH 0051).

B. Micocrystalline quartz clast enclosed by amethyst and quartz crystals with cockade textures. Also shown are late crustiform amethyst and quartz bands with zoned amethyst crystals exhibiting white bases and purple terminations. DDH 715, 153 m, 12400 N, 30 RL, Hulubai (PHH 0092).


are typically zoned with clear quartz bases and purple terminations (Fig. 5.33 A and B). Microscopically, amethyst may exhibit growth zoning defined by fluid inclusions, ghost rings and fluid inclusion trails. Amethyst constitutes stage 5 infill and typically occurs as a late stage product, after the ore-bearing vein stages 3 and 4. It is most abundant in vein splits and bifurcations at Permata, as a late stage infill along the North Permata vein, and in the Hulubai north hanging-wall split veins.

5.10.2 Adularia

White to pale pink, massive adularia forms extremely fine-grained colloform bands in stage 3 veins. It also occurs as small, well formed, rhombic crystals (up to 3 mm) in vuggy cavities and as fine-grained crystals in quartz adularia veins in the late basalt dyke at Permata (Fig. 5.34). Cobalt-nitrate staining was used to detect the presence of adularia,
since it is too fine-grained to be recognized in hand specimen. Using this technique, very finely disseminated adularia was detected across the microcrystalline quartz of stage 2 infill, but adularia was not recognized in stages 1, 4, 5 or 6. In stage 3, adularia can be associated with high grade gold and silver ore shoots. Tabular adularia may be replaced by clay during late stage, acid sulfate overprint or weathering.

5.10.3 Carbonates

Carbonates range from pale pink to white to clear and occur as prismatic, dog tooth crystals deposited in crustiform, cockade and comb textures (Fig. 5.35). The scope of this study did not allow a detailed examination of the different carbonate species, although whole rock analysis (section 5.13) indicates the pink carbonate contains a significant amount of manganese and is interpreted to be a manganoan-calcite (likely rhodochrosite). Calcite veins in the south of the Permata deposit and in deep sections of the PBH vein are white in color and exhibit classic crustiform textures. Coarse, pink (manganoan-) calcite occurs in hanging-wall splay veins at Hulubai (Fig. 5.35 A) and also fills faults which cross-cut earlier vein stages 1 to 5. Microscopically, the calcite exhibits well defined growth bands delineated by fluid inclusion trails (Fig. 5.35 C). At PBH, carbonate is always precipitated after the main ore-bearing stages and is only present in stage 6.

5.9.4 Clays

Unidentified clays in stage 3 occur as soft, white to pale bluish-green minerals in
Figure 5.35 PBH carbonate

A Photomicrograph in plane-polarized light of manganese carbonate vein showing botryoidal textures. 165 RL. Huleba (AWH 0054). Scale = 2000 μm.

B Photomicrograph of the same view as Fig. 5.35A across nicols. Manganese carbonate vein showing botryoidal textures. 165 RL. Huleba (AWH 0054). Scale = 2000 μm.


D Photomicrograph of the same view as Fig. 5.35D in cross nicols of euhedral calcite (cal) crystals in stage 6 vein. 165 RL. Permata (AWP 0070). Scale = 2000 μm.

E Photomicrograph in cross-polarized light of calcite (cal) vein from late coherent basalt (BAS) dyke. A clast of basalt enclosed in the vein is chlorite altered. 165 RL. Permata (AWP 0035A). Scale = 550 μm.

F Photomicrograph of the same view as Fig. 5.35E in cross nicols of calcite (cal) vein from late coherent basalt (BAS) dyke. A clast of basalt enclosed in the vein is chlorite altered. 165 RL. Permata (AWP 0035A). Scale = 550 μm.
veins and acicular to tabular shaped voids. Clays are also present in bands interstitial to microcrystalline quartz (Fig. 5.36 A). These clays are assumed to be illite and smectite (based on SWIR analyses; section 7.5). Chlorite is generally present as clumps in vein stage 5 and 6 (Fig. 5.36 B).

5.10 Kerikil Gangue Mineralogy

At Kerikil, the gangue mineralogy is dominated by a wide variety of carbonate and silica polymorphs. As at PBH, high gold grades coincide with massive banded microcrystalline quartz. However, unlike PBH, bonanza gold grades at Kerikil are coincident with rhodochrosite.

5.10.1 Silica polymorphs

Silica polymorphs are a characteristic feature of periods 1 and 3 but are less common in period 2. Microcrystalline quartz is the major infill in stages 1 and 2 of period 1 and stages 5 and 6 of period 2. The quartz can be massive or can exhibit fine, cockade and crustiform textures. It is typically buff-brown-grey, massive to thinly banded, very fine-grained, hard and cleaves with a conchoidal fracture, having the appearance of grey-brown flint. Microcrystalline quartz occurs in breccia stockworks immediately adjacent to colloform veins of stage 2 and in the footwall of the main breccia and vein stockwork (Fig. 5.36). Clasts of microcrystalline quartz from vein stage 1 are typically enclosed by later infill stages.

Crystalline quartz is present as infill in stages 3 and 4 of period 1 and stages 8 and 9.
**Figure 5.37** Kerikil silica polymorphs


C. Photomicrograph in cross-polarized light of crystalline quartz showing euhedral, zoned quartz crystals with plumose texture deformed by fluid inclusions. Growth zones are marked by fluid inclusion trails. Stage 7, Kenkol 2 (AWK 00318). Scale = 2000 μm.

D. Photomicrograph in cross-polarized light of microcrystalline quartz and crystalline quartz showing euhedral, quartz crystals with crystals. The plumose texture is deformed by fluid inclusions. Stage 3, Kenkol 2 (AWK 10417). Scale = 2000 μm.


F. Photomicrograph in cross-polarized light of crystalline quartz showing euhedral, zoned crystals. Zoning is marked by fluid inclusion trails. Stage 8, Kenkol 2 (AWK 0-118). Scale = 2000 μm.
of period 3, with lesser amounts in stages 6 and 7 of period 2. Crystalline quartz exhibits a range of textures from cockade, crustiform and colloform banding to more massive varieties. It also occurs as vuggy infill with well formed, clear crystals. Quartz ranges from white to clear and from fine-grained and massive to coarsely crystalline. It may also exhibit moss and dogs-tooth textures. Crystalline quartz typically occurs interstitial to sulfide bands within vein stages 8 and 9 of period 3. In period 2, the quartz locally occurs as lattice textures possibly replacing earlier bladed calcite (Fig. 5.36 C, D, E and F).

Amethyst is abundant in stage 3 of period 1 and stage 7 of period 2. In period 1, the amethyst typically occurs as clasts enclosed by later infill stages and exhibits a range of open style deposition textures such as cockade, crustiform and colloform banding and vuggy infill with well formed prismatic crystals. In period 2, there are several alternating cycles of amethyst and rhodochrosite deposition; up to three cycles were noted in one sample. As at PBH, amethyst is always deposited after the main stages of ore deposition.

5.10.2 Adularia

Adularia is rare at Kerikil but does occur in stages 2 and 6, immediately before and within the ore-bearing vein stages. Adularia is white to cream and forms rhombohedral crystals in vuggy cavities and fine-crystals in vein material. Simmons and Browne (1990) also commented on the rarity of adularia in the Kerikil deposit.

5.10.3 Carbonates

Rhodochrosite at Kerikil is present in stages 5, 6 and 7 of period 2. It exhibits colloform and crustiform textures in association with sulfide bands in stage 5 and with microcrystalline quartz in stage 6. In stage 7, there are several alternating bands of amethyst and rhodochrosite. Microscopically, the rhodochrosite occurs as brown, turbid fans and spikey clusters of fine-grained, acicular and bladed crystals (Fig. 5.37). In the southern section of Kerikil 2, stage 5 rhodochrosite is directly associated with ore. Abundant rhodochrosite is also associated with breccia infill of stages 6 and 7 in the northern portion of Kerikil 2.

Ankerite is recognized as honey to dark brown crystals and occurs as massive infill after amethyst in stage 7. It is most common in the southern portion of Kerikil 1. Ankerite
Figure 5.38 Kerbal carbonates

A Photomicrograph in cross-polarized light of bladed, acicular rhodochrosite needles with microcrystalline quartz, Stage 5, Kerbal 2 (AWK 0523). Scale = 1000 μm.


C Photomicrograph in plane light of bladed, acicular rhodochrosite needles and later course grained amethyst, Stage 7, Kerbal 2 (AWK 0318). Scale = 1000 μm.

D Photomicrograph in cross-polarized light of bladed quartz pseudomorph after calcite, Stage 7, Kerbal 2 (AWK 0318). Scale = 500 μm.

E Photomicrograph in plane-polarized light of ring and fan shaped masses of rhodochrosite. Crystalline quartz is seen surrounding the rings, Stage 7, Kerbal 2 (AWK 0426). Scale = 1000 μm.

F Photomicrograph in plane-polarized light of fan shaped masses of rhodochrosite, Stage 7, Kerbal 2 (AWK 420). Scale = 500 μm.
also locally occurs in several alternating bands with deep purple amethyst (as part of period 2).

5.12 Discussion of PBH and Kerikil gangue mineralogy

The following discussion addresses the occurrence of gangue minerals at PBH and Kerikil and implications for the physico-chemical environment of deposition. Previous studies have shown that temperature is the major control on the deposition of silica minerals, although pressure, salinity, pH, rate of deposition and the presence of complexing agents can also have an effect (Fournier, 1985a). Carbonate deposition is thought to be the result of either temperature increases (Corbett and Leach, 1998) or boiling (Simmons and Christenson, 1994). Adularia also requires boiling conditions to precipitate (Browne and Ellis, 1970; Browne, 1978; Henley, 1985, Hedenquist, 1990a).

Jasper: The presence of jasper at PBH but not at Kerikil suggests contrasting physio-chemical conditions. Very few studies have documented hematitic jasper veins in low sulfidation epithermal deposits (e.g. Albinson, 1988). Fournier (1985a) categorizes jasper as massive bodies of silica that may have several different origins. Jasper can form from recrystallized hot spring deposits or from the mixing of rising hot water with shallow cold water. It can also be formed by rapid decompressional boiling, particularly where overpressurized hydrothermal fluid expands into open, hydrostatically pressured cavities. At PBH, a recrystallized hot spring origin for jasper formation can be discounted, due to the form and geometric relationships of the jasper bodies to their host rocks (i.e., the jasper bodies are not stratabound or strataform and cross-cut volcanic layering as vein or fault infill). The other two mechanisms of jasper deposition (mixing and depressurization) are plausible however, and both are consistent with low sulfidation epithermal processes. Jasper occurs at shallow levels in the PBH deposit and thus could have formed from the mixing of warm geothermal fluids and cool, oxidized, meteoric waters. Vein and breccia textures are also consistent with a hydrostatically over-pressurized system which has been rapidly depressurized during the initial formation of dilational structures (e.g. narrow confined veins and lens shaped pods with brecciated wall rock, displaying slabby breccia clasts and jigsaw fit textures).

Microcrystalline quartz: Microcrystalline and cryptocrystalline quartz are common
features of many low sulfidation epithermal deposits. The quartz typically occurs in proximity to high grade ore but does not actually host significant ore metals (e.g. Cracow, Queensland, Dong et al., 1995; and Golden Cross, New Zealand, Faure and Braithwaite, 2002). Miners working the Au-rich low sulfidation epithermal Empire Vein at Golden Cross in New Zealand at the beginning of the 1900's, described massive grey to brown microcrystalline quartz (called "fairy" quartz) which was used as a proximal indicator to high grade ore, even though the quartz itself did not carry precious metal (Fraser, 1910). At both PBH and Kerikil, microcrystalline quartz is spatially associated with areas of high grade ore although it also occurs in pre-ore in fill stages.

The variety of textures and mineral associations related to microcrystalline quartz (as described in the previous sections) suggests a range of depositional conditions. Several researchers have suggested various origins for microcrystalline quartz from different geological environments. Dong et al. (1995) interpreted saccharoidal quartz with a crude mesh texture to result from the replacement of earlier deposited calcite (although the grain size suggests that they may have been referring to the more typical bladed quartz pseudomorphs of bladed calcite). Grid-work textures in microcrystalline quartz are recognized in other geological settings, including: jasper bodies from Picher Field in the Pb-Zn Mississippi Valley Type district, U.S.A. (McKnight and Fischer, 1970); silicified fluorite mineralized bodies in the southern Alps of Italy (Isoli, 1972); quartzitic groundmass of jasper rocks from the Pando area, Colorado U.S.A. (Lovering and Heyl, 1980); silicified crust type (SCT) polymetallic mineral deposits from Italy, China, Brazil, U.S.A, Mexico, South Africa and Australia (Camana et al., 2002); and highly alkaline cherts from Lake Magadi in Kenya (Schubel and Simonsen, 1990). In several of these cases, grid-work texture has been suggested to be related to high SiO2 activity and/or a high rate of crystal nucleation (Hay, 1968; Camana et al., 2002). These textures are recognized in microcrystalline quartz at both PBH and Kerikil (in stages 2 and 1, respectively). These conditions are consistent with the physico-chemical effects induced by boiling and/or high rates of fluid influx associated with an epithermal system.

Another relevant theory for the origin of silica-rich fluids and grid-work texture in microcrystalline quartz is based on a study of SCT deposits by Camana et al. (2002). This study suggests that illitization of clay-rich basinal sediments during diagenesis and
convection of basinal fluids are responsible for the concentration of silica-rich solutions, which are then deposited as microcrystalline quartz-filled faults. Although the geological environment at PBH is different to the basinal setting described by Camana (2002), the same variables and processes may be applicable (i.e., significant clay production from illite alteration of wall rocks and reactive fluids to form silica rich solutions). In the deepest parts of the PBH vein, there is a transition from moderately illite + pyrite + adularia altered wall rocks to strongly, illite + pyrite + adularia altered wall rocks containing small microcrystalline quartz + pyrite stringer veins (Fig. 5.39). These stringer veins in turn occur adjacent to sections of thick banded, colloform microcrystalline quartz infill in the main PBH structure.

Other microcrystalline quartz textures recognized in the early infill stages of the Mt Muro deposits are colloform bands, moss textures and ghost rings (e.g., Fig. 5.10 C and D). Dong et al. (1995) suggest that these textures form from the re-crystallization of less ordered quartz pseudomorphs that were deposited from a precursor silica gel. Silica gels occur when the fluid is supersaturated with respect to silica (Fournier, 1985b), possibly in direct response to boiling conditions (Dong et al., 1995).

Geothermal wells provide a modern analogue of the low sulfidation epithermal environment (White, 1955; Henley and Ellis, 1983; Simmons and Browne, 2000). Processes and products occurring within geothermal wells are frequently recognized in fossil geothermal systems represented by low sulfidation epithermal veins. For example, the crystallization of banded, colloform, cryptocrystalline and microcrystalline quartz on pipe walls in modern geothermal wells is directly analogous to the fine-grained, banded textures seen in epithermal veins (Fig. 5.40). In modern wells, continuous quartz deposition on pipe walls can eventually constrict the well aperture, presenting a significant problem to well production flow rates. Constriction of the wells is analogous to sealing of veins by early infill stages 2 and 3 at PBH and stages 1, 2, 5 and 6 at Kerikil. Flow can only proceed after the development of a new conduit or opening of the seal by brecciation (brecciation and re-sealing by microcrystalline quartz is recognized at both PBH and Kerikil).

Evidence from geothermal wells also suggests that microcrystalline quartz forms in areas of high flow rates (e.g., colloform banded microcrystalline quartz forms where flow rates are kept at a maximum to provide the optimum kinetic energy for electricity
Figure 5.39 Development of microcrystalline quartz vein in the deep sections of the PBH deposit

A Deep drill hole section drilled (from the pit floor at 145 RL), through the Permata deposit below the ore zone. The enlarged section shows the vein stratigraphy and development of microcrystalline quartz veins. Positions of Figure 5.39 B, C, D, and E is labeled

B Intensely illite + pyrite altered coherent andesite. Permata (RD 2925, 941 m).
C Microcrystalline quartz stringer veins formed in intensely illite + pyrite altered coherent andesite. Permata (RD 2925, 8325 m).
D Breccia clasts of intensely illite + pyrite altered coherent andesite clasts and colloform microcrystalline quartz clasts cemented by later microcrystalline quartz with cockade textures with pyrite blebs. Permata (RD 2925, 795 m).
E Colloform dark microcrystalline quartz bands and white colored massive microcrystalline quartz. Permata (RD 2925, 785 m).
CHAPTER 5 MINERALIZATION

generation). Thus, the recognition and location of microcrystalline quartz infill in epithermal systems may point to upflow zones and areas of fluid flux. At PBH and Kerikil, the deposition of microcrystalline quartz at the vein wall in the initial stages of the epithermal system may be a significant factor in vein preparation. Microcrystalline quartz precipitate may seal off the wall rocks against further reaction with ore fluids thus creating an efficient, non-reactive conduit for the transport of ore solutions to the site of boiling and ore deposition. The size of the orebody will depend on the duration of the hydrothermal system and the maintenance of an open fissure or aperture, which provides a continuous supply of ore fluid to the site of boiling. The dilational structures recognized at PBH are ideal for maintaining an open conduit and high flow rates for boiling and metal deposition.

Crystalline quartz: A common feature of the PBH and Kerikil deposits is a distinct transition from fine-grained infill in early paragenetic stages to much more coarsely crystalline gangue + sulfide in later infill stages. Coarse crystalline quartz and sulfide infill stages being deposited after fine crystalline quartz and sulfide infill stages is a relationship which has been observed in other low sulfidation deposits (e.g., Stage D, Bulldog Vein, Creede, Plumlee and Whitehouse-Veaux, 1995). Studies by Dong et al. (1995) suggest that the formation of coarse-grained comb and crustiform textures in quartz requires relatively slow changing conditions in an open space during crystal growth. This is because the textures form where the competition for space between quartz crystals causes them to grow in a direction of the maximum growth rate, which is perpendicular to the growth.
surface. Thus, the transition from microcrystalline to coarsely crystalline quartz deposition in the Mt Muro deposits may be attributed to a decrease in the rate of cooling and/or a decrease in the overall flow rate. Flow rate decrease can occur as a result of vein dilation, since an increase in the vein aperture would result in lower flow rates and a drop in pressure. Alternatively, flow rate and pressure decreases can be caused by the waning of the hydrothermal system. Both factors likely contributed to the change from microcrystalline to coarse crystalline vein stages in later infill stages at PBH and Kerikil.

Rare lattice-textured quartz is recognized in the deeper portions of the PBH and Kerikil deposits (e.g., Fig. S.38D). These textures are interpreted as pseudomorphs after calcite and are a good indicator of boiling conditions (Simmons and Christenson, 1994).

_Amethyst:_ Amethyst is a relatively common mineral that frequently occurs as a late stage product in the vein paragenesis of many low sulfidation epithermal vein deposits (e.g. Comstock, Nevada, Southwest U.S.A., Hudson, 2003; Santo Nino, Fresnillo, Mexico, Gemmell et al., 1988; Toodogone District, British Columbia, Canada, Pantaleyev, 1988; Cracow, North Queensland, Australia, Worsley and Golding, 1990; Wirralie, Queensland, Australia, Fellows and Hammond, 1988; Waihi, New Zealand, Faure and Braithewaite, 2002). Amethyst derives its purple color from Fe$^{3+}$ and darker purple varieties contain greater Fe$^{3+}$ than pale purple to clear amethyst (Dennen and Puckett, 1972). Substitution of Fe$^{3+}$ into quartz and the formation of amethyst can occur under a variety of conditions (Dennen and Puckett, 1972) including: formation from a Fe-rich and/or Al-poor solution; oxidizing conditions (with respect to ferrous-ferric iron species); moderate temperatures (i.e., the incorporation of the larger Fe$^{3+}$ ion for either Si$^{4+}$ or Al$^{3+}$ should increase at higher temperature; Sorokin, 1968); low pressures (which permit an increase in cell size and thus the incorporation of the larger Fe$^{3+}$ ion); and/or post-crystallization irradiation (probably not applicable in epithermal systems). Zoned crystals that exhibit a change in color from a clear base to a purple termination likely form from a change from reducing to oxidizing conditions, a change in solution composition (from Fe-poor to rich ± Al-rich to poor) and/or a rise in temperature and drop in pressure (Dennen and Puckett, 1972).

The presence of amethyst in many low sulfidation deposits suggests a commonality of processes at the waning stages of Au-Ag low sulfidation mineralization. The fact that amethyst growth is promoted by a change from Al-rich to Al-poor conditions (as
suggested by Dennen and Puckett, 1972) is consistent with an epithermal fluid that has previously boiled and deposited Al(OH)- as either sericite/illite or adularia. This implies that amethyst is more likely to be precipitated after boiling and by association after precious mineral deposition.

At PBH, amethyst precipitates after the precious metal-rich stages 3 and 4 and at Kerikil, it precipitates after the ore stages (stages 2 and 5). The presence of amethyst as a late stage product reflects changes in the physico-chemical environment of quartz deposition, suggesting oxidizing, lower temperature, lower pressure, Al-poor and Fe-rich, stable steady state, open space infill conditions. The development of coarse, comb textured amethyst crystals indicates slow rates of crystallization into open space (Dong et al., 1995).

A review of the literature suggests that coarse, euhedral amethyst is absent in modern geothermal wells. This absence may reflect the fact that geothermal production wells are never allowed to reach steady state conditions and are always in a state of high flux or no flux. High flux conditions are more conducive to precipitation of fine-grained microcrystalline and cryptocrystalline quartz species (Dong et al., 1995). Boiling is also suppressed in geothermal wells until they are opened and flashing occurs. This suggests that the solution prior to boiling is rich in AlOH- and therefore unlikely to deposit amethyst.

**Adularia:** Adularia is the low temperature polymorph of K-feldspar and is an indicator of boiling in the epithermal environment (Browne and Ellis, 1970; Browne, 1978; Henley, 1985; Hedenquist, 1990a; Dong and Morrison, 1995). Browne (1978) suggests that adularia deposition is the result of the fluid becoming more alkaline due to boiling conditions. This is supported by the thermodynamic research of Reed and Spycher (1985) and Drummond and Ohmoto (1985) who showed that cooling, as a result of boiling, destabilizes Al(OH)- and causes the deposition of silicates such as adularia and sericite.

At both PBH and Kerikil, the presence of adularia and its association with microcrystalline quartz provides further evidence for boiling in the early infill stages. Adularia crystal morphologies may also reflect different modes of deposition. For example, rhombic adularia crystals reflect rapid crystallization (as a result of boiling) whereas tabular adularia forms as a result of violent boiling (Dong and Morrison, 1995). Both crystal morphologies are recognized at PBH (e.g., Figs. 5.34 and 5.36A) although tabular adularia
appears to be restricted to stage 3 - one of the main stages of ore deposition. The correlation of adularia with high grade ore at PBH is not unusual; a similar correlation was noted by Buchanan (1981) in a study of over 60 epithermal deposits in the South Western United States and Mexico.

**Carbonate.** At PBH, carbonate is always late and forms in the last infill stage (stage 6) either cross-cutting earlier vein stages or as the final infill stage in crustiform veins and vugs. At Kerikil, calcite is observed in stage 4 (of period 1) and manganoan carbonates characterize period 2, and are associated with ore minerals in stage 5. Late stage overprinting carbonate veins and late carbonate cavity infill is a common feature of many low sulfidation epithermal deposits (e.g., Comstock, South West USA, Romberger, 1993; Topia, Mexico, Loucks et al., 1988; Santo Nino, Fresnillo, Mexico, Gemmell et al., 1988; Golden Cross, New Zealand, Simmons et al., 2000; and Pongkor, Java, Indonesia, Warmada and Lehman, 2003).

Due to its retrograde solubility, calcite forms from reheating fluids that are sufficiently saturated with respect to $\text{CO}_3^{2-}$ (Simmons and Christensen, 1994). $\text{CO}_3^{2-}$-rich fluids can be produced through deep boiling of $\text{CO}_2$-rich chloride waters which partitions $\text{CO}_2$ into steam, a process that was recognized at the Broadlands-Ohaaki geothermal field (Romberger, 1993; Hedenquist, 1990b; Simmons et al., 2000; Fig. 5.41). The condensation of this steam and absorption into cool meteoric waters at shallow levels produces a fluid saturated in $\text{CO}_3^{2-}$ from which the calcite precipitates (Hedenquist, 1990b). The $\text{CO}_3^{2-}$-rich fluids have a fairly high density and Simmons et al. (2000) suggested that such fluids were kept out of the active upflow zone at the Empire Vein (New Zealand) due to buoyancy effects created by the upwelling fluids and thermal plume (Fig. 5.42). The $\text{CO}_3^{2-}$-rich fluids then migrated down into the Empire Vein after the upwelling of chloride waters stopped, depositing late stage carbonates (such as calcite and rhodochrosite) in vugs and cross-cutting veins. Late stage calcite at PBH and Kerikil was likely deposited under similar conditions, from a migration of bicarbonate fluids back into the system.

Rhodochrosite is common in many low sulfidation epithermal deposits and is frequently associated with high base metal grades (e.g., Kelian, Kalimantan, Indonesia, Davies et al., 2000; Pongkor, Java, Indonesia, Milé et al., 1993; San Batolomé, Ecuador, Mulshaw et al., 1997; Cirotan, Java, Indonesia, Leroy and Hube, 2000). The occurrence of
**Figure 5.41** Boiling effects and origin of carbonate in the epithermal environment

Schematic diagram showing the effects of boiling (B) and the production of bicarbonate fluids (A) above a boiling zone in an epithermal system. Also shown is the likely origin of deep and shallow calcite veins (diagram modified from Romberger, 1993). The X-axis on Fig 5.41B corresponds to physical aspects and products of a boiling geothermal fluid as it rises from 500 to 200 m below the surface.

**Figure 5.42** Origin of late calcite at the epithermal Empire Vein, New Zealand

Summons et al. (2001) interpreted the origin of late calcite veins in the Empire Vein at Golden Cross, New Zealand, to be a two-stage process:

A  Bicarbonate fluids from above the Empire Vein due to boiling of an upflowing neutral chloride water which deposits Au-Ag mineralization. The bicarbonate fluids are excluded from the vein by buoyancy effects created by the thermal plume and up-flowing chloride waters.

B  After the collapse of hydrothermal activity and waving of the thermal plume, bicarbonate fluids migrate down into the system and fill cavities and structures as late calcite vein and vug fill.
rhodochrosite in period 2 at Kerikil requires the presence of a manganese rich fluid. Previous studies have shown that manganese is commonly transported in the near surface environment as manganese chloride, sulfate and/or carbonate complexes (Crerar et al., 1980). The manganese at Kerikil may have resulted from an ascending manganese-rich fluid and/or by liberation from manganese-bearing mafic mineral phases in the andesite and basaltic andesite host rocks during hydrothermal alteration. This study favors the latter explanation, since data from modern geothermal wells indicate that manganese is typically depleted in hydrothermal fluids (e.g. Broadlands, New Zealand, Henley, 1984; Rotakawa, New Zealand, Reyes et al., 2002). The depletion of manganese in alteration phases is discussed in detail in Chapter 7.

At PBH, manganoan calcite occurs at shallow levels in deposit while calcite is concentrated deeper in the system. This may be attributed to manganese production from intense alteration of host rocks within the steam heated zone at shallow levels. Rhodochrosite is known to be highly soluble under low pH conditions and has retrograde solubility in dilute solutions and prograde solubility in saline solutions (Gammons and Seward, 1993). Since the solutions which formed the rhodochrosite at PBH and Kerikil were dilute (based on fluid inclusion evidence, chapter 8), it is likely that the precipitation of rhodochrosite was controlled by heating, boiling (pH change), and/or the exsolution of CO$_2$ in upflow regions of the hydrothermal system.

**Clays:** Chlorite, illite and smectite clays are recognized within veins at both PBH and Kerikil and are distinct from clays produced by wallrock alteration (which are addressed in Chapter 7). The clays within the veins may represent the alteration or weathering of bands of adularia and wallrock fragments (5.36 Å and B).

### 5.13 PBH and Kerikil infill stage geochemistry

Whole rock analyses were determined for representative samples from each infill stage at PBH and Kerikil (with the exception of stage 4 Kerikil, due to insufficient sample material). Methods used for major and trace element analysis are outlined in Chapter 3.9.2. Tables 5.1 and 5.2 give the ranges and statistical averages for major and trace element data for PBH and Kerikil, respectively. The complete whole rock geochemical dataset is given in Appendix 2. Schematic representations of selected average elemental abundances are
shown in Figures 5.43 and 5.44 for PBH and Kerikil infill stages, respectively.

5.13.1 PBH infill stage geochemistry

At PBH, stages 1 through 5 have relatively high abundances of silica, while stage 6 has relatively high amounts of manganese, calcium and carbon (Table 5.1 and Fig. 5.43). Stage 1 and 4 have elevated iron contents.

Stages 3 and 4 are the prominent ore stages at PBH. Stage 3 has relatively high abundances of gold, silver, copper, zinc and lead with moderate amounts of sulfur, arsenic, antimony and mercury. Stage 4 has relatively moderate amounts of gold and silver compared with stage 3 with higher abundances of sulfur, copper, zinc, lead, cadmium and tellurium. Stage 4 has relatively lower arsenic, antimony and mercury abundances than stage 3.

Trace to negligible amounts of sulfur, gold, silver, copper, lead, zinc, cadmium, arsenic, antimony, mercury, thallium, selenium and tellurium are present in stages 1, 2, 5 and 6.

5.13.2 Kerikil infill stage geochemistry

At Kerikil, stages 1, 2, 3, and 8 have relatively high silica content, while stages 5, 6 and 7 have relatively high abundances of manganese, calcium and carbon with lesser silica (Table 5.2 and Fig. 5.44). Stage 9 has a relatively moderate silica content compared to other vein stages.

Stages 2, 5, 8 and 9 are the primary ore stages at Kerikil. Stage 2 contains high amounts of gold, silver, with moderate abundances of sulfur, copper, lead, zinc, arsenic and selenium. Stage 5 contains high gold, silver, copper, zinc, lead, and selenium with moderate abundances of sulfur, lead, arsenic and cadmium and a low abundance of tellurium. Stage 8 has high abundances of lead and zinc, moderate amounts of sulfur, copper and gold, low abundances of silver, arsenic, cadmium and mercury and trace amounts of thallium, selenium and tellurium. Stage 9 has relatively high iron, sulfur, arsenic antimony and thallium abundances, moderate abundances of gold, silver and mercury and low base metal contents.
<table>
<thead>
<tr>
<th>Infill Stage</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
<th>Stage 6</th>
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<td></td>
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<td>Min</td>
<td>Average</td>
<td>Max</td>
<td>Min</td>
<td>Average</td>
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<tr>
<td>SiO₂ (wt %)</td>
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<td>89.28</td>
<td>89.29</td>
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<td>90.61</td>
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<tr>
<td>TiO₂ (wt %)</td>
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<td>0.06</td>
<td>0.14</td>
<td>0.02</td>
<td>0.09</td>
</tr>
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<td>1.36</td>
<td>1.36</td>
<td>4.41</td>
<td>0.58</td>
<td>2.17</td>
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<tr>
<td>Fe₂O₃ (wt %)</td>
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<tr>
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<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
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<td>3.13</td>
<td>1.66</td>
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<td>Total</td>
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<td>99.14</td>
<td>99.45</td>
<td>100.19</td>
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<td>C (wt %)</td>
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<td>0.43</td>
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<td>H (wt %)</td>
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<td>0.05</td>
<td>0.07</td>
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<td>S (wt %)</td>
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<td>1.12</td>
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<td>0.03</td>
<td>0.15</td>
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</tr>
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<td>3.00</td>
<td>4.50</td>
<td>2.47</td>
<td>3.53</td>
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<td>10.2</td>
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<td>127.7</td>
<td>959.0</td>
<td>9.7</td>
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<td>14.6</td>
<td>39.4</td>
<td>543.0</td>
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<td>0.11</td>
<td>0.43</td>
<td>0.11</td>
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<td>23.2</td>
<td>36.6</td>
<td>7.9</td>
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<td>Sb (ppm)</td>
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<td>2.1</td>
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<td>9.7</td>
<td>3.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Ti (ppm)</td>
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<td>0.00</td>
<td>0.01</td>
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<td>Hg (ppm)</td>
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</tr>
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</tr>
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<td>Te (ppm)</td>
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<td>0.18</td>
<td>0.38</td>
<td>0.11</td>
<td>0.37</td>
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- **Dash** = below detection; blank space = not analyzed for
<table>
<thead>
<tr>
<th>Period</th>
<th>Period 1</th>
<th>Period 2</th>
<th>Period 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infill Stage</td>
<td>Stage 1</td>
<td>Stage 2</td>
<td>Stage 3</td>
</tr>
<tr>
<td>Min</td>
<td>Max</td>
<td>Ave</td>
<td>Min</td>
</tr>
<tr>
<td>SiO₂ (wt %)</td>
<td>45.84</td>
<td>46.63</td>
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<td>MnO (wt %)</td>
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<td>0.8</td>
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<td>0.6</td>
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<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>LOI (wt %)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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**Table 5.2: Geochemistry of Kerikil vein stages.**
Relative elemental abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
<th>Stage 6</th>
</tr>
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<tbody>
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<tr>
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<tr>
<td>Te</td>
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</table>

Figure 5.43 Relative elemental abundances of PBH infill stages
Schematic representation of selected average elemental abundances in the PBH infill stages. This diagram is based on PBH infill stage data presented in Table 5.1. The relative abundance of each element is determined with respect to the same element across different vein stages and also to the same element in the Kerikil infill stages (shown in Fig. 5.44).

Relative elemental abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>High</th>
<th>Low</th>
<th>Moderate</th>
<th>Trace</th>
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<tr>
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</table>

Figure 5.44 Elemental abundances of Kerikil infill stages
Schematic representation of selected elemental abundances in the Kerikil infill stages. This diagram is based on Kerikil infill stage data presented in Table 5.2. The relative abundance of each element is determined with respect to the same element across different vein stages and also to the same element in the PBH infill stages (shown in Fig. 5.43).
Trace to negligible amounts of sulfur, gold, silver, copper, lead, zinc, cadmium, arsenic, antimony, mercury, thallium, selenium and tellurium occur in stages 1, 3, and 7.

5.13.3 PBH and Kerikil infill stage geochemical interpretation

Geochemical data for PBH and Kerikil infill stages suggests that there are three main types of samples that have distinct geochemical signatures. These classes of samples correspond to hand specimen observations and include: a silica-dominant type, Mn + Ca + C-bearing samples, and Fe + S-dominant samples. The first two infill types are recognized at both PBH and Kerikil, and the last occurs only as a late stage at Kerikil.

Geochemical data (Tables 5.1 and 5.2, Figs. 5.43 and 5.44) has also shown that ore-related elements are confined to discrete infill stages in the vein paragenesis. Precious and base metals are associated with high silica abundances in stages 4 and 5 at PBH and stages 2 and 5 at Kerikil. Stage 5 at Kerikil also contains high manganese, calcium and carbon. The geochemical dataset has also highlighted distinct trace element characteristics between the PBH and Kerikil deposits and between different infill stages.

High silica contents in stages 1 through 5 at PBH reflect the abundance of quartz gangue, while higher manganese, calcium and carbon in stage 6 reflect the presence of manganoan-calcite in the final infill stage. High iron contents in stage 1 are attributed to the jasper infill. Elevated precious metals with moderate base and toxic (e.g., Hg, As, Sb) metals in stage 3 at PBH correlate directly with the presence of sulfides observed in hand specimen and microscopically (e.g., electrum, chalcopyrite, galena, sphalerite, japaite and silver sulfosalts). Higher base metal and moderate precious metal contents in stage 4 are consistent with a greater abundance of chalcopyrite, galena and sphalerite. Moderate amounts of aluminum in stages 2 and 3 at PBH can be attributed to the presence of minor adularia and clays.

At Kerikil, high silica contents in stages 1, 2, 3 and 8 are consistent with the abundance of quartz gangue. In stages 5, 6, and 7, comparatively lower levels of silica and high levels of manganese, calcium and carbon are consistent with the presence of rhodochrosite-bearing infill. Elevated precious metals and moderate base and toxic metal abundances in stage 2 and 5 at Kerikil correlate with the presence of ore minerals observed both in hand specimen and microscopically (e.g., electrum, chalcopyrite, galena, sphalerite,
In stage 8, relatively higher base metals and lower precious metal contents reflect the greater abundance of chalcopyrite, galena and sphalerite. Stage 9 has only moderate silica and significant iron and sulfur, which is consistent with its massive pyrite (+ marcasite) composition. This stage also has high thallium, mercury and arsenic contents and is unlike any other infill stage at either PBH or Kerikil.

The geochemical dataset highlights several important differences between the two deposits, specifically the presence of elevated thallium (with associated mercury and arsenic) and significant selenium at Kerikil but not at PBH. These differences reflect specific physico-chemical characteristics and depositional conditions in the Kerikil system. For example, high thallium, mercury, antimony and arsenic contents in marcasite can be associated with deposition from cool (160°C), low pH fluids (Ewers and Keays, 1977; Sobott et al., 1987). Such fluids occur in the surface waters of modern geothermal systems at Broadlands-Ohaaki (in geothermal pools and geothermal water samples at less than 200 m depth; Ewers and Keays, 1977). Thus, the geochemical signature of stage 9 infill at Kerikil, in association with kaolinite alteration, suggests cool and acidic fluid conditions (Henley and Ellis, 1983; Reyes, 1990). This implies that there may have been a migration of cool acid sulfate surface waters down into the deposit during the last phase of hydrothermal activity at Kerikil.

The elevated selenium signature of the Kerikil deposit suggests an oxidized environment of mineral deposition (Simon et al., 1997). Such an environment also favors gold deposition (Hannington and Scott, 1989) and a positive correlation between gold, silver and selenium has been recognized at the Pongkor low sulfidation epithermal deposit in Indonesia (Warmada and Lehman, 2003). Similarly, Reyes et al. (2002) demonstrated that copper, silver, tellurium, zinc, lead and gold were deposited by boiling in geothermal pipes at the Rotakawa geothermal field, whereas mercury, boron, arsenic, antimony and selenium are deposited at a distance from the wellhead, due to cooling and mixing. The occurrence of elevated gold values in stage 8 infill at Kerikil in association with low silver concentrations may reflect gold deposition by acidification. Spycher and Reed (1995) calculated that a typical Broadlands geothermal water will deposit higher fineness gold on mixing with acid waters.
5.14 Mineral Chemistry

Selected ore minerals from PBH and Kerikil were analyzed by electron microprobe using the Cameca SX 50 instrument at the Central Science Laboratory, University of Tasmania. The purpose of this study was primarily to determine mineral residencies of silver and electrum fineness. Secondary objectives were to determine the iron, manganese and cadmium contents in sphalerite and measure the selenium levels in silver sulfides.

5.14.1 Silver residency and selenium substitution

Preliminary electron microprobe investigations have shown that there is a large diversity of silver sulfides, tellurides and sulfosalts at both PBH and Kerikil. These mineral phases contain various combinations of silver, copper, iron, zinc, antimony, arsenic, selenium, tellurium and sulfur. Important silver-bearing minerals at PBH and Kerikil are native silver, electrum (Au,Ag), freibergite (silver-rich tetrahedrite (Ag,Cu,Fe)12(Sb,As)4S13), jalpaite (Ag(CuS2), and mckinstryite (Ag,Cu)2S. In contrast, silver was found to be below detection in galena from both PBH and Kerikil.

At Kerikil, silver-copper sulfides and sulfosalts contain appreciable selenium with values up to 5 wt%. A roughly linear correlation between both selenium and sulfur and copper and silver suggests that selenium is substituting for sulfur and copper is substituting for silver (Figs. 5.45 A and B). These substitutions appear to be coupled, as indicated by the plot in Fig. 5.45 C. In contrast, selenium is below detection in all sulfides and sulfosalts analyzed from PBH. These data are consistent with whole rock geochemical analyses which showed elevated levels of selenium in the Kerikil ore stages (stages 2 and 5) but no selenium in the ore stages at PBH (stages 3 and 4).

Simon et al. (1997) suggest that selenium substitution in sulfide minerals has important implications for fluid composition and oxidation state. They showed that selenium substitution is far more common in oxidizing environments and that a selenium-rich source fluid alone cannot account for the precipitation of selenide minerals. A highly oxidizing environment is essential for selenium deposition (Simon et al., 1997). The fact that selenium substitution does not occur in any stage of PBH but is common at Kerikil suggests significantly different depositional conditions in the two deposits.
Figure 5.45  Selenium substitution in silver-copper sulfides at Kerikil

A  Selenium and sulfur contents of jalpaite (as wt%) sampled from Kerikil stage 5 infill. Selenium is plotted against sulfur, showing a rough linear inverse relationship between selenium and sulfur.

B  Copper and silver contents of jalpaite (as wt%) sampled from Kerikil stage 5 infill. Copper is plotted against silver, showing a rough linear inverse relationship between selenium and sulfur.

C  Cu/Ag plotted against Se/S in jalpaite sampled from Kerikil stage 5 infill. Data shows a rough linear relationship and positive correlation between the two ratios.
5.14.2 Electrum fineness

Electrum fineness ($\text{Au}/(\text{Au + Ag}) \times 1000$) was measured in ore samples from both PBH and Kerikil to determine if electrum is an important residency of silver in the two deposits. All measurements were recorded in weight percent and are listed in Appendix 4.1. Results are summarized in Fig. 5.46. At PBH, electrum ranges from 219 to 761 fine, with an average of 481 fine. Relatively higher values were recorded from the Kerikil samples with values ranging from 480 to 764 fine, with an average of 687 fine. PBH electrum also contained trace amounts of Hg and Cu (generally less than 5 wt%). Variations in the gold content of single electrum grains were recorded with values ranging from 600 fine to 800 fine between rim and core. This is recognized optically as lighter and darker shades of yellow (Fig. 5.23 F). This variation is also associated with a change in trace metal content with elevated Hg contents in the gold-rich cores.

Previous studies have suggested that electrum fineness can be indicative of depositional mechanisms in epithermal systems. For example, Spycher and Reed (1995) calculated that a typical Broadlands geothermal water will deposit silver-rich electrum (average fineness of 300) from boiling, but that gold-rich electrum (average fineness of 700) forms by mixing with acid waters. They also showed that the composition of electrum may vary with time. At PBH, the lower electrum fineness, in combination with other mineralogical and textural evidence, supports boiling as the primary mechanism for gold deposition. In contrast, the higher fineness electrum at Kerikil suggests that mixing may have been an important factor in gold precipitation in this deposit.

A comparison of electrum fineness at the Mt Muro deposits with other low sulfidation epithermal systems is included in Fig. 5.45. In general, the lower electrum fineness values at PBH correlate well with the silver-rich low sulfidation epithermal deposits of Mexico, while the higher values at Kerikil correlate well with carbonate base metal-rich low sulfidation epithermal deposits in the Southwest Pacific.

5.14.3 Sphalerite Fe and Mn content

The trace element composition of sphalerite from PBH were measured in unzoned grains from several different veins. The aim was to identify any variation of trace element
Figure 5.46  PBH and Kerikil electrum fineness

PBH and Kerikil electrum fineness ($\frac{Au}{(Au+Ag) \times 1000}$) values. PBH electrum fineness ranges from 219 to 761 with an average of 481. Kerikil electrum fineness range from 480 to 764 with an average of 687. Also shown is a comparison of PBH and Kerikil electrum fineness with other epithermal deposits from Mexico and the Southwest Pacific. PBH electrum values correlate well with data from silver-rich low sulfidation epithermal deposits of Mexico. Kerikil electrum values correlate well with data from low sulfidation epithermal deposits in the Southwest Pacific. Electrum fineness values for quartz-silver-gold deposits are taken from Camprubi et al. (2001) for La Guitara, and Loucks and Petersen (1999) for Tapa. Adularia-sericite gold-silver, quartz gold-silver and carbonate base metal-gold deposit types are defined in Corbett and Leach (1995). Ranges and averages for electrum fineness are also taken from data collated from references in Corbett and Leach (1995).

KEY: Lines represent the range of values and stars represent the average. Thicker lines and larger stars next to the deposit types represent the range of average values for the deposits and the mean of the average values, respectively.
contents across fine sulfide and sulfosalt bands of the crustiform colloform veins. Trace element abundances in sphalerite (such as iron, manganese, cadmium) can be used an indicator of the physico-chemical environment of deposition (specifically temperature, pressure and composition of the ore fluid; Sims and Barton, 1961). As sphalerite occurs across the fine sulfosalt bands of stage 3 and 4 at PBH it may highlight changes in the mineral deposition history of the infill stage (Fig 5.47).

The majority of sphalerite at PBH contains very low iron concentrations (e.g., 0.3 to 1.3 wt %, Fe) and trace amounts of manganese and cadmium (e.g., 0.1 to 0.33 wt %, Mn and 0.15 to 0.2 wt %, Cd ). Sphalerite grains in individual bands of a crustiform banded vein were found to contain broadly similar Mn/Zn ratios from vein wall to vein centre. Locally however, the Mn/Zn ratio of sphalerite grains increases towards the centre of the veins (Fig 5.47).

Iron-poor sphalerites generally result from ore fluids with a low temperature and high sulfur fugacity, while higher manganese contents are consistent with higher concentrations of manganese in the source fluid or host rocks and independent of temperature and sulfur fugacity (Sims and Barton, 1961; Katsuhiro et al., 1987). The increase in Mn relative to Zn in sphalerite analyzed in younger sulfide bands and younger infill stage, therefore reflects an increase in manganese (which has been scavenged from the host andesites) in the ore fluid in the later stages of infill stage 3 and also in infill stage 4 sulfide deposition.

5.15 PBH structural and hydrothermal evolution

The development of the structures that host the PBH and Kerikil deposits were addressed in Chapter 4. Movement on basement northwest structures lead to high angle dilational north-south and north-northwest to south-southeast trending structures being opened in classic Reidel style mechanics (Fig 4.22 and 4.23). Dilational north-south and north-northwest trending structures provided openings for the influx of hydrothermal fluids. The hydrothermal fluids then underwent rapid depressurization and boiling. Continued gradual opening of the north-south and north-northwest striking structures has lead to the rhythmic deposition of narrow banded colloform veins (Fig. 5.5 and 5.48). Each infill stage represent a different environment of deposition in the evolution of the hydrothermal system. Therefore, structure and dilational history are intricately linked to the evolution of the hydrothermal system.
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Figure 5.47 Mn/Zn ratios in sphalerite across sulfide-sulfosalts bands at PBH

A Mn/Zn ratio in sphalerite grains measured across sulfide bands in a colloform vein. There is an increase in Mn relative to Zn in later sulfide bands. The sphalerites analyzed where iron-poor and internally unzoned (as determined optically and with the aid of the back scattered electron image) Stage 3, Permata (NM 4).

B Mn/Zn ratio in sphalerite grains measured across sulfide bands in a symmetrical crustiform vein. The sphalerites analyzed where iron-poor and internally unzoned (as determined optically and with the aid of the back scattered electron image) Stage 3 and stage 4, Permata. (AWP 0840)
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Stage 1 jasper infill

- North-west striking structure at PBH
- Maximum compressive stress
- Vein and infill at PBH in shear zone

Stage 2 microcrystalline quartz infill

- North-west striking quartz veins
- Maximum compressive stress

Stage 3 microcrystalline quartz + sulfide + sulfosalt + precious metal infill

- Microcrystalline quartz and sulfosalt developed in main north-west striking tensile fracture direction

Stage 4 coarse crystalline quartz + sulfide infill

- Coarse crystalline quartz and sulfide infill developed at vein bifurcations in the tensile fracture direction

Stage 5 amethyst infill

- Coarse crystalline amethyst veins and infill

Stage 6 carbonate infill

- Coarse crystalline carbonate infill and infill at younger faults

Figure 5.48 PBH structural and hydrothermal evolution

Structural development is linked to infill stage paragenesis controls. The relative timing of infill stages 1, 2, 3, 4, 5 and 6 at PBH represented by A, B, C, D, E and F respectively. Vein fills are as per the key on figure 5.1 on page 121.
PBH highlights the relationship between structural dilation and paragenesis. At PBH, stage 1, jasper veins mark the start of the hydrothermal system and are the result of the initial introduction of the hydrothermal fluid to oxidized ground waters at the extremities of the vein (Fig. 5.48 A). The oldest south-southeast trending jasper veins have intensely brecciated and altered wall rocks indicating rapid depressurization and exposure of hot hydrothermal fluids to juvenile ground waters. A progressive evolution of successive vein stages in a northwest orientation are then recorded from stage 2 through to stage 6 (Fig. 5.48). Stage 2, microcrystalline quartz is the first stage deposited in the north-northwest trending dilation structures and is observed at vein wall margins in close proximity to high grade ore and interpreted up flow zones (Fig. 5.48 B). Stage 3, microcrystalline quartz + sulfide + sulfosalt and stage 4, sulfide + quartz, sulfide are the ore forming stages and are deposited in the tensional fracture direction (Fig. 5.48 C and D). Stage 3 has fine microcrystalline quartz gangue and is sulfosalt rich while the later stage 4 is sulfide-rich with coarse crystalline quartz textures. Stage 5, amethyst, has coarse crystalline crustiform textures and suggests an open environment and slow rate of deposition (Fig. 5.48 E). Stage 6, carbonate infill postdates the ore-forming event (Fig. 5.48 F). In the last stage of structural development continued movement on northwest trending structures has led to the formation of late northeast striking faults which offset the main ore veins and are typically filled with manganoan calcite (Fig. 5.48 F). Calcite represents a change in the physio-chemical and depositional environment of the vein.

Structural evolution at Kerikil involves the same structural elements as at PBH but relationships of structural evolution to paragenesis are complex. A structural and hydrothermal evolution for Kerikil, could therefore not be given as simply as the one presented for PBH.

5.16 Summary of PBH and Kerikil mineralization

A comparison of infill stage characteristics for PBH and Kerikil highlights some important features of the two deposits (Table 5.49 and 5.50). At PBH, six infill stages are recognized and include early jasper to microcrystalline quartz, to microcrystalline quartz + sulfide + sulfosalt to coarse crystalline quartz + sulfide to amethyst and late carbonate. Veins at PBH exhibit thin, colloform, crustiform and cockade, banded, fine-grained microcrystalline textures early in the paragenesis but thick, crustiform and cockade, coarse-grained crystalline textures in the late infill stages (Fig. 5.49). Both the composition and texture of the infill stages can be linked to the dilational history of the vein over time. Stage 1 jasper likely represents the influx of hydrothermal fluid into oxidized ground water
associated with the basinal sediments and volcanics at PBH. Stage 1 and the other pre-ore infill stages were deposited rapidly in structures that frequently sealed and reopened. Ore stages 3 and 4 are very fine-grained. Microcrystalline quartz is spatially associated with areas of high grade ore and may be an indicator of rapid depressurization and boiling conditions; both of which are conducive to precious metal deposition. Immediately after ore deposition, the precipitation of coarsely crystalline amethyst marks the final stages of the hydrothermal system. Calcite is present as a late cross-cutting vein stage and as cavity infill. It is not associated with ore in the upper parts of PBH.

In general, the gangue mineralogy at PBH is dominated by silica; carbonate is only deposited during the last infill stage. Ore mineralogy is dominated by pyrite, sphalerite, galena, silver sulfosalts and argentian electrum. Jalpaite, freibergite and acanthite are all important residencies of silver. Gold-silver tellurides are recognized as inclusions in stage 4 pyrite. The trace element compositions of sphalerite are locally variable and change from early cadmium-rich varieties to late manganese-rich varieties. The mineralogy and composition of the PBH deposit is classic of a Ag-Au low sulfidation epithermal vein system, as described in the model by Buchanan (1981). Other examples of this type of deposit type occur in southwest USA and Mexico (e.g., Gemmell et al., 1988).

At Kerikil, nine vein and breccia stages are recognized within three distinct paragenetic periods of the hydrothermal system (Fig. 5.50). The first period at Kerikil is characterized by large amounts of silica infill. It is similar to the entire sequence of mineral deposition at PBH, with early microcrystalline quartz veins, microcrystalline quartz + sulfide + sulfosalt ore, post-ore amethyst and late calcite. However, period 1 at Kerikil lacks both jasper and a coarsely crystalline quartz + sulfide stage that are recognized at PBH. The lack of jasper at Kerikil is attributed to relatively impermeable lithological units and therefore a lack of source of oxidized fluids. Coarse quartz + sulfides do occur at Kerikil, but only in later depositional periods (due to sealing of the hydrothermal system). The second period at Kerikil consists of three infill stages and represents a distinct change in composition and style of mineralization. The period characterized by large amounts of rhodochrosite and includes an important ore stage, often associated with bonanza grades. The sequence of mineral deposition in period 2 includes rhodochrosite + sulfide + sulfosalt to rhodochrosite + microcrystalline quartz infill to postore amethyst and rhodochrosite. The final stage was deposited in an open environment and cycles between
Figure 5.49 Summary of PIBH infill stage characteristics and implications for environment of deposition and primary fluid characteristics.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Structural development and orientation</th>
<th>Style, size and distribution of infill hosting structures</th>
<th>Infill stage type</th>
<th>Infill stage mineralogy</th>
<th>Infill stage wall-rock and clastic abrasion</th>
<th>Relative elemental abundances between infill stages</th>
<th>Environment of opening, deposition and physico-chemical characteristics, associated with each infill stage</th>
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<tbody>
<tr>
<td>Stage 1</td>
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<td>Stage 5</td>
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<td>Stage 6</td>
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</tbody>
</table>

- Summary of PIBH infill stage characteristics and implications for environment of deposition and primary fluid characteristics.
- Structure, development orientation, and style, size and distribution of infill hosting structures.
- Infill stage type.
- Infill stage mineralogy.
- Infill stage wall-rock and clastic abrasion.
- Relative elemental abundances between infill stages.
- Environment of opening, deposition and physico-chemical characteristics, associated with each infill stage.

- **Environmental of opening, deposition and physico-chemical characteristics, associated with each infill stage**:
  - Stage 1: Anoxic, reducing, and high temperature environment, characterized by high-sulfur, high-alkalinity fluids.
  - Stage 2: Subaerial, high-temperature environment, characterized by high-alkalinity fluids.
  - Stage 3 (ore): Subaqueous, moderate-temperature environment, characterized by high-sulfur, high-alkalinity fluids.
  - Stage 4 (ore): Subaqueous, moderate-temperature environment, characterized by high-sulfur, high-alkalinity fluids.
  - Stage 5: Subaerial, high-temperature environment, characterized by high-alkalinity fluids.
  - Stage 6: Subaerial, high-temperature environment, characterized by high-alkalinity fluids.
Figure 5.50 Summary of Kharlil infill stage characteristics and implications for environment of deposition and primary fluid characteristics.

**Oldest**

**Stage 1**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 2**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 3**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 4**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 5**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 6**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 7**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 8**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 9**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Youngest**

**Stage 1**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 2**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 3**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 4**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 5**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 6**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 7**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 8**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.

**Stage 9**
- **Infill stage type**: Marine silty/dust + shallow
- **Infill stage mineralogy**: Quartz, feldspar, calcite, dolomite, and trace amounts of pyrite
- **Relative elemental abundances between infill stages**: No data
- **Environment of opening, deposition, and physico-chemical characteristics**: Associated with infill stage.
rhodochrosite and amethyst. The third period at Kerikil reverts to vein-style mineralization and includes only one stage of base metal sulfide veins, which cross-cut all earlier infill stages.

Gangue mineralogy at Kerikil is dominated by quartz and carbonates (either manganoan or iron carbonates and most commonly rhodochrosite). This is in contrast to PBH, where manganoan carbonates are rare. At Kerikil, high ore grades are typically associated with rhodochrosite and sulfide assemblages of stage 5. The ore mineralogy is dominated by pyrite and chalcopyrite with lesser sphalerite, galena, silver sulfosalts and electrum. Electrum is of the auriferous variety and typically occurs as inclusions in pyrite and associated with chalcopyrite. Selenian-rich jalpaite, acanthite, and native silver are important hosts for silver. The substitution of sulfur by selenium is an important feature of the Kerikil deposit and distinguishes it from PBH, where selenium is rare. The occurrence of selenian jalpaite suggests an oxidizing environment of mineral deposition.

Kerikil is an example of a carbonate Au-Ag low sulfidation epithermal breccia and stockwork system. Bicarbonate fluids were able to migrate back into the upflow area after sealing of the fluid conduit by early vein stages. Re-brecciation allowed further mixing of bicarbonate waters with the renewed upflow of hydrothermal fluids. Deep exposures of Kerikil that contain early clasts of colloform and crustiform veins within the hydrothermal breccias suggest that a vein system was established in period 1, but subsequently destroyed due to multiple sealing and brecciation events. Gold and base metal deposition is attributed to the combined effects of boiling and mixing. A component of mixing is supported by the presence of selenian jalpaite (that suggests an oxidizing environment) and auriferous electrum in pyrite. As at PBH, amethyst marks the end the Kerikil ore system. Two further infill stages (stage 8 base metal stage and stage 9 pyrite) only seen at Kerikil may result from the sealing of the conduit and slow rates of deposition and the influx of cool iron and sulfur rich fluids from acid sulfate waters from the surficial steam heated zone.

Paragenetic relationships indicate that Kerikil has a more complex hydrothermal history than PBH. This is attributed to the position of Kerikil within the volcanic architecture (i.e., particularly a lack of pre-existing structural features in the central vent environment; chapter 3) and dominance of brittle coherent andesite host rocks. Pressure release at Kerikil is not via the steady dilation of the structure as at PBH, but by sealing
and the resultant over-pressurization and hydraulic fracturing of the host rock. Brecciation and sealing occurred in a periodic fashion, allowing the development of multiple fluid pathways and enhanced fracture permeability. This enhanced fracture permeability may have resulted in the dominance of carbonate (as rhodochrosite) in period 2, when bicarbonate waters were able to descend into the zone of metal deposition. In contrast, rhodochrosite does not occur at all during the pre- or syn-ore infill stages at PBH. The coarse grained base metal veins at Kerikil are equivalent to stage 4 at PBH. The youngest pyrite veins at Kerikil are equivalent to the youngest pyrite and kaolinite filled fault gouge seen in the footwall of the PBH vein.