CHAPTER 4

STRUCTURE
### Stratovolcano facies environment

<table>
<thead>
<tr>
<th>Central Zone</th>
<th>Proximal Zone</th>
<th>Medial Zone</th>
<th>Distal Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad chert layers</td>
<td>Broad chert to thin layers</td>
<td>Pyroclastics dominate</td>
<td>Fine low-density rocks with glass shards in the air mass core and fine ash and with an outsized increasing ratio of glass to crystals</td>
</tr>
<tr>
<td>Conspicuous dikes, especially those that are radial to random orientation</td>
<td>Interbedded coarse-grained pyroclastics and plagioclase</td>
<td>Blocks with angular or subangular blocks up to 10 m in size</td>
<td>Blocks with blocks that reach a coherent structure and have rounded or subrounded particles in their matrix</td>
</tr>
<tr>
<td>Conspicuous soil that are concentrated with mudstone to steep inclined dips</td>
<td>Moderately steep inclined dip</td>
<td>Clastic debris, resolvable by water</td>
<td>Interbedded shallow-water sediments and organo-edsents</td>
</tr>
<tr>
<td>Breccia pipes and stocks</td>
<td></td>
<td>Moderate to shallow dips</td>
<td></td>
</tr>
<tr>
<td>Conformable units</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Stratovolcano setting

- General view or core of stratovolcano
- Slopes of stratovolcano
- Long plan of stratovolcano and valley head deposits
- Sub-aerial to sub-marin environment or marine basin setting

### PBH and Kerikil host rock setting

<table>
<thead>
<tr>
<th>Feature</th>
<th>Feature</th>
<th>Feature</th>
<th>Feature</th>
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</thead>
<tbody>
<tr>
<td>Kerikil tuff</td>
<td>Kerikil breccia</td>
<td>Kerikil breccia wall</td>
<td>Kerikil breccia wall</td>
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<tr>
<td>Foot of Active</td>
<td>Foot of Active</td>
<td>Foot of Active</td>
<td>Foot of Active</td>
</tr>
<tr>
<td>Coherent faces predominant</td>
<td>Volcaniclastic facies equal to coherents</td>
<td>Volcaniclastic facies, greater than cohesive</td>
<td>Volcaniclastic facies, greater than cohesive</td>
</tr>
<tr>
<td>Rhyolite andesite and basaltic andesite pipes, dikes</td>
<td>Rhyolite andesite pipes, dikes and mudstone</td>
<td>Rhyolite andesite pipes, dikes and mudstone</td>
<td>Rhyolite andesite pipes, dikes and mudstone</td>
</tr>
<tr>
<td>Beccac andesite</td>
<td>Beccac andesite</td>
<td>Beccac andesite</td>
<td>Beccac andesite</td>
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<tr>
<td>Tuff</td>
<td>Tuff</td>
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</tr>
<tr>
<td>Andesite breccia</td>
<td>Andesite breccia</td>
<td>Andesite breccia</td>
<td>Andesite breccia</td>
</tr>
<tr>
<td>Step dip to volcanic lavas, moderate dip to volcano lavas</td>
<td>Moderate to shallow dip to volcanic lavas and sediments, layering</td>
<td>Moderate to shallow dip to volcanic lavas</td>
<td>Moderate to shallow dip to volcanic lavas and sediments, layering</td>
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<tr>
<td>Aplite</td>
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<td>Indicators</td>
<td>Indicators</td>
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<td>Indicators</td>
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<tr>
<td>This volcanic and sedimentary sequence</td>
<td>Distribution controlled by basin faults</td>
<td></td>
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</tr>
</tbody>
</table>

**Figure 3.30** Facies environments associated with a sub-aerial andesitic stratovolcano compared with facies and features observed at PBH and Kerikil

Facies environments associated with a sub-aerial andesitic stratovolcano. Also shown is a summary of possible facies and features expected with each environment, compared with facies and features and their locations observed at PBH and Kerikil. (Stratovolcano diagram modified after Williams and McManus, 1979; Exposed facies and features from Vessel and Davies, 1981; Smith, 1987; Cas and Wright, 1986; Wolinsky and Heiken, 1992; McPhee et al., 1993.)
CHAPTER 4

STRUCTURE

4.1 Introduction

Chapter 4 documents the structural geology of the Permata-Batu Badinding-Hulubai (PBH) and Kerikil deposits, and suggests a mechanism and driving force for veining and brecciation. Structural data for veins, faults, shears and fractures were collected from roadcut mapping on the CoW and pit wall mapping at PBH and Kerikil. Remote sensing and geophysical data were used to define CoW-scale linear and circular features, since regional structural mapping was inhibited by an extensive tropical weathering profile and dense jungle cover. Faults were classified according to their orientation, timing, overprinting relationships and style. Veins were principally classified by infill and overprinting relationships using the paragenetic framework outlined in Chapter 5. Documentation and careful observation of structural features has constrained a dynamic regional stress field at Mt Muro. The volcanic architecture outlined in Chapter 3 also helped to define and constrain the structural setting of this district. A Riedel-style fracture model for the progressive formation of structural elements and ore-hosting structures at Kerikil and PBH is used to describe the geodynamics and geometry of observed structures.

4.2 Island-scale structural trends and features

The major tectonic and structural features of Borneo are shown in Figure 4.1. Epithermal ore deposits in Kalimantan, including Mt Muro, Kelian, Marsupa Ria, Mirah and Muyup, lie along an apparent northeast trend defined by van Leeuwen et al. (1994) as the “Kalimantan Gold Belt”, which is coincident with the eastern portion of the Central Kalimantan Arc (Fig. 4.1). Northwest extension in the Makassar Straits to the southeast of Borneo is associated with the opening of the northeast trending Makassar Basin; the offshore extension of the Kutai Basin. The northeast orientated Palawan trough is associated with the latest subduction event offshore to the northeast of Sabah. The western margin of the Kutai basin has a northeast trending boundary, which separates
Tertiary from later Quaternary basin sediments and volcanics. Basement features beneath the Kutai Basin such as the Muyup Hinge and Kutai Lakes are present as northeast trending gravity highs (Moss et al., 1999; Fig. 4.1).

Large northwest to north-northwest striking fault zones such as the Adang Fault Zone and the Sangkulirang Fault Zone define the southern and northern margins of the onshore Kutai basin and offshore Makassar Basin (Fig. 4.1). The Sangkulirang Fault Zone cuts across Borneo in a northwest trend as the Mangkalihat Ridge and the Tinjar Fault (which is also known as the West Baram Line). The Adang Fault Zone can be traced northwest across Borneo and has a dextral sense of movement. Various trajectories for the Adang Fault Zone have been suggested by different authors. Syarafuddin et al. (1999) suggest the Adang Fault Zone swings towards the west-northwest and defines the southern margin of the Melawi-Ketangau Basin and the northern margin of the Schwanner block, which they name the Adang Flexure. Alternatively, Satyana et al. (1999) suggest that the Adang Fault Zone continues in a northwest trend and connects to the Lupar Line,
which truncates the northern margin of the Melawi-Ketangau Basin and defines the southern margin of the Embaluh Group (Fig. 4.1). They name this structure the Adang-Lupar Megashear. In either scenario, the Adang structure passes in close proximity (within 30 kilometers) of the Mt Muro deposits and its geometry and dynamics may have influenced structural features at Mt Muro.

4.3 District-scale structural features

In this study, very limited structural data could be determined outside the PBH and Kerikil pits due to the dense jungle cover and tropical weathering profile (e.g., Fig. 1.2 C). To assist with placing the deposits within a gross regional structural and tectonic framework, analysis of lineaments seen on synthetic aperture radar (SAR) imagery and airborne magnetic data was undertaken. Information on structural features was also collected from visits to other deposits on the Mt Muro CoW. Where possible, historical data was reviewed from limited confidential internal company reports on the Bantian-Batu Tembak, Serujan Central, Serujan East, Muro Sawang pits, as well as data from Moyle et al. (1996) for the Serujan North and Tengkanong pits.

4.3.1 Remote sensing and geophysical interpretation

Numerous circular and linear features are visible on SAR and airborne magnetic imagery (Fig. 4.2 and 4.3). The dominant linear features occur in northeast, northwest, north-northwest and north-south orientations on the SAR image, and in northeast, northwest and east-west orientations on the first vertical derivative of airborne magnetic imagery. A detailed characterization of these different linear features is important, since only the north-south, north-northwest and west-northwest structures are currently known to host ore at Mt Muro.

*Synthetic Aperture Radar (SAR) Various circular features, ranging in diameter from one to ten kilometers, can be seen on the SAR image (Fig. 4.2 A and B). These features are defined by positive topography and occur as circular areas of textural similarity or as arcuate lines or zones that disrupt textural continuity. The features occur along a broadly northeast alignment (Fig. 4.2 B) that corresponds with an important regional trend controlling sites of intrusive and extrusive magmatic activity.*
Figure 4.2 Synthetic aperture radar (SAR) features.

Two large (10 kilometer diameter) roughly circular features in the centre of the CoW enclose the deposits. The PBH, Bantian - Batu Tembak, Tengkanong, Muro Sawang, Serujan East, Serujan North and Serujan Central deposits are situated towards the margins of the large western feature, and the Kerikil deposit is located near the centre of the large eastern feature. Kerikil is also bisected by the circumference of two smaller circular features to the east and west of the deposit. In some cases, smaller circular features (approximately 1 kilometer diameter) have been field checked and are known to correlate with topographic spires consisting of late dacitic, dioritic and basaltic andesite plugs (Fig. 1.2 D).

Numerous linear features ranging in length up to 5 kilometers are also discernable on the SAR image (Fig. 4.2). The dominant features are represented by northeast, northwest, north-northwest and north-south lineaments that are defined by ridges, valleys, and rivers, or as lines and zones disrupting layering and textural continuity. The linear features can be field checked in areas where they intersect road cuttings, pits and/or have been drilled. The majority of these features represent faults and shears, basalt and basaltic andesite dikes, as well as veins and breccia bodies.

Three northeasterly trending lineaments occur as swarms that cross the CoW. The largest is the central swarm which passes through the PBH, Bantian-Batu Tembak and Tengkanong deposits and coincides with the main trend of the circular SAR features (Fig. 4.2). A northeast lineament also passes through the Kerikil deposit. Regionally, this northeast trend can be correlated with the eastern portion of the central Kalimantan Arc and the “Kalimantan Gold Belt” (van Leeuwen et al., 1994; Fig. 4.1, 4.2 A and B).

Major northwest trending linear features are roughly evenly spaced across the CoW (Fig. 4.2 C). Northwest linear features are observed in basement rocks to the northwest of the CoW and seem to control the course of the Menawing River. This trend also appears to control the distribution of limestones and sediments in the southwest corner of the CoW (Fig. 4.2 B and Fig. 2.5). A swarm of northwest linear features cuts through the PBH, Bantian - Batu Tembak, Muro Sawang, Serujan North, Serujan Central and Serujan East pits. A major northwest linear feature also passes through the Kerikil deposit, where it has been observed to be a shear.

Analysis of the SAR image (Fig. 4.2 D) suggests that in most cases, the northwest linear features are later than the northeast features and offset the latter in a dextral sense.
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(Fig. 4.2 D). However, some of the movement on the northeast features appears to postdate the northwest striking structures (evident from sinistral offset on the SAR image; Fig. 4.2 D). This is consistent with information determined from pit mapping (presented later in this Chapter) which indicates that at least some northeast structure movement postdates the northwest trending features. These relationships suggest that there may have been reactivation of the northeast trending features, or that the northeast and northwest orientations were active at the same time (as a conjugate fracture set).

Major west-northwest trending linear features occur mostly in the southwest of the CoW and appear to be younger than the northwest and northeast features. The west-northwest linear features are extensive and can be traced (by SAR) over longer distances than northwest or northeast features. The west-northwest trend is an important structural control at the Tengkanong, Serujan North, Serujan Central and Serujan East deposits. In the Tengkanong and Serujan Central pits, the west-northwest features are represented by mineralized faults with a dextral sense of movement. The minor mineralized Pertim, Hultim, Julan Bukit and Bali veins in the PBH region are also orientated in a west-northwest direction (Fig. 3.16).

Two north-northwest trending lineament swarms occur within the circumference of two major circular SAR features noted previously (Fig. 4.2 C). One swarm passes through the PBH, Bantian-Batu Tembak, Muro Sawang, Serujan North, Serujan Central and Serujan East deposits in the west, and the other through the Kerikil deposit in the east. The north-northwest trend is an important structural control at the Bantian-Batu Tembak, PBH and Kerikil deposits, where north-northwest features are observed as veins, vein stockwork and breccia-filled mineralized faults.

Airborne Magnetic Imagery: Airborne magnetic imagery for the Mt Muro CoW is shown in Figure 4.3 A. Two major circular regions of low magnetic relief can be recognized, one in the PBH and Serujan area in the west and the other in Kerikil area to the east (Fig. 4.3). The PBH, Bantian, Batu Tembak, Tengkanong, Muro Sawang, Serujan East, Serujan North and Serujan Central deposits are situated near the margins of the large western feature that is approximately four kilometers in diameter. The Kerikil deposit is situated near the centre of the smaller eastern feature, measuring roughly three kilometers in diameter. The regions of low magnetic relief represent areas of magnetite destruction. These areas are interpreted to be related to alteration associated with two extinct
Figure 4.3  First vertical derivative magnetic image

A First vertical derivative magnetic image over the Mt Muro CoW, showing the location of two circular magnetite destructive regions centered on Mt Muro and Ganung Barub.

B Circular magnetic features and lineaments overlain on faded geology fills from Figure 2.5.
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hydrothermal systems, related to the two stratovolcanos proposed in Chapter 3.8 (Fig. 3.19). Smaller circular “bull’s-eye” magnetic highs (less than one kilometre in diameter) have been field checked and correlate with late dacitic, dioritic or basaltic andesite plugs (Fig. 1.2 D).

Numerous linear features, ranging in length from less than one kilometer up to greater than four kilometers, are discernable on the first vertical derivative image of airborne magnetic data (Fig. 4.3 B). The dominant linear features are represented by northeast, northwest, west-northwest, north-south and east-west trending lineaments defined by areas of high and low magnetic contrast and breaks in textural continuity. Several of the linear features were field checked in areas where they intersect road cuttings, pits and/or have been drilled. The majority of field checked high magnetic relief areas represent basalt and basaltic andesite dikes, and andesite lava flows. Faults, shears, veins and breccia bodies are represented by zones of low magnetic relief and in many cases correspond well with SAR features, due to associated alteration and silicification. The north-northwest linear features hosting the Bantian-Batu Tembak, PBH and Kerikil deposits that can be recognized on the SAR are not as readily observable on the magnetic image.

4.3.2 Faulting

Northwest shears and faults: Northwest striking faults cross-cut the Kerikil and PBH haul roads where they occur as graben bounding faults and shear zones. In some cases, northwest striking faults are intruded by basaltic andesite dikes (e.g., Tengkanong deposit and central Permata: MAP 1 Permata). The juxtaposition of different volcanic facies environments across northwest striking faults, as seen at Bantian-Batu Tembak, PBH and Tengkanong, implies that a component of dip-slip or strike-slip movement has occurred. However, the latest sense of movement across these faults is generally dextral strike-slip. Movement sense and geometry for northwest faulting was determined at PBH and Kerikil from pit mapping (MAP 1 Permata; MAP 2 Hulubai; MAP 3 Kerikil).

Northeast faults: Northeast striking faults cross-cut the PBH and Kerikil haul road and occur as strike slip faults and reverse faults. In some cases, northeast striking faults are exploited by basalt dikes (e.g. southern Permata hanging-wall). Northeast striking faults are
characterized by several episodes of movement, however the latest event is dominantly represented by a component of sinistral strike-slip movement (e.g., as seen offsetting the Bali vein at PBH).

4.3.3 Folding

Regional mapping has identified several large scale, tight, upright folds with east-northeast trending axial planes immediately northwest of the CoW (Pieters and Supriatna, 1990). The north-northeast trending axial planes of these structures are consistent with a north-northwest directed component of compression.

Within the CoW, regionally folding is rarely observed in outcrop due to dense jungle and lack of outcrop exposures. Folding was not observed in either the PBH or Kerikil pit mapping. Small-scale folding was only recognized within sedimentary units interfingered and overlain by coherent andesite facies in a road cutting on the Kerikil haul road, in the Menawing River valley immediately south of the Menawing River (Fig. 4.4). In the southern part of this exposure (Fig. 4.4), sediments are interfingered with andesitic lavas which strike 120° and dip shallowly at 10° to the north. The shallow dip to the north is truncated by a 120° trending northwest striking fault which dips 60° towards the north. To the north of the fault, sedimentary layering trends 100° and steepens to dips of 50°.

![Figure 4.4 Folding at Mt Muro](image)

Cross-section showing the relationship of sedimentary to volcanic rocks and the geometry of faulting and folding in a north-west trending fault (exposed in a road cutting on the Kerikil haul in the Menawing River valley). The fold closure indicates north-south compression. Inclination of the fold axial plane indicates a component of south-north reverse movement. The hinge line dips shallowly to the east indicating a component of dextral movement. Bearing of the section is 10°N.
Layering then steepens to 85° towards the north on the southern limb of a small anticline before flattening to 60° to the north on the northern limb. The contact of the sedimentary rocks and the overlying welded ignimbrite is obscured, but the ignimbrite sheet has entrained sedimentary clasts at its base suggesting that it was emplaced later than the sedimentary rocks. The ignimbrite strikes at 120° and dips 10° to the north. It is possible that there has been detachment and movement between the ignimbrite-sedimentary rock contact due to the large competency contrast between the two units. The small-scale, tight, inclined anticline has an 85° inclined axial plane which dips 70° to the north (Fig. 4.4). The fold closure indicates north-south compression. The fold axial plane indicates a component of south over north reverse movement and the hinge line dips shallowly to the east, indicating a component of dextral movement to compression. These relationships are consistent with the north-south to north-northwest directed compression which was determined from folding observed on regional mapping (Pieters and Supriatna, 1990). This north-south to north-northwest directed compression is correlated with the island-scale Mid-Miocene basin inversion event across the Kutai Basin (Chapter 2.2).

4.3.4 Mineralized structures

Over 75 epithermal veins have been recognized within the Mt Muro CoW (Moyle at al., 1996). Two main structural trends control the vein and breccia bodies; west-northwest to east-southeast and north-northwest to south-southeast.

**West-northwest mineralized structures:** Tengkanong, Seruan Central, Seruan North, Seruan East, and Muro Sawang are examples of west-northwest to east-southeast oriented deposits (Fig. 4.5).

The Tengkanong deposit consists of several braided, near vertical to steeply north and moderately south dipping, west-northwest trending mineralized faults, quartz veins and breccia bodies (Fig. 4.5 A). The deposit is 400 meters long and up to 20 meters in width. The structure widens as it swings to the northwest from a west-northwest strike, and then narrows as it returns to a west-northwest strike. Mineralization extends from surface (at 100 RL) to 0 RL, representing a vertical extent of 100 meters. At depth the structure dips shallowly, but steepens and flares out towards the surface (Fig. 4.6 A). The west-northwest fault separates considerably different footwall and hanging-wall volcanic facies environments at Tengkanong. A basaltic andesite dike has been intruded along the
Figure 4.5  West-northwest mineralized structures

A Tengkanong vein and pit outline (after Moyle et al., 1996)
B Serujan North vein and pit outline (after Moyle et al., 1996)
C Serujan Central vein and pit outline (this study, MK mapping)
main west-northwest fault and subsequently boudinaged due to later shear movement.

Tectonic movement on east and west-northwest trending faults both pre- and post-date quartz fissure filling (Moyle et al., 1996). Vein walls are wavy and irregular. Slickenslides are uncommon, but where they do occur they are sub-horizontal, indicating that there was at least some component of strike-slip displacement (Moyle et al., 1996). High grade shoots (> 5g/t Au and > 340 g/t Ag) are located at bifurcations and swellings along the structure. The fault geometry throughout the deposit is consistent with a jog that has developed due to dextral movement and dislocation along a pre-existing, west-northwest normal master fault (Fig. 4.5 A).

The Serujan North deposit consists of veins and a steeply south dipping, west-northwest trending mineralized fault that bifurcates and splays at its western and eastern ends (Fig. 4.5 B). The deposit is 300 meters long and up to 5 meters in width. Mineralization extends from surface (at 165 RL) to 75 RL, representing a vertical extent of 90 meters. The main mineralized fault is bound to the north by the west-northwest striking and moderately south dipping Nambar Fault, and to the south by the northwest striking
and moderately south dipping S4 Fault. In cross-section, the deposit anastomoses and is joined to the Nambar Fault by a steeply dipping linkage structure, which is also mineralized. Patchy mineralization is also associated with the S4 fault to the south. High grade shoots (as determined by Aurora Gold mine staff of > 5g/t Au and > 340 g/t Ag) are located at bifurcation points. Fault geometry is consistent with a tension vein and fracture array that has developed due to dextral movement between the Nambar Fault and S4 Fault (Fig. 4.5 B).

The high-grade Serujan Central deposit has a complex structural history. It comprises near vertical to steeply and moderately south dipping, west-northwest to north-northeast trending, anastomosing mineralized faults, quartz veins and breccia zones, with several smaller bifurcations, splays and side structures (Fig. 4.5 C). The deposit is 450 meters long and up to 20 meters in width. The majority of the structure is orientated west-northwest, but changes to an east-northeast trend in the centre of the deposit before returning to an east-west orientation in the eastern part of the deposit. Mineralization extends from surface (at 200 RL) to 0 RL, representing a vertical extent of 200 meters. At depth, the structure is a single, narrow near vertical vein which bifurcates and flares into several near vertical and steeply north dipping veins and breccias at surface (Fig. 4.6 B). The vein is localized by several fault zones. The eastern segment is localized by moderately north dipping, west-northwest striking fault zones that exhibit a dextral sense of movement. In the west, the vein is controlled by steeply south dipping, east-west trending faults showing a dextral sense of movement. The central segment is constrained by a moderately west dipping, north-northeast striking fault with a sinistral sense of movement that has offset the western and eastern segments of the deposit. Minor cross-cut deposits are hosted by moderately to steeply west and east dipping, north-northwest striking structures which have a dextral sense of movement. Several smaller, moderately west dipping, north-northeast cross-cut deposits also occur in the western part of the pit. The main west-northwest fault zone at Serujan Central separates considerably different footwall and hanging-wall volcanic facies. Fault styles and offsetting relationships suggest that a pre-existing, west-northwest normal master fault has been dilated by later movement on cross-cutting, high angle, north-northeast dilational faults with a sinistral sense of movement. High grade shoots (> 5 g/t Au and > 340 g/t Ag) are located at bifurcations and intersections of the later north-northeast structures.
The structural controls on the Muro Sawang and Serujan East deposits could not be determined because both deposits were inaccessible at the time of writing. The disused Muro Sawang pit is part of the current tailings dam and the Serujan East pit had been backfilled with waste rock from Serujan Central.

**North-northwest to north-south mineralized structures:** Bantian, Batu Tembak, PBH and Kerikil are all examples of north-northwest to north-south orientated veins and breccia bodies (Fig. 4.7). On a district scale, the Bantian - Batu Tembak vein system represents a structural repetition of the PBH vein system with similar volcanic facies, volcanic architecture relationships and structural characteristics (see Fig. 4.9 for details).

The Batu Tembak vein is a cymoidal and attenuated structure, striking north-northwest with a length of 1 kilometer and width of up to 5 meters (Fig. 4.8 A). The vein is a structural repetition of the Permata vein and mineralization extends from surface at 150 RL to 50 RL, representing a vertical extent of 150 m. In cross-section the vein is west dipping, pinching and swelling along its length, with a subsidiary near vertical hanging-wall split vein. High grade shoots (> 5 g/t Au and > 340 g/t Ag) are located at swellings and bifurcations of the vein structure. Tectonic movement along the vein post-dates quartz fissure filling. Lithofacies at Batu Tembak include andesite and basaltic andesite lavas, basaltic andesite dikes and flows, basalt flows, tuffs, and monomict andesite breccia, consistent with a proximal slope environment (Fig. 4.8). Lithologies could not be correlated between the footwall and hanging-wall, suggesting that there may have been at least 400 m of vertical movement on the main vein structure.

The Bantian vein was not yet fully accessible at the time of writing. A review of internal company reports suggests that the main Bantian vein is a structural repetition of the Hulubai vein. It is steeply west dipping, north-northwest to north-south striking, braided, cymoidal and attenuated with a length of 1 kilometer and a width of up to 5 meters (Fig. 4.7). Mineralization extends from surface at 175 RL to 25 RL, representing a vertical extent of 150 meters. In cross-section, the vein is moderately west dipping, with several near vertical hanging-wall split structures. High grade shoots (> 5 g/t Au and > 340 g/t Ag) are located at swellings and bifurcations along the vein structure. Initial reconnaissance of the strip-back prior to mining, in addition to drilling reports and discussions with IMK geologists, suggest that the host rocks are sedimentary rocks, tuffs and basalts. This is consistent with the distal basin fill environment, described for the
Figure 4.7 North-northwest mineralized structures

A Bantian at 140 RL showing faulting and mineralized faults and veins (LMK and author mapping).

B Kerikil 1 and Kerikil 2 at 175 RL and Kerikil 3 at 240 RL showing faulting, veins and breccias.

C Batu Badinding and Hulubai at 145 RL showing faulting and mineralized faults and veins.

D Permata at 150 RL showing faulting and mineralized faults and veins.
northern part of the Hulubai pit.

The PBH and Kerikil mineralized faults, veins and breccias represent the focus of work completed in this study and are discussed in detail in sections 4.4 and 4.5, respectively.

4.4 PBH structural features

The distribution of volcanic facies at PBH is defined by pre-mineralization faulting (Fig. 4.9). The PBH pit walls are dominated by several major structural elements including northwest, north-south and south-southwest faults and veins and northeast faults. Small-scale faults, fractures and veining are less common outside the trend of the main vein structure. For section 4.4, the reader is referred to MAP 1 (Permata) and MAP 2 (Hulubai).
Figure 4.9 PBH and Bantian-Batu Tembak (BBT) veins showing structure and volcanic environments. Map of the main PBH and BBT veins (in blue) showing structural and environment of deposition relationships. Also shown are the minor Hulubai, Julian Bukit, Permata, Maantung and Bali veins. Bedding measurements are displayed as strike dip signs. Dip on veins is given in blue arrows. Red circles on dip indicators represent downthrown sides of previously normal, northwest-bounded faults. Black circles on dip indicators represent down-thrown sides of faults activated in the formation of the north-south pull apart basin. Movement sense directions on faults are shown as arrows in corresponding color to fault (EMK and author mapping). Inset: position of map area.
4.4.1 Pre-mineralization structures

*PBH volcanic layering, volcanic intrusion and sedimentary bedding trends:* To the south of PBH, coherent andesite lavas and tuffs in the Permata footwall and hanging-wall strike at $110^\circ$ and dip $20^\circ$ to the north-northeast (MAP 1 Permata and Fig. 4.9). In the Maantung area to the southwest of the Permata vein, coherent andesite lavas and tuffs strike at $136^\circ$ and dip $48^\circ$ to the north-northeast. In the Pertim area to the south east, andesite lavas, autobreccias and tuffs strike at $135^\circ$ and dip $40^\circ$ to the northeast. Coherent andesite lavas, tuffs and non-stratified, poorly-sorted, muddy polymict breccia facies in the Batu Badinding footwall strike at $20^\circ$ and dip $10^\circ$ towards the east-southeast (MAP 2 Hulubai).

Sedimentary rocks and volcanics deposited in the north-south fault bounded Batu Badiding graben strike $75^\circ$ and dip $15-10^\circ$ towards the north-northwest (Fig. 4.9). Late stage, northwest trending, basaltic andesite dikes and northeast basalt dikes are found in central Permata and in the southern Permata hanging-wall, respectively (Map 1 Permata).

*Northwest faults and shears:* Northwest striking lineaments that occur as prominent features on remote sensing and geophysical imagery are related to faults, shears or coherent basaltic andesite dikes (MAP 1 Permata). Northwest faults are topographically defined by northwest trending valleys and scarps to the west and east of the PBH pit. The magnetic response of northwest lineaments observed on airborne magnetic data is due to moderately magnetic, coherent basaltic andesite dikes intruded along northwest faults (Chapter 3, Fig. 3.4). This occurs at Permata, where an interpreted northwest fault is filled by a basaltic andesite dike (MAP 1 Permata). This structure defines the boundary between different depositional environments in the Permata hanging-wall and footwall and the Batu Badinding hanging-wall (Map 1 Permata and Map 2 Hulubai). No shearing is observed at the margins of the basaltic andesite dike, implying that it was intruded post fault movement. The lack of alteration, and the fact the dike only hosts post-mineralization vein stages five and six (see Chapter 5), suggest that the dike was emplaced post mineralization. Offset relationships and veining developed in northwest structures imply a dextral component of movement (Fig. 4.10 A).

A northwest fault also defines the boundary between different depositional environments in the Batu Badinding footwall and the Hulubai footwall. Complete movement history of this fault is not certain due to a high degree of alteration, weathering
Figure 4.10  PBH structural elements

A  Northwest fault with cyanid vein displaying a dextral sense of movement; Permena.
B  Slickenlides surfaces on north-south fault showing reverse fault movement; Permena.
C  North-northwest Permena North split vein showing simple opening and crustiform texture with late infilling amethyst; Permena North.
D  North-south fault at footwall to the main vein displaying fault gouge with entrained clasts. Clasts leave gouge marks in the fault wall implying an oblique dextral sense of movement; Hulubai.
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and clay fault gauge. The latest sense of movement, as indicated by en echelon step veins, likely had a component of dextral movement. The northwest magnetic linear feature that crosses the Hulubai pit is not observed in the hanging-wall but is coincident with the northwest faulting in the footwall (Fig. 4.9). The structure has been covered and concealed by the emplacement of the distal basin environment rocks of the Hulubai footwall and therefore pre-dates deposition of the distal basin sequence (Fig. 4.9).

North-south faults: North-south faults define the trend of mineralization at PBH. Prior to mining, the main mineralized fault was expressed as a intensely silicified north-south trending ridge. The north-south mineralized fault at PBH separates the Batu Badinding and Hulubai footwall from the Batu Badinding and Hulubai hanging-wall (MAP 2 Hulubai). The movement history of this fault is uncertain, due to a well developed fault gauge and lack of kinematic indicators however, vertical slickenslide planes are recognized in the fault wall at Permata (Fig. 4.10 B). There is also a large offset between lithologies in the Hulubai hanging-wall and those in the Batu Badinding footwall. These lithologies cannot be correlated, suggesting at least 300 meters relative vertical movement on the fault (Fig. 3.16 B). The fault must have had several periods of activation with a component of normal or reverse dip-slip movement in order to juxtapose the distal environment of deposition of the Batu Badinding and Hulubai footwall, against the medial and proximal environment of deposition represented by the Batu Badinding and Hulubai hanging-wall.

A north-south fault is also recognized at Permata, between the footwall and hanging-wall sequences (Fig. 3.16 A). Volcanic layering is only moderately offset however and there is no change in environment of deposition across this structure. The volcanic architecture therefore suggests limited movement on this north-south striking structure at Permata, compared with significant movement along similar structures at Batu Badinding and Hulubai.

4.4.2 Mineralized structures

North-northwest to north-south mineralized faults and veins: The main mineralized structure at PBH is a north-northwest to north-south striking mineralized fault and vein, approximately 2.2 kilometers long and up to 5 meters wide (Fig. 4.11). The structure ranges in dip from vertical to 65° towards the west. The fault hosts veins and breccias
which are infilled with jasper, microcrystalline quartz, sulfides, sulfosalts, crystalline quartz, amethyst, calcite and manganoan-carbonates.

The Permata segment of this structure is a north-south striking, west dipping vein which bifurcates into a cymoid loop at 30°00'N. A near vertical, hanging-wall "split" vein branches off to the north-northwest at 30°30'N (Fig. 4.10 C). The main vein, including the hanging-wall split, is 1.25 kilometer long and up to 5 meters wide. Mineralization extends from the surface (between 200 to 225 RL) down to 75 RL, representing a vertical extent of 125 to 150 meters. The vein has a uniform width and dips moderately to the west (Figs. 3.15 A, 4.10 C and 4.11). An orthogonal stockwork of thin crustiform, crystalline quartz amethyst veins is also developed within a lens of andesite that is enclosed by the cymoid structure. The location of the cymoid loop and bifurcation of the hanging-wall split coincide with the intersection of a northwest structure at 31°10'N and a basaltic andesite dike at 31°20'N. High-grade ore shoots (> 5 g/t Au and > 340 g/t Ag) are located at bifurcations of the vein structure and the intersection of hanging-wall splits.

The deposit geometry is consistent with a tensional fracture and cymoid loop developed

Figure 4.11  Permata, Batu Badinding and Hulubai deposit Vulcan™ model
Three dimensional Vulcan™ model of Permata, Batu Badinding and Hulubai (PBH) vein system (bright colors) with final pit shell outline (light brown). Vein colors relate to planned mining stages. View is looking towards the south. Scale as per grid and level, north and east are marked near the centre of the deposit (Internal company MJK Vulcan™ modeling, 2000).
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in response to north-northwest compression.

The Batu Badinding segment of the PBH structure consists of a singular north-south to north-northwest striking, west dipping vein. The vein bifurcates into a braided vein with several hanging-wall splits that branch off to the north-northwest at 31°N (Fig. 4.7 C, Fig. 4.11, and MAP 2 Hulubai). In cross-section, the vein has a uniform width and dips moderately to steeply west. The vein anastomoses and has several cymoid loops along its length (Fig. 4.11). The Batu Badinding deposit extends over 0.9 kilometer and is up to 5 meters wide. Mineralization extends from the surface (at 200 RL) down to 100 RL, representing a vertical extent of 100 meters. Overall, the deposit geometry is consistent with a reactivated and dilated north-south fault in response to north-northwest compression.

The Hulubai segment of the PBH structure is a north-northwest striking, west dipping braided vein with several hanging-wall splits that branch off to the north-northwest at 31°N (Fig. 4.7 C, MAP 2 Hulubai). The location of bifurcating hanging-wall splits coincides with the intersection of a northwest striking structure at 31°200N (Fig. 4.9). Mineralization extends from surface (at 200 RL) down to 75 RL, representing a vertical extent of 125 meters. In cross-section, the vein is uniform in width with several near vertical hanging-wall split veins (Fig. 3.15 B). High-grade ore shoots (> 5g/t Au and > 340 g/t Ag) are located at bifurcations of the vein structure and at the intersection of the hanging-wall splits. A diffuse stockwork of chaotic, thin, wispy, crystalline quartz and calcite veins is developed in the hanging-wall to the main veins (MAP 1 Hulubai). The deposit geometry is consistent with a series of tension fractures and a reactivated north-south fault that have opened in response to north-northwest compression.

West-northwest to northwest veins: The west-northwest orientated vein and vein breccias at Pertim, Maantung, Bali, Hultim and Julan Bukit represent the expression of later dextral movement on northwest basement structures (Fig. 4.9). Orientation for these deposits comes from regional mapping and drill core data.

The Pertim vein breccia is 0.25 to 2.5 meters wide and can be traced intermittently over a 400 meters length. The western segment of the vein strikes at 283° and dips 82° towards the northeast (Fig. 4.9). The easterly part of the vein strikes at 105° and dips 80° to the southwest. The Maantung vein breccia is much larger than Pertim, ranging from 2 to 7
meters in width and extending intermittently over 1100 meters. This structure strikes between 113 and 120° and dips from 72° to 84° towards the north. The Bali vein is up to 3 meters wide and 550 meters in length with strikes between 160° to 170° and dips from 50° to 80° to the southwest (Fig. 4.9). The vein is offset along its length by northeast faults with a sinistral sense of movement. The Julan Bukit vein strikes at 120° and dips 70° to 85° west. The Hultim structure strikes at 110° and dips 80° north (Fig. 4.9).

4.4.3 Post-mineralization structures

Northeast to north-northeast faults: Several major northeast striking faults offset mineralized veins throughout the Mt Muro district. The Hulubai vein is offset by late, sinistral, north dipping, 60° striking, reverse faults that are infilled with calcite (MAP 2 Hulubai and Fig. 4.9). At Permata, northeast structures host late basalt dikes. Major northeast striking faults also offset the Bali, Julan Bukit, and Maantung veins. One major northeast fault passes through and offsets the Permata, Bali, Batu Tembak and Maantung veins. Sinistral movement on northeast faulting occurred post mineralization. Northeast faults documented in the Permata and Maantung area also have a component of reverse movement.

North-south shearing: The most recent sense of movement on the north-south striking structure at Permata is dextral strike slip shearing. This is expressed as well developed fault gauge with entrained angular to sub-rounded breccia clasts within the fault (Fig. 4.10 D). The fault clasts leave scour marks along rare slickenslide surfaces and indicate an oblique, dextral strike slip sense of movement. Brecciated fragments of the vein and wallrock are included in the clay fault gauge. Pervasive kaolinite alteration and pyrite development occur along the sheared footwall contact and may extend for up to 40 meters vertically down from surface. No veining or vein fill is recognized post fault gauge and shearing.
4.5 Kerikil structural features

The Kerikil deposit has a complex structural history with a range of structural styles, orientations and overprinting relationships. The deposit is strongly influenced by several major, northwest striking structures (Fig. 4.9 and Fig. 4.10). Kerikil has low lithological diversity with coherent andesite and basaltic andesite lavas and intrusions as the dominant rock types observed. The rocks have behaved in a brittle manner in response to the regional stress field, forming an extensive stockwork and a large range of breccias (Fig. 4.12). The breccias are of hydrothermal, tectonic or volcanic origin, as discussed in Chapter 3 (volcanic architecture) and Chapter 5 (mineralization). The reader is referred to MAP 3 Kerikil for details of all structural features discussed in this section.

4.5.1 Pre-mineralization structures

*Kerikil volcanic layering and volcanic intrusion trends:* In the hanging-wall of the Kerikil 1 deposit, layered coherent andesite flows strike at 20° and dip at 52-54° to the west (Fig. 4.13, 4.14 A, and MAP 3 Kerikil). In the Kerikil 2 footwall, coherent andesite lavas strike at 20° to 25° and dip 50° west. The margin of the coherent basaltic andesite intrusion exposed in the hanging-wall of the Kerikil 2 deposit trends north-south and has both an intrusive and faulted contact with the andesite lavas. The contact between the basaltic andesite and andesite is often obscured by brecciation. Exposed parts of the Kerikil 3 pit are dominated by massive coherent andesite lavas and non-stratified coarse poorly sorted polymict breccia facies (TALBRX). TALBRX, which is also observed in Kerikil 1, are
Figure 4.13  Kerikil complex with main structural features
Major structures and generalized volcanic distribution of the Kerikil veins and breccias (IMK and author mapping). Dilational Kerikil 1 and Kerikil 2 north-northwest structures are developed between major dextral strike-slip northwest faults. Bedding measurements are displayed as strike-dip symbols. Dip on veins is given by blue arrows. Red circles on dip indicators represent down-thrown sides of previous normal northwest basin-defining faults. Black circles on dip indicators represent down-thrown sides of faults activated in the formation of the north-south pull apart basin. Movement sense directions on faults are shown as arrows in corresponding colours to fault (IMK and author mapping). INSET: Location of map in relation to PNH and mine offices.
bound by northwest and north-northwest structures (Fig. 4.14 B). Poorly sorted rounded exotic polymict breccia facies (PEBBRX) is localized along northeast striking faults and cuts through the TALBRX.

**Northwest faults and shears:** Northwest striking lineaments that are prominent on remote sensing and magnetic imagery of the Kerikil area (Fig. 4.2 C and Fig. 4.3 D) are represented by faults and shears. Northwest faults are topographically defined by northwest trending valleys to the west of the Kerikil deposit and offsets in the silicified, north-south trending Ganung Baruh scarp to the east (Fig. 4.13 and Fig. 4.14). Northwest faults also transect the Kerikil 1, 2 and 3 pits (Fig. 4.13, Fig. 4.15 and Fig. 4.16). At Kerikil 2 and 3, these structures are observed in the north, east and west walls pits and where they dip moderately to the north east and southwest (Fig. 4.13 and Fig. 4.15).

Northwest faulting and shearing have been active throughout the genesis of the Kerikil deposit. Pre-mineralization northwest faulting controls the distribution of volcanics at Kerikil 1, 2 and 3 (e.g., non-stratified coarse poorly sorted polymict breccia facies; MAP 3 Kerikil, Fig. 3.6 B, Fig. 4.14 B and 4.17 A). Syn-mineralization northwest faulting has caused dilation and blowouts of the main vein and breccias (e.g. blowouts in the main vein at northwest intersections in Kerikil 2). Post-mineralization northwest faulting offsets veining and brecciation (e.g. offset of Kerikil 1 from Kerikil 2). A component of normal fault movement is indicated by normal offset of volcanic layering within the Kerikil 2 footwall. The latest sense of movement is dextral strike-slip, as determined from horizontal movement indicators on minor subsidiary structures and slickenslides on fault plane surfaces. The main northwest striking structure that truncates the basaltic andesite
intrusion in the northern wall of the Kerikil 2 pit was traced 500 meters to the northwest where it is expressed as a shear displaying quartz augen and S-C fabrics indicating a dextral sense of movement (Fig. 4.17 B).  

**North-south, north-northwest and north-northeast faults:** North-south, north-northwest and north-northeast striking lineaments are prominent on remote sensing and geophysical imagery of the Kerikil area and are represented by sharp faults, shears, veins and breccias (MAP 3 Kerikil). North-south faults are topographically defined by the silicified Ganung Baruh scarp to the east. The basaltic andesite intrusion in the Kerikil 2 pit also has a north-south orientation with intrusive margins to the north and faulted margins to the south.  

The main Kerikil 1 structure is a steeply west dipping, north-northwest striking fault. Similar north-northwest striking faults and steeply west dipping north-northeast striking faults are also observed in the southern wall of the Kerikil 2 pit, but are truncated to the north by a northwest striking fault.
Figure 4.16 Kerikil pitwall stereonets and rose diagrams of fracture arrays

The Kerikil 1 south wall rose diagram and stereonet of fracture directions shows a predominance of northwest striking, east dipping fractures and faults with minor north-northwest to south-southwest dipping faults. The Kerikil 1 west wall (hanging-wall) diagrams show a predominance of northwest striking east dipping fractures and faults and northeast striking and shallowly dipping southwest volcanic layering. The Kerikil 1 north wall diagrams indicate a predominance of northwest striking east dipping fractures to west-northwest striking, west dipping fractures and faults, northeast striking and shallowly dipping southwest volcanic layering. The Kerikil 1 east wall (footwall) diagrams show an array of fracture directions with northwest striking, east dipping fractures being marginally more prominent and northeast striking and shallowly dipping southwest volcanic layering. The Kerikil 2 west wall diagrams show a predominance of northeast to east striking, shallowly west and steeply east dipping fractures. The Kerikil 2 south wall (hanging-wall) diagrams show a predominance of north-northwest and northeast striking, steeply east and west dipping fractures and faults with minor steeply, south dipping, east striking faults. The Kerikil 2 north wall diagrams indicate a predominance of northwest and northeast striking, steeply east dipping, and west dipping fractures with north-south east dipping fractures. The Kerikil 2 east wall (footwall) diagrams show a predominance of northwest striking, moderately east and west dipping fractures and faults with very minor northeast or north-south fractures.
4.5.2 Mineralized structures

At Kerikil 1 and 3, veins and minor breccia-filled mineralized faults are the main ore-hosting structures. Fault-hosted breccias, with either a tectonic and/or hydrothermal origin, are common at Kerikil 2. All Kerikil faults and veins are infilled with microcrystalline quartz, sulfosalts, sulfides, crystalline quartz, amethyst, calcite and manganese carbonates.

North-south, north-northwest, north-easterly faults, veins and breccias: The Kerikil 1 deposit is 200 meters long and up to 5 meters wide. Mineralization extends from the surface at 200 RL down to 75 RL, representing a vertical extent of 125 meters. The base of the deposit consists of two main veins; one trending north-northwest with a near vertical dip, and the other trending northeasterly and dipping moderately to the northwest at 50° (Fig. 4.18 A and 4.18 C). The north-northeast trending vein has exploited primary volcanic layering and has an orientation consistent with the strike and dip of andesite lavas in the northern part of the deposit. Dextral movement on the main north-northwest trending vein has caused opening along the boundary on the western side of the structure. On the eastern side of the vein, however, the boundary exhibits compression with slickenslides and fault gouge (Fig. 4.18 B and C). Dilation at the intersection of the two structures has produced an inverted “v-shaped” ore shoot which dips steeply to the north (Fig. 4.18 C and D).

The Kerikil 2 deposit is 500 meters long and up to 30 meters wide. Mineralization extends from surface (at 250 to 225 RL) down to 50 RL, representing a vertical extent of
Figure 4.18 Kerikil 1 structural elements

A. North-northwest striking, steeply west dipping vein. South wall, Kerikil 1.

B. Sheared contact of south-southwest striking volcanic layering in Kerikil 1 footwall to the east. This contact has been dilated in the Kerikil 1 hanging wall to form the shallowly dipping, south-southwest striking Kerikil 1 vein on Fig 4.9 C. Field of view is 5 m across.

C. South-southwest striking, shallowly west dipping vein within volcanic layering. West wall, Kerikil 1.

D. Intersection of the north-northwest trending vein and south-southwest trending vein that forms the high grade vented Y-shaped Kerikil 1 shoot. East wall, Kerikil 1. Field of view is 10 m across.
Figure 4.19 Kenikil 2 structural elements

A View of the northern pit wall (Kenikil 2) showing the moderately dipping coherent andesite and contact with the north-south striking coherent basaltic andesite intrusion. Later northwest striking faults cut the coherent andesite.

B View of the southern pit wall (Kenikil 2) showing northwest and south-southwest striking structures.

C View of the west pit wall (hanging wall, Kenikil 2) showing northwest striking structures. The high grade colloform vein can be seen in the southwest corner.

D View of the east pit wall (footwall, Kenikil 2) showing northwest striking structures. Shallow, south dipping structures are related to down-thrown on northwest striking faults.
175 to 200 meters. At the base of drilling, the deposit consists of a narrow, north-south striking, mineralized fault which flares out at surface into an intense stockwork and breccia zone. The breccia zones are localized by north-south, north-northwest and north-northeast structures. North-northwest and north-northeast trending mineralized faults are prominent in the southern wall of the pit and dip moderately to steeply west. The north-northeast and north-northwest structures have been dilated and truncated by prominent northwest shears with a dextral sense of movement (Fig. 4.19).

The Kerikil 3 deposit is 300 meters long and up to 5 meters wide. Mineralization extends from surface at 225 RL down to 100 RL, representing a vertical extent of 125 meters. The deposit consists of a steeply west dipping, north-south trending vein in the north. To the south, the vein is intersected by a vertical north-northwest trending vein from the west. A hanging-wall split vein is connected to the main structure by shallowly dipping transfer structures that exploit primary volcanic layering. At the time of this study, only the eastern wall of the pit was exposed and the dominant structures were north-northwest veins and faults (Fig. 4.20). Additional information on the Kerikil 3 veins was determined from DDH sections and Vulcan™ modeling (Fig. 4.15).

**Figure 4.20 Kerikil 3 structural elements**

A Looking along bench at breccias bound by northwest faulting. East wall, Kerikil 3. Bench height = 5 meters.

B Breccias (BRX) bound by northwest faulting and valley associated with northwest faulting. East wall, Kerikil 3. Scale = Toyota Land Cruiser, 4 meters.
4.5.3 Post-mineralization

**Northwest faulting and veining:** Late dextral movement of major northwest faults has accommodated a carbonate-amethyst filled breccia zone in the north of Kerikil 2. Late, northwest striking, base metal and pyrite veins are observed cross-cutting all earlier vein stages, and a pervasive kaolinite-clay alteration along northwest structures can extend for depths of up to 150 meters (Chapter 8).

**Northeast to east-northeast faults:** Regionally, major northeast trending faults offset northwest faults and the continuation of the north-south trending Kerikil structure (Fig. 4.9).

**North-south, north-northwest, north-northeast shearing:** The most recent sense of movement on the Kerikil 1 north-northwest striking structure is dextral strike slip. This is expressed as a well developed, clay fault gauge with fragments of vein and wallrock. A pervasive kaolinite-clay alteration is also present along the footwall contact of this structure and extends to depths of up to 100 meters from surface. No veining or vein fill is observed.

4.6 Structural architecture and geodynamics of the Kutai Basin and Mt Muro

Basin architecture and geodynamic relationships documented as part of hydrocarbon exploration in the Kutai Basin by Cloke et al. (1999) are broadly consistent with basin architecture and geodynamics determined in this study at Mt Muro. This suggests a uniformity of processes and geodynamics across the Kutai basin from the Middle Eocene, Late Oligocene and through to the Middle Miocene.

**Eocene extension:** At Mt Muro, there is limited evidence for the Eocene northwest-southeast directed extensional event recognized by van Leeuwan et al. (1990) at the Kelian deposit, 80 kilometers to the northeast (Fig. 4.21 A). Marine sediment and carbonate basins in the northwest of the Mt Muro CoW have a northeast-southwest orientation and may have been deposited in this period of northwest directed extension. Similarly, north-south faulting at PBH may have occurred in the Eocene. Volcanological relationships, however, suggest that north-south faulting is more likely related to pull-apart basin formation in response to the Middle Miocene inversion event, north-northwest to south-
Figure 4.21 Structural architecture and geodynamics of the Kutai Basin and Mt Muro.

A In the Middle Eocene, northwest directed extension led to the development of north-northwest, northeast and north-south trending basins (evidence derived mainly from the east Kutai Basin and Kuran modified after Cloke et al., 1999). Sense of movement directions in the basement structures have been changed from sinistral to dextral, based on evidence from this study.

B In the Late Oligocene, northeast directed extension led to the development of northwest and north-south trending basins. During this period the Batu Badanung hanging-wall and footwall volatiles were depocentered into northwest and north-south basins. North-west trending fault scarps were developed (e.g., Kerkil 2 footwall). Flat-lying linkage structures resulted from extension on the northwest structures, and talus breccias (TAMBAX) were shed off northwest fault scarps (modified after Cloke et al., 1999). Sense of movement directions in the basement structures have been changed from sinistral to dextral as a result of evidence from this study.

C In the Early Miocene, a period of basin inversion began in the Kutai, giving rise to north-northwest directed compression. North-northwest compression and basin inversion resulted in north-northwest tensional dilution fractures that host the PBH and Kerkil vein and breccia bodies (modified after Cloke et al., 1999). Sense of movement directions in the basement structures have been changed from sinistral to dextral as a result of evidence from this study.

D From the Early Miocene through to the Middle Miocene compression had rotated 15° anticlockwise (Hall, 1995). This resulted in late movement and footwall gauge and dilution of west-northwest structures at Seruan Central, Seruan North and Pengkalan (modified after Cloke et al., 1999). Sense of movement directions in the basement structures have been changed from sinistral to dextral as a result of evidence from this study.
southeast directed compression, and resultant dextral movement on northwest basement structures. Volcanic centres at Mt Muro are aligned in a northeast to southwest orientation and some early magmatic activity may be associated with an Eocene extension event.

**Late Oligocene extension and Early Miocene compression and basin inversion:** Prior to this study, there was limited information on the Late Oligocene structural architecture of the Kutai Basin. Simmons and Browne (1990) published preliminary interpretations based on limited exposures at Mt Muro, which were subsequently re-interpreted by Cloke et al. (1999).

In this study, detailed mapping of volcanic architecture and graben relationships in the PBH pit, and basin relationships and folding in the Kerikil haul road, provide evidence for early northeast-southwest directed extension followed by later north-south compression (Fig. 4.21 B and C). North-south trending pull-apart basins formed in response to dextral movement on reactivated, northwest striking basement structures. The observation that the pull-apart basins are filled with mature sediments and reworked volcanics suggests that there has been uplift and erosion of preexisting lithologies in the providence region of the basins (e.g. Batu Badinding and Hulubai hanging-wall and Bantian deposit). Uplift may have been related to the same north-south compression that facilitated the formation of the pull-apart basins. North-south compression and subsequent dextral movement on northwest orientated basement structures has given rise to north-south and north-northwest tension fractures that host the PBH and Kerikil deposits.

**Middle Miocene compression and basin inversion:** Cloke et al. (1999) suggest that compression within the Kutai basin may shift as much as 15° from the Early Miocene to Middle Miocene, swinging from north-northwest to northwest orientation (Fig. 4.21 D). A change to northwest compression is consistent with reverse fault movement on northeast faults at PBH, as well as late opening of northwest structures that host late pyrite and base metal veins at Kerikil 2 (Chapter 5). A slight rearrangement of the stress field would also account for the dextral shearing and fault gouge observed at the footwall contact of the main north-northwest striking structure at PBH.
4.7 Geodynamics

4.7.1 Riedel-style brittle faulting, fracturing, and dilation in the volcanic cover sequence at PBH

The structural architecture at PBH is analogous to the classic Riedel clay model experiment. This experiment (Fig. 4.22) and consequent fracture analysis showed the structures expected from progressive shearing in a basement (represented by a gap in wooden boards) covered by a transitional brittle-ductile cover (clay block). The fracture set that developed was orthogonal to the maximum plane of shearing (Riedel, 1929). At PBH, the volcanics (which are analogous to the unconsolidated cover of the Riedel experiment),
have been deposited on a competent basement with prominent northwest dextral transverse faults and shears. These northwest striking structures extend into the basin and are observed in basement rocks to the northwest of the CoW (Fig. 4.2 A and Fig. 4.12 C). North-northwest compression, basin inversion and reactivation of concealed northwest basement structures facilitated the opening of pre-existing north-south striking structures to form north-south trending pull-apart basins. These basins are evidenced by the distal basin environment recognized in the Hulubai and Batu Badinding hanging-wall.

Given that dextral movement on northwest striking basement structures is the major geodynamic driving force for fracture formation, the structural architecture of PBH can be analyzed by Riedel-style mechanics. Using this model, the earliest extensional fracture set will form in the R1 (north-south and north-northeast) and R* (west-northwest) orientations (Fig. 4.23). This is consistent with the mineralized faults and veins recognized at PBH, which are predominantly dilational north-south and north-northwest striking structures (Fig. 4.23). Post-ore infill stages also occupy dilational north-south to north-northwest trending orientations. Cross-cutting relationships indicate that the north-northwest striking structures post-date the north-south structures (details see Fig. 5.46, Chapter 5). This change in dilation from north-south to north-northwest is interpreted as being due to a relative rotation of the maximum component of regional stress field by 15°. The rotation may be correlated with the regional Kutai basin inversion event and/or may be related to a relative 15° rotation of Borneo in the Early to Mid Miocene (Hall et al., 1995: Fig. 4.21 C and D). The PBH vein paragenesis is addressed in further detail in Chapter 5. Vein and breccia infill stages record the hydrothermal evolution of the deposit and the progressive opening of north-northwest dilational structures in response to northwest basement movement. The evolution of vein stages is correlated with a change in fluid composition and the physiochemical environment as structures become progressively dilated.

The last structural movement at PBH is represented by shearing along the footwall of the main structure and sinistral offset of veins by northeast trending faults. At Hulubai, northeast striking faults are filled with carbonate at shallow levels, representing a post-mineralization infill. At Permata, late post-mineralization basalt dikes intruded northeast faults and post-mineralization sinistral shearing, fault gouge and advanced argillic alteration developed along the main north-south vein structure.
Maximum compressive stress

Northwest trending basin defining structures activated in a north-northwest to south-southeast stress field to give a dextral sense of movement in basement. Dextral basement movement causes Riedel fracture development.

No evidence at PBH

Late northeast (60°) sinistral faults offsetting main vein at Hulubai. Late basalt dykes in Permata South.

Earliest jasperite vein stage at PBH forms in R1, at 20°.

Ore veins at PBH from north-south to north-northwest (210°-185°) in the tensional fracture direction.

Figure 4.23: Riedel fracture analysis applied to PBH

Riedel fracture analysis oriented to fit the stress field characteristics of the PBH and BBT vein complexes. The fracture array predicted from the Riedel model corresponds well with the structural characteristics and kinematics of the PBH and BBT veins, shear zones and faults. Colors on the fracture array correspond to structures observed in the PBH and BBT map (DSEI).

Numbers relate to the order in which specific structures form (1 being the oldest and 4 being the youngest formed).
An important characteristic of the Riedel model of fracture development is that faults, fractures and veins will form at regular intervals in response to shearing (e.g., en echelon structures). This characteristic is observed at Mt Muro where the Bantian and Batu Tembak (BBT) structure is a repetition of the PBH structure (Fig. 4.23). Another structure is recognized to the west of Bantian and Batu Tembak, reflecting classic en echelon-style features. Dilation in response to late P-shearing is also recognized at Mt Muro with the development of the Hultim, Maantung, Tengkanong, Serujan North, Serujan Central veins (Fig. 4.23).

4.7.2 Riedel style brittle faulting, fracturing and dilation in the volcanic cover sequence at Kerikil

Riedel-style mechanics are recognized at Kerikil on a broad-scale, but are not as readily discernable at the deposit-scale due to a high degree of brecciation, fracturing and formation of localized internal stress fields. On a broad scale, several major northwest trending structures cross-cut the Kerikil deposit (Fig. 4.24). North-northwest compression and subsequent dextral movement on these structures provide the driving force for the formation and dilation of north-south, north-northwest and north-northeast vein and breccia deposits. The north-northwest and north-south dilational set is related to the tensional fracture direction in the Riedel model (Fig. 4.24). Late northeast trending structures offset earlier dilational veins and northwest faults.

Characteristics of regional-scale geodynamics and the stress field were determined by the study of several key outcrops at Kerikil 1 and Kerikil 2. Reflection of large-scale structural dynamics by small-scale features is common in terrains under compressive stress, due to fracture arrays forming under a uniform local stress field. In a brittle, homogeneous, low diversity, lithological medium, as at Kerikil, fractal or power law scaling can be used to infer the overall dynamics of the system (cf Henley and Berger, 2000). Key outcrops at Kerikil 1 indicate that early mineralized northwest trending veins have open textures and are dextrally offset by later north-northwest trending veins (Fig. 4.25). These veins in turn are dextrally offset and dilated by later north-northeast trending veins (Fig. 4.25). This structural architecture is also recognized at the Serujan Central deposit (Fig. 4.5 C).

At Kerikil 2, dextral movement on northwest structures dilated north-south striking
Late 90°-110° faults in Kerikil pit

Late northeast (60°) sinistral faults offsetting main vein at Kerikil 2.

85° folds in Kerikil Haul Rd have developed perpendicular to maximum compressive stress providing evidence for north-northwest to east-southeast compressive stress.

Veins and breccias at Kerikil from north-south to north-northwest (210°-165°) in the tensional fracture direction.

Maximum compressive stress

Northwest basin defining structures activated in a north-northwest to south-southeast stress field to give a dextral sense of movement in basement. Dextral basement movement causes Riedel fracture development. Northwest structures also have associated avalanche breccias (TALBRX).

Northwest striking structures have associated breccias (TALBRX) at Kerikil 1 and 2.

85° folds in Kerikil Haul Rd have developed perpendicular to maximum compressive stress providing evidence for north-northwest to east-southeast compressive stress.

Figure 4.24 Riedel fracture analysis applied to Kerikil

Riedel fracture analysis accentuates the stress field characteristics of the Kerikil veins and breccia complex. The fracture array predicted from the Riedel model corresponds well with the structural characteristics and kinematics of the Kerikil veins, breccia bodies, shears and faults. Colors on the fracture array correspond to structures observed in the Kerikil map (INSL). Numbers relate to the order in which specific structures form (1 being the oldest and 4 being the youngest formed).
CHAPTER 4 STRUCTURE

Figure 4.25 Kerikil structural elements
A Vein and fracture array (Kerikil 1) showing dextral movement on northwest-striking structures (130°) and formation of north-northwest (200°) to west-northwest (160°) trending dilation veins.
B Close up of area in Fig. 4.25A showing dilation of north-northwest veins by sinistral movement on younger north-northeast striking structures.

Figure 4.26 Kerikil 2 vein and breccia relationships
A Northwest (120°) striking breccia vein off-set by a younger north-northeast (220°) striking colloform sulfide vein. Kerikil 2 (Fig. 4.26A is located immediately south of Fig. 4.26B).
B North-northeast striking vein (continuation to the north of the same south-southeast trending vein shown in Fig. 4.26A), off-set by dextral movement on northeast trending vein filled shear. Kerikil 2.
structures and facilitated the formation of north-northwest openings. A late northeast striking structure is responsible for the offset of Kerikil 2 from Kerikil 1 (Map 3 Kerikil). At an outcrop-scale, the regional stress field and geodynamics are less apparent due to the high degree of brecciation and fracturing and the predominance of local internal stress fields. Perturbations within the larger stress field form due to the brecciation, shuffling and rotation of rigid internal blocks of coherent andesite and basaltic andesite host rocks (Fig. 4.25 and Fig. 4.26).

4.8 Summary

Structural elements at Mt Muro are repeated at a regional-, district- and deposit-scale. These characteristics are integral to the formation and style of the Mt Muro deposits.

Northeast structures: Regionally, northeast structures control volcanic activity and define the “Kalimantan Gold Belt”. This trend not only identifies the location of Kalimantan epithermal gold deposits but also the site of the Late Oligocene Sintang volcanism. On a district-scale, northeast structures define intrusions and circular features that are interpreted as volcanic centres across the CoW. On a deposit-scale, northeast structures host basalt dikes at Permata.

Northwest structures: Northwest structures define basin margins and have a history of strike-slip reactivation in response to northwest and north-northwest compression. Regionally, the northwest striking Sangkulirang and Adang Fault Zones define the northern and southern extents of the Kutai Basin and offshore Makassar Basin. The Adang Fault Zone is a northwest striking dextral strike-slip fault zone that extends across Kalimantan in close proximity to Mt Muro. On a district-scale, northwest faults define the distribution of volcanic facies and environments at PBH, Tengkanong, Bantian - Batu Tembak and Serujan. On a deposit-scale, northwest structures define the distribution of the non-stratified coarse poorly sorted polymict breccia facies at Kerikil. Reactivation and dextral strike-slip movement on northwest structures at both the district- and deposit-scale (due to north-northwest and northwest orientated compression), formed north-northwest dilational fracture sets that host the Kerikil and PBH deposits. West-northwest trending deposits such as Tengkanong, Serujan North, Serujan East and Serujan Central represent jogs and bends within the dextral strike-slip northwest structures. A comparison of the pre-, post-, and syn-mineralization structural elements for PBH and Kerikil is documented.
in Table 4.1.

Overall, the PBH and Kerikil vein and breccia dilation structures are a direct result of deformation in an unconsolidated cover due to dextral movement in northwest basement structures. Basement movement occurred in response to north-south to northsouth orientated compression related to Riedel mechanics. The structure architecture at Kerikil is far more chaotic and complex than PBH due to the coherent, brittle host rocks and high degree of brecciation.
### Summary of PBH and Kerikil pre-, syn- and post-mineralization structural features and their orientations

<table>
<thead>
<tr>
<th>Timing of structural feature</th>
<th>PBH</th>
<th>Orientation of structural feature</th>
<th>Kerikil</th>
<th>Orientation of structural feature</th>
</tr>
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<tbody>
<tr>
<td><strong>Pre-mineralization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Volcanic layering</td>
<td>proximal slope, volcanic, and sedimentary layering towards the south.</td>
<td>central vent environment, volcanic layering steepens towards the south.</td>
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<td>Volcanic intrusion</td>
<td>basaltic andesite with north-northwest and northwest dikes</td>
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<td>Faulting</td>
<td>graben bounding structures and pull apart basin structures</td>
<td>graben bounding structures and pull apart basin structures</td>
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<td>15°/15°NW</td>
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<td>cryptocrystalline quartz infill</td>
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<tr>
<td>Volcanic intrusion</td>
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