CHAPTER 5.0 STRUCTURAL GEOLOGY AND VEINS SYSTEM

5.1 Introduction

Penjom is classified as orogenic gold (Flindell, 2003) after Groves et al. (1999) and has many characteristics that are common with other orogenic systems such as the Victorian gold fields (Eastern Australia) and the Meguma terrain (Nova Scotia, Canada). These systems have a similar structural environment-controlling veins system related to compressional and transpressional regimes that produce folds, reverse and strike slip faults.

5.2 Regional structural geology

Penjom Gold Mine is situated in the Central belt of Malaysian Peninsula in an area with the topography elevation lower than 300 m, except several granitic hills such as Bukit Lima and the Benom Complex. Despite this low topography, a series of strike-ridge lineaments coupled with negative lineaments trending NNE-SSW to NS can be seen on radar set images. Penjom is situated along one of the splays of the Bentong–Raub suture (Kidd and Zainuddin, 2000), about 30km east of these main sutures.

Due to lack of exposure, structural study is always limited in coverage, but an attempt to interpret the regional structural geology by radar set images has been made (Tjia and Harun, 1985). NS and NNW faults are reported to be the most common faults direction in the Malaysia Peninsula, compared to the NNE-trending fault. However, within the West Pahang, NS trending lineament and NNE splay are easily seen on the radar-sat image.

Structural deformation of peninsular Malaysia is summarized by Shuib (2009) as shown in Table 5.1. Late Triassic-Early Jurassic has been highlighted as an important period that applicable to the study area.
**Table 5.1: Summary of deformation events in Peninsular Malaysia (Shuib, 2009)**

<table>
<thead>
<tr>
<th></th>
<th>Western belt</th>
<th>Central belt</th>
<th>Eastern belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Cambrian</td>
<td>Uplift and deformation</td>
<td></td>
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<tr>
<td>Early to Mid-Devonian</td>
<td>?Deformation, metamorphism, uplift</td>
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<tr>
<td>Pre-Early Permian</td>
<td></td>
<td>Dextral transpressive deformation, metamorphism, uplift</td>
<td></td>
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<tr>
<td>Post-Early Permian</td>
<td></td>
<td>Transpressive deformation and transtensional opening of continental pull-apart basins</td>
<td></td>
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<tr>
<td>Mid-Devonian to Mid-Permian</td>
<td>Rifting, extension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mid-Permian to Early Triassic</td>
<td>Dextral transpressive deformation, metamorphism</td>
<td>Dextral transpressive deformation, metamorphism, uplift, subsidence &amp; further dextral transpression along Bentong-Raub Suture Zone</td>
<td>Dextral transpressive deformation, metamorphism</td>
</tr>
<tr>
<td>Middle Triassic-Late Triassic</td>
<td>?Extension/?Transtension</td>
<td>Dextral transpressive/transtension deformation</td>
<td></td>
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<tr>
<td>Late Triassic-Early Jurassic</td>
<td></td>
<td>Dextral transpressive deformation, metamorphism</td>
<td></td>
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<tr>
<td>Latest Triassic to Cretaceous</td>
<td></td>
<td>Transtensional opening of dextral pull-part basins</td>
<td></td>
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<tr>
<td>Mid to Late Cretaceous</td>
<td>Sinistral transpressive deformation</td>
<td>Sinistral transpressive deformation, metamorphism (Stong Complex)</td>
<td>Sinistral transpressive deformation</td>
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<tr>
<td>Early to Middle Eocene</td>
<td></td>
<td>Late brittle faulting</td>
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</table>

The most prominent structure in the Central Belt is the Bentong–Raub Suture along the eastern footwall of the Main Range Granite. It has been interpreted as the subduction line between the Sibumasu and Indochina Blocks (Hutchison, 2009; Metcalfe, 2000, 2013) and is correlated toward the north as Nan Uttaradit and Sra Kaeo sutures of Thailand.
Tectonic and magmatic events are summarized by Metcalfe (2013) as shown in Figure 5.1. The Bentong–Raub Suture represents the closure of the Palaeo-Tethys and is made up of suture lithologies including oceanic radiolarian cherts recording the age from Devonian to Upper Permian, melange and serpentinite (Metcalfe, 2002, 2013).

![Figure 5.1: Tectonic-magmatic event involving the collision of Sibumasu-Indochina terrain (Metcalfe, 2013).](image)

5.3 Previous studies

5.3.1 Geological modelling 1 (1997–1999)
NS-trending mineralization made up the NS corridor, which hosts laminated to ribbon quartz (Corbett, 1997), and the thrust zone hosts sheared ribbon quartz. At higher elevation, both ore zones are high in carbon or carbonaceous content, but only the thrust zone has been recognised and highlighted as a high-graphitic ore zone during that period and characterized as the Penjom Thrust ore body.

The NS fault (now classified as quartz-bearing NS trending bedding-parallel shear related to folding episode) was interpreted as hosting and control mineralization or as the main conduit for fluid at depths.

5.3.2 Geological modelling 2 (2000–2001)

A second geological modelling reinterpreted and recognises the laminated vein-bearing NS corridor as a new element of bedding slip fault so that it emphasizes more on stratigraphy control. However, the NS fault is still maintained in the model and considered to a certain extent as responsible for reactivating the bedding slip fault and partly hosting the mineralization. The role of the NS fault is unclear, but this structure is still maintained and inferred as the structural conduit. Ore zones in Kalampong East during this period were classified as:

1) Penjom Thrust ore zone
2) Stratigraphy concordant ore zone at certain structural setting
   a. Felsite sill-hosted ore zone
   b. Stratigraphy parallel ore zone
3) Minor NS-bearing ore zone.

Around the jewel box, the previous NS corridor has been re-classified to a bedding-parallel zone; however, in other area away from this area, the earlier element of NS shears/fault hosted ore is still maintained. The change of NS-trending quartz-bearing
bedding slip fault, previously classified as the NS fault mined during earlier pit development (geological model 1), to a stratigraphy concordant or bedding-parallel veins (geological model 2) has downgraded the previous theory about the role of the NS fault as the main controlling factor in mineralization.

5.3.3 This study

This study upgrades the second geological modelling with a focus on the genesis and structural setting of the bedding-parallel veins and several stages of the extensional veins. Setting of the shear veins are shown in the map as depicted in Figure 5.2. The relationship between these two veins types were also described in detail. The shear and the extensional veins can occur in a single ore zone normally in areas where a competency contrast unit exist, for example the contact of carbonaceous shale with sandstone, conglomerate or felsite intrusive. The bedding-parallel veins were interpreted as occur during flexural slip folding during the D2 compressional event (Endut and Teh, 2010; Endut et. al, 2014; Endut et. al, 2015a). With this new understanding, this structure is only considered as a trap and not the conduit at depth. The conduit may have been provided by the main thrust, parallel structure, splays and associated fractures during the deformation. Another phase of faulting is responsible for a second stage of extensional veins.
Figure 5.2: Geological map of Kalampong pit (2008), inset photo shows bird eye view of Kalampong and Manik pit.
5.4 Folding

5.4.1 Introduction

Folds can be divided into two phases. The overall east-dipping sequences developed during the D1 event that is part of regional folds, and Penjom is located at the eastern limb. Local re-folding of the sequences forming anticline–syncline sets associated with the Penjom Thrust structure can be seen in the Kalampong pit. Folding was certainly the earlier structural event, and this episode was modified and overprinted by the movement of the thrust-parallel structure with reverse and dextral sense of movement and later by the sinistral to normal sense of movement by the northerly trending fault. The fault also accommodated along the fold axis that separates the eastern and western limbs. Both limbs formed two separate corridors that host two significant ore bodies along the same rock unit. The photo of north and south walls with the structural outlines are shown in Figures 5.3 to 5.6.

Other corridors are tight-incline folds, which are along the fold axis and the refolded western limb which hosts Kalampong West, Manik and Jalis ore zone particularly along the fault zone or shear vein. Study of fold-related structures other than the veins includes bedding outline, stratigraphy correlation (fold geometry) and fold related products such as cleavage.
Figure 5.3: North wall as current pit slope (2009). Area for the bedding analysis plotted in stereonet. Bedding at area 1, 2 and 3 are dipping east and area 4 is dipping west.

Figure 5.4: North wall before cutback shows the same style of folding.
Figure 5.5: South wall during third cutback. Hill 6 NS fault intercepted along the eastern limb.

Figure 5.6: South wall of Kalampong pit before 2009 cutback shows recumbent fold of tight inclined fold.
5.4.2 Bedding

Bedding should not be thought as a passive surface during deformation. It is commonly an ideal accommodator of strain, especially progressive shearing strain (Davis, 2005b) which results in bedding slip fault as indicated by the slickenside surface along the bedding shear. The bedding can be an active surface during deformation as a result of its physical and mechanical properties such as lamination and, in particular, layering of fine grain sediment in between coarse grain sediment. The process is usually associated with the folding process and is also referred to as flexural slip fault.

5.4.2.1 Bedding analysis

Bedding orientation around the pit has been measured and plotted on stereonet. Data collection has been divided into two structural domains referred to as hanging walls and footwalls. Footwalls represent the overall east-dipping sequence that undergoes a compressional event resulting in the host rock being folded in the pit area to an antiform-synform couple below the main thrust. The Jalis thrust reactivates along synform and is probably responsible for another fold that is currently to the west of the current pit.

Figures 5.7 to 5.8 show stereonet plot for the dip and the dip direction of bedding in various parts of the Kalampong pit. Based on the geometry of the fold, comprised of anticline-syncline at the footwall, the dip direction of the bedding can be divided into three main groups such as east-dipping eastern limb parallel to the main thrust (Area 1-3), west dipping western limb (Area 4) that is part of the Kalampong anticline and east dipping sequence that forms a synform that hosts Jalis–Manik corridor (Area 5). Tight incline fold around the fold axis also has an east dipping bedding.
Figure 5.7: Hanging wall, Area 1 - Hill 6: Mean Orientation = 44/126 (Dip/dip direction). Area 2 – Hill 5: Mean Orientation = 46/147 (Dip/dip direction). Foot wall, area 3 (zone B) - Eastern Limb near fold axis: Mean Orientation = 38/157. Area 4 (zone C) – West wall North: Mean Orientation = 64/277.

Figure 5.8: Jalis-Manik corridor. Stereonet plot of bedding at Jalis west wall shows mild cross fold of the east dipping bedding: Mean Orientation = 30/094
Stereonet analysis shows that the structure of folded rocks in the footwall of the Penjom Thrust changes from open fold to tight-incline fold towards the south. The Western limb becomes refolded in the western side, resulting in the east-dipping sequence of the sediment from the west wall of Kalampong towards Jalis and Manik.

5.4.2.2 Stratigraphy correlation and style of the fold

A complete understanding of the stratigraphy is essential to understand the style of the folded rock. Detailed explanation of the stratigraphy unit is covered in chapter three. The overall stratigraphy sequence in Penjom can be divided into three sequences to enable simplified geology to be incorporated into the fold analysis. The cross-section of the ore body is shown in Figure 5.9 to 5.12, and this provides the overview of the fold geometry. Several important stratigraphy units are calcareous shale, thick carbonaceous units and thick conglomerate units. The occurrence of mineralized bedding-parallel vein and felsite also helps in determining stratigraphy correlations on the smaller scale.

Main fold is considered as folded rock associated with the Penjom Thrust that has resulted in antiform and synform couples below the main thrust from Janik to Kalampong North. Around the Kalampong anticline, fold settings of the ore domain can be divided into a tight-incline fold (zone A), eastern limb (zone B), western limb (zone C) and west limb of the synform (zone D). Western limb (zone C) is also known as a NS corridor because of the same strike direction. Areas for this zone (A to D) were shown in Figure 5.9 to 5.12. Figure 5.13 shows a plan view of pit geology and stereonet plot of the fault direction. The active bedding slip shear at the western limb contributes to the intense west dipping fault.
Figure 5.9: Cross-section at 49700.

Figure 5.10: Cross-section at 49000.
Figure 5.1: Cross-section at 50100.

Figure 5.12: Cross-section at 50 200.
Figure 5.13: The stereonet plot of fault orientation in several zones. Numbers of data are in bracket.
Figure 5.14: (Left) Undeformed shear vein with fracture cleavage S2 below the vein (western limb). (Right) S3 fold axis cleavage also affected the shear vein (refolded western limb).

5.4.3 Cleavage development

Cleavage consists of penetrative planar rock fabrics that are developed during deformation and formation of folds. Their intensity is commonly heterogeneous across various scales, and shear zones represent zones of cleavage intensification (Davis, 2005b).

The occurrence of cleavage will help to understand the effects of folds and faults on the host rock and veins in order to constrain the time relationship between the structure and mineralization. Several styles of cleavage can be observed within the Kalampong Pit, either developed locally or broadly across the fold axis, such as bedding-parallel cleavage or foliation, fractured cleavage, crenulation cleavage and pressure-solution cleavage.

Bedding-parallel cleavage $S_1$ develops during the regional deformation event before refolding related to Penjom thrust. Fracture cleavage ($S_2$) that is perpendicular to the bedding locally developed below the bedding parallel shear vein is formed during the D2 fold activity (Figure 5.14 left). Northerly strike-fractured cleavage $S_3$ probably formed during the later stages of compressional event or refolded activity associated with fault. It forms below the NNE reversed fault that cross cut the earlier bedding-parallel shear vein (Figure 5.14 right).
Bedding-parallel cleavage is more intense in inclined fold and also well developed in conglomerates, especially along reactivation of the fault. Similar fractures can also be observed in small felsite sills (Figure 5.15 right) as a result of reactivation along the shear vein. Contact of felsite intrusive and shear vein during the veining process, as in Figure 5.15 (left), is only shows a narrow deformed rock.

Figure 5.15: (Left) Shearing at contact of felsite intrusive as indicate by shear vein V1, intrusive is undeformed. (Right) Shearing as a result of reactivation of the fold at contact with intrusive produced parallel fracture in narrow sill (refolded of the western limb)

Figure 5.16: (Left) S2 develop in refolded fold below incline fold. (Right) Close up view of northerly strike parallel fracture cleavage. Dash line is bedding outline.

The occurrence of the fault along the fold axis that separates the east and west limb of the fold has probably accommodates the stress during deformation so that less intense S2 fracture cleavage is developed along the main axis of the anticline within the competence
unit such as felsite intrusive. The other fracture cleavage S3 develops adjacent to the D3 fault (Figure 5.16).

5.5 Fault

5.5.1 Introduction
Fault is not always a straight line or plane. It bends or splays from the main fault plane forming a network of faults. The direction of fault can locally change from NNE to NS-trending so that classification of fault is based on the direction only could result in misinterpretation of the fault system.

Several steps of studying the fault, in particular the major fault, start with the study of individual major faults at the pit wall and across the pit. Direction of the fault can be in the range of 30 degrees and, direction-based classification should be done with regard to this range. For example, Fold Axis Fault has a NS direction to the south but a NNE direction to the north. The fault is also assigned a specific name to differentiate among a series of faults.

After the individual fault has been recognized, sense of movement for every fault will be determined based on marker-bed displacement and slickenside direction. The fault will be grouped based on the direction and sense of movement. The strike direction takes into account certain ranges of the fault orientation.

Based on the study, several fault orientation can be observed; including NE to NNE reversed and lateral fault, E-W, NNW and NS trending lateral to normal fault. At least four mine-scales NE to NNE reversed faults and several NS normal faults with a minor component of lateral strike slip have been recognised. Based on crosscutting relationships, three groups of faults and structural deformation can be established (Figure 5.17).
5.5.2 Fold related fault

The Penjom thrust is a fold-related structure developed after initial folding and characterized by occurrences of tight-incline folds to open folds at the footwall of the structure. The Penjom Thrust appears as highly carbonaceous because it is reactivated along the carbonaceous shale and has physically remobilized the carbon along the fault.

The Kalampong anticline that developed below the Penjom Thrust has a fault accommodated along the fold axis that is referred as fold-axis fault. This fault has a normal sense of movement that separates the east limb and west limb of the open fold and is thus classified as a fold-related fault. Direction of this fault is NS near to the thrust and turns NNE towards the north.

<table>
<thead>
<tr>
<th>D2 Deformation</th>
<th>D3</th>
<th>D4 Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fold Thrust</td>
<td>NE to NNE Reversed to dextral fault</td>
<td>(Post thrusting)</td>
</tr>
<tr>
<td>Bedding slips fault/shear/vein</td>
<td>Other Extension/brecciated vein.</td>
<td>NS trending normal to oblique fault</td>
</tr>
<tr>
<td>(Former NS fault)</td>
<td>NNW fault in Jalis corridor</td>
<td>Sinistral (NS fault)</td>
</tr>
<tr>
<td>Extension vein</td>
<td></td>
<td>Extensional calcite vein</td>
</tr>
<tr>
<td>Fold related fault</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW faulting</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.17: Structural classification for Kalampong East (KE) Pit shows three main structural events.

5.5.3 Compression fault

Several series of NNE to NE fault can be observed in the Kalampong pit cross cut the western limb of the fold. This fault is referred to as the R1 to R5 reverse fault (Figure 5.18 to 5.19). The R1 fault in the north is likely to be a part of the Jalis-reversed fault with
reverse slickenline as exposed in the south and this structure has been displaced by the NS DMF fault. The NNE faults are very important and control the extension veins at fault-intrusive contact even though the veins mostly yields a lower grade ore but a larger zone if at felsite contact. Displacement by this fault can be up to 20 m such as the R1 fault (Figure 5.18), and the other fault has a displacement of less than 5 m.

Figure 5.18: (Left) R1F and R2F displace felsite body, looking south (852mRL). (Right) R1F as expose on the wall.

Figure 5.19: (Left) R4F (NNE fault) displace felsite rock in incline fold zone, base level 834mRL (looking south) after cutback. (Right) Close up view, intense quartz below R4F at contact with felsites intrusive.
5.5.4 Strike slip regime

Based on observations of the slickenside on the fault plane, several faults show multiple movements such as reverses with dextral (e.g. NNE to NE faults) and normal with sinistral movement (NS fault).

5.5.4.1 Dextral fault

Some of the NNE and NE faults have a component of dextral and oblique-reversed movement as shown by the R2 fault; a steep NNE fault and a NE fault in the Jalis corridor. This movement is thought to occur after the reverse sense of movement when the stress changes from compressional to transpressional.

5.5.4.2 Sinistral fault

Sinistral movement can be observed along the NS Jalis fault at southern wall of the Kalampong pit but normal to oblique normal sense of movement is prominent along a series of Hill 6 NS fault, as indicated by the movement of marker bed and fault striation.

NS Jalis fault is considered here as a major sinistral to normal fault and not responsible for the folding but reactivating along Penjom thrust parallel to the fold axis. NS Jalis fault has downthrown all the sequences and reactivates along the Penjom thrust. This explains why the younger sequences have occurred above the Penjom thrust (not vice-versa) along the fault reactivation.

5.5.5 Extensional regime

Several normal to oblique-normal NS-trending faults can be observed to reactivate, diffract and cross-cut the Penjom Thrust zone. From east to west, these faults are recognized as Hill-4 NS fault (slickenline as in Figure 5.20), Hill-6 NS fault, NS Jalis and Dancing Man...
Fault (DMF) (Figures 5.21 and 5.22). These faults are well defined above the Penjom Thrust. Other small-scale NS-trending normal fault cross cut the horizontal D2 bedding-parallel vein with a normal sense of movement (Figures 5.23 and 5.24).

Figure 5.20: Slickenline striation on Hill 6 NS fault plane shows slightly oblique normal fault

Figure 5.21: At the southernmost part of the Kalampong pit, a steeply dipping N-S normal fault (DM Fault) (right side of the picture) cuts the gently dipping NNE-SSW reverse fault and high carbon zone. Another normal fault (NS Jalis) at left side reactivates along Penjom Thrust.
Figure 5.22: NNW fault developed as a Riedel fault in between NS indicating normal sense of movement.

Figure 5.23: Fault striation indicate normal sense of small scale NS fault cross cut quartz-carbonate shear vein.

Figure 5.24: (Left) Normal north south fault displace flat dipping high grade laminated vein (looking south, 834mRL). (Right) Close up view of normal NS fault displace a flat bedding parallel vein.
5.5.6 Summary of the new structural framework

Structural deformation can be divided into at least five structural episodes, from compressional and transpressional (D1 to D3), which also involves strike-slip movement and later transtensional regime (D4-D5). The first episode is responsible for the regional fold followed by a local fold, thrust activity and later stage NNE to NE-reversed fault after the fold has locked up. Further deformation episodes involving dextral movement (strike slip) of earlier NNE to NE structures and Jalis corridor NNW trending fault with apparent sinistral fault movement. NNW fault is not prominent in Kalampong pit and only occurs in Jalis corridor sub-parallel to the carbonaceous shale unit. Final D4 deformations are the NS-trending cross-cutting faults with sinistral and reactivated as normal and oblique normal sense of movement. The faults also reactivate and diffract along Penjom Thrust mainly after veining and mineralization events. The summary is shown in Table 5.2.

Table 5.2: Summary of structural event in PGM indicates two main structural events. D2 to D3 deformation involving compression to transpressional event and D4 to D5 extensional period.

<table>
<thead>
<tr>
<th>Events</th>
<th>D2 Deformation</th>
<th>D3 Deformation</th>
<th>D4-5 Deformation</th>
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<tbody>
<tr>
<td>Fold and fold related fault</td>
<td>---------------</td>
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</tr>
<tr>
<td>Penjom Thrust</td>
<td>---------------</td>
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</tr>
<tr>
<td>NE to NNE reverse fault</td>
<td>---------------</td>
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<tr>
<td>NE to NNE dextral</td>
<td>---------------</td>
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</tr>
<tr>
<td>NNW sinistral and reverse fault (Jalis corridor)</td>
<td>---------------</td>
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<tr>
<td>EW Lateral fault</td>
<td>---------------</td>
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<td>------------------</td>
</tr>
<tr>
<td>NS sinistral fault</td>
<td>---------------</td>
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<td>------------------</td>
</tr>
<tr>
<td>NS to NNW Normal</td>
<td>---------------</td>
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</tbody>
</table>
5.6 Quartz-carbonate vein system

5.6.1 Introduction

Quartz veins are derived from the hot hydrothermal fluid from deeper levels or from dissolution from the host rock, deposited into confining spaces such as faults, bedding-parallel faults, dilational spaces and extensional fractures. Veins are important components of most epigenetic hydrothermal ore systems. Understanding their formation and different styles of quartz veining is the key to unraveling the structural controls on these ore systems (Davis, 2005b and Robert and Poulsen, 2001).

Many researchers regard quartz veins as a tectonic fossil which records the structural control on gold mineralization so that any structural studies must be able to explain vein formation. Some reasons to study such veins are as follow (Mawer, 1987).

- Veins have considerable potential as indicators of at least part of their host rock’s strain history.
- The fluid inclusions they invariably contain represent a direct sample of vein-forming fluids.
- Veins generally represent paths of focused fluid flow.
- Quartz veins contain precious metals such as gold.

It is very important to study episodes of vein formation to distinguish features due to vein formation and superimposed features caused by later deformation. Vein classification is based on Davis (2005b), Hodgson (1989), Robert and Paulsen (2001) and Ramsay and Huber (1987). Veins that host gold indicate that they come together with veins and remobilized during the ongoing deformation and brecciation of the veins (Davis, 1998) so that some gold appear as infilling fractures in veins.
In Kalampong pit, several vein-hosted ore bodies have been given names such as “highly graphitic Penjom shear”, “jewel box”, “high carbon North-South (NS) corridor”, “low carbon NS corridor” and “the North-West (NW) corridor ore body”. Despite specific references made to these high-grade ore bodies, the boundaries between them and the vein formation has not properly been discussed.

The structural classification of veins helps in the discussion of how the vein was formed and the relationship to mine scale structural deformation. Relative chronology of the structure and vein formation can be related to the initial development of thrust and fold, and later development of reversed fault after the fold had locked up. Continuous movement resulted in dextral slip of parallel faults. Two main groups of veins are the veins associated with folds and thrust that is mainly shear veins and associate discordant veins and those associated with faulting as reactivated shear vein and other types of extension veins.

5.6.2 Different style of quartz veining

Two systems of quartz veining can be observed such as shear veins with associated extension veins and extensional veins related to fault. The latter is a different term from extensional fault which commonly related to basin development and normal fault. Fault controlled veins also include reactivated bedding parallel shear veins by fault such as along the Penjom Thrust and shearing along carbonaceous shale close to this fault.

Based on the structural control of the vein system, the main setting of the quartz veins hosted mineralization are mainly developed during the fold, thrust and parallel fault activity. The movement of thrust has reactivated several series of bedding slip fault along the massive and thin carbonaceous shale before the faulting has further reactivate and channeling the auriferous fluid into the vein structures.
The movement of the bedding slip fault and other fault subsequently followed with the quartz veining referred as shear vein and within the extensional site referred as extension vein.

Veins have become the main subject of discussion related to mineralization and deformation as early as in first geological modeling at PGM. Corbett (1997) describes vein as laminated to ribbon quartz characterize the NS corridor and Fillis (2000) redefined this vein as bedding parallel vein. Endut (2004, Internal memorandum), Endut and Teh (2010) propose that bedding parallel vein was developed during the folding and thrusting and not during extensional faulting. Davis (2005a) recognized this style of veins and confirmed the D2 structural deformation for this event.

Different stylolitic features and texture suggested bedding parallel shear veins along the thrust and refolded western limb have been reactivated as a result of ongoing deformation.

5.6.3 Thrust and fold (D2) related veins

Shear veins were formed as a result of shear opening of the structure including bedding and carbonaceous layers and intermittent veins deposition. They were formed under high differential stress and a local compressional environment. Two geological features that host this vein are exclusively along the Penjom Thrust zone and bedding-parallel shear. The shear veins continue across the felsite dyke. Several types of extension veins are associated with these shear veins, including sheeted extension veins, breccias and stockworks. Breccias and stockworks can be observed within the same ore body.
5.6.3.1 Penjom Thrust shear vein

The Penjom Thrust was reactivated along the eastern limb of the Kalampong anticline, in particular, along a thick carbonaceous shale unit which may already hosted earlier bedding-parallel veins (Figures 5.25a and 5.25b) and formed shear vein type 1 (Table 5.3). This is a common feature where a reverse fault is rooted along the bedding plane. Reactivation by the thrust has further created new textures in the form of ribbon, breccias, boudinage, fold and shear. Furthermore, the vein infills the shear fabric with a thickness of individual vein up to 10 cm but at very close spacing of less than 10 cm and formed a discontinuous pinch and swell veins structures. The Penjom Thrust ore zone can be divided into two areas with respect to its location within the fold axis or the limb of the Kalampong anticline as follows:

- **Within fold axis**

  The style of folding around the main fold axis at the southern half of KE is a tight recumbent fold, in the northern area as an open fold (Figure. 5.26). Saddle reef type or style of gold mineralisation is present in the fold nose of the dominant carbonaceous unit above the felsic intrusive body and extends as quartz stockwork or irregular veins inside the intrusive close to its contacts. At greater vertical depths within the fold, the veins become narrower at the intrusive–shear vein contact and are less developed in the intrusive. Veins are massive at the fold nose with ribbon textures at the veins margin indicating repeated opening of the structures and introduction of fluid into the local low mean stress area normally above the rigid competent unit such as an intrusive (felsic) body.

- **Within fold limb**

  This is a deeper Penjom Thrust ore zone parallel to the eastern limb and forms linear ore bodies made up of veins from massive shear-parallel veins to narrow ribbon quartz veins. The main mineralised area is observed when there is an embedded small scale
intrusive body enveloping massive carbonaceous shale that increases the physical and chemical contrast. Veins in this area are variably deformed because of the reactivation of the late NS trending sinistral to normal faults along the thrust. This reactivation was also responsible for the thinning of carbonaceous material at certain segments and the localisation of ore zones along the thrust.

Figure 5.25: (a) Penjom Thrust ore zone trending NNE and subparallel to bedding. (b) Close up of area ‘A’ shows a laminated to ribbon quartz. (c) Another bedding parallel vein below the thrust ore zone (after further digging of area ‘B’ in photo ‘a’). (d) Ore zone comprised of shear veins (black zone), cross cutting through intrusive rock (ITN). (e) Q2W shear veins as shown by slivers of host rock in sheared intrusive. Blocky intrusive on the right side lack quartz veining.
Figure 5.26: Looking mine north (35° from true north), cross section at 50100 at the center of Kalampong Pit, shows structural framework of shear veins (Q1W, Q2W and Q3W) in the fold setting of the Kalampong Anticline. Inset figure is an evolution of the folding.

5.6.3.2 Bedding-parallel shear veins

This type refers to quartz veins infill along carbonaceous shale units and represents an active bedding plane-slip fault or flexural-slip fault with an intermittent deposition of shear vein type 2 (Table 5.3). This process occurred during fold activity to form a ribbon or lamination texture. Recrystallization of quartz occurs along the shear plane where a band of fine quartz grains represented an active plane (Davis and Hippert, 1998). Remnants of the carbonaceous layer represent multistage opening of the structure through an episodic opening during fluctuation of stress and fault-valve behaviour (Cox et al., 2001; Sibson, 2001). This type of vein is structurally classified as shear vein (Hodgson, 1989). The presence of slip lineations, slickensided and lamination surfaces are attributed to shear opening of the veins during the folding process. The fault striations commonly show
reverse movement, indicating flexural slip during folding. As shown in Figure 5.26, there are at least five bedding-parallel shear veins identified within the Kalampong pit. Two are along the eastern limb and three within the western limb sequences. This bedding shear vein cut across the felsite unit with remnant carbonaceous material Figures 5.25d and 5.25e and that the term bedding parallel shear vein in felsite unit can be confusing if overall understanding and genetic of the structure is not properly understood.

These veins, in particular, are very important as they host a majority of high-grade ores in Penjom gold mine, particularly gravity recoverable gold. Ribbon quartz which is a part of a shear vein was previously recognised as high-grade veins (Corbett, 1997; Endut and Teh, 2010) and forms the NS trending mineralisation. However, certain segments of the same vein, particularly on the limb and away from the intrusive body, are very low in gold content. Field observation shows that high-grade laminated veins can be observed close to or at the contact with the intrusive, along the fold axis and the Penjom Thrust. Thus, chemical and physical conditions of ore fluids, interactions with host rock and structural control play important roles in controlling gold precipitation.

Three different morphologies of veins are recognised as follows:

- **Planar laminated (<20 cm)**

  Planar, thin (<3 mm) graphitic or carbonaceous material of irregular thickness comprise the lamination within these veins. Laminations can be at different angles to an earlier veins-wall-parallel lamination. Q2W and Q3W (Figure. 5.27) are fine examples of these veins and as a narrow shear vein (<20cm) associated with a zone of discordant extension vein. Q3W has significant carbonate (mainly calcite as analysed by XRD) as well as galena and sphalerite either along the lamination or within the buck or thicker segment of the veins. Host rock comprises very thin carbonaceous shale and siltstone units interbedded with a
sandstone unit. Carbonaceous material could also have been leached out and become lighter colour.

- Roughly laminated (ribbon texture)

This is a common bedding-parallel vein in dominant or thicker carbonaceous shale interbedded with minor sandstone units. It is also referred to as ribbon quartz. The graphitic layer that forms the ribbon varies in thickness and is irregular and undulating in nature as the upper part of the vein (Figure. 5.27a). Furthermore, this vein is commonly associated with different forms of stylolite, either the planar or wavy type. It is roughly laminated as a result of continuous deformation and in many places it is associated with vein breccias.

- Massive bedding-parallel quartz (>20 cm)

This form of thick quartz occurs parallel to bedding and localised at the intersection with dominant felsic rocks and at the fold axis. Host rock remnants within these veins occur similar to the case of vein types 1 and 2 with a few stylolites at the vein margin. The upper part of the shear vein is comprised of thicker vein with massive appearance or quartz dominated. In the other parts, massive quartz can be brecciated, form a gradual boundary with the host rock or become veins stockwork. Quartz grains within the thicker and massive portion are typically coarse with variable size and exhibit a buck texture.

- Foliation-/cleavage-parallel veins

This is a minor type of vein and is commonly associated with bedding-parallel shear veins. This vein type is hosted in sandy silt to shale units, forms a laminated texture and is parallel to the main shear vein. This vein is thought to fill a weak plane along the foliation or bedding-parallel cleavage as the shear vein developed. The overall thickness of such veins is less than 5 cm at a very close spacing of 1 mm. These veins were formed by the
crack-seal mechanism in which the vein grew in thickness by the reopening of wall rock and progressive deposition of minerals.

5.6.3.3 Sheeted extension veins

Different styles of extension veins reflect the structural control and physical properties of the host rock during vein formation. These veins were formed by extensional filling particularly for extension vein array or sheeted and quartz stockwork. Vein direction is broadly East–West parallel to maximum compressive stress, vertical to sub vertical and either formed an individual zone or dangling below bedding-parallel shears (Figures. 5.25c, 5.27b and 5.27c).

Minor vugs and comb textures are locally observed in this vein type. Many of these veins can occur together in one zone and are usually controlled by movement of shear veins or faults that produce different extension veins type in different lithological units. The different styles of extension veins are described as follows:

A) High angle EW extensional veins array

Zones of extension veins type 1 (Table 5.3) can be up to 15m wide at a vein spacing of up to 1 m. Individual vein thickness can be up to 8 cm. This set of veins is only weakly mineralised, and based on a 3 m sampling for ore mining, commonly returns grade values less than 0.5g/t. The main reason to classify this vein as formed during similar compressive event is the EW direction parallel to the maximum compressive stress. Quartz is the main vein component with rare carbonate. This style of vein can be observed locally along the fold axis within the competent lower mine sequences of either massive siltstone or thick conglomerate.
Figure 5.27: (a) Roughly laminated veins in carbonaceous shale unit with more planar laminations inside the veins. This shear vein type 2 in Table 1 was formed through shear induced lamination. (b) E-W extension vein array type 2 or planar sheeted vein developed at θ equals to 90° below the main shear vein (red dash line), looking south and at level 840mRL. (c) A series of E-W striking sheeted veins (extension vein array type 2) exposed after the excavation of the main shear veins (looking east, at level 834mRL). (d) Equal area, lower-hemisphere stereographic projection showing the average dip and dip-direction and pole to vein.

B) Moderate angle EW extensional vein array

This vein array is mainly characterised by a moderate to steeply dipping, sheeted parallel vein set aligned EW. The veins in the array are sub-vertical to the bedding and commonly below the bedding-parallel shear veins (Figure 5.27b). The occurrences and intensity of extension veins are very important to represent the thickness of the overall ore body below the main and higher grade shear quartz veins. There are two lithological
settings of this extensional vein array occurring in Kalampong pit: hosted either in a stiffer sedimentary unit below thin carbonaceous-hosted shear vein or brittle intrusive host rock.

In both lithologies, vein orientation is parallel to maximum compressive stress and axes of incremental shortening (dZ) or perpendicular to the elongation (dX) as a result of shortening (Robert and Poulsen, 2001). The veins extend from the sediment into the intrusive rock with no change in orientation indicating similar direction of stress acting on both host rocks and that the intrusive event predates the deformation giving rise to the vein set.

- In a harder rock unit (sediment) below shear veins (D2 event)

This extension vein type 2 (Table 5.3) is the main source of ore, in particular, for the less carbonaceous host rocks. Sheeted veins occur as extensional veins below a laminated vein and trend sub vertical to a bedding-plane-slip fault (Figures 5.27b and 5.27c). Widths can be up to 20 cm at a spacing of 5 cm to 2 m with bulk gold grade varying from low to high. No quartz occurs above laminated veins unless in between two bedding-slip faults; this suggests a coeval relationship between these two types of veins.

- In brittle host rock (intrusive)

The felsite unit within the ore body hosts this extension vein type 3 (Table 5.3) similar to the case of the harder rock unit. These veins extend from the sediment and into the felsic rock in almost a similar direction; however, the veins developed in the felsite unit can be more intense (Figure 5.28). Thickness of the veins can be up to 15 cm, and the veins predominantly comprise more quartz than carbonate. Furthermore, the EW striking veins are a dominant set compared to the other direction.
5.6.3.4 Quartz breccias

Quartz breccias are defined as a body of quartz vein in which country rock fragments exceed the vein volume. It can be divided into two categories: hydrothermal quartz breccias which normally form in dilatants zones along bedding-slip faults and fault breccias which form as a result of shear movement and are part of the shear veins. Movement of two closely spaced bedding-slip shear veins at a competency contrast unit or near a fold axis provides space for the development of hydrothermal breccias, particularly in the competent felsic unit (Figure. 5.29a). Vein also developed in the sedimentary rock around the boundary forming a localised jog along relatively narrow shear vein. The hydraulic fracturing mechanism is involved during the formation of brecciated veins due to high fluid pressure and fluid volume (Cox et al., 1991).

5.6.3.5 Quartz stockworks

Quartz stockworks (extension vein type 4- Table 5.3) are associated with shear veins and are described as a network of more than two set of veins that commonly occur in competent units such as felsite. The individual veins can be up to 10 cm thick. This vein type is mainly formed in the localised felsic sill within the eastern limb shear vein or along Penjom Thrust ore zone forming linear ore shoot, whereas at other places, it is more localised along the interception with bedding-parallel shear veins.

5.6.4 Fault (D3) related veins

Faulting events that are active after fold lock-up are not observed as hosting the laminated or ribbon vein. The fault is occasionally infilled with very thin quartz with a thickness of less than 3 cm and does not make up a significant ore zone. This fault system generates
either sheeted, brecciated or stockwork extension veins at the interception with brittle units such as the felsic rocks and dominantly in the felsite unit and to a lesser extent in other rock types. This constitutes felsite-hosted ore body which has a good grade near the fault plane. Furthermore, the intensity of the veins is important to form higher grade ore.

5.6.4.1 Sheeted extension veins

A) Sub-vertical sheeted veins

Sub-vertical veins in brittle host rocks, commonly felsic bodies, are formed at the contact with a fault. Parallel sheeted veins (planar extension vein array) with an individual thickness of less than 10 cm occur perpendicular to the fault and the fold axis, striking from 90° to 120°. Vein intensity also increases in the narrow felsic rock (Figure. 5.28b) compared with surrounding host rock. As a result, the trend of economic mineralisation at several places follows the shape of this intrusive rock. Several other vein directions associated with the vertical set; however, the vertical set is commonly much more dominant over other directions.

Figure 5.30a shows stereonet plots of EW sheeted veins at three different localities. Overall orientations of bedding and sheeted veins are in Figures 5.30b and 5.30c respectively. Strike direction of the veins is normally parallel to the main compression force (Robert and Poulsen, 2001, Figure 5.31 left) acting in the EW direction. Figure 5.31 (Right) shows the example of the vein in the felsite unit at fault interception in which the EW direction is dominant over other directions at a ratio of 30:1.

B) Low-angle sheeted extension veins

Low-angle sheeted extension veins Type 3 (Table 5.03) with a maximum thickness of 10 cm perpendicular to the wall occur in sub-vertical narrow felsic intrusives of less than 5
m to 8 m width (Figure. 5.28a). In Kalampong East pit bottom, felsic dyke near the fold axis is cross cut by a series of NNE trending fault. Deformation induced by the faulting; but, the trend of parallel fractures with the veins infilled may have been controlled by the wall contact that produced flat, dipping veins perpendicular to the felsite contact. Within the intrusive near the shear or fault plane, veins grade into stockworks (Figure. 5.28c). Transition to other forms can be observed as shown in the same Figure 5.28a and Figure 5.29. This type is locally observed along the western limb of the felsic dyke that extends toward the fold axis, particularly where there is a cross-cutting NNE trending fault or shear veins.

5.6.4.2 Quartz breccias

Quartz breccias were formed within the narrow felsite bounded by two faults. The occurrence is similar to the shear vein of D2 fold-related hydrothermal quartz breccias; however, this vein is exclusively hosted within the felsite intrusive along the fault contact and rarely extends outside the felsite into sedimentary rocks. Fault breccias is defined in cases where the wall rock fragments exhibit evidence of rotation and are dominant with respect to quartz fragments. However, it can be quite common, that further inside the zone, the quartz becomes dominant over the wall rock fragments in which case it is referred to as hydrothermal quartz breccias. Overall, both hydrothermal quartz breccias and fault breccias exist within the same ore zone.
Figure 5.28: (a) Dominant low angle extension veins Type 3 in felsite dyke perpendicular to contact, bedding and fault. Location: north of KE pit; Spacing: from 5 to 50cm; Thickness: from 1 to 10cm. (b) Dominant vertical E-W extension veins Type 1 across the bedding and felsite intrusive at Jalis West Wall. Spacing: from 5 to 50cm; Thickness: from 1 to 20cm. vein intensity increases in intrusive. (c) Dash line represent west dipping shear plan across felsite. 1-vein stockwork near shear plane (D2 deformation), 2-vein infilling parallel fracture resulted to low angle vein array, 3-less vein away from the shearing. (d) Vein across the lithology contact.
Figure 5.29: (a) Stockwork (ST) veins (extension vein Type 4) in intrusive rock below North-South trending West dipping shear veins (red line) and hydrothermal breccias (HB) in between two shear veins in intrusive and siltstone. (b) Fractures cleavage (S3) locally developed below NNE D3 fault affected the D2 shear vein. (c) Normal D5 fault (green line) displaces flat dipping along synform axis D2 shear vein.

5.6.4.3 Quartz stockwork

A faulting event also generates quartz stockworks mainly in felsite units at fault intersection. At several places, a dominance NNE reverse-dextral fault generates multi directional set of vein directions.
5.6.5 Structural explanation of veins formation

Most of the quartz veining in the Penjom gold mine occurs within the sequences of thick or thinly bedded carbonaceous shale and occur as several bodies of low to high-grade veins along, below or between active bedding-plane-slip faults. Fault-generated veins mostly occur at the intersection with intrusive rocks.

The overall shape of the Kalampong Fold can be explained as an antiform–synform couple in the foot wall of the Penjom Thrust. Parallel to the main thrust are several series of NNE faults including the Jalis Reverse Fault southwest of the Kalampong pit. Bedding-parallel shear veins and associated vein stockwork and sheeted veins are mainly hosted in the middle mine sequence and at the boundary of the middle–lower sequence. This boundary is characterised by thin to thick layers of carbonaceous shale which normally become the site of type 1 and type 2 laminated veins. Structural control of these veins is comparable with other bedding-parallel veins particularly in fold- and thrust dominated areas elsewhere in the world such as at Bendigo (Schaubs and Wilson, 2002) and Meguma Terrane (Mawer, 1997), as summarised in Table 9.2. The Bendigo area exhibits a superimposed reactivation by faulting, after the fold has locked up as a consequence of the folding process. The shear vein can further be described as being similar to the backbone structure of Cox et al. (2001) and the discordant extensional vein as the dead end or a dangling extensional vein. Additionally, the high-grade shear vein hosts abundant early sulphide mineralisation including pyrite and arsenopyrite with or without a base metal.

Structural classification of veins provides an indication of the manner in which the veins were formed and their relationship to mine-scale structural deformation. The relative chronology of the structures and vein formations is characterised by initial development of thrusts and folds (D2) and later development of reversed faults (D3) after the folds have become locked up. Continuous movement resulted in dextral strike slip on several D3 faults
including splay faults and NNE faults. Sinistral strike-slip movement and normal to oblique-normal fault reactivation of NS faults is interpreted from fault striations.

Interpretations of structural control indicate that the various vein arrays were mainly developed during folding and thrusting (D2). The movement of the thrust fault has reactivated several series of bedding-plane-slip faults along the massive and thin carbonaceous shale forming the type 1 and associated type 2 veins. Reactivation of faulting during D3 deformation continues to channel auriferous fluids into the vein structures following fold lock up forming only type 2 veins. In summary, two structural settings of vein formation can be discussed such as fold- and thrust-related D2 and later phase faulting D3 events.

5.6.5.1 Fold- and thrust-related veins (D2)

The Penjom Thrust and associated Kalampong Fold are responsible for bedding-slip activity throughout the Penjom pit particularly along the carbonaceous unit. Quartz veining that subsequently follow the movements of the bedding-plane-slip faults and other faults is referred to as a shear vein type (same category as fault fill vein, Robert and Poulsen, 2008), whereas within the extensional site, it is referred to as an extension vein type. Sheeted extension veins, stockworks and breccias associated with bedding-parallel shear vein (Table 5.3) are also considered fold-related veins.

Veins were formed during repeated opening of the structures particularly along bedding-plane-slip faults (D2) which produced lamination and ribbon texture in the veins. The western limb ore zone is the main area for these types of veins and is the main ore zone mainly during earlier pit development. On the veins surface, slickenline or fault striation is commonly observed and this is indicative of continuous deformation particularly flexural-slip movement.
The fold related veins system forms several ore zones, whereas the intensity and grade are controlled by several other factors such as fold geometry, either on the limbs or around the fold axis. High-grade veins occur at the fold nose above the intrusive rock. On the limb, mineralisation is still very good at the contact of bedding-parallel shear veins and felsic intrusives. The shear veins become narrower on the far limb, and veins associated with brittle fracturing due to faulting, such as extension veins array or sheeted veins within small intrusives, become more dominant.

5.6.5.2 Fault-related veins (D3)

Except for the Penjom Thrust, structures including reverse, oblique-reverse or dextral strike-slip faults which control the second stage of vein development are classified as D3 deformation. These faults are mainly NNE trending reverse to dextral strike-slip faults (Figure. 5.18) which occurred during the late stage of folding after the fold had locked up. Locally, fracture cleavages are well developed below this fault and disrupt the early high-grade shear veins of the D2 deformation (Figure. 5.29b). NNW fault controlled significant mineralisation at the west-dipping sequence in the west wall of the Jalis corridor marks the reactivation of a fault sub parallel to the western flank of the synform. This fault is probably a splay or conjugate fault to the main NNE fault.

Faults trending dominantly NS (Figure. 5.21) as recognised above the hanging wall of Penjom Thrust are diffracted, cut across or reactivated along the thrust. Based on a slickenline direction observed on few faults, these faults exhibited sinistral strike-slip movement but on the other faults, normal to oblique-normal movements are dominantly exhibited. These faults are locally associated with calcite veins mainly on the hanging wall. Reactivation of these structures resulted in the deformation and displacement of earlier formed quartz veins; however, no economic mineralised veins are associated with these
structures. A normal fault that separates the eastern and western limbs of the fold is an exception; it occurs as a splay from the Penjom Thrust and is considered as an accommodation of the folding process.

As in the case with fold-related veins, fault-related veins are also classified as shear or extension veins. Faults that are not parallel or sub-parallel to bedding or within the lower mine sequence were not observed to host laminated or ribbon shear veins. This characterises the brittle movement of this fault as a late stage event after the fold had locked up and also indicates that this structure is a brittle event related to fault valve behaviour (Sibson, 2001). The types of vein included in this structural event are quartz breccias and sheeted vein as either low to steeply dipping veins. Veins are best developed at the contacts inside intrusives near this fault.

A) North-northeast (NNE) fault-related veins

The NNE parallel fault is a secondary structure which overprints the Penjom Thrust and its associated folding and was active after the fold was locked up. It is more prominent along the western limb of the open fold and the tight inclined fold that is discordant to bedding at the intercept with an intrusive body. This structure might also reactivate the earlier fold related structures.

Veins associated with this fault are usually flat dipping extension veins in a narrow felsite intrusive body but are always discordant to the wall, massive, stockwork, brecciated veins and irregular vein arrays mostly at contacts or close to intrusive rocks. The overall grades of the veins are usually lower compared with those of the bedding- or shear-parallel ribbon quartz but can form larger zones with erratic grades especially in the more competent rocks. However, patchy high-grade veins can be locally observed close to the intersection of faults and intrusives; at such sites, galena and pyrite are also developed.
Figure 5.30: Lower hemisphere equal-area of sheeted veins orientation (poles plot of dip direction and dip) shows dominant steeply north dipping extension veins discordant to bedding from three areas. (b) Overall lower hemisphere equal-area of bedding orientation (poles plot of dip direction and dip, n = 1187), (c) Vein (poles plot of dip direction and dip, n = 797), 0.5% interval.

Figure 5.31: (Left) Stress field diagram shows relationship of extensional fractures perpendicular to maximum compressive stress. (Right) Dominance E-W sheeted extension vein Type 2 in felsite unit at fault intercept. Looking east at east wall.
B) North–northwest (NNW) fault-related veins

NNW trending faults oriented sub parallel to the bedding host high and low-grade gold-mineralised extension and shear veins parallel to bedding and shearing in the Jalis corridor. Shear veins occur within carbonaceous shale in the middle mine sequence and commonly yield higher gold grades compared with other vein types. Bedding-parallel veins with ribbon texture within this zone may have already been developed during fold-related bedding-plane-slip before the reactivation of NNW faults that generated more veins within this zone. This is particularly the case around competent intrusive bodies mainly at sites of low stress such as dilational jogs between two NNW faults.

5.6.6 Role of competence contrast

Several vein hosted gold deposits are hosted in extension veins in competent units such as dyke-like felsic intrusives at the St. Ives goldfield (Sibson, 2001). Competency contrast refers to different rock properties where strong brittle or competent units are juxtaposed with weaker units such as carbonaceous-rich host rock or shear zones. Maximum compressive stress is normally perpendicular to the weak plane, and strain partition results in a fracture array parallel to the shortening direction.

Frictional drag along the contact reduces the minimum principal stress in the competent unit (Sibson, 2001). This results in an increase in hydraulic pressure in the brittle unit causing shear failure especially in narrow competent units embedded in less competent rock. Veins are commonly formed as narrow veins within the shear failure zone but can be intensive in the narrow embedded competent unit in the form of extensional veins such as breccias, stockwork or sheeted veins. In Penjom gold mine, shear veins within the mineralised ore body at many places contain higher gold grades than in extension veins.
indicating shear failure and pressure drop play a significant role in concentrating gold bearing solutions and creating favourable sites for deposition.

Figure 5.32: (a) Crenulated extension veins as a result of the ongoing deformation that also produced the cleavage at high angle to veins. (b) Late vein stringers across gold network within brecciated calcite vein. (c) Ribbon quartz from the side view with gold along vein margin. (d) Laminated veins with sign of fault striations affecting the gold itself on the vein margin.
Figure 5.33: Location of Jalis NNW Fault Zone sub-parallel to carbonaceous shale (looking north). Red line is an outline of the shear vein within and outside the fault zone. Economic mineralization (ore body) localised at intercept with dominant felsic host rock.

In contrast to the above condition, mineralised veins mainly occur in the weaker zone at contact with massive competent units, such as the bigger intrusive rock, massive conglomerate or thick silicified rock. These units behave like rigid bodies, providing resistance to stress, and contain only minor vein networks around the contact. The weaker zones are deformed and provide more space or dilational sites for mineralised veins. A fold hinge or saddle reef style ore body above the massive felsic rock are the main examples of this ore body.

5.7 Relative roles of fold and fault on quartz veining

Structurally controlled veins exhibit varying degrees of deformation. It is important to distinguish primary textures of initial vein formation from textures developed by secondary processes or post-vein deformation. Several features of post-vein deformation can be observed at Penjom such as folding of veins, vein margin striations, breccias, internal deformational fabrics such as stylolites and various micro-scale structures. EW extension veins were buckled (Figure. 5.32a) along the cleavage development as a result of on-going
compressional deformation parallel to \( \sigma_1 \). Even the gold itself is striated along the shear margin (Figures 5.32c and 5.32d), indicative of very late stage reactivation along the shear vein margin. Veinlets crosscut the gold streak (Figure. 5.32b) indicating the vein formation outlast the gold mineralization event.

In the KE pit, the presence of bedding-parallel veins in both the eastern and western limbs of the Kalampong anticline and the western flank of the Kalampong synform suggest that they were formed during the folding process. Ore zones in thick carbon-rich (>1.0% C based on 3 m sampling) units occur in both the eastern and western limbs although veins close to intrusive rocks are more mineralised. This indicates the additional influence of the rheological and chemical contrast provided by country rocks in controlling the development of gold mineralisation. Penjom Thrust hosted veins in carbon-rich host rocks are highly deformed as a result of the reactivation compared to the less deformed primary shear veins in carbonaceous rocks of the western limb. This highlights the post-vein deformation that occurred along the eastern ore zone.

Reverse and dextral strike-slip faults belonging to the deformation phase D3 followed by D4 and D5 deformation of sinistral and normal faults displace bedding-parallel quartz veins. However, intense extensional quartz veining has been observed at the contact between intrusives and sediments near the NNE reverse/dextral faults (e.g. R1 and R2 faults, Figure 5.18). These observations suggest that reverse faulting occurred during late stage compression after the development of bedding-parallel veins but subsequently still reactivated and channelled the mineralised fluid. NS sinistral and normal faulting (D4 and D5) were observed to not commonly generate quartz veining in intrusives and sediments compared to the bedding-slip, NNW and NNE faults.

These important roles in controlling the vein system provide evidence for interpreting bedding-parallel shear veins associated with fold and thrust, and later faults
including NNE and NNW (Figure 5.33) faults are a continuous event that controls gold mineralisation. In contrast, sinistral and normal to oblique-normal faults including Hill 6 NS Fault and Jalis NS Fault occurred at a very late stage, displacing earlier veins (Figure 5.29c) and occurring after the mineralising episode but may also have been responsible for at least some remobilisation of gold.

5.8 Conclusions

Gold mineralisation at the Penjom gold mine is hosted within quartz-carbonate veins that display varying degrees of overprinting events developed during episodic failure in ductile–brittle environment. The two main types of vein identified are shear and extension veins. The dominant shear veins in Penjom gold mine are either bedding-parallel or fault-hosted sub parallel to bedding such as the Penjom Thrust ore zone. Associated with these dominant shear veins are extension vein arrays such as sheeted discordant extension veins, stockworks, irregular veins and brecciated veins. This group of veins was formed during folding and thrusting. Other vein systems were developed during the later stages of deformation and may represent reactivation of the earlier formed shear veins. Later fault movements, particularly reactivation of sinistral to normal mainly those extending from the hanging wall faults, disrupt a majority of both quartz veins and gold mineralisation.
<table>
<thead>
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<th>Veins</th>
<th>Morphology or Type</th>
<th>Lithology site</th>
<th>Reactivation by later fault/process</th>
<th>Type</th>
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<td>Ribbon, roughly laminated, massive Planar to roughly laminated</td>
<td>Carbonaceous shale</td>
<td>Parallel reactivation resulted to fault/shear fill vein</td>
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<td>Thin carbonaceous shale</td>
<td>No parallel reactivation</td>
<td>Shear vein Type 2</td>
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<td>Carbonaceous shale at felsites contact or cross cutting</td>
<td>No parallel reactivation</td>
<td>Shear vein Type 2</td>
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<tr>
<td></td>
<td>Vein septa/book texture, (Hodgson, 1989)</td>
<td>Siltstone below shear vein</td>
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<td>Associated with Type 1 and 2</td>
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<td>At or near fault contact</td>
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<td>Stockwork Multi directional</td>
<td>Mostly in felsites rock</td>
<td>Fracture induce by shear vein or fault</td>
<td>Extension vein Type 4</td>
</tr>
<tr>
<td></td>
<td>Hydrothermal breccias Non rotated angular wall rock fragment</td>
<td>All rock except massive conglomerate</td>
<td>At intercept of shear vein/fault with rheological contrast unit</td>
<td>Associated with shear vein type 1, 2 and other faults</td>
</tr>
</tbody>
</table>