Structural analysis and vein episode of the Penjom Gold Deposit, Malaysia: Implications for gold mineralisation and tectonic history in the Central Belt of Malaysia

Zakaria Endut *, T.H. Ng, Jasmi Hafiz Abdul Aziz, G.H. Teh

Department of Geology, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia

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A B S T R A C T

Gold mineralisation at the Penjom Gold Deposit, in the Central Belt of Peninsular Malaysia is dominantly hosted in structurally controlled quartz-carbonate veins that display a variable degree of overprinting events under a ductile–brittle regime. Mineralised veins are categorised into two main episodes: fold and thrust-related veins mainly comprised of bedding and Penjom Thrust parallel shear veins and associated extension veins developed during a D2 event. In addition, NE to NNE trending splays and Penjom-Thrust-parallel reverse–dextral and locally NNW to NS reverse-sinistral faults overprint earlier vein events forming a new episode of extensional veins during D3 event, mostly at the fault contacts of intrusives either as shallow-dipping or vertical sheeted, stockwork or brecciated veins. At least two episodes of faulting D4–D5 are evident which postdates the main episodes of veining and mineralisation. This is indicated by a series of late episodes NS trending sinistral and oblique to normal faults which transect and displace the Penjom Thrust and the folded footwall sequence at low angles and responsible for intensive vein deformation along the Penjom Thrust and displacement of ore body. Structural interpretations of mineralised veins suggest that the veins were formed under a compressional to transpressional regime with later post-vein displacement in a transtensional to extensional regime. Vein formation in response to deformation observed at Penjom reflects regional structural deformation within the Central Belt of Peninsular Malaysia and specifically along the Bentong–Raub Suture zone.

1. Introduction

The Penjom gold mine (Penjom) is located 10 km south of Kuala Lipis town, Pahang State, Peninsular Malaysia. The current operation commenced in December 1996 and was operated by Avocet Mining PLC, before the company was taken over by the current operators, publicly listed mining company PT J Resources. The company acquired Penjom through intermediary PT J Resources Nusantara along with several assets in Indonesia from UK-based Avocet Mining PLC in 2011. These assets were placed directly under J Resources control early in 2012. Gold mineralisation at Penjom exhibits many characteristics of orogenic gold deposit (Groves et al., 1998) and dominantly hosted in structurally controlled veins that display a variable degree of overprinting events under a ductile–brittle regime along anticline–syncline below the Penjom Thrust. Gold is hosted within a quartz-carbonate vein with a sulphide content of less than 3–4%; a high gold to silver ratio of approximately 8.5:1 (Sonny et al., 2001; Abdul Aziz, 2007). The main objective of this study is to classify the different types of veins present at Penjom, their structural attributes and setting. Terms used for vein types are based on Hodgson (1989), Robert and Poulsen (2001) and Ramsay and Huber (1983). The type and texture of veins on hand specimen at Penjom based on Dowling and Morrison (1998) are similar to those observed in orogenic gold deposits that formed in terrains subjected to compressional or transpressional events involving folding, thrusting, reverse and strike-slip faulting.

This paper compiled the work from field measurement including pit wall mapping, mapping of ore mining face, observations during ore mining processes and limited diamond core from in-pit exploration drilling since 1997 during the working period of the first author as mine geologist at Penjom. The main observations focus on morphology or texture and mesoscopic aspects such as orientation and form. These descriptive aspects have been correlated to the process of vein formation and overall structural timing and control, which is the basis for classification of vein in this study.

2. Mining history

During the 19th and 20th centuries prior to 1990, mining activity at the Penjom Gold Deposit (Penjom) was intermittent and restricted to exploiting oxide ore and alluvial deposits with minor underground production. No production record on old alluvial and underground mining is available. A review of the economic potential of gold by the Pahang State Government in early 1990 led to major exploration work which
culminated in the development of Penjom as the first large-scale gold mining operation in Peninsular Malaysia.

Production commenced in December 1996 and for one year exploiting an oxidised ore from higher elevation site (Manik and Kalampong West) approximately up to 80 m above river base datum. The past activity did not leave much tailing material and during the starting of mining operation, only small amount of tailing from old working was mined. Fresh rock below the river datum gave an ultimate challenge to Penjom production where highly carbonaceous ore body (>0.6% C) has become the main type of ore. After nearly two years, more competent rock and felsite hosted vein were exposed and this gave less carbonaceous material and resulted to better plant processing recovery. A total production of 1 Moz by 2007 has made Penjom the largest gold producer in Peninsular Malaysia. By the end of 2013, Penjom has produced approximately 1.4 Moz and remaining resources (measured and indicated) are 21 Mt @ 1.63 g/t or 1.2 Moz (J Resources website 2014). The main Kalampong pit contributed 87% (tonnes) and 91% (ounces) of the total gold produced compare to Manik pit.

The rise of gold price in 2007 has allowed other miners of small-scale hard rock and alluvial gold operations along the belt to venture into hard rock and larger scale primary gold mining as well as generated a new interest in understanding the geological settings and controls of the gold deposits.

3. Geological setting

3.1. Regional setting

The geological terrain known as the Central Belt of Peninsular Malaysia is characterised by numerous vein-hosted gold deposits particularly within a 50 km wide corridor on the east side of the Bentong–Raub Suture, a major transcrustal lineament. The Penjom gold mine lies 30 km east of this suture in the Kuala Lipis district of Pahang State within the Central Belt of Peninsular Malaysia (Fig. 1B). Regional structures delineated on radar satellite images show that Penjom is located on a NNE trending splay from the main Bentong–Raub Suture (Fig. 1A) (Kidd and Zainuddin, 2000). Shuib (2009) describes a series of NNE to NS trending strike ridge lineaments within these zones. These lineaments cover a narrow zone to the south but a much wider zone to the north. Gold deposits located within this zone include Raub, Tersang and Selinsing gold mines close to the Bentong–Raub Suture whereas Kechau Tui and Penjom are close to the eastern NNE spays (Fig. 1A). Located further north towards Kelantan and the Thailand border is Batu Melintang (location ‘A’ in Fig. 1B), Katok Batu and several small-scale primary gold deposits (Goh et al., 2006; Pereira, 1996). All these vein-hosted gold deposits east of Bentong–Raub Suture are classified as orogenic gold deposits (Groves et al., 1998). These veins hosted deposits are grouped under the collective term, Zone 2 (Pereira, 1996).

Subduction and collisional models within the margin of the Sibumasu and East Malaya Terranes (Sukhotai Arc; Sone and Metcalfe, 2008) during Early to Late Triassic times along the Bentong–Raub Suture have been proposed by many researchers such as Metcalfe (2000, 2013). The model explains the change of faunal affinities from a Gondwana assembly prior to Early Permian to an independent Sibumasu Province that merges into Cathaysian affinities during the Permo-Triassic orogenic event. 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, 2000, 2013). The East

Fig. 1. (A) Map shows the Bentong–Raub Suture (continuous line on the left) and NNE splay (dashed line on the right). Several primary mesothermal gold deposits are located in between these structures. 1—Penjom, 2—Raub, 3—Tersang, 4—Selinsing and Buffalo Reef, 5—Damar West, 6—Kechau Tui, 7—Sungai Teris (alluvial). (B) Map shows Peninsular Malaysia and location of gold deposits. (A—Batu Melintang). (C) Geological map of Penjom Gold Mine.
Malaya volcano-plutonic arc or island arcs with I and S-type granitoids were developed as a result of subduction along the western side of the Indochina–Eastern Malaya terrain. U–Pb zircon ages from the Eastern Belt Granitoids range from Middle Permian to Early–Late Triassic (Searle et al., 2012). Continuous sedimentation which occurs during this period is represented by the Permian Gu Musang and Triassic Semantan formations within the forearc basin (Hutchison, 2007). Kuroko type sulphide occurrence or submarine exhalative such as Tasik Chini (Yeap, 1993), base metal deposit including Galena and Monson’s Lode of Ulu Sokor, and Mengapor (porphyry copper Au skarn) were classified as volcanic arc-related mineralisation (Hutchison, 2009) occurring in the eastern side of the Central Belt. This early episode of exhalative gold mineralisation could be important for enrichment during later deformation and metamorphism.

The Main Range Granite west of the suture records narrow U–Pb emplacement ages of 230 ± 9 Ma to 207 ± 14 Ma with a peak at around 210 Ma (Liew and Page, 1985; Cobbing et al., 1986; Schwartz et al., 1992). Recent U–Pb zircon dating of the Kuala Lumpur Main Range Granite yields an age of 215–210 ± 7 Ma (Searle et al., 2012). Several isolated and narrow bands of plutons are distributed east of the suture throughout the Central Belt of Peninsular Malaysia and this includes post-orogenic granites of Cretaceous age. The Central and Eastern Belt plutons are grouped as the Eastern Granite Province by Cobbing et al. (1986). These plutons include the Benom Complex (Fig. 1A) which comprises a calc-alkali and alkali series. The northern tip of the Benom Alkali Series is about 10 km from the Penjom mine. The age of these intrusives ranges from 123 Ma to 199 Ma (biotite), 169 Ma (muscovite), 207 ± 7 Ma (whole rock) and 197 Ma (K–Ar) as reported by Ghani (2009). This gives a wide age range for the Benom Intrusive and is interpreted here as being dominantly intruded into the Permo-Triassic after Late Triassic times just shortly after the Main Range Granite. The alkali series is characterised by high contents of large-ion lithophile elements suggesting a contribution from mantle fluid source (Ghani, 2009). A felsic dyke and sill in Penjom have ages determined as 222.8 ± 1.7 Ma (U–Pb on zircon) (Samuel Ng, Oxford, pers. comm. 2012).

3.2. Local setting

3.2.1. Stratigraphy setting

The Penjom sedimentary host rocks are characterised by shale, sandstone and conglomerate in repeated or rhythmic sequences as in Fig. 1C. These rocks are interpreted as being deposited in shallow to deep-sea environments with an age based on fossils in the calcareous shale unit as Upper Permian (Leman et al., 2005). The age is similar to the Padang Tengku area north of Penjom and part of the Musang Shale Formation (Leman, 1995). Deposition occurred in the basin while experiencing tectonic instability and volcanic activity as a result of ongoing subduction process. A similar idealised depositional setting within the Central Belt is suggested by Campi et al. (2002) which suggests the depositional environment of Permian Leptodus shale where sedimentation occurred above the subducted slab. The multiply-deformed Permo-Triassic rocks have undergone low-grade regional metamorphism and several localities attained middle to high amphibolites facies such as multiply deformed Taku Schist in the northern side of Central Belt. In contrast singly-deformed Middle to Upper Triassic shows only mild metamorphic conditions (Shuib, 2009).

Sedimentary host rocks based on pit wall mapping can be divided into 3 main facies: upper, middle and lower mine sequences. This subdivision has been made on the basis of sedimentary facies changes from well bedded siltstone and calcareous siltstone to alternate carbonate-sandstone (middle sequences) and thicker conglomerate at the bottom as well as the setting of bedding parallel shear veins that are only in middle sequences. These sequences have been folded into an anticline–syncline couple below the Penjom Thrust structure. Two schematic stratigraphy profiles from the east and west wall were illustrated including the sitting of bedding parallel quartz veins in the middle sequence as in Fig. 2. Several felsite bodies as a sill and dyke within the sequences were not shown in Fig. 2 but that unit provides an important competency contrast along the shear vein and fault contact.

3.2.1.1. Upper Mine Sequence (UMS). Upper mine sequence comprised of sandstone, laminated siltstone and calcareous shale units that represent the upper most of the stratigraphic sequences especially on the east wall of Kalampong pit or hanging wall of the Penjom fault. As for the west wall of the pit at the footwall of Penjom Thrust, the sandstone unit (UMS) is not clearly exposed as it has probably been above the current topography. On the other hand, a unit of volcanic originated sediment graded from siltstone to minor medium-grained sandstone and reworked tuff was observed to be intercalated with the lower calcareous shale at Jalis Corridor (southwest wall of Kalampong East, KE) formed part of the UMS. Remarkably, most of the units in this sequence do not host mineralization even though they are located below or along the Penjom Thrust zone and locally highly folded below the Penjom Thrust.

3.2.1.2. Middle mine sequence (MMS). Middle mine sequence is located below calcareous shale of upper mine sequence. Penjom Thrust reactivates along the carbonaceous shale of the eastern limb that also contributed into highly deformed carbonate zone along this structure. Below this carbonaceous unit, the sequence changes to a dominant sandstone with thinly interbedded carbonaceous shale and bedded grey conglomerate. The overall thickness of the sequences is approximately 80 m. Kalampong West (KW) ore body which is hosted in weathered MMS at higher elevation (from 990 to 1039 mRL) separated by massive felsite
intrusive can be correlated with MMS of lower elevation in KE. This correlation indicates that the western rock has been refolded and then further separated by NS normal fault. The cutback of Kalampong West had continued exposing this stratigraphy unit which has been truncated and separated by NS fault and massive felsite intrusive. This sequence is a favourable site for vein system especially at fold axis and when competency contrast exists with occurrence of small unit of felsite intrusive.

3.2.1.3. Lower mine sequence (LMS). Lower mine sequence comprises greenish fine-grained tuffaceous silstone, sandstone intercalated with tuffaceous greenish and reddish–purple conglomerate. The main characteristic is the thickness of individual units such as conglomerate which is often more than 5 m and up to 20 m. Further below, this facies change to well bedded siltstone with a possible interfering relationship. This unit is greenish in colour and only expose at the western wall of Kalampong pit.

The boundary between this sequence and middle mine sequence is not easily defined but distinguishable by their colours. The LMS tends to be more greenish or purple in colour and is homogeneously thicker unit than carbonaceous shale unit. The lowest thin layer of carbonaceous shale which is in many places hosts a shear vein is a good marker for the boundary of lower and middle mine sequences.

3.2.2. Felsite intrusive

A suite of I-Type felsic intrusives related to Eastern Belt granite that range from medium-grained quartz porphyry with minor albite, possibly microgranite to fine grain intrusive (possibly trachyte) is intruded into the country rocks, with variable sizes and different directions, as sills and dykes. They are one of the main components of the gold-mineralised host rock lithology together with carbonaceous shale, as they provide a competence contrast for the formation of dilational sites during deformation which allows the ingress of ore fluids and the precipitation of gold-sulphides. This felsic rock as a brittle unit is more fractured than other rock types during structural deformation; hence, it potentially hosts an extensional vein set. Sixteen percent of the drillholes exploration samples are logged as felsite intrusion. Samples with above 0.2 g/t, logged as felsite made up 3% of all samples and 30% of all felsite intrusive samples.

Felsic intrusive within the lower sequence host rock at the west wall is observed as it continues into the upper sequences at the east side of the pit wall, suggesting that the felsite generally formed a sill as well as cross-cutting the overall east-dipping sequence. Based on these criteria, the felsite intrusive was inferred to have been emplaced into east limb sequence of a regional fold. Andesitic dykes at Manik pit that also cut across the felsic rock and are displaced along the Penjom thrust show that the latter structure postdates the dyke as well as the felsite intrusive. The shear veins that are parallel to bedding in sedimentary rock cut across the felsite dyke and are responsible for the vein-related shearing in felsite. Furthermore, this felsite is observed as folded along the main fold axis (Sonny et al., 2001), supporting a pre-main fold event. Felsite within lower mine sequences at the northern site away from the Penjom thrust zone as well as in upper mine sequence is not hosted significant vein system. This indicates that the shearing along carbonaceous shale is important in generated vein system in the host rock including the felsite unit.

3.2.3. Timing of mineralisation

K/Ar dating of alteration sericite related to mineralisation in the intrusive host rock yielded ages of 197 Ma (Bogie, 2004) and 191–194 Ma (Bogie, 2002). This coincides with the late-stage Indonesian orogenic event of the Triassic–Early Jurassic involving the dextral transpressional event along the Bentong–Raub Suture (Shuib, 2009). Faulting episodes continued into the Late Jurassic and Cretaceous periods or even later with the sinistral and normal sense of movement that resulted in basin development for the Late Jurassic to Cretaceous continental sedimentary deposits. However, these may be insignificant with regard to gold mineralisation and responsible for the displacement of the earlier structures, veins and ore bodies.

4. Structural deformation event

An early deformation event can be correlated with the main Late Triassic orogeny along the Bentong–Raub Suture and the formation of Main Range Granite. This event is possibly responsible for the development of strike ridge lineaments and the tilted strata at Penjom. During the late stage of this orogeny or shortly after, a Central Belt intrusive such as the Benom Complex was emplaced into Permo-Triassic rocks with the injection of many felsic sills and dykes, including those seen in the Penjom area. Continuous deformation, low-grade metamorphism and early broad folding are classified as a D1 deformation event. The structural deformation that controls the gold-mineralised vein systems affects the intruded felsic rocks which, in this case, provide an important rheological contrast. Host rock sequences dominantly strike NNE, similar to the regional strike of the previously known Padang Tengku Formation (Gunn et al., 1993) which is now included as part of the Gua Musang Formation (Leman, 1995). Rock sequences at the north and south end of the pit are orientated 35° NNE parallel to the regional strike. This may represent the eastern limb of the broad fold interpreted as formed during the D1 event.

Continuous compressive to transpressive deformation along the Bentong–Raub Suture (Shuib, 2009) which includes the Penjom area resulted in D2 thrusting and folding. Penjom thrust is the westward-directed structure appears to have broached the fold rather than caused the folding itself (Flindell, 2003) suggesting middle to late D2 event possibly after the formation of early bedding parallel vein. In the KE pit, the sequence is refolded to an antiform–synform below the Penjom thrust where the antiform is referred as the Kalampong antcline. Middle mine sequences with carbonaceous unit are the most affected by the folding episode as it formed the tight and recumbent fold along the fold axis. The anticline plunges towards the south and is further truncated by the major east-dipping D4 to D5 NS trending normal fault partly along the synform axis. The western limb of the antcline forms a major ore body where the previously mined zone at the upper levels was known as the North–South Jewel Box corridor. Broad cross folds with EW axes affect the limb of the synform, resulting in NNW trending bedding in the southwest and northwest of the Kalampong pit and Manik pit. Bedding-plane-slip activity and development of bedding-parallel quartz or shear veins were formed during this period of deformation.

Continuous tightening of the Kalampong fold especially involving middle mine sequence resulted in fold lock-up and development of a fault to accommodate the stress in a D3 deformation event. A lower sequence is more resistant to folding processes and only developed an open fold but still affected by faulting episode. Dominant NNE trending faults exhibiting reverse, oblique-reverse and dextral sense of movements can be observed to displace earlier shear veins; however, such faults also control significant extension veins mainly at the contact with the felsic intrusives. A sinistral-reverse sense of movement can further be observed on NNW to NS trending faults which are sub-parallel to bedding and carbonaceous shale in the Jalis-west wall corridor; such movements are considered merely as local deformation as they reactivate on existing D2 shear. These fault movements may in part reactivate the early shear vein by adding more fluid into the structure. Several EW faults offset the ore body and are inferred to be a later stage of the D3 event prior to the change of stress direction before the D4 and D5 events.

Mine scale NS trending D4 (sinistral) and D5 (normal–oblique-normal) faults are easily recognised on the hanging wall of the Penjom thrust (Fig. 5). They are cut across, reactivated or refracted along the Penjom thrust or along NNE trending bedding shears. Striations on slickensided surfaces indicate a normal to slightly oblique sense of movement. Fault striations on a NS trending fault on the hanging wall of the Penjom thrust together with an apparent displacement of a
marker bed, indicate that sinistral strike-slip movement may have occurred prior to a normal sense of movement. Recognising this, sinistral movement is inferred as representing a D4 event before relaxation of stress or an extensional period that resulted in normal movement of the same fault; this normal movement is classified as a D5 deformation phase. The D1 to D3 deformations are regarded as developing during the

Fig. 3. Mine looking north (35° from true north), cross section at 50100 at the centre of Kalampong Pit, shows structural framework of shear veins (Q1W, Q2W and Q3W) in the fold setting of the Kalampong anticline. Inset figure shows chronology of folds from D1 to D3. D2 includes fold episode and development of the Penjom Thrust.

Fig. 4. (A) R1F and R2F reverse to dextral faults displaces felsite intrusive bodies and generates intense quartz veining at intersections with intrusive (looking south—852 mRL). (B) R1F and R2F as exposed on the west wall. (C) Fracture cleavage (S3) locally developed below NNE D3 fault affected the D2 shear vein. (D) Normal D5 fault (green line) displaces flat dipping along synform axis D2 shear vein. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
compressional to transpressional activity, whereas the later D4 deformation marks a change in stress direction with the development of a new NS trending fault. The D4 and D5 events are considered as being developed during the transtensional regime. The final phase of the D5 deformation event may be related to intensive faulting which occurred within the Central Belt and was responsible for basin development and deposition of Cretaceous continental deposits.

4.1. Structural setting of individual pits

The Penjom gold mine comprises two pits, namely, Kalampong and Manik located along the Penjom Thrust separated by the Jaleh River. During October 2013, Jaleh River was diverted allowing the two pits to be combined and ore mining to be continued below this level. The Kalampong pit was earlier developed as two separate pits known as the Kalampong East (KE) and Jalis pits. Almost all economic gold mineralisation is observed below the Penjom Thrust structure. During earlier pit (Kalampong East) development, mineralised NS trending veins comprising ribbon quartz within carbonaceous shale representing early ductile veins were previously recognised below the NNE trending Penjom Thrust ore zone. Since then, mine development has provided good exposures and ongoing mapping has allowed better classification of vein structures and their structural control. In Kalampong East pit, Sonny et al. (2001) reported the occurrence of bedding-parallel veins in the NS trending ore zone which was previously referred to as ribbon quartz in slightly deformed carbonaceous shale. Endut and Teh (2010) have further suggested that bedding parallel shear veins were formed during repeated opening of bedding-parallel faults related to D2 folding and thrusting.

4.1.1. Kalampong East pit

The Kalampong East pit ore body is structurally controlled by the Penjom Thrust and the fold-related bedding-plane-slip fault within the Kalampong anticline–syncline especially within middle mine sequences and at the boundary with lower mine sequences. Lower grade ore within the lower mine sequences is hosted in felsite dyke at interception with fault. Open to tight and recumbent folds along the fold axis can be observed from north to south. Tight and recumbent folds have been further superimposed by NNE trending fault which is a splay from the main thrust and mainly developed a vein system where they transect brittle felsic units. Saddle reefs occur at the fold axis and commonly above the felsite body below the Penjom Thrust. Movement sense of the NNE fault is reverse, oblique-reverse and dextral. This sense of movement can be observed on the basis of displacement of the felsite body and fault striation on the fault surface. Another splay fault oriented NS in the southern part but turns NNE towards the south separating the western and eastern limb of the anticline with a normal sense of movement is still classified as a fold related structural event. This structure is referred to as the fold axis fault.

A major NS trending fault known as the ‘DM’ fault, with several parallel sets of minor faults, cuts across the folded rock including the bedding-parallel vein. These faults are aligned from the southeast to northwest corner of Kalampong pit with a normal sense of movement. All D3 NNE faults can be observed as displaced by ‘DM’ NS fault, confirming a post-D3 event. On the east side of this fault, a series of NS trending fault networks with NNW link faults (or riedel fault) in between them can be observed on the hanging wall (Fig. 5). A majority of these NS trending faults are reactivated along the Penjom Thrust and diffracted further into the fold axis fault and east limb sequences. A few fault planes exhibit sinistral fault striation (D4) but the dominant sense of movement is normal to oblique-normal (D5).

4.1.2. Jalis pit

Two main structures at Jalis are NE to NNE dextral strike-slip faults, where they transect felsic dykes and NNW faults sub-parallel to the stratigraphy. Additionally, this NWW trending ore zone hosts ribbon to laminated, bedding-parallel shear veins. The NNW faults displace the felsite dyke with reverse-sinistral sense. The NNE faults cut across the NNW faults but exhibit only a small displacement of approximately 1–3 m with a reverse–dextral sense although both episodes were interpreted as occurring within D3 event. The NNW faults most probably occurred as conjugate faults and were only significant in the Jalis corridor where the faults were reactivated along carbonaceous shale.

Fig. 5. Felsite intrusive as a marker in tight incline fold (recumbent fold) in zone A along Penjom Thrust and the western limb (Zone C). Inset photo shows massive vein above intrusive body on the fold hinge of tight incline fold.
4.1.3. Manik pit

In Manik pit, the same ore bodies including the Penjom Thrust and several series of NNE-parallel faults are reactivated along the same trending bedding-plane shear parallel to the carbonaceous unit locally with embedded felsite forming three mineralisation zones. The lithostratigraphic sequences are dominantly east dipping and vein styles are the same with those at Kalampang pit. However, the ore zone forms a linear shoot lacking sheeted or discordant extension veins except in felsite unit. Ore zones associated with shear veins, which have been reactivated by NNE fault along carbonaceous-rich sediments. Because the fault plane is subparallel to the stratigraphy, the total displacement is not easily determined. However, slickensided fault striation indicates a reverse sense of movement. Manik mineralisation zone was normally to sinistrally displace from Kalampang pit ore zone by DM (NS trending) fault at least 20 m.

5. Structural control of vein formation

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

The overall shape of the Kalampang Fold can be explained as an antiform–synform pair 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 Kalampang 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 layers of carbonaceous shale which normally become the site of type 1 and type 2 laminated veins. 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. 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 been locked up. Continuous movement resulted in dextral strike slip on several D3 faults including splay faults and NNE faults as a late D3 event.

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 vein. In summary, two structural settings of vein formation can be discussed such as fold and thrust-related D2 and later phase faulting D3 events.

5.1. Fold- and thrust (D2)

The Penjom Thrust and associated Kalampang Fold are responsible for bedding-slip activity throughout the Penjom pit particularly along the carbonaceous unit. Quartz veining that subsequently followed movements of the bedding-plane-slip faults and other faults is referred to as a shear vein type (the same category as fault fill vein of Robert and Poulsen, 2001), 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 1) are also considered as fold-related veins.

Veins were formed during repeated opening of the structures particularly along bedding-plane-slip faults (D2) which produced laminated quartz 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 vein surface, slickenline or fault striations are commonly observed and this is indicative of continuous deformation particularly flexural-slip movement. The WNW to EW sheeted vein can also form significant zone.

The fold vein system forms several ore zones, whereas the intensity and grade are controlled by several other factors such as fold geometry either on the limb 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 vein array or sheeted vein within small intrusives, become more dominant.

5.2. Fault (D3)

Except 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 (Fig. 4) which occurred during the late stage of folding after the fold was locked up. Locally, fracture cleavages are well developed below this fault and disrupt

| Table 1 Classification of vein type, host rock and superimposed reactivation by later fault. |
|-----------------------------------|------------------------------------|--------------------------------|--------------------------------|--------------------------|
| Vein                             | Morphology or type                 | Lithology site                  | Reactivation by later fault/process | Type                     |
| Shear vein                       | Ribbon, roughly laminated,         | Carbonaceous shale              | Parallel reactivation resulted to fault/shear fill vein | Shear vein type 1        |
|                                  | massive                            | Thin carbonaceous shale          | No parallel reactivation           | Shear vein type 2        |
|                                  | Planar to roughly laminated        | Carbonaceous shale at felsites   | No parallel reactivation           | Shear vein type 2        |
|                                  |                                   | contact or cross cutting         |                                  |                          |
| Extension vein (high angle)      | Vein septa/book texture.           | Siltstone below shear vein       | No parallel reactivation           | Associated with types 1 and 2 |
|                                  | (Hodgson, 1989)                    | (low angle)                      |                                  |                          |
|                                  | Planar                             | Competence rock including        | Strike parallel to σt,             | Extension vein type 1    |
|                                  |                                   | massive siltstone and            | No parallel reactivation           | Extension vein type 2    |
|                                  |                                   | conglomerate.                   |                                  |                          |
| Sheeted vein (moderate angle)    | Planar                             | Competent rock below shear       | No parallel reactivation. Stress   | Extension vein type 3    |
|                                  |                                   | vein including felsites          | induces by shear vein or fault.    |                          |
|                                  |                                   | Mostly in sub-vertical felsites   | At or near fault contact           |                          |
|                                  |                                   | dyke/sill                       |                                  |                          |
| Stockwork                        | Multi-directional                  | Mostly in felsites rock          | Fracture induce by shear vein or   | Extension vein type 4    |
| Hydrothermal breccias            | Non rotated angular wall rock       | All rock except massive          | At intercept of shear vein/fault   | Associated with shear    |
|                                  | fragment                           | conglomerate                     | with rheological contrast unit     | vein type 1, 2 and other faults |
the early high-grade shear veins of the D2 deformation (Fig. 4C). NNW fault controlled significant mineralisation at the west-dipping sequence in the west wall of the Jalis corridor that 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 (Fig. 6).

As in the case with fold-related veins, fault-related veins are also classified as shear or extension veins. Faults which 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 these 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.

Based on a slickenline direction observed on a few crosscutting faults, sinistral strike-slip movement is noted but on the other faults, normal to oblique-normal movements are dominantly exhibited. These faults are locally associated with barren calcite veins mainly on the hanging wall and along the reactivation of Penjom Thrust where the barren calcite veins up to 0.7 m thick locally occur within the mineralised Penjom Thrust ore body. Reactivation of these structures resulted in the deformation and displacement of earlier formed quartz veins with normal sense of movement (Fig. 4D). 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.

5.2.1. North-northeast (NNE) fault

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 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.

5.2.2. North-northwest (NNW) fault

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 (Fig. 6). 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 mean stress such as dilational jogs between two NNW faults. Other than pre-existing vein, the NNW fault generates minor vein network at felsite contact in particular within lower mine sequence. Local variation of stress resulted to some small scale NS fault which also controlled minor veins around felsite interception.

6. Details of vein systems

Understanding vein formation and styles is fundamental to unravelling the structural controls on the associated ore systems. Certain fracture-infilled veins such as metasomatic wall rock replacement veins (Robert and Poulsen, 2001) are not related to structural controls and are not subject to stress mechanism analysis.

Several styles of quartz veining related to folding, faulting or superimposing of these two processes as summarised in Table 1 can be observed at the Penjom gold mine. Attributes such as orientation, texture or morphology and development intensity characterise the vein type. The vein system classifications are best described on the basis of formational aspects; these reflect structural control and stress direction imposed during vein formation. Two main vein systems are recognised as (a) Thrust- and fold- (D2) related vein and (b) Fault- (D3) related vein which are described as follows.

6.1. Thrust and fold (D2) related vein

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

6.1.1. Penjom Thrust shear vein

The Penjom Thrust (middle to late D2 event) was reactivated along the eastern limb of the Kalampong anticline, in particular, along a thick carbonaceous shale unit which may have already hosted earlier bedding-parallel veins (Fig. 7A, B) and formed shear vein type 1 (Table 1). This is a common feature where a reverse fault is rooted along the bedding plane. Reactivation by the thrust has further created new textures and types in the form of ribbon, breccia, 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 forms a discontinuous pinch and swell vein 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, whereas in the northern area it is an open fold (Fig. 3). Saddle reef type 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 vein becomes narrower at the intrusive–shear vein contact and is less developed in the intrusive. Veins are massive at the fold nose with ribbon textures at the margin indicating repeated opening 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 intrusive body that increases the physical and chemical contrast. Veins in this area are variably deformed because of the reactivation of 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.

6.1.2. Bedding-parallel shear vein

This type refers to quartz vein infill along carbonaceous shale units and represents an active bedding plane-slip fault or flexural-slip fault with intermittent deposition of shear vein type 2 (Table 1). This process occurred during fold activity to form a ribbon or lamination texture. Recrystallisation 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, 1995; Cox et al., 2001; Sibson, 2001). This type of vein is structurally classified as shear vein (Hodgson, 1989). The presence of slip lineations, slickensides and lamination surfaces is 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 Fig. 3, there are at least five bedding-parallel shear veins identified within the Kalampong pit. Two are along the eastern limb including Q2E (Fig. 7C) and three within the western limb sequences (Fig. 7D). These shear veins cut across the felsite unit with a remnant of carbonaceous material (Fig. 7E).

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 a high-grade vein (>6 g/t based on grade control sampling for mining) (Corbett, 1999; 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 along the Penjom Thrust.

Three different morphologies of veins (Fig. 8A) are recognised as follows:

• Planar laminated (<20 cm)
  Planar, thin (<3 mm) graphitic or carbonaceous material of irregular thickness comprises the lamination within these veins. Laminations can be at different angles to an earlier vein-wall-parallel lamination. Q2W (Fig. 8A) and Q3W (Fig. 8D) are fine examples of this vein and as a narrow shear vein (<20 cm) associated with a zone of discordant extension vein. Q2W hosted in moderate to thin carbonaceous shale and commonly has a thin layer of roughly laminated vein and dominant planar laminated vein or with vein breccias (Fig. 8F). 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 vein. Host rock comprises very thin carbonaceous shale and siltstone units interbedded with a more competent rock horizon. Roughly laminated vein is commonly absent for this shear vein.

• Roughly laminated (ribbon texture)
  This is a common bedding-parallel vein in dominant or thicker carbonaceous shale interbedded with a minor sandstone unit. 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 (upper part of vein in Fig. 8A). Furthermore, this vein is commonly associated with different forms of stylolite dominantly wavy type. It is roughly laminated as a result of continuous deformation and in many places it is associated with vein breccias. Roughly laminated vein formed a thicker segment than other types of veins within Penjom Thrust and other thicker carbonaceous host rock.

• Massive bedding-parallel quartz (>20 cm)
  This form of thick quartz occurs parallel to bedding 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

![Fig. 8. (A) Laminated veins (Q2W) in carbonaceous shale unit with more planar laminations inside the veins. This vein was formed through shear induced lamination. (B) E–W extension vein array or planar sheeted vein developed at θ equals to 90° below the main shear vein (Q3W—red dash line), looking south and at level 840 mRl. (C) A series of E–W striking sheeted veins (extension vein array) exposed after the excavation of the main shear veins (looking east, at level 834 mRl). (D) Planar laminated vein Q3W with galena and sphalerite. (E) Vein septa or parallel band of vein infilling foliation fabric. (F) Quartz breccias associated with shear vein with laminated quartz at the margin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
and 2 with a few stylolites at the vein margin commonly on the upper part of the shear vein but the vein comprised of thicker vein with massive appearance or quartz dominated and occasionally intergrowth with calcite (Fig. 8A). In the other parts, massive quartz can be brecciated (Fig. 8F), form a gradual boundary with the host rock or become vein stockwork. Quartz grains within the thicker and massive portion are typically coarse with variable size and exhibit a buck texture.

- Foliation-/cleavage-parallel vein
  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 vein septa (Fig. 8E) 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.

6.1.3. 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 subvertical and either formed an individual zone or dangling below bedding-parallel shears (Fig. 8B and C) suggesting that they are co-evolved with bedding-parallel veins.

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 vein types in different lithological units. The different styles of extension veins are described as follows:

6.1.3.1. High angle EW extensional vein array

Zones of extension vein type 1 (Table 1) can be up to 15 m wide at a vein spacing of up to 1 m. Individual vein thickness can be up to 10 cm. This set of veins is only weakly mineralised, and based on a 3 m sampling for ore mining, it commonly returns grade values less than 0.5 g/t; hence, it is not made up a main sources of ore. 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 and lack of sulphide. 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 of the lower mine sequences.

6.1.3.2. 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 (Fig. 8B). 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 more competent sedimentary unit below thin carbonaceous-hosted shear vein or in brittle intrusive host rock.

In both lithologies, vein orientation is parallel to maximum compressive stress and axes of incremental shortening (dZ) or perpendicular to 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 predate 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 1) is responsible for the higher tonnage for the less carbonaceous host rocks. Sheeted veins occur as extensional veins below a laminated vein mainly Q3W and Q2W and trend subvertical to a bedding-plane-slip fault (Fig. 8B and C). Widths can be up to 20 cm at a spacing of 5 cm to 2 m with bulk gold grade varying from low to medium grade (up to 4 g/t) with higher gold grade occurring in laminated bedding parallel vein with bulk grade of ore block can be up to 10 g/t. Generally, 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 1) 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 concentrated. Thickness of the veins can be up to 15 cm, and predominantly comprise more quartz than carbonate. Furthermore, the EW striking veins are a dominant set compared to other direction. Veins set in felsite are relatively lower in grade approximately 2 g/t compared to those near the shear veins but can have higher tonnage.

6.1.4. Quartz breccias

Quartz breccias are defined as a body of quartz vein in which country rock fragments exceed vein volume. It can be divided into two categories; hydrothermal quartz breccias which normally form in dilatant zones along bedding-slip faults or shear vein (Fig. 8F) and fault breccias which form as a result of shear movement and are part of the shear veins. Movement between two closely spaced bedding-slip shear veins at a rheological contrast or near a fold axis creates space for the development of hydrothermal breccias, particularly in the narrow competent felsic unit as well as in the sedimentary rock around the boundary forming a localised jog along relatively narrow shear vein. The hydrothermal quartz breccias have relatively much higher grades relative to other part of the ore body and commonly exhibit visible gold especially along the 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., 2001).

6.1.5. Quartz stockworks

Quartz stockworks (extension vein type 4—Table 1) are associated with shear veins and are described as a network of more than two set of veins which 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 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. Gold grade of the stockworks is quite erratic and the overall grade of ore body depends on the intensity of the vein.

6.2. Fault (D3) related veins

Faulting events that are active after fold lock-up are not observed as hosting the laminated or ribbon vein. However, 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.
6.2.1. Sheeted extension veins

6.2.1.1. Subvertical sheeted veins. Subvertical 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 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 are associated with the vertical set but the vertical set is commonly much more dominant over other directions.

Fig. 9A shows stereonet plots of EW sheeted veins and bedding at three different localities. Stereonet plot of overall bedding (Fig. 9B) and vein (Fig. 9C) shows a variable bedding orientation as a result of folding and consistent near E–W trend of sheeted veins. Strike direction of the veins is normally parallel to the main compression force (Fig. 10C) (Robert and Poulsen, 2001) acting in the near EW direction. Fig. 10D shows the example of a vein in the felsite unit at fault interception in which the EW direction is dominant over other directions at a ratio of 30:1. The average grade of sheeted veins in that area based on grade control of 3 m sampling yielded a 2.0 to 3.0 g/t Au, but grab samples at fault intercept can be up to 6 g/t.

6.2.1.2. Low-angle sheeted extension veins. Low-angle sheeted extension veins type 3 (Table 1) with a maximum thickness of 10 cm perpendicular to the wall occur in subvertical narrow felsic intrusives of less than 5 m to 8 m width. The bottom of the Kalampong East pit has a felsic dyke near the fold axis which is cut across by a series of NNE trending faults. Deformation is 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 and quartz breccias. This type of extension veins is locally observed along the western limb of the felsic dyke that extends towards the fold axis, particularly where there is a cross-cutting NNE trending fault or shear vein. Average grade from ore block and average blast hole sampling can be up to 4 g/t (example from the pit bottom where the fault intersects felsite dyke).

6.2.2. Quartz breccias

Quartz breccia is within the narrow felsite bounded by two faults or intercept felsite with low angle fault. The occurrence is similar to the shear vein of D2 fold-related hydrothermal quartz breccia; however, this vein is exclusively hosted within the felsite intrusive along the fault contact (Fig. 10A and B) and rarely extends outside the felsite into sedimentary rocks. A fault breccia is defined in cases where the

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Fig. 9. (A) Lower hemisphere equal-area of sheeted vein 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.
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 can exist within the same ore zone. Fault breccias have commonly higher grades than hydrothermal quartz breccias. All quartz portions inside the quartz reef can locally be barren.

6.2.3. Quartz stockworks

A faulting event also generates quartz stockworks mainly in felsite units at fault intersection such as the Jalis corridor. A transition to sheeted vein is common and dominantly controlled by NE to NNE reverse–dextral fault. Locally NS to NW trending generates multi-directional sets of vein direction especially in the northern side resulting in isolated small high grade (>4 g/t) veins at fault intersections with felsite rocks in lower mine sequences.

7. Discussion

7.1. Relative role of fold and fault on quartz veining

Structural events and host rock properties can influence the formation of different types of veins. Details of vein style and shear vein dominantly form during ductile deformation such as folding and thrusting (D2) and at the same time forming extension veins in more competent and brittle units. 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 sedimentary rocks near the NNE reverse/dextral faults (e.g. R1 and R2 faults, Fig. 4). These observations suggest that reverse faulting occurred during late stage compression after the development of bedding-parallel veins but could subsequently still be reactivated and channelled the ore fluids. NS sinistral and normal faulting (D4 and D5) and in particular the extension of hanging wall faults were observed not to commonly generate quartz veining in intrusives and sedimentary rocks 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 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 as identified at the hanging wall that reactivates along the Penjom Thrust at certain segment occurred at a very late stage or post the mineralising episode but may also have been responsible for at least some remobilisation of gold.

7.2. 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). Competence 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 narrow embedded competence rock. Veins are commonly narrow within the shear failure zone but can be intensive in the narrow embedded competent unit in the form of extensional veins such as breccias, stockworks or sheeted veins. In Penjom gold mine, shear veins within the mineralised ore body in many places contain higher gold grades than in extension veins suggesting that shear failure and pressure drop play significant role in contributing metals.

In contrast to the above condition, mineralised veins mainly occur in the weaker zone and are less developed in competent units, in particular, the larger intrusive rocks, massive conglomerate or thick silicified rocks. 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 is the main example of this ore body.

7.3. Mineralisation and deformation

XRD analyses of the wall rock and ore show the occurrence of sericite (fine grained muscovite) and illite suggesting that phyllic alteration affected the host rock and is much more developed in deformed felsite intrusives. Pyrite and arsenopyrite are dominant within the ore zone especially during D2 vein formation. Main sulphide minerals comprise early D2 pyrite and arsenopyrite, precipitated in both quartz and wall rocks, and later D2 to D3 pyrite-base metal sulphide in veins with minor arsenopyrite. High level of As accompanies Au mineralisation in particular along shear vein parallel to carbonaceous shale and this is supported by geochemical analysis (Ariffin and Hewson, 2007) from early exploration data (grab samples with more than 100,000 ppm As at a gold grade of 26.13 ppm and in drillhole 11 with 85,000 ppm As with a gold grade of 18.54 g/t). Fault related vein (D3) and extension vein in felsite have lesser arsenopyrite compared to pyrite.

Early sulphides show evidence of deformation particularly within the Penjom Thrust shear vein such as cataclase, fractured and with pressure shadows in wall rock that indicate a paragenetically earlier phase of deformation (D2). However, away from the fault plane, the paragenesis of all sulphides shows a spatial co-existence and the sulphides are considered to have crystallised synchronously. The study of sulphide paragenesis along the deformed zone may be inaccurate, as the occurrence of galena and chalcopyrite with gold could be sulphide paragenesis along the deformed zone may be inaccurate, as the occurrence of galena and chalcopyrite with gold could be remobilised. Fluid inclusions exhibiting a CO2 rich (up to 100 mol%) in the occurrence of galena and chalcopyrite with gold could be remobilised. Fluid inclusions exhibiting a CO2 rich (up to 100 mol%) inclusions in quartz with total homogenisation temperature of 250 to 300 °C (Makoundi, 2012) suggest the contribution of metamorphic fluids in gold genesis.

The main event of gold introduction during the formation of D2 bedding-parallel ribbon/laminated vein, associated extension vein and D3 fault-related extension vein occurred during ductile–brittle deformation. Introduction or remobilisation of earlier gold into secondary textures and fractures within earlier formed veins may have occurred during the late stage. In KE, brittle deformation is related to NNE reverse to dextral strike-slip faults that were reactivated after the folds had locked-up. These structures may have reactivated early shear veins and induced extensional fracturing for EW sheeted veins, striking parallel to the main compressive stress. EW extension veins below narrow bedding-parallel shear veins contributed to a larger size of the overall ore body; however, the latter at many places has a consistent and higher ore grade.

The mechanism of gold introduction into vein systems is subject of ongoing debate. Significant gold may have already been introduced during the ductile event with early sulphides such as pyrite and arsenopyrite mainly in highly carbonaceous host rock. The Penjom project is known for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach for the successful treatment of high-grade carbonaceous ore by implementation of a gravity circuit to recover coarse gold and resin-in-leach.

The structural evolution and veining episodes at Penjom suggest that a compressional event was followed by a transpressional and later post-vein extensional episodes. These structural events illustrated in Fig. 12 may reflect the deformation which affected the Central Belt. In terms of structural timing of vein episodes, a deformation phase was started with the D2 deformation fold and thrust, followed by D3 reverse and dextral strike-slip faults, then sinistral D4 deformation and much later normal faulting D5. The D2 mineralised veins such as bedding-parallel shear veins, associated discordant extension vein and saddle reef style veins are characteristic of formation under a compressional regime reflecting the regional orogenic event.

Based on the age of hydrothermal sericite (Bogie, 2002, 2004; Flindell, 2003) which is considered here as the age of mineralisation, it is proposed that the compressional or transpressional regime that controlled mineralised vein formation at Penjom and possibly other vein-hosted deposits such as at Bukit Koman, Raub along the Bentong–Raub Suture occurred in Early Jurassic times. Richardson (1939) reported that the eastern and western lode channels of Bukit Koman are located along a compression fault which is also parallel to the bedding.

The term ‘post-collisional’ is used to describe geological activity after the termination of subduction due to the collision of the Sibumasu terrain and the Eastern Malaya. As a result, the host rocks along the Bentong–Raub Suture zone and the parallel structures underwent deformation, providing a conduit and trap for ore fluids. Despite the term post-collisional, the timing is considered as the late stage of the orogenic event which is a common characteristic of orogenic gold (Groves et al., 1998; Goldfarb et al., 1998).

The quiet period during the Early to Late Jurassic without a stratigraphic record indicates that the Central Belt was already uplifted from the marine environment to form a land mass as a possible result of the collision between the Sibumasu and Indochina blocks. Faulting during the Late Jurassic responsible for basin development and deposition of continental deposits may be reflected by the series of normal faults at Penjom.
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 refailure 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 subparallel 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.

Structural control of the bedding parallel 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, 1987), as summarised in Table 2. The Bendigo area exhibits a superimposed reactivation by faulting, after the fold has locked up as a consequence of the folding process. Localisation of ore at certain structural setting such as fold axis, at intersection of shear and felsite unit and variability of grade at different vein textures suggest that chemical and physical conditions of ore fluids, interactions with host rock and structural control play important roles in controlling gold precipitation.

Classification of veins into different structural types greatly helps geologists to better understand the different structural controls of vein formation and gold mineralisation processes. Vein style together with other aspects of gold mineralisation observed at Penjom is consistent with that in other deposits which are classified as being orogenic gold deposits (Goldfarb et al., 1998; Groves et al., 1998). Age of the mineralisation at the Penjom deposit is 191–198 Ma which provides

Fig. 11. (A) Crenulated extension veins as a result of 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 side view with gold along vein margin. (D) Laminated veins with sign of fault striations affecting the gold on the vein margin.

Fig. 12. Hypothetical model of structural episodes in Penjom Gold Mine and regional tectonic event.
constraint in terms of the orogenic timing. This type of gold deposit is always formed at the late stage of a major tectonic event.

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References


Table 2

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<td>(Schaubs and Wilson 2002)</td>
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<td>(Tremblay, 2001)</td>
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