Origin and Characteristics of the Shwetagun Deposit, Modi Taung-Nankwe Gold District and the Kunzeik and Zibyaung Deposits, Kyaihto Gold District in Mergui Belt, Myanmar: Implications for Fluid Source and Orogenic Gold Mineralization

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The Mergui Belt of Myanmar is endowed with several important orogenic gold deposits, which have economic significance and exploration potential. The present research is focused on two gold districts, Modi Taung-Nankwe and Kyaihto in the Mergui Belt comparing their geological setting, ore and alteration mineralogy, fluid inclusion characteristics, and ore-forming processes. Both of the gold districts show similarities in nature and characteristics of gold-bearing quartz veins occurring as sheeted veins, massive veins, stockworks to spider veinlets. These gold deposits are mainly hosted by the mudstone, slaty mudstone, greywacke sandstone, slate, and slaty phyllite of Mergui Group (dominantly of Carboniferous age). The gold-bearing quartz veins generally trend from NNE to N-S, whereas some veins strike NW-SE in all deposits. The gold-bearing quartz veins are mainly occurred within the faults and shear zones throughout the two gold districts. Wall-rock alterations at Shwetagun are mainly silicification, chloritization, and sericitization, whereas in Kyaihto, silicification, carbonation, as well as chloritization, and sericitization are common. At Shwetagun, the gold occurred as electrum grains in fractures within the veins and sulfi des. In Kyaihto, the quartz-carbonate-sulfide and quartz-sulfide veins appeared to have formed from multiple episodes of gold formation categorizing mainly as free native gold grains in fractures within the veins or invisible native gold and electrum within sulfi des. At Shwetagun, the ore minerals in the auriferous quartz veins include pyrite, galena, and sphalerite, with a lesser amount of electrum, chalcopyrite, arsenopyrite, chalcopyrite, and sericite. In Kyaihto, the common mineralogy associated with gold mineralization is pyrite, chalcopyrite, sphalerite, galena, pyrrhotite, arsenopyrite, marcasite, magnetite, hematite, ankerite, calcite, chlorite, epidote, albite, and sericite.
INTRODUCTION

The Mergui Belt (MB) is one of the largest and most economically important gold provinces in Myanmar. This belt has a diverse style of mineralization such as orogenic gold deposits (e.g., Modi Taung), vein-type tin and tungsten deposits (e.g., Hermyingyi), and stratabound antimony deposits (e.g., Kaw Hket–Taunggalay–Htimiwa) (Ye Myint Swe et al., 2017; Khin Zaw, 2017; Mitchell, 2018). The MB was intruded by several granitic rocks of the Central Granite Belt of Myanmar (Khin Zaw, 1990) which extends into peninsular Thailand, and these granites form part of the Western Granite Province of Southeast Asia (Cobbing et al., 1986, 1992). The northern part of MB is characterized by high-grade metamorphic rocks such as gneiss, granitoid gneiss, marble, and calc-silicates associated with Late Proterozoic to Mesozoic sedimentary sequences. The southern part of MB consists of Upper Carboniferous to Lower Permian metasedimentary rocks of predominantly Mergui Group and the rocks are metamorphosed to greenschist facies with small zones of amphibolite facies along the margins of the belt, close to major shear zones and granite intrusions (Figures 1, 2; Cobbing et al., 1986, 1992; Schwartz et al., 1995; Mitchell et al., 1999, Mitchell et al., 2004, Mitchell et al., 2007, 2012; Khin Zaw, 1990; 2017, 2019; Khin Zaw et al., 2014a, 2018; Ye Myint Swe et al., 2017; Mitchell, 2018; Myo Kyaw Hlaing et al., 2019).

Orogenic gold deposits are one of the main groups of gold deposits making up a major source of gold produced worldwide (e.g., Groves et al., 1998; Dubé and Gosselin, 2007). They occur in convergent plate margins in accretionary and collisional orogens, indicating subduction-related metamorphic (thermal events) processes in deep-crustal environments (Barley and Groves, 1992; Groves et al., 1998; Goldfarb et al., 2004, 2005; Bierlein et al., 2006, 2009; Groves and Bierlein, 2007). These gold deposits are typically hosted by rocks of greenschist to amphibolite metamorphic grade, and locally up to granulite facies conditions of various ages, displaying variable degrees of deformation (Groves, 1993; Groves et al., 1998, 2003; Goldfarb et al., 2001, 2005, 2015; Connolly, 2010; Tomkins, 2010). Giant orogenic gold deposits are commonly located in second-order structures linked to shear zones and lithospheric-scale faults, indicating first-order fluid conduits (McCuaig et al., 2010; Groves et al., 2018; Davies et al., 2019).

At Shwetagun, the mineralization occurred at a varying temperature from 250 to 335°C, with a salinity range from 0.2 to 4.6 wt% NaCl equivalent. The Kyaihto gold district was formed from aqueous–carbonic ore fluids of temperatures between 242 and 376°C, low to medium salinity (<11.8 wt% NaCl equivalent), and low CO₂ content. The ore-forming processes of the Shwetagun deposit in the Modi Taung-Nankwe gold district and the Kyaihto gold district are remarkably comparable to those of the mesozonal orogenic gold systems.

Keywords: Shwetagun, Kyaihto, Mergui belt, Mesozonal, Orogenic gold systems

REGIONAL GEOLOGIC SETTING

The gold deposits of Myanmar comprise six major north-south trending geological linkages or tectonic terranes/belts (Figure 1). The Mogok-Mandalay-Mergui Belt (MMMB) is exposed in a 1,300 km long belt of 20–100 km in width at the western margin of the Sibumasu (Figures 1, 2; Bender, 1983; Mitchell et al., 2004; Gardiner et al., 2014, 2018; Mitchell, 2018). The southern part of MMMB is defined here as Mergui Belt (MB) and it is also known as Slate Belt in Myanmar. We used the term MB as the Slate Belt is a misnomer due to the presence of abundant other lithologies such as sandstones, carbonaceous siltstones, greywackes, and calcareous mudstones rather than slate unit. These lithologies belong to the Mergui Group, running a distinctly north-south direction from Mandalay towards Dawei (Tavoy) and Myeik (Mergui) and southeastward through Phuket, southern Thailand, and eastern Sumatra to Bangka Island in Indonesia. This belt is made up of interbedded slaty mudstones, slate and pebbly wackes, less abundant quartzites, and rare calcareous beds, and the northern part of the belt extend an additional...
00 km long in the west of the Gaoligong Range in southern China (Figures 1, 2; Mitchell et al., 2004, 2012; Gardiner et al., 2015, 2018; Mitchell, 2018).

The Mogok Metamorphic Belt (MMB) is described as the northern part of the MMMB (Figures 1, 2). Although the local linkages between the MMB and the MB remain an open question.

FIGURE 1 | Major structural belts, and gold occurrences in Myanmar (Modiﬁed after Mitchell et al., 2004; Ye Min Swe et al., 2017; Myo Kyaw Hlaing et al., 2019), PFZ, Papun Fault Zone; TPFZ, Three Pagodas Pass Fault Zone; MMMB, Mogok-Mandalay-Mergui Belt.

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Gardiner et al., 2015), they defined the MB as the southern part of the MMB. In MMB, the granites are found in the east of the Sagaing Fault and at the west of the Panlaung-Mawchi Zone, which was located west of the Shan scarps (Figures 2, 3). The MB is bordered on the west by schists, gneisses, marbles, and granites of the MMB (Chhibber, 1934), which are intruded by calc-alkaline dykes and granites (Mitchell et al., 2004). The MB is located along the north-trending zone related to the suturing of the Shan Plateau as part of the Sibumasu (a fragment of Gondwana) and the West Myanmar block, and between the Indo-Myanmar Ranges to the east and the South China block to the south and the Indochina block to the east (Figures 1, 2). The MB consists of several NE-/W-trending faults which are formed within the central to the southern part of Myanmar and are notable for the existence of a large number of orogenic-style gold deposits (Figures 1, 2). Most of the important gold deposits in the MB are associated with the second-order fault, N to NW trending upright folds, 1–6 km long, ductile shear zones, and are best referred to as orogenic gold deposits (e.g., Mitchell et al., 2004). The eastern boundary of the Shwetegun gold deposit in the MB is bordered by the Pan Laung fault, and the eastern margin is represented by the Paung Laung-Mawchi Zone (Shan Scarp) and the strata are dipping steeply to the west from the east of Nankwe to the Sakadaga Taung fault (Figures 2, 3; Mitchell et al., 2004).

The Upper Jurassic rocks of the Paunglaung-Mawchi Zone are overthrusted by the Pan Laung fault along their western margins. The Papun fault lies in the south of the Modi Taung-Nankwe gold district in the MB and MMB, and at the west of the Paunglaung-Mawchi Zone (Figures 2, 3). Gold occurrences in the Kyaikhto area occur close to the NNW–SSE striking Papun fault in the north and the Three Pagodas fault in the south. The Three Pagodas fault is almost parallel to the Papun fault and continuous from the Papun area to the southeast into Thailand, where it is regionally known as the Mae Ping fault or the Wang Chao fault (Figure 2; Ridd and Watkinson, 2013). The MB is originally referred to as the Lower Jurassic regional metamorphic belt of major east-convergence origin that hosts several orogenic gold occurrences (Mitchell et al., 2004, 2012). The gold deposits within the MB are commonly associated with supracrustal rocks or in the vicinity of regional, crustal-scale deformation zones with a brittle to ductile type of deformation (e.g., Mitchell et al., 2004; Mitchell, 2018). The metasedimentary rocks within this belt are intruded by the granitoids of Central Granitoid Belt of Myanmar (or) Western Granite Province of Southeast Asia (Figures 1, 2; Mitchell, 1977; Khin Zaw, 1990; Cobbing et al., 1992; Mitchell et al., 2004, 2012). The MB was also intruded by several generations of granitoid comprising numerous I-type and S-type two-mica granites of Cretaceous-Paleogene age (Khin Zaw, 1990; Cobbing et al., 1992; Barley et al., 2003; Searle et al., 2007; Mitchell et al., 2012; Gardiner et al., 2015, 2018; Aung Zaw Myint et al., 2017). The S-type granites are associated with significant tin-tungsten mineralization (Khin Zaw, 1990, 2017; Gardiner et al., 2014; Aung Zaw Myint et al., 2017; Mitchell, 2018). However, there is no geological evidence of preferential relationships of orogenic-type gold deposits with the...
Cretaceous-Eocene granite intrusions (Mitchell et al., 1999, 2004; Gardiner et al., 2014; Mitchell, 2018).

**THE GEOLOGY OF GOLD DISTRICTS**

Numerous orogenic gold deposits have been discovered in the MB. The Modi Taung-Nankwe and Kyaikhto gold districts lie within the MB from central to southern Myanmar (Figures 2, 3). The geology of the Shwetagun deposit in the southwestern part of the Modi Taung-Nankwe gold district and the Kyaikhto gold district are described below.

**Shwetagun Gold Deposit in Modi Taung-Nankwe Gold District**

The gold mineralization of the Shwetagun deposit is located about 3 km south of the Modi Taung deposit (Figures 3, 4). The Kogwe mudstone and Poklokka Pebble wackestone are mainly exposed at the Shwetagun area (Mitchell et al., 2004; Myo Kyaw Hlaing,
and the gold mineralized veins are hosted by the Kogwe Mudstone Unit which consists of pebbly mudstone, siltstone and sandstone (Mitchell et al., 2004). Gold-quartz veins are oriented in NE-SW and N-S directions and can be grouped into one of the three vein systems within exploration Adit I, II and III (Figures 4, 5A–C). The Adit I and II are located along the NE-SW strike, whereas Adit III trends north-south. Each vein system consists of either a single vein or multiple parallel veins separated by host rocks. Quartz veins in Adits I and II show stylolitic lamination and sheeted structure (Figures 5A–C) which indicate the movement on the shear planes during the formation of gold veins (e.g., Mitchell et al., 2004).

In Adit III, the strong post-vein faulting more or less along the plane of the shear resulted in pinched and swelled structure, and brecciation. F1 and F2 faults are mainly related to the mineralized veins where bedding is usually low angle with southeast-northwest trending fold axes; most veins intersect bedding at a high angle, cut crenulation cleavage where visible, cut the bedding plane, and accompanied by pervasive silicaification of the mudstone (Figures 5A–C). The general trend of bedding is NE-SW direction parallel to the mineralized veins (Figure 4). En-eclinal sigmoidal tension gashes filled with barren to weakly auriferous fibrous quartz are widespread in the mudstone sometimes kilometers away from the mineralized veins (Figures 6A–D). The tension gash veins in the shear zone imply ductile deformation which is evident for later faulting (Figure 6C). The Shwetagun area is structurally complex; there have been at least two or three deformation phases in both small-scale and major structures (e.g., Mitchell et al., 2004). No igneous rocks have been found at the Shwetagun area, and the nearest igneous rocks to the Modi Taung deposit are the microgranite porphyry at Theingi vein and the late dacite and andesite porphyry dykes which cut across the ore zone at Shwesin vein (Traynor et al., 2015, 2017) and Momi Taung, approximately 3 km northeast of Shwetagun (Figure 3).

**Kyaikhto Gold District**

The Kyaikhto gold district in the southern part of MB consists of several gold deposits and occurrences, including Kunzeik, Zibyaung and Meyon (Figure 7). The Kyaikhto gold occurrences are formed as sheeted veins, massive veins, network veinlets, stockworks, and disseminations. The structural setting at the Kyaikhto gold occurrences is dominated by NNE-SSW, and NW-SE striking faults (Figure 7). Mineralization in the Kyaikhto gold district is hosted by metasedimentary rocks of sandstone, slate, phyllite, and schist, and associated with the biotite granite and biotite granodiorite (Figure 7). The granitic rocks in this area can be correlated to the Mokpalin quartz diorite and the Kyaikhtyo granite that have yielded the LA-ICP-MS zircon U-Pb ages of 90.8 ± 0.8 Ma and 63.3 ± 0.6 Ma, respectively (Figure 7; Mitchell et al., 2012; Myo Kyaw Hlaing et al., 2019). The metamorphic grade of the metasedimentary rocks is greenschist facies, characterized by a mineral assemblage of epidote, biotite, muscovite, and chlorite. Locally, fine-grained pyrite crystals are disseminated in the slate, phyllite, and schist (Myo Kyaw Hlaing et al., 2019).

The quartz vein systems almost invariably appear to be related to regional NNW-SSE trending structures which are commonly recorded along the MB (Figure 2). Brecciation and fracturing of the quartz vein contributed favorable sites for supergene gold enrichment processes (Zaw Naing Oo and Khin...
The thickness of the tension gash veins and stockwork veins varies from a few 20 cm to 2 m wide. All of these gold deposits feature extensive, steeply dipping, vein systems, usually with multiple stages of vein development. In some deposits, the veins are slightly narrow (1–2 m) and separated, and there may be several parallel veins set within broad structural zones (e.g., Meyon). In other areas, such as at Kunzeik, the multiple vein systems form stockwork structures. At Zibyaung, the mineralized quartz veins are found as white to milky quartz. Mineralization in the Kyaikhto gold district is dominantly related to the deformation of the host rocks and occurred within structurally-controlled dilatant fractures.
MATERIALS AND ANALYTICAL METHODS

During the years 2012–2018, representative samples of the Shwetagon deposit in the Modi Taung-Nankwe gold district and Kyaikhto gold district were collected from active mining operations. Forty samples were examined using a Rigaku Ultima IV X-ray diffractometer to detect alteration minerals, running at 40 kV and 20 mA with a CuKa varying from 2.0 to 65.0 (2θ).

Forty-five thin sections and seventeen polished sections were prepared for the examination of ore and gangue minerals from...
the Shwetagun deposit and Kyaikhto gold occurrences using NIKON ECLIPSE LV100N POL petrographic microscope and the scanning electron microscope (SEM) with energy-dispersive X-ray spectroscopy (EDS) of HITACHI-SU3500 at the Center of Advanced Instrumental Analysis, Kyushu University. SEM-EDS analysis was used to determine the elemental composition of pyrite, chalcopyrite, sphalerite, arsenopyrite, galena, hematite, and other ore minerals, including the Au-Ag ratio of electrum.

Fifteen doubly polished thin sections of mineralized quartz were prepared from the Shwetagun deposit and Kyaikhto gold occurrences for fluid inclusion studies. Microthermometric measurements were conducted at Kyushu University using a Linkam-THMS600 heating-freezing stage equipped on a NIKON ECLIPSE LV100N POL petrographic microscope. The heating/freezing rate was generally 0.2−5.0°C/min but was <0.2°C/min near a phase transition. The uncertainties for the measurements are ±0.5, ±0.2 and ±2.0°C for runs in the range of −120 to −70°C, −70−100°C, and 100−600°C, respectively. The fluid inclusions were classified by the criteria of Roedder (1984). Total salinities of NaCl-H2O inclusions were calculated from the final melting temperatures of ice using the equation by Bodnar (1993). Salinities of the inclusions of the CO2-bearing fluid inclusion studies. Microthermometric fluid inclusion studies. Microthermometric inclusions were classified from the intensity of brittle and ductile deformation and the degree of hydrothermal alteration (Figure 8).

Kyaikhto Gold District
The quartz-gold veins in the Kyaikhto gold district are hosted within an intensely deformed sedimentary sequence comprising sandstone and carbonaceous mudstones (Myo Kyaw Hlaing et al., 2019). The host mudstone and phyllite are silicified and hydrothermally altered to assemblages with sericite, chlorite, kaolinite, and pyrite (Myo Kyaw Hlaing et al., 2019). At Kunzeik, the strongly altered rocks adjacent to the auriferous quartz veins are typically enriched in sulfide minerals (e.g., pyrite and chalcopyrite). Silicification and pyritization are easily observable close to the veins. Silicification was followed by sericitization in the felsic host rocks. At Zibyaung, the host phyllite is affected by an earlier (chlorite) alteration and later silicification and sericitization. Chloritization overprinting sericitization becomes more pervasive proximal to the distal parts of ore bodies. At Meyon, hydrothermal alterations are characterized by silicification and chloritization, sericitization, carbonate alteration, kaolinite, and albite alteration and quartz infill of the metasedimentary rocks and ore breccias are also recorded. Sulfides are sparsely disseminated in the rock and completely altered to limonite (Zaw Naing Oo et al., 2010; Zaw Naing Oo and Khin Zaw, 2015, 2017).

Ore Mineralogy
Microscopically, the ore samples show various mineral assemblages and indications of fracture fillings as well as replacement textures. Based on microscopic observation, there are two types of gold-bearing sulfide ore textures: the disseminated and fracture-filling sulfide types (Figures 9A,B,D,E). The electrum occurs as submicron-sized inclusions in the fracture of sulfides at Shwetagun (Figures 9A,B). Most of the electrum grains are identified as free grains, but some are intergrown with pyrite, chalcopyrite, galena and sphalerite. Locally, it is concentrated as clumps of irregular electrum grains dispersed in alteration minerals. Some electrum grains are lighter and gradually change to whitish color with very high reflectivity, due to presence of high silver content. The electrum grains at Shwetagun yielded an Au content of 72.9−74.3 atomic %. Sphalerite is one of the major ore minerals and appears in euhedral to subhedral aggregates up to 5 mm in size (Figure 9C). The FeS mol% of sphalerite is between 4.02 and 8.41. Chalcopyrite is a primary important hypogene mineral in the ore textures (Figure 9E).

Pyrite is the most abundant sulfide mineral at Shwetagun. It occurs as fine-grained, massive aggregate and euhedral to subhedral crystals along the outer margin of the quartz veinlets. The earliest sulfide mineral is invariably pyrite, with deeply fractured sub-euhedral crystals that are locally replaced by other base-metal sulfides (Figures 9A-E). A few grains of pyrite are replaced by chalcopyrite along their grain boundaries and microfractures (Figure 9E).

At Kunzeik, the quartz-carbonate-sulfide vein consists of chloritized host rock fragments surrounded by irregular to massive aggregates of pyrite, chalcopyrite, and sphalerite...
together with quartz and chlorite (Figure 9F; Myo Kyaw Hlaing et al., 2019). Electrum, sphalerite, and galena are mostly found in pyrite at Zibyaung (Figures 9G,H; Myo Kyaw Hlaing et al., 2019). Sphalerite forms as a fissure filling mineral within pyrite. Galena occurs as fine-to medium-sized grains filling cracks in pyrite and sphalerite. Electrum grains with an atomic % of 74.5–78.1 Au can be detected as minute grains in pyrite with galena, and sphalerite (Figure 9F–H). The FeS mol% of sphalerite ranges from 4.98 to 7.26. At Meyon, chalcopyrite is associated with pyrite and covellite. Covellite occurs as a secondary replacement mineral of chalcopyrite (Myo Kyaw Hlaing et al., 2019). Native gold also develops as free grains in the oxidized zone and fracture fillings within pyrite. Pyrite occurs as two generations, idiomorphic grains intergrown with chlorite aggregates or in contact with massive chalcopyrite, pyrrhotite, arsenopyrite, marcasite, magnetite and hematite (Zaw Naing Oo and Khin Zaw, 2009; Zaw Naing Oo et al, 2010; Zaw Naing Oo and Khin Zaw, 2015; 2017; Myo Kyaw Hlaing et al., 2019).
FIGURE 9 | Photomicrographs showing (A) electrum inclusion in subhedral pyrite (py II) with sphalerite of the gold-bearing quartz vein in adit-I from Shwetagun, (B) fractured electrum filled with euhedral pyrite (py I) and galena, suggesting their chronological relationship of the gold-bearing quartz vein in adit I from Shwetagun, (C) euhedral pyrite (py I) associated with sphalerite and chalcopyrite of the gold-bearing quartz vein in adit-III from Shwetagun, (D) backscattered electron image with an electrum grain in pyrite from Shwetagun, (E) electrum inclusion is surrounded by chalcopyrite, sphalerite and arsenopyrite in pyrite from Shwetagun, (F) massive pyrite aggregates with chalcopyrite, and sphalerite of quartz-carbonate-sulfide vein from the Kunzeik, (G) and (H) fractured electrum filled with euhedral pyrite, galena and sphalerite of quartz-sulfide vein from Zibyaung. Figures (g) and (h) are taken from Myo Kyaw Hlaing et al. (2019). Abbreviations: py = pyrite, gn = galena, ccp = chalcopyrite, sp = sphalerite, apy = arsenopyrite, el = electrum and qz = quartz.
Fluid Inclusion Characteristics

Fluid inclusions studies have been performed in quartz, quartz-sulfide and quartz-carbonate-sulfide veins from the Shwetagun, Kunzeik and Zibyaung deposits (Figures 10A–D). At Shwetagun, fluid inclusions were found in quartz in the mineralized veins quartz. There are two types of fluid inclusions: Type A (vapor-rich) and Type B (liquid-rich). Type A (vapor-rich) and Type B (liquid-rich) aqueous fluid inclusions were observed in all quartz samples and occur as isolated groups of primary inclusions as clusters and pseudo-secondary trails. Secondary fluid inclusions (trail-bound) are also present but are extremely small (<2 μm) and have not been studied. Most fluid inclusions were aqueous (H₂O) fluid inclusions. At Kunzeik and Zibyaung, two types of fluid inclusions were found in quartz and calcite of quartz-carbonate-sulfide and quartz-sulfide veins at room temperature (Figures 11A–H). Based on the criteria described by Roedder (1984), the fluid inclusions were classified as primary, pseudo-secondary, and secondary, and given below: Type A (aqueous-carbonic) inclusions, Type B (aqueous) inclusions.

Type A (aqueous-carbonic inclusions): This type belongs to the H₂O–CO₂–NaCl system and occur in quartz and calcite of the mineralized vein quartz. They are 5–10 μm in size and have biphase (liquid and vapor) at room temperature. These inclusions also show presence of three phase (liquid H₂O, liquid CO₂, vapor CO₂) and clathrate during freezing runs. The CO₂:H₂O ratio in these inclusions range from 80:20 to 50:20. Occasionally vapor bubbles are moving but no liquid CO₂ is present (Figures 11C–E–G).

Type B (aqueous inclusions): have been identified in quartz and calcite of the mineralized vein quartz. These inclusions are biphase with a vapor bubble and liquid at room temperature (Figures 11C–F,H).

Fluid Inclusion Microthermometry

Fluid inclusion characteristics of the gold deposits are summarized in Table 2 and Figures 12, 13. At Shwetagun, the final ice melting temperatures (Tm-ice) for Type A (vapor-rich) aqueous inclusions in quartz range from →0.1 to →2.8°C (n = 10) (Table 2). The homogenization temperatures of Type A (vapor-rich) aqueous fluid inclusions in quartz of veins vary from 250 to 335°C (n = 15), with salinities from 0.2 to 4.8 wt% NaCl equivalent (Table 2; Figures 12A,B). The final ice melting temperatures (Tm-ice) of Type B (liquid-rich) aqueous inclusions in quartz of veins studied range from →1.2 to →2.7°C (n = 14). The homogenization temperatures of Type B (liquid-rich) aqueous fluid inclusions in quartz were from 261 to 320°C (n = 16), with salinities from 3.1 to 4.5 wt% NaCl equivalent (Table 2; Figures 12A,B).

At Kunzeik, complete homogenization temperatures (Th) of (Type A) aqueous-carbonic fluid inclusions in quartz vary between 315°C and 356°C (n = 21) (Figure 12C). Homogenization temperatures (Tm) of the (Type B) aqueous fluid inclusions in quartz of the mineralized vein quartz yielded a range approximately 246°C–376°C (n = 21) (Figure 12D). The melting of CO₂ (Tm-CO₂) in (Type A) aqueous-carbonic inclusions in quartz were between →58.2°C and →56.8°C (Table 2). The CO₂ phases of the (Type A) aqueous-carbonic inclusions in quartz were fully homogenized to the liquid phase at temperatures (Tm-CO₂) of 25.5°C–30.9°C. The melting temperatures of clathrates in quartz (Tm-cla = 7.6°C–9.2°C) (n = 10) suggest that the salinity of these clathrate inclusions is low, around 1.6 to 4.6 wt% NaCl equivalent. The final ice melting temperatures of (Type B) aqueous fluid inclusions in quartz range between →0.6 and →7.2°C (n = 14) corresponding to salinities between 1.1 and 10.7 wt% NaCl equivalent.

Total homogenization temperatures (Tm-ice) of (Type A) aqueous-carbonic fluid inclusions in calcite range from 273°C to 318°C (n = 17) (Figure 12C). Homogenization temperatures (Tm) of (the Type B) aqueous fluid inclusions in calcite of the vein quartz yielded a range from 248°C to 325°C (n = 20) (Figure 12D). The melting of CO₂ (Tm-CO₂) in (Type A) aqueous-carbonic inclusions in calcite took place between →57.2°C and →56.8°C (Table 2). The CO₂ phases of the (Type A) aqueous-carbonic inclusions in calcite were completely homogenized to the liquid phase at temperatures (Tm-CO₂) of 21.5°C–29.9°C. The melting temperatures of clathrates in calcite (Tm-cla = 8.6°C–9.2°C) (n = 11) indicates that the salinity of these clathrate inclusions are generally low, about 1.6–2.8 wt% NaCl equivalent. The final ice melting temperatures of (Type B) aqueous fluid inclusions in calcite range from →1.2°C to →6.8°C (n = 13) corresponding to salinities from 2.1 to 10.2 wt% NaCl equivalent.

At Zibyaung, homogenization temperatures of the (Type A) aqueous-carbonic fluid inclusions in quartz of vein range between 312°C and 348°C (n = 19). The homogenization temperatures of (Type B) aqueous fluid inclusions in quartz of the vein vary between 242°C and 358°C (n = 19). The values of (Type A) aqueous-carbonic inclusions Tm-CO₂ fall in the range of →57.3°C to →56.8°C, indicating the only presence of pure CO₂. However, a few inclusions show Tm-CO₂ values around -60°C, which can be due to the presence of minor other volatile components (Roedder, 1984). The first melting of ice (Tm-ice) in most of the (Type A) aqueous-carbonic fluid inclusions in quartz occurred between 20.5 and 30.9°C (n = 8) (Table 2). The temperatures of clathrate melting (Tm-cla) are between 4.6 and 9.6°C wt% NaCl equivalent (Table 2; Figure 12E). Final melting of ice (Tm-ice) in (Type B) aqueous fluid inclusions in quartz was observed in a temperature range from →0.5°C to →8.1°C (n = 11) (Table 2), suggesting the salinities of 0.9 to 11.8 wt% NaCl equivalent (Figure 12F). Box and whisker plots of results from two and three phase fluid inclusions in the two gold districts are shown in Figures 13A,B.

DISCUSSION

Comparison With Orogenic Gold Deposits Worldwide

Several geological and geochemical characteristics of the MB gold deposits are comparable with those of the typical orogenic gold deposits worldwide (Table 3; e.g., Groves et al., 1998; Hagemann and Cassidy, 2000; Kerrich et al., 2000; Poulsen et al., 2000; Goldfarb et al., 2001; Robert and Poulsen, 2001; Groves et al., 2003; Goldfarb et al., 2005; Robert et al., 2005; Large et al., 2011; Groves et al., 2019). The gold deposits of the MB have a number
of characteristics that are consistent with an orogenic gold system, including a close association between mineralization and deformation, and mineral assemblages of veins and alteration that are similar to Archean and Paleozoic gold systems (e.g., Groves et al., 1998; Bierlein and Crowe 2000; Hagemann and Cassidy 2000; Large et al., 2007). The orogenic gold systems are formed from the crustal fluids produced during the prograde metamorphism at the greenschist-amphibolite facies transformation and developed at intermediate depths (2–10 km) (Groves et al., 1998, 2003, 2020; Bierlein and Crowe, 2000; Goldfarb et al., 2001, 2005; Phillips and Evans, 2004; Dubé and Gosselin, 2007; Phillips and Powell, 2009, 2010; Tomkins, 2013; Goldfarb and Groves, 2015). Metamorphic fluids are generally regarded to be significant in the formation of orogenic gold deposits (e.g., Groves et al., 1998, 2003). There is still some debate over the appropriate source of orogenic gold ore fluids and the metals they transport (Tomkins, 2013; Goldfarb and Groves, 2015; Wyman et al., 2016; Groves et al., 2020). In comparison, Wyman et al. (2016) explored the presence of magmatic fluids in various orogenic gold deposits worldwide, as well as providing a comprehensive review of mineralizing fluids in orogenic gold systems. The formation of the widespread alteration of albite-silica-chlorite-sericite-carbonate-pyrite associated with the gold-bearing quartz veins in the MB was a major enhancing mineralizing mechanism for many other orogenic gold deposits worldwide (e.g., Phillips, 1993; McCuaig and Kerrich 1998; Goldfarb et al., 2005). The worldwide examples of these structural setting of the orogenic gold deposits are recorded at Golden Mile in Kalgoorlie, Western Australia, Western Lachlan Orogen in Victoria, SE Australia, Buller Terrane in western South Island, New Zealand, Meguma Terrane in Nova Scotia, Canada and Main Divide and Pingfengshan gold mine in Taiwan (Table 3; Shackleton et al., 2003; Bierlein et al., 2004; Groves et al., 1998, 2003; Goldfarb et al., 2001, 2005; Craw et al., 2010). Similar structural settings of the gold deposits are found in Myanmar at Phayaung Taung, Modi Taung and Shwegyin (Table 3; Mitchell et al., 2004; Win Phyo et al., 2016; May Thwe Aye et al., 2017; Ye Myint Swe et al., 2017).

**Fluid Evolution and Depth Estimation**

The microthermometric characteristics of fluid inclusions, alteration types, host rocks and tectonic setting related to various stages of vein formation of the mineralized quartz vein systems of Shwetagan (Modi Taung-Nankwe) and the Kyakhto gold districts are remarkably similar. A majority of orogenic gold deposit studies have reported ore-mineralizing fluids to be of low salinity and aqueous-carbonic in composition (e.g., McCuaig and Kerrich 1998; Ridley and Diamond, 2000; Groves et al., 2003;
FIGURE 11 | Photographs showing the quartz veins of the deposits. (A) quartz-carbonate-sulfide vein from Kunzeik, (B) quartz-sulfide vein from Zibyaung, and photomicrographs (C) and (D) showing Type A (aqueous-carbonic) and Type B (aqueous) fluid inclusions in calcite of the quartz-carbonate-sulfide vein from Kunzeik, (E) and (F) showing Type A (aqueous-carbonic) and Type B (aqueous) fluid inclusions in quartz of the quartz-carbonate-sulfide vein from Kunzeik, (G) and (H) Type A (aqueous-carbonic) and Type B (aqueous) fluid inclusions in quartz of the quartz-sulfide vein from Zibyaung. Abbreviations: ccp = chalcopyrite, cal = calcite and qz = quartz.
### TABLE 2 | Comparative analyses of fluid inclusion types and microthermometric results of the Shwetagun, Kunzeik and Zibyaung deposits.

| Deposit Name | Vein Type | Type | \(T_{m-CO_2}\) (°C) | \(T_{m-cla}\) (°C) | \(T_{h}\) (°C) | \(T_{m-ice}\) (°C) | Host mineral | Salinity (wt% NaCl eq.) | \(CO_2\) density (g/cm\(^3\)) | Bulk density (g/cm\(^3\)) | References |
|--------------|-----------|------|---------------------|-------------------|----------------|---------------------|---------------|------------------------|-------------------------|--------------------------|------------|
| Shwetagun    | Gold quartz vein | Types A | — | — | 260 | to 335 | — | Quartz | 0.2 to 4.6 | — | 0.62 to 0.83 | This study |
|              |           | Type B | — | — | 261 | to 320 | — | — | 3.1 to 4.5 | — | 0.67 to 0.82 | |
| Kunzeik      | Quartz-carbonate-sulfide vein | Type A | — | — | 315 | to 368 | — | Quartz | 1.6 to 4.6 | 0.53 | — | Myo Kyaw Hlaing et al., 2019 |
|              |           | Type B | — | — | 246 | to 376 | — | Calcite | 1.6 to 2.8 | 0.61 | — | This study |
| Zibyaung     | Quartz-sulfide vein | Type A | — | — | 312 | to 348 | — | Quartz | 4.6 to 9.6 | 0.53 | — | Myo Kyaw Hlaing et al., 2019 |
|              |           | Type B | — | — | 242 | to 368 | — | Calcite | 2.1 | 0.67 | 0.53 to 0.91 | This study |

**Notes:** \(T_{m-CO_2}\) — melting temperature of CO\(_2\); \(T_{m-cla}\) — melting temperature of CO\(_2\) clathrate; \(T_{h}\) — partial homogenization temperature of CO\(_2\) inclusions; \(T_{m-ice}\) — final ice melting temperature; wt% NaCl eq., weight percent NaCl equivalent.

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**FIGURE 12 |** Histograms of total homogenization temperatures (\(T_{h}\)) and salinities of primary fluid inclusions in quartz, quartz-sulfide and quartz-carbonate-sulfide veins from the deposits. (A) Histograms of \(T_{h}\) of primary fluid inclusions in gold-bearing quartz veins from the adit-I, II and III at Shwetagun. (B) Salinities of fluid inclusions in gold-bearing quartz veins from the adit-I, II and III at Shwetagun. (C) Histograms of \(T_{h}\) of primary fluid inclusions in quartz-carbonate-sulfide veins from Kunzeik. (D) Salinities of fluid inclusions in quartz-carbonate-sulfide veins from Kunzeik. (E) Histograms of \(T_{h}\) of primary fluid inclusions in quartz-sulfide veins from Zibyaung. (F) Salinities of fluid inclusions in quartz-sulfide veins from Zibyaung. Figures (C), (D), (E) and (F) are adapted from Myo Kyaw Hlaing et al. (2019). **Abbreviations:** \(n\) = number of fluid inclusions.
The abundant aqueous fluid inclusions are similar to gold-related fluids throughout the belt, and typical of orogenic gold deposits elsewhere (e.g., Ridley and Diamond, 2000; Groves et al., 2003).

At Shwetagun, Type A (vapor-rich) inclusions are much less abundant than the Type B (liquid-rich) fluid inclusions, but they were observed as primary and pseudo-secondary inclusions in all samples. The secondary fluid inclusions have similar microthermometric properties to the primary inclusions, indicating that they represent events of vein reactivation in an evolving hydrothermal environment (Roedder, 1984). The ore fluid of Shwetagun ore-forming fluids evolved from a low to medium temperature (250–335°C), low salinity (0.2–4.6 wt% NaCl equivalent).

According to microthermometric results, a drop in salinities is found simultaneously with a decrease in temperature, suggesting that the system is diluted with cooling during the fluid evolution at Shwetagun. The major mechanism of ore and gangue mineral precipitation in veins is temperature drop (Figure 14). The absence of CO₂ in the gold-bearing veins at the Shwetagun deposit is in contrast to many ancient orogenic gold deposits, where separate phases of CO₂ are commonly found in fluid inclusions (Groves et al., 1998; McCuaig and Kerrich 1998; Bierlein and Crowe 2000; Goldfarb et al., 2004, 2005; Craw et al., 2010). However, the abundant CO₂ in the fluid is not a prerequisite for orogenic gold mineralization. (e.g., Main Divide and Pingfengshan gold mine in Taiwan; Craw et al., 2010 and references therein). The bulk densities of ore fluids from the Shwetgun deposit range from 0.62 to 0.83 g/cm³ (Table 2). Although no depth estimation of the Shwetgun deposit is possible by fluid inclusion evidence, Mitchell et al. (2004) estimated a depth of 4–7 km based on stratigraphic and structural evidence.

In comparison, fluid inclusions in these deposits at Kunzeik and Zibyaung are dominated by earlier Type A (aqueous-carbonic) and Type B (aqueous) fluids. Histograms of homogenization temperatures and salinities, as well as a diagram of homogenization temperatures versus salinities, show a wide range of homogenization temperatures between 242 and 376°C, and low to medium salinities between 0.9 and 11.8 wt% NaCl equivalent, respectively (Table 2; Figures 12–14).

According to microthermometric results, the range of total homogenization temperatures (242–376°C) indicate that there may have been more than one episode of CO₂ phase separation during vein formation. The wide range of salinity also indicates a source of fluid, possibly mixed with low-salinity exotic fluid (Figure 14). Based on the relative timing of fluid inclusions, Type B (aqueous) fluids formed first, followed by Type A (aqueous-carbonic) fluids (Figure 14). The Kunzeik and Zibyaung fluids show two totally identical processes of total homogenization of Type A (aqueous-carbonic) and Type B (aqueous) inclusions within a similar temperature range, indicating that they were trapped together and may represent the same H₂O-CO₂-NaCl system (Table 2; Figures 12–14).

The coexistence of Type A (aqueous-carbonic) and Type B (aqueous) fluid inclusions allows to estimate the depth of ore formation using the method of intersecting of the isochores based on the CO₂–H₂O–NaCl system. Using the CO₂ density formulae of the state of the isochores of Span and Wagner (1996) and the H₂O density isochores of Steele-MacInnis et al. (2012), and the pressure conditions of Sterner and Pitzer (1994), the bulk composition and density of fluid inclusions of these gold deposits were determined as below. The isochores of the Type A (aqueous-carbonic) and Type B (aqueous) fluid inclusions were plotted using the Roedder and Bodnar (1980) and Bowers and Helgeson (1983) state of equations, respectively (Figure 15).

The trapping pressures of fluid inclusions have been determined using CO₂-rich inclusions in quartz veins of the Kunzeik and Zibyaung deposits. The bulk densities vary from 0.53 to 0.91 g/cm³ and the densities of CO₂ range between 0.53 and 0.77 g/cm³ (Table 2; Figure 15). The Types A and B fluid inclusions from the Kunzeik deposit indicate that the deposit was formed at 376–246°C and 54–164 MPa (Figure 15), and for Zibyaung, it is estimated to be 358–242°C and 53–156 MPa (Figure 15). These data suggest a temperature and pressure variation during the ore-forming process. Depending on the pressure, the depth of mineralization was estimated. Given that studied areas are in a compressive orogenic environment, the formula can be used to estimate the metallogenic depth by lithostatic pressure: H = P/(ρ x g) (ρ represents average density of rocks, such as 2.70 g/cm³). These pressures correspond to the
### Table 3: Comparative table showing characteristics of the Shwetagun, Kunzeik and Zibyaung deposits with other orogenic gold deposits in Myanmar and worldwide.

| Name of Deposit/Prospect | Location and Geologic Setting | Host Rocks | Mineralization Styles | Alterations | Metal Associations | Ore Fluid Systems, Temperature and Salinity | Regional Peak Metamorphism Events | Age of Host Terranes | References |
|--------------------------|--------------------------------|------------|-----------------------|-------------|-------------------|-------------------------------------------|----------------------------------|---------------------|------------|
| Golden Mile              | Kalgoorie, Western Australia  | Black shale, slate, basalts, and dolerite | Quartz vein and stockwork | Carbonation, Sericitization, Sulfidation | Cu, Fe, As, Pb, Zn, Bi, Sb, Mo, Te, Ag, Au | H$_2$O-CO$_2$-H$_2$O-NaCl, 200–400°C (0.5–10 wt% equiv. NaCl) | Lower greenschist | Archean | Shackleton et al., 2003; Groves et al., 1998, 2003; Goldfarb et al., 2001, 2005 |
| Western Mergui Belt      | Nova Scotia, Canada           | Slate, argillite or meta-sandstones | Laminated bedding-parallel veins | Carbonate, Sericite, Chlorite, Sulphidation, Ankerite, Chlorite-Carbonate | Cu, Fe, As, Pb, Sn, Ag, Au | H$_2$O-CO$_2$-H$_2$O-NaCl, 300–400°C (<10 wt% equiv. NaCl) | Lower greenschist–Upper amphibolite, Devonian | Upper Cambrian–Middle Ordovician | Groves et al., 1998, 2003; Goldfarb et al., 2001, 2005; Bierlein et al., 2004 |
| Shwetagun                | Southern Myanmar              | Phylite, schist, and quartzite | Sulfide quartz vein | Silicification, Phyllic/Sericite, Chloritization, Oxidation | Cu, Fe, As, Pb, Sn, Bi, Te, Ag, Au | H$_2$O-NaCl, 243–426°C (0.4–8.4 wt% equiv. NaCl) | Lower greenschist–Upper Amphibolite | Upper Carboniferous to Lower Permian | Win Phyo et al., 2016; Ye Myint Sve et al., 2017 |
| Modi Taung               | Southern Myanmar              | Mudstone, graywacke, and slate | Laminated or ribbon banded quartz vein, Sheeted vein | Carbonation, Sericitization, Sulfidation | Cu, Fe, As, Pb, Zn, Ag, Au | Unknown | Lower Jurassic - Eocene | Upper Carboniferous to Lower Permian | Mitchell et al., 2004; Traynor et al., 2015, 2017 |
| Shwegyin                 | Southern Myanmar              | Slate, phylite, schist, and quartzite | Sulfide quartz vein, Sheeted vein | Carbonation, Sericitization, Sulfidation | Cu, Fe, As, Pb, Zn, Ag, Au | H$_2$O-NaCl, 250–335°C (0.2–4.6 wt% equiv. NaCl) | Lower greenschist–Upper Amphibolite | Upper Carboniferous to Lower Permian | This study |
| Kunzeik                  | Southern Myanmar              | Slate, biotite granite, granodiorite | Sulfide quartz vein, stockwork | Sulphidation | Cu, Fe, Mo, Ag, Au | H$_2$O + CO$_2$–NaCl | Lower greenschist–Upper Amphibolite | Lower Jurassic - Eocene | May Thwe Aye et al. (2017) |
| Zibyaung                 | Southern Myanmar              | Slate, biotite granite, and dolerite | Sulfide quartz vein, stockwork | Sulphidation | Cu, Fe, Mo, Ag, Au | H$_2$O + CO$_2$–NaCl | Lower greenschist–Upper Amphibolite | Lower Jurassic - Eocene | This study |
|                          |                                |            |                       |             |                   |                                           |                                  |                     | (Continued on following page) |
TABLE 3 (Continued) Comparative table showing characteristics of the Shwetagun, Kunzeik and Zibyaung deposits with other orogenic gold deposits in Myanmar and worldwide.

| Location          | Metal Associations | Alterations                          | Mineralization Style | Host Rocks and Stratigraphic Setting | Metallogenic Implications                                                                 |
|-------------------|--------------------|--------------------------------------|----------------------|-------------------------------------|--------------------------------------------------------------------------------------------|
| Shwetagun         |                   |                                      |                      |                                     | The Shwetagu gold-bearing quartz veins and, in particular, the Zibyaung and Kunzeik deposits in MB show a structural relationship between the first-order structures, mostly N-S to NNE-NNW oriented, and second order, one trending NW–SE. The fault-valve model for orogenic gold deposits represents the cyclic fluctuation in fluid pressures, from lithostatic to hydrostatic, due to episodic shear stress (Sibson et al., 1988; Ridley 1993; Robert et al., 1995; Cox et al., 1995, 2001; Sibson and Scott 1998; Kisters et al., 2000; Oliver and Bons 2001; Groves et al., 2003). The available sulfur isotopic data along MB indicate that the δ34S values of pyrite range from ~2.80–4.43‰ in Meyon, (Zaw Naing Oo and Khin Zaw, 2009) and a range of +1.33–4.75‰ in Modi Taung (Traynor et al., 2015). These data suggest that the sulfur responsible for gold mineralization is likely to have been derived from a dominant magmatic source with a possible other minor fluid such as metamorphic fluid (e.g., Wyman et al., 2016; Groves et al., 2020). The age of the gold district of Modi Taung-Nankwe was stratigraphically considered between the Upper Permian and the Middle Jurassic (Mitchell et al., 2004). They considered that it was an orogenic style gold, linking its genesis to the crustal fluids generated during the metamorphism of the MMB (Mitchell et al., 2004; Gardiner et al., 2016). This metamorphism was defined as Jurassic in age, contemplating this age for gold mineralization (Mitchell et al., 2004). However, Searle et al. (2007) suggested a much younger age of Paleogene for peak metamorphism in MMB. Here, at Modi Taung, the Theingi vein is cut by a 20 m wide dyke, and the Shwesin and Momi Taung veins are cut by small dykes and sills (Mitchell et al., 2004; Traynor et al., 2015, 2017). LA ICP-MS U-Pb zircon dating of granitoid unit intruding the host sequence of the Modi Taung gold deposit yielded 95 ± 30 Ma and the age of the... |
| Zibyaung          |                   |                                      |                      |                                     |                                                                                            |
| Meyon             |                   |                                      |                      |                                     |                                                                                            |

Notes: a = Aquous-carbonic fluids, b = Aquous fluid inclusions.
FIGURE 14 | Diagram showing (A) typical trends in the $T_h$ (°C)–Salinity space caused by various fluid evolution mechanisms (from Wilkinson, 2001), and (B) variations of homogenization temperature and salinity of fluid inclusions with hydrothermal fluid evolution from Shwetagun, Kunzeik, and Zibyaung. The green arrows indicate that both temperature and salinity are decreasing.

FIGURE 15 | P-T diagram displaying isochores of the minimum and maximum densities of two types of fluid inclusions (modified from Roedder and Bodnar, 1980; Bowers and Helgeson, 1983). Figure indicates the density values (in g/cm$^3$) for respective inclusions. P-T estimation by intersecting isochores of Type A (aqueous-carbonic) (dashed lines) and Type B (aqueous) (solid lines) inclusions.
andesitic dyke cross-cutting the mineralization by LA ICP-MS U-Pb dating of apatite was determined to be 49 ± 1 Ma (Traynor et al., 2015, 2017). Further work on U-Pb dating of zircon from the cross-cutting dyke is required to ascertain the robust age for the dyke intrusion, the age of the orogenic gold mineralization at the Shwetagun deposit in the Modi Taung-Nankwe gold district appeared that it was formed relatively late. The age of mineralization of the Meyon is proposed to be Lower Cretaceous to Paleogene and may have been consistent with deformation and metamorphism as being structurally-controlled and linked to movement along the Papun Fault Zone (Figure 16; Zaw Naing Oo and Khin Zaw, 2009, 2017).

During the Lower Cretaceous to Oligocene, Myanmar was influenced by at least two main orogenic events (Cretaceous and Eocene), which may have contributed to widespread regional metamorphism which is possibly linked to gold mineralization in the MB (e.g., Mitchell et al., 2004; Gardiner et al., 2014; Khin Zaw et al., 2014a; Zaw Naing Oo and Khin Zaw, 2015; Khin Zaw, 2017; Gardiner et al., 2018). Gold veins were formed during the ascent of metamorphic fluids following the uplifting and prograde metamorphism of the entire MMB. The generation of this high-grade metamorphic process was associated with the subduction and collision of the India-Eurasia Plate (Khin Zaw et al., 2014b). Thus, we suggest that the age of mineralization for the orogenic gold deposits in the MB may have been Lower Cretaceous to Oligocene, and the emplacement of the mineralizing fluids was associated with retrograde metamorphism of the MMB and dehydration at a depth of 2–12 km (e.g., Mitchell et al., 2004).

All the evidence presented for the orogenic gold deposits of the MB also suggest that the mineralizing fluids were derived from multi-sources and the initial ore-forming fluids were thought to be either due to fluids produced by metamorphic devolatization and/or mixed with magmatic fluid (e.g., Wyman et al., 2016; Groves et al., 2020). These multi-sourced fluids may have been transported from the deep crust to the shallower level via first-order faults during the evolution of the ore fluid, especially in the late stages of ore precipitation (e.g., Kerrich and Fyfe, 1981; Higgins and Kerrich, 1982; Cameron and Hattori, 1987; Phillips and Powell, 1993; Mikucki, 1998; Diamond, 2001; Wilkinson, 2001). The derivation of the ore fluids from the supracrustal rocks below the continental crust is widely accepted for the source(s) of orogenic gold deposits (Phillips and Powell, 2010; Goldfarb and Santosh, 2014), either from the subducted slab, with overlying oceanic sediments, or from the lithosphere below (Figure 16; Groves and Santosh, 2015). Dehydration and metamorphism within the oceanic crust and sediments have been well-observed mechanisms for producing abundant aqueous-carbonic and low-salinity fluids, as
documented in orogenic gold deposits from fluid inclusions that induce massive energy and mass transport, culminating in the fractionation of mobile and even immobile elements (Pearce and Peate, 1995; Ridley and Diamond, 2000; Spandler et al., 2003).

In this context, the MB is a tectonic component of the Sibumasu terrane during the Jurassic to Cretaceous when the main tectonic transition from N-S compression to NNE-SSW shearing was progressively occurred. The large-scale circulation of fluids, granitic magmatism and metallogenesis took place during the Lower Cretaceous to Oligocene in the MB, as a result of which the initial ore fluids of the orogenic gold deposits were likely formed by dehydration, decarbonization and desulfidation of the subducting Neo-Tethys slab (Figure 16; e.g., Ridley and Diamond 2000; Phillips and Powell, 2010; Goldfarb and Santosh, 2014; Yardley and Bodnar, 2014; Khin Zaw et al., 2014b; Yardley and Cleverley 2015; Groves and Santosh, 2016; Groves et al., 2020).

**CONCLUSION**

This integrated study provided a framework for the genesis and metallogenic significance of gold mineralization in the Mergui Belt as below:

1. The comparison of the two gold systems in Mergui Belt suggests that the gold deposits are mainly hosted by the mudstone, slaty mudstone, greyschist sandstone, slate, and slaty phyllite of Mergui Group (dominantly of Carboniferous age), and are structurally-controlled by the NNE-NNW trending faults system. Hydrothermal alteration processes of various extents developed along the NNE-NNW trending structures and the alteration process was dominated by chloritization, sericitization, carbonatization, silicification. The most common sulfides are pyrite, sphalerite, chalcopyrite, and galena with native gold and electrum.

2. Comparing the fluid inclusion characteristics, evolution of fluid and depth estimation indicate that the ore fluids are composed of high temperature, low salinity, low CO₂, aqueous–carbonic fluid belonging to a H₂O-CO₂-NaCl system. The ore-bearing fluids are considered to have derived from dominantly of metamorphic with possible magmatic fluid inputs. Intersection of isochores of fluid inclusions in this study suggests that gold deposits were formed under the PT-depth conditions comparable to the global orogenic gold systems as evidenced by temperatures ranging from (242–376°C) to pressure (53–164 MPa) corresponding to a depth at around 2.0 and 6.1 km under lithostatic conditions.

3. The regional tectonic setting provided by comparison of the Shwetagon, Zibyaung and Khunzeik deposits raises the question of the timing of gold mineralization in Mergui Belt. The orogenic gold deposits in the Mergui Belt may have been genetically linked to the deformation and metamorphism of the host Paleozoic sequence at the time of the inferred Cretaceous to Oligocene age of mineralization. This prolonged tectonic and metallogenic event was associated with the subduction of the Neo-Tethys oceanic slab (Figure 16).

4. Additional ongoing controversies remain to investigate the origin of the gold deposits of the Mergui Belt in Myanmar whether the source of the gold was derived from deeper mantle or recycling and remobilization of crustal gold syngenetically accumulated in back arc basins of Sinbumasu. Further systematic investigations are required to successfully establish the relative timing of magmatism, metamorphism, and to address the importance of ore-forming processes involved in orogenic gold mineralization and future exploration.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

**AUTHOR CONTRIBUTIONS**

This work is a late result of the first author’s Master thesis (Department of Geology, University of Yangon, 2013) combined with some part from Ph. D thesis (Department of Earth Resources Engineering, Kyushu University, 2019). All authors finally endorsed the findings and contributed to the final manuscript.

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