Gold, Silver, and Copper Metallogeny of the Eastern Sunda Magmatic Arc Indonesia

Metalogeni Emas, Perak, dan Tembaga Busur Sunda Bagian Timur, Indonesia

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ABSTRACT
With the recent discovery of another world class gold-silver-copper deposit at the Tujuh Bukit Project (30.1 million ounces of gold and 19 billion pounds of copper), the Eastern Sunda Arc has continued to prove itself as an emerging economically important magmatic belt. This paper provides a general description of the metallogeny of the Eastern Sunda Arc, covering a wide spectrum of topics, from its tectonic setting, general geology, magmatic evolution, metal endowment and prospectivity, mineralization styles and implications towards exploration. The Eastern Sunda Magmatic Arc is constructed on a thinner island arc crust, bounded by the margin of Sundaland to the west and by the Australian continental crust to the east. As one of five different ages of magmatic belts defined along the arc, the Neogene magmatic belt is considered to be important as an overwhelming number of gold, silver, and copper deposits and prospects are spatially associated with Late Miocene-Pliocene age intrusions. The metallogeny of the Eastern Sunda Magmatic Arc is dominated by gold, silver, and copper which are predominantly contained in porphyry and epithermal deposit types. With a world class gold-silver-copper endowment of 92.44 million ounces of gold, 279.17 million ounces of silver and 61.92 billion pounds of copper, the Eastern Sunda Magmatic Arc has emerged as one of the most prospective gold-copper belts in the world. Porphyry gold-copper and epithermal gold-silver mineralization styles in the Eastern Sunda Magmatic Arc share similarities to those in typical island arc settings, e.g. the Philippines. They also display some unique characteristics that are spatially and genetically associated with ore and its environment and provide selection criteria for prospective regions and a further basis for construction of exploration models. District and deposit exploration models are refined on the basis of shared key features of the deposits in the region as guides during exploration. These key features provide vectors to ore, applicable in identifying the central, proximal, and distal parts of mineralized systems during exploration activities. Keys to exploration success include understanding the characteristic features of ore systems, observing key geological features in the field and determining vectors to ore.

Keywords: Gold-Silver-Copper, metallogeny, Eastern Sunda, magmatic arc, porphyry, epithermal

ABSTRAK
Dengan penemuan terakhir deposit emas-perak-tembaga tingkat dunia pada Proyek Tujuh Bukit (30,1 juta ons emas dan 19 miliar pon tembaga), Busur Sunda Bagian Timur telah berlanjut dengan
INTRODUCTION

With the recent discovery of another world class gold-silver-copper deposit at the Tujuh Bukit Project, Banyuwangi, East Java, in addition to another two known world class deposits, the Eastern Sunda Arc (Figure 1) has continued to prove itself as an emerging economically important magmatic belt. Despite legal and social concerns, recent positive exploration drilling results in Java, Lombok, and Sumbawa have reinforced the prospectivity of the arc.

This paper provides a general description of the metallogeny of the Eastern Sunda Arc with an emphasis on gold, silver, and copper. The description of the arc covers a wide spectrum of topics from its tectonic setting, general geology, magmatic evolution, metal endowment and prospectivity, mineralization styles and implications to exploration.

The general description of regional and local scale geology of the arc, given here, aims to define the shared key geological features related to criteria important for exploration area selection, and construction of a gold-silver-copper deposit model for the region. This paper provides exploration criteria for this region and other regions with similar tectonic and geologic settings to the Eastern Sunda Arc. In addition, much recent understanding of the gold and gold-copper deposit systems in the region relies on publications on individual deposits; this paper provides the first comprehensive deposit compilation for the region.

Regional Perspective and Prospectivity

The islands of Java, Bali, Lombok and Sumbawa constitute an east-west trending Eastern Sunda Magmatic Arc with a total length of about 1,800 km, part of the 3,940 km-long Sunda-Banda Arc extending from the northern tip of Sumatra Island through Java to east of Damar Island (Hamilton, 1979; Carlile and Mitchell, 1994; Setijadji et al., 2006).

Keywords: emas-perak-tembaga, metalogeni, Sunda Bagian Timur, busur magma, porpiri, epitermal
The Eastern Sunda Magmatic Arc was constructed on thin island arc crust, transitional with the margin of Sundaland in the west and bounded by Australian continental crust in the east (Hamilton, 1979; Carlile and Mitchell, 1994; Hall, 2002). It consists of a chain of islands that have undergone a similar geodynamic history from Java to Sumbawa. These islands share similarities in tectonic setting, regional geology with dominantly Neogene and Quaternary volcanic rocks, magmatic evolution since the Late Oligocene, and consistent northward magmatic migration.

The Eastern Sunda Magmatic Arc is predominantly composed of Oligocene to Quaternary magmatic rocks with widespread Late Miocene and Pliocene intrusions exposed along the southern part of the belt. The belt is considered to be prospective with several fertile districts identified along the islands on the basis of lithgeochemical studies (Setijadji et al., 2006; Loucks, 2009).

The Eastern Sunda Arc ranks among the most endowed magmatic belts in the Southwest Pacific region. The region contains more than fifteen magmatic belts in fifteen countries with a total strike length of more than 21,050 km and total gold endowment of 744.8 million ounces. About 45.1% or 321.2 million ounces are hosted in Neogene magmatic arcs and 42.6% or 317.3 million ounces have been discovered in Indonesia. The Eastern Sunda Arc contains 92.44 million ounces of gold, second to the Papuan Fold Belt on Papua Island (Maryono and Power, 2009).

For explorers, the competitive advantages of the Eastern Sunda Arc include a proven record of exploration successes including the recent discovery of another world class gold-copper deposit at Tujuh Bukit, existing infrastructure with the presence of an active world-class operating mine at Batu Hijau on Sumbawa, and a copper-gold smelter at Gresik East Java.
Regional Tectonics and Geology

The Eastern Sunda Arc is located along the tectonically active zone that marks the convergence of three major tectonic plates: Eurasian, Indo-Australian, and Pacific Plates (Hamilton, 1979). The western segment of the arc (West to East Java) developed on thick continental crust on the southern margin of Sundaland, whereas the eastern segment (East Java to Sumbawa) was constructed on a thinner island arc crust bounded by Australian continent crust further east (Sumba and Timor) (Hamilton, 1979; Carlile and Mitchell, 1994; Hall, 2002; Setijadji et al., 2006).

The geology of the islands of the Eastern Sunda Arc is characterized by island arc-type volcano-sedimentary successions of Oligocene to Quaternary age (Hamilton, 1979; Carlile and Mitchell, 1994; Metcalfe, 1996; Garwin, 2002; Setijadji et al., 2006) (Figure 2). Igneous rocks of Paleocene-Eocene age are thought to be present locally along the southernmost parts of Java at Bayah dome (Cikotok Formation), and at the Cikotok Formation and Jatibarang Volcanic Formation (JVF) in west Java (Hutchison, 1982; Sujatmiko and Santoso, 1992; Setijadji et al., 2006). The earliest magmatic activities can be traced, scattered toward east of Java as far as Pacitan, western part of East Java (JICA-JOGMEC, 2004; Setijadji et al., 2006).

While the Paleocene-Eocene volcanic centers are poorly defined and restricted in the area, Late Oligocene to Middle Miocene magmatic rocks are widespread and continuously distributed along the whole belt. Volcaniclastic rocks of Late Miocene to Pliocene age are more abundant than the older volcanic rocks, following the southern margin of the belt with a relative northward shift over time. Low-K calc-alkaline to weakly alkaline andesitic volcanic and interbedded volcaniclastic rocks, associated low-K intermediate intrusive rocks and minor shallow water marine sedimentary rocks extend from Java to Bali, Lombok and Sumbawa (Maula and Levet, 1996; Garwin, 2002; Setijadji et al., 2006).

![Regional geology of the Eastern Sunda Arc](image)

Figure 2. Regional geology of the Eastern Sunda Arc (summarised from Hamilton, 1979; Carlile and Mitchell, 1994; Hall, 2002; Setijadji et al., 2006).
The islands display progressively younger volcanic complexes of Pleistocene to Quaternary age towards the north, with recently active volcanoes, Mt. Krakatau in westernmost Java, Mt. Agung in Bali, Mt. Rinjani in Lombok, and Mt. Tambora and Mt. Sangeangapi in Sumbawa Islands. In total there are more than fifty-six Quaternary volcanoes along the belt from Java to Sumba.

Numerous Eocene to Pliocene (50.9 Ma to 2.7 Ma) intrusions occur scattered along the belts from Java to Sumbawa. Gabbro in Ciletuh, West Java is dated at 50.1-50.9 Ma (Pertamina-ITB, 2002), a dioritic dyke in Karangsambung, central Java at 37.6 Ma (Soeria-Atmadja et al., 1994), an andesitic intrusion in the Pacitan area at 38.7 Ma (JICA-JOGMEC, 2004). Miocene felsic intrusions were recognized include quartz diorite at Ciletuh - Ciemas (13.7 Ma) and rhyolite at Cirotan (9.6 Ma). At Cineam in West Java, Widi and Matsueda (1998) reported ages from 13.5 to 8 Ma for hydrothermal activity related to magmatism and epithermal mineralization in this area. Further east, late stage quartz diorite to tonalite dykes at 5.0 to 2.7 Ma have been reported from East Java, Lombok, and Sumbawa where they are associated with gold and gold-copper mineralization (Clode et al., 1999; Garwin, 2002, Maryono et al., 2005).

The Eastern Sunda Arc is segmented by a series of north-northeast trending arc-normal structures that are evident in topographic and satellite image data. Tectonic factors appear to have localized volcanic centres along the arc-normal structures.

RESULT AND DISCUSSION

Magmatic Evolution

In total, the Eastern Sunda Arc consists of five different ages of magmatic belts: Pre-Tertiary, Paleocene-Eocene, Oligocene-Middle Miocene, Late Miocene-Pliocene (Neogene) and Quaternary (Hamilton, 1979; Carlile and Mitchell, 1994; Hall, 2002; Setijadji, 2006) (Figure 3). The Arc is defined by a similar tectonic setting, constructed on thinner island arc crust, bounded by the margin of Sundaland in the west and by Australian continent crust in the east.

Earliest volcanism in the Eastern Sunda Arc is poorly understood and restricted to Java. It is thought to have developed during the initiation of the Java Trench in the Paleocene-Eocene as older volcanic rock units are restricted to a belt from West to East Java as far as Pacitan. The earliest magmatism resulted from the development of the Western Sunda Arc (Sumatra) that migrated to the east, in which the resulting magmatic arc was located along the edge of Sundaland, from Sumatra through Java, Sumba, and western Sulawesi (Hamilton, 1979; Carlile and Mitchell, 1994; Hall, 2002).

The spatial evolution of the volcanic arcs since the Oligocene is better understood and can be reconstructed. Collision between West Sulawesi and micro continents in the Miocene led to change the location of the subduction system to a more southerly position. The following volcanic activity then gave rise to the islands of Bali, Lombok, and Sumbawa. During the Oligocene to Pliocene, the volcanic centres have shifted northward (towards the back arc-side). The shifting distances increase relatively eastwards, and such spatial movement may have resulted from counter-clockwise rotation of the volcanic arcs, with westernmost Java (around Bayah dome) as the rotational pole.

The Early Tertiary volcanic arcs occupied the southern coast of the island, and perhaps also offshore to the south, as indicated by a high gravity anomaly. In the Late Miocene significant northward migration of volcanic centres was noteworthy in the eastern part.
of West and Central Java, but not in East Java. Again during the Pliocene, volcanic centres shifted northward. The back arc-ward volcanic shift ended after the Pliocene, and the trench-ward volcanic shift started in the Quaternary. The trench-ward shift is demonstrated by the ‘invasion’ of Late Tertiary volcanic centres by Quaternary volcanoes in West and Central Java, and the ‘missing’ Pliocene volcanoes in most of East Java. This may be due to their being completely covered by Quaternary volcanoes. Radiometric data from the Quaternary cross-arc volcanic chain of Merapi-Merbabu- Telomoyo-Ungaran also suggest that the Quaternary volcanism gradually moved trench-ward (Kohno et al., 2005). An exception occurs at westermmost Java, where Quaternary volcanism (Krakatau and Danau) migrated back arc-ward due to the Sunda Strait opening (Nishimura et al., 1986).

Back arc magmatism only took place since the latest Miocene to Quaternary. With recent physiography as reference, there are two main locations of back arc magmatism, i.e., on Java where the current depth of the subducted slab is around 320 - 350 km (Quaternary Muria and Lasem volcanoes), and offshore Java where the current depth of the subducted slab is around 600 km (Quaternary Bawean island). Analogous to the volcanic arc trench-ward shift after the Pliocene, the locations of back arc magmatism seem also to shift trench-ward from the Karimunjawa Islands to the Muria-Lasem volcanoes.

**Gold-Copper Endowment and Prospectivity**

Total metal endowment of the Eastern Sunda Arc is dominated by gold, silver, and copper with very insignificant other metals (iron, lead, and zinc). The arc contains 92.44 million ounces of gold, 279.17 million ounces of silver, and 61.92 billion pound of copper from 14 deposits and prospects. This large metal endowment is mainly contributed from three world class gold-copper deposits at Batu Hijau, Elang, and Tumpangpitu. The gold endowment of the Eastern Sunda Arc
accounts for 26.1% of the total gold endowment of Indonesia (317.3 million ounces; Maryono and Power, 2009).

In the regional context, the Eastern Sunda Arc stands among the top in the Southwest Pacific region (Maryono and Power, 2009). The region covers fifteen countries and hosts fifteen magmatic arc belts with total of more than 21,050 km strike length of magmatic arc belts and total gold endowment of 744.8 million ounces (Figure 4). The Eastern Sunda arc contains 11.1% of total region gold endowment, second to the Papuan Fold Belt (281.0 million ounces). A similar rank is seen in the Indonesian context that the arc contains 26.1% of the total Indonesian gold endowment (317.3 million ounces), second to the Indonesian part of the Papuan Fold Belt.

For such a short extent of magmatic arc length (1,800 km), with world-class gold, silver, and copper endowment the Eastern Sunda arc ranks it as one of the world’s most prospective magmatic belts, with potential similar to that of the Papuan Fold Belt and the Solomon-Lihir Magmatic Arc in the region. With remarkable known metal endowment and potential for new discoveries, the Eastern Sunda Arc has high prospectivity. On that basis the arc is considered to be one of the world’s emerging gold-copper belts.

Almost 100% of the metal endowment in the Eastern Sunda Arc is related to the Neogene magmatic stage, one of five stages of magmatic activities identified along the belt. Dating of mineralization age and/or related intrusion age shows similar features to the magmatic host rocks where mineralizing intrusions have been dated as Neogene in age (3.6 - 3.8 Ma) at Batu Hijau, 2.7 Ma at Elang, 7.5 Ma at Selodong, 2.5 Ma at Pongkor, and 3 Ma at Arinem. This is consistent with the Western Pacific region where the largest gold endowment (about 45.1% or 321.2 million ounces) is hosted in Neogene magmatic arcs (Maryono and Power, 2009).

![Figure 4. The Eastern Sunda Magmatic Arc with three world class-porphyry Cu-Au deposits discovered along the belt, making it one of the world’s most fertile and prospective magmatic belts.](image-url)
Three of 26 gold deposits containing >5 million ounces of gold in the western Pacific region occur along the belt in the form of porphyry Cu-Au deposits. These three world-class Cu-Au deposits are Batu Hijau (19.9 million ounces of gold and 19.6 billion ounces of copper; Clode et al., 1999; Newmont Annual report, 2009), Elang in Sumbawa (25.4 million ounces of gold and 16.3 billion ounces of copper; Newmont Mining Corporation, 2012) and at Tumpangpitu in East Java (27.4 million ounce of gold and 15.4 billion pounds of copper; Intrepid Mines Ltd, 2012). Active mine operations along the belt that are major contributors to Indonesia’s gold and copper production include gold mines of Pongkor, Cibaliung, and Cikotok in West Java, and Batu Hijau Cu-Au mine in Sumbawa, NTB Province.

Recent intense exploration programmes have delineated another world-class porphyry copper-gold deposit at Tumpangpitu, the Tujuh Bukit Project, recently discovered through intense drilling programmes by Intrepid Mines Ltd since September 2007. Other recent intense exploration drilling programmes have been carried out at Hu’u and Pangulir in Sumbawa, Brambang, Pelangan, and Mencanggah in Lombok and Selogiri and Trengalek in Java; they have all intersected significant copper and gold mineralization of porphyry and high sulfidation epithermal styles.

**Gold-Silver-Copper Mineralization Styles**

Porphyry Cu-Au mineralization style is a prime metal source for gold and sole source for copper in the Eastern Sunda Arc, contributing about 90.3% of total gold or 74.5 million ounces and 100% of copper endowment or 53.1 billion pounds. Epithermal mineralization styles are second with 8 million ounces of gold endowment or about 9.7%. This endowment is similar to that for the Western Pacific region in that about 88% of total gold endowment or 655.1 of 744.5 million ounces of total gold endowment are contributed by porphyry mineralization. Other deposit types, e.g. skarn and sediment-hosted, are insignificant.

In the eastern segment of the arc, significant porphyry deposits or districts are spaced approximately every 100 km along the east-west trending arc from Empang/Hu’u in the east, Elang, Batu Hijau in Sumbawa, Selodong/Brambang in Lombok, and Tumpangpitu in East Java, to the west. A long gap is seen further west to Selogiri in Central Java. Paucity of significant porphyry occurrences in the west segment of the arc is marked a contrast to the east segment.

Three world class porphyry deposits at Tumpangpitu, Batu Hijau, and Elang are thought to be restricted in the eastern segment on thin island arc crust. In contrast the western segment is dominated by low to intermediate sulfidation epithermal gold-silver deposits at Pongkor, Cikotok, Cikondang, Cibaliung, and Arinem, with no significant porphyry copper-gold deposits. As for porphyry deposits, high sulfidation epithermal deposits/prospects are also confined to the eastern segment at Empang, Sane/Rinti, Pangulir, Ladam/Elang, Sabalong/Lantung in Sumbawa, Pelangan and Mencanggah in Lombok, and Zone A, B. C (Tumpangpitu) in East Java.

Porphyry and epithermal mineralization styles in the Eastern Sunda arc have their own distinctive characteristics that have developed across the arc, resulting from their specific tectonic setting and host lithologies. Porphyry and epithermal deposits in the Eastern Sunda Arc share many characteristics with those in other island arcs in the Western Pacific region e.g. Philippines, Solomon Islands, PNG, and Fiji. They display significant differences to the Lamaride
porphyry systems in continental margin and cratonic settings in the eastern Pacific region.

Characteristics of gold-silver-copper mineralization systems along the Eastern Sunda Arc can be seen from regional, district to deposit scale. At a regional scale porphyry Cu-Au and epithermal Au-Ag deposits are located along active convergence plate boundaries.

Strong conjugate northwest (NW) and northeast (NE) fault systems are the dominant structural features of the islands, both at regional and district scales. North-west and north-eastern trending lineaments are evident from air photo analysis and satellite-airborne image interpretation and are thought to be cross structures, related to the emplacement of intrusions, and consequently to formation of major porphyry Cu-Au deposits. Major NE trending structures can be seen in the mineralized districts at Batu Hijau, Elang, Empang, and Hu’u (Garwin, 2002; Maryono et al., 2005), whereas NW trending major structures are observed at Tumpangpitu, Selodong, and Brambang. Some deposits, e.g. Batu Hijau and Elang, are localized at fault intersections (arc-parallel and NE trending major structures).

The deposits are spatially associated with Neogene intrusive bodies with low-K calc-alkaline to weakly alkaline, dioritic to tonalitic composition (Garwin, 2002; Maryono et al., 2005; Setijadji, 2006; Roe, per comm., 2012). Intrusion ages range from 2.7 Ma at Elang, 3.7 Ma at Batu Hijau to 7.5 Ma at Selodong. The causative intrusions generally form a series of nested, small dioritic to tonalitic intrusive complexes. Mineralizing intrusive bodies consist of multiple phases, mostly early, intermediate and late tonalite intrusions. These multiphase intrusive complexes are generally part of remnant volcanic centres or stratovolcanoes with dioritic to andesitic batholiths/stocks as premineralization intrusions.

Intrusive bodies are elongate, with pencil-like apophyses 200 m to 500 m in diameter with >2 km vertical extent. The apophyses rise within or from the margins of coarse-grained, equigranular stocks/batholiths. The depth of porphyry intrusions ranges from 1 to 2 km below the paleo surface and extend a further 5 km depth. The intrusions are characterized by porphyritic textures, with 30 to 60% phenocrysts consisting of abundant plagioclase, minor alkali feldspar, hornblende, and quartz.

Host stratigraphy is generally characterized by Miocene volcanic rocks and associated volcaniclastic rocks as a volcanic edifice. The volcaniclastic rock sequence contains thin calcareous sedimentary rocks and limestone, which form thin skarn mineralization, e.g. at Elang, Batu Hijau, and Tumpangpitu.

Structural fabrics at district scale are dominated by strong conjugate systems of NW and NE faults that are apparent in some mineralized districts. NW-trending structural corridors exist at Pelangan, Mencanggah, and Brambang in Lombok, and Tumpangpitu in East Java. A series of ore-bearing quartz ledges of intermediate to high sulfidation epithermal character with NW to NNW orientation are developed at Pelangan, Mencanggah, and Brambang in Lombok, and Tumpangpitu in East Java. A series of ore-bearing quartz ledges of intermediate to high sulfidation epithermal character with NW to NNW orientation are developed at Pelangan, Mencanggah, and Tumpangpitu. A similar NW alignment of mineralized porphyry centres is seen at Brambang and Tumpangpitu. NE alignment of porphyry prospects or intrusion centres occurs further east in the eastern segment of the arc at Batu Hijau, Elang, Rinti, and Gapit in Sumbawa, where porphyry Cu-Au prospects and other Cu-Au mineralized centres in the district are aligned along a NE trending structural corridor with different levels of exposure.
District Mineralized System and Exploration Model

District mineralized systems as illustrated by conceptual deposit models in Figures 5 and 6, are zoned with a spatial association of a central porphyry and overprinting high sulfidation epithermal, marginal low sulfidation epithermal veins, skarn and sediment-hosted gold-silver mineralization. Intermediate to high sulfidation epithermal mineralization forms a telescoped system above or adjacent to underlying porphyry systems, e.g. Elang, Gapit, and Tumpangpitu. Low sulfidation systems are developed further away from the porphyry centres.

Most significant porphyry and related epithermal mineralization occurrences are associated with diatreme breccia bodies. The breccia is developed at the margin or adjacent to the porphyry systems, resulting in disruption to the mineralized bodies, e.g. Rinti, Elang, Batu Hijau, Selodong, Brambang, and Tumpangpitu. Major disruption can be observed at Selodong, SW Lombok where the Motong Botek porphyry mineralization system has been fragmented by late diatreme breccia. Rootless porphyry mega fragments occur within large breccia bodies.

An example showing the full spectrum is the Elang District, Sumbawa, in a telescoped system where a high-sulfidation system at Ladam occurs on top of porphyry Cu-Au mineralization (25.4 million ounces of gold and 16.3 billion pounds of copper; Newmont Mining Corporation, 2012). Gold-bearing quartz vein sets of low sulfidation epithermal character is developed 1 km to the south at Sebu and 1.5 km north-northeast at Kokar Ika within the diatreme body (Maryono et al., 2005). Insignificant skarn mineralization with calc-silicate alteration is developed in thin calcareous intercalations in the host volcaniclastic sedimentary sequence of Miocene age.

Another good example occurs in the Tumpangpitu District in East Java. An overlying

Figure 5. Conceptual district scale exploration deposit model in section view showing central porphyry gold-copper deposit with peripheral epithermal, skarn, and sediment-hosted deposits.
Gold, Silver and Copper Metallogeny of the Eastern Sunda Magmatic Arc Indonesia (A. Maryono et al.)

High-sulfidation epithermal deposit (2.4 million ounces Au and 80 million ounces Ag) in Zones A, B and C penetrates as deep as 1 km below the current surface over a porphyry Cu-Au deposit (28.0 million ounces Au and 19.0 billion pounds Cu; Intrepid Mines Ltd, 2012). Low sulfidation epithermal mineralization is developed at Gunung Manis approximately 3 km east of the main porphyry Cu-Au deposit. Minor skarn mineralization occurs in thin beds of calcareous sedimentary rocks and limestones in the Miocene volcaniclastic host rocks.

Alteration systems at district to deposit scale with underlying porphyry Au-Cu systems and peripheral intermediate to high sulfidation epithermal Au-Ag systems are generally manifested at surface by large lithocap alteration bodies (Figure 7). Low sulfidation epithermal systems have limited alteration envelopes at the surface, confined to quartz vein selvages. Large surface lithocap features more than 20 km² in area with barren to very weak stream geochemical signatures can be seen at Hu’u Sumbawa and Brambang Lombok, where the porphyry Au-Cu systems are totally concealed. Mineralized overlying lithocap bodies with obvious surface geochemical signatures occur at Tumpangpitu (Zones A, B and C) and Elang (Ladam) where high sulfidation epithermal Au-Ag mineralization styles overprint porphyry Cu-Au systems at depth. The lithocap bodies are composed of central mineralized vuggy and pervasive quartz ledges. They are zoned outward to peripheral advanced argillic, argillic and outermost propylitic alteration zones. The advanced argillic alteration is composed of acid clay minerals, dominant kaolinite-dickite at shallow levels and dominantly phylolitite-diaspore-topaz at depth. Argillic alteration zones are made up of neutral clay minerals illite, and montmorillonite with little kaolinite. Alunite in the
form of crystals or pervasively dispersed is observed in the central quartz ledge and residual vuggy quartz zones.

A gradual alteration change to the underlying porphyry system can be seen with the presence of abundant illite, quartz veins, and relict magnetite/hematite. Shreddy chlorite (after hydrothermal biotite) and hydrothermal magnetite increase downwards, giving way at depth to preserved early porphyry alteration (biotite-magnetite-actinolite-plagioclase and potassium feldspar assemblages). Porphyry alteration types and zones recognized on a district scale include early, transitional, late, and very late assemblages. Early biotite-actinolite-oligoclase-magnetite alteration is overprinted by retrograde chlorite-magnetite to form a chlorite-actinolite-biotite-magnetite+oligoclase alteration assemblage. Zones of early alteration contains porphyry vein types “A”, “EB”/“EDM”, and “A- family” of Gustafson and Hunt (1975) and Brimhall (1977) with dominant chalcopyrite and bornite mineralization. Early porphyry alteration is spatially associated with porphyry Cu-Au ore which measures more than 1.5 km in diameter at the three world-class porphyry systems, Batu Hijau, Elang, and Tumpangpitu. Dominance of biotite alteration, a lack of potassium feldspar alteration, and the presence of significant actinolite are marked differences compared to porphyry Cu-Au systems in other parts of the world (Lowell and Gilbert, 1970; Sillitoe and Gappe, 1984).

Transitional porphyry alteration produced widespread zones of chlorite-sericite-magnetite+clay assemblages overprinting early porphyry alteration. This transitional alteration tends to form an alteration shell and is closely associated with early chlorite-actinolite-biotite-magnetite alteration. Typical characteristics of this transitional alteration are marked by the presence of shreddy chlorite, green sericite and hematite. Weak sericite-clay-chlorite+magnetite assem-
blage is associated with the late Echo Tonalite intrusion (Maryono et al., 2005). The sericite-chlorite- magnetite/hematite+clay assemblage is thought to be comparable to the sericite-chlorite-clay zone (SCC) of Sillitoe and Gappe (1984) and pale green mica assemblage of Clode et al. (1999). Porphyry type veins, especially “B” and “C” veins, are associated with transitional alteration.

Late alteration overprints involve broad zones of advanced argillic and argillic alteration. A broad argillic zone (sericite-illite-kaolinite) extends for 5 km along the NNE trending alteration corridor from Ladam to Sepekat.

Three main zones of advanced argillic alteration (pyrophyllite-dickite-kaolinite-alunite) occupy high topography at Elang, Gerbang, and south Sepekat. High sulfidation (quartz-enargite- tennantite) and intermediate sulfidation (quartz-base metal) epithermal veins are associated with late advanced argillic and argillic alteration respectively. Very weak argillic alteration (weak sericite-clay±chlorite) associated with the diatreme breccia and post-mineralization dacite porphyry is considered to be a product of a very late alteration stage. Similarly, narrow sericite-kaolinite selvages on quartz-base metal veins are related to a very late hydrothermal stage. Copper and gold ore- bearing alteration is intense biotite-magnetite alteration (lacking potassium feldspar) measuring from 1 to more than 1.5 km in diameter (Maryono et al., 2005).

Porphyry mineralization in the Eastern Sunda Arc is typified by gold-rich porphyry systems, similar to those in island arc settings in the Philippines. Copper-gold mineralization is formed during emplacement of cogenetic porphyritic intrusion. Hypogene mineralization at three world-class deposits at Batu Hijau, Elang and Tumpangpitu is typical of porphyry Cu-Au deposits. It is associated with a series of small multiphase porphyry intrusions (early, intermediate and late tonalite phases) emplaced close together in space and time in an area 1.5 km by 1 km. The mineralized zone, as marked by 0.3 % Cu zones in surface projections of drill hole data, measures on average more than 1 km in diameter, centred at small porphyritic dioritic to tonalitic mineralizing intrusions. Porphyry mineralization forms an annular or inverted shell that lies within and around the margins of deep tonalite intrusive bodies.

Significant supergene copper enrichment is developed beneath advanced argillic alteration only at Batu Hijau and Elang. A weak chalcocite blanket averaging 40 m thick and 0.5 to 0.7 % Cu has been intercepted in drill holes. The copper enriched zone measures in excess of 500 m by 750 m in plan with variable thickness and is characterized by an overlying goethite-hematite leached cap at the surface. Very thin supergene copper mineralization (0.3 to 0.5% Cu, 10 to 20 m thick) intersected at Brambang does not form a significant chalcocite blanket.

CONCLUSIONS

The metallogeny of the Eastern Sunda Magmatic Arc is dominated by gold, silver, and copper which are predominantly contained in porphyry and epithermal deposit types. With world class gold-silver-copper endowment of 92.44 million ounces of gold, 279.17 million ounces of silver and 61.92 billion pounds of copper, the Eastern Sunda Magmatic Arc has emerged as one of the most prospective gold-copper belts in the world. Porphyry gold-copper and epithermal gold-silver mineralization styles in the Eastern Sunda Magmatic Arc share similarities to those in typical island arc settings, e.g. the Philippines, and display some unique characteristics. At district scale the mineralized
system is zoned with a spatial association of central porphyry and overprinting high sulfidation epithermal mineralization, and marginal low sulfidation epithermal, skarn, and sediment-hosted gold-silver mineralization. Post-mineralization diatreme breccia bodies are common, developed at the margin or adjacent to the porphyry systems, and disrupt the mineralized bodies.

At regional to district scales, key deposit features can be summarised to include an association of deeply eroded volcanic centres, NNE and NW trending major structures, Oligocene to Miocene volcaniclastic host rocks, Neogene multiple small nested intrusive complexes, a spatial association of central porphyry and distal epithermal systems and large surface lithocap footprints. At deposit scale key deposit features include gold-copper ore bearing intense biotite-actinolite-magnetite alteration, gold-silver bearing vuggy and pervasive quartz alteration, gold-silver bearing quartz veins, porphyry veining types and patterns, sulfide species and pattern, hypogene Fe-oxides, supergene Fe-oxides, mineralization forms and textures, and detailed alteration types and patterns. These key deposit features are spatially and genetically associated with ore and its environment that provide selection criteria for prospective regions. Exploration area selection is based on the presence or absence of these specific geological features, and geochemical, geophysical, and geomorphological features which reflect underlying geological features.

District and deposit exploration models can be further refined on the basis of shared key features of the deposits in the region as guides during exploration. These key features provide vectors to ore, applicable in identifying the central, proximal, and distal parts of mineralized systems during exploration activities. Keys to exploration success include understanding the characteristic features of ore systems, observing key geological features in the field, and determining vectors to ore.

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