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Paragenetic and Genetic Characteristics and Mode of Occurrence of some Gold-bearing Copper Deposits in Island Sumatra, Indonesia

Ivan JURKOVIĆ & Božidar ZALOKAR

Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, Pierottijeva 6, YU-41000 Zagreb

Ključne riječi: Pirometasomatska Au-Cu ležišta, Parageneze, Tektonski sklop.

Authors give in this paper the tectonic framework of the Sunda arc-trench system and that of the Island Sumatra as well as the results of field and laboratory researches into some copper deposits in North and Central Sumatra. The prospected ore occurrences are: (a) the hydrothermal veiny-impregnation type Dolok Pinapan with gold-bearing pyrite, chalcopyrite and tetrahedrite as the main minerals, and with sphalerite, neodigenite, bornite and galena as subordinate minerals; (b) the pyrometasomatic occurrence Huta Pungkut related to the garnet-pyroxene skarn with martitized magnetite and high temperature chalcopyrite (exsolution of sphalerite and cubanite) as the main constituents, and with gold-bearing pyrite and enargite as accessories; (c) the pyrometasomatic copper deposit Timbulun, located in the garnet-pyroxene skarn with neodigenite and chalcopyrite as the main minerals, and with gold-bearing pyrite, ascedent chalcocite, covellite, bornite with exsolution of chalcopyrite, sphalerite as scarce minerals. The prospected deposits are of very modest economic value. They are related to the Late Jurassic volcanic activity. Large scale mineral explorations in the last two decades in Sumatra and in Java revealed that no porphyry copper deposits of economic importance are present in these islands although the mature stage of development and related calc-alkali magmatism in the main arc indicate very favourable condition related to the formation of these types of deposits. Authors cite several major factors from recent literature which are held responsible for the scarcity of economic mineralization.

Key words: Pyrometasomatic Au-Cu deposits, Paragenese, tectonic setting.

Autori prikazuju u ovom radu tektonsku građu Sunda »arc-trench« sistema, zatim tektonski sklop Sumatre kao i rezultate svojih terenskih i laboratorijskih istraživanja nekih bakarnih ležišta u Sjevernoj i Srednjoj Sumatri. Prospektirane rudne pojave su: (a) hidrotermalni žično-impregnacijski tip Dolok Pinapan sa zlatonosnim piritom, halkopiritom i tetraedritom kao glavnim mineralima te sa sfaleritom, neodigenitom, bornitom i galenitom kao podređenim mineralima; (b) pirometasomatska pojava Huta Pungkut vezana na granatsko-piroksenski skarn sa martitiziranim magnetitom i visokotemperaturnim halkopiritom (izdvajanja sfalerita i kubanita) kao glavnim sastojcima te sa zlatonosnim piritom i enargitom kao akcesorijama; (c) pirometasomatsko bakarno ležište Timbulun, locirano u granatsko-piroksenskom skarnu s neodigenitom i halkopiritom kao glavnim mineralima, te sa zlatonosnim piritom, ascedentnim halkozinom i kovelinom te bornitom s izdvajanjima halkopirita i sfaleritom kao sporednim mineralima. Prospektirana rudna ležišta su vrlo skromnih ekonomskih vrijednosti. Genetski su vezana na mlađi jurski magmatizam. Opsežna mineralna istraživanja provedena zadnja dva desetljeća na Sumatri i Javi otkrila su da na tim otocima ne postoji niti jedno porfirno bakarno ležište od ekonomskog značaja premda zreli stadij razvoja i kalcijsko-alkalijski magmatizam u glavnom magmatskom luku indiciraju vrlo povoljne uvjete za stvaranje tog tipa ležišta. Autori navode različite važnije faktore iz savremene literature za koje se smatra da su odgovorni za oskudnost ekonomski vrijedne mineralizacije.

Introduction

In the Late Carboniferous-Early Permian period, a subduction zone, dipping in the direction of the Asian continent with andesitic volcanism and granitic emplacement, existed in or west of Sumatra. At the same time a subduction zone dipping toward the south-west existed in the eastern part of the Malay Peninsula and western Kalimantan (Katili, 1973, 1984). Since this time the Sundaland has been at core of an accreting subduction system. The subduction zones moved away from the continent towards the ocean, older subduction zones occur closer to the continent, whereas the younger ones are situated nearer to the ocean.

A reorganization of the subduction system occurred in the Late Cretaceous-Early Tertiary period as the result of rifting within the Gondwana continent of India and Australia from the Gondwana in the Early Cretaceous time (Bender et al., 1983; Katili, 1984). During this time interval active subduction in the north-eastern margin of the Sundaland ceased, in the south-east, subduction migrated from east to south-east Kalimantan. Since Early Palaeozoic times a double arc-trench system with opposing subduction zones, generated by a spreading centre situated in the Indian Ocean and the South China Sea, existed in the western Indonesia region (Katili, 1973, 1974, 1984) (Fig. 1).

Seismic and geological profiles carried out across the Indonesian arc-trench system showed that large islands (Sumatra, Java) with silicic and intermediate volcanism were formed due to the subduction of oceanic plate under a more than 20 km thick and relatively old continental crust, and small islands in the eastern Indonesia with intermediate and mafic volcanism by subduction of an oceanic plate underneath a thin and young continental crust (Coulon-Thorpe, 1981, Katili, 1984, Windley, 1986).

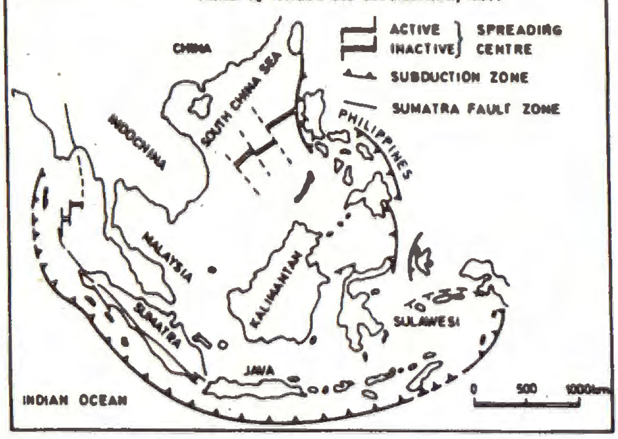
The Indonesia islands have grown by the progressive addition of accumulated volcanic debris from many successive arc systems (Katili, 1984).

During the Tertiary age a new spreading center in the Indian Ocean generated an arc system, dipping towards the continent, stretching 2600 km from northwestern Sumatra to Buru and Buton islands (Kkatili, 1984).

The Tectonic Framework of Sumatra

Across the island of Sumatra, from SW to NE, the following tectonic settings have been observed:

Fig. (Sl.) 1. DOUBLE ARC-TRENCH SYSTEM OF INDONESIA
DVOSTRUKI "ARC – TRENCH" SISTEM ARHIPELAGA INDONEZIJE
(mode by TAYLOR and Van LEEUWEN, 1980)



a shallow trench with the base of the trench slope moving 6,5 cm/yr in a NNE direction, seaward side of the ridge, outer arc(fore-arc), an outer arc trough(fore-arc basin), all making an accretionary prism or arc-trench gap, then a magmatic(volcanic) arc with calc-alkaline andesitic volcanism, a back-arc magmatic belt and back-arc basin. The Benioff zone exibite a shallow dip and is characterized by great thrust earthquakes. Stress in the volcanic arc area is compressional (Fig. 2).

The trench slope rises partially to a submarine ridge, partially to a subaeral ridge (Mentawai islands) forming a major topographic high separated from the volcanic arc by an outer arc trough or fore-arc basin. On the seaward side of the ridge there are almost entirely flysch sediments with minor granitic rocks intruded into flysch; they differ in origin from the volcanic arc magma which is more directly related to subduction (Mitchell-Garson, 1984). On the volcanic arc side (outer arc basin) there is a tectonic mélange with few ophiolites and basic lavas, more with metamorphic rocks and flysch sediments. The Mentawai Trough of the Sunda is part of an accreationing prism, beneath it is a well developed largely submarine outer arc succession (Hamilton, 1973); the magmatic arc is probably the most important source of the outer arc trough (Mitchell-Garson, 1984).

This profile corresponds to that described by Windley (1986): the trench contains pelagic and turbidite sediments, an accretionary prism of thrusted oceanic and terrigenous sediments and layers of ophiolites, an inactive fore-arc basin with diverse sediments.

The island of Sumatra is built up of the continental crust, over 20 km thick, consisting of earlier subduction complexes metamorphosed by low pressure/high temperature metamorphism (Garcia, 1978; Windley, 1986). Amongst the metamorphosed rocks there are Pre-Tertiary (predominantly of Palaezoic

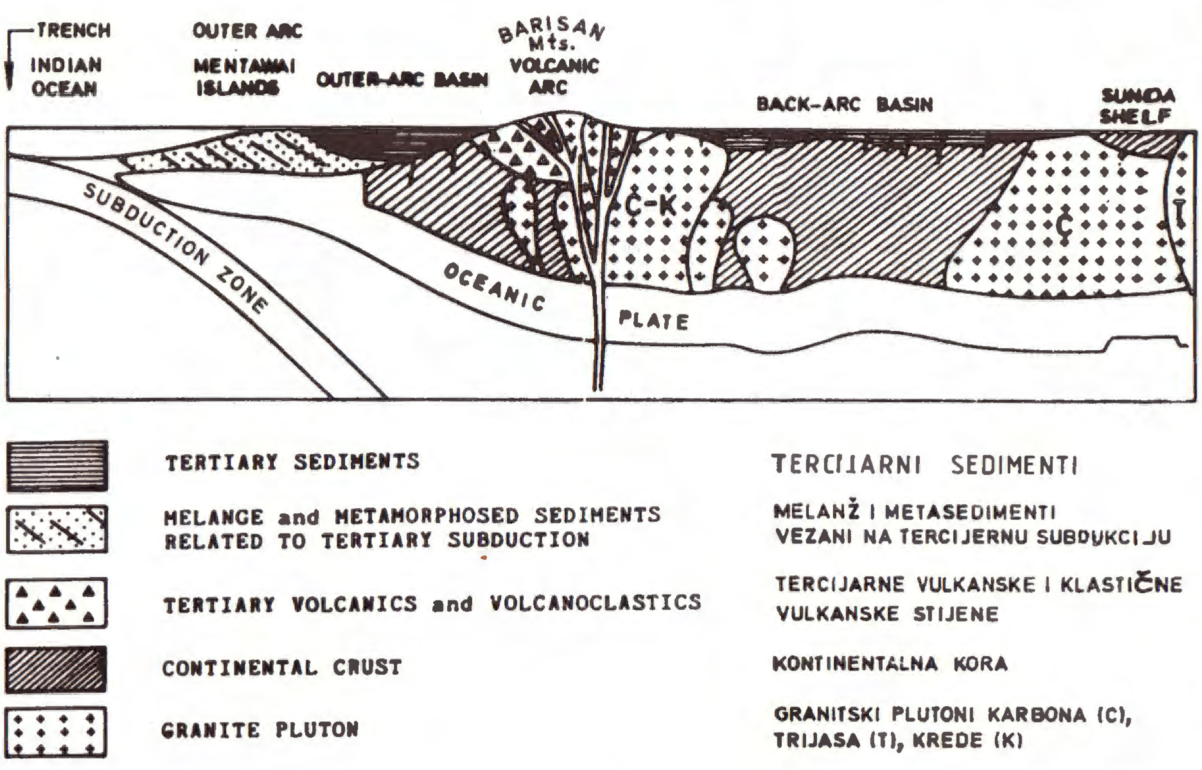


Fig. (sl.) 2. SECTION ACROSS SUMATRA ISLAND
(PROFIL OTOKA SUMATRA)
By GAGE and WING (1980); KATILI (1984)

age) phyllites with intercalations of quartzose sediments, and local conglomerates as well as limestones. (The Tapanuli group). Very big masses of intruded granites and diorites with contact-metamorphic aureoles and quartz veins exist from the Carboniferous to the Cretaceous era. It is a co-called Barisan complex. Vorbarisan is characterized with Permian-Triassic basic, intermediary and acid effusives and their tuffs, sandstones and conglomerates. (The Peusangan group). Mesozoic sandstones, limestones and shales are rare. In Late Jurassic and Lower Cretaceous the Woyla groups developed, comprising a complex of arc-related sediments and volcanics. Tertiary sediments, volcanic rocks and tuffs cover metamorphosed, schistose Barisan and Vorbarisan formations (Tobler, 1917; Van Bemmelen, 1949). During the Early Tertiary age intensive volcanism and granitic plutonism were developed along the west coast of Sumatra; in the Oligocene andesitic volcanism started in Sumatra and lasted until the Early Miocene era; at the end of the Miocene subduction ceased (Katili, 1974). The volcanic arc of Sumatra is characterized by a high proportion of pyroclastic rocks interbedded with thick deposits of metamorphosed greywackes and sandstones. The uplift of the Barisan Mountain Chain occurred during the Tertiary, especially in the Quaternary.

A modern back-arc marine compressive basin is that east of Sumatra, although the back-arc thrust belt is poorly developed. The back-arc sediments are derived from both the active Sunda volcanism in Sumatra, and the much older uplifted granitic Main Range in Malaysia on the continental side of the basin. The back-arc rifting is associated with strike-slip faulting, parallel and adjacent to the magmatic arc, and the Semangko Rift in Sumatra is an incipient marginal basin (Mitchell-Garson, 1984). The Sumatran back-arc basin rest on a continental crust of Mesozoic-Late Palaeozoic age (Katili, 1984).

The relation between volcanic island arc structure and mineralization

The earliest observations on the relationship of mineralization to plate boundaries concerned deposits of porphyry copper, formed in magmatic arcs on overriding plate boundaries (Sillitoe, 1970). Stanton (1972) strongly suggests a fundamental connection between many porphyry copper deposits and volcanic arc structure. This volcanism evolves from a mafic and ultramafic type in the later stages of arc development. It would therefore appear that deposits of this type are most likely to be found in the more mature portions of modern volcanic arcs, in the older, larger islands or in older (Mesozoic and Palaezoic) arc structures that have escaped erosion or whose underlying faults have remained active over very long period of time.

Depostis are in calc-alkaline, mostly porphyric, plutons or subvolcanic intrusions varying in composition from diorite to quartz-monzonite or adamellite. They commonly form small stocks or subvolcanic intrusions which lie at a depth of up to 4 km, but mostly less than 2 km during mineralization (Mitchell-Garson, 1984). Most islands arc porphyry copper deposits contain gold and some molybdenum, rather than molybdenum with little or no gold, as in the continental margin arc (Hollister, 1975; Mitchell-Garson, 1984).

According to Feiss (1978) »the association of porphyry deposits with calc-alkaline intrusives both in continental margin arcs and in some island arcs of the Western Pacific (Mason-Feiss, 1979), depends on the partition of copper and similar metals between silicate magmas and crystallizing minerals. The Cu^{2+} ion in silicate melts is probably preferentially partitioned into sites with octahedral co-ordination rather than tetrahedral sites. As the proportion of tetrahedral sites in silicate melts increases with alkali and silica and decreases with alumina content, it follows that sites copper tends to partition into the silicate liquid, concentrating in residual and becoming involved in a magmatic hydrothermal phase. In contrast, in silicate liquids with high alkali contents copper tends to partition into crystallizing minerals such as biotite, becoming »fixed« and unavailable for subsequent mineralization.«

According to Windley (1986) across island arcs there is a succession of mineral deposits that correlates with the variation of rock types and geological structure; much of the mineralization is characteristic of consuming plate boundaries of the island arc type. There are three stages of arc growth: (1) in the *Early tholeiitic stage* no massive sulphide deposits have yet been found; (2) in the *Main calc-alkaline stage* three types of mineralization are established as follows: 2/a *Besshi type* stratiform sulphide deposits related to andesitic or basáltic, largely pyroclastic volcanism and deep water sediments in the arc-trench gap; 2/b *porphyry copper deposits* in association with calc-alkaline intrusions in the main arc; 2/c *pyrometasomatic skarn deposits* at carbonate-magmatic contacts. The intrusions may have associated vein deposits of tin, or gold, or mercury; (3) in the waning *late calc-alkaline stage* of arc development, *Kuroko-type* stratiform sulphide mineralization is associated with dacitic-rhyolitic lava domes erupted in the main arc under submarine condition (Sillitoe, 1982), or more rarely, with andesitic pyroclastic rocks together with shallow-water marine sediments (Urabe-Sato, 1978).

Sillitoe (1980) suggests that porphyry deposits are associated with andesitic and dacitic rocks erupted in strato-volcanes, while Kuroko ores occur within rhyolitic rocks erupted in resurgent calderas situated above zones of lithospheric tension, and support a broad tectonic control on the nature of the mineralization and hence a tendency for the type of deposit to be related to the arc's orientation, and consequently to some extent to its position relative to a continental margin (Mitchell-Garson, 1984).

Uyeda and Nishiwaki (1980) discussed the relationship of porphyry copper distribution in some arc systems to horizontal stress during mineralization, and suggest that the generation of porphyry copper deposits requires a compressional regional stress environments (as in Chile); conversely, they argued that Kuroko deposite were emplaced in tensional environments (as in the Mariana arc system) (Mitchell-Garson, 1984). According to Mitchell-Garson (l.c.), the regional distribution of Late Cenozoic deposits with abundant porphyry copper deposits suggests a possible relationship of mineralization to the tectonic regime. The porphyry copper deposits develop in oceanic arcs facing west, in compressive settings, while Kuroko deposits are characteristic of tensional environments.

The more evolved stage of volcanism in an arc with crustal thickness more than 20 km, as in Sumatra, is characterized by the calc-alkaline series with higher abundance of K, U, Ba and with fractionated REE patterns, the alkali series is present but unimportant, and tholeiitic volcanism uncommon (Coulon-Thorpe, 1981; Windley, 1986). The Sumatra deposits are closely associated with the Sumatra fault system (Katili, 1984).

Paragenetical characteristics of some Sumatran copper ore occurrences

The prospected copper ore occurrences (Zalokar, 1962) are situated along the Semangko Fault Zone, in the North and South Tapanuli Province (North Sumatra) and in the area of Sinkarak Lake (Central Sumatra).

The aim of the prospecting works in Sumatra was a rough estimation and evaluation of the known copper occurrences, so that it would be possible to choose that ore which proves to be promissing by its genetic type as well as by its mode of occurrence, thus eventually justifying systematic exploration work and exploitation.

More or less parallel to the west coast of Sumatra between its most northwest point, Banda Atjeh, and Semangko Bay in the south-east a series of elongated depressions or fault valleys (graben), with widths up to 17 km, and linear valleys extends (Van Bemmelen, 1949, Westerveld, 1952). Thus entire feature has been named the Semangko or Sumatra Fault Zone.

Katili (1970) concluded that the Sumatra Fault Zone was probably characterized by vertical movements during its earlier history, but that right slip dislocations have been predominant during the Quartenaire. Tjia and Posavec (1972) have revealed that in addition to right slip displacements, the morphology also reflects sinistral slip and vertical throws along parts of the fault zone. The larger and wider depressions of the Sumatra Fault Zone are bounded by a set of parallel faults. The depressions come into being by step-faulting, vertical movements having been important.

The prospected gold-bearing copper deposits are situated in the magmatic rocks related to I-type calc-alkaline intrusive activity of Late Jurassic age formed within an arc-related volcano-sedimentary sequence. According to Beddoe-Stephens, B. et al., (1987) K/Ar age show a range 181 to 142 m.y., whereas Rb-Sr isotopes show a range of 158 ± 23 m.y. (Late Jurassic). Ratio $^{87}Sr/^{86}Sr$ indicates a juvenile granitoid. Trace elements reflect a magmatic series granitoid affinity (Ishihara, 1981). The emplacement of these intrusions occurred in an immature orogenic setting, in an island-arc environment underlain by relatively thin continental crust.

A. ORE OCCURRENCES
IN THE NORTH TAPANULI PROVINCES (Fig. 3)

The area of Dolok Pinapan is situated in the North Tapanuli Province (North Sumatra). The prospected ore occurrence is located on the northwestern slopes of the Pinapan massif (+2037 m), prominently elevated above the surrounding contours. The existing mine workings are situated about 16 km northeast of Pakkat village, and some 35–40 km in a bee-line from Barus port, a natural harbour on the western Indian Ocean coast of Sumatra. That area may be reached by road, branching off at Siborongborong from the main Medan-Sibolga road.

The copper occurrences of this area were already explored by the Dutch at the beginning of this century, but they were not interested in copper, only in gold, which is contained in the ore of these deposits.

The surrounding terrain is composed of plutonic porphyroid granites, volcanic rhyolites and rhyolite-tuffs, sandstones and black shales and phyllites. The zone adjacent to the ore occurrence is composed of greenish-grey to greenish effusive porphyric rock belonging to the group of basalts and intermediate rocks (andesites and latites).

The mining prospecting works (adits) are situated at elevations of 1200–1300 m. At the time of our prospecting visit all the adits had caved in and were not accessible for observation purpose. The terrain is covered by a thick overburden. No single ore outcrops were noticed, only specimens of rocks and ores in the old dumps beside the adits. More interesting occurrences of mineralization with copper minerals were observed on the same slopes but on their southern side, at an elevation of 1600–1700 m. These slopes are built of considerably hydrothermally altered, somewhat acid effusive rocks and of plutonic rocks and hence more interesting regarding the discovery of a possible deposit of a disseminated type.

Mineragraphic study of the ore specimens in polished sections revealed the following paragenesis:

(a) *hypogene minerals:* pyrite, sphalerite, tetrahedrite, chalcopyrite, neodigenite, bornite, galena, elemental gold I, mineral »X«;

Pyrite is the main and the oldest mineral in the paragenesis of the Dolok Pinapan deposit. The interstices are filled with tetrahedrite, chalcopyrite, bornite, neodigenite and gold I. *Sphalerite* is noticed only as inclusions in tetrahedrite in skeletal form. *Tetrahedrite* is abundant but the amount is smaller than that of pyrite. It is isotropic, but of an unusual, slightly pinkish-grey tint which indicates the presence of other elements (as As). Tetrahedrite is strongly fissured and crushed by postgenetic tectonic movements. The cataclased portions show strong internal reflexes. In tetrahedrite there is some skeleton of sphalerite. The cataclased zones are replaced by *quartz* along the cracks and fissures. In the somewhat coarse-grained tetrahedrite even terminal planes are noticed. *Chalcopyrite* represents a considerable constituent of the paragenesis, but the amount is smaller than that of tetrahedrite. *Bornite* and *neodigenite*

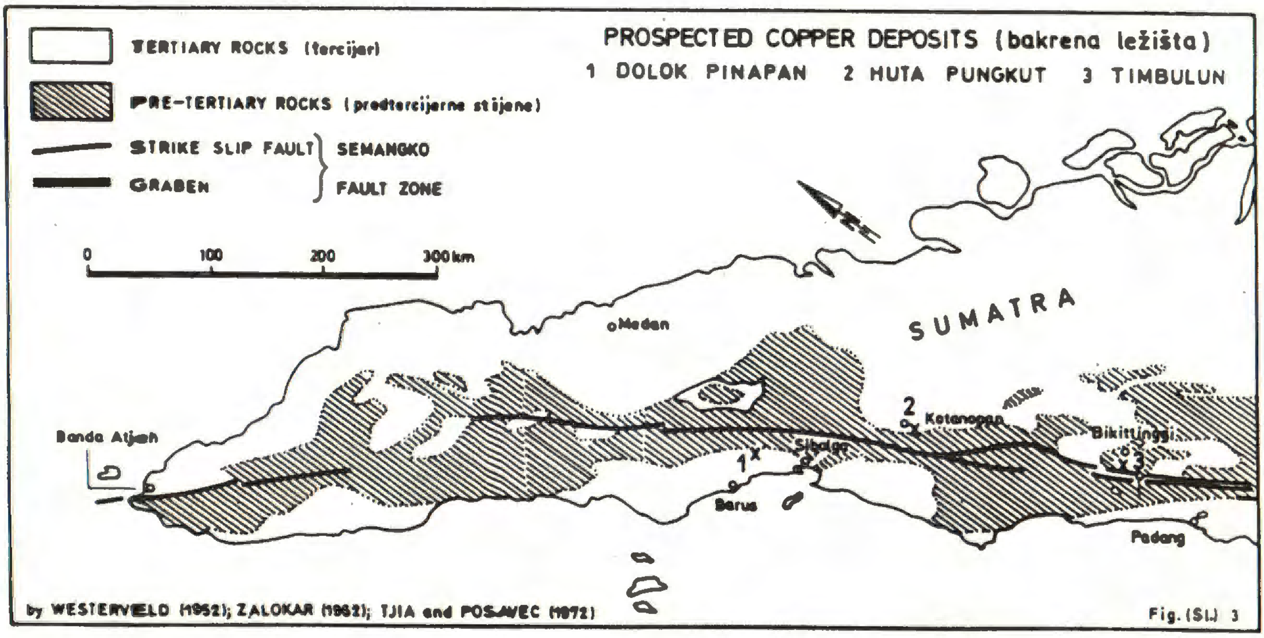


Fig. (Sl.) 3

are subordinate minerals in the paragenesis. *Galena* is also a scarce mineral, visibly cataclesed. *Elemental gold I* is noticed in pyrite as an accessory constituent.

(b) *hypergene minerals:* Among them there is quite a noticeable amount of *malachite,* further some scarce *covellite* and *chalcocite,* scarce oval masses of *gold II,* and *goethite* and *lepidocrocite.*

The mineralization is of the hydrothermal veiny type, but in the adjacent rocks built of somewhat acid effusive rocks and of plutonic rocks which are considerably altered by hydrothermal processes there are some impregnations by pyrite and chalcopyrite (disseminated copper deposits) especially on the south-eastern and eastern slopes of the Pinapan Mountain.

B. THE AREA OF KOTANOPANA, MUARA SIPONGI AREA, SOUTH TAPANULI PROVINCE IN NORTH SUMATRA

There are a few old mine workings around the Kotanopana locality: *Huta Pungkut, Tambangbustang, Aer Sipongi and Aer Malalir.*

The Huta Pungkut (Aer Notarus) locality is the most interesting amongst these ore occurrences. It is situated about 4 km south-east of Huta Pungkut village, on the slope of the mountain range, about 600 m above sea level. The area is built of plagiogranite, marble and skarn according to a microscopic study made by prof. V. Majer (University of Zagreb).

Plagiogranite is composed prevailingly of hypidiomorphic to allotriomorphic plagioclases (oligoclases), displaying pollysynthetic twinning and zonar structure, more or less fresh, showing often intensive kaolinization and sericitization. There are alkaline feldspars also. Quartz is developed in the interstices of plagioclases. Along the quartz-plagioclase contact a myrmekite rim is developed. Laths of amphybole showing actinolitization and chloritization and irregular leaves of biotite partially replaced by chlorite are also components of the rock. The accessories are apatite and magnetite. The zonar structure of plagioclase indicates a consolidation in shallow depths.

The skarn rock is composed predominantly of garnet (andradite – grossular), consisting of very small, irregular isometric grains. The rock appears in hand specimens to be brown-yellowish to brown-reddish in colour, in the thin sections it is of a barely perceptible greyish-yellow colour. The individual portions of garnet are isotropic, but quite a considerable portion displays anisotropic effects, and a zonar structure in some places, which indicates a contact metamorphic origin. Sporadically the garnets are somewhat opaque, as if they contained some kaolin substance. Small amounts of strongly altered pyroxenes are also present.

The marble-rock displays a mosaic structure with grains of isometric section, their size varying from 1,5 mm down to 0,15 mm. Only a very small amount of quartz may be detected in the patchy and nest-like forms. There is also some »limonite substance« and a kind of leafy mineral, most probably talc.

By mineragraphic study the following paragenesis was established:

(a) *hypogene minerals:* magnetite, pyrite, hematite, martite, chalcopyrite, cubanite, enargite, sphalerite, elemental gold I.

Magnetite occurs either in the form of individual crystals (prevailingly) or in aggregates, where several crystals are partly intergrown. The magnetite grains are square-shaped, triangular and of other types of section. The largest individual crystals reach a size of 1,5 mm, but their average size is 0,25 mm and smaller. In the examined polished sections magnetite is rarely fresh (though some of the grains are almost entirely fresh), mostly they are affected by a process of martitization following the octahedral crystallographic planes of magnetite. In the process of martitization the number of *martite* plates increases and they become thicker, coming in contact with one another, but sometimes all of the magnetite is affected by martitization, leaving only some sporadic remnants of magnetite. *Pyrite* is coarsely crystalline, it is developed in a pentagonal-dodecahedron form more or less expressively, often entirely replaced by goethite and lepidocrocite, so that only some remnants are left within the contours of the former large crystals. Pyrite has a considerably smaller extension than that of magnetite. Small grains of *elemental gold I* were sometimes noticed in pyrite, but they are relatively scarce. *Chalcopyrite* is the main ore mineral. It is coarsely crystalline, lamellar, containing exsolutions of *sphalerite* in the form of irregular skeleton of microscopic size and exsoluted spindle-shaped *cubanite,* indicating a high temperature origin. *Enargite* is rare, occuring in association with chalcopyrite.

(b) *hypergene minerals:* cuprite, covellite, chalcocite, tenorite, elemental gold II, elemental copper, malachite, goethite and lepidocrocite.

Goethite and *lepidocrocite* replace both magnetite and martite in the oxidized zone of the skarn deposit. Pyrite is also oxidized and replaced pseudomorphically by a mixture of goethite and lepidocrocite. In the zone of supergene enrichment pyrite is sometimes replaced by supergene *chalcocite* and *covellite.* The character of the supergene processes, affecting chalcopyrite and enargite, depends on whether that part of the ore was more intensively subjected to oxidation or to supergene enrichment in the cementation zone. The final products of the weathering (decomposition) process of copper minerals, in the upper part of the oxidation zone (zone of leaching), are goethite and lepidocrocite, with a large or smaller amount of *malachite.* As we move down the zone of cementative enrichment, the participation of the richer copper supergene minerals becomes more and more intensive, so that at the first lower level a fairly large participation of malachite becomes noticeable, and then, at the subsequent level, there is a remarkably large participation of *cuprite* and *tenorite.* In the immediate vicinity of decomposed chalcopyrite, there are already individualized cuprite and tenorite, *elemental copper,* and, in certain cases, chalcocite and covellite. Between the uppermost zone of weathering with individualized oxides and the zone of comentative enrichment there is pretty well as a rule, a more or less wide zone of intimately mixed copper oxides and iron hydroxides. The gold I camouflaged within the lattice of pyrite and probably of chalcopyrite has been leached during the process of decomposition and it appears as *gold II* in the form of small masses and veinlets within the transitional zone of supergene enrichment. Gold is found around the remnants of the pyrite masses within decomposition products. Gold is comparatively aboundant, some of the gold masses are of fairly large size, i.e. 30×100 micrometers. The composition of this gold is characterized by 5 to 35 at. percent Ag and up to 0.8 at. percent Cu (Beddoe-Stephens, B. et al., 1987). The texture of the hypergene minerals is usually coloidal rhytmically developed structures are scarce. The texture is porous, the porosity increasing with the progress of leaching. This process affects copper minerals to a greater extent than others, so that the final products are become richer in iron hypergene minerals.

Coarse-grained magnetite and pyrite, besides high-temperature chalcopyrite with exsolution of sphalerite and cubanite related to the contactmetamorphic rocks (marbles and andradite garnet rocks), indicate obviously that this deposit belongs to the *contact pyrometasomatic copper deposit in* contact with granitic (plagiogranitic) magma. The gold content increases the value of such type of deposit.

The Tambangbustang locality is represented by a small old open cut where the Dutch were concerned with prospecting for glod in the garnet rocks which contain large amount of quartz, with some ore minerals completely oxidized to limonite.

The Aer Sipongi locality is also a skarn deposit in a silicified epidote skarn. The primary sulphides are completely oxidized, there are only thin malachite coatings.

The Aer Malalir locality has the some appearance as the Aer Sipongi locality. The ore occurrences are related to contact metamorphosed marls, i.e. to fine grained cornite, consisting of rather dense patch-like and lamellar aggregates of cryptocrystalline quartz and of pyroxene and clinozoisite. The sulphides occur in two parallel, very thin veins 12–15 cm distant from each other. The immediate vicinity is tinted by malachite. Hypogene minerals are *pyrite, sphalerite* with exsolution of *chalcopyrite I, chalcopyrite II* as the main mineral (with exsolution of oval or rounded masses of sphalerite containing itself inside discs and droplets of chalcopyrite I). Remnants of corroded pyrite are noticed in chalcopyrite II. *Malachite* is the main hypergene mineral. *Covellite, chalcocite* and *cuprite* replace chalcopyrite II. *Goethite* and *lepidocrocite* are also present. The veins represent the hydrothermal phase of the skarnification process.

C. THE AREA EAST OF THE SINKARAK LAKE, TIMBULUN PROVINCE, CENTRAL SUMATRA

The Sinkarak Lake is situated south of Bikittinggi in Central Sumatra. In the area east of this lake there are several zones of contact pyrometasomatic copper deposits. The most important and the most explored (and even partially exploited during World War II) is the Timbulun deposit.

The ore occurrence had been first explored by the Dutch, who were prospecting for gold and not for copper, and it was subsequently exploited by the Japanese during World War II. The Japanese were engaged in ore exploitation in a small open cut. They erected a primitive furnace for the smelting of ore, and some dumps of copper slag were found not far from the open cut. The terrain in the immediate vicinity of the garnet skarn was explored and examined by means of 14 shallow pits and one bore hole. Finally, the American firm »White Engineering Co« sank four bore holes. All these investigations lacked positive results. No great concentration of copper minerals was observed in the exposed rocks, except for some malachite and azurite coatings and nests.

The mineralized zone is very well opened and expressed. The contact zone is rather wide, showing all transitional types of contact-metamorphosed rocks, from garnet skarn to marbled limestones and altered granodiorite as well as protrusions of basic effusive rocks.

The garnet rock is composed of fine grained garnet, zonary in structure, showing strong anisotropic effects with inclusions and nests of pyroxenes. Besides garnet rock there is a fine grained rock composed of epidote, quartz and opaque minerals. The marbled limestones also contain small amounts of opaque minerals, lamellar chlorite and inclusions of oval grains of pyroxene. The granodiorite is composed of plagioclase, alkaline feldspar, amphibole, uralitized amphibole, some biotite and magnetite and apatite as accessories. Kaolinite and sericite are secondary minerals. The effusive porphyritic rock is composed of pollysynthetically twinned phenocrists of plagioclase in the holocrystalline matrix which is composed of columnar plagioclase, short laths of green amphibole, some quartz and supergene zoisite and, sporadically, of dispersed pyrrhotite and chalcopyrite.

The following paragenesis was established by mineragraphic study of the ore specimens taken from the open cut:

(a) *hypogene minerals*: pyrite, bornite, neodigenite, chalcopyrite I. sphalerite, chalcopyrite II, mineral »X«, gold I, chalcocite, covellite.

Pyrite is the oldest mineral in the paragenesis and almost completely replaced by other suphides and sulphosalts. Only very small grains are left in the bornite, but in some places it is still intact and well preserved within garnet rock. *Bornite* is the oldest amongst the copper minerals. In bornite itself there are very small masses of ascedent chalcocite, chalcopyrite and *sphalerite*. *Chalcopyrite I* occurs in the form of exsolutions in bornite. *Neodigenite* is the main ore mineral which is in different stages of decomposition in low-temperature *chalcocite*, which is found also as a rim around neodigenite. Nearly always there is also at least a very fine neodigenite rim around bornite, surrounded by low-temperarure chalcocite. *Chalcopyrite II* is younger than bornite, in some places very aboundant. *Covellite* replaces neodigenite in the form of small plates along the (111) crystallographic planes, often associated with fine grained sericite.

(b) *hypergene minerals: malachite* and *azurite* are predominant in the ore specimens investigated. Malachite is developed mostly in well-shaped and fine-looking radial aggregates, or else is micrograined. Azurite occurs mostly as films or coatings. *Low-temperature chalcocite* occurs as a weathering product of neodigenite, bornite and chalcopyrite II. *Chrysocolla* is a rather scarce weathering product. *Goethite* and *lepidocrocite* are frequently noticed, occuring in a typical rhytmically colloidal structure.

The Timbulun deposit is a typical *contact-pyrometasomatic skarn deposit* related to granodiorite intrusion.

Succession of the ore formation

The first phase is characterized by formation of the anhydrous garnet-pyroxene skarn along the contact between the Late Jurassic diorite-granodiorite with the limestones (marbles) of the Permo-Triassic Peusangan group. This phase was developed in the areas of Huta Pungkut and Timbulun deposits. It is a pneumatolytic stage formed between 600^0 to 400^0C.

The subsequent (second) phase manifests its presence by partial or complete propylitization and hydration of all skarn minerals (actinolitization, epidotization, clinozoisitization) accompanied with the older (first) phase of the ore formation. It is a transitional low-temperature pneumatolytic to high-temperature hydrothermal phase (katathermal) formed between 450^0 to 225^0C. This phase is very well developed only in the Huta Pungkut locality with magnetite, high-temperature chalcopyrite I (with exsolutions of sphalerite and cubanite), coarse-grained gold- bearing pyrite and with accessory bornite. In the Timbulun locality this phase is characterized only with gold-bearing pyrite, and bornite (with exsolutions of chalcopyrite I). In the adjacent effusive porphyric rocks there are dispersed pyrrhotite and chalcopyrite I.

The mezo-epithermal phase of the ore formation is developed in all prospected deposits. It is characterized with the younger (second) gangue and ore minerals. Among the gangue minerals there are quartz, lamellar chlorite, sericite, kaolinite. In the Dolok Pinapan locality copper mineralization is localized in the porphyroid granite and in the porphyric effusive rocks. It is of the veiny type localized in a strongly hydrothermally altered rock which contains some dispersed impregnations of pyrite and chalcopyrite. The deposit contains gold-bearing pyrite as the main ore mineral. Tetrahedrite with inclusions of sphalerite is the main copper mineral, followed with chalcopyrite, while bornite and neodigenite are subordinate minerals. Galena is present as very scarce mineral. In the Huta Pungkut locality this phase is manifested by strong martitization of magnetite and with the occurrence of scarce enargite. In the Aer Malalir locality this phase occur as thin veins filled with pyrite II, sphalerite (with exsolutions of chalcopyrite) and chalcopyrite (with exsolutions of sphalerite). In the Timbulun locality this phase is characterized with low-temperature chalcocite, chalcopyrite II, and ascedent covellite.

Discussion

Among the modern arcs, islands such as Sumatra, New Guinea, Japan, Cuba stand out and they lock to be promising areas of potential porphyry copper occurrences. The porphyry copper deposits are most likely to be found in the mature portions of these modern volcanic arcs (Stanton, 1972), with andesitic, dacitic and rhyolitic types of volcanism in the later stages of arc development. Crustal thickness in Sumatra is thicker than 20 km and it indicates a mature stage of development (Coulon-Thorpe, 1981). The Sumatran arc system is characterized by the calc-alkali series of magmatic rocks (Windley, 1986) the volcanic rocks are commonly more silicic and potassic then those of ocean arcs, consisting of calc-alkaline to high potash dacites, rhyolitic ignimbrites and dacites; basaltic rocks are rare (Mitchell-Reading, 1986). According to Mitchell-

Garson, (1984), in oceanic arcs facing west (as in Sumatra) they are under compression and therefore might favour porphyry copper mineralization.

The explorations made in Sumatra by the Dutch before World War II, by the Japanese during World War II, during our prospection (Zalokar, 1962) and by large scale mineral exploration in Sumatra and Java by Rio Tinto-Betlehem and Kennecott revealed that no porphyry copper deposits of economic importance are present in the islands. The last prospect was near northwestern Sumatra (Uyeda-Nishiwaki, 1980). Already in 1974 Katili stated that the western part of Sumatra and the south coast of Java seem to be barren of porphyry copper, while the west-arc of the Sulawesi appear to be a very promising area for mineralization. Mitchell-Garson, (1984) are also of the opinion that the Semangko Fault Zone in Sumatra is unmineralized, although the Sumatran oceanic arc, facing west, is under compression and therefore favourable theoretically for copper mineralization. The Tertiary mineralization in Sulawesi, Halmaheira, and New Guines all generated by spreading and subduction of the Pacific Ocean-floor is more significant as compared with that of Sumatra, Java, and the Lesser Sunda Islands (Katili, 1984).

Several factors are held responsible in the literature for the scarcity of economic mineral deposits in Sumatra and Java. Katili (1984) argues the relative poor content of metallic mineral from the Indian Ocean source, the successive penetration of magmas of different ages in the same orogenic belt, the presence of recent volcanic cover etc. Taylor-Hutchison (1978) suggested that the subduction was too young to have generated a suitable melt. Katili (1984), comparing the west-facing continental magmatic arcs of the Andes and Sumatra, established that the former has numerous porphyry copper bodies, while the latter has none. Mitchell-Garson (1984) emphasize the lack of economic porphyry deposits in the south-west facing arc in Sumatra, suggesting the view that there is possibly a relationship between volcanism and the age of the subducted lithosphere, as in South America, or that the abundance or scarcity is depedent on the dip of the Benioff zone. It is the very interesting suggestion of Milson (1978) that the western Pacific complex arcs wich have undergone reversals in subduction polarity are preferentially mineralized with porphyry copper deposits. This is perhaps related to the fact that, while most arcs face east, porphyry mineralization took place when they faced west, prior to a flip in the Benioff zone.

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Paragenetske i genetske karakteristike i način pojavljivanja nekih zlatonosnih bakarnih pojava na otoku Sumatri, Indonezija

I. Jurković & B. Zalokar

Geološkom prospekcijom dijela Sjeverne i Srednje Sumatre, jednog od autora (Zalokar, 1962), obuhvaćene su hidrotermalne bakarne rudne pojave u masivu Pinapan oko 40 km istočnije od luke Barus u provinciji Sjeverni Tapanuli, zatim skarnske željezno-bakarne pojave u području Kotakopana u provinciji Južni Tapanuli te skarnske bakarne pojave kod jezera Sinkarak u provinciji Timbulun (slika 3). Uzorke stijena u kojima se nalaze navedena ležišta istražio je V. Majer (Zalokar, 1962), a mineragrafske studije je izradio I. Jurković (Zalokar, 1962).

Sve navedene rudne pojave leže uzduž Semangko Fault Zone koja se pruža od Banda Atjeh na krajnjem NW dijelu otoka Sumatre do Semangko Bay na SE dijelu otoka. Ta tektonska linije karakterizirana je nizom užih i širih riftnih dolina i grabena te glavnom magmatskim lukom Sumatre. (Barisan Mountain Chain).

Dolok Pinapan ležište nalazi se na padinama masiva Pinapan koji je izgrađen od porfiroidnog gornjojurskog granita, riolita i riolitskih tufova, od sedimentita pješčenjaka i konglomerata te od metamorfnih slejtova i filita. Mineralizacija je uočena u hidrotermalno izmijenjenim eruptivnim stijenama. Pretežno je žičnog tipa, a ima i impregnacija. Glavni rudni mineral je *pirit*, u značajnoj mjeri su prisutni *tetraedrit* i *halkopirit*, *bornit* i *neodigenit* su podređeni, dok je *galenit* rijedak. *Sfalerit* je uočen samo kao inkluzije u tetraedritu. Pirit je zlatonosan, jer su u njemu identificirane sitne masice i zrnca *elementarnog zlata*. U površinskim zonama ležišta sulfidi i sulfosoli su značajno rastrošeni u sekundarne minerale: *halkozin, kovelin, malahit, getit* i *lepidokrokit*. Oksidacijom pirita oslobođeno je *zlato*.

Kotanopana grupa ležišta u provinciji Južni Tapanuli predstavlja dio duge kontaktnometamorfne skarnske zone. Granatski skarnovi formirani su na kontaktu gornjojurskog plagiogranita i mramoriziranih vapnenjaka. Pregledana su četiri ležišta od kojih su Tambangbustang, Aer Sipongi i Aer Malalir manjih razmjera, dok je ležište *Huta Punghut* značajnije. U paragenezi dominira krupnije zrnati *magnetit* koji je u raznim stupnjevima intenziteta *martitiziran*. Od bakarnih minerala najobilniji je visokotemperaturan *halkopirit* s izdvajanjima skeleta *sfalerita* i vretena *kubanita*. *Enargit* je rijedak. Ima dosta krupnije zrnatog *pirita* s inkluzijama *elementarnog zlata*. U zoni cementacije uočeni su hipergeni *halkozin* i *kovelin* te *elementarni bakar*. U donjem dijelu oksidacione zone prevladavaju *kuprit* i *tenorit*, a u gornjoj oksidacionoj zoni *getit, lepidokrotit* i *malahit*. *Zlato* oslobođeno trošenjem pirita vezano je na bazu nivoa željeznih hidroksida.

Od ostala tri lokaliteta jedino u ležištu Aer Malalir nađeni su djelomično svježi rudni uzorci u kojima su od primarnih minerala utvrđeni *pirit, sfalerit* s izdvajanjima halkopirita, *halkopirit* s izdvajanjima sfalerita. U druga dva ležišta svi su uzorci bili potpuno rastrošeni u hipergene minerale.

Timbulun ležište je najznačajnija rudna pojava u području jezera Sinkarak u Srednjoj Sumatri. Mineralizacija je vezana na piroksenskogranatski skarn formiran na kontaktu između intruzije gornjojurskog granodiorita i mramoriziranih vapnenjaka. U paragenezi najobilniji mineral je *neodigenit* obrubljen finim obrubom ascedentnog nisko-temperaturnog *halkozina* i potiskivan duž (111) ravnina pločicama *kovelina*. Obilan je i *halkopirit* te znatno manje *bornit* s izdvajanjima halkopirta. *Pirit* je u značajnoj mjeri potiskivan bakarnim mineralima te se vide samo relikti, obilniji je u dijelu skarna koji nije orudnjen bakarnim mineralima. Od hipergenih minerala uočeni su *malahit, azurit, halkozin, hrizokola, getit* i *lepidokrokit*.

Sve pregledane rudne pojave bile su predmet opsežnih istražnih radova Nizozemaca prije II svjetskog rata, Japanaca u toku rata te nakon toga raznih rudarskih kompanija kao što su White Engeneering Co, Rio Tinto-Betlehem, Kennecott, ali su rezultati bili izuzetno skromni. Istraživanja su vršena i na drugim dijelovima Sumatre i Jave, ali bez vidnijih rezultata. Nasuprot tim negativnim rezultatima istraživanjima otkrivena su značajnija bakarna ležišta na otocima Sulawesi, Solomon, Filipini, Nova Gvineja.

Diskusija

Od ranog paleozoika pa do danas u području Zapadne Indonezije aktivan je bio dvostruki »arc-trench system«, sa nasuprotno usmjerenim subdukcionim zonama. Jugozapadna subdukciona zona s centrom širenja u Indijskom oceanu podvlačila se u NE smjeru pod azijski kontinent, a druga na sjeveroistoku s centrom širenja u Južnom Kineskom moru podvlačila se u SW smjeru. Indonežanski otoci rasli su progresivno u toku nekoliko sve mlađih lučnih sistema. Veći otoci kao Sumatra i Java nastali su subdukcijom na debljoj i starijoj kontinentalnoj kori, a manji Sunda otoci na tanjoj i mlađoj kontinentalnoj kori (slika 1).

Otok Sumatra je otočni luk koji je formiran uz kontinentalnu koru za razliku od intraoceanskih (Marijana arhipelag), semioceanskih (Japan) ili kontinentalnih (Ande). Sumatra je kao otočni luk u zrelijem stadiju razvoja, magmatske stijene iz kojih je izgrađen magmatski luk su kalcijsko-alkalijske s prelazima u kalijske dacite, riolitske ignimbrite i andezite s malo bazalta. Magmatski luk je u kompresionom tektonskom sklopu i okrenut je prema zapadu. Takvi otočni lukovi su teoretski vrlo podobni za razvoj bakarnih porfirnih ležišta kao i bakarno-željeznih ili bakarnih pirometasomatskih skarnskih ležišta.

Relativno slabu orudnjenost bakrom na otocima Sumatra i Java više autora obrazlaže raznim uzrocima: (a) siromaštvom na metalima centra širenja u Indijskom oceanu što se očituje u pomanjkanju značajnijih pojava hidrotermalnih i hidatogenih željezno-manganskih nodula uz potpuno obrnutu situaciju u centru širenja u Pacifičkom oceanu; (b) penetracijom magmi raznih starosti u isti orogenetski prostor što je moglo uzrokovati kamuflažu; (c) prekrivanjem starijih produktivnih ciklusa recentnim vulkanskim pokrovom; (d) »nezrelošću« vrlo mlade subdukcione zone da generira pogodnu taljevinu; (e) promjenom nagiba Benioff zone; (f) promjenom smjera orijentacije Benioff zone prebacivanjem (flip).