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The Exploration Potential of Japan

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This report presents a review and analysis of the relevant geological, metallogenic, metal production and mineral exploration history of northern Tōhoku to discuss the exploration potential of the region and Japan. The interpretation is based mainly on empirical and practical arguments, in contrast to the also important petrogenetic and tectonic criteria. The case is made that for the discussion of the mineralization potential of Japan, northern Tōhoku serves as a valid proxy. One conclusion is that ignificant exploration on land in Japan for base- and precious-metal deposits, in particular for porphyry copper type systems, stopped too early, before it could have benefitted from key metallogenic developments of the past 25+ years. The full mineralization potential of Japan is excellent and far from being fully realized.

Key Words : Japan, Tōhoku, exploration, hydrothermal ore deposits, gold, copper, silver, zinc

1 INTRODUCTION

Japan is a land rich in mineral deposits, with a long mining history [1]. Access to the mineral riches of Zipangu, as Japan was known in Europe from Marco Polo's accounts, was one of the drivers behind Columbus' expedition from Spain to the West and discovery of a new, mineral-rich landmass (the Americas). Among the most common mineral deposits in Japan are base- and/or precious-metal deposits of a hydrothermal origin which occur across the country in a variety of commodities and deposit types. Interestingly, there are no known porphyry copper deposits - the prime exploration target worldwide for base- and precious-metals deposits. This is unexpected because the tectonic setting of Japan is dominated by plate collision and subduction zone magmatism, precisely the setting for formation of porphyry copper systems.

Just like our understanding of porphyry copper deposits has evolved over the past decades, exploration since the 1980s has delivered remarkable results globally and specially in countries with a metallogeny similar to that of Japan. This report presents a review and analysis of the relevant geologic, metallogenic, metal production and exploration history of Akita Prefecture in northern Tōhoku, a region that serves as a proxy in the discussion of the exploration potential of Japan.

2 GEOLOGICAL SETTING OF N. TŌHOKU

The geologic basement of northern Tōhoku consists of a diverse mixture of sedimentary, igneous and metamorphic rocks of Silurian-Devonian through Triassic age which are found in the Southern Kitakami Belt of northeastern Honshu (Figure 1). Like the rest of Japan, this region has been in a zone of subduction-related accretionary tectonics since the Permo-Triassic, when it sat on the eastern edge of Gondwana. Much of northern Tōhoku is underlain by an accretionary complex of Jurassic to Cretaceous age (the Oshima Belt) consisting of terrigenous, hemipelagic and pelagic sedimentary rocks accompanied by subsidiary limestones, cherts, and basalts. Together with the older rocks of the southern Kitakami

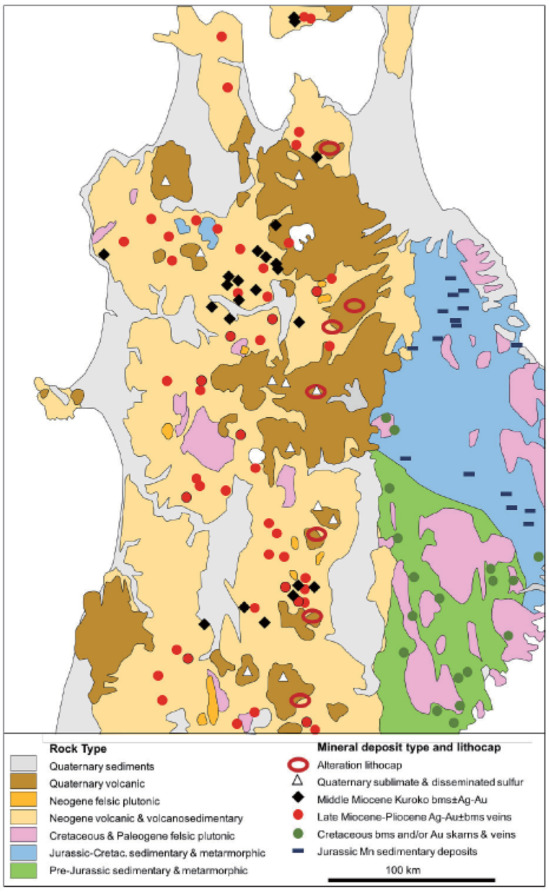

Figure 1 Schematic geology and mineral deposits of N. Tōhoku [3].

Belt these units were crosscut by magnetite-series intrusive rocks of a magmatic arc during the Cretaceous and Paleogene.

The present day geology and metallogeny of northern Tōhoku are controlled by the tectonic interactions between the Amur (Eurasia) and Okhotsk (Northamerica) subplates with the Pacific Plate. Subduction along the Japan Trench at a speed of about 9 cm/y is concurrent with convergence near the eastern edge of the Sea of Japan. Arc volcanoes form the main backbone of the region. On the back arc (Japan Sea) side, the structure was controlled by inversion tectonics, where extensional basin formation (~30-13 Ma) was followed by a transitional stage characterized by weak crustal deformation (13-3.5 Ma) that changed to contraction, folding and significant uplift since ~3.5 Ma [2].

3 MINERAL DEPOSITS OF N. TŌHOKU

In northern Tōhoku there are four main types of metallic deposits, which are distributed consistently within the geologic domains discussed above (Figure 1). The younger of these metallic deposits formed within magmatic- hydrothermal systems and includes two main deposit types: Late Miocene to Pleistocene Ag-Au ± base-metal epithermal/subepithermal veins and Middle Miocene base-metal ± Ag-Au submarine, stratiform VMS (Kuroko) deposits [1,3]. Both types of deposits typically contain copper, zinc and lead, and both may contain silver and gold although precious metals reached concentrations necessary to be the main metal produced only in the vein deposits. Both types of deposits are associated with arc and back-arc magmatism that was generated mostly in the central and western part of northern Tōhoku during subduction of the Pacific Plate beneath the Japan Arc since the Early Miocene.

Cretaceous age Mesothermal base- and/or precious-metal skarn and vein deposits are associated with magnetite-series granitoids within the Jurassic and Pre-Jurassic basement rocks of the Kitakami and Oshima belts. Within the Northern Kitakami complex of the Oshima Belt, numerous but typically small Jurassic-age chert-hosted manganese deposits were exploited from the 1930s to 1960s [1,3].

3.1 Late Miocene-Pleistocene Ag-Au ± base-metal vein deposits

The Late Miocene to Pleistocene Ag-Au ± base-metal vein deposits are broadly similar from a genetic perspective to epithermal deposits observed throughout Japan. Within those in northern Tōhoku, some deposits, typically the largest in size such as Osarizawa and Ani, were discovered many centuries ago. For example, gold is recorded to have been mined first at Ani in 1309 and silver in 1387, and by the 1700s the veins in the Ani district had been mined to deeper levels, where copper became the main economic resource. At Osarizawa, gold was reportedly discovered in the 700s. Due to resource exhaustion and a series of economic issues, all the vein mines in Akita Prefecture had ceased operations by 1980, 15 years ahead of Kuroko deposits (Figure 2).

Against this backdrop of closure of the vein deposits in Tōhoku, the 1970s to early 1980s was a period of peak mining and research activity of the VMS Kuroko deposits. As a result of the economic and scientific interest, the exploration focus and research effort went overwhelmingly to the Kuroko deposits [4, 5]. Very few studies were conducted, or have been conducted since, on the important group of epithermal vein deposits in Tōhoku, with the exception of scattered fluid inclusion and stable isotope measurements as part of broad reviews of mineral deposits in Japan [6]. As an illustration, even reliable estimates of the total (including historical) metal production from the vein deposits are not available.

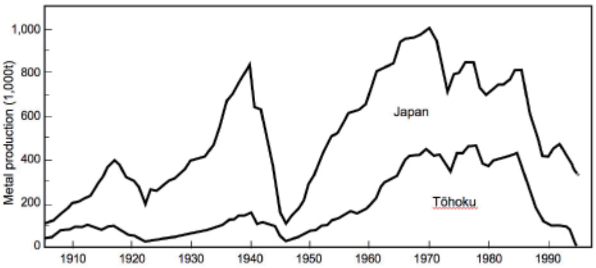

Figure 2 Production profile 1905-1995 for Japan and Tōhoku. Vertical axis is Cu equiv. of Cu, Pb, Zn, Ag and Au production combined [3].

The deposits in this group of hydrothermal veins can be classified broadly as epithermal to subepithermal. Large deposits like Osarizawa, with a 3 by 2 km vein mine area and 700 km of tunnels and production from at least 400 m vertical, compare well with some of the classic Neogene intermediate-sulfidation epithermal vein systems of the world. These include veins that occur in districts with economic porphyry copper deposits, such as those in the Philippines (Mankayan district, both the Victoria veins and adjacent Far Southeast porphyry deposit) [7], Baguio district [8], Romania (Apuseni Mountains) [9] or Argentina (Farallón Negro Volcanic Complex, with the Farallón Negro veins and Bajo de la Alumbrera porphyry deposit [10]. (However, the world-class intermediate-sulfidation deposits of Mexico so far have not been found to be associated with economic porphyry copper mineralization.)

3.2 Middle Miocene base-metal ± Ag-Au submarine, stratiform VMS (Kuroko) deposits

These deposits, particularly those located in the Hokuroku district, are the best documented in Akita Prefecture and northern Honshu. They were the main metal producer in the region during the post-1945 period and, together with the Ashio and Besshi districts in central Honshu and the island of Shikoku, respectively, they were the main copper producers in Japan. They are widely known as Kuroko deposits [11]. The first Kuroko deposit to be mined (starting in the 1860s, with Ag recovered from oxidized ores) eventually became the large Motoyama deposit located in the Kosaka area, 20 km north of Osarizawa.

Unlike the vein deposits, the age of Kuroko deposits has been exhaustively studied and is well bracketed within a short period at 14.3±0.5 Ma [12]; only the Nurukawa deposit near lake Towada seems to fall outside this range (11.7 Ma) [13]. Combined with the well-documented tectonic setting and models for the evolution of Japan since the Neogene [2], a ~14 Ma mineralization age establishes with a degree of accuracy the tectonic and paleogeographic setting of these deposits: a period of crustal extension within the back arc, possibly only ~50 km from the volcanic front, and in marine water depths of 600 to 800 m [14].

Although the tectonic setting of Kuroko and the younger epithermal vein deposits differs substantially – causing the basic differences in deposit morphology and syngenetic vs epigenetic nature – the fundamental nature of the hydrothermal fluids responsible for both types of deposit are roughly similar in their origin: in both cases metals were contributed by magmatic-hydrothermal fluids originating from exsolving intermediate to felsic magmas at depth, with dilution by marine and meteoric water, respectively.

4 MINERAL EXPLORATION OF N. TŌHOKU

As suggested in Figure 2, the region encompassing the mines and mining districts of Akita Prefecture and its surrounding districts serves as a valid proxy for Tōhoku (the Hokuroku district was the major metal producer in Tōhoku after the 1960s) and for Japan in general.

The results of an analysis of mineral exploration in northern Tōhoku show that exploration activity took place between the early 1960s and 1995 [14]. According to this analysis, thirty percent of the activity, as represented by the number of drill holes, took place during the 1960s, 67% in the 1970-1980s, the period of maximum activity (the "Kuroko boom"), and less than four percent in the 1990s. By target type, the overwhelming focus was for Kuroko deposits, with 85% of the budget and 91% percent of the drilling. By contrast, exploration for Au-Ag-bearing vein deposits accounted for about 15% of the budget and only nine percent of the drilling. In both cases, exploration on the ground ceased in 1993; thus, it may be argued that the metallogenic science and exploration models and technology applied date back to the 1980s, more than thirty years ago.

As with the other targeted and methodical exploration programs conducted by MMAJ in Japan (e.g., in the Hokusatsu district of southern Kyushu in the 1970s, leading to the discovery of Hishikari in 1981) [15], exploration in northern Tōhoku achieved significant success. In the exploration projects targetting Kuroko mineralization i) the deposit host formation was identified in all project areas, ii) several VMS deposits were discovered (e.g., Ezuri in 1976; Nurukawa in 1984) [16], and iii) within the Tazawa project area with only 16 holes, Mo mineralization was identified in granite basement, Cu-Pb-Zn veins were found around a Neogene intrusion, and a Au-Ag vein was intersected.

4.1 Comparison to global mineral discovery record

A comparison of the metal production profile of Tōhoku with the research by R. Schodde [17] on discovery of major mineral deposits worldwide highlights the impact of exploration in the past thirty years (Figure 3). Half of all deposits were discovered after 1980 and the 2000-2014 decade was the most prolific discovery period in history.

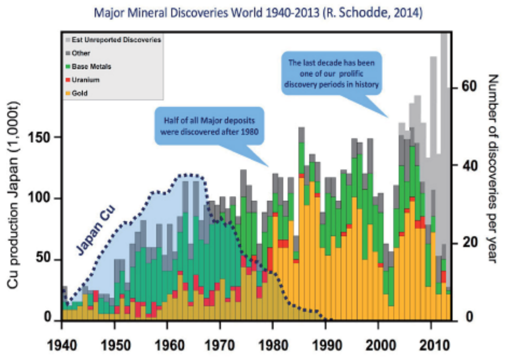

Figure 3 1940 to 2014 copper production profile for Japan (left scale) overlain over the number of major mineral discoveries in the world excluding non-ferrous or bulk commodities and satellite deposits within existing camps (right scale) [17]. Japan Cu production data from World Mineral Statistics-British Geological Survey.

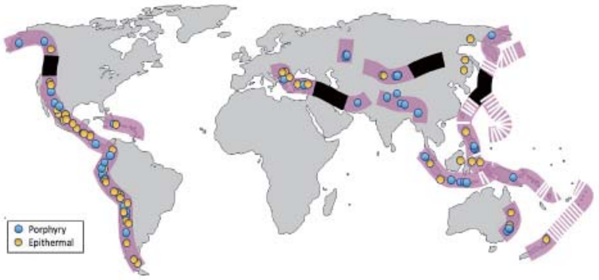

Figure 4 Significant porphyry copper and epithermal deposits discovered within arc-related metallogenic belts (purple lines) since 1990. Black lines denote arc segments with no apparent deposit discovery during the period 1990-2017.

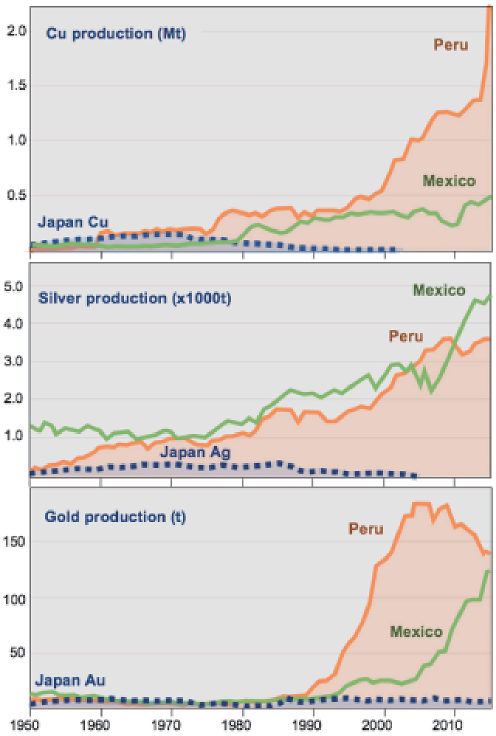

Figure 5 Mine production profiles (1950 to 2015) for copper, silver and gold in Peru, Mexico and Japan. Sources of data: Mexico (Servicio Geológico Mexicano), Peru (Ministerio de Energía y Minas), Japan (World Mineral Statistics-British Geological Survey).

Geographically, and contrasting Japan to comparable arc-related metallogenic terranes worldwide, Japan appears as one of a small number of arc segments of significant length (>1500-2000 km) that show no documented epithermal or porphyry deposit discovery since 1990 (Figure 4). Similar to other such apparent 'barren' belt segments, such as Iran or western USA, the main explanation appears to be a lack of exploration, and not an absence of mineralization.

A truly stark comparison with the Japanese data results from plotting the record of copper, silver and gold production for

Mexico and Peru, two countries of dimensions and metallogenic setting comparable to that of Japan (Figure 5). As a direct result of exploration in these countries, production of all three metals, compared to the 1970s (the peak period of peak production in Japan) have grown by an order of magnitude or more (Figure 5).

5 DISCUSSION

The experience in Japan with targeted and methodical exploration that applied the state-of-the-art metallogenic science and technology at the time, such as in the 1970s and 1980s looking for Kuroko deposits, shows that exploration in Japan can be successful. On the other hand, the type of exploration that could have led to porphyry discovery, apart from being minimal, applied concepts of the 1980s and earlier. Since then, the understanding of the relationship between porphyry and epithermal deposits has evolved significantly; the following is a timeline of the major related breakthroughs relevant to exploration for these deposits.

Broadly speaking, the 1990s witnessed an improved understanding of the origin of acid-sulfate alteration and its relationship to magmatic hydrothermal and geothermal systems [18]. The magmatic fluid contributions to high-sulfidation Cu-Au epithermal deposits was proven and their environment of formation, intermediate between an exsolving shallow magmatic intrusion and the surface, was established [19]. A temporal and genetic connection between porphyry and high-sulfidation epithermal deposit was demonstrated [20]. Nevertheless, many geologists worldwide still held on to the 1970s porphyry model.

In the 2000s, the concept and term ‘lithocap’ [21] began to be used by some explorers, both in the scientific literature and in exploration. A revised classification scheme of epithermal deposits was introduced which distinguished among high-, intermediate-, and low-sulfidation epithermal deposits [22, 23]. Building upon new insight from regional studies of magmatic-hydrothermal mineralization in the western USA, a compelling case for specific linkages between volcanotectonic setting and epithermal and porphyry deposits was introduced [24].

Within the current decade, the concept, i.e., understanding, of a ‘porphyry copper system’ [25] has gained acceptance by many (but not all) geologists. This has been enhanced by a sophisticated understanding of its mineralogical and geochemical characteristics as well as an improved definition of the chemical and physical fluid structure and modeling [26]. Focused research projects have developed criteria, vectors and associated exploration tools [27]. On the practical side, it has become evident that successful greenfields porphyry exploration requires deep (>800-1000+m) drilling [28-31].

Without a doubt, the current genetic context and geologic and exploration models will continue to evolve in the near future, as new studies are completed and new questions addressed. For example, do all magmatic-hydrothermal systems above a shallowly emplaced exsolving magmatic intrusion - of the appropriate composition and evolution - form a porphyry deposit with or without some of the associated deposit types? Or can, e.g., an intermediate- or high-sulfidation deposit form without a requisite porphyry copper deposit?

In parallel with subaerial settings, the understanding of submarine magmatic-hydrothermal systems and associated mineralization has also evolved greatly over the past few decades. As a result, the potential for porphyry-type (i.e., intrusion-related, stockwork or disseminated) mineralization may not be limited to subaerial magmatic-hydrothermal conditions such as those in the Late Miocene to Plesitocene in northern Honshu, with obvious temporal restrictions.

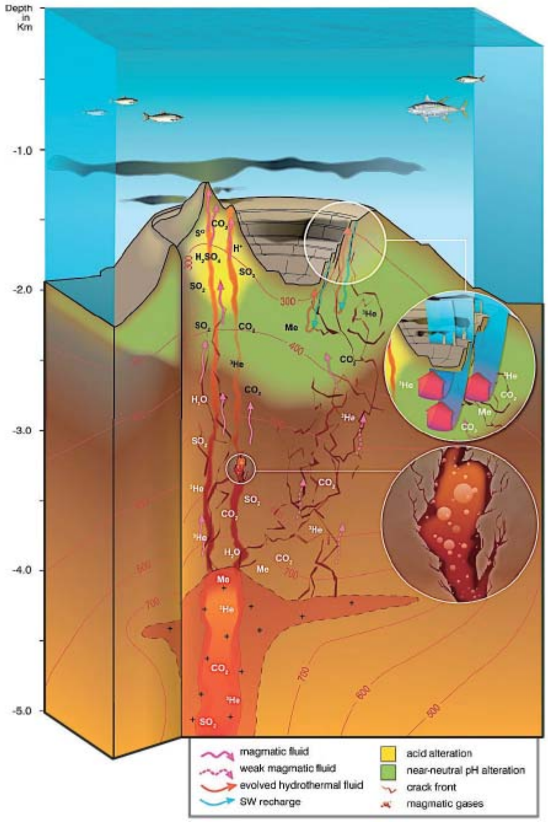

Figure 6 Schematic diagram of the hydrothermal system at Brothers volcano in the Kermadec intraoceanic arc. The diagram shows two distinct vent fields with contrasting geology, permeability, vent fluid compositions, mineralogy, and ore-forming conditions which are interpreted to represent stages along a continuum between water/rock- and magmatic/hydrothermal-dominated end-members as illustrated by the conditions at depth [33].

Recently, research on active submarine systems has focused increasingly on hydrothermal venting in submarine volcanic arcs, such as those discovered in the Izu-Bonin, Mariana or Kermadec arcs [32]. Indeed, a deep-ocean drilling expedition scheduled for mid-2018 to Brothers Volcano in the Kermadec Arc will test, among other scientific objectives, the existence of metallic mineralization at depths of several hundred meters beneath the ocean floor beneath the flanks of a stratovolcano, in an environment which is fundamentally similar to that of porphyry-type deposits (Figure 6). Envisioning the potential for such mineralization within the paleo-volcanic front of northern Honshu during the Middle Miocene, when Kuroko VMS deposits were forming in the back-arc region (a setting similar to that of the Mariana arc vs. Mariana trough), is not a stretch of the imagination.

6 CONCLUSIONS

Until proven otherwise, the Japanese porphyry has not yet been found, given the permissive evidence in the shallow epithermal environment. It may be argued that exploration stopped too early three decades ago, before it could have benefitted from recent metallogenic and technologic breakthroughs, applicable both to porphyry copper systems, epithermal deposits, and hydrothermal mineralization in submarine volcanic arcs. Exploration today for these types of deposits, in particular porphyry copper and epithermal deposits would be done differently, e.g., looking more for indirect evidence, such as beneath – and lateral to – lithocaps, spatially associated with high- and intermediate sulfidation epithermal/ subepithermal veins, and with necessary deep drilling.

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References

[1] Watanabe Y.; Takagi T.; Kaneko N.; Suzuki Y., “Mineral and hydrocarbon resources” *The Geology of Japan, Geological Society, London*, 435-459 (2016).

[2] Sato H. “The relationship between late Cenozoic tectonic events and stress field and basin development in northeast Japan” *J. Geophys. Res*., 99, 22, 261-22, 274 (1994).

[3] Sudo S.; Igarashi T. “Mineral resources map of Tohoku”, *Geological Survey of Japan* (1997).

[4] Ishihara S. (Ed.) “Geology of the Kuroko Deposits” *Soc Mining Geol Japan, Sp Iss* 6, 435 p (1974).

[5] Ohmoto H.; Skinner B.J. Eds. “The Kuroko and Related Volcanogenic Massive Sulfide Deposits”. *Econ. Geol. Monograph*. 5, 604 p. (1983).

[6] Shikazono N. “Geochemical and Tectonic Evolution of Arc-Backarc Hydrothermal Systems-Implication for the Origin of Kuroko and Epithermal Vein-Type Mineralizations and the Global Geochemical Cycle” *Elsevier* 478 p (2003).

[7] Chang Z.; Hedenquist J.W.; White N.C.; Cooke D.R.; Roach M.; Deyell C.L.; Garcia J.S. Jr.; Gemmell J.B.; McKnight S.; Cuison, A.L. “Exploration tools for linked porphyry and epithermal deposits: Example from the Mankayan intrusion-centered Cu–Au district, Luzon, Philippines”. *Econ. Geol*., 106, 1365-1398 (2011).

[8] Cooke D.R.; Deyell C.L.; Waters P.J.; Gonzales R.I.; Zaw K. “Evidence for magmatic-hydrothermal fluids and ore-forming processes in epithermal and porphyry deposits of the Baguio district, Philippines” *Econ. Geol*., 106, 1399-1424 (2006).

[9] Wallier S.; Rey R.; Kouzmanov K.; Pettke T.; Heinrich C.H.; Leary S.; O’Connor G.; Tamas C.G.; Vennemann T.; Ullrich T. “Magmatic fluids in the breccia-hosted epithermal Au-Ag deposit of Rosia Montana, Romania” *Econ. Geol*., 101, 923-954 (2006).

[10] Márquez-Zavalía F.; Heinrich C.A. “Fluid evolution in a volcanic-hosted epithermal carbonate–base metal–gold vein system: Alto de la Blenda, Farallón Negro, Argentina” *Mineral. Deposita*, 51, 873-902 (2016).

[11] Sato T. “Kuroko deposits: their geology, geochemistry and origin, *Geol. Soc. Lond. Spec. Publ*., 7, 153-161(1977).

[12] Terakado Y. “Re-Os dating of the Kuroko ore deposits from the Hokuroku district, Akita prefecture, Northeast Japan” *J Geol Soc Japan* 107, 354-357 (2001).

[13] Ishiyama D.; Hirose K.; Mizuta T.; Matsubaya O.; Ishikawa, Y. “The characteristics and genesis of the kaolinite-bearing gold-rich Nurukawa Kuroko deposit, Aomori Prefecture, Japan”. *Proceed. 10th Int Symp Water Rock Interaction, Villasimius*, 1, 717-720 (2001).

[14] Arribas A.; Mizuta T. “The potential for porphyry copper deposits in northern Tōhoku (or the exploration potential for base- and precious-metal deposits in Japan 2020). *Resour. Geol*. (in press) (2018).

[15] Izawa E.; Urashima Y.; Ibaraki K.; Suzuki R.; Yokoyama T.; Kawasaki K.; Koga A.; Taguchi S. “The Hishikari gold deposit: High-grade epithermal veins in Quaternary volcanics of southern Kyushu” *Japan. J. Geochem. Explor*., 36, 1-56 (1990).

[16] JOGMEC “Exploration of the Kuroko deposits” *Metal Mining Technology in Japan* 10, 17 p. (2005)

[17] Schodde R.C. “The global shift to undercover exploration - How fast? How effective?” *Soc Econ Geol Keystone 2014 Conference, Keystone, Colorado* (2014).

[18] Rye R.; Bethke P; Wasserman M. “The stable isotope geochemistry of acid-sulfate alteration” *Econ Geol*, 87, 225-262. (1992).

[19] Arribas A.; Hedenquist J. W.; Itaya T.; Okada T.; Concepción R. A.; Garcia J.S. “Contemporaneous formation of adjacent porphyry and epithermal Cu-Au deposits over 300 ka in northern Luzon, Philippines” *Geology*, 23, 337-340 (1995).

[20] Hedenquist J.W.; Arribas A.; Reynolds T.J. “Evolution of an intrusiin-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines” *Econ. Geol*., 93, 373-404 (1998).

[21] Sillitoe R.H. “Gold-rich porphyry deposits: Descriptive and genetic models and their role in exploration and discovery” *Rev. Econ. Geol*., 13, 315-345 (2000).

[22] Hedenquist J.W.; Arribas A.; Gonzalez-Urien, E. “Exploration for epithermal gold deposits”. *Rev. Econ. Geol*., 13, 245-277 (2000).

[23] Einaudi M.T.; Hedenquist J.W.; Inan, E.E. “Sulfidation state of fluids in active and extinct hydrothermal systems: Transitions from porphyry to epithermal environments”. *Soc Econ Geol Sp Pub* 10, p. 285-313 (2003).

[24] Sillitoe R.H.; Hedenquist, J. ”Linkages between volcanotectonic settings, ore fluid compositions, and epithermal precious metal deposits” *Soc Econ Geol Sp Pub* 10, p 315-343 (2003).

[25] Sillitoe R.H. “Porphyry copper systems” *Econ. Geol*., 105, 3-41 (2010).

[26] Kouzmanov K.; Pokrovski G.S. “Hydrothermal controls on metal distribution in porphyry Cu (-Mo-Au) systems” *Soc Econ Geol Sp Pub* 16, 573-618 (2012).

[27] Chang Z.; Hedenquist J.W.; White N.C.; Cooke D.R.; Roach M.; Deyell C.L.; Garcia, J. S.; Gemmell, J.B.; McKnight, S.; Cuison, A.L. “Exploration tools for linked porphyry and epithermal deposits: Example from the Mankayan intrusion-centered Cu-Au district, Luzon, Philippines” *Econ. Geol*., 106, 1365-1398 (2011).

[28] Sillitoe R.H.; Burgoa C.; Hopper D.R. “Porphyry copper discovery beneath the Valeriano lithocap Chile” *Soc Econ Geol Newsletter*, 106, 1-20 (2016).

[29] Sillitoe, R.H.; Tolman J.; Van Kerkvoort G. “Geology of the Caspiche porphyry gold-copper deposit, Maricunga belt, northern Chile” *Econ. Geol*., 108, 585-604 (2013).

[30] Moorehead C. “NI 43-101 technical report on the Wafi-Golpu property in Morobe province, Papua New Guinea” Prepared for Newcrest Mining, Ltd. Report date: 29 August 2012,

Melbourne, 150 p. (2012).

[31] Rohrlach B. “The discovery history and geology of the Tujuh Bukit copper-gold project, Java, Indonesia” *AMEBC Mineral Exploration Roundup Conference*, Vancouver BC (2011).

[32] De Ronde C.E.J; Hein J.R.; Butterfield D.A. (Eds.) “Metallogenesis and mineralization of intraoceanic arcs II: The Aeolian, Izu-Bonin, Mariana, and Kermadec Arcs, and the Manus backarc basin – Introduction” *Econ Geol*, 109, p. (2014).

[33] De Ronde C.E.J.; Bach R.; Arculus R.; Barriga F.; Caratori-Tontini K; and 19 other co-authors “Gateway to the Sub-Arc Mantle: Volatile Flux, Metal Transport, and Conditions for Early Life” *IODP Proposal 818 https://docs.iodp.org/Proposal_ Cover_Sheets/818-Full_deRonde_cover.pdf* (2017).