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Thematic Article

Potential for Porphyry Copper Deposits in Northern Tōhoku (or the Exploration Potential for Base and Precious Metal Deposits in Japan 2020)

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Abstract

There are no known porphyry copper deposits in Japan. Attempts were made in the past to explain this paradox as the Japanese islands sit above a subduction zone of the type widely accepted to give rise to porphyry-type deposits within subvolcanic magmatic–hydrothermal systems. Is it possible that porphyry copper systems are incompatible with the volcanoplutonic setting of the Japanese islands? In other words, is the established model for the genesis of porphyry copper systems not completely correct, or is it that the elusive Japanese porphyry deposit has not yet been found? We argue that, until proven otherwise, the answer lies in the latter option.

In this article, we focus on Akita Prefecture and the surrounding areas and consider the potential for the existence of porphyry copper deposits mainly from an empirical and practical point of view, in contrast with the obviously important petrogenetic and/or tectonic perspectives. We argue that this region is representative of the Tōhoku province of northern Honshu and that it serves as a proxy for Japan in general. Akita is rich in mineralization styles and deposits, including two main magmatic-hydrothermal deposit types of Neogene age: (i) middle Miocene submarine stratiform volcanogenic massive sulfide (VMS) deposits (Kuroko) and (ii) late Miocene to Pleistocene Ag–Au-bearing polymetallic epithermal/subepithermal veins. In particular the Au–Ag-bearing polymetallic veins, which are comparable to intermediate-sulfidation epithermal deposits commonly associated with porphyry copper systems, were discovered and mined for several centuries before the first Kuroko deposits were found in the late 1800s. Osarizawa, the last active vein mine, closed in 1978. Kuroko deposits, the main source of metal production in Akita in the 20th century, had peak of production in the 1970s, followed by a rapid decline during the 1980s and complete cessation of all mining by 1995. Not surprisingly, the end of mining in Akita, combined with a series of strategic decisions made by the Government and the Japanese metal mining industry, coincided with a cessation of mineral exploration, both in Akita and throughout Japan, with the exception of VMS deposits offshore and limited exploration for bonanza-grade, low-sulfidation epithermal gold deposits in Hokkaido. Our analysis of post-1945 regional exploration in northern Tōhoku indicates that Kuroko deposits were by far the dominant target and that the number of drill holes in the 1990s accounted for less than 4% of the total completed from the early 1960s to 1995. These data indicate that essentially no mineral exploration has been conducted in Tōhoku for Au–Ag-bearing polymetallic vein deposits during the past 30+ years. We conclude that exploration stopped too early and certainly before it could have benefited from the significant applicable metallogenic and technological breakthroughs of the last few decades.

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Keywords: Akita Prefecture, copper–gold–silver–zinc, epithermal deposits, exploration potential, Japan, porphyry copper systems.

1. Introduction

Japan is a land rich in mineral deposits, with a long mining history. Access to the mineral riches of Cipangu, 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 hydrothermal origin, which occur across the country as a variety of commodities and deposit types. However, there are no known porphyry copper deposits among those discovered in Japan. This is unexpected given that the tectonic setting of Japan is dominated by plate collision and subduction zone magmatism, precisely the setting required for the formation of porphyry copper deposits (Fig. 1; Sillitoe, 1972; Hedenquist & Lowenstern, 1994; Audetat & Simon, 2012).

Our understanding of porphyry copper deposits has evolved over the past decades. In the context of mineral exploration, many explorationists now view porphyry copper deposits as the main constituent of a broader mineral system driven by shallow intrusions of oxidized, intermediate composition magma that exsolved magmatic fluids, as illustrated by Sillitoe (2010). In addition to the porphyry copper deposit itself, the 'porphyry copper system' encompasses several environments of hydrothermal mineralization and alteration, including lithocaps of advanced argillic alteration, which in some cases host high-sulfidation epithermal Au–Ag–Cu–As deposits, more distal intermediate-sulfidation Au–Ag and Ag–Au ± base metal epithermal vein deposits, and deeper base metal±Au–Ag subepithermal veins and skarns (Fig. 2). With the exception of porphyry copper deposits, all of the ore deposits listed above are known in Japan, including several lithocaps (Takeouchi & Abe, 1970; Hirano & Sudo, 1994; Watanabe *et al.*, 1997), some of which host the Nansatsu gold deposits (Urashima *et al.*, 1981). Within this context, a question seems unavoidable: is it possible that porphyry copper deposits and, by extension, porphyry copper systems are incompatible with the volcanotectonic setting of the Japanese islands? If so, something may be fundamentally wrong with the established model for the genesis of porphyry copper systems. We do not believe this to be the case.

To address these questions, we review and analyze the relevant geology, metallic deposits, metal production,

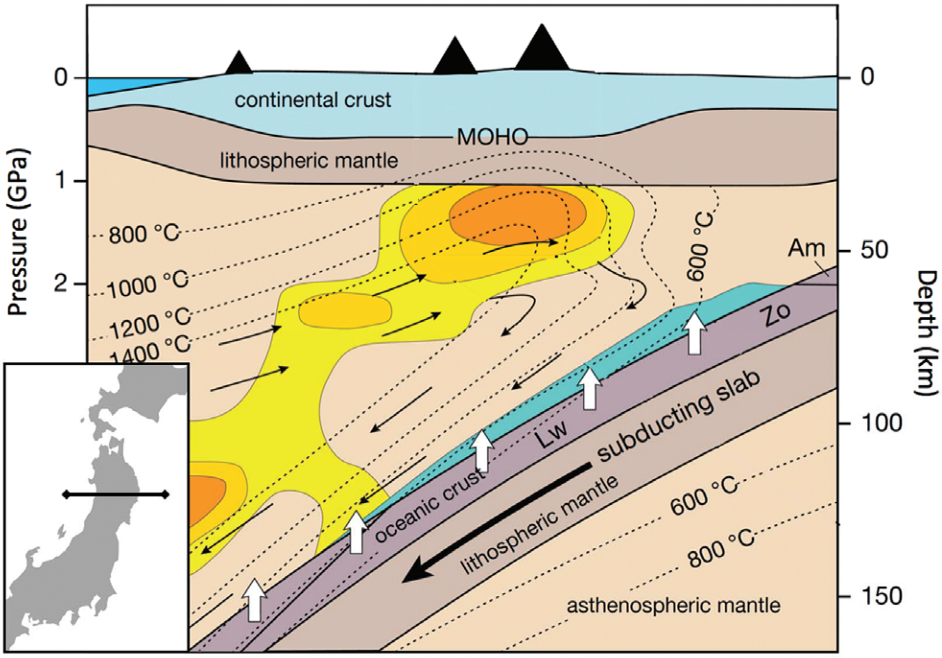

Fig. 1 Cross section looking north through the subduction zone in northeastern Honshu (line in inset map) used by Audetat and Simon (2012) (from Kimura & Nakajima, 2014), to illustrate some of the key magmatic processes relevant to porphyry copper genesis, including partial melting of the asthenospheric and lithospheric mantle.

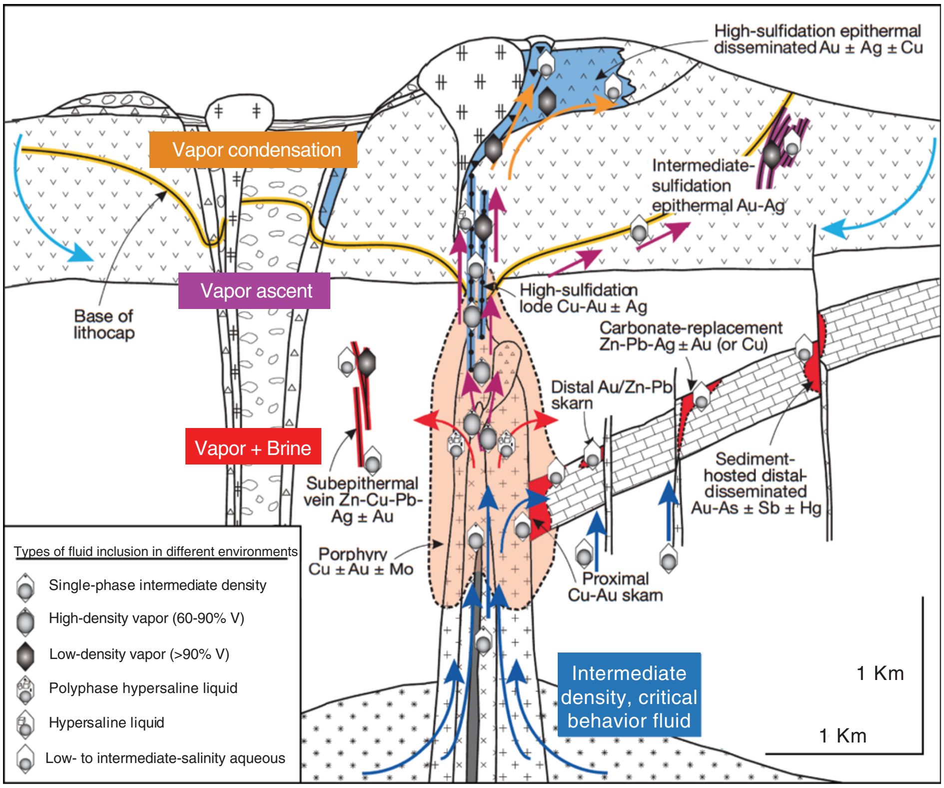

Fig. 2 Anatomy of a non-eroded, telescoped porphyry copper system showing spatial interrelations of a centrally located porphyry Cu ± Au ± Mo deposit and high- and intermediate-sulfidation epithermal deposits in and alongside the lithocap environment (mod. from Sillitoe, 2010). Not all depicted features are necessarily present in any single district. The fluid inclusions characteristic of the different environments present in this magmatic–hydrothermal system were added by Kouzmanov and Pokrovski (2012). The main fluid regimes shown apply mainly to the early stages of the evolution of a porphyry copper system.

and mineral exploration history of northern Tōhoku. The emphasis of our analysis is on empirical and practical arguments, in contrast with the also important petrogenetic and tectonic studies. We argue that northern Tōhoku serves as a proxy for Japan, both with respect to the potential existence of porphyry copper deposits as well as the mineralization potential of the country as a whole. We conclude that, as far as the discovery of porphyry copper deposits is concerned, exploration in Japan stopped too early, before it could have benefited from key metallogenic developments of the past 25+ years. In our view, the elusive Japanese porphyry deposit has not yet been defined, and the full mineralization potential of the country is far from being fully realized.

2. Background

2.1 Brief history of metal mining and production in Japan

Evidence of metal mining in Japan dates back to the 7th century when gold, silver, copper, tin, iron, cinnabar, coal, petroleum, and other mineral substances started to be mined on a small scale (Wada, 1893). However, by the time the Great Buddha of Nara was completed in 751, an estimated 500 t of copper necessary to build this 15 m tall statue (plus 8.5 t Sn, 2.5 t Hg and 440 kg Au; Kaku, 2015) had been produced domestically from mines in western, central, and northern Japan (the Nagato, Musashi, and Oshu districts, among others). European explorers, traders, and missionaries who arrived in Japan in the 16th century witnessed the vast amounts of silver extracted from the Iwami Ginzan district in southwestern Honshu, the largest silver mine in Japan and one of the largest silver producers in the world at the time (Yamaguchi, 2004).

Mining in Japan continued at limited rates throughout the Edo period and picked up with the Meiji Restoration, particularly after the mid-1880s when the government transferred most large mines to individuals and companies committed to their mechanization and exploitation at rates capable of supplying the efforts to industrialize and modernize the country. Through ownership of these mines, several of these companies eventually grew to become some of the largest industrial and business conglomerates in the country, for example, Mitsubishi with the Sado (Au–Ag), Takashima (coal), and Osarizawa (Cu–Pb–Zn–Ag) mines; Mitsui with the Kamioka (Ag–Pb–Zn) and Miike (coal) mines; Furukawa with Ashio (Cu); Dowa with Kosaka (Cu–Pb–Zn–Au); Nippon Mining (now part of JX Group) and Nissan; and, indirectly, Hitachi, with ownership of the Hitachi (Cu) mine in Ibaraki Prefecture (Yamaguchi, 2004).

In the 20th century, the production of metals in Japan peaked in ~1917, fell in the ensuing economic depression, rose again prior to the beginning of the Pacific War, and decreased sharply until about 1945 (Fig. 3). In the postwar period, metal production revived, and production peaked in 1970 during the period of rapid growth of the Japanese economy. The introduction in 1971 of a floating exchange rate and the subsequent appreciation of the yen (from 360¥/$ in 1970 to 160¥/$ in 1986 and 80¥/$ in 1995) hit the international competiveness of Japan's domestic mining industry hard. Combined with ore depletion – and other factors, such as a mixed environmental and safety record, increasing pollution control costs, and popular opposition – the number of mines in the country collapsed, from 943 non-ferrous mines in 1970 to only 132 five years later (Kaku, 2015). Facing the challenges mentioned above and an ever-increasing metal supply deficit to support the national economy, both the central government and business conglomerates made a strategic decision to decrease their reliance on domestic mining and to shift the procurement of the mineral resources needed for industry to mines abroad. In Tōhoku, one of the traditional mining regions of the country, mining of metallic ore ceased entirely by 1995 (Fig. 3). Today, only the Hishikari Au–Ag deposit, plus a few small Au deposits in the Nansatsu district of southern Kyushu (largely used as sources of silica flux), are mined in Japan (the Kamioka skarn and Toyoha Ag–In base metal epithermal mines closed in 2001 and 2006, respectively).

2.2 Previous studies

The lack of porphyry copper deposits in Japan, while paradoxical and widely acknowledged, has not been the subject of significant attention or detailed analysis until this special issue. Part of the explanation is a result of, in our view, the attention given by Japanese researchers and the national exploration and mining interests to mineral deposits abroad and, in the domestic scene, to deposit types that were more in favor at the respective time: submarine VMS deposits in the 1970 and 1980s, particularly in the Hokuroku district (see below); low-sulfidation epithermal bonanza veins in the mid-1980s and early 1990s, such as Hishikari; and offshore VMS systems since the mid-1990s within Japanese territorial waters (Iizasa, 2008). During a brief period in the mid-1990s, limited exploration of advanced argillic lithocaps was also conducted (Watanabe *et al.*, 1997; Izawa & Hayashi, 2018).

The most recent and extensive effort to explain the lack of porphyry deposits in Japan was undertaken by Qin and Ishihara (1998) ("On the probability of porphyry copper mineralization in Japan"). These authors identified a number or prerequisites for the formation of porphyry copper deposits and then discussed a series of related potentially unfavorable factors present in the Japanese islands, such as: (i) extensional tectonics and submarine setting (which favor VMS mineralization; cf., Sillitoe, 1980), (ii) absence of a rigid continental crust, (iii) relatively low percentage of oxidized, magnetite-series magmatic intrusions, (iv) low metal (Cu) abundance in Japanese granitoids, and (v) the fact that Japan is long and narrow. Nevertheless, following a review of relevant exploration and scientific breakthroughs at the time, including the discovery of the Zijinshan high-sulfidation Au–Cu

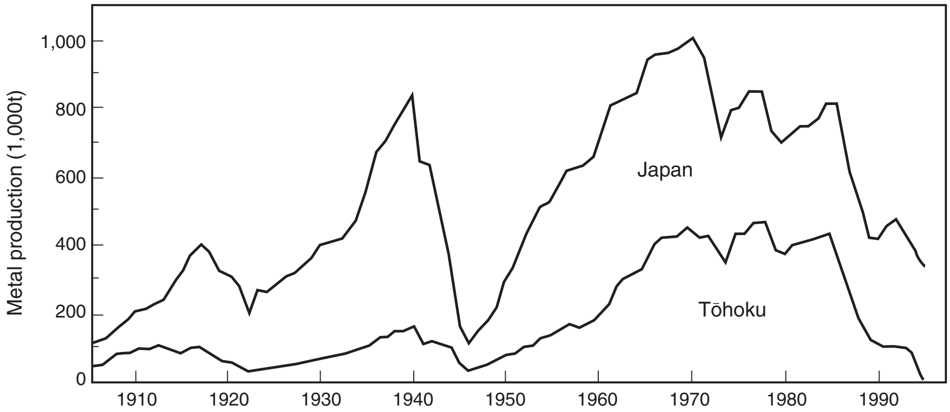

Fig. 3 Metal production profile 1905–1995 for Japan and Tōhoku (Sudo & Igarashi, 1997). The absolute value of the *Y*-axis is of no quantitative significance; it represents a copper-equivalent amount for production of Cu, Pb, Zn, Ag, and Au combined using mass ratios based on element abundances in the Earth's crust (Sudo & Igarashi, 1997).

deposits in southeastern China (Zhang *et al.*, 1994) and the proven link between world-class porphyry and epithermal deposits at Far Southeast and Lepanto in the Philippines (Arribas Jr. *et al.*, 1995), Qin and Ishihara (1998) are unambiguous about their final verdict: *"The possibility of the existence of porphyry copper deposits in Japan cannot be ruled out… porphyry coppers probably did form, and will be found, in the deeper part of a hydrothermal alteration zone of some high-sulfidation epithermal Au deposit or vein Pb–Zn–Cu deposits, or even at the periphery of some skarn Pb–Zn–Cu deposits"*. We subscribe fully to this assessment, including the fact that a number of geological factors may explain why porphyry copper deposits are scarce in Japan compared to subduction-related magmatic arcs elsewhere. Some of these factors are discussed in this volume (e.g. Hattori, 2018; Sillitoe, 2018; Watanabe *et al.*, 2018; Williamson *et al.*, 2018).

2.3 Lessons on exploration for porphyry copper deposits from the East Sunda-Banda arc

The exploration history, over a period of nearly five decades (since the early 1970s), of the East Sunda-Banda arc in Indonesia presents a particularly illustrative case relevant to the discussion here. Following the early knowledge of porphyry copper mineralization in the Philippines (e.g. the Atlas deposit in Cebu), a series of important discoveries was made in other island arcs of the western Pacific, namely, as a result of grassroots exploration in the then Australian-administered territories of Papua New Guinea, including Panguna in 1964 and Ok Tedi in 1969 (Hope, 2011).

Based on these discoveries, the geographic proximity, similarity in tectonic setting, and lack of previous focused exploration, the Eastern Sunda and Banda arcs became the target of exploration for porphyry copper deposits in the 1970s. Although subeconomic porphyry mineralization was found in northern Sulawesi, the overall results were disappointing – not surprising for only the first round of grassroots exploration over such a large region – and, as summarized by van Leeuwen (1994), *"by the early 1980s porphyry copper deposits had fallen out of favor as an exploration target"*. However, the discovery in 1988 of the giant Grasberg porphyry Cu–Au deposit adjacent to the Ertsberg Cu–Au skarn in the western part of the island of New Guinea and the successful grassroots campaign by Newmont Corp. in Sumbawa, with the discovery of the Dodo-Elang and Batu Hijau porphyry Cu–Au deposits in 1987 and 1991, respectively, demonstrated that this negative view was indeed premature. Incidentally, with the discoveries of a giant porphyry Cu–Au deposit at Tujuh Bukit in Java in 2007 (Rohrlach, 2011; Maryono *et al.*, 2018) and recently at Hu'u in eastern Sumbawa (Maryono *et al.*, 2018), the East Sunda-Banda arc is, today, arguably one of the more densely mineralized porphyry copper belts worldwide.

3. Geological setting of northern Tōhoku

The geological basement of northern Tōhoku consists of a diverse mixture of sedimentary, igneous, and metamorphic rocks of the Silurian-Devonian to the Triassic age, which are found in the South Kitakami Belt of northeastern Honshu (Fig. 4). 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. Accretion has continued, and 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 (Isozaki, 1997). Together with the older rocks of the South Kitakami Belt, these units were crosscut by magnetite-series intrusive rocks of a magmatic arc during the Cretaceous and Paleogene (Watanabe *et al.*, 2016).

The present-day geology and metallogeny of northern Tōhoku are controlled by the tectonic interactions between the Amur and Okhotsk subplates with the Pacific Plate. Subduction along the Japan Trench at a rate of about 9 cm year^{-1} is concurrent with convergence near the eastern edge of the Sea of Japan (Taira, 2001). Arc volcanoes, including at least five large Quaternary volcanic massifs, form the main backbone of the region (Fig. 4). On the back-arc (Sea of Japan) side, the structure was controlled by inversion tectonics, where extensional basin formation (active between ~30 and 13 Ma) was followed by a transitional stage characterized by weak crustal deformation (between 13 and 3.5 Ma) that changed to contraction, folding, and significant uplift since ~3.5 Ma (Fig. 5; Sato, 1994).

4. Mineral deposits of northern Tōhoku

In northern Tōhoku, there are four main types of metallic deposits, which are distributed consistently within the

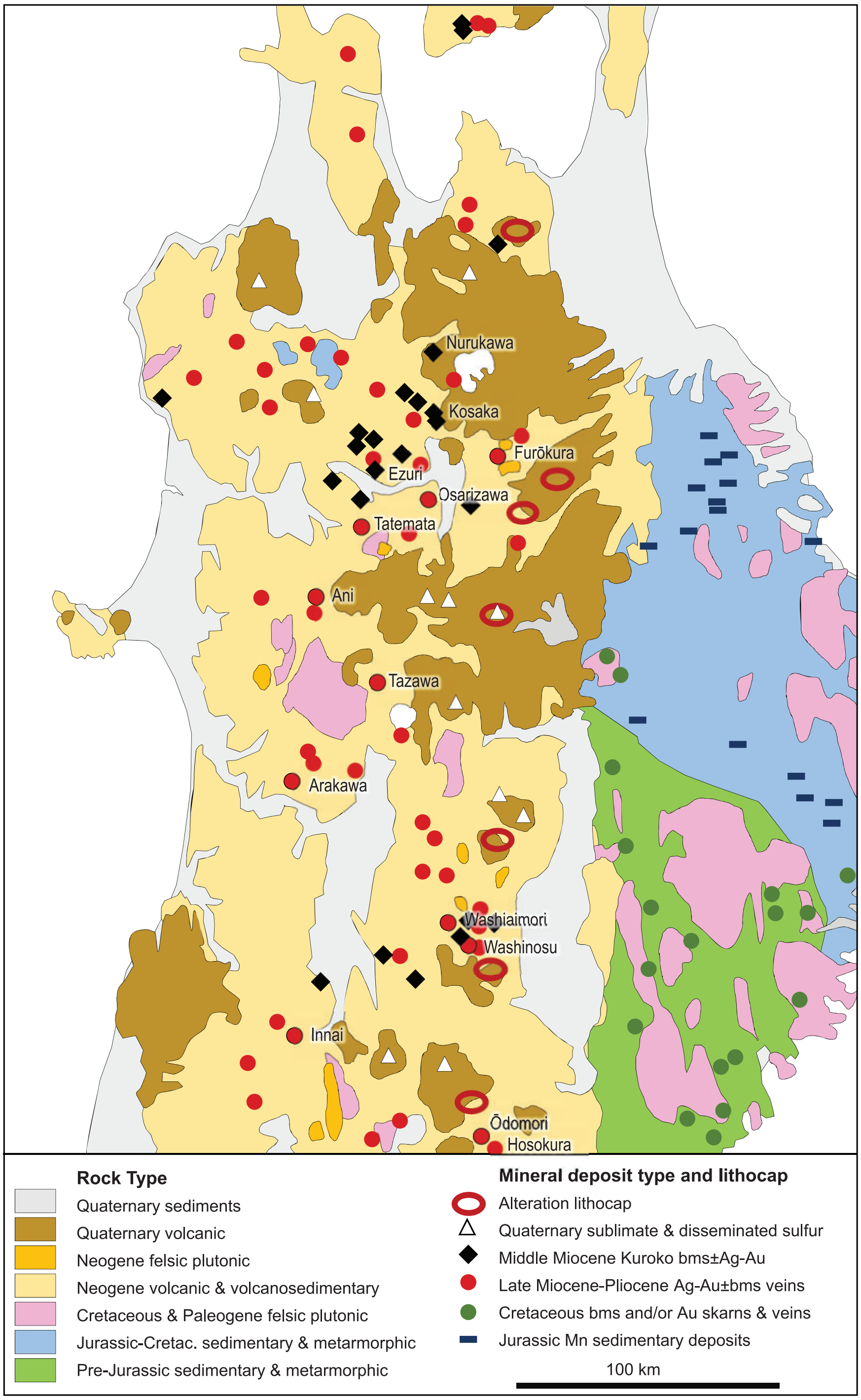

Fig. 4 Schematic geology and mineral deposit map of northern Tōhoku (based on 1:500,000 scale map by Sudo & Igarashi, 1997; lithocaps include those in Watanabe *et al.*, 1997; bms, base metal sulfides). Deposits mentioned in the text or tables are identified.

geological domains discussed above (Fig. 4). The Miocene and younger of these metallic deposits were formed within hydrothermal (i.e. magmatic–hydrothermal) systems and are of particular interest to this discussion on the potential existence of porphyry copper deposits as they may form part of porphyry copper systems (Sillitoe, 2010). They consist of late Miocene to Pleistocene Ag–Au ± base metal epithermal/subepithermal veins and middle Miocene base metal±Ag–Au submarine, stratiform VMS (Kuroko-type) deposits (Fig. 4). Both types of deposit typically contain copper, zinc, and lead, and both may also contain silver and gold; in addition, rare metals such as indium, bismuth, germanium, and gallium were recovered from some of the VMS deposits (Ishihara & Endo, 2007). Precious metals reached concentrations necessary to be the only main metal produced 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 (Fig. 5; Watanabe *et al.*, 2016).

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. These continental basement rocks and Cretaceous felsic-intermediate plutons, without associated mesothermal vein mineralization, can be observed in erosional windows (uplifted blocks) within the volcanic and sedimentary rocks of the Cenozoic Japan arc (Watanabe *et al.*, 2016).

Within the Northern Kitakami complex of the Oshima belt, numerous but typically small Jurassic-age, chert-hosted manganese deposits (Fig. 4) were exploited from the 1930s to 1960s (Watanabe *et al.*, 2016). These deposits formed within pelagic sediments, initially as manganese oxyhydroxide precipitates analogous to modern ferromanganese nodules in the deep ocean.

Although not a metallic concentration, sulfur deposits are common within Quaternary volcanic rocks (Fig. 4). These are typically small, sublimate deposits, although at least in one case, the Matsuo mine (Takeouchi & Abe, 1970), sulfur was extracted from a large (160 Mt) disseminated and replacement Pleistocene or younger strata-bound sulfur and iron (plus accessory As, Bi, Sb, and Hg) sulfide deposit, which may overlie a large crosscutting hydrothermal vein system at depth.

Because of the significance to this study, the first two deposit groups are described in more detail, particularly their contrasting geological settings and discovery and development histories.

4.1 Late Miocene to Pleistocene Ag–Au ± base metal epithermal/subepithermal veins

This is the most common type of deposit in northern Tōhoku, with over 50 large- and medium-sized former mines catalogued in the regional metallogenic map of Tōhoku (Sudo & Igarashi, 1997) and more

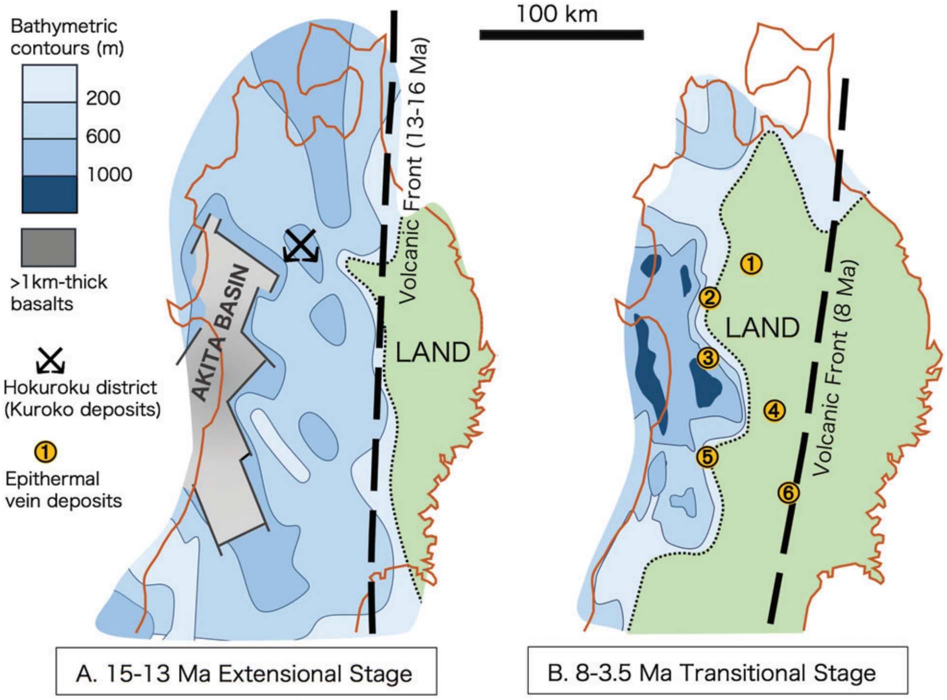

Fig. 5 Tectonic setting and paleobathymetric maps of northern Tōhoku (simplified from Sato, 1994) showing the approximate location of the Hokuroku district of middle Miocene base metal±Ag–Au Kuroko deposits and of selected late Miocene–Pleistocene Ag–Au ± base metal epithermal/subepithermal vein deposits/districts: 1, Osarizawa; 2, Ani; 3, Arakawa; 4, Washinosu; 5, Innai; 6, Hosokura.

than 60 additional identified prospects or mineralized localities (Fig. 4; large- and medium-sized deposits defined by Sudo & Igarashi, 1997, as containing production plus reserves of more than 10 t Au, 500 t Ag, or 10,000 t Cu). These deposits are closely associated with the Neogene volcanic and volcanosedimentary rocks of the central and western part of northern Honshu. They typically form hydrothermal veins, which have previously been classified as epithermal (Shikazono, 1986, 1999, 2003; Shikazono *et al.*, 1992; Watanabe *et al.*, 2016) and are broadly similar, from a genetic perspective, to those observed throughout Japan.

Among those in northern Tōhoku, some deposits, typically the largest in size, such as Osarizawa and Ani (Table 1), were discovered many centuries ago. For example, gold is recorded to have first been mined 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 (Historical Museum, 2017). This pattern of metal zoning, from precious to base metals with increasing depth, is common among these deposits in Japan, including the large vein deposit at Osarizawa (Japan Mining Industry Association, 1968), where gold was reportedly discovered in the 700 s. This is a time period that correlates well with the early Japanese settlement of northern Honshu, with Akita Castle built near Akita city in 733 and Shiwa Castle built in 803 in present-day Morioka. A map of the approximate extent of present-day Akita Prefecture during the Edo period (the Ugo Province) would have shown at least a dozen gold and silver mines and a smaller number of copper mines spread throughout the region. This widespread mining activity nurtured a mineral prospecting culture that led, late in the 19th century, to the discovery of fine-grained polymetallic mineralization near the town of Kosaka (Fig. 6). Soon, this would become the first Kuroko deposit to be mined. Due to resource exhaustion and the broader economic issues discussed above, all the vein mines in Akita Prefecture had ceased operations by 1980 (Innai in 1954; Furōkura, 1963, Arakawa, 1966; and Ani and Osarizawa in 1978; Fig. 4, Table 1).

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 Kuroko-type VMS deposits. The research studies were timely given the discovery in the late 1970s of active hydrothermal vents depositing submarine sulfide bodies along the East Pacific Rise (Francheteau *et al.*, 1979). As a result of the economic and scientific interest, exploration focus and research effort went overwhelmingly into the Kuroko deposits (e.g. Ishihara, 1974; Ohmoto & Skinner, 1983). 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 (Shikazono, 1986, 2003). As an illustration, even reliable estimates of the total (including historical) metal production from the vein deposits are not available (E. Izawa, pers. comm., 2017).

In our view, the deposits in this group of vein deposits can be classified broadly as epithermal to partly subepithermal. Detailed studies will be needed, but most deposit characteristics, such as textures (Fig. 7), ore and gangue mineralogy, wall rock alteration, metal assemblages, and metal zoning (Table 1) as well as fluid inclusion temperatures (Hosokura: 130–230°C, Arakawa: 170–240°C, Osarizawa: ~260°C, Ani: 190–280°C; Shikazono, 2003), all suggest an intrusion-centered, intermediate-sulfidation epithermal environment of mineralization. Some deposits do not clearly show classic epithermal vein textures; possibly for this reason, they have also been termed xenothermal (e.g. Watanabe *et al.*, 2016). Large deposits like Osarizawa, with a 3 by 2 km vein mine area, 700 km of tunnels, and production from at least 350 m vertically (Fig. 8), 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; Chang *et al.*, 2011; Baguio district; Cooke *et al.*, 2006), Romania (Apuseni Mountains; Wallier *et al.*, 2006), or Argentina (Farallón Negro Volcanic Complex, with the Farallón Negro veins and Bajo de la Alumbrera porphyry deposit; Márquez-Zavalía & Heinrich, 2016). However, the world-class intermediate-sulfidation deposits of Mexico so far have not been found to be associated with economic porphyry copper mineralization (White *et al.*, 2017).

To our knowledge, only three hydrothermal vein deposits in Tōhoku have been dated: Ani 11 Ma (no error given; Yamaoka & Ueda, 1974), Osarizawa 9 Ma (no details; Kazuno Mining History Museum, 2017), and Hosokura 5.8 ± 0.2 Ma (adularia; Shikazono &

Table 1 Summary data for selected hydrothermal vein deposits in Akita Prefecture and environs

Deposit name	Furōkura	Osarizawa	Tatemata	Ani	Arakawa	Washinosu	Washiaimori	Innai	Ōdomori
Latitude, longitude	40.28 N, 140.932 E	40.186 N, 140.748 E	40.131 N, 140.57 E	39.982 N, 140.421 E	39.805 N, 140.592 E	39.282 N, 140.808 E	39.229 N, 140.867 E	39.053 N, 140.364 E	38.818 N, 140.885 E
Metals produced (ref. 2)	Cu Pb Zn	Cu Zn Au Ag Pb	Cu Zn Pb Ag	Cu Pb Ag Au Zn	Cu Au Ag	Cu Au Ag	Cu Au Ag	Au Ag Cu	Zn Pb Ag
Ag/Au (ref. 3)	38	41		31		7		400	
Grade	Copper grade (avg.): 1.0–3.0 wt%. Jimori vein: 3.5 wt% Zn	Copper grade (avg.): 1.4–4.4 wt%	Individual veins: 0.3–1.7 wt% Cu, 1.8–7.5 wt % Zn, 2–5.6 wt% Pb. ~1965: 650 g/t Ag	Individual veins: 2.0–5.7 wt% Cu. ~1965: 1.10 wt% Cu	2.5 wt% Cu	Qtz stockworks: 6–10 g/t Au, 20–30 g/t Ag, 0.5–1.5 wt% Cu. Qtz veins: ~17 wt% Cu	5.0 wt% Cu	Individual veins: 3–6 g/t Au, 250–590 g/t Ag	Individual veins: 1.6–3.1 wt% Zn, 4.9–7.9 wt% Pb
Late Miocene–Pliocene subvolcanic rocks in mine area?	Yes	Yes, dacite dikes	Yes	Yes	Yes	Yes	Yes	Yes	Unknown
Vein dimensions	Width (avg): 80–200 cm; length: up to 1400 m; height: up to 450 m	Width (avg): 50–113 cm; length: up to 400 m; height: up to 550 m	Width (avg): 40–120 cm; length: up to 1300 m; height: up to 450 m	Width (avg): 20–70 cm; length: up to 800 m; height: up to 400 m	Width (avg): 30–70 cm; length: up to 2200 m; height: up to 450 m	Qtz stockwork orebodies: 20–80 m long, 10–50 m wide, 30–90 m high. Quartz veins: 60–250 m long, 20–50 cm wide, 30-170 m high	Width (avg): 50 cm; length: up to 900 m; height: up to 400 m	Width (avg): 20–150 cm; length: up to 600 m; height: up to 400 m	Width (avg): 110–180 cm; length: up to 2200 m; height: up to 450 m
Orebody structure/texture	Quartz veins	Quartz veins: symmetrically banded, massive, and brecciated veins	Quartz veins: banded (main ore stage)	Quartz veins: brecciated and massive veins	Quartz veins: symmetrically banded with cm-sized comb-shaped quartz, drusy textures, some brecciation	Quartz vein stockwork orebodies and individual quartz veins; banded and comb vein textures in both	Sheared veins	Quartz veins: black (ginguro) bands, rhodochrosite-calcite bands	Sheared veins

Table 1 Continued

Deposit name	Furōkura	Osarizawa	Tatemata	Ani	Arakawa	Washinosu	Washiaimori	Innai	Ōdomori
Ore minerals (minor)	Chalcopyrite, sphalerite, galena, pyrite (hematite, marcasite, native copper, electrum)	Pyrite, chalcopyrite, sphalerite, galena (hematite, marcasite, native copper, electrum)	Magnetite, pyrrhotite, chalcopyrite, sphalerite, galena (hematite, siderite, gersdorffite, arsenopyrite, stannite, native Bi, bismuthinite, molybdenite, cubanite, tetrahedrite)	Chalcopyrite, pyrite (chalcocite, galena, sphalerite, electrum, native silver, djurleite, anilite, hematite)	Chalcopyrite, pyrite, marcasite, sphalerite, galena (hematite, bismuthinite, tetradymite, hessite, tsumoite, pavonite, matildite; ref. 4)	Pyrite, chalcopyrite (sphalerite, galena, chalcocite, bornite, covellite, Au–Ag minerals)	Pyrite, chalcopyrite (sphalerite, galena, tetrahedrite, bornite)	Argentite, acanthite (pyrargyrite, stephanite, freislebenite, polybasite, pyrite, chalcopyrite, galena, sphalerite, electrum)	Galena, sphalerite (chalcopyrite, freibergeite, pyrargyrite, stibnite, pyrite, marcasite, pyrrhotite, magnetite, hematite)
Gangue	Quartz, rhodochrosite, barite, chlorite, calcite	Quartz, rhodochrosite, barite, calcite, chlorite	Quartz, chlorite, calcite, sericite, epidote, rhodochrosite, inesite	Chlorite, quartz, calcite, sericite, barite	Quartz, calcite, chlorite, barite, apatite	Quartz, sericite, chlorite, calcite, hematite, barite, gypsum	Chlorite, quartz, calcite, sericite	Quartz, rhodochrosite, rhodonite, calcite	Quartz, chlorite, sericite, kaolinite, montmorillonite, calcite, fluorite
Wall rock alteration	Quartz, Qz-chlorite, Qz-sericite	Quartz, Qz-chlorite, Qz-sericite	Quartz, Qz-chlorite, Qz-sericite	Quartz, chlorite, sericite	Quartz, chlorite, sericite	Quartz, sericite, chlorite, montmorillonite	Quartz, chlorite, sericite		Quartz, sericite, chlorite, montmorillonite
Secondary minerals		Cuprite, covellite, chalcocite, bornite, malachite, azurite, anglesite, linarite	Chalcocite, covellite, bornite	Goethite	Native copper, cuprite, azurite, malachite, brochantite, linarite	Malachite, cuprite, Fe-hydroxides			Chalcocite, covellite, native copper, native silver
Metal zoning	Copper grade decreases towards the south and lower elevations	Au–Ag (>360 m elev), Au–Ag–Cu (390–330 m elev), Cu–Pb–Zn (360–300 m elev), pyrite (<240 m elev)		Surface gold mineralization disc. 1309, Ag-rich Mukaiyama vein disc. 1387		Surface gold mineralization disc. 1901, copper processing starts at deeper levels in 1915			

Table 1 Continued

Deposit name	Furōkura	Osarizawa	Tatemata	Ani	Arakawa	Washinosu	Washiaimori	Innai	Ōdomori
Fluid inclusion, isotope data		250–190°C Showa vein: 230–200°C (>5%Cu zone), 210–200°C (Pb–Zn zone) (ref. 1); 268–156°C, 7.5–0 wt% NaCleq (ref. 5)		266–207°C, 12 wt% NaCleq (ref. 5)	240–170°C (ref. 5)			δ34S: 5.2, 4.4 permil (ref. 5)	230–130°C, 9–0 wt % NaCleq (data for nearby Hosokura deposit; ref. 5)
Age		9 Ma (no details, ref. 6)		11 Ma (adularia, no analytical errors; ref. 7)					

Main source: Japan Mining Industry Association (1968). Other sources; ref. 2: Sudo and Igarashi (1997); ref. 3: Shikazono (1986); ref. 4: Satori *et al.* (2017); ref. 5: Shikazono (2003); ref. 6: Kazuno Mining History Museum (2017); ref. 7: Yamaoka and Ueda (1974).

Tsunakawa, 1982). These ages indicate that they are younger than the Kuroko deposits and have most likely formed under subaerial conditions or, at most, shallow marine depths (Fig. 5), similar to epithermal veins at Izu (Hattori, 1975). As discussed in more detail below, the fact that veins went out of favor in the 1970s, and mining totally ceased in Tōhoku by the early 1990s, means that these deposits have seen essentially no exploration for the past 40 years, that is, no exploration with modern concepts and techniques.

4.2 Middle Miocene base metal±Ag–Au submarine, stratiform VMS (Kuroko) deposits

These deposits, particularly those located in the Hokuroku district (Figs 4, 6), are the best documented in Akita Prefecture and northern Honshu. They were the main metal producers 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, after the name Kuroko (meaning 'black ore') given in 1885 to their characteristic ore, consisting of massive, very fine-grained mixtures of dark Fe-rich sphalerite, galena, barite, and minor quantities of pyrite and chalcopyrite (Sato, 1977). 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, only 20 km north of Osarizawa.

Kuroko deposits are stratiform accumulations of massive polymetallic sulfides, typically presenting as lenses and irregular bodies that may be up to 800 m long by 300 m wide and 100 m thick (Sato, 1977). Internally, they are chemically and mineralogically zoned, with different layers of sulfide and sulfate minerals distributed in a recurrent pattern. The footwall of Kuroko deposits is composed of a silicic (plus chlorite) stringer zone with crosscutting mineralized quartz veins in what is interpreted to form the hydrothermal feeder zone of the massive sulfide orebodies, which are commonly overlain by ferruginous chert. In the Hokuroku district, Kuroko deposits are invariably associated with felsic volcanic domes of 'white rhyolite' (Sato, 1977).

The hydrothermal origin of Kuroko deposits and their association with submarine volcanism was understood early (Ohashi, 1920, in Ohmoto & Skinner, 1983). Also recognized early were key deposit features that were successfully applied to exploration,

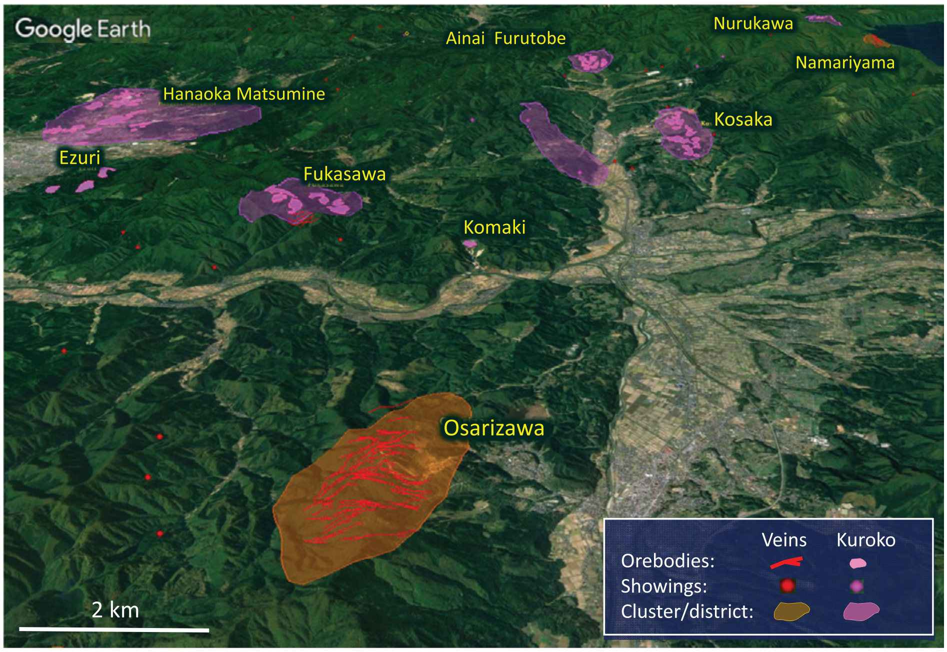

Fig. 6 Google Earth oblique aerial view showing locations of Kuroko-type deposits (in pink; deposits clusters in light pink) of the Hokuroku district. Vein deposits (in red) and districts (orange envelope) such as the Osarizawa intermediate-sulfidation vein system are also shown. Due to the perspective, the scale bar applies only to the foreground, and the distance between Kosaka and Ezuri or Osarizawa is ~17 km.

such as the fact that all the deposits in the Hokuroku district were strata-bound and occurred within the same stratigraphic horizon (Horikoshi, 1960) and that the deposits formed within large isolated basins related to calderas (Sato, 1977). Other mineralogical, geochemical, and geophysical characteristics of the deposits were identified and successfully developed into exploration vectoring tools. Three were perhaps the most widely applied (JOGMEC, 2005): (i) chargeability anomalies to detect the clay–fine-grained pyrite alteration halos; (ii) magnetic low anomalies, which were due to hydrothermal conversion of wall-rock magnetite to pyrite; and (iii) low Na_2O geochemical anomalies, present in the deposit footwalls, due to hydrothermal sericitization of igneous plagioclase.

Fig. 7 Vein fragment from the Tazawa Ag–Au ± base metal deposit in central Akita Prefecture, consisting of pyrite, chalcopyrite, sphalerite, and galena sulfide ore with accessory sulfides and sulfosalts in a gangue of calcite, rhodochrosite, and quartz. Note the typical epithermal crustiform texture (Akita Mining Museum, specimen AK-1400).

Unlike the vein deposits mentioned above, the age of Kuroko deposits has been exhaustively studied and is well bracketed within a short period at 14.3 ± 0.5 Ma (Terakado, 2001); only the Nurukawa deposit near lake Towada seems to fall outside this range, with a slightly younger mineralization age (12.5–10.7 Ma; Ishiyama *et al.*, 2001). Combined with the well-documented tectonic setting and models for the evolution of Japan since the Neogene (Sato, 1994), 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 at marine water depths of 600–800 m (Fig. 5).

Although the tectonic setting of the Kuroko and younger epithermal vein deposits differs substantially – causing the basic differences in deposit morphology and syngenetic versus epigenetic nature – the fundamental nature of the hydrothermal fluids responsible for both types of deposit are roughly similar in their

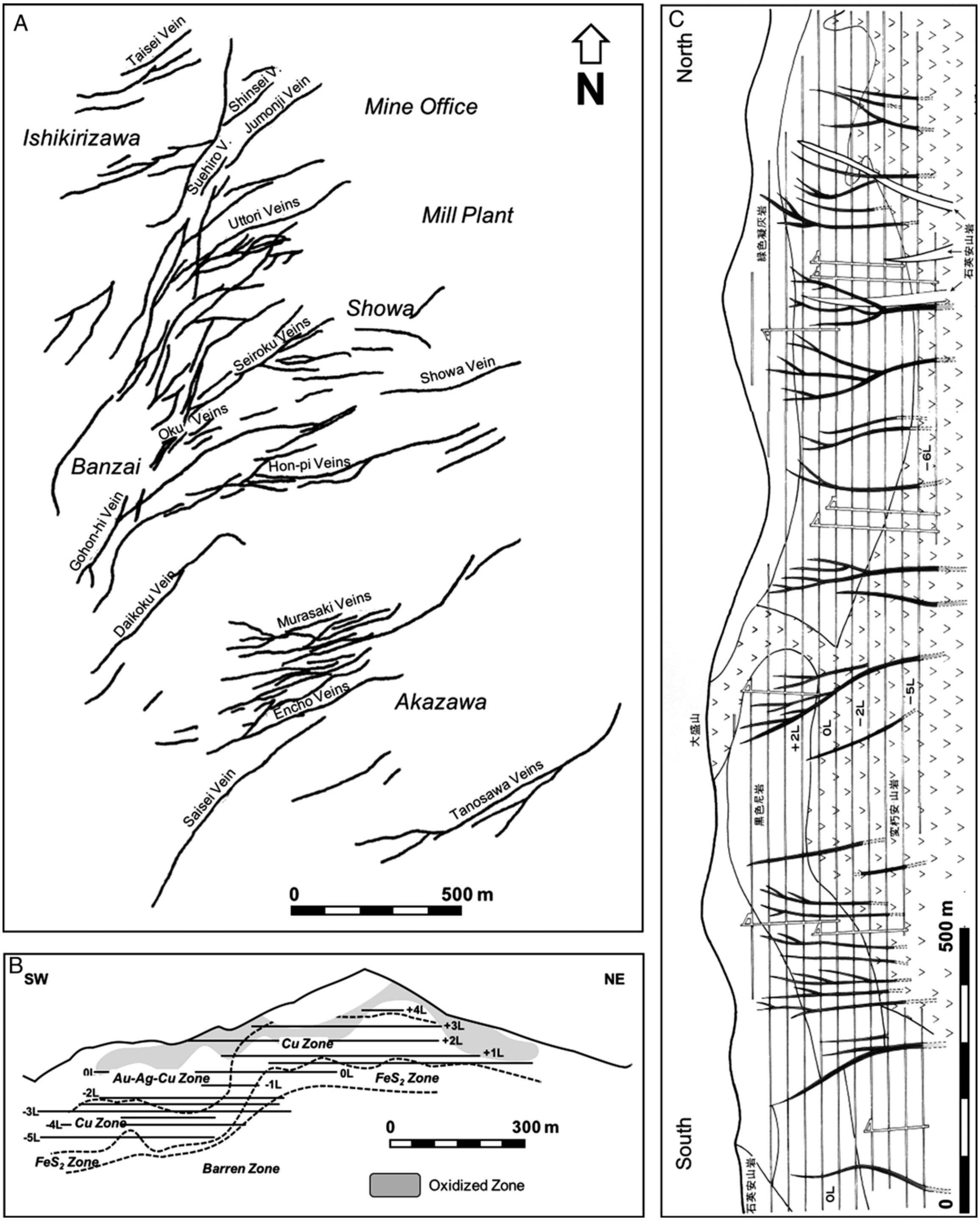

Fig. 8 A. Plan of the Osarizawa vein system at the 0 level (300 m.a.s.l). B. Vertical section of the Saisei vein of the Osarizawa mine showing mineral zoning. C. Schematic N–S cross section of the Osarizawa vein system (A and B after Shikazono *et al.*, 1992, modified from Shimizu & Matsunaga, 1964; C. after Kazuno Mining History Museum).

origin: in both cases, metals were contributed by magmatic–hydrothermal fluids exsolved from intermediate to felsic magmas at depth, with dilution by marine and meteoric water, respectively. As noted by Sato (1977), the Pb-isotope evidence from Kuroko deposits indicates a source of metals from magmatic–hydrothermal fluids and not just metal leaching from the country rocks. The latter explanation is preferred by researchers who focused on the seawater signature indicated by the calculated O/H isotopic composition of the hydrothermal fluids. However, over the life of a hydrothermal system, ambient water convection by the shallow intrusion dominates any magmatic fluid input by more than an order of magnitude; the magmatic component is episodic, short-lived, and overprinted by subsequent collapse of the marine or meteoric water, making its documentation difficult (Hedenquist & Richards, 1998).

5. Mineral exploration in northern Tōhoku

For an ore deposit to be known and amenable to exploitation, it must first exist, and then, it must be found. A discussion on the potential existence of porphyry copper deposits in Japan, or elsewhere, must therefore include an analysis of the applicable exploration history of the region of interest. Here, as in many other mineral exploration situations (see East Sunda-Banda arc section above), the saying "absence of evidence is not evidence of absence" must be taken into account.

As discussed above, we believe the region encompassing the mines and mining districts of Akita Prefecture and surrounding districts is a valid proxy for northern Tōhoku and Japan in general, as implied by the subtitle of this paper. The post-1945 period is appropriate for an analysis of the exploration history given the historical circumstances of Japan and its mining industry during the 20th century. In addition, porphyry copper deposits are a comparatively new mining venture as their low-grade, bulk-tonnage attributes require mining and metallurgical technology that has been available only since the early 1900s, and development outside the Americas started only after the 1950s.

Mineral exploration in Japan post-1945 has been structured around three types of surveys: (i) regional (greenfield) surveys were funded entirely by the central government through the Metal Mining Agency of Japan (MMAJ); (ii) detailed surveys, which followed the regional surveys as appropriate, were financed through three-way joint ventures between the central and local governments and private companies; and (iii) the final stage of exploration was undertaken entirely by the resident private companies. Our analysis, which is based on MMAJ summary data and is not exhaustive, considers the first two types of surveys, regional and detailed, by grouping them into 11 exploration project areas (Fig. 9; Table 2).

The results of our analysis show that exploration activity in northern Tōhoku took place between the early 1960s and 1995 (Table 2); 30% of the activity, as represented by the number of drill holes, took place during the 1960s (176 drill holes out of a total of 596); 67% in the 1970–1980s, the period of maximum activity (the "Kuroko boom"); and less than 4% in the 1990s (21 drill holes out of 596). By target type, the overwhelming focus was on Kuroko deposits, accounting for 85% of the budget and 91% of the drilling. By contrast, exploration for Au–Ag-bearing vein deposits accounted for about 15% of the budget and only 9% 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, about 30 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; Izawa *et al.*, 1990), exploration in northern Tōhoku achieved significant success. In the Kuroko program, (i) the Kuroko host formation was identified at depth in all project areas where it was targeted; (ii) several Kuroko deposits were discovered (e.g. Iwagami in 1975; Ezuri in 1976; Nurukawa in 1984); and (iii) within the Tazawa project area (Fig. 9), with only 16 drill holes, molybdenum mineralization was identified in granite basement, Cu–Pb–Zn veins were found around a Neogene intrusion, and an Au–Ag vein (4.96 g/t Au and 18.6 g/t Ag) was intersected.

5.1 Comparison to global mineral discovery record

A comparison of the metal production profile of Tōhoku with the research by R. Schodde (Minex Consulting) on major mineral deposits (defined as >1 Moz Au, >1 Mt. Cu, etc.; Schodde, 2014) worldwide discovery highlights the impact of exploration in the past

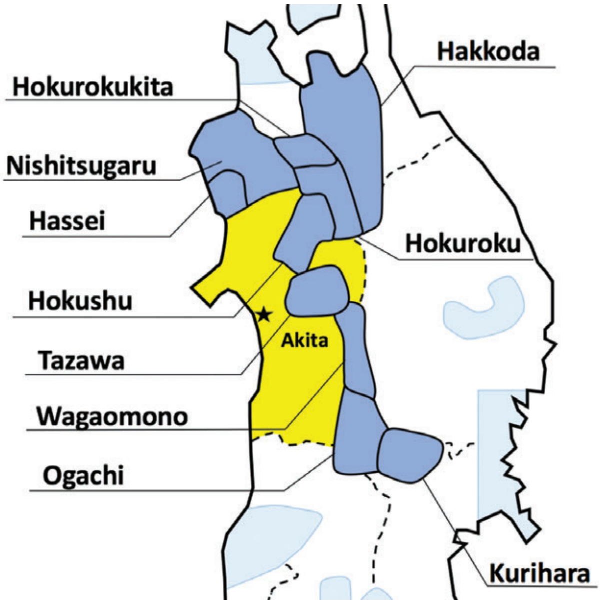

Fig. 9 Map showing regional exploration areas listed in Table 2 (from MMAJ reports, courtesy of K. Sawada, Mineral Economics Strategy Group, Tokyo).

30 years (Fig. 10). Half of all major deposits known were discovered after 1980, and the 2000–2014 decade was one of the most prolific discovery periods in history.

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 (Fig. 11). Similar to other such 'barren' arc segments, like Iran, we believe that the main explanation is 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 of Mexico and Peru, two countries of dimensions and metallogenic setting broadly comparable to that of Japan (Fig. 12).

6. Discussion

In agreement with Qin and Ishihara (1998), we believe porphyry copper deposits exist in Japan. Based on the evidence from other magmatic arcs, there will likely be no more than a few deposits of the size and geological and economic parameters necessary to be found and classified categorically as such. We also agree with Qin and Ishihara (1998), and other authors in this volume, that several features of the geology of Japan make the archipelago less fertile than other parts of the world for porphyry copper mineralization (extensional tectonic setting, reduced magmatism, depth of erosion of Miocene and younger volcanic products, short time window, etc.). However, lessons from other Pacific Ocean island arcs, such as the East Sunda-Banda (see above), show that mineral discovery takes multiple focused campaigns and that the increased attention (i.e. exploration) resulting from an

Table 2 Summary data for post-World War II exploration in Akita Prefecture and environs (see Fig. 9)

Exploration area	Regional survey[†]	Detailed survey[†]	Budget (¥ million)	Drilling (no. holes)	Drilling (meters)	Target deposit
Hakkoda	1971–1988		1227	36	25,370	Kuroko
Hokurokukita	1970–1978	1974–1987	3284	38	20,337	Kuroko
Nishitsugaru	1975–1985		399	5	3273	Kuroko & Veins
Hassei	1970–1972	1988–1990	339	17	8523	Kuroko
Hokuroku	1963–1965[‡]	1964–1967	528	153	72,505	Kuroko
	1974–1988		6516	188	116,916	Kuroko
Hokushu	1973–1980		358	10	7800	Kuroko
Tazawa	1980–1995	1991–1993	766	16	9137	Veins
Wagaomono	1966–1969	1969–1973	688	89	56,386	Kuroko & Veins
Ogachi	1987–1994		125	1	500	Kuroko
Kurihara	1973–1986	1978–1986	1463	36	23,606	Veins
N. Tohoku[§]	1994–2000		314	7	2752	Kuroko

[†] Includes follow-up regional or detailed survey.
[‡] Executed by the Geological Survey of Japan.
[§] Area not shown in Fig. 9.
Data from Metal Mining Agency of Japan reports, courtesy of K. Sawada (Mineral Economics Strategy Group, Tokyo).

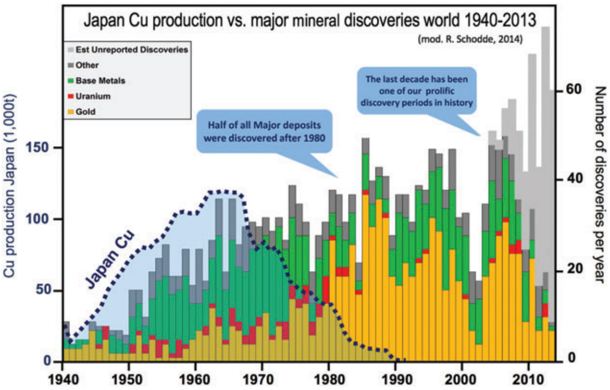

Fig. 10 The 1940–2014 copper production profile for Japan (left scale) overlain over the number of major world mineral discoveries, excluding non-ferrous or bulk commodities and satellite deposits within existing camps (right scale; Schodde, 2014). Japan Cu production data from World Mineral Statistics-British Geological Survey.

earlier find may uncover potential that did not appear likely in the initial survey.

The porphyry deposit that could possibly be found in Japan may not closely resemble the classic image of a porphyry copper deposit. Although we argue that, with few exceptions (e.g. Izawa & Hayashi, 2018), exploration in Japan did not target porphyry deposits and stopped comparatively early, we believe that the yet-to-be-found deposit is unlikely to crop out. Therefore, attention to indirect evidence, such as an association of the porphyry system with other deposits and/or lithological environments, will be key. Among these, lithocap-related alteration (Hedenquist *et al.*, 2018), high-sulfidation epithermal deposits, and intermediate-sulfidation epithermal or subepithermal veins, such as Osarizawa and Ani in Tōhoku (or Toyoha or Ashio elsewhere in Japan), constitute particularly prospective environments.

The experience in Japan, with targeted and methodical exploration that applied the state-of-the-art metallogenic science and technology of the time, such as in the 1970s and 1980s, to 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:

1 Broadly speaking, the 1990s witnessed an improved understanding of the origin of advanced argillic alteration and its relationship to magmatic hydrothermal and geothermal systems (Rye *et al.*,

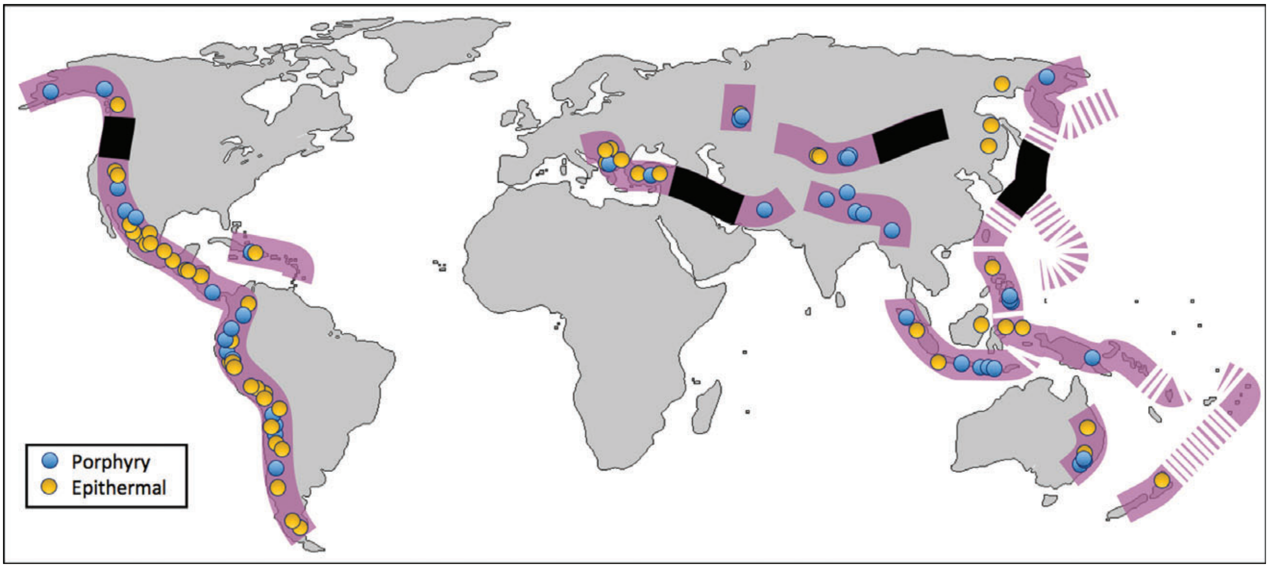

Fig. 11 Significant porphyry copper and epithermal deposits discovered worldwide since 1990. Arc-related metallogenic belts (purple lines) are modified from Richards (2013). Dashed lines indicate submarine portions of the volcanic arcs. Black lines denote arc segments with no apparent deposit discovery during the period 1900–2017 (base map, www.outline-world-map.com).

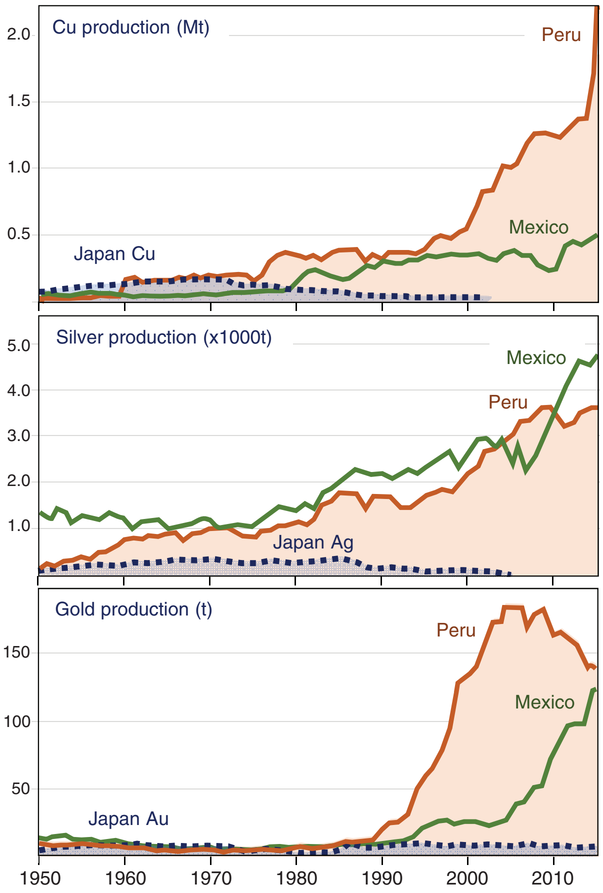

Fig. 12 Mine production profiles (1950–2015) for copper, silver, and gold in Peru, Mexico, and Japan. Sources of data: Mexico (Servicio Geológico Mexicano), Peru (Ministerio de Energía y Minas), Japan (World Mineral Statistics-British Geological Survey).

1992). The magmatic fluid contributions to high-sulfidation epithermal Cu–Au deposits were proven, and their environment of formation, intermediate between a shallow magmatic intrusion and the surface, was established (Arribas Jr., 1995). A temporal and genetic connection between porphyry and high-sulfidation epithermal deposits was demonstrated (Arribas Jr. *et al.*, 1995; Hedenquist *et al.*, 1998). Nevertheless, many geologists worldwide still held on to the Lowell and Guilbert (1970) porphyry model.

2 In the 2000s, the concept and term ‘lithocap’ (Sillitoe, 1995, 2000) began to be used by some, both in the scientific literature and in exploration. A revised classification scheme of epithermal deposits was introduced, which distinguished between high-, intermediate-, and low-sulfidation epithermal deposits (Hedenquist *et al.*, 2000; Einaudi *et al.*, 2003). Building on new insight from regional studies of magmatic–hydrothermal mineralization in the western USA (John, 2001), a compelling case for specific linkages between volcano–tectonic setting and epithermal and porphyry deposits was introduced (Sillitoe & Hedenquist, 2003).

3 Within the past decade, the concept, that is, the understanding of a ‘porphyry copper system’ (Sillitoe, 2010) 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 (Richards, 2011; Kouzmanov & Pokrovski, 2012; Weis *et al.*, 2012). Focused research projects have developed criteria, vectors, and associated exploration tools (Chang *et al.*, 2011; Halley *et al.*, 2015; Arribas *et al.*, 2017). On the practical side, it has become evident that successful greenfield porphyry exploration requires deep (>800–1000+ m) drilling (Rohrlach, 2011; Moorehead, 2012; Sillitoe *et al.*, 2013, 2016).

Without a doubt, the current genetic context and geological and exploration models will continue to evolve as new studies are completed and new questions addressed. For example, do all magmatic–hydrothermal systems above a shallowly emplaced magmatic intrusion – with the appropriate composition and evolution – form a porphyry deposit with or without some of the associated deposit types? Or can, for example, an intermediate- or high-sulfidation deposit form without a requisite porphyry copper deposit (cf. Richards, 2011; White *et al.*, 2017).

Parallel to 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 Pleistocene in northern Honshu (Fig. 5b), with obvious temporal restrictions. Recently, research on active submarine systems has focused increasingly on hydrothermal venting in submarine volcanic arcs (de Ronde *et al.*, 2014; Petersen *et al.*, 2016), such as those discovered in the Izu-Bonin, Mariana, and Kermadec arcs (Hannington *et al.*, 2010; de Ronde *et al.*, 2011). Indeed, a deep-ocean drilling expedition scheduled for mid-2018 to Brothers volcano in the Kermadec arc (de Ronde *et al.*, 2017) will test, among other scientific objectives, the existence of metallic mineralization at depths of several hundred meters beneath the ocean floor below the flanks of a stratovolcano, an environment fundamentally similar to that of porphyry-type deposits. Envisioning the potential for such mineralization within the paleovolcanic front of northern Honshu during the middle Miocene (Fig. 5a), when the Kuroko 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.

7. Conclusions

Until proven otherwise, the Japanese porphyry copper deposit has not yet been found, notwithstanding the permissive evidence in the shallow epithermal environment. In our view, exploration stopped too early, essentially thirty years ago, certainly before it could have benefited from metallogenic and technological breakthroughs applicable both to porphyry copper systems and to hydrothermal mineralization in submarine volcanic arcs. Exploration for porphyry copper deposits today would be conducted differently, for example, looking more for indirect evidence, such as beneath – and lateral to – lithocaps, spatially associated with high- and intermediate-sulfidation epithermal/subepithermal veins, and with the necessary deep drilling.

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