



Geological Characteristics and Metallogenic Setting of Representative Magmatic Cu-Ni Deposits in the Tianshan-Xingmeng Orogenic Belt, Central Asia

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Abstract: A great number of magmatic Cu-Ni deposits (including Kalatongke in Xinjiang and Hongqiling in Jilin) are distributed over a distance of almost 3000 km across the Tianshan-Xingmeng Orogenic Belt, from Tianshan Mountains in Xinjiang in the west, to Jilin in eastern China in the east. These deposits were formed during a range of magmatic episodes from the Devonian to the Triassic. Significant magmatic Cu-Ni-Co-PGE deposits were formed from the Devonian period in the Nalati arc (e.g. Jingbulake Cu-Ni in Xinjiang), Carboniferous period in the Puerjin-Ertai arc (e.g. Kalatongke Cu-Ni-Co-PGE in Xinjiang), Carboniferous period in the Dananhu-Touquan arc (e.g. Huangshandong, Xiangshan and Tulaergen in eastern Tianshan, Xinjiang) to Triassic period in the Hulan arc (e.g. Hongqiling Cu-Ni in Jilin). In addition to the overall tectonic, geologic and distribution of magmatic Cu-Ni deposits in the Tianshan-Xingmeng Orogenic Belt, the metallogenic setting, deposit geology and mineralization characteristics of each deposit mentioned above are summarized in this paper. Geochronologic data of Cu-Ni deposits indicate that, from west to east, the metallogenic ages in the Tianshan-Xingmeng Orogenic Belt changed with time, namely, from the Late Caledonian (~440 Ma), through the Late Hercynian (300–265 Ma) to the Late Indosinian (225–200 Ma). Such variation could reflect a gradual scissor type closure of the paleo Asian ocean between the Siberia Craton and the North China Craton from west to east.

Key words: Geochronology, magmatic Cu-Ni-Co-PGE deposits, Tianshan-Xingmeng Orogenic Belt, Central Asia

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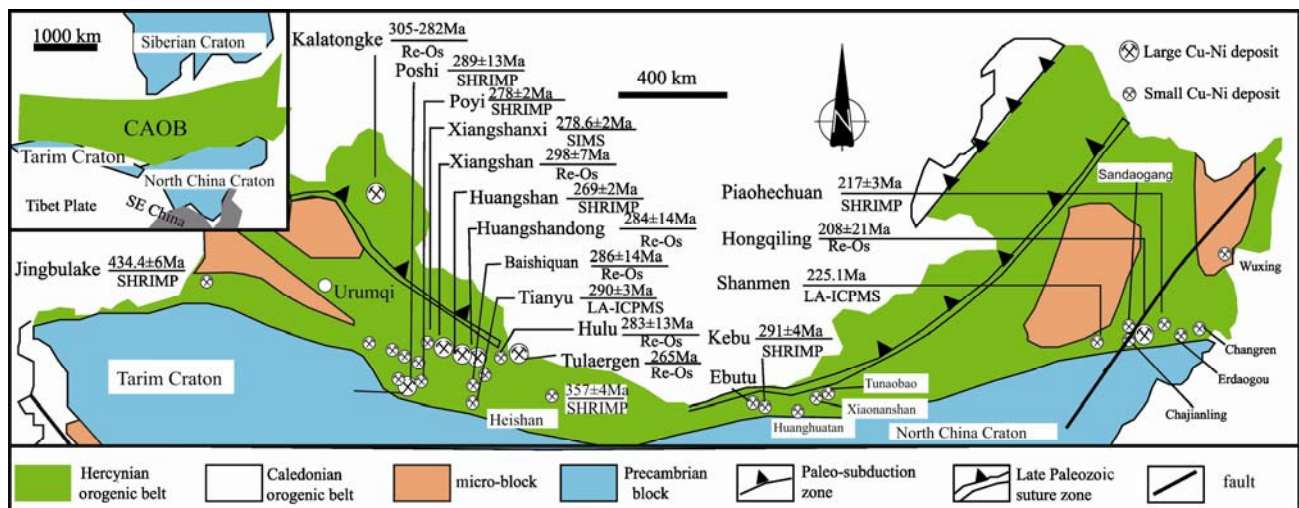
1 Introduction

The E-W trending Tianshan-Xingmeng Orogenic Belt (TXOB) lies in the eastern segment of the Central Asian Orogenic Belt, and extends along the northern margin of the Tarim and North China cratons (Jahn, 2004; Xiao et al., 2003, 2010). This composite orogenic belt is also the most important Cu-Ni ore province in China (Chen et al., 2012), and the important metallogenic zone for Fe, Mo, Pb-Zn, Au and W. Most Cu-Ni deposits in the Tianshan-Xingmeng Orogenic Belt occur in the northern margin of the North China Craton (NCC), but several newly discovered deposits are distributed within the Tianshan orogenic belt (e.g., Lubei, Baixintan, Shaquan, Tianyu, Tulaergen, Heishan and Guaishishan deposits) (Fig. 1; Table.1).

The TXOB is located in the eastern segment of the Central Asian Orogenic Belt (CAOB), and the largest global Phanerozoic accretionary belt with some of the best-preserved examples for the production of juvenile crust (Jahn, 2004; Jahn et al., 2009). In the western part, the

southern Altaids began its oceanic evolution and accretionary history mostly in the early Paleozoic. The Chinese Altay-East Junggar orogenic collage is situated in the southern Altaids (Xiao et al., 2009). Its northern boundary is a Late Devonian-Early Carboniferous tectonic collage (Dobretsov et al., 2004), and its southern boundary is separated from the late Paleozoic Eastern Tianshan orogenic collage by mélanges, which include ophiolitic fragments that represent a branch of the Paleasian Ocean that closed by double, two-way subduction (Xiao et al., 2004). Farther south, a huge accretionary complex (Kokshaal-Kumishi) occupies the final suture zone along which the Tarim craton was accreted to what by then had become the southern Siberian accretionary collage (Xiao et al., 2004). In the eastern part, it is characterized by voluminous magmatic rocks, and most of these rocks were emplaced during Jurassic to Early Cretaceous time (190–115 Ma), and some in the Paleozoic (Zhang et al., 2010). In the Mesozoic, the eastern part of CAO was tectonically linked to the closure of the Mongol-Okhotsk Ocean and the subduction of the Paleo-Pacific Ocean. Because of this complex plate-tectonic regime, the corresponding geodynamic settings of the Mesozoic

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The CAOB is a complex collage of fragments of ancient microcontinents and arc terranes, fragments of oceanic volcanic islands (e.g. seamounts), perhaps also volcanic plateaux (e.g. Junggar block), oceanic crust (ophiolites), and successions formed at passive continental margins. The amalgamation of these terranes occurred at various times from the Neoproterozoic (ca. 1250 Ma) to the Mesozoic and was accompanied by several episodes of magmatism. Geochronological data well constrained magmatic events ranging from the Ordovician (ca. 450 Ma) to Triassic-Cretaceous (ca. 220–120 Ma), resulting in the emplacement of large volumes of granitic intrusions (Jahn, 2004) and mafic volcanic rocks (Zhang et al., 2009), accompanied by lesser volumes of mafic-ultramafic intrusions. A-type granitic and peralkaline intrusions in the CAOB are common and are associated with post-collisional extension (Jahn, 2004). It is more likely that the granites of the region include syn- to post-orogenic, as well as anorogenic types, as shown in the published geological maps of Xinjiang. Radiometric dating of these post-orogenic granites indicates that they were emplaced during Carboniferous and Triassic period range from

Table 1 Summary of major copper-nickel deposits in the East Tianshan orogenic belt

Deposit	(long. and lat.) ^a	Metals	Length× width(km)	Scope (km ²)	Shape	Resource and grade	Mafic-ultramafic rock associates	Ore minerals
Jingbulake	82°18'00"E, 42°56'00"N	Cu-Ni-Co	2.5×1.3	3.25	Funnel-shaped	Ni: 24973.47t@0.3-2.0%, Cu: 13085.35t@ 0.1-1.0% Co: 1606.77t@0.01-0.03%	Olivinegabbro, wehrlite, dunite	Pyrrhotite, chalcopyrite, pentlandit
Kalatongke No.1	89°39'45"E, 46°44'15"N	Cu-Ni-PGE	0.70×0.29	0.203	Funnel-shaped	Ni: 154000t@0.88%, Cu: 232000t@ 1.40% Pt: 174t, Pd: 216t	Biotite amphibole olivine norite, hornblende-gabbro	Pyrrhotite, chalcopyrite, pentlandit
Kalatongke No.2	89°40'32"E, 46°44'34"N	Cu-Ni-PGE	1.40×0.20	0.28	Vein-shaped	Ni: 500000t@0.60%, Cu: 1060000t@ 1.10%	Biotite amphibole perillite, Biotite-hornblende-gabbro	Pyrrhotite, chalcopyrite, pentlandit
Kalatongke No.3	89°42'04"E, 46°45'31"N	Cu-Ni-PGE	1.32×0.40	0.528	Lenticular-shaped	Ni: 460000t@0.60%, Cu: 810000t@ 1.10%	Amphibole perillite, Hornblendenorite	Pyrrhotite, chalcopyrite, pentlandit
Lubei	90°19'15"E, 42°10'32"N	Cu-Ni	1.5×0.33	0.495	Lenticle	Cu: @ 0.20-0.74%, Ni: @ 0.30-0.72%,	gabbro, pyroxenite, olivine pyroxenite	Pyrrhotite, pentlandite, chalcopyrite
Baixintian	92°10'00"E, 42°31'18"N	Cu-Ni	1.4×0.72	0.75	Lenticle	Cu: 84270.9t@ 0.60%, Ni: 64912t@ 0.29%,	gabbro, olivine pyroxenite and wehrlite,	Pyrrhotite, pentlandite, chalcopyrite
Tudun	94°10'00"E, 42°13'15"N	Cu-Ni	1.4×0.7	0.90	Irregular ellipse	Cu 3000t, 0.20%; Ni 15000t, 0.30%	Gabbro, pyroxene-hornblende-peridotite, Pyroxite, olivine- hornblende-pyroxenite	Pyrrhotite, pentlandite, violarite, cubanite, chalcopyrite
Erhongwa	94°17'00"E, 42°07'30"N	Cu-Ni	3.33×2.56	6.25	Irregular round	Cu 4000t, 0.20%; Ni 18000t, 0.20%	Lherzolite, gabbro-norite, olivine-gabbro, pyroxene-diorite, quartz-diorite	Pyrrhotite, pentlandite, pyrite, chalcopyrite
Xiangshan	94°33'18"E, 42°18'17"N	Cu-Ni-Co-PGE	10×3.5	2.8	Lotus root	Cu 20000t, 0.30%; Ni 40000t, 0.50%	Cortlandite, peridotite, pyroxene-diorite, hornblende-gabbro	Pyrrhotite, pentlandite, violarite, cubanite, chalcopyrite
Huangshan	94°37'00"E, 42°15'00"N	Cu-Ni-Co-Au-A g-PGE	3.8×8	1.71	Comet shape	Cu 0.2083Mt, 0.31%; Ni 0.334Mt, 0.47%; Co 19500t, 0.026%	Hornblende-gabbro, gabbro-diorite, hornblende-gabbro-norite, hornblende-lherzolite, hornblende-websterite	Pyrrhotite, pentlandite, violarite, cubanite, chalcopyrite
Huangshandong	95°51'45"E, 42°17'00"N	Cu-Ni-Co-Au-A g-PGE	5.3×1.12	2.8	Rhombus lenticle	Cu 0.1882Mt, 0.27%; Ni 0.3836Mt, 0.52%; Co 16700t, 0.024%	Hornblende-olivine-gabbro, pyroxene-hornblende-gabbro, gabbro-diorite, gabbro-norite, olivine-gabbro-norite, pyroxene-cortlandite	Pyrrhotite, pentlandite, pyrite, chalcopyrite
Huangshanhan	94°40'00"E, 42°11'30"N	Current producer	Cu-Ni	5.2×1.3	4.22	Lenticle	Cu 1300t, 0.30%; Ni 10000t, 0.40%	pyroxene-cortlandite, hornblende-pyroxenite, lherzolite, peridotite, hornblende-gabbro,
Hulu	95°41'48"E, 42°31'18"N	Current producer	Cu-Ni-Co-Au-A g-PGE	1.4×0.72	0.75	Lenticle	Cu 39600t, 0.10-0.49%; Ni 80200t, 0.23-0.61%; Co 5100t, 0.02-0.042%	Pyroxite-peridotite- pyroxenite
Tulaergen	95°51'49"E, 42°37'34"N	Current producer	Cu-Ni-Co	0.74× (0.02-0.07)	<0.005	Tabular -shaped	Ni: 125000t@0.60%, Cu: 80000t@ 0.40%, Co: 100000t@0.03%	Gabbro, gabbro-diorite
Tianyu	94°53'30"E, 41°52'00"N	Current producer	Cu-Ni-Co	1.125×0.07	0.079	Bedded -shaped	Ni: 22278t@2.97%, Cu: 3128t@ 0.69%, Co: 804t@0.151%	Peridotite, olivine pyroxenite, pyroxenite, gabbro, diorite
Baishiquan	94°55'00" E, 41°55'00"N	Resource	Cu-Ni-Co	2.0×1.60	3.20	Lenticle	Cu 39600t, 0.22-0.43%; Ni 0.2-0.57% ; Co: 0.01-0.03%,	Troctolite-peridotite -olivine-pyroxenite

Continued Table 1

Deposit	(long. and lat.)a	Status	Metals	Length×width (km)	Scope (km ²)	Shape	Resource and grade	Mafic-ultramafic rock associates	Ore minerals
Poshi	91°31'29"E, 40°34'28"N	Current producer	Cu-Ni-Co	1.125×0.07	0.079	Bowl-shaped	Ni:147000t@0.3-0.6%, Cu:16400t@0.08-0.14% Co:4000t@0.016-0.017%	Plagioclase pyroxene, Plagioclase peridotite, peridotite	Pyrrhotite, chalcopyrite, pentlandit
Heishan	95°59'58"E, 41°23'03"N	Current producer	Cu-Ni	0.80×0.47	0.376	layered, podlike and irregular branching	Ni:962000t@0.60%, Cu:46500t@0.29%	Harzburgite, lherzolite, olivine gabbro-norite	Pyrrhotite, chalcopyrite, pentlandit
Tunaobao	111°24'00"E, 41°46'00"N	Resource	Cu-Ni-Co	0.5×0.11	0.055	Lenticle	Cu500t @0.16%; Ni 1000t @0.34%; Co:50t@0.017%; Pt+Pd:70t@0.22g/t	Gabbro, yroxenite	Pyrite, chalcopyrite, pentlandit
Xiaonanshan	111°22'00"E, 41°45'00"N	Resource	Cu-Ni-Co	1.2×0.14	0.168	Lenticle	Cu:9000t @0.40-0.63%; Ni:12600t @0.66-0.78%;Co:380t@0.02%; Pt:780t@0.40g/t; Pd:890t@0.44g/t	Gabbro, gabbro-diorite	Pyrrhotite, chalcopyrite, pentlandit
Huanghuatan	110°34'00"E, 41°38'25"N	Resource	Cu-Ni-PGE	1.0×0.20	0.20	Lenticle,veined	Cu:@1.0-1.5%; Ni: @0.05-1.43%;; Co:380t@0.02%; Pt+Pd:@0.30-2.46g/t;	Gabbro, gabbro-diorite, amphibolite	Pyrrhotite, chalcopyrite, pyrite
Ebutu	105°08'20"E, 42°31'18"N	Resource	Cu-N	0.42×0.51	0.214	Lenticle	Ni:3500t @0.46%;	Gabbro, pyroxenite	Pyrite, chalcopyrite, pentlandit
Erdaogou	127°09'57"E, 43°12'15"N	Current producer	Cu-Ni	1.44×0.07	0.101	Vein	Cu:1.55 @0.04-0.38%, Ni:4.67 @ 0.34-0.40%	Ol-pyroxenite, Pl- pyroxenite Hornblende pyroxenite	Pyrrhotite, pentlandite, chalcopyrite, violarite,pyrite
Shanmen	124°28'00"E, 43°09'00"N	Current producer	Cu-Ni	0.7×0.29	0.261	Bedded	Cu: 0.04-0.38%, Ni: 0.34-0.40%	Pyroxene peridotite	Pyrrhotite, chalcopyrite, pentlandit
Sandaogang	127°09'57"E, 43°12'15"N	Current producer	Cu-Ni	0.47×0.008	0.084	Vein-shaped	Cu:@0.26-0.48%, Ni:@ 0.68-0.74%	Pyroxenolite Hb- pyroxenolite	Pyrrhotite, pentlandite, chalcopyrite
Chajianling	126°21'00"E, 42°52'00"N	Current producer	Cu-Ni		0.10	lens-shaped	Cu:@0.14%, Ni:@ 0.30-0.65%	Pyroxene -amphibolite, Hb- pyroxenolite	Pyrrhotite, pentlandite, chalcopyrite
No.1 of Hongqingling	126°25'02"E, 42°53'10"N	Current producer	Cu-Ni	0.98×0.20	0.196	Bedded,vein, lens,sack-like	Ni: 275.6 @ 0.54%, Cu:54.2 @ 0.63%	pyroxenolite, Ol- pyroxenolite, Pyroxene -peridotite	Pyrrhotite, pentlandite, chalcopyrite, pyrite
No.7 of Hongqingling	126°44'40"E, 42°59'30"N	Current producer	Cu-Ni	0.75×0.03	0.023	Bedded,vein, lens,sack-lik	Ni: 200.10@2.30%, Cu:54.73@0.63% Co:0.31@ 0.05%	Orthopyroxenite, Pyroxene -peridotite	Pyrrhotite, pentlandite, chalcopyrite,violarite, pyrite
Piaohechuan	127°22'10"E, 43°15'50"N	Current producer	Cu-Ni	0.63×0.20	0.126	Vein, lens-shaped	Ni: 10.56@ 0.12-1.04%, Cu:3.94@ 0.05-0.39%,	Pl- Hb -Ol-pyroxenite	Pyrrhotite, pentlandite, chalcopyrite, pyrite
Changren	128°57'11"E, 42°49'44"N	Current producer	Cu-Ni		0.33	Bedded, veined	Ni: 18.9@ 0.44%, Cu:6.6@ 0.15%,	Pyroxene -peridotite	Pyrrhotite, pentlandite, chalcopyrite
Wuxing	126°16'00"E, 43°09'00"N	Current producer	Cu-Ni	4.7×1.7	7.99	Bedded , lens-shaped	Ni: 8.63@ 7%, Cu:14.88 0.20%,	Diopsidite	Pyrrhotite, pentlandite, chalcopyrite, merenskyite

approximately 330 to 230 Ma; Jahn, 2004).

In the western part (NW China), ophiolite mélanges form the South Tianshan suture, and in the Beishan orogeny, they also include accreted magmatic arcs (Xiao et al., 2010).

In the eastern segment, the boundary between the NCC and the CAOB is referred to as the Manchurides by Şengör and Natal'in (1996), where ophiolitic rocks constitute the Solonker suture (Eizenhoefer et al., 2014), bordering the Great Hinggan volcanic province, and superimposed on the Hinggan Orogen. The eastern end of the CAOB in China is represented by the Erguna Block and Jiamusi Block (also referred to as massifs/inliers; Zhou et al., 2010a), and microcontinental fragments in the Hinggan-Mongolia orogen belt.

Nd-Sr isotope studies of Mesozoic and Cenozoic volcanism indicate that the Xing'an-Mongolia orogenic belt located between the northern margin of the NCC, the Jiamusi Block and the Erguna Block to the northeast, experienced a complex and protracted geodynamic evolution (Jahn, 2004; Zhou et al., 2009, 2010a, b, c). From Triassic to Middle Jurassic period, the closure of the Mongol-Okhotsk Ocean and collision between the Siberian craton and the amalgamated Mongolia-Sino-Korea (North China) blocks occurred at the early-middle Jurassic period (Zorin, 1999), with subsequent thrusting, folding and magmatism until the latest Jurassic. Late Paleozoic arc magmatic rocks are spread out along the east-west-trending faults (e.g., Datong–Chengde) as well as zoned mafic-ultramafic intrusions, in the northern margin of the NCC. The Jiamusi and Erguna Blocks are microcontinental fragments located at the eastern end of the CAOB (Wu et al., 2012). The granulite facies metamorphic rocks are distributed within the Erguna and Jiamusi block, including sillimanite- and garnet-gneiss, biotite-plagioclase gneiss, hornblende-plagioclase gneiss, granitic orthogneiss and carbonate rocks (called khondalite), which are part of the ca. 496 Ma Mohe Complex and Mashan Complex, respectively (Zhou et al., 2011).

However, from the Late Carboniferous to Early Permian, a paleo-oceanic basin (Paleo-Asian ocean) still existed in the south of the active continental margin, notably in the Beishan-Inner Mongolia-Jilin area (Xiao et al., 2003, 2009). The final closure of the Paleo-Asian Ocean was completed in the Middle-Late Permian, thereby terminating the accretionary orogenesis in the eastern part of the CAOB. From the Triassic to Jurassic, the area was affected by the subduction of the Paleo-Pacific Ocean (Zhou et al., 2010a,b,c). Suturing appeared to have occurred earlier in the west than in the east, suggesting a diachronous closure (Li, 2006; Li et al., 2009). In the northeast of the CAOB, the Mongo-Okhotsk oceanic basin extended from northeastern Mongolia to the sea of Okhotsk and is generally thought to have existed in the Jurassic (Zorin, 1999; Tomurtogoo et al., 2005).

A number of Ni-Cu sulfide deposits are hosted in Permian-Triassic mafic-ultramafic intrusions in the Central Asian orogenic belt in TXOB, making up a ~4,000-km-long Ni-Cu sulfide mineralization zone along the belt. The intrusions that host economically important Ni-Cu

sulfide deposits include Permian Kalatongke, Huangshandong, Huangshan, Poyi, Poshi, and Tulaergen intrusions in the western part and Triassic Hongqiling intrusions in the eastern part of the belt (Fig. 1). This region is becoming one of the most important world-class Cu-Ni productions areas (Han et al., 2014). They contain major Cu-Ni deposits (Kalatongke, Huangshan, Huangshandong, Tulaergen and Hongqiling) (Fig. 1).

3 Description of Representative Magmatic Cu-Ni Deposits

The paper summarizes representative magmatic Cu-Ni deposits in TXOB, from the western Tianshan Mountains in Xinjiang to near the Pacific Ocean coast in northeast China (Table 1).

3.1 Kalatongke

The Kalatongke Cu-Ni deposit is located 28 km southeast of Fuyun city, northern Xinjiang. Its geographical coordinates are 46°45'N and 89°40'E respectively. The Kalatongke is the largest, and most economically important deposit in the southern Chinese Altay belt, and its explored reserves include 419000 tons of Cu, 240000 tons of Ni, 2.5 tons of Pt, 3.4 tons of Pd and 8355 tons of Co (Yan et al. 2003). It was discovered in 1978 and exploited during the period 1979-1986; construction of the now-operating mine began in 1989.

The host rocks are composed of sedimentary rocks of the Lower Carboniferous Nanmingshui Formation (Fig. 2). The sedimentary rocks are divided into three sequences (Wang et al., 1991). The first consists of conglomerates, tuffaceous siltstones, argillites and siliceous rocks. The second is composed of volcanic breccias and gravel-bearing sedimentary tuffs. The third sequence contains sedimentary tuffs and carbonaceous-tuffaceous slates. Faults are well developed in the Kalatongke mine, including NW-, NNW-, EW- and NE-trending ones.

11 mafic-ultramafic intrusions have been identified in the Kalatongke deposit (Fig. 2). They intruded into the first and second sequences of the Lower Carboniferous Nanmingshui Formation. Major Cu-Ni orebodies are concentrated within three intrusions. These three intrusions are relatively large in scale, well differentiated, and exhibit the zonation in composition and strongly mineralized (Yan et al., 2003; Zhang et al., 2004). Zhang et al. (2004) reported that these intrusions can be further divided into four rock series, from top to bottom, biotite diorite, biotite-hornblende norite, biotite-hornblende-olivine norite and biotite-hornblende-gabbro-dolerite. Economic sulfide mineralization occurred in biotite-hornblende norite and biotite-hornblende-olivine norite. Among these intrusions, the No. 1 contains the well-developed mineralization. It is 695 m long and 159 m in the widest part, with an exposed area of ~0.1 km², and strikes 330° and dips E, with the upper part dipping at 70°–90° and the lower part at 0°–60°. Intrusion No. 1 may be further divided into the diabase-gabbro, olivine norite, norite and diorite zones, which exhibit gradational relationships and are pervasively mineralized. The

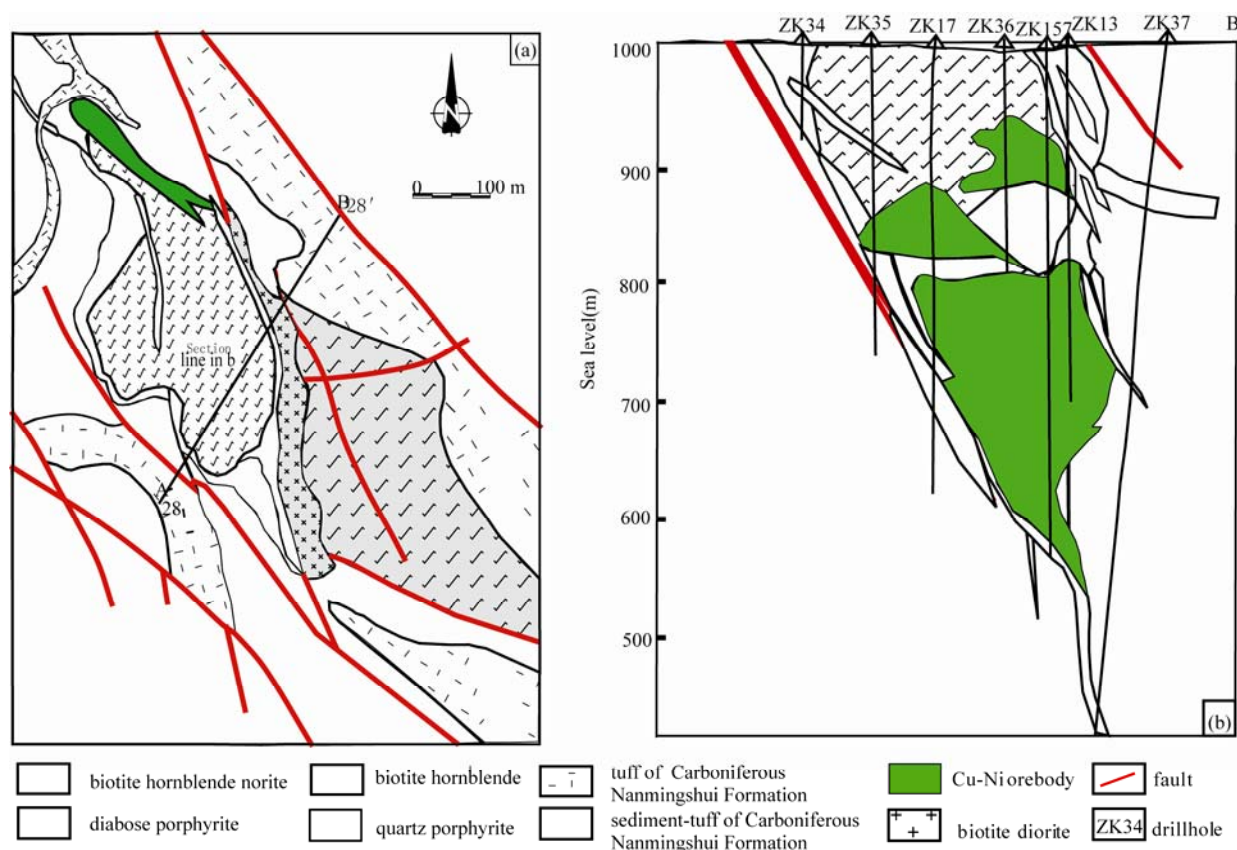


Fig. 2. Geological map of the Kalatongke Cu-Ni deposit. Plan view (a) and cross-section of exploration (b) (modified from Li et al., 1998).

mineralization occurs in olivine norite, norite and small amount of diabase-gabbro. The rocks are Mg-rich and Ca-poor, and the Mg/Fe ratio is about 1.33 in the upper part, ~1.59 at the base, ~2.55 in the middle-upper part, and ~2.45 in the middle-lower part.

Based on mineralization style and Cu-Ni grade, Chen et al. (2004) classified primary ores into five types: (1) weakly disseminated ore with low Cu and Ni grades, Cu/Ni=1.41; (2) weakly disseminated ore and associated veinlets with low Cu and Ni grades, with ore grades of averaging 0.36–0.50% Cu (3) moderately to highly disseminated ore with high Cu grade (1.25%) and moderate Ni grade (0.65%), Cu/Ni=1.92. (4) Massive and high grade Cu (6.11%) and Ni (3.53%) ore, Cu/Ni=1.73; (5) Massive Cu-Ni ore with exceptionally high copper grade (20.52%) and Ni (1.91%), Cu/Ni=10.54. The mineralization shows a circular zoning pattern, from high-grade massive ore in the center, outward to disseminated ores that gradually grade into sub-economic grades whereas sulfide minerals are more widely disseminated.

More than 50 kinds of metal minerals are identified in the Kalatongke deposits (Chen et al., 2004). They are dominantly pyrrhotite, chalcopyrite, pentlandite, violarite and magnetite, and associated noble metal minerals are melonite, michenerite, bitepalladite, sperrylite, hessite and electrum. According to mineral assemblages and crosscutting relationships of the ore veins, three mineralization stages can be identified. The first stage

(magmatic crystallization stage) is characterized by disseminated ores, with sperrylite, violarite and magnetite. The second stage (magmatic hydrothermal stage) is characterized by formation of the massive and vein-like high grade Cu and Ni ores, which overprint the disseminated ores, an assemblage consisting of Cu and Ni-bearing, precious metal-bearing arsenides, tellurides, and tellurobismuthides. The third stage (supergene assemblage) is marked by supergene oxidation which led to development of thick gossan and formation of some secondary minerals such as melanterite, chalcantite and gypsum.

3.2 Hongqiling deposit

The ore district is located at the area between Panshi County and Huadian County in the central part of Jilin Province. Its geographical coordinates are 42°01'30"N and 125°23'00"E respectively. It is estimated to contain a reserve of 275600 t Ni, 542000 t Cu and 3100 t Co, with ore grades averaging 0.54–2.30% Ni, 0.11–0.63% Cu and 0.05% Co (Lü et al., 2011). An ultramafic body and copper-nickel mineralization were first discovered in the area in April 1959 by No.7 Exploration Party, Jilin Nonferrous Metals Corporation; later, some mafic-ultramafic bodies were found in succession. Since the discovery of the deposit, numerous studies have been carried out on its mineralization and the host mafic-ultramafic rocks (Fu and Chen, 1988; Qin, 1995; Wu et

al., 2004).

The host rocks of the Hongqiling Cu-Ni deposit are metamorphic rocks of the Lower Paleozoic Hulan Group (Fig. 3), which consists predominantly of garnet-two-mica gneiss, biotite gneiss, amphibolite, muscovite schist, all of which show strong ductile deformation. Intruding the Hulan Group in the area of the Hongqiling deposit are five mafic-ultramafic intrusions, of which two intrusions (Nos. 1 and 7) in the southern part of the deposit area (Fig. 3) are well differentiated and zoned, and have concentrations of Cu-Ni mineralization (Wu et al., 2002).

The No. 1 intrusion is 980 m long and up to 270 m wide. It extends as much as 576 m down-dip and, the surface outcrop occupies an area of $\sim 0.20 \text{ km}^2$ (Fig. 4). In a plan view, the intrusion is an irregular lens in shape, but in the vertical cross-section, the intrusion is a funnel-shaped body and become vein-like at depth (Fig. 4). The No. 1 intrusion intrudes the Hulan Group and contains four intrusive units with the following rock types from the base upwards (Qin, 1995; Wu et al., 2004): olivine websterite (4%) and lherzolite (89%) in the lower part, pyroxenite (6%) and gabbro (1%) in the upper part. The nature of the contacts between the different units is unclear in the field (Wu et al., 2004).

The No. 7 intrusion is located 10 km southeast of Hongqiling town (Fig. 3). Its long axis strikes 300° and dips at $75\text{--}80^\circ$ to NE (Fig. 5). It is 700 m in length, has an average width of 35 m, a maximum extension of about 600 m, and a surface outcrop of $\sim 0.013 \text{ km}^2$ (Qin, 1995; Wu et al., 2004). The intrusive units include orthopyroxenite (96%), and minor norite and peridotite (Qin, 1985; Wu et al., 2004).

As stated above, the Hongqiling Cu-Ni deposit consists of the No.1 and No.7 orebodies. Cu-Ni sulfide ores are hosted in the olivine websterite unit and the No. 1 orebody contains 15,200 t of Cu and 71,600 t of Ni, based upon

average ore grades of 0.54% Ni and 0.11% Cu (Lü et al., 2011). The No.7 orebody is hosted in the orthopyroxenite, norite and peridotite units and contains 204,000 t of Ni and 39,000 t of Cu, based upon the average ore grades of 2.30% Ni and 0.63% Cu (Lü et al., 2011). In addition, 3,100 t of Co may be recovered as by-products (Lü et al., 2011).

Mineralogically, the ore minerals of the Hongqiling Cu-Ni deposit are dominantly pyrrhotite, pentlandite, chalcopyrite, violarite, pyrite, vallerite, millerite, nickeline, ilmenite, galena and magnetite, and the gangue minerals are olivine, pyroxene, plagioclase, hornblende, biotite, chlorite and serpentine.

The textures of the ore minerals include euhedral, subhedral, anhedral, subhedral-anhedral, gabbroic, poikilitic, reaction rim, sideronitic, interstitial and corrosion textures, and the structures are mainly massive, disseminated, sparsely disseminated, spotted and banded.

Based on cross-cutting relationships between minerals and mineral assemblages, mineralization in the Hongqiling orebody can be subdivided into the following three stages. The first is the magmatic crystallization stage, characterized by disseminated and massive ores with pentlandite+violarite+ millerite +magnetite. The second is the auto-metamorphic stage that is characterized by the formation of massive and vein-like high grade Cu and Ni ores, and forming Cu- and Ni-bearing minerals, represented by chalcopyrite+pyrrhotite. The third is the magmatic-hydrothermal stage that is characterized mainly by chlorite and carbonate alteration, forming the carbonate+pyrite+chalcopyrite assemblage that occurs as veins.

Wall-rock alteration related to mineralization in the Hongqiling Cu-Ni ore deposit includes chloritization, carbonatization, serpentinization, talcization, uralitization, sericitization, tremolitization (Qin, 1995). Characteristic minerals in the alteration zones are talc, chlorite, serpentine, sericite and carbonate.

4 Discussion

4.1 Regional Cu-Ni mineralization characteristics

Zhou et al. (2002) pointed out that the most important characteristics that can explain the origin of Cu-Ni sulphide accumulations are the ore texture and ore distribution, which are affected by sulphide saturation and intrusion dynamics. Cu-Ni sulphide deposits in the East Tianshan mainly contain low-grade disseminated ore, while high-grade massive ore only occurs in Kalatongke and Tianyu (Mao et al., 2008). However, both of these types reflect the injection of ore-bearing magma in a late mineralization stage. The ore-bodies are mainly stratiform and usually form at the bottom of a magma chamber. The sulphide mineralization formed as sulphide liquid injections and as hydrothermal veins, during post-magmatic stages.

In TXOB, Cu-Ni sulphide deposits belong to one of two types: net-textured and conduit. The former is represented by the Kalatongke, Huangshan, Huangshandong, and Hongqiling deposits, while

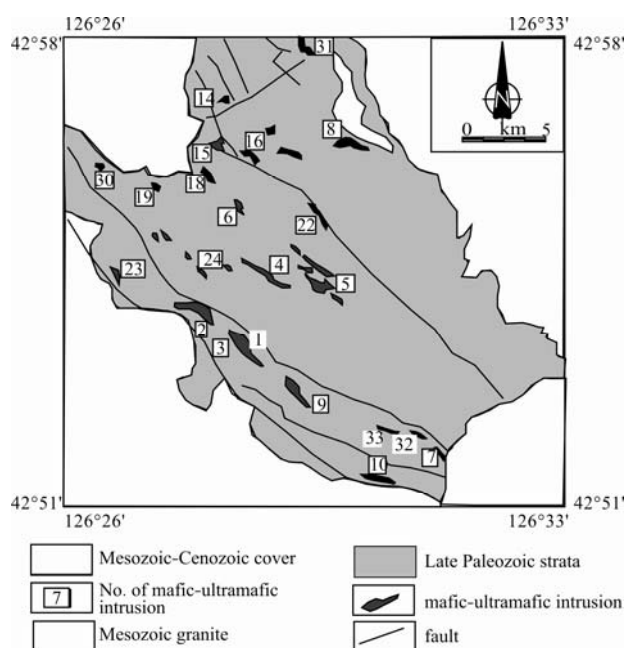


Fig. 3. Geology map of the HQL (Hongqiling) mafic-ultramafic complex (Modified from Lü et al., 2011).

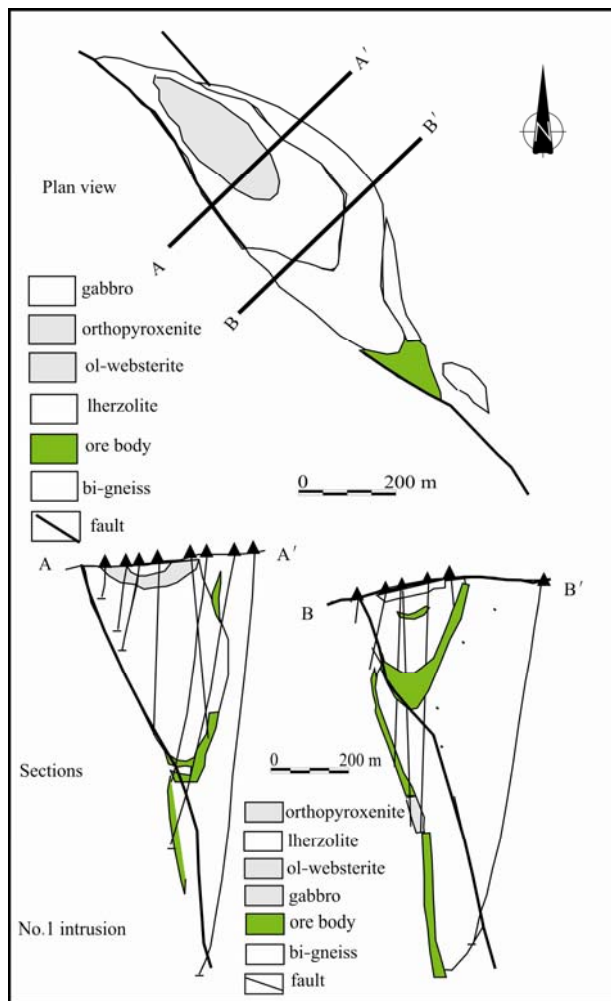


Fig. 4. Geological map of the Hongqiling Cu-Ni No.1 deposit. Plan view (a) and cross-section of exploration (b) (modified from Lü et al., 2011).

representative deposits for the latter include the Baishiquan, Tianyu, Tula'ergen and Xiangshan deposits. Based on a study of the world-class Jinchuan deposit, Tang (1996, 2002) found that the Jinchuan intrusion has only an area of 1.34 km² but contains 5.45 million tonnes of Ni metal (with a grade of 1.06%) and 3.50 million tonnes of Cu metal. Tang (1996, 2002) proposed that a large ore deposit forms in a small intrusion when the parent magma underwent fractional crystallization at depth before it intruded into the present position, resulting in separation of the parent magma into ore-rich magma, and barren magma. This may be followed by one or multiple injections of sulphide liquid. Based on the chemical composition of the intrusion, Chai and Naldrett (1992) proposed another model, namely that Cu and Ni sulphides are derived by the differentiation of Mg-rich basaltic magma, and that the ore-rich dunite is in the root zone of the magma chamber. Extensive Mg-rich basalt may have erupted at the surface and is probably eroded away. The superlarge Noril'sk deposit of Russia is in general terms similar to the model proposed by Tang (1996, 2002), although the Noril'sk deposit is the product of

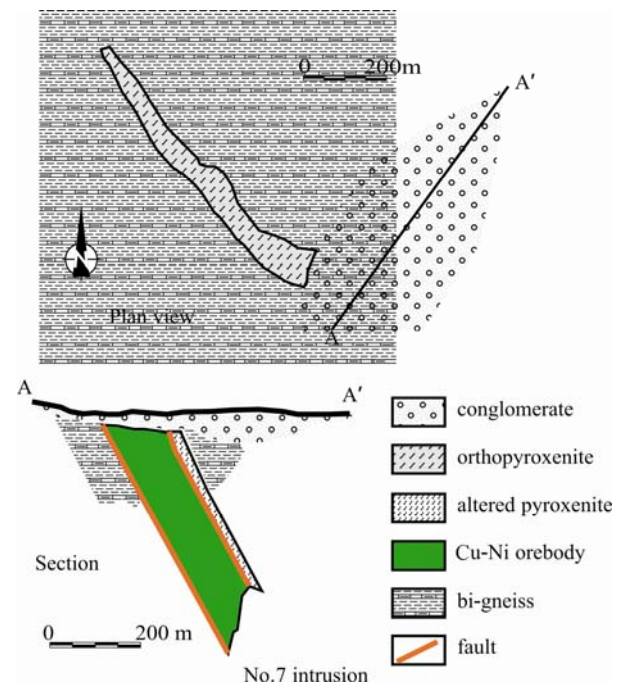


Fig. 5. Geological map of the Hongqiling Cu-Ni No.7 deposit. Plan view (a) and cross-section of exploration (b) (modified from Lü et al., 2011).

emplacement of subvolcanic magma along conduits, associated with the outpouring of continental flood basalt in Siberia.

The mafic-ultramafic bodies and their contained Cu-Ni deposits of TXOB, are all comparatively small, and even the Kalatongke, Huangshan, Huangshandong and Hongqiling intrusions, which have distinct zonings due to magmatic differentiation, are all <5 km² in area. Drilling also indicates that these mafic-ultramafic complexes are funnel-shaped, or lotus root-shaped, becoming smaller with depth. Thus, it is possible that both types are magma conduits forming differentiated intrusions distributed along deep faults and emplaced in the same period of time. The intrusions are commonly elongated, which seems to reflect the features of the root zone of extensive continental magmatism (Mao et al., 2008).

The Cu-Ni sulphide deposits of TXOB are predominantly characterized by sparsely disseminated sulphides and are generally of low-grade. Li et al. (2003) argued that the reason for this phenomenon is the lack of adequate sulphur concentration in the magma system. Although the Re/Os isotope (Mao et al., 2002; Zhang et al., 2005; Han et al., 2006; Li et al., 2006) and S-C isotope (Wei et al., 2019) studies suggest that the magma chamber was contaminated by crustal materials. The crustal materials incorporated in the magmas were mostly turbidite, clastic rocks, carbonaterocks, and schist, all of which are deficient in sulphide. This is unlike the superlarge Jinchuan Ni deposit, where a large amount of black shales in its surrounding Proterozoic strata may have provided the sulphur contaminant to the parental magma (Tang and Li, 1995) or the Noril'sk deposit, where the magmas may have interacted with evaporite beds

(Naldrett, 1999).

4.2 Cu-Ni mineralization time in TXOB

The western part of TXOB includes a large number of Cu-Ni deposits, for example, the Jingbulake in West Tianshan, the Kalatongke in eastern Junggar, the Huangshan, Huangshandong, Xiangshan, Hulu and Tulaergen deposits along the Kanggurtag suture in the Chinese East Tianshan, Baishiquan, Tianyu and Tianxiang deposits along the southern segment of the Aqikkuduk fault in the Central Tianshan, the Poyi, Poshi, Luodong and Hongshishan deposits in the southern part of the Baidiwa Fault in the Beishan orogenic belt, the Ebutu, Kebu, Huanghuatan, Xiaonanshan and Tunaobao in the Solonker suture zone and the OndorSum terrane. Shanmen, Hongqiling, Piaohechuan, Chajianling, Erdaogou and Changren deposits occur in the southeastern part of the Central Asian Orogenic Belt (Fig. 1). The formation ages of some ore deposits and associated intrusions have been well determined (Table 2), using whole-rock K-Ar and Sm-Nd ages, and a few Re-Os and U-Pb ages.

These ages indicate that tectonic activity in the CAOBS diminished with time from west to east, namely from the Late Caledonian (~440 Ma), through the Late Hercynian (300–265 Ma), to the Late Indosinian (225–200 Ma). Such variation could reflect a gradual scissor-type closure of the paleo-central Asian ocean between the Siberia Craton and the North China Craton from west to east (Han et al., 2014).

4.3 Geodynamic setting of representative mafic-ultramafic complexes and associated Cu-Ni deposits

The Jingbulake mafic-ultramafic rock belt is distributed in West Tianshan of Xinjiang. There are about ten intrusions in Jingbulake, with Jingbulake being the largest one. As part of the copper-nickel sulfide metallogenic belt related to mafic-ultramafic intrusions in northern Xinjiang, it was previously considered to be formed in a tectonic environment similar to that of the Kalatongke complex on the southern margin of the Altay orogenic belt and the Huangshandong complex in East Tianshan, i.e., in a post-collisional extensional environment. In recent study, Zhang et al. (2007) and Yang et al. (2009) obtained the high precise SHRIMP zircon U-Pb age of (434–431) Ma for the pyroxene diorite of the Jingbulake basic complex. These ages represent the diorite formed during Early and Middle Silurian. According to the geochemical data, the Jingbulake mafic complex is characterized by low content of Ti, depletion of Nb and Ta and enrichment of large lithophile elements and slight enrichment of LREE. The magma also displays some features of inland arc magma (Zhang et al., 2007). The magma was probably derived from the MORB type depleted mantle, and was not or was even slightly contaminated by the crust or the wall rock during the emplacement. Combined with the recent research achievements on regional tectonic evolution, it is considered that the formation of the complex might have been closely related to Early Silurian subduction of the South Tianshan oceanic crust to central Tianshan plate (Yang et al., 2009).

The Alaskan-type zoned mafic-ultramafic complex in the Kalatongke area outcrops in a 10 km² area, slightly elongate towards NW, on the southern side of the Irtysh fault zone. A well-defined differentiation sequence characterizes the Kalatongke complex, with zoning downwards and/or inwards from biotite-diorite, biotite-hornblende norite, biotite-hornblende-olivine norite and biotite-hornblende diabase gabbro. All of the mafic-ultramafic rocks are enriched in large-ion lithophile elements (LILE) and LREE, display negative Nb and Zr anomalies and have low TiO₂ contents (generally <1%) (Han et al., 2007). These features indicate that the intrusive rocks formed in a subduction-related island-arc setting (Zhang et al., 2004). In addition, hornblende and biotite are observed in almost all thin sections, supporting the above interpretation since subducted-related magmas are usually enriched in hydrous minerals. Based on the low Ti content and depleted Nb and Ta concentrations of the No. 2 intrusion, Ran and Xiao (1994) proposed that Kalatongke intrusive complexes were formed in an island arc setting. The Kalatongke intrusive complexes clearly show an island-arc geochemical signature, including negative anomalies for Nb, Ta, Zr and Ti, and LILE enrichment. The Kalatongke belt also featured MORB type magmatism, in which intrusions were emplaced within accreted, soft sediments of the Early Carboniferous Nanmingshui Formation. All the rocks are characterized by low initial ⁸⁷Sr/⁸⁶Sr ratios and high $\epsilon_{\text{Nd}}(t)$ values, suggesting that they were derived from a depleted MORB-type mantle source (Zhang et al., 2005). The Kalatongke intrusion was previously considered as linked to a post-orogenic extensional setting in the Late Carboniferous–Early Permian. However, Re-Os geochronological and geochemical results indicate that the Kalatongke mafic-ultramafic intrusion, along with the Cu-Ni deposit, was generated by subduction-accretion of oceanic crust in the Late Carboniferous–Early Permian, rather than in a post-orogenic extension setting (Han et al., 2007).

The mafic-ultramafic rocks in the East Tianshan orogen are most likely to have formed in a tectonic setting analogous to the Alaska-type zoned ultramafic complexes (Xiao et al., 2004). As mentioned, the Chinese East Tianshan is the easternmost segment of the Tianshan Mountain Range in the southern Altaids, extending eastwards from the Beishan orogenic belt to Inner Mongolia and occupying a key position between the Central Asian orogenic belts to the west and east (Fig. 1; Xiao et al., 2004; Han et al., 2006). The geodynamic evolution of the East Tianshan orogen was closely associated with the subduction of the Paleasian ocean between the Tarim and Siberia (Angaran) blocks (Xiao et al., 2004). The subduction of the Paleo Asian ocean formed a series of arc-related terranes with Alaskan-type complexes in the Eastern Tianshan area. One such terrane is the Danahu terrane that is composed of arc-related volcanic and sedimentary rocks and Alaskan-type complexes (Xiao et al., 2004). The latter are remarkably similar to those in Alaskan-type belts (Xiao et al., 2004). The Permian ultramafic-mafic intrusive complexes along the Kanggurtag fault extend from Huangshan to Jingerquan, constituting a large Ni-Cu-PGE metallogenic

province that can be traced for at least 270 km in the Paleozoic East Tianshan subduction belt. These ultramafic–mafic complexes were previously thought to be an ophiolite representing a consumed ocean based on geochemical and geological data (Ji et al., 1999, 2000; Zhou et al., 2001). They consist of peridotite, lherzolite, gabbro, olivine gabbro, hornblende gabbro–norite, pyroxenite diorite and diorite. A well-defined differentiation sequence characterizes the Huangshan complex, with zoning downwards and/or inwards from dunite, through peridotite, to olivine pyroxenite and then hornblende gabbro (Ma et al., 1997; Xiao et al., 2004). The Cu–Ni bearing mafic–ultramafic rocks are characterized by enrichment in LILE, strong negative anomalies for Nb, Ta, P, and Ti and positive anomalies for Rb, Ba and Th (Zhou et al., 2004; Li YC et al., 2006). These intrusions yield an arrow $^{143}\text{Nd}/^{144}\text{Nd}$ range varying from 0.5129 to 0.5131 and $^{87}\text{Sr}/^{86}\text{Sr}$ values from 0.6912 to 0.7053 (Li et al., 1998), which are transitional between depleted mantle and EMII values and closer to the former in terms of $^{87}\text{Sr}/^{86}\text{Sr}$ – $^{143}\text{Nd}/^{144}\text{Nd}$. They have positive $\varepsilon\text{Nd}(t)$ values ranging from +6.6 to +9.3 (Li et al., 1998). The high $\varepsilon\text{Nd}(t)$ values and generally low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are similar to those of typical oceanic island basalts (OIB) (Rollinson, 1993). Isotopic age data for the orebearing mafic–ultramafic intrusions indicate that the magmatism occurred in the late Carboniferous to Early Permian. Thus, we suggest that the magmatic Cu–Ni–PGE deposits in the East Tianshan orogen were developed in a subduction–accretion setting, and their mineralization styles and features are comparable to those of the Ural–Alaskatype mafic–ultramafic intrusions in arc environments.

Lithospheric thinning of the NCC is a deep seated process, which started in the Early Mesozoic (~220 Ma, Wilde et al., 2003) and gradually extends outward from the northern margin of the NCC and the adjacent CAO (Han et al., 2004). The Indosinian S-type granites are widely distributed in central Inner Mongolia and spread in a nearly E–W direction, which form a giant composite granite belt in a post-collisional setting (Tao et al., 2003). Davis et al. (2004) described first Indosinian extension in the Solonker suture belt of Inner Mongolia. Late Triassic magmatic activity produced intrusions of ~220 Ma age, with characteristics of bimodal magmatism and crust–mantle derivation. The formation of mafic–ultramafic intrusions at ~220 Ma is coeval with the intrusion of A-type granite in the region, but slightly later than regional metamorphism (~240 Ma) and syn-orogenic granitic magmatism (~250 Ma). These mafic–ultramafic complexes are likewise considered to be post-orogenic in origin, thus indicating a short period of lithospheric stabilization of about 30 Ma after cessation of orogenic activity (Wu et al., 2004). The formation of giant Ni–Cu metallogenic domains is associated with strong interactions between mantle and crust, with accretion, transition, and tectonic processes of the CAO. Based on geochemical studies, the primitive ultramafic magma of the Hongqiling deposits is mantle-derived basaltic magma produced by the uplifting of asthenosphere, which is caused by the delamination and thinning of the lithospheric plate during post-orogeny (Wu et al., 2004),

as well as contaminated by crustal materials during the lifting and magmatic segregation or crystal fractionation.

4.4 Evolution of the mafic–ultramafic magmatism and associated Cu–Ni metallogeny in TXOB

The CAO is a collage of terranes bounded by the Siberian craton in the north, the Tarim craton and NCC in the South, the Urals in the west, and the Sea of Japan in the east (Jahn, 2004; Windley et al., 2007; Xiao and Santosh, 2014; Kröner et al., 2014). It is considered to be one of the most significant sites of crust generation during the Phanerozoic but there is considerable debate on the relative proportions of newly created juvenile crust and reworked crust (Jahn, 2004; Kröner et al., 2014). Accretion of island arcs, ophiolites and microcontinents probably began during the Mesoproterozoic at about 1000 Ma and ended during the Late Paleozoic to early Mesozoic at about 250 Ma (Şengör et al., 1993; Şengör and Natal'in, 1996; Jahn, 2004; Windley et al., 2007; Kröner et al., 2014). The CAO was widely affected by postorogenic magmatism following re-accretion (Jahn, 2004; Kröner et al., 2014). Magmatic Cu–Ni sulfide deposits are known to occur in the TXOB, in association with either subduction-related or postorogenic magmatism. For example, those at Erbutu and Kalatongke probably are related to subduction-related, boninitic magmatism (Peng et al., 2013; Li CS et al., 2012), whereas those at Huangshan and many others might be related to extension-related, basaltic magmatism (Zhou et al., 2004; Song and Li, 2009). Recently, we propose that the mafic–ultramafic in TXOB are most likely to have formed in a tectonic setting analogous to the Alaska-type zoned ultramafic complexes (Han et al., 2010).

The TXOB magmatic Cu–Ni deposits are genetically associated with and hosted in funnel-shaped, differentiated layered and/or zoned mafic–ultramafic intrusions (Mao et al., 2008; Han et al., 2010). The TXOB mafic–ultramafic intrusions have features in common with Alaskan-type complexes (Pirajno et al., 2008). Concentrically zoned and funnel-shaped Alaskan-type mafic–ultramafic intrusions were first recognised, as the name implies, in southeastern Alaska (Taylor, 1967). A review of Alaskan-type complexes is provided by Johan (2002). Ishiwatari and Ichiyama (2004) reported on Alaskan-type complexes in northeast China. Typically, Alaskan complexes consist of an ultramafic core surrounded by an envelope of earlier gabbroic rocks, as observed in the case of the NW China mafic–ultramafic intrusions. Alaskan-type complexes are usually of small size ranging from 12 to 40 km². The area of NW China complexes ranges from 0.1 km² (Kalatongke) to about 3 km² (Huangshandong). The general zoning of Alaskan-type complexes passes from a dunite core, through successive zones of olivine-clinopyroxenite, biotite and hornblende-bearing clinopyroxenite, then hornblende and finally to an outer zone of monzonite-gabbro (Johan, 2002). A similar pattern, albeit with variations, characterises the NW China intrusions. In both Alaskan-type and NW China the ultramafic rocks have rhythmic layering and mineralogical evidence to show that their liquidus temperatures decrease outwards through the successive zones, as in a fractional

crystallisation sequence, with hornblende being a late product in the outer zones (Johan, 2002; Zhou et al., 2004). A generally accepted model for the origin of Alaskan-type complexes is that of intrusions of a tholeiitic magma, which gives rise to gabbro or gabbro-norite, followed at a later stage by ultramafic magmas that are emplaced at localised centres as multiple intrusions in order of increasing liquidus temperature, from pyroxenite, then wehrlite to dunite (Zhou et al., 2004). The mineralization styles include massive sulphide, sulphide-matrix breccias, interstitial sulphide networks, and disseminated sulphide (Pirajno et al., 2008). Sulphide veins and dissemination locally penetrate footwall rocks. The environment of emplacement of the multiple ore-bearing intrusions of ultramafic magma (probably mantle-derived) is the upper crust in tensional environments associated with rifting. Contamination of the magma was an important factor for sulphur saturation and formation of a sulphide phase (Naldrett, 1997).

Numerous mafic-ultramafic intrusions with magmatic Cu-Ni mineralization occur in the eastern TXOB (Fig. 1). In the Hongqiling region, 33 intrusions have been identified (Lü et al., 2011; Wei et al., 2013, 2019). seven of them contain Cu-Ni sulfide mineralization and two of them, Daling and Fujia (or the Nos. 1 and 7 intrusions, respectively), host the most important sulfide ores. They represent the second largest Ni producer in China following the Jinchuan deposit. The Daling intrusion is about 980×150–280 m in size and 560 m thick. It is composed mainly of ilmenite and minor olivine websterite, pyroxenite, gabbro, hornblende, and leucogabbro. The Fujia intrusion is about 700×350 m in size and 600 m thick. It is composed mainly of orthopyroxenite and minor norite, gabbro and ilmenite. Wu et al. (2004) undertook a geochronological and geochemical study of the Hongqiling complex. Its magmatic age of ~216 Ma postdates Early Triassic syn-orogenic granitic magmatism and regional metamorphism, implying that the Hongqiling complex is postorogenic in region. Geochemical data indicate that most rocks of the complex are cumulates from a juvenile basaltic parental magma derived from the lithospheric mantle the underwent minor crustal contamination (Wu et al., 2004). These findings are in line with Os-isotope data reported by Lü et al. (2011) and S-C isotopes by Wei et al. (2019) for sulfide ore from the complex.

5 Conclusions

Due to the analysis of geological characteristics, spatial and temporal distribution and metallogenic dynamics setting of the major magmatic Cu-Ni-Co-PGE sulfide deposits in the Tianshan-Xingmeng Orogenic Belt, some conclusions can be drawn as followings.

It is found that a large number of magmatic Cu-Ni-Co-PGE sulfide deposits developed in northern Xinjiang were formed from the end of late Carboniferous to early Permian, and formed into an environment similar to Alaskan- Ural Cu-Ni sulfide deposit, mafic-ultramafic rocks and related deposits were formed before ancient Asian ocean closure and were the products of island arc

environment formed by subduction-accretion. The magmatic Cu-Ni sulfide deposits in the Hongqiling area is the result of the combined action of the central Asian orogenic belt and the Pacific plate. The major Cu-Ni deposits in the Tianshan-Xingmeng Orogenic Belt are considered to have formed by the accretion and collision processes of the CAOB.

Together with the widespread occurrence of the mafic-ultramafic complexes and associated Cu-Ni deposits in the Tianshan-Xingmeng Orogenic Belt, geochronology variation could reflect a gradual scissor-type closure of the paleo-central Asian ocean between the Siberia Craton and the North China Craton from west to east.

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