A review of the Cu–Ni sulphide deposits in the Chinese Tianshan and Altay orogens (Xinjiang Autonomous Region, NW China): Principal characteristics and ore-forming processes

Jing Wen Mao a,*, Franco Pirajno b, Zuo Heng Zhang a, Feng Mei Chai c, Hua Wu d, Shi Ping Chen e, Lin Song Cheng d, Jian Min Yang a, Chang Qing Zhang a

a Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China
b Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia
c School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
d No. 6 Geological Party, Xinjiang Bureau of Geology and Mineral Exploration and Development, Hami 839000, Xinjiang, China
e Hami Bureau of Land and Resources, Hami 839000, Xinjiang, China

Abstract

Several Cu–Ni sulphide deposits and occurrences have recently been discovered along parallel deep faults in the Chinese Tianshan and Altay orogenic belts, Xinjiang Province, NW China. The Kalatongke and several other Cu–Ni mineralized intrusions are located along the Irtsh fault, which separates the Altay orogenic belt from the Junggar basin. The Huangshan, Huangshandong, Xiangshan, Tudun, Erhongwa, Tula’ergen, and Hongling deposits occur along the Kanggurtag suture, which separates the Jueluotage orogenic belt from the Turpan-Hami (Tuha) basin. The Baishiquan, Tianyu, and Tianxiang deposits are located along the Arqikekuduke fault, which separates the Jueluotage orogenic belt from the Central Tianshan Precambrian terrane. The Poyi, Poshi, and Luodong deposits are located along the Baidiwa fault, which separates the Central Tianshan Precambrian terrane from the Beishan Paleozoic rift. Re–Os dating of Cu–Ni sulphide ores reveals that these Cu–Ni ore belts formed in a narrow age range of 298–282 Ma. This age range is about the same as those of associated intrusions and dykes dated by the SHRIMP zircon U–Pb method. Tectonic and geochronological constraints suggest that the amalgamation of continental blocks mainly occurred during the Late Carboniferous in the Central Asian orogenic belt. Large-scale hydrothermal and magmatic metallogenesis in the region occurred during post-collisional stages of Latest Carboniferous to Early Permian age. The Cu–Ni sulphide deposits are part of this metallogenic event.

The Cu–Ni orthomagmatic sulphide deposits in northern Xinjiang are represented by: (1) net-textured type deposits by segregation of a Cu–Ni metal sulphide melt and (2) magma conduit type. Some mafic–ultramafic suites exhibit lithological zoning caused by strong differentiation. Stratiform orebodies are hosted by ultramafic rocks at the base of the magma chamber. Good examples are the Kalatongke, Huangshandong, and Poshi deposits. Others, such as the Xiangshan, Baishiquan, Tianyu, and Tula’ergen deposits, are hosted by magma conduits, consisting of peridotite, troctolite, and pyroxenite. These ultramafic rocks either occur within faults or are surrounded by gabbroic and dioritic intrusions. These two types of orthomagmatic Cu–Ni sulphide deposits are also distributed along the same ore belts. For instance, the differentiated sill-related Huangshandong deposit co-exists with the magma conduit type Tula’ergen deposit in the Jueluotage orogenic belt.

Orthomagmatic Cu–Ni sulphide deposits in northern Xinjiang formed during post-collisional extension and are possibly related to a Late Carboniferous–Early Permian mantle plume event. The mafic–ultramafic suites and associated Cu–Ni deposits are commonly accompanied by dyke swarms and are characterized by elongated outcrops occurring along parallel E–W-trending regional faults. These mafic–ultramafic suites and accompanying dyke swarms are generally fractionated, implying that they were feeders of presently eroded flood basalts.

Crown copyright © 2007 Published by Elsevier Ltd. All rights reserved.
Keywords: Cu–Ni sulphide deposit; Post-collision; Mantle plume; Tianshan–Altay; Xinjiang; China

1. Introduction

In the 1970s, Cu–Ni sulphide deposits (Kalatongke, Huangshan, Huangshandong, Xiangshan, Tudun, and Hulu) were discovered in the southeastern Altay Mountains and in the East Tianshan, Xinjiang, China. In recent years, exploration successes for magmatic Cu–Ni sulphide deposits include the discoveries of Baishiquan, Tianyu, and Tianxiang on the northern margin of the Central Tianshan, south of the Huangshan–Jing’erquan ore belt, and the Poshi, Poyi, and Luodong occurrences in the Pobei area, in the Paleozoic Beishan rift south of the Central Tianshan. More recently, the Tula’ergen Cu–Ni deposit was found at the eastern end of the Huangshan–Jing’erquan ore belt and the Hongling deposit was identified at the western end of this ore belt. Re–Os dating of sulphide ores and SHRIMP zircon U–Pb dating of related mineralized mafic intrusions indicate that these Cu–Ni sulphide deposits formed at 298–270 Ma (Li et al., 1998; Mao et al., 2002; Han et al., 2004; Zhou et al., 2004; Wu et al., 2005; Zhang et al., 2005) during post-collisional extensional tectonism.

In the past 20 years, many researchers have discussed the basic features of the Kalatongke, Baishiquan, Huangshan, and Huanshandong deposits (Wang et al., 1991; Pan and Wang, 1992; Yan et al., 2003). Wang et al. (1992), Li (1996), and Wang et al. (2000) summarized the metallogenic characteristics of local districts in northern Xinjiang. Ni (1992), Gao (1992), Bai (2000), Shen (2003), Zhang et al. (2003), Zhou et al. (2004), and Chai et al. (2006) discussed the mineralization associated with these mafic–ultramafic rocks. Based on previous research, combined with the new advances in current mineral exploration and prospecting, in this paper we summarize the main characteristics of these deposits, examine ore-forming processes, and attempt to understand the relationship of these deposits and host mafic–ultramafic rocks with the geodynamic evolution of the region and explore their possible link with mantle plume activity.

2. Geological setting

In NW China (Xinjiang Province), the Altay Mountains, the lower mountains and hills of the East Junggar, Junggar basin, and the East Tianshan ranges, in northeastern Xinjiang Uygur Autonomous Region, are on the southern margin of the Altai or Central Asia Orogenic Belt (Sengör et al., 1993; Jahn, 2004; Li et al., 2006b; Windley et al., 2007). The main tectonic features of NW China consist of Late Paleozoic NW- and nearly E–W-trending orogenic belts with inliers of pre-Sinian blocks (Li et al., 2003b). These orogenic belts were originally separated by a Paleo-Asian Ocean, developed during the Paleozoic. From north to south, the principal tectonic units of Xinjiang are the Altay orogen, eastern Junggar orogen, Junggar block, Bogda Shan orogen, Tuha basin, East Tianshan (or Jueluotage), and Beishan orogens (Li et al., 2006b).

The tectonic evolution in the region was divided into the pre-Sinian, Sinian-Carboniferous, Permian to Cenozoic stages. The pre-Sinian stage includes an Archean–Paleoproterozoic basement and the Mesoproterozoic to early Neoproterozoic successions of the Tarim craton, as well as microcontinental fragments within the Tianshan and other areas which correspond to the stages of assembly of the supercontinents Columbia and Rodinia (Li et al., 2006). In the Middle Neoproterozoic, concomitantly with the breakup of the supercontinent Rodinia, a Paleozoic ocean formed in Central Asia. The Altay and Tian Shan orogens, the Tarim craton and the microcontinental fragments that are included in these orogenic belts were separate terranes within this paleo-ocean. The Sinian–Cambrian stage was a period of seafloor spreading, but from the Ordovician onward, the paleo-ocean began closing and in the Late Carboniferous the terranes became amalgamated to form the continental crust of present day Central Asia.

A stage of extensional tectonics began in the Permian and continued through the Triassic to the Neogene. The Permian was a stage of post-collision crustal evolution in the region characterized by mantle-derived magmatism. From the Late Triassic to Jurassic, the crustal evolution of the region was mainly dominated by the closing of the Paleo-Pacific Ocean (an ocean that was the precursor of the Mongolia-Ochotsk orogenic belt) and Paleo-Tethys Ocean (an ocean that was the precursor of the Kunlun Mountains). The Cretaceous to Neogene was a period of relative quiet and stability in the geological history of the region. From the Pleistocene on, as a result of the India–Eurasia collision, reactivation and on-going uplift of the orogenic belts took place, forming the present basin-range framework.

3. Cu–Ni sulphide deposits

Northern Xinjiang is one of the regions in the world where Cu–Ni sulphide deposits are particularly numerous. Up to now, 19 Cu–Ni sulphide deposits and occurrences including Huangshan, Huangshandong, Xiangshan, Huangshannan, Tudun, Erhongwa, Kalatongke, Xingdi, and Qingbulate deposits were discovered in the 1970s and 1980s, with the Hongling, Baishiquan, Tianyu, Tianxiang, Tula’ergen, Poshi, Poyi, and Luodong deposits discovered in the past few years. The distribution of these deposits and occurrences are shown in Fig. 1 and their main characteristics are given in Table 1. Due to the preli-
minary levels of exploration, demonstrated reserves are all of a medium or small size. The Huangshandong and Kalatongke deposits may be assigned to the large category according to China’s current reserve classification, but they are not comparable to world-class Cu–Ni sulphide deposits, such as Jinchuan of China, Sudbury and Voisey’s Bay of Canada, and Noril’sk of Russia. Except for the Xingdi and Qingbulake deposits (whose mineralization ages are controversial), the majority of Cu–Ni sulphide deposits discussed in this paper (Kalatongke in the southern Altay, Huangshan–Jing’erquan ore belt in the East Tianshan, Bai-shiquan–Tianyu district in the Central Tianshan, and Pobei district in the Beishan rift) were formed during a post-collisional tectonic regime. The above mentioned Cu–Ni sulphide deposits in Xinjiang fall into two main styles: (1) net-textured (2) magma conduit system. Net-textured type deposits form by fractional crystallization of the magma after its emplacement with segregation of a Cu–Ni metal sulphide melt and its settling at the base or in the lower parts of a magma chamber. Typical examples are the Huangshan, Huangshandong, Kalatongke, and Poshi deposits. Conduit type deposits, on the other hand, form in a lower magma chamber with several pulses of melt being channeled upward through a conduit. The melts solidify in the conduit, segregating sulphide ore. Tang and Li (1995) emphasized that a large ore deposit can be formed from a small intrusion in this way, as exemplified by the Tula’ergen, Baishiquan, and Tianyu deposits.

3.1. Kalatongke ore district

The Kalatongke (or Karatungk) ore district is located in the southern Altay Mountains, 28 km southeast of the town of Fuyun. It was found by the Fourth Geological Party of the former Xinjiang Bureau of Geology and Mineral Resources (now Xinjiang Bureau of Geology and Mineral Exploration and Development) in 1978 and exploration was completed in 1985. The measured reserves in the Kalatongke ore deposit included 420,000 tonnes of Cu, 240,000 tonnes of Ni, more than 4000 tonnes of Co, 2.5 tonnes of Pt, and 3.4 tonnes of Pd (Yan et al., 2003). The deposit has been mined since 1989.

The Kalatongke ore district is located on the southern side of the Ertix (or Ertyish) fault, which marks the boundary between the Altay Caledonian orogenic belt and the Junggar Hercynian orogenic belt (Coleman, 1989; Huang et al., 1990). A series of mafic–ultramafic bodies intruded along the Sarbulak-Sasekbastao synclinorium and faults (Fig. 2a). These folds and fold-parallel faults trend NW and NNW. The rock successions in the area belong to the Lower Carboniferous, >450 m thick (Yan et al., 2003) Nanmingshui Formation. This formation consists of red argillaceous sandstone, argillite, tuffaceous slate with limestone and chert at the base or in the lower parts of a magma chamber. Typical examples are the Huangshan, Huangshandong, Kalatongke, and Poshi deposits. Conduit type deposits, on the other hand, form in a lower magma chamber with several pulses of melt being channeled upward through a conduit. The melts solidify in the conduit, segregating sulphide ore. Tang and Li (1995) emphasized that a large ore deposit can be formed from a small intrusion in this way, as exemplified by the Tula’ergen, Baishiquan, and Tianyu deposits.

Fig. 1. Distribution of magmatic Cu–Ni sulphide deposits in northern Xinjiang (modified from Wang et al., 2006 and Chen et al., 1997).
Table 1
Main features of the major Cu–Ni–(PGE) deposits in the Chinese Tianshan–Altay

<table>
<thead>
<tr>
<th>Ore district name and geographical location</th>
<th>Tectonic position</th>
<th>Deposit</th>
<th>Intrusion size (length × width)</th>
<th>Reserves (10,000 tonnes) @ grade</th>
<th>Mineralized rock</th>
<th>Orebody shape</th>
<th>Ore type</th>
<th>Country rocks of intrusion</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalatongke ore district; E: 89°40′32″– 89°42′04″, N: 46°44′34″–46°45′31″, Fuyun County, Altay area</td>
<td>Junction between Altay Caledonian fold system and Junggar Hercynian fold system</td>
<td>I</td>
<td>0.7 × 0.29</td>
<td>Cu: 23.2@1.4%, Ni: 15.4@0.88%</td>
<td>Biotite–hornblende–biotite norite and hornblende pyroxenite</td>
<td>Funnel-shaped</td>
<td>Dominantly disseminated and massive and subordinately colloidal and vein</td>
<td>Clastic rocks with volcanic rocks of Lower Carboniferous Namingshui Formation (Rb–Sr isochron age 311 Ma; Wang et al., 1991)</td>
<td>Wang et al. (1991, 2000), Yan et al. (2003), No. 4 Geological Party et al. (2003)</td>
</tr>
<tr>
<td>Huangshan–Jing’erquan ore belt; E: 94°00′–95°00′, N: 42°00′–42°20′, Hami City, Hami area</td>
<td>Interarc basin on north margin of Tarim plate</td>
<td>II</td>
<td>0.875 × 0.52</td>
<td>Cu: 10.6@1.1%, Ni: 5.0@0.6%</td>
<td>Biotite–hornblende norite and biotite–hornblende gabbro</td>
<td>Flat vein</td>
<td>Dominantly disseminated and subordinately cumulophytic and massive</td>
<td>Turbidite of Lower Carboniferous Gandun Group</td>
<td>Wang and Li (1987); Qin et al. (2003), No. 6 Geological Party et al. (1987), Geophysical and Geochemical Exploration Party (1996), San et al. (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>III</td>
<td>1.3 × 0.2</td>
<td>Cu: 8.1@1.1%, Ni: 4.6@0.6%</td>
<td>Hornblende gabbro and hornblende norite</td>
<td>Lenticular and bed-like</td>
<td>Dominantly disseminated and subordinately massive and stockwork</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Huangshan-dong</td>
<td>5.3 × 1.12</td>
<td>Cu: 18.8@0.3%, Ni: 36@0.52%</td>
<td>Gabbro norite and hornblende lherzolite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huangshan</td>
<td>3.8 × 8</td>
<td>Cu: 21@0.31%, Ni: 32@0.49%</td>
<td>Hornblende gabbro and hornblende lherzolite</td>
<td>Comet-shaped</td>
<td>Dominantly disseminated and subordinately massive and stockwork</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tudun</td>
<td>1.4 × 0.7</td>
<td>Cu: 0.3@0.2%, Ni: 1.5@0.3%</td>
<td>Hornblende peridotite, hornblende gabbro and norite</td>
<td>Lenticular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xiangshan</td>
<td>10 × 3.5</td>
<td>Cu: 2@0.3%, Ni: 4@0.5%</td>
<td>Hornblende wehlite, pyroxenite and hornblende gabbro</td>
<td>Lotus root joint-shaped</td>
<td>Disseminated and massive</td>
<td>Volcanic rocks of Lower Carboniferous Wutongwozi Formation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tula’ergen Dyke swarm</td>
<td>Cu: @0.27%, Ni: 10@0.24–0.42%</td>
<td>Gabbro and hornblende–olivine gabbro</td>
<td>Tubular</td>
<td>Disseminated</td>
<td>Turbidite with volcanic rocks of Carboniferous Tudun Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
Table 1 (continued)

<table>
<thead>
<tr>
<th>Deposit name and geologic location and district/county</th>
<th>Ore district name and geologic location and district/county</th>
<th>Tectonic position</th>
<th>Ore type</th>
<th>Country rocks of intrusion</th>
<th>Data sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huangshan–Jing’erquan ore belt</td>
<td>Pobei ore district; E: 91°27’–91°50’; N: 40°32’–40°34’; Ruoping County, Bayingolin Prefecture</td>
<td>South</td>
<td>Massive and disseminated</td>
<td>Yue et al. (2005), Wu et al. (2005), Yang et al. (1994)</td>
<td>Party et al. (2003), Chai et al. (2006), Wu et al. (2005)</td>
</tr>
<tr>
<td>Erhongwa</td>
<td>Sheng er district; E: 93°51’–94°59’; N: 41°11’–41°26’; Hulun City, Hulun Prefecture</td>
<td>South</td>
<td>Massive and disseminated</td>
<td>Yue et al. (2005), Wu et al. (2005)</td>
<td>Wu et al. (2005)</td>
</tr>
<tr>
<td>Ruoqiang</td>
<td>Hongling ore district; E: 93°49’–93°59’; N: 42°01’–42°08’; Qiemo County, Kizil Prefecture</td>
<td>North</td>
<td>Massive and disseminated</td>
<td>Yue et al. (2005), Wu et al. (2005)</td>
<td>Wu et al. (2005)</td>
</tr>
<tr>
<td>Baishiquan</td>
<td>Baishiquan ore district; E: 94°44’–94°45’; N: 42°52’–42°56’; Qiemo County, Kizil Prefecture</td>
<td>North</td>
<td>Massive and disseminated</td>
<td>Yue et al. (2005), Wu et al. (2005)</td>
<td>Wu et al. (2005)</td>
</tr>
<tr>
<td>Poshi</td>
<td>Beishan rift; E: 94°35’; N: 41°38’; Ruojiang County, Bayingolin Prefecture</td>
<td>North</td>
<td>Massive and disseminated</td>
<td>Yue et al. (2005), Wu et al. (2005)</td>
<td>Wu et al. (2005)</td>
</tr>
<tr>
<td>Ruoqiang</td>
<td>Ruoqiang ore district; E: 94°35’–94°39’; N: 41°38’–41°42’; Ruojiang County, Bayingolin Prefecture</td>
<td>North</td>
<td>Massive and disseminated</td>
<td>Yue et al. (2005), Wu et al. (2005)</td>
<td>Wu et al. (2005)</td>
</tr>
</tbody>
</table>

The ores consist of sulphides, arsenides, tellurides, oxides, native metals, and metal compounds. The dominant ore minerals are pyrrhotite, chalcopyrite, and pentlandite, with subordinate magnetite, pyrite, violarite, and ilmenite and minor sphalerite, galena, alabandite, vallerite, bornite, and skutterudite, as well as noble metallic minerals such as native gold, native silver, electrum, hessite, Pt–Pd–melo- nitite, merenskyite, Ni–merenskyite, Ag–Bi–merenskyite, and sperrylite. A total of more than 50 ore minerals have been identified.

3.2. Huangshan–Jing’erquan ore belt

The Huangshan–Jing’erquan Cu–Ni sulphide ore belt is currently the largest known ore belt in Xinjiang, with the newly found Tula’ergen deposit in the east (San et al., 2003), the Hongling deposit in the west (Fig. 1), and the
Huangshan, Huangshandong, Huangshannan, Xiangshan, Erhongwa, and Tudun deposits in the central parts of the belt (Figs. 1 and 3). This ore belt extends more than 200 km along the Kanggurtag fault. The relatively differen-
tiated mafic–ultramafic intrusion bodies and related dykes are distributed discontinuously as E–W-elongated lenses. The intrusions have a small outcrop area, generally 2–6 km², and some intrusions probably represent magma conduits. The country rocks belong to the Carboniferous Gandun Formation and Middle Carboniferous Wutongwozi Group or Qi'e Group. The former consists predominantly of turbidites with small amounts of limestone and volcanic rocks, while the latter is a suite of basaltic–andesitic rocks, spilite–keratophyre, andesitic tuff with tuffaceous sandstone and sandy conglomerate.

3.2.1. Huangshandong deposit

The Huangshandong deposit, located 160 km southeast of the town of Hami, is the largest and the best representative in the Huangshan–Jing'erquan ore belt. The Huangshandong mafic–ultramafic intrusions intruded into the Middle Carboniferous Gandun Group turbidites. The Cu–Ni ore is hosted in a well-differentiated intrusion (Fig. 4a) with an outcrop area of 2.8 km². The Huangshandong complex is a multiple intrusion formed in three stages (Wang and Li, 1987). The first stage consists of gabbro, olivine gabbro, hornblende gabbro–diorite, ilmenite gab- bro, and diorite, with rhythmic layering and banding. The second stage is represented by dark-colored olivine gabbro–norite, to the west, north, and south of the first stage gabbro. The third stage is characterized by peridotite, and lherzolite–pyroxene–hornblende peridotite. The ore-bodies are from 120 to 1140 m long with thicknesses of 15.5–30.6 m (Wang et al., 1986). The modes of occurrence of the orebodies include: stratiform sulphide lenses in the middle and lower parts of the ultramafic rock (Fig. 4b), or along contact zones between the ultramafic and gabbro rocks; as steeply dipping en-echelon lenses in gabbro–norite, and as small copper-rich veins hosted by gabbro. The stratiform sulphide lenses, constitute economically viable ore. Three ore types are recognized: massive sulphide, densely disseminated, and sparsely disseminated sulphides. The massive sulphide ores are further subdivided into massive pyrrhotite–pentlandite–chalcopyrite ore, chalcopyrite–pentlandite ore and late-stage chalcopyrite veins. Chalcopyrite, pentlandite, and pyrrhotite are also the dominant ore minerals in the disseminated ores, and may be dispersed in hornblende lherzolite and hornblende gabbro. Other ore minerals are chromite, ilmenite, rutile, titanomagnetite, ulvite, chalcopentlandite, chalcopyrro-
titite, trigonal polydimite, nickelite, cubanite, cobaltite, siegenite, gersdorffite, nickeliferous stibnite, wehrlite, violarite, machinawite, vallerite, marcasite, sphalerite, and bornite.

3.2.2. Xiangshan Cu–Ni sulphide deposit

The Xiangshan complex (Fig. 5) is located to the northwest of the Huangshan complex, at the intersection between the Tudun-northern Jing’erquan ductile shear zone (F8 in Fig. 5) and the Huangshan ductile shear zone. The complex generally strikes /C2460/C176 and extends discontinuously for ~10 km, with widths of 100–800 m and an outcrop area of ~6 km². This intrusion is also interpreted as representing a magmatic conduit (Zhu et al., 1995). In plan view its shape resembles a lotus root. Local geologists have named the three lotus root shapes of the complex: Xiangshandong (eastern part), Xiangshanzhong (middle), and Xiangshanxi (western) intrusions (Wang et al., 2006). The intrusion consists of a hornblende gabbro envelope surrounding lenses of ultramafic rocks, which include peridotite, harzburgite, pyroxenite, and diorite. The Cu–Ni sulphide orebodies are mainly hosted by peridotite and harzburgite (Fig. 5) (Li et al., 1996; Sun et al., 1996). The conduit is within volcanic rocks of the Lower Carboniferous Wutongwozi Formation. The Xiangshan complex contains more than 10 major Cu–Ni sulphide orebodies, divided into three types (Sun et al., 1996): (1) orebodies that form beds and lenses at the bottoms of the peridotite, pyroxenite, and gabbro zones. These ores are of low-grade, with Cu + Ni < 1% and Cu/Ni < 1, and there is no distinct boundary between the orebodies and wall rocks. (2) Orebodies that form lenses and veins at the contact zones between gabbro-norite and hornblende peridotite and probably resulted from the injection of ore-bearing magma along zones of structural weakness. These orebodies and...
wall rocks have clear-cut boundaries and the ore grade is Cu + Ni > 1% with Cu/Ni > 1. (3) Orebodies that occur as veins in fractures of various rock types, which consist of sulphide veinlets or sulphide-bearing quartz veins or carbonate veins and are small in size, with Cu + Ni ≈ 1% and Cu/Ni > 1.

Ore minerals are pyrrhotite, pentlandite, chalcopyrite, millerite, violarite, pyrite, marcasite, cubanite, machinawite, sphalerite, galena, magnetite, chrome-spinel, gersdorffite, nickelite, wehrlite, and bismuthotellurite.

Zhang (2003) and Wang et al. (2006), recently, reported that, in addition to Cu and Ni sulphides, there is also Ti–V–Fe mineralization in the Xiangshanxi area. Using a TiO₂ cut-off grade of 5%, five orebodies were identified, ranging in size from 400 to 1000 m long and 1–15 m thick and extending to depths off 100–250 m. The TiO₂, Fe₄Tot, and V₂O₅ grades are 5–8.4%, 9–19%, and 0.1–0.3%, respectively. These Ti–V–Fe ores are vein-like and lenticular in a plan view and stratiform in section, and consist of disseminated ilmenite in a gabbro host within hornblende gabbro. The boundary between these orebodies and wall rocks is not well defined. The dominant ore minerals are ilmenite, titanomagnetite, and magnetite, with minor hematite, siderite, pyrite, chalcopyrite, pyrrhotite, ulvite, and celite (Wang et al., 2006). In the Xiangshanxi area, although Cu–Ni sulphide minerals and V–Ti magnetite coexist, their orebodies are separated, and even in the same stage two types of ore occur as separate bands in the gabbro body. The mechanism for the coexistence of Cu–Ni and Ti–V–Fe mineralization remains to be further studied.

### 3.2.3. Tula’er’gen deposit

Tula’er’gen is a Cu–Ni sulphide deposit discovered in 2002 during the follow-up of a geochemical anomaly by the 704 Geological Party of the Xinjiang Bureau of Nonferrous Metals Exploration (San et al., 2003). This deposit is at the easternmost edge of the Huangshan–Jin’erquan belt, about 200 km east of Hami (Fig. 1) (Xiao et al., 2005). The rocks in the district are predominantly turbidites of the Carboniferous Tudun Formation, whereas on the northern side of the Kanggurtag fault are volcanic rocks of the Devonian Dananhu Formation (Fig. 6a). In the southern part of the district a Late Paleozoic granitic pluton is present, whereas within the district itself, apart from mafic-ultramafic intrusions, there is a swarm of WNW- and E-W-trending granitic dykes and Late Paleozoic granodiorite, andesite porphyry, diorite porphyry, and granite porphyry intrusions. The mafic–ultramafic intrusions comprise hornblende peridotite, harzburgite, and hornblende gabbro. The Cu–Ni sulphide mineralization is at the margin of hornblende peridotite, near the contact between gabbro and hornblende peridotite. The mineralization has gradational boundaries with the wall rocks, and is concordant with the boundaries of the intrusion (Fig. 6b). The orebody is 740 m long and 5–12 m thick at the surface, but the thickness intersected by recent drilling reaches a maximum of 31 m. Nickel ore reserves are 100,000 tonnes, with average grades of 0.24–0.42% Ni, 0.27% Cu, and 0.024% Co (San et al., 2003). The mineralization is associated with alteration which includes mineral phases such as serpentine, talc, epidote, and tremolite, in addition to malachite, limonite, and jarosite at the surface. The dominant ore minerals are pyrrhotite, pentlandite, and chalcopyrite. This deposit is still in the exploration stage.

### 3.2.4. Hongling deposit

The Hongling Ni deposit is located at the western end of the Huangshan–Jing’erquan belt, south of the Kanggurtag
fault, about 120 km southwest of Hami (Fig. 1). The deposit was found and first evaluated by the Geophysical–Geochemical Survey Party of the former Xinjiang Bureau of Geology and Mineral Resources during ground follow-up of an airborne geophysical survey in 1991, followed in 1996 by a reconnaissance program. The rocks exposed in the district are mainly from the lowermost part of the Lower Carboniferous Yamansu Formation and include tuffaceous...
sandstone and pyroclastic rocks with lesser limestone. The main intrusions are ultramafic rocks, albite porphyry, and quartz porphyry dykes. The ultramafic rocks may be divided into Nos. 1 and 2 intrusions, which strike nearly E–W. In the west is the No. 1 intrusion, which is 180 m long and 30 m wide at the surface. In the east is the No. 2 intrusion, which is 400 m long and about 40–50 m wide. Both intrusions dip north steeply at 70–85°. The intrusions lie in a fracture zone, and there is serpentine and talc alteration. Cu–Ni mineralization is present at the base of No. 2 intrusion and is in fault contact with the footwall rocks. The mineralized zone is 200 m long and about 5–15 m wide at the surface. It extends as a sheet in a nearly E–W direction and is concordant with the host intrusion. The Ni grade is 0.4–0.8% and may reach a maximum of 0.77%; the Cu grade is 0.15–0.5% and may reach a maximum of 1.1% (Geological–Geophysical Survey Party of the Xinjiang Bureau of Geology and Mineral Resources, 1996). The mineralization consists of sulphides in vein-stockworks, disseminated, and massive sulphides. The dominant ore minerals are pyrrhotite, pyrite, magnetite, and azurite, and limonitization and jarositization are developed at the surface. The dominant gangue minerals are serpentine, talc, chloride, and carbonate. The deposit is still being evaluated.

3.3. Baishiquan ore district

The Baishiquan Cu–Ni sulphide ore district, situated about 170 km southeast of Hami (Fig. 1), is on the northern margin of the Central Tianshan block and on the southern side of the Shaquanzi fault. The latter is the boundary between the Jueluotage Late Paleozoic fold belt and Central Tianshan block. In this ore district there are the Baishiquan and Tianyu Cu–Ni sulphide deposits, and Tianxiang occurrences, all of which belong to conduit type magmatic mineralization. The three deposits (or occurrences) were recently discovered and preliminarily evaluated by the Xinjiang Bureau of Geology and Mineral Exploration and Development. These deposits are close to one another and share similar features. Chai et al. (2008) provide details of the geology and geochemistry of the Baishiquan deposit.

The Baishiquan deposit is the first Cu–Ni sulphide deposit found in the Central Tianshan. It was discovered in 2002 by the No. 6 Geological Party of the Xinjiang Bureau of Geology and Mineral Exploration and Development during a mineral reconnaissance survey. The area is underlain by metamorphic rocks of the Xingxingxia Formation of the Proterozoic Changchengian System and the Kawabulak Formation of the Jixianian System. The main structure in the ore district is the Shaquanzi deep fault and its subsidiary structures. There are 20 small mafic–ultramafic intrusions at the surface, with the largest being 0.8 km². The overall shape of the Baishiquan intrusions is quasi-elliptical with the long axis oriented NE–SW (Fig. 7). The Baishiquan intrusions are composed mainly of olivine pyroxenite, pyroxene peridotite, troctolite, hornblendite, diorite, norite, and gabbro. These were
emplaced in two stages. The first stage comprises 90% of the complex and consists of diorite, gabbro, and norite. The boundary of these rocks is indistinct, but zones of contact metamorphism mark the boundaries between diorite and wall rocks. The second stage forms dikes and irregular bodies of hornblendeite, peridotite, troctolite, and pyroxenite, which have well-defined boundaries. Both peridotite and olivine pyroxenite of the first stage are the host rocks to Cu–Ni ores Chai et al. (in this issue).

So far, 14 mineralized Cu–Ni sulphide zones have been found, of which five are exposed and 9 are buried (Wu et al., 2005). The exposed five zones are hosted in ultramafic intrusions and are mainly distributed at the margins of the diorite bodies in the central part of the ore district. The buried mineralized zones, are mainly distributed in the southern part of relatively large ultramafic bodies. Pyroxenite hosting mineralization has commonly undergone alteration with chlorite, sericite and magnetite mainly. Most orebodies occur as bands and veins. The dominant ore minerals are chalcopyrite, pentlandite, native copper, pyrite, and chalcocite. The gangue minerals are olivine, pyroxene, plagioclase, uralite, chlorite, and sericite. Ores are mainly sparsely disseminated. The average grades are Cu 0.22–0.44%, Ni 0.2–0.57%, and Co 0.01–0.03%.

3.4. Pobei area

The Pobei area is located in the Hercynian Beishan rift zone, northeast of Lop Nur and 300 km southwest of Hami (Fig. 1). In this area is a mafic–ultramafic complex comprising the Pobei gabbroic intrusion and the Poyi, Poshi ultramafic bodies, which were found in 1989 during the implementation of the Xinjiang’s 305 project. The mafic–ultramafic complex is located on the south side of the ENE-trending Baidiwa deep fault, encompassing an area of approximately 16 × 8 km (Gao, 1992; Li, 1994) (Fig. 8). In recent years, the No. 6 Geological Party of the Xinjiang Bureau of Geology and Mineral Exploration...
Fig. 9. Geological map of the mafic–ultramafic complex and ore zones (a) and cross-section showing distribution of sulphide lenses (b) in the Poshi Cu–Ni sulphide deposit (after the Xinjiang Bureau of Geology, Mineral Resources, Exploration and Development, 2005).
and Development discovered Cu–Ni mineralization in Poyi and in Poshi. At a later stage, Yang et al. (2003) found the nearby Luodong intrusion, further to the west and on the north side of the Baidiwa fault (Fig. 8), by using remote sensing image interpretation and field follow-up, which led to the discovery of Cu–Ni sulphide mineralization. In the following year, the No. 6 Geological Party resumed work in the area and exploration is still under way. The Pobei area is underlain by Proterozoic basement rocks, mainly schist and migmatites, Lower Carboniferous pyroclastic rocks of the Hongliuyuan Formation, and Middle Carboniferous tuff with marble of the Maotoushan Formation, and lavas of the Upper Carboniferous Shengliqian Formation (Yang et al., 2002).

The Poyi and Poshi ultramafic bodies, intruded the Pobei gabbroic rocks and Precambrian metamorphic rocks. The Poyi ultramafic body occurs in the western part of the larger gabbroic intrusion, has a trapezoidal shape in plan view, is up to 3.2 km long from east to west and \( \sim 1.08 \) km wide from north to south, with an outcrop area of \( 3.6 \) km\(^2\). It dips gently in the south at \( \sim 40^\circ \) and steeply in the northeast at \( 70^\circ \). The Poshi body has an elliptical shape and is located west of Poyi (Fig. 8), is \( \sim 2 \) km long from east to west and \( 1.6 \) km wide from north to south, covering an area of \( \sim 3.2 \) km\(^2\) (Fig. 9a). The two ultramafic bodies have distinct and similar zoning with gabbro to pyroxene peridotite to peridotite and dunite from the ore-bearing rock outward (Fig. 9a). To the west and on the other side of the Baidiwa fault is the 370 m long and 210 m wide Luodong complex (Fig. 10). The Luodong complex consists of gabbro, olivine gabbro, peridotite, harzburgite, and pyroxenite. The ultramafic rocks were emplaced during a later phase than the gabbro. N–S- and NW-trending diabase dykes were intruded last. Sulphide mineralization is present in the peridotite.

Although the surface geochemical Ni and Cu anomalies over the Poyi ultramafic body are pronounced, most Ni is contained in the olivine (Dai, 2005) and no sulphide miner-
alization has yet been identified. On the other hand, sulphide zones have been identified in the Poshi ultramafic body. Exploration drilling has outlined four outcropping sulphide zones and five below the surface. The outcropping mineralization has a semi-circular shape (Fig. 9a). The sulphide mineralization forms lenses, which more or less follow the shape of the lithological zones (Fig. 9b) and dip toward the center of the complex at 22–80°. The styles of the mineralization are net-textured, and injection veins of sulphides. Grades range from 0.3% to 0.6% Ni with maximum values of up to 0.96%. The Cu and Co contents in the ores are low, generally below the cut-off grade, but locally where the Ni content ≥0.6%, the Cu and Co grades rise above the cut-off grades. The Ni resources in the Poshi complex are 147,000 tonnes, but further exploration is ongoing. The dominant ore minerals are pentlandite, chalcopyrite, pyrrhotite, magnetite, and chrome-spinel with very small amounts of vallerite, bornite, and millerite. The dominant gangue minerals include olivine, augite, enstatite, hornblende, phlogopite, and plagioclase. The ore minerals have euhedral-subhedral granular textures and locally net-textured, forming mainly sparse disseminations, locally densely disseminated and massive.

4. Discussion and conclusions

4.1. Main characteristics of Cu–Ni sulphide mineralization in the Chinese Tianshan and Altay orogens

Zhou et al. (2002) pointed out that the most important features that can explain the origin of Cu–Ni sulphide accumulations are the ore texture (massive vs. disseminated) and ore distribution (stratiform vs. stratabound), which are affected by sulphide saturation and intrusion dynamics (cumulate magma conduit vs. differentiated sill). Copper–Ni sulphide deposits in the Jueluotage (East Tianshan) mainly contain low-grade disseminated ore, while high-grade massive ore only occurs in Kalatongke and Tianyu. However, both of these types reflect the injection of ore-bearing magma in a late mineralization stage. The orebodies 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 the Chinese Tianshan and Altay orogens, Cu–Ni sulphide deposits belong to one of two types: net-textured and conduit. The former is represented by the Kalatongke, Huangshan, Huangshandong, and Poshi deposits, while 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 undergoes fractional crystallization at depth before it is 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 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 sulphide deposits of the Chinese Tianshan and Altay orogens, are all comparatively small, and even the Kalatongke, Huangshan, Huangshandong, and Poshi 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 (Figs. 2b and 4b). 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.

The Cu–Ni sulphide deposits of the Chinese Tianshan and Altay orogens are predominantly characterized by sparsely disseminated sulphides and are generally of low-grade. Li et al. (2003a) 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; Li et al., 2006; Han et al., 2006) and Sm/Nd isotope studies (Zhou et al., 2004) studies suggest that the magma chamber was contaminated by crustal materials. The crustal materials incorporated in the magmas were mostly turbidite, clastic rocks, carbonate rocks, 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. Tectonic environment and mineral deposit model

There are a number of classification schemes of mafic Cu–Ni (PGE) sulphide deposits, which are all related to the characteristics of mafic–ultramafic rocks and their geological environment (Chai et al., 2005). Naldrett (1989, 1997) distinguished four deposit types: (1) greenstone belt, (2) continental-margin rift, (3) cratonic, and (4) active orogenic belt. The last type may be subdivided into
deposits related to synorogenic intrusive rocks and deposit related to the Alaskan type complexes. The Alaskan type mafic–ultramafic complexes are concentrically zoned intrusions that may have been emplaced in an island-arc setting and/or possibly in a back-arc setting. The possibility that some of the Tian Shan and Altay mafic–ultramafic intrusions have similar features to Alaskan type complexes is discussed by Pirajno et al. (2008). Tang and Li (1995) classified magmatic ore deposits into: (1) Proterozoic deposits related to meteorite impact structures; (2) post-Proterozoic deposits in small intrusions emplaced in continental rifts, (3) Phanerozoic deposits related to continental flood basalt, (4) deposits related to komatiite fields in an Archean greenstone belt, and (5) Paleoproterozoic deposits related to continental layered intrusions. Pirajno (2000) emphasized the close relationship between mantle plumes and magmatic Cu–Ni sulphide. Typical examples are the world-class Cu–Ni sulphide deposits of Noril’sk in Russia and the smaller deposits of Jinbaoshan, Yangliuping, and Limahe, and the Panzhihua superlarge V–Ti–magnetite deposits related to the Emeishan mantle plume in SW China. The Cu–Ni sulphide deposits of the Chinese Tian Shan and Altay are in orogenic belts; however, they are neither the product of orogenic processes nor of active continental margins, but are associated with post-collision tectono-thermal events.

Recently Re–Os dating of Cu–Ni sulphide ores from the Kalatongke, Huangshandong, and Xiangshan deposits (Table 2) yielded ages of 298–282 Ma (Mao et al., 2002; Zhang et al., 2005; Li et al., 2006c; Zhang et al., 2008); zircon SHRIMP U–Pb dating of mineralized intrusions (including Kalatongke, Huangshandong, Huangshan, Baishiquan, Poshi, and Poyi) yielded ages of 285–270 Ma (Han et al., 2004; Zhou et al., 2004; Wu et al., 2005; Li et al., 2006a; Jiang et al., 2006). These age data indicate that these Cu–Ni sulphide ore districts are associated with the same geodynamic event. In addition, and importantly, they overprint deformation fabrics in the Altay, Junggar, and Jueluotage orogenic belts, Central Tianshan block, and Beishan Hercynian rift. In fact, this ore-forming event, occurring in the period from the Late Carboniferous–Early Permian, not only generated magmatic Cu–Ni sulphide deposits but also hydrothermal Fe, Fe–Cu, and Pb–Zn–Ag deposits related to granite activity, shear zone-hosted orogenic Au deposits, and epithermal Au deposits (Li et al., 1998; Mao et al., 2005). Therefore, we conclude that this is a large-scale ore-forming event not only in the Chinese Tianshan and Altay, (Xinjiang Province), but also in the adjacent Central Asian Tianshan and Altay. For example, world-class gold metallocenic belt also formed in this same period of time in the South Tianshan (Yakubchuk et al., 2001; Mao et al., 2004).

There are contrasting views as to the geodynamic evolution, the role of the closure of oceanic basins, accretionary tectonics and the suturing of colliding terranes in the Central Asia Orogenic Belt of northern Xinjiang and Central Asia (Ma et al., 1990; Xiao and Tang, 1991; Xiao et al., 2004; He et al., 1994; Li et al., 2003b). Most researchers prefer the view that a Paleo-Thetys Ocean closed during the Mid-Late Carboniferous to Early Permian. The timing of the opening and closing of this paleo-ocean in northern Xinjiang and its adjacent regions differed from place to place (Li et al., 2006b). The study of Xia et al. (2004) indicates that the extensive 345–325 Ma volcanism affected an area of 1.5 × 10⁶ km² in the Tianshan formed in a rift environment and was probably related to mantle plume activity. In recent years there has been a growing interest in post-collisional tectonic processes in Xinjiang and its adjacent regions. Wang and Xu (2006) suggested that the post-collision in northern Xinjiang experienced two cycles, one

<table>
<thead>
<tr>
<th>Name of deposit or complex</th>
<th>Tectonic position</th>
<th>Analytic method and rock/ore</th>
<th>Age (Ma)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalatongke deposit</td>
<td>Altay orogenic belt</td>
<td>Re–Os isochron; sulphide ore, No. 1 orebody, No. 2 orebody SHIRMP zircon U–Pb; norite</td>
<td>282.5 ± 4.8, 282.5 ± 4.8</td>
<td>Zhang et al. (2005)</td>
</tr>
<tr>
<td>Kalatongke No. 1 intrusion</td>
<td>Altay orogenic belt</td>
<td>SHIRMP zircon U–Pb; norite</td>
<td>287 ± 5</td>
<td>Han et al. (2004)</td>
</tr>
<tr>
<td>Huangshandong deposit</td>
<td>Jueluotage orogenic belt</td>
<td>Re–Os isochron; sulphide ore</td>
<td>282 ± 20</td>
<td>Mao et al. (2002)</td>
</tr>
<tr>
<td>Huangshandong complex</td>
<td>Jueluotage orogenic belt</td>
<td>SHIRMP zircon U–Pb; biotite–olivine norite</td>
<td>274 ± 3</td>
<td>Han et al. (2004)</td>
</tr>
<tr>
<td>Xiangshan deposit</td>
<td>Jueluotage orogenic belt</td>
<td>Re–Os isochron; sulphide ore</td>
<td>298 ± 7.1</td>
<td>Li et al. (2006c)</td>
</tr>
<tr>
<td>Xiangshan intrusion</td>
<td>Jueluotage orogenic belt</td>
<td>SHIRMP zircon U–Pb</td>
<td>285 ± 1.2</td>
<td>Qin et al. (2003)</td>
</tr>
<tr>
<td>Huangshan intrusion</td>
<td>Jueluotage orogenic belt</td>
<td>SHIRMP zircon U–Pb; diorite</td>
<td>269 ± 2</td>
<td>Zhou et al. (2004)</td>
</tr>
<tr>
<td>Baishiquan complex</td>
<td>Central Tianshan block</td>
<td>SHIRMP zircon U–Pb; Quartz diorite, Gabbro diorite, Gabbro</td>
<td>285 ± 10, 284 ± 9, 284 ± 8</td>
<td>Wu et al. (2005)</td>
</tr>
<tr>
<td>Poyi complex</td>
<td>Beishan Paleozoic rift</td>
<td>SHIRMP zircon U–Pb; gabbro</td>
<td>278 ± 2</td>
<td>Li et al. (2006a)</td>
</tr>
<tr>
<td>Poshi complex</td>
<td>Beishan Paleozoic rift</td>
<td>SHIRMP zircon U–Pb; hornblende gabbro</td>
<td>274 ± 4</td>
<td>Jiang et al. (2006)</td>
</tr>
</tbody>
</table>
of the Early Carboniferous extension–Late Carboniferous compression and uplift and one of Early Permian extension–Late Permian compression and uplift. The earlier extension was probably associated with lithospheric delamination, following the main accretion/collision event, whereas the second extension was probably related to the impingement of a mantle–plume onto a more rigid continental crust. Voluminous mafic volcanic rocks of the Early Carboniferous extension stage are present in northern Xinjiang, whereas for the Early Permian extension stage only sporadic volcanic rocks remain, probably due to erosion, although thick sequences of basaltic rocks are locally present. For example, the thickness of the Early Permian volcanic rocks in the Santanghu basin between the Tianshan and Altay are >1000 m (Hao et al., 2006), and Yang et al. (2006) discovered Permian (272 ± 4 Ma) andesite–rhyolite in middle part of the North Tianshan during regional geological mapping. Moreover, Chen et al. (1997) confirmed 200,000 km² of flood basalt based on the data of outcrop distribution, drilling wells and aeromagnetic anomalies in Tarim basin. Xing et al. (2004) recognized the basalt in the periphery of the Tu–Ha basin. As stated above, large-scale mineralization occurred during the Early Permian post-collisional extension event, accompanied by A-type granite intrusions with $\varepsilon_{Nd} = +6.7$ to $+9.3$ and that produced vertical crustal accretion (Jahn et al., 2000, 2004; see also Pirajno et al., 2008). For both large-scale mineralization and crustal vertical accretion, large amounts of heat energy are required. The contemporaneous mafic and felsic magmatism was the consequence of a regional geodynamic event, which may have been part of the mantle plume activity that affected the whole of Central Asia (Dobretsov and Buslov, 2005; Borisenko et al., 2006; Pirajno et al., 1997). The E–W-trending mafic–ultramafic bodies that are distributed along several regional faults and their associated Cu–Ni sulphide deposits are likely to have been the roots or feeder conduits of the overlying lavas. Following the closing of the Neo-Tethys ocean, the collision of India with Asia and the uplift of the Tibetan Plateau, the Tianshan–Altay were reactivated and significantly uplifted in the Cenozoic. This reactivation and uplift caused the erosion of the Early Permian volcanic rocks, however their feeders and magma chambers, which form the mafic–ultramafic complexes are still preserved. The Cu–Ni sulphide mineralization is contained in these feeders and magmatic chambers (Fig. 11).

4.3. Reflections on further mineral exploration

With the rising prices of mineral commodities, more prospecting and exploration are being carried out in China than ever before. In the past few years several new Cu–Ni sulphide deposits and occurrences have been discovered in Xinjiang and several low-grade deposits have begun production. More attention is now directed to where and how more deposits, especially large and superlarge deposits can be discovered.

Two main types of Cu–Ni sulphide deposits are distinguished: (1) deposits in large layered complexes such as the Bushveld Igneous Complex of South Africa and the Sudbury Igneous Complex of Canada, although the latter is related to a meteorite impact and (2) differentiated sill and conduit type deposits related to small intrusive complexes. In the eastern part of northern Xinjiang, the Cu–Ni deposits belong to second type. Therefore, we suggest that mineral exploration should focus along the regional deep faults both in Xinjiang and the Central Asia region in order to identify small exposed mafic–ultramafic complexes and associated diabase dykes swarms. Most parts of Xinjiang have good exposure and mafic–ultramafic complexes related to Cu–Ni sulphide deposits usually exhibit strong alteration, such as serpentinization, uralitization, chloritization, and tremolitization. In such conditions, the use of remote sensing techniques to recognize hydrated minerals and/or copper-bearing minerals can be very effective. We suggest that attention be given to areas with black shales and evaporites rocks, because these may have provided the necessary sulphur contamination to the mafic–ultramafic magmas.

Acknowledgments

This research was jointly supported by National Natural Science Foundation of China (No. 40402012), Geological
Survey Project (Nos. 1212010561506, 1212010633911) and State Key Laboratory of Geological Processes and Mineral Resources (No. GPMR200627). We are grateful to the Xinjiang Bureau of Geology and Mineral Exploration and Development and its affiliated Nos. 6 and 4 geological parties and related leaders and staff members of the State 305 Project for their great logistical and moral support. We have greatly benefited from the exchange of ideas with our colleagues such as Li Jinyi, Liu Dequan, and Qin Kezhang. Franco Pirajno publishes with the permission of the Executive Director of the Geological Survey of Western Australia.

References


