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# Late Paleozoic base and precious metal deposits, East Tianshan, Xinjiang, China: Characteristics and geodynamic setting

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*The East Tianshan is a remote Gobi area located in eastern Xinjiang, northwestern China. In the past several years, a number of gold, porphyry copper, and Fe(-Cu) and Cu-Ag-Pb-Zn skarn deposits have been discovered there and are attracting exploration interest. The East Tianshan is located between the Junggar block to the north and early Paleozoic terranes of the Middle Tianshan to the south. It is part of a Hercynian orogen with three distinct E-W-trending tectonic belts: the Devonian-Early Carboniferous Tousuquan-Dananhu island arc on the north and the Carboniferous Aqishan-Yamansu rift basin to the south, which are separated by rocks of the Kanggurtag shear zone. The porphyry deposits, dated at 322 Ma, are related to the late evolutionary stages of a subduction-related oceanic or continental margin arc. In contrast, the skarn, gold, and magmatic Ni-Cu deposits are associated with post-collisional tectonics at ca. 290–270 Ma. These Late Carboniferous - Early Permian deposits are associated with large-scale emplacement and eruption of magmas possibly caused by lithosphere delamination and rifting within the East Tianshan.*

## Introduction

During the 1970s, exploration by the Xinjiang Bureau of Geology and Mineral Resources (XJBGMR) in the East Tianshan identified at least ten new iron skarn deposits. In the 1980s, the XJBGMR subsequently discovered and evaluated the Huangshan, Huangshandong, Xiangshan, and other magmatic Cu-Ni sulfide deposits, as well as a few small copper-molybdenum porphyry occurrences. During the last decade, follow-up work on geochemical anomalies by the XJBGMR led to the discovery of a number of new gold and copper deposits.

Ongoing scientific research, particularly by the No. 305 State Project, has attracted many geologists from the other parts of China to work jointly with local geologists of the XJBGMR. As a result, a series of new scientific contributions on many aspects of Xinjiang

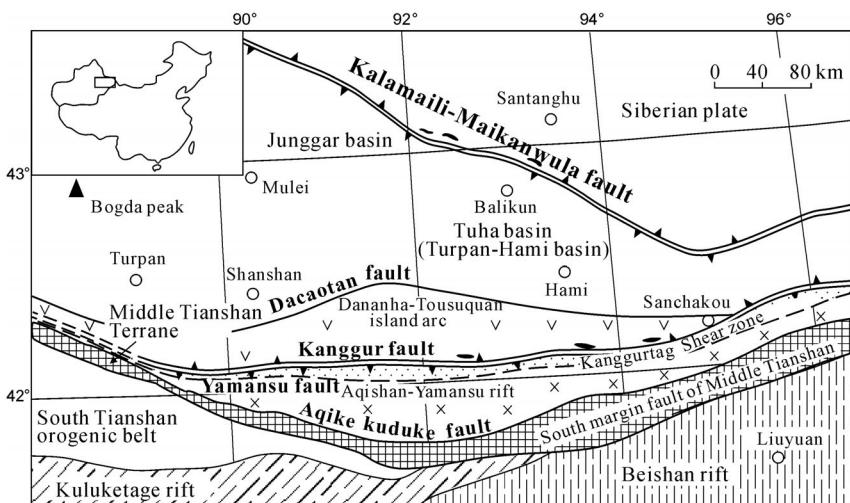
geology have been published. These include studies mainly in the Chinese literature on:

1. the tectonic evolution of the East Tianshan (Zhang and Wu, 1985; Yan, 1985; Zhang, 1990; Ma et al., 1993, 1997; Yang, 1996; Yang et al., 1999);
2. relationships between tectonic evolution and metallogenic processes (Ji et al., 1994a, 1994b; Yang et al., 1997, 1998; Zhang et al., 1998a, 1999a; Zhang and Ji, 1999; Mao et al., 2002a);
3. isotopic dating of rocks and mineral deposits (Ji et al., 1996, 1999; Zhang and Ji, 1997; Li et al., 1998; Zhang et al., 1999a; Rui et al., 2002b; Mao et al., 2003);
4. petrochemistry and ore deposit geochemistry (Zhang et al., 1998b, 1999b, 2000; Zhang and Ji, 1999);
5. regional metallogeny (Yang et al., 1998; Zhang et al., 1998c; Xu, 1998; Chen, 1999; Feng et al., 1999);
6. structural controls on mineralization (Ma et al., 1998; Zhang et al., 1998a); and
7. ore-forming processes (Ji et al., 1994b, 1997; Rui et al., 2002a; Mao et al., 2002a; and Han et al., 2002). Contributions by Pirajno et al. (1997) and Rui et al. (2002c) initially introduced the gold deposits of Xinjiang to the international community.

In addition, Zhang et al. (2002, 2003, 2004) and Wang et al. (2003) published detailed English-language descriptions of the Kanggur gold deposit and belt, which were translated from the original Chinese publications. Synthesizing the recent findings from many of the above workers, we summarize the distribution and defining characteristics of base and precious metal mineral deposits in the East Tianshan region of Xinjiang, and suggest a new metallogenic model.

## Geological setting

The East Tianshan is herein defined as that part of the Tianshan mountain range located east of the Urumqi-Kuerle highway. It is bounded (1) to the north by the Turpan-Hami (shorter form: Tuha) basin, which is a part of the Junggar block, (2) to the south by the Aqikekuduke fault, which separates this northern belt of the Tianshan from the so-called Middle Tianshan (or Central Tianshan), and (3) to the east by the late Paleozoic Beishan rift (Figure 1). This area, which covers more than 600,000 km<sup>2</sup>, is also called the Jueluotage orogenic belt (Ji et al., 2000; Chen, 1999). It is a region with an abundance of metallic mineral deposits and, as a result, has become one of Xinjiang's most important areas for mineral exploration. Although Li et al. (2002, 2003) named all parts of the mountain range east of the Urumqi-Kuerle highway, and bounded by the southern margin of Tuha basin and the northern margin of Tarim



**Figure 1** Map showing location of the East Tianshan and adjacent tectonic units (modified from Ma et al., 1993). The East Tianshan is defined as that region north of the Middle Tianshan and south of the Tuha basin, and consists of the Tousuquan-Dananhu island arc, Kanggurtag suture zone, and Aqishan-Yamansu rift basin, which are separated by several large regional faults.

basin, as the East Tianshan, herein we refer to East Tianshan (or Juluotage orogenic belt) as only the part of this region to the north of the Middle Tianshan.

Geological surveys at scales of 1:200,000 and 1:50,000, and 1:200,000 geochemical surveys, have demonstrated there are three main units, or belts, in the East Tianshan. These include the Silurian to Carboniferous Tousuquan-Dananhu oceanic arc in the north, the Carboniferous Aqishan-Yamansu rift belt in the south, and the Kanggurtag (or Quigemengtashi-Huangshan) shear zone between these rocks (Figure 2).

The Kanggurtag shear zone (or Quigemengtashi-Huangshan shear zone of Zhang et al., 2004) is an important regional structure that separates terranes of the Junggar block from those of the Tarim block. The ocean that separated these terranes, partly marked by the rocks of this broad fault zone, closed during the Late Carboniferous (Zhou et al., 1994; Jiang et al., 1997; Ji et al., 2000) at about 310–300 Ma (Li et al., 2002). The shear zone is a boundary between the cold-water Boreal fauna and Angara flora to the north, and the Palaeo-Tethyan realm of the warm-water Australian fauna and Cathaysian flora to the south (Zhang L.C., oral commun., 2001). The Carboniferous Gandun Formation, within the Kanggurtag shear zone, is a 6 to 7 km wide belt of fine-grain sandstone and carbonaceous argillites. This rock package is considered to represent an abyssal facies or a

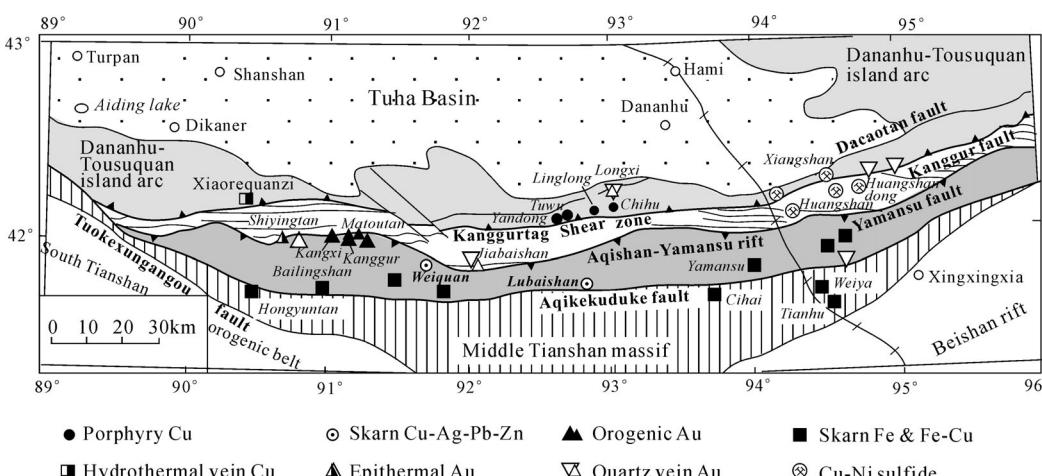
restricted oceanic basin that was part of the closing Paleo-Asian or East Turkey Ocean (Xiao et al., 1992).

The Tousuquan-Dananhu arc is located between the Kanggurtag fault and the Dacaotan fault that forms the southern margin of the Tuha basin (Figure 1). The base of the arc sequence is represented by basaltic to andesitic volcanic rocks, with locally overlying Lower Carboniferous carbonates and calcareous mudstones. This suite is known as the Qi'eshan Formation east of the Qiketai-Kanggurtag road and as the Xiaorequanzi Formation west of the road. Rui et al. (2002b) determined the ages of the volcanic rocks of the Qi'eshan Formation to be in a range of 443±26 to 361±8 Ma using the single-grain U-Pb zircon method. Overlying the arc rocks are (1) Late Carboniferous greywacke and tuff, intercalated with carbonates, of the Tuwu Formation; (2) local occurrences of rift-related Permian basalt, tuff, and volcanic breccia of the Aqikeblak Formation; and (3) Jurassic terrestrial clastic rocks of the Xishanyao Formation.

The Aqishan-Yamansu rift belt lies between the Aqishan-Yamansu fault (or Kushui fault), which marks the southern boundary of the Kanggurtag shear zone (or fault zone), and the Aqikekuduke fault. The belt comprises a 5 km thick section of Lower Carboniferous Yamansu Formation bimodal volcanic rocks, middle Carboniferous flysch of the Shaquanzi Formation, and Upper Carboniferous clastic rocks, andesitic tuff, and intercalated carbonate of the Tugutublak Formation. Overlying Permian marine and terrestrial clastic rocks are intercalated with bimodal volcanic rocks and carbonates. Due to the Lower Carboniferous bimodal volcanic rocks and exceptional thickness, Li et al. (2002) suggested that they represent a rift zone, rather than an island arc as was inferred by Ma et al. (1993, 1997), Liu et al. (1996), and Zhang et al. (2003, 2004).

Large volumes of Late Carboniferous and Early Permian granitic rocks outcrop in the East Tianshan. The granitoids comprise quartz diorite, granodiorite, monzonite, and K-feldspar granite. Their ages, as dated by single zircon U-Pb and, less commonly, by Rb-Sr isochron methods, mainly range from 290 Ma to 261 Ma (Li et al., 2002). The K-feldspar granites are the youngest intrusive suite. Recent isotopic dating indicates that additional intrusions in the Tousuquan-Dananhu arc probably formed in the Early Carboniferous, and perhaps as early as the Late Devonian (Rui et al., 2002a; Qin, 2000). Using SHRIMP U-Pb zircon analyses, Liu et al. (2003) obtained dates of 333±2 Ma and 334±2 Ma for the monzonite and diorite porphyry hosting the Tuwu and Yandong porphyry copper deposits.

A series of Late Carboniferous to Early Permian mafic and ultramafic stocks intruded along the Kanggurtag shear zone for a length of 270 km. Some of the intrusions host the magmatic Cu-Ni sulfide deposits that are discussed below (Wang et al., 1987; Liu et al., 1996).



**Figure 2** Map showing the tectonic units and distribution of major metallic mineral deposits in the East Tianshan (compiled based on Yang et al., 1997; Mao et al., 2002a; Li et al. 2002 and Rui et al., 2002b).

## Metallogenetic associations

Mineral deposits in the East Tianshan may be either precious metal or base metal dominant (Figure 2). The base metal deposits are divisible into four deposit types: 1) Early-Middle Carboniferous por-

phyry copper deposits; 2) Late Carboniferous to Early Permian Fe-(Cu) skarn deposits and related polymetallic vein deposits; 3) Late Carboniferous to Early Permian copper-rich vein deposits; and 4) Late Carboniferous to Early Permian mafic-ultramafic rock-related Cu-Ni sulfide deposits. Gold mineralization is not associated with the base metal-rich mineralization, but occurs in other gold-dominant deposits. The main characteristics of the different deposit types are summarized in Tables 1 and 2.

## Porphyry copper deposits

The economically most significant recent discoveries in East Tianshan are the buried Tuwu and Yandong porphyry copper deposits. The Tuwu, Yandong, and other associated porphyry occurrences, such as Chihu, Linglong and Sanchakou, form the Tuwu copper belt. Preliminary estimates indicate 4.7 million tons of contained copper metal, with an average grade of 0.67 % Cu. Tuwu and Yandong are 8 km apart, are relatively unexposed (i.e., only a few hundred square meters of exposed igneous rock above the Gobi), and drilling between them has confirmed additional mineralization. The two main porphyritic phases are monzonite and diorite. Most copper mineralization is in the monzonitic porphyry, which has a peralkaline line chemistry with a porphyritic texture and massive structure (Liu et al., 2003). No significant mineralization is present in the volcanic country rocks of the Qi'eshan Formation.

The mineralized bodies have elongated geometries (Figure 3a) that parallel their monzonitic porphyry host stock. The Tuwu mineralized zone is narrow at the surface (~ 40m), but widens to 136 m with depth (Figure 3b). The Yandong mineralization is similar to that at Tuwu, as it also thickens with depth. Drilling has identified mineralization to depths of 600–700 m, remaining open at depth. Hypogene veinlets and disseminations are dominated by chalcopyrite and pyrite, with local bornite, covellite, and molybdenite. The gangue minerals are dominated by quartz and sericite, with minor chlorite, kaolinite, epidote, K-feldspar, biotite, and carbonate. Wang et al. (2001a,b) and Liu et al. (2001) have described an inner potassic (biotite) alteration zone, grading outwards to a phyllitic (quartz-sericite) zone and to distal zones of propylitic and kaolinite alteration. Near-surface supergene mineralization is dominated by malachite, but not in significant enough amounts to constitute an oxide orebody.

The Linglong and Chihu deposits, located 15 km and 30 km east of Tuwu, respectively, and the Sanchakou deposit, located in the easternmost East Tianshan, are also part of the same porphyry copper belt. Their features appear similar to those of the Tuwu and the Yandong deposits, but they have not been studied in detail.

The mineralizing fluids for the porphyry copper deposits in the belt have been described by Rui et al (2002a). Primary fluid inclusion homogenization temperatures are stated to range from 150 to 280°C, which, if correct, are extremely low for such a deposit type. Although in some cases the fluid salinities are high, reaching 25–40 wt% NaCl equiv., most are moderate, in the range of 9–12 wt% NaCl equiv. (Ji et al., 2000; Rui et al., 2002a). The  $\delta^{34}\text{S}$  values of pyrite and chalcopyrite in the Sanchakou copper deposit are -2 to +3 per mil, whereas those of the Tuwu and Yandong copper deposits are +0.2 to +8.0 per mil (Rui et al., 2002a). The source for the sulfur in the hydrothermal fluids is equivocal. The  $\delta\text{D}$  and  $\delta^{18}\text{O}$  fluid values are -69 to -44 per mil and +0.3 to +0.8 per mil respectively, indicating that the magmatic fluids mixed with meteoric water.

A Re-Os isochron of molybdenite from the Tuwu porphyry copper deposit yielded an age of  $322.7 \pm 2.3$  Ma (Du et al., 2001; Rui et al., 2002b). Recent SHRIMP U-Pb zircon dating of the monzonite porphyry host rocks to mineralization at the Tuwu and the Yandong yielded ages of  $333 \pm 2$  Ma and  $334 \pm 2$  Ma, respectively (Liu et al., 2003). These data indicate that the diorite porphyry and associated copper mineralization are early Carboniferous in age, but because ten million years separated these events, it is possible that the monzonite porphyry is not the causative intrusion.

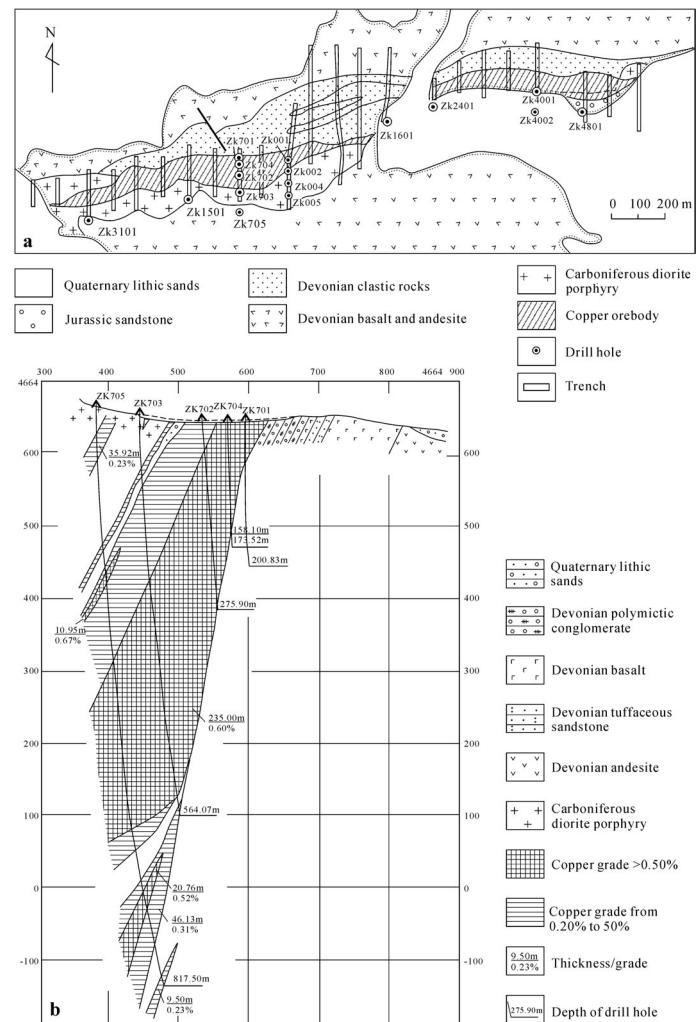


Figure 3 Tuwu porphyry copper deposit: (a) plan view and (b) drilling intersections showing that the width of the orebody increases downward.

## Fe(-Cu) and Cu-Ag-Pb-Zn skarn deposits

Skarn deposits are common in the East Tianshan. They can be divided into Fe(-Cu) and Cu-Ag-Pb-Zn types. The former have been recognized since the 1970s, but some researchers suggest that they are oxidized VHMS-type deposits because the mineralization is hosted in Lower Carboniferous volcanic rocks (e.g. Liu et al., 1996; Qin et al., 2002). We disagree with this hypothesis because, as described below, the features of the deposits are clearly consistent with a skarn model. The Cu-Ag-Pb-Zn skarn types have been recognized during more recent exploration.

### Fe(-Cu) skarn deposits

Dozens of iron-rich magnetite skarn deposits, including Yamansu, Bailingshan, Heijianshan, Chilongfeng, Hongyuntan, Aqishan, Heilongfeng, Shuangfengshan, and Shaquanzi, occur within a 400 km long by 15 km wide corridor between the Aqishan-Yamansu and Aqikekuduke faults. Several similar iron-rich deposits, including the large Cihai deposit, occur along the northern margin of the Middle Tianshan. Most skarn deposits in the East Tianshan are small, although the Yamansu and Heijianshan deposits have been mined for many years. Yamansu contains a reserve of 32 Mt with an average grade of 51% Fe, and 20,000 t with a mean of

0.06% Cu (Table 1). During the mining process, both reserves of iron and copper were increased, but exact amounts have not been reported. The skarns are hosted in Lower Carboniferous volcanic rocks, which are intercalated with limestone of the Yamansu Formation. They developed either near the contacts of late Paleozoic granite plutons (e.g. Heifengshan and Shaquanzi) and limestones, or at the contacts between limestones and volcanic rocks that lack exposures of intrusive rock (e.g. Yamansu). Some iron deposits have associated copper mineralization, such as in the Saquanzi and the Heijianshan skarn deposits. Magnetite, the main iron ore mineral, formed early during skarn paragenesis, whereas chalcopyrite and pyrite developed later and typically replace magnetite. The magnetite also occurs as quartz-calcite-sulphide veins that cut the skarn and iron orebodies. The skarn minerals consists of grossular-andradite, diopside-hedenbergite, vesuvianite, and wollastonite. This prograde skarn assemblage is locally replaced by actinolite, chlorite, epidote, sericite, and calcite during retrograde alteration.

The Yamansu deposit is the largest and is hosted in the Lower Carboniferous submarine bimodal volcanic and clastic rocks of the Yamansu Formation, mainly consisting of andesitic tuff, andesitic tuff breccia, limestone, potash-keratophyre, potash-porphyritic fel-

site, and felsite in the vicinity of iron-rich mineralization. The skarns developed between limestone, which may be intercalated with andesitic breccia, tuff, agglomerate, basaltic andesite, and andesitic tuff, and rhyolitic tuff (Figure 4). A sub-volcanic, pyroxene-bearing diorite porphyry is present 500 m southwest of the orebodies in the Yamansu deposit area, where it is cut by a northerly-trending fault (Figure 4). Although other granitoids are not exposed at the surface, a gravity survey indicates that an additional buried pluton may lie beneath the deposit area (Xinjiang Bureau of Geology, 1966, 1972). Ore minerals at Yamansu are dominated by magnetite, hematite, pyrite, and chalcopyrite, with garnet, diopside, epidote, and albite as the dominant gangue minerals. The ore textures are disseminated, massive, and banded.

Studies on the Yamansu iron skarn deposit indicate that formation temperatures were 330–340°C for magnetite and 150–220°C for pyrite (Liu et al., 1996), and ore fluid salinities were 2.7 to 12.9 wt% NaCl equiv. Stable isotope values of magnetite give a mineral  $\delta^{18}\text{O}$  range from 5.3‰ to 12.8‰, and  $\delta^{34}\text{S}$  for disseminated pyrite is between -22‰ and -25‰ (Liu et al., 1996), implying that the ore fluids and sulfur may be derived from the upper crust. This suite of Fe-(Cu) deposits have a range of K-Ar whole rock dates between 360 and 190 Ma (Liu et al., 1996). A Rb-Sr isochron age of 286 Ma for ore-

**Table 1 Major porphyry and gold deposits in East Tianshan**

Names	Types	Metallic association	Mineral assemblages	Ore structures	Host rocks	Contained metal /grade	References
Tuwu (+Yandong)	Porphyry	Cu-Mo	Chalcopyrite, pyrite, chalcocite, molybdenite, quartz, chlorite, sericite, epidote	Disseminated, veinlet	Carboniferous diorite porphyry	4.7 Mt/0.5–0.7% (Cu)	Rui et al., 2001; Qin et al., 2002, 2003
Xiaorequanzi	Hydrothermal vein and replacement	Cu-Zn (Ag-Au)	Chalcopyrite, cubanite, cobaltite, galena, sphalerite, sericite, quartz, calcite, native carbon, chlorite	Massive, banded, disseminated	Up. Carboniferous andesite and clastic rocks	250,000t/0.43–4.4% (Cu)	Han et al., 2002; Mao et al., 2002a
Yamansu	Skarn	Fe-(Cu)	Magnetite, hematite, pyrite, chalcopyrite, chalcocite, epidote, andradite, diopside, albite, vesuvianite, amphibole, chlorite, carbonate	Massive, banded and disseminated	L. Carboniferous volcanic rocks	32 Mt /51% Fe, 20,000 t/0.06% Cu	Xinjiang Bureau of Geology, 1966, 1972
Weiquan	Skarn	Ag-Cu-Pb-Zn	Pyrite, galena, sphalerite, molybdenite, chalcopyrite, andradite, diopside, vesuvianite, epidote, actinolite, chlorite, fluorite	Massive, disseminated, vein-like	Mid-Carboniferous pyroclastic rocks, Permian granite	No reserves, 0.2 to 4.1% Cu, 466 g/t Ag, 2.7% Pb+Zn	Mao et al., 2002b
Kanggur (including Matoutan)	Replacement type	Au (Pb-Zn)	Pyrite, magnetite, galena, sphalerite, chalcopyrite	Vein, disseminated	Up. Carboniferous andesite and tuff	45t/12g/t	Zhang et al., 2003; Wang et al., 2003
Shiyingtan	Low-sulfidation epithermal	Au	Pyrite, native gold, chalcedony, quartz, sericite, andularia, calcite, electrum	Disseminated, vein, stripped, lenticular	Permian andesite, tuff	7t/12g/t	Jiang et al., 1997; Li et al., 1998
Jiabaishan (or Xifengshan)	Quartz vein	Au	Pyrite, arsenopyrite, chalcopyrite, tetradyomite, native gold, quartz, calcite	Massive, vein, lenticular	Carboniferous granitoid rock	2t/10–15 g/t	Ji et al., 2000; Mao et al., 2002b
Longxi	Quartz vein	Au	Pyrite, native gold, chalcopyrite, quartz, calcite	Massive, vein, disseminated	Carboniferous granodiorite porphyry	2.5t/10g/t	Wang et al., 2003

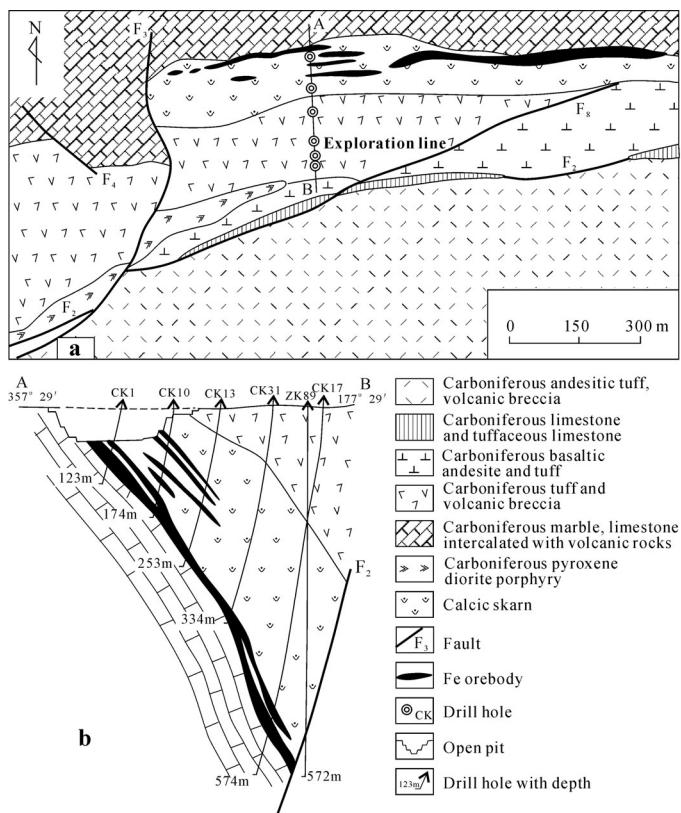


Figure 4 Plan (a) and section (b) of the Yamansu Fe (Cu) skarn deposit.

bearing quartz veins in the Bailingshan Fe(-Cu) deposit (Li and Liu, 2003), located in the western part of the Aqishan-Yamansu rift belt (Figure 2), may provide the best approximation of the age of mineralization.

### Cu-Ag-Pb-Zn skarn deposits

Copper-Ag-Pb-Zn skarn deposits are widely distributed in the Yamansu-Aqishan rift belt. These occurrences are newly recognized from following-up of geochemical anomalies in 2000 by the XJBGMR. The Weiquan deposit is the largest of these skarns and small-scale mining of its high-grade ores began in 2001; other subsequent discoveries include the Shuangqing, Heiyingshan and Lubaishan occurrences. The host rocks of the middle Carboniferous Tugutubulake Formation include an increasingly felsic-upward-trending series of pyroclastic rocks, locally intercalated with limestone. The carbonate lenses are pervasively altered to skarn and the orebodies occur locally within this alteration. A number of diorite dikes are exposed near the skarns, and 2 to 3 km to the south, a large (100 km<sup>2</sup>) Late Carboniferous-Early Permian biotite granite intrusion is exposed and hosts NW-trending diabase dike swarms. Prograde skarn is composed of andradite, diopside, vesuvianite, and epidote, whereas the retrograde assemblage is dominated by actinolite, chlorite, and fluorite. A near-surface supergene oxide body is dominated by malachite, covellite, and jarosite. At the surface, the main Weiquan orebody is 250 m long and 0.4 to 24 m wide. Drilling has revealed vertical metal zoning with a silver-lead-zinc orebody above the copper orebody. The copper grade of the oxidized ore varies from 0.2 to 36.7% and of the primary ore from 0.2 to 4.1%, the average silver grade is 466 g/t, and the average hypogene lead-zinc grade is 2.7% (No.1 Geological Team, XJBGMR, 2001). The metallic minerals in the primary ore are chalcopyrite, bornite, magnetite, pyrite, sphalerite, galena, argentite and molybdenite. The deposit has not been explored in detail, but the high grades have led to the No.1 Geological Team mining the deposit at a small scale.

SHRIMP U-Pb dating of zircon from the related diorite dike suggests a possible ore-forming age for the Weiquan Cu-Ag-Pb-Zn deposit between 290-280 Ma (Li and Liu, 2003). This is consistent with the  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau age of  $276 \pm 2.8$  Ma determined on amphibole from the skarn (Mao et al., 2002b). It thus appears that both the iron-rich and polymetallic skarns are roughly of the same age, and both are about 50 million years younger than the porphyry deposits to the north.

### Hydrothermal vein copper-zinc

The Xiaorequanzi deposit is the only known example of this deposit type. It was discovered during a regional geological and geochemical survey, when a zinc geochemical anomaly was followed-up in 1993 by XJBGMR. After preliminary exploration conducted by the No. 11 Geological Team of XJBGMR, a local company started to mine the higher grade ores at the deposit in 1994. In the past three years, exploration efforts have defined a metal reserve of 300,000 tonnes copper with a grade of 0.43 to 4.4%, averaging 1.8% and 150,000 tonnes zinc with 0.3–17%, averaging 1.25%. Although both Au and Ag are by-products, with an average grade of 2–3 g/t and 50 g/t, respectively, there are presently no reserve estimates for the precious metals.

The Xiaorequanzi Cu-Zn deposit is at the westernmost end of the Dananhu-Tousuquan arc. Although stratabound in Lower Carboniferous siltstone, fine-grained sandstone, tuff, and andesite of the Xiaorequanzi Formation, the orebodies mainly developed along a discordant NE- and ENE-trending zone (Figure 5a). A NW-trending dome and an S-dipping monocline define the structure of the Xiaorequanzi deposit area. The major faults in the area are NE- to N-trending, but minor faults are NW-trending zone (Sun and Shang, 1988).

Several albite porphyry and dacite porphyry stocks and dikes are exposed in the mine area (Figure 5a). A gravity survey indicates that a granitic pluton may exist beneath the area. A dacite porphyry yielded a Rb-Sr isochron age of  $290 \pm 7$  Ma, and an albite porphyry yielded single zircon U-Pb ages of  $266 \pm 5$  and  $245 \pm 9$  Ma (Li et al., 1998). This relationship is displayed in Figure 5a, where a dacite porphyry dike is shown to be cut by an albite porphyry stock. If the polymetallic ores are related to these intrusive rocks, then the ores are much younger than the porphyry deposits described above within the arc.

The present mine area is 2.5 km long by 2 km wide, and contains 22 orebodies, with the largest being 520 m long by 1 to 30 m wide, averaging 12.5 m (Figure 5a). The orebodies are generally ENE-trending and dip to the SE at  $30^\circ$ - $80^\circ$ . They occur as lenticular and banded veins that formed along an anticlinal axis (Figure 5b). The mineralization generally exhibits zoning, with copper ore in the shallower parts and zinc enrichments at depth (Figure 5b). The major orebody is hosted by dark, carbon-rich, fine-grained sandstone along an array of shallowly-dipping fractures that are subsidiary to the more significant, steeply-dipping ore veins.

The primary ore minerals are chalcopyrite, cubanite, sphalerite, chrysocolla, digenite, tennantite, cobaltite, pyrite, pyrrhotite, galena, altaite, clausenthalite, arsenopyrite, and electrum; the gangue minerals are quartz, chlorite, sericite, carbonate, rutile, and fluorite; supergene minerals include malachite, chalcocite, limonite, chrysocolla, szomorokite, melanerite, and jarosite. Alteration is dominantly silicification, sericitization, chloritization, epidotization, and carbonation. The width of the altered zones exhibits a positive correlation to the thickness of the ore veins or orebodies. Limonite and jarosite developed at the surface or in the subsurface.

Values of  $\delta^{34}\text{S}$  for pyrite and chalcopyrite range from +3.3 to +11.1 per mil, and from +1.5 to +7.2 per mil, respectively (Figure 6). Measured  $\delta^{18}\text{O}$  values of quartz from the ores vary from 8.0 to 9.3 per mil, with corresponding fluid values of about 3–5 per mil. Measured  $\delta\text{D}$  values from fluid inclusions in the ore quartz are -66 to -21 per mil. Noble gas and silicon isotopes from fluid inclusion extractions have been interpreted to suggest that the ore-forming fluids

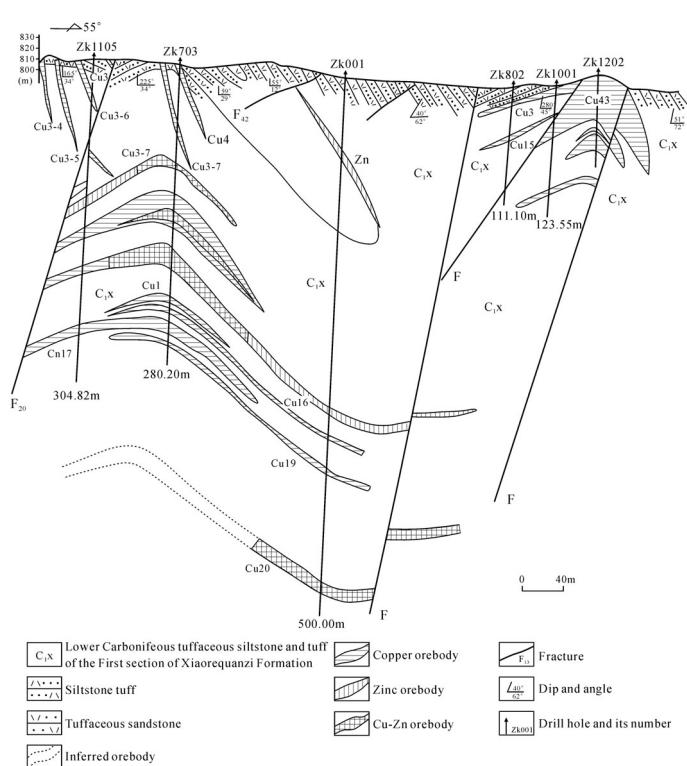
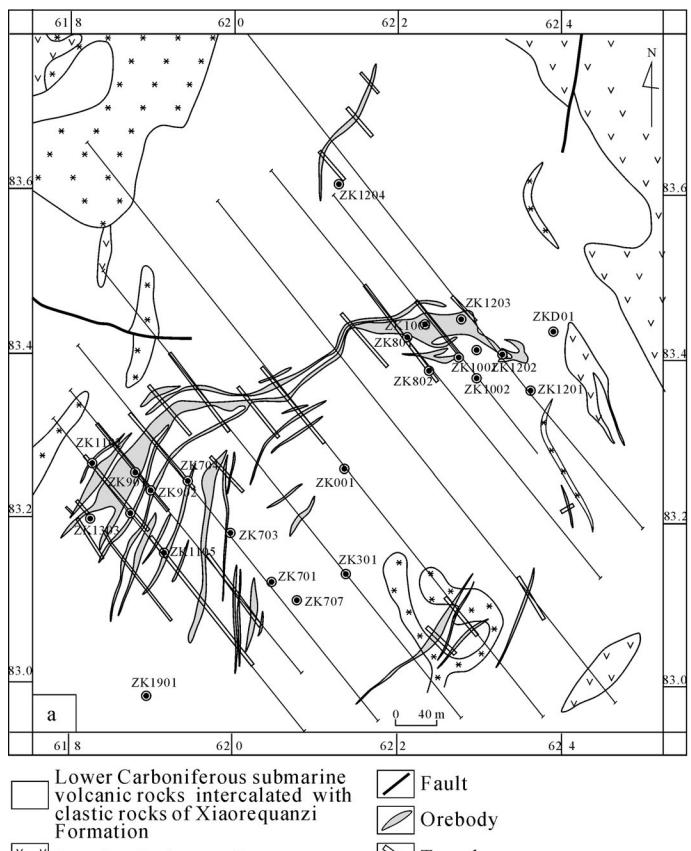


Figure 5 Geological map (a) and cross section (b) of the Xiaorequanzi copper-zinc deposit. The copper bodies occur along a group of NE- and NEN-trending fractures (a) and they are largest along the axis of a local anticline (b).

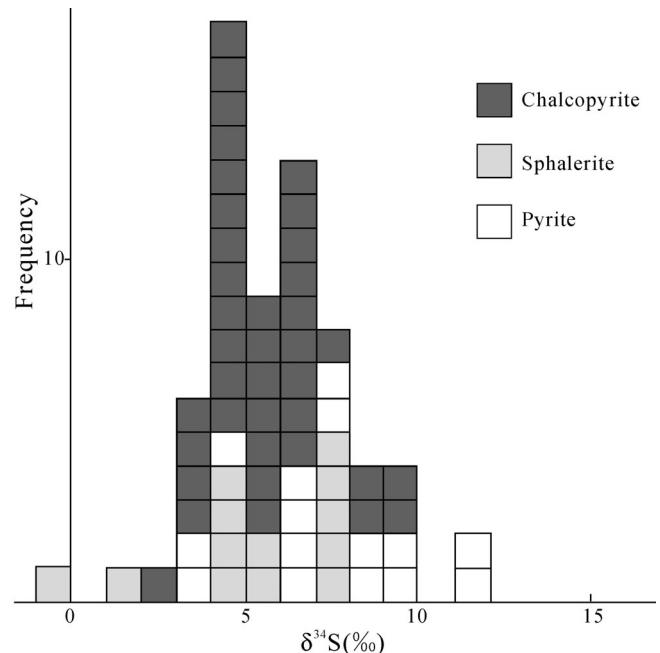


Figure 6 Histogram of sulfur isotope data for sulfide minerals from the Xiaorequanzi copper deposit (after Chen, 1999).

have a mixed crustal-mantle signature (Chen, 1999). None of these data preclude the possibility that the Xiaorequanzi copper ores are genetically associated with the Permian magmatism. However, because the orebodies locally appear to be associated with specific units, and high-grade ores occur in areas with an abundance of organic carbon, it has also been proposed that the ores are Carboniferous VHMS deposits (Liu et al., 1996; Xu, 1998; Chen, 1999; Qin et al., 2002).

## Orthomagmatic copper-nickel sulfide deposits

Numerous, small mafic-ultramafic plutonic complexes occur near the contact between the Tousuquan-Dananhu arc and the northern side of the Kanggurtag shear zone. From west to east, these are the Tudun, M102, Erhongwa, Xiangshan, Huangshannan, and Huangshandong complexes (Figure 7a), as well as the Hongshigang, Heishiliang, Huludong, Chuanzhu, and Madi complexes in the Jing'erquan copper-nickel district (Yang, 1994; Tang and Li, 1996; Li, 1996). The Huangshandong, Huangshan, Huangshannan, Xiangshan, Tudun and Hulu plutons host economic Cu-Ni sulfide mineralization (Table 2). Exposed plutonic rocks include peridotite, lherzolite, pyroxenite, gabbro, and diorite. Geomorphologically, diorite usually forms in positive landforms, whereas the ultramafic rocks form recessive landforms. Orebodies are localized near the base of the ultramafic rock sequences that is dominated by lherzolite and pyroxenite (Figures 7b, 8). Most plutons have multiple stages of intrusion, or intrusive facies, possibly resulting from differentiation of the same magma, and display gradational relationships, but locally showing intrusive contacts (No. 6 Geological Team, XJBGMR, 1987) (Figure 8b).

The orebodies are lenticular and layered in shape (Figure 7b; Figure 8) (Wang and Li, 1987; Wang et al., 1986). Ore veins also are occasionally present, but are sub-economic. The disseminated ores are commonly low-grade, with combined Cu+Ni grades never exceeding 1%. The ore minerals are mainly pyrrhotite, pentlandite, and chalcopyrite, and less commonly chromite, magnetite, titanomagnetite, heazlewoodite, violarite, niccolite, cubanite, cobaltite, siegenite, gersdorffite, ullmannite, wehrlite, marcasite, bornite, and

Table 2 Features of Huangshan-Xiangshan mafic-ultramafic Cu-Ni sulfide deposits in East Tianshan (after Qin et al., 2003)

Complex name	Length x width (km)	Area (km <sup>2</sup> )	Size Grade	Shape	Mafic-ultramafic rock Association
Xiangshan	10×3.5	2.8	Cu 20000t, 0.3% Ni 40000t, 0.5%	Lotus root	Hornblende-peridotite, peridotite, pyroxenite diorite, hornblende-gabbro
Huangshan	3.8×8	1.71	Cu 0.21Mt, 0.31% Ni 0.32Mt, 0.49%	Comet shape	Gabbro-diorite, hornblende-gabbro, hornblende-gabbro-norite, hornblende-lherzolite, hornblende- websterite
Huangshandong	5.3×1.12	2.8	Cu 0.18Mt, 0.27% Ni 0.36Mt, 0.52%	Rhombus lens	Hornblende-olivine-gabbro, pyroxene-hornblende-gabbro, gabbro-diorite, gabbro-norite, olivine-gabbro-norite, pyroxene-cortlandite
Huangshannan	5.2×1.3	4.22	Cu 1300t, 0.3% Ni 10000t, 0.4%	Lens	Pyroxene- cortlandite, peridotite, hornblende-pyroxenite, lherzolite, hornblende-gabbro, norite
Huangshanbei	10×0.9	9	Cu 2000t, 0.2% Ni 12000t, 0.4%	Lens oblique row	Gabbro-pyroxenite-peridotite, diorite-gabbro
Erhongwa	South 3.33×2.56 North 1.72×1.14	6.25	Cu 4000t, 0.2% Ni 18000t, 0.2%	Irregular round	lherzolite, gabbro-norite, olivine-gabbro, pyroxene-diorite, quartz-diorite
Tudun	1.4×0.7	0.9	Cu 3000t, 0.2% Ni 15000t, 0.3%	Irregular ellipse	Gabbro, pyroxene- hornblende-peridotite, pyrolite, olivine-hornblende-pyroxenite

Note: According to the Chinese standard for nickel deposits, the tonnage of large, medium and small-sized Ni deposit is >10 t, 2-10 t and <2 t of metals, respectively.

sphalerite. The associated wall-rock alteration is dominated by amphibole and chlorite, and weak development of talc, serpentine, and tourmaline. At present, local people mine both the Huangshandong and Huangshan deposits at a very small scale. At Huangshandong, they produce about 400 tons/day of ore, whereas at Huangshan, there is much less production. Cut-off grades are >0.6% Cu+Ni. Due to absence of sorting and smelting facilities for the ores, material must be transported great distances to the mill at Jinchuan, the site of the biggest nickel mine in Gansu province.

The  $\delta^{34}\text{S}$  values of the ore range from -2.2 to +1.5 per mil, which is consistent with sulfur derivation from the mantle. Initial Sr isotope values of 0.7045–0.7046 of the host olivine gabbro are consistent with a mantle source for the magma. Ni (1992) indicates that the mineralized composite intrusions formed by deep-seated, comagmatic differentiation. The tholeiitic magmas formed by partial melting of garnet lherzolite of the upper mantle (Zhong, 1990). Wang and Li (1987) suggested that the rock suite intruded at pressures <4–5 kbar and  $f_{\text{O}_2}=10^{-10\sim 9}$ .

Li et al. (1991) obtained a Rb-Sr isochron age of 285 Ma for the mineralized igneous rocks, whereas Li et al. (1998) obtained a whole-rock Sm-Nd isochron of 320±38 Ma and an ore Sm-Nd isochron age of 314±14 Ma. Single-zircon age dating of the Xiangshan stock by Qin (2000) yields a date of 286±1.2 Ma. The Re-Os dating of seven samples of Cu-Ni sulfide ore from the Huangshandong deposit yields an isochron of 282±20 Ma (Mao et al., 2003). These data show that the copper-nickel mineralization and their related mafic-ultramafic rocks formed in the Late Carboniferous-Early Permian, which was significantly subsequent to the magmatism and associated copper porphyry formation within the same arc.

## Gold deposits

The gold vein deposits in the East Tianshan include classic low sulfidation epithermal types, as well as many lacking sufficient information for adequate classification (Mao et al., 2002a). These

deposits have been previously studied by Pirajno (1997), Rui et al. (2002c), and Qin et al. (2002).

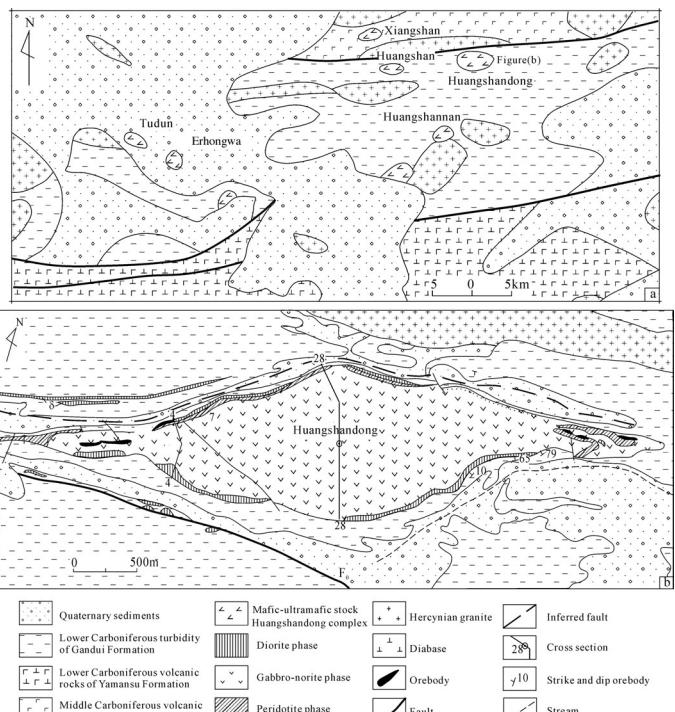
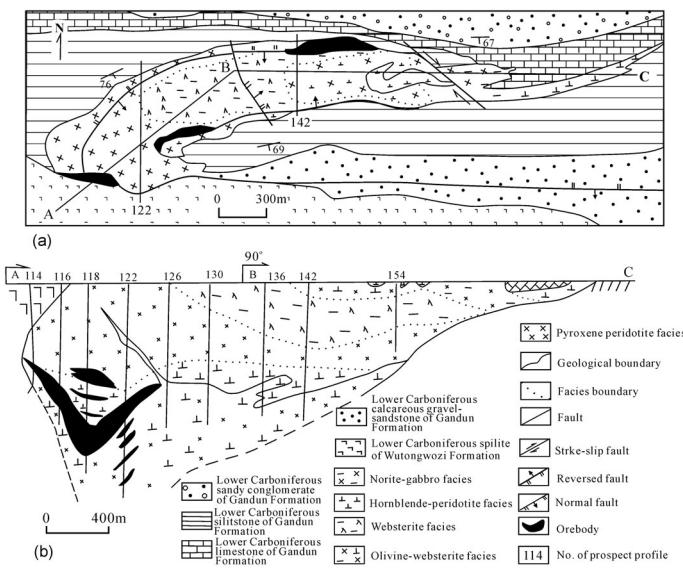


Figure 7 Distribution map of the mafic-ultramafic intrusions between the Tousuquan-Dananhu island arc and Kanggurtag suture zone in Huangshan area (a). The zoned Huangshandong mafic-ultramafic complex is associated with the largest Cu-Ni sulfide deposit in the area (b).

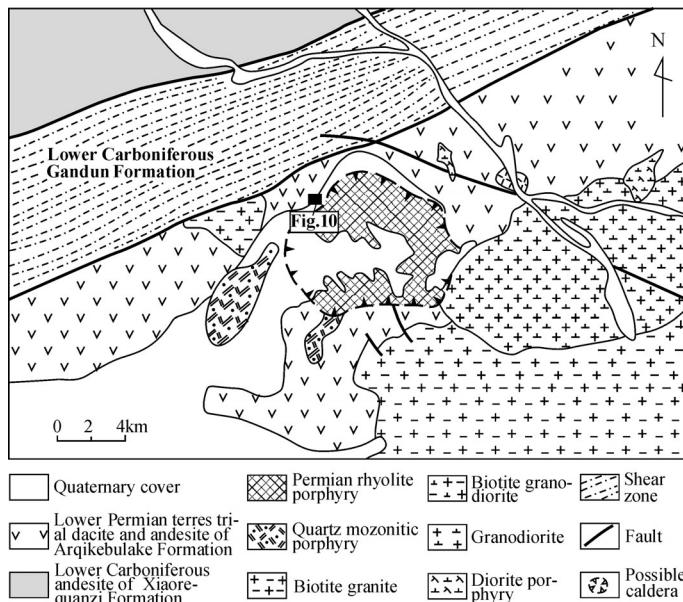


**Figure 8** Geological plan (a) and section (b) of the Huangshan copper-nickel sulfide deposit (After No. 6 Geological Team of Xinjiang Bureau of Geology and Mineral Resources, 1987). The magmatic Cu-Ni sulfide minerals are disseminated in the middle-lower part of the mafic-ultramafic complex.

tion occurs in the Dananhu-Tousuquan arc, economic gold deposits currently occur only in the northern margin of the Aqishan-Yamansu rift belt. These gold deposits are epithermal in the west, but could be more deeply formed replacement-style epithermal gold vein systems in the east.

### Epithermal gold

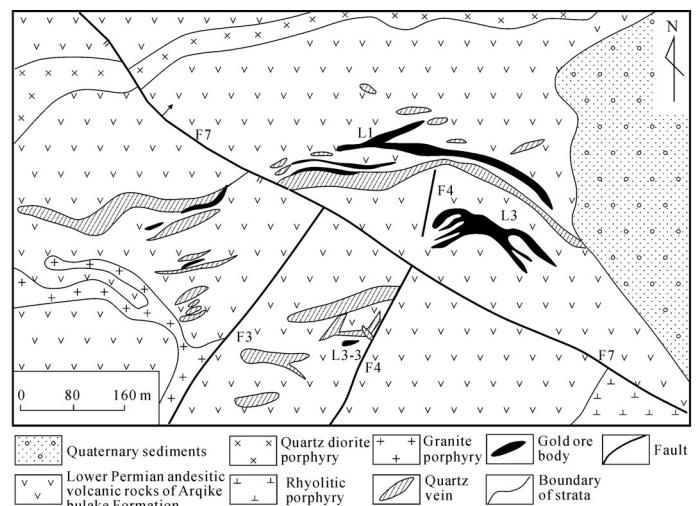
Epithermal mineralization includes the Shiyingtang (also named Xitan) gold deposit located in the western part of the East Tianshan (Figure 2). It contains approximately 10 tons Au, with an average grade of 12.5 g/t Au; silver grades are about 20 g/t (Zhang et al., 2004). The region is mainly underlain by Permian andesitic-dacitic rocks and volcanic breccia and their subvolcanic equivalents. Jiang et al. (1997) suggested that there was a Permian volcanic caldera in



**Figure 9** Geological map of the Shiyingtang gold mine area (After Feng et al., 1999; original map from Jiang et al., 1997). The deposit is located within a Permian andesitic caldera.

the vicinity of Shiyingtang (Figure 9). Li et al. (1998) recognized amygdaloidal andesite and medium- to fine-grained tonalite near the gold deposit and obtained Rb-Sr whole rock isochron ages for these of  $285 \pm 12$  Ma and  $293 \pm 1$  Ma, respectively.

Eighteen ore-bearing veins have been identified in the mine at Shiyingtang. The orebodies are along a nearly WNW set of tensile faults and form a swarm of auriferous quartz veins (Figure 10). The largest vein (No. 3) is 25 m thick and 200 m long, and extends 100 m downward, striking N20°E and dipping 55°–70°. The distribution of the orebodies is considered to be controlled by the intersection of the fracture system of the caldera with regional faults (Ji et al., 2000).



**Figure 10** Geological map of the Shiyingtang gold deposit (after Li et al., 1998). The ore veins and barren quartz veins are hosted in Permian volcanic rocks.

The Shiyingtang deposit has three stages of mineralization. Stage I veins (microcrystalline quartz) contain minor sulfide minerals, have a low gold grade, and are generally sub-economic. Stage II (chalcedony-calcite) is the main mineralization stage, with ore filling fissures with microcrystalline quartz and locally forming ore shoots in areas of most intense fracturing. The ores can be classified into chalcedony-calcite-electrum-native gold ore and quartz-pyrite-sericite-native gold ore (Ji et al., 2000). Sericite, adularia, laumontite, and kaolinite, which appear in small amounts in the ore, are typical of low sulfidation epithermal deposits. The bladed structure formed by calcite and microcrystalline quartz or chalcedony is also observed, and is typical of boiling of hydrothermal solutions as described by Simmons and Christenson (1994). Stage III barren calcite veins cut earlier formed mineral assemblages. Unlike many epithermal gold deposits, including the Axi gold deposit in the West Tianshan, the Shiyingtang gold deposit shows relatively weak wall-rock alteration, which is silicification, sericitization, chloritization, and carbonatization.

### Replacement gold

Replacement-style epithermal ores occur in mafic volcanic rocks of the Yamansu Formation along the Aqishan-Yamansu fault (Rui et al., 2002c). The Kanggur and Matoutan gold deposits (Figure 2) are within 4 km of each other, and possibly occur along the same shear zone (Figure 11). Recently, another promising deposit, the Kangxi gold deposit, has been discovered 10 km further west and may also occur along the same shear zone. The E-W-trending shear zone is composed of a series of mylonitized rocks that display well developed S-C fabrics, stretching lineation and rotational porphyroclasts (Ma et al., 1998). In addition, a set of NE- and NW-trending post-ore conjugate brittle faults is developed in this Kanggur district

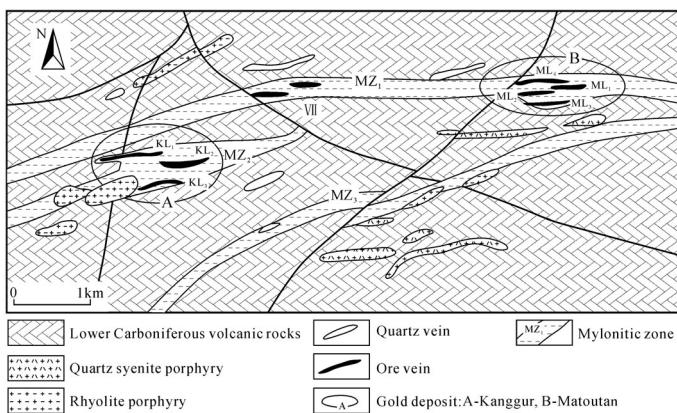


Figure 11 Geological map of Kanggur-Matoutan gold deposits (After Han *et al.*, 2002).

(Figure 11). The major ore veins are located in the transition zone between intense and moderate ductile strain (Figure 12a).

Ore zones include magnetite- and sulfide-rich auriferous quartz veins and massive lenses, as well as barren quartz-carbonate or carbonate veins. Sulphide-rich quartz veins occur either as large vein swarms or as fine stockworks in highly altered volcanic rock. The quartz-carbonate and carbonate veins formed during the second stage contain sparse pyrite, but no gold. Copper, lead and zinc are also highly anomalous in the ores. Kanggur, Matoutan and Kangxi constitute a high-grade gold district with gold grades ranging from 3 to 50 g/t, and averaging 8–10 g/t. The present gold reserve for the district is more than 40 tons (Zhang *et al.*, 2003), although the region also has high potential for additional reserves. The local people are mining high grade gold ores at both the Kanggur and Matoutan deposits, but do not recover any of the base metals, in large part due to the remote location of the mining operations.

Approximately 100 to 300 m wide hydrothermal alteration zones surround the orebodies, which can be divided into three zones. An inner zone of altered mafic rocks, part of the orebodies themselves, consists of quartz, chlorite, pyrite, chalcopyrite and magnetite; a middle zone comprises a pyrite-bearing phyllitic and/or a sericitic alteration assemblage; and distal alteration is characterized by a sericite-chlorite assemblage. Vertically, the zoning consists of Au-Ag-As ores in the upper 170–200 m and Cu-Pb-Zn ores below this depth (Figure 12b). Almost all gold occurs as native gold, with minor electrum and gold-bearing tellurides. Ji *et al.* (1994b) divided the hydrothermal activity in the Kanggur deposit into five stages: (1) early gold-pyrite-sericite-quartz, (2) pyrite-magnetite-chlorite-quartz, (3) gold-pyrite-chalcopyrite-muscovite, (4) pyrite-chalcopyrite-galena-sphalerite-quartz, and (5) pyrite-chalcopyrite-calcite-quartz. All but the final stage deposited some gold.

The main mineralization stage of the Kanggur gold deposit formed at  $290.4 \pm 7.2$  to  $282.3 \pm 5$  Ma, and the late stage quartz-carbonate veins at  $254 \pm 7$  Ma (Li *et al.* 1998). This group of ages is coincident with the Rb-Sr isochron age of  $282 \pm 16$  Ma for a syenite porphyry in the Kanggur gold district (Li *et al.* 1998). These ages are identical to those for the Shiyigutan deposit approximately 40 km to the west.

### Mesozonal gold-bearing quartz vein deposits

Mesozonal gold-bearing quartz vein deposits developed in the eastern part of the area, including Jiabaishan (or Xifengshan), Baiganhu, Chihu and Longxi, are all worked by small-scale mines and have reserves ranging from <1 to 3 tons Au, although grades typically average 10–15 g/t. These deposits occur in the Dananhu-Tousuquan arc, the Aqishan-Yamansu rift belt (e.g. Baiganhu), and the Kanggurtag shear zone (e.g. Jiabaishan). Mineralization is composed of sulfide-bearing quartz veins dominated by pyrite and arsenopyrite, with minor chalcopyrite, tetrahedrite, galena, and sphalerite. Generally gold grades are higher with elevated sulfide content. The host rocks are mostly granitic stocks, although some veins cut the volcanic and sedimentary rocks. The width of wall-rock alteration is proportional to the thickness of the ore veins. The main alteration types are silicification and sericitization. The only exception is the Baiganhu gold deposit. The mineralization is dominantly controlled by a set of NNE- to NE-trending tensile fractures. Rb-Sr isochron dating of fluid inclusions in quartz from the Jiabaishan ore district by Ji *et al.* (2000) yielded age of  $272 \pm 3$  Ma. It is still uncertain as to the genetic classification of these gold occurrences.

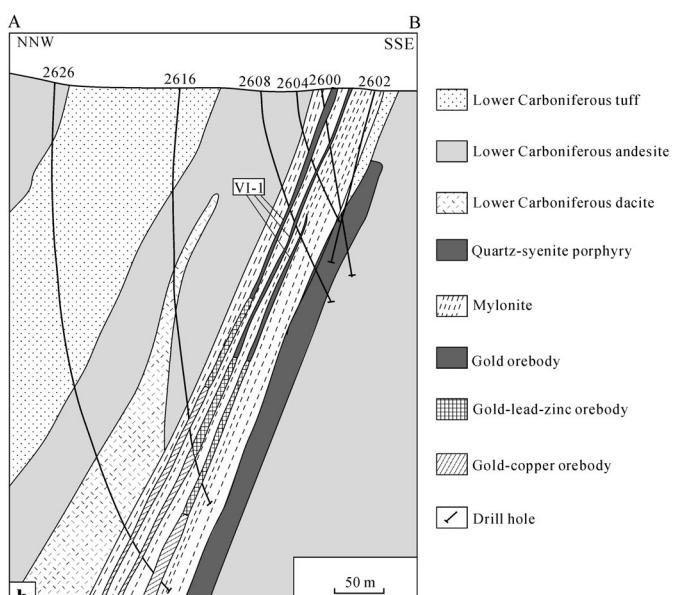
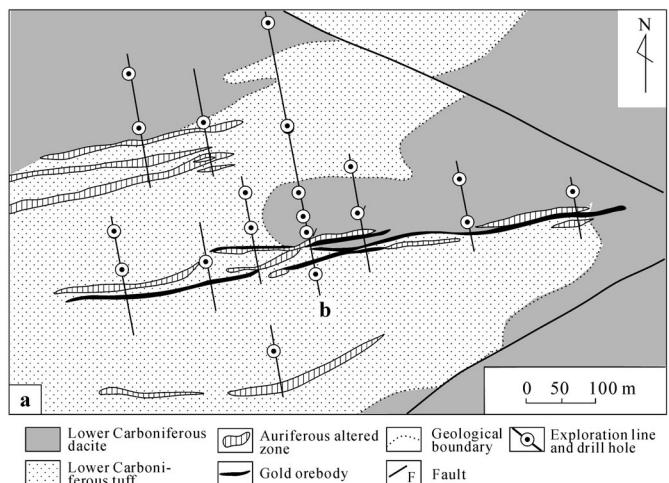


Figure 12 Geological map and cross-section of the Kanggur gold deposit (after Li *et al.*, 1998). The orebodies are accompanied by an auriferous alteration zone at the surface (a) and metallic elements showing a vertical zoning in the section (b).

As stated above, the gold deposits in the East Tianshan are widely distributed, but their ore-forming ages are concentrated between 290 and 272 Ma, suggesting they might be the products of the same geological event. All three types of gold in the area are likely to be genetically related to the late Paleozoic igneous activity (Figure 13). The larger Shiyigutan and Kanggur epithermal and replacement deposits formed nearly contemporaneously with Permian volcanic and subvolcanic rocks, so the depth of vein formation

### Metallogenesis and genetic link of the three gold deposit styles

As stated above, the gold deposits in the East Tianshan are widely distributed, but their ore-forming ages are concentrated between 290 and 272 Ma, suggesting they might be the products of the same geological event. All three types of gold in the area are likely to be genetically related to the late Paleozoic igneous activity (Figure 13). The larger Shiyigutan and Kanggur epithermal and replacement deposits formed nearly contemporaneously with Permian volcanic and subvolcanic rocks, so the depth of vein formation

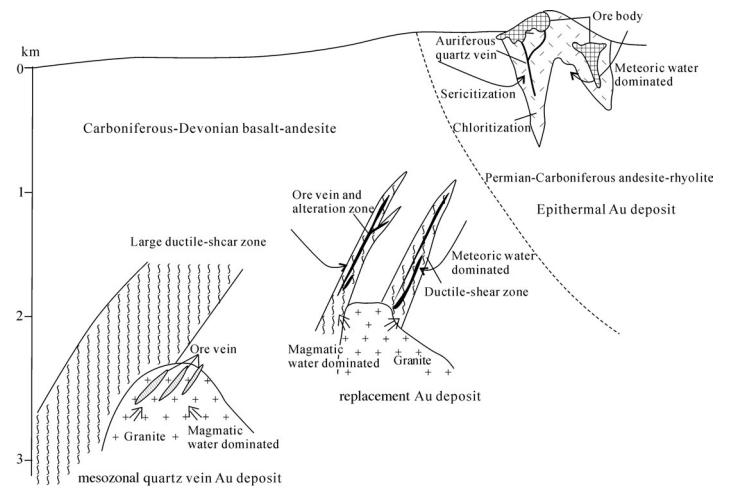
was likely shallow, probably within several hundred meters of the surface. Microthermometric measurements of fluid inclusions from the Shiyingtan gold deposit indicate homogenization temperatures range from 125 to 236°C and salinities from 1.9 ~ 2.7 wt% NaCl equiv. (Mao et al., 2002b). Homogenization temperatures and salinity of the Kanggur gold ores vary from 214 to 408 °C and 9.0 ~ 16.0 wt% NaCl equiv. for stage I, and 141 to 214 °C and 7.8 ~ 10.5 wt% NaCl equiv. for stage II (Mao et al., 2002b). The homogenization temperatures for fluid inclusions from the Longxi deposit vary from 222 ~ 313 °C and their corresponding salinity is 6.3 ~ 11.1 wt% NaCl equiv. (Wang et al., 2004). These data could reflect a deeper epithermal environment and perhaps a more significant magmatic component for some of the East Tianshan gold ores.

Fluid  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values are 2.5 ~ 5.3 per mil and -67 ~ -77 per mil for quartz vein type, 2.4 ~ 4.7 per mil and -42 ~ -56 per mil for replacement type, and -1.6 ~ -12.7 per mil and -87 ~ -119 per mil for epithermal deposit type (Zhang and Ji, 1999; Zhang et al., 2000; Ji et al., 1997; Xue et al., 1995; Mao et al., 2002b). These data might be interpreted to suggest that from the mesozonal quartz vein type and replacement type to epithermal type of gold deposit, the ore fluids changed gradually from dominantly magmatic to fluids with a significant meteoric water component (Figure 13). Sulfur isotope composition shows that the  $\delta^{34}\text{S}$  values range from -0.3 to +0.2 per mil for replacement gold deposits (Zhang et al., 1998b) and from +0.1 to +2.3 per mil for epithermal gold deposits (Feng et al., 1999), suggesting that sulfur in these gold systems may have a mantle or magmatic origin. In support of this are the carbon and oxygen isotope data for the Kanggur deposits ( $\delta^{13}\text{C} = -2.4 \sim -6.2$  per mil and  $\delta^{18}\text{O} = 8.5 \sim 10.8$  per mil, respectively). They are distinct from the surrounding Carboniferous carbonate rocks ( $\delta^{13}\text{C} = -2 \sim 1.5$  per mil and  $\delta^{18}\text{O} = 14.2 \sim 17.0$  per mil for the Yamansu Formation and  $\delta^{13}\text{C} = 3.9 \sim 4.0$  per mil and  $\delta^{18}\text{O} = 24.4 \sim 25.5$  per mil for the Gandun Formation) (Wang et al., 2003, 2004).

## Geodynamic evolution and mineralization

The East Tianshan is a part of the Palaeo-Asian orogenic belt and Pan-Altaides of Yakubchuk et al. (2001). Its geodynamic evolution is closely related to that of neighboring Chinese West Tianshan and the adjacent Central Asian Tien Shan. The final collisions along the Kanggurtag suture zone between the amalgamated Tarim craton/southern Tianshan/central Tianshan and the arcs of the northern Tianshan are documented by some researchers have occurred in Late Carboniferous (Ma et al., 1993, 1997; Ji et al., 1994a, 2000; Yang et al., 1997; Goldfarb et al., 2001; Li et al., 2002; Qin et al., 2002). In light of the geochronological data (Table 3), the metallic mineral deposits in the East Tianshan are recognized to be parts of two age groups, i.e. porphyry copper systems that formed at ca. 330 ~ 320 Ma, and a variety of other deposits that formed at ca. 290-270 Ma. These two age groups are considered to be the periods of subduction and post-collisional tectonism, respectively.

The Xiaorequanzi, Qi'eshan and Wutongwozi Formations between the Kanggurtag and Dacaotan faults have long been considered to represent a Carboniferous island arc. However, recent dating by Rui et al. (2002b) and Qin (2000) indicates that the volcanic rocks between the faults are Devonian to Early Carboniferous. Li et al. (2003) subsequently summarized that this suite of rocks are dominated by Devonian to Early Carboniferous basalts, andesite, and rhyolite, and associated volcanic clastic sedimentary rocks, with a combined total thickness of 20 km. Rocks of the arc are intruded by a number of batholiths comprising diorite, granodiorite, and granite bodies. Song et al. (2002) obtained SHRIMP U-Pb ages of  $383 \pm 9$  Ma, and  $357.3 \pm 6.2$  Ma on zircons from these intrusions. These intrusive and extrusive rocks represent either island arcs or continental magmatic arcs that were formed by northward subduction of an oceanic plate in the late Paleozoic (Zhou et al., 1994) (Figure 14A,



**Figure 13 Metallogenic model of the three types of gold deposits in the East Tianshan (modified from Mao et al., 2002a). Three types of gold deposits formed in the Late Carboniferous - Early Permian and are genetically related to granitic rocks. Shallower ores have a significant contribution of meteoric fluid into the magmatic-hydrothermal system.**

B). Geochemical compositions of the volcanic rocks and plutons (Xiao et al., 1993; Zhou et al., 1994) indicate they are calc-alkaline in composition, thus suggesting a continental arc. The porphyry-related magmas at the Tuwu-Yandong were emplaced at ca. 334 Ma (Li and Liu, 2003) and, therefore, the associated copper ores are assumed to have formed during the late stages of subduction and >50 m.y. after arc evolution. Because the porphyry copper mineralization developed 10 million years after crystallization of the monzonite host rock (Du et al., 2001; Rui et al., 2002b; Li and Liu, 2003), and assuming dates on the mineralization and intrusion to be reliable, we conclude that subduction-related magmatism continued until at least ca. 320 Ma and the latest magmatism is the most likely to be associated with porphyry copper systems.

The post-collisional Permian granitic intrusions are widely exposed throughout the East Tianshan and adjacent northern margin of the Middle Tianshan. They are composed of quartz diorite, quartz syenite, granodiorite, monzonite, K-feldspar granite, and alkaline gabbro plutons, as well as an abundance of dikes. Their measured ages range from ca. 290 Ma to 228 Ma, with the most widespread magmatism at ca. 280 Ma and 240 Ma (No. 1 Geological Team, XJBGMR, 1993, 1995a; 1995b; Li et al., 2002).

Most of the post-collisional metallic mineral deposits in the East Tianshan formed at ca. 293 to 245 Ma, with a peak at ca. 290-280 Ma (Table 3), reflecting a clear temporal association with the earliest post-collisional magmatism (Figure 14D). The Permian Fe-(Cu) and Cu-Ag-Pb-Zn skarn deposits formed during emplacement of intrusions in the Aqishan-Yamansu rift belt and the northern margin of the Middle Tianshan, with associated hydrothermal activity resulting in the replacement of Carboniferous and Neoproterozoic carbonate and calcic clastic rocks. The Xiaorequanzi Cu-Zn deposit formed at approximately the same time, in the westernmost part of the Tousuquan – Dananhu arc, within clastic rocks intercalated with volcanic rocks, but where carbonates are absent. The Aqishan – Yamansu rift basin formed throughout the Carboniferous (Li et al., 2002) along the northern edge of a passive continental margin defined in the Middle Tianshan (Figure 14C). The more important Fe-(Cu) skarn deposits in the rift belt were originally suggested as forming during Early Carboniferous basin evolution because some deposits occur near a pyroxene diorite porphyry dated by K-Ar at ca. 350 Ma (Liu et al., 1996). However, recent SHRIMP zircon U-Pb dating of 290 Ma (Li and Liu, 2003) indicates a much later, post-collisional timing for skarn development, subsequent to the main period of subduction and to the development of the Carboniferous basin.

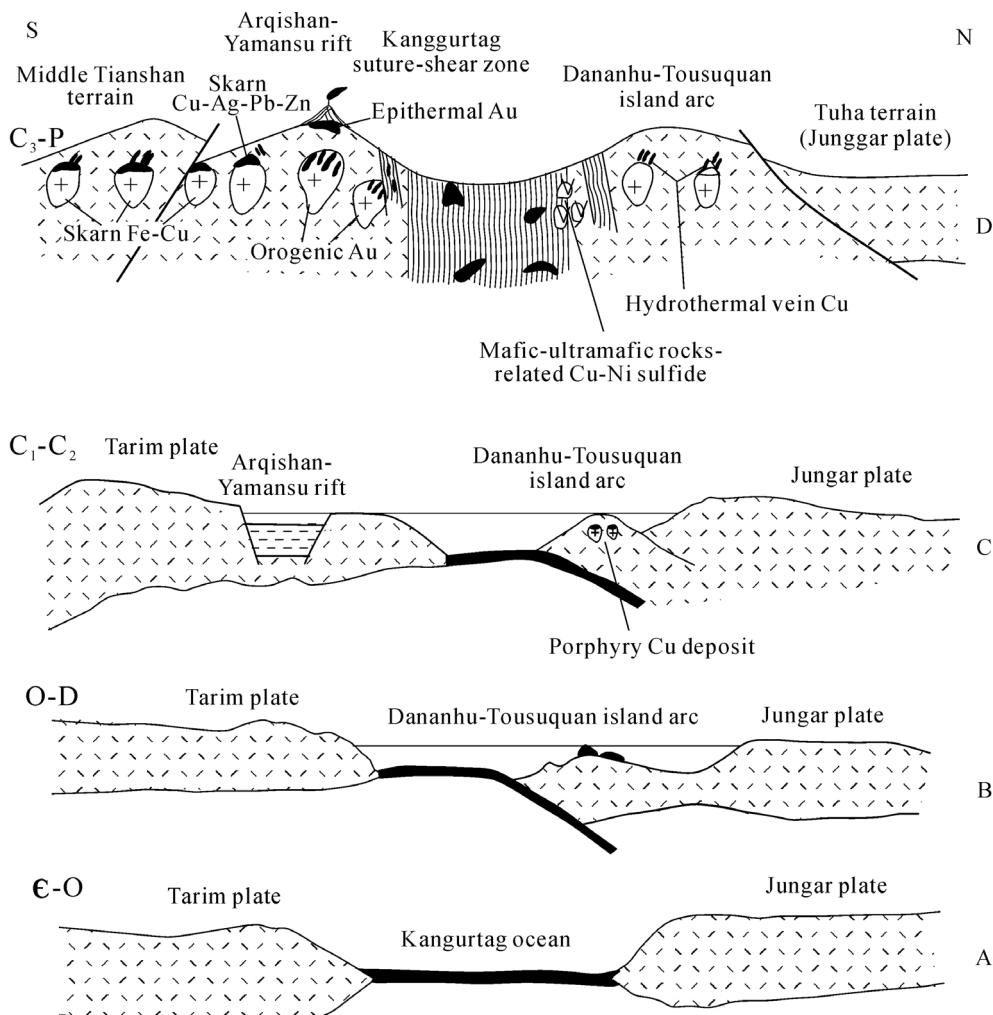


Figure 14 Late Paleozoic geodynamic evolution and mineralization model for the East Tianshan. This diagram is compiled based on the data of Zhou et al. (1994), Li et al., (2002), and Mao et al. (2002a, b). The model is discussed in the text.

Most of the epithermal, replacement, and mesozonal quartz vein type gold deposits in the East Tianshan are located along the Arqishan-Yamansu fault system. Mao et al. (2002a) proposed that the depth of the mineralization controlled the mineralization types and all three gold deposit types are spatially-temporally and genetically associated with Permian granitic rocks (Figure 13), which is accord with the suggestion by Rui et al. (2002c). Strike-slip movement along an irregularly shaped fault system can lead to convergence or divergence at sites of bending, depending on the sense of motion and the sense of curvature (Davis and Reynolds, 1996). Along the Arqishan – Yamansu fault, there are two main bends that appear to be the main sites of dilation for magmatism and hydrothermal fluid circulation, which include fluids responsible for the shallow formation of the Shiyingtan ores, and the deeper deposition of quartz veins at the Jiabaishan deposit (Wang et al., 2003). Because the amount of erosion in

the east is greater than that in the west along the fault zone (Li et al., 2002), both of the gold occurrences, although originally formed at different depths, are now exposed at the same level. The Kanggur – Matoutan, Kangxi, and Dadonggou occurrences, are localized where

Table 3 Summary of geochronological data for various metallic deposits in East Tianshan

Name of deposits	Dated minerals/rocks	Dating methods	Ages/Ma	Data sources
Tuwu-Yandong porphyry Cu	Molybdenite	Re-Os isochron	322.7±23	Du et al., 2001; Rui et al., 2002b
Bailingshan Skarn Fe-(Cu)	Monzonite porphyry Ore-bearing quartz veins	SHRIMP zircon U-Pb Rb-Sr isochron	333±2, 334±2 286	Liu et al., 2003 Li and Liu, 2003
Weiquan skarn	Amphibole in skarn	$^{40}\text{Ar}$ - $^{39}\text{Ar}$ plateau	276±2.8	Mao et al., 2002b
Cu-Ag-Pb-Zn	Diorite dike	SHRIMP zircon U-Pb	290-280	Li and Liu, 2003
Xiaorequanzi hydrothermal Cu-Zn	Dacite porphyry	Rb-Sr isochron	290±7	Li et al., 1998
Xiangshan Cu-Ni	Albite porphyry	Single zircon U-Pb	266±5, 245±9	Li et al., 1998
Xiangshan Cu-Ni	Mafic-ultramafic rocks	Rb-Sr isochron	285	Li et al., 1991
Huangshandong Cu-Ni	Mafic-ultramafic rocks	Single zircon U-Pb	286±12	Qin, 2000
Shiyingtan epithermal Au	Cu-Ni sulfide ores	Re-Os isochron	282±20	Mao et al., 2003
	Amygdaloidal andesite	Rb-Sr isochron	285±12	Li et al., 1998
	Tonalite	Rb-Sr isochron	293±1	Li et al., 1998
	Tonalite	Single zircon U-Pb	287±3	Li et al., 1998
	Quartz fluid inclusion	Rb-Sr isochron	288±7-276±7	Li et al., 1998
Kanggur replacement Au	Early stage gold ore	Rb-Sr isochron	290±7.2-282±5	Li et al., 1998
	Late stage gold ore	Rb-Sr isochron	254±7	Li et al., 1998
	Syenite porphyry	Rb-Sr isochron	282±16	Li et al., 1998
Jiabaishan quartz vein Au	Quartz fluid inclusion	Rb-Sr isochron	272±3	Li et al., 1998

the fault system is more linear and sheared, suggesting much of the length of this fault system is likely favorable for the discovery of precious metal deposits.

The Cu-Ni sulfide deposits and their mafic-ultramafic host stocks in the Huangshan area formed at ca. 284 Ma (Li et al., 1991; Qin, 2000; Mao et al., 2003). During mapping at a scale of 1:50,000, another two groups of small mafic-ultramafic stocks, Haibaotan and Qiateka'ertage, were identified. These are located 50 km and 170 km west of the Tuwu-Yandong porphyry copper deposits along the Dacaotan fault (No. 1 Geological Team, XJBGMR, 1995b). They have many of the same rock phases, mineral assemblages, and geochemical features of the well-studied Huangshan area deposits. Li et al. (2002) dated the Haibaotan and Qiateka'ertage stocks at  $269.2 \pm 3.2$  Ma and  $277.0 \pm 1.6$  Ma, respectively, using SHRIMP zircon U-Pb methods. Thus, we suggest that the Cu-Ni sulfide deposits formed over a 15- to 20-m.y.-long period, which also overlaps with the post-collisional timing of formation of the lode gold and skarn deposits in East Tianshan (Figure 14d). Due to their linear distribution along the Kanggurtag fault, the mafic-ultramafic stocks were considered to be slices of Early Carboniferous ophiolite from the late Paleozoic ocean (Bai, 1991; 2000; Xiao, 1995; Ma et al., 1993, 1997). However, the new absolute dating for both mafic-ultramafic rocks and related Cu-Ni sulfide mineralization indicates a later formation that was coeval with widespread post-collisional granitic magmatism. The Cu-Ni deposits, as well as the gold and skarn ores, may be products of post-collisional Late Carboniferous to Early Permian lithospheric thinning and delamination and mantle-crust interaction driven by a mantle plume (Xia et al. 2003) in East Tianshan.

## Conclusions

The East Tianshan is dominated by two stages of late Paleozoic mineral deposit formation. Late Devonian to Early Carboniferous subduction-related magmatic arc development was associated with the genesis of Tuwu porphyry copper ores in the more northerly Tousuquan-Dananhua arc. The porphyry deposits apparently formed about 10 m.y. subsequent to their ca. 334 Ma magmatic host rocks. Small copper- and zinc-rich veins at Xiaorequanzi, located at the western end of the presently exposed arc rocks, may be related to seafloor volcanic activity during arc formation; alternatively, the veins could be products of later Late Carboniferous to Early Permian magmatic activity.

The various intrusion-related ores within the more southerly Kanggurtag shear zone and Arqishan-Yamansu rift basin formed during the Late Carboniferous and Early Permian. During the first half of a ca. 290–260 Ma period of magmatism, zoned mafic-ultramafic bodies were emplaced within the northern side of the Kanggurtag shear zone. Disseminated nickel and copper sulfide ores are associated with these intrusions. At the same time, intermediate intrusions emplaced into volcanic sequences within the rift basin generated Fe-Cu and polymetallic skarns where magmatic fluids interacted with calcareous units interbedded with the volcanic rocks. Along the northern margin of the basin and within the adjacent Kanggurtag shear zone, auriferous magmatic fluids led to formation of shallow epithermal and deeper replacement style ores at ca. 293–282 Ma.

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