

**Pt-Os isotopic constraints on the age of hydrothermal overprinting on the Jinchuan Ni-Cu-(PGE)  
deposit, China**

Shenghong Yang<sup>1,2,3\*</sup>, Gang Yang<sup>1,2,4\*</sup>, Wenjun Qu<sup>1</sup>, Andao Du<sup>1</sup>, Eero Hanski<sup>3</sup>, Yann Lahaye<sup>5</sup>, Jiangfeng  
Chen<sup>2</sup>

1. Key Laboratory of Re-Os Isotope Geochemistry, Chinese Academy of Geological Sciences, Beijing  
100037, China

2. Department of Earth and Space Science, University of Science and Technology of China, China

3. Oulu Mining School, University of Oulu, 90014, Finland

4. AIRIE program, Department of Geosciences, Colorado State University, Fort Collins, CO  
80523-1482, USA

5. Geological Survey of Finland, 02151, Espoo, Finland

Corresponding author

Shenghong Yang: [shenghong.yang@oulu.fi](mailto:shenghong.yang@oulu.fi)

Gang Yang: [ygang421@gmail.com](mailto:ygang421@gmail.com)

## Abstract

Platinum Group Elements (PGE) mineralization occurs associated with mafic-ultramafic rocks in different environments. Although the PGE enrichment is primarily caused by magmatic processes, remobilization of Pd and Pt by hydrothermal fluids has likely been an important mechanism in increasing the precious metal grade in many cases. However, the timing of PGE enrichment by hydrothermal fluid processes is commonly difficult to constrain.

The Jinchuan ultramafic intrusion in northwest China is ranked the world's third largest magmatic Ni-Cu sulfide deposit. Besides the main ore body consisting of net-textured and disseminated sulfides, there is hydrothermal mineralization associated with sheared contact zones of the intrusion, which shows elevated Cu and Pt concentrations. The unusually high Pt is hosted mainly in sperrylite within altered silicates. In this study, we applied the Pt-Os geochronometer to a Cu-Pt-rich ore body, yielding an isochron age of  $436 \pm 22$  Ma. This age is significantly younger than the main ore formation age of ca. 825 Ma, but similar to that of the continental collision event between the Qaidam-Qilian Block and Alax Block of North China. This indicates that the intrusion may have been uplifted during the Paleozoic orogenic processes from deeper crust, resulting in the generation of the Cu-Pt-rich hydrothermal ore body. Our new data provide the first strong age constraints on the hydrothermal PGE enrichment, showing that the Pt-Os isotope system is potentially a powerful tool for dating hydrothermal overprinting on Ni-Cu-(PGE) sulfide deposits.

**Key words:** Pt-Os dating; Jinchuan; Ni-Cu-(PGE) deposit; Hydrothermal overprinting; Orogenic uplift

## Introduction

Platinum group element (PGE) mineralization occurs in large layered intrusions in association with Ni-Cu sulfides or chromitites (e.g., Bushveld, Great Dyke, Stillwater), conduit-type small intrusions (e.g., Noril'sk), and komatiite-hosted Ni-Cu sulfide deposits (e.g., Kambalda). Platinum group elements are primarily collected by immiscible sulfide melt in magmatic processes due to high partition coefficients of these elements for sulfide melt (Naldrett 1980), or as platinum group minerals (PGM) or alloys (e.g., Pt-Fe alloy) directly crystallized from silicate magma (Godel et al. 2007; Maier et al. 2015). Remobilization of Pd and Pt by hydrothermal fluids is also likely an important mechanism in redistribution of these metals (Wood 2002 and reference therein), increasing the metal grade in many

cases. Examples include the PGE enrichment in the footwall of the Sudbury igneous complex (Naldrett et al. 1999; Farrow et al. 1994; Molnar et al. 1997; Mukwakwami et al. 2014a,b); the Lac des Iles deposit in Canada (Hinchey and Hattori 2005); the McBratney PGE-Au occurrence in the Flin Flon greenstone belt, Canada (Olivo and Theyer 2004; Bursztyn and Olivo 2010); the Ni-As-PGE-rich halo around the Miite and Sarah's Find komatiite-hosted Ni sulfide deposit in Australia (Le Vaillant et al. 2015, 2016); the Duluth complex (Ripley 1990; Ripley et al. 1993, 2001; Mogessie et al. 1991; Gal et al. 2013); and the off-set type PGE mineralization in the country rocks of the Portimo complex, Finland (Iljina 1994; Iljina and Hanski 2005; Anderson and Thalhhammer 2006).

Platinum and Pd are much more mobile in sulfide-rich than in sulfide-poor systems (Liu and Barnes 2012; Le Vaillant et al. 2015). In some cases, a metal-enriched halo around mafic-ultramafic igneous bodies is used as an exploration tool to detect Ni-Cu-PGE mineralization (Le Vaillant et al. 2015, 2016). However, it is difficult to distinguish whether a fluid-overprinting event took place in a late-magmatic stage or occurred later as a result of regional tectonic events. Precise dating of PGE enrichment would help to solve this problem. Until now, there have been few methods to determine the timing of hydrothermal overprinting of Ni-Cu-(PGE) ores, which may have significant implications for the study of PGE mineralization and further mineral exploration.

Our research target, the Jinchuan Ni-Cu-(PGE) sulfide deposit, has Ni-Cu sulfide ore resources of nearly 500 million tonnes, grading 1.2 wt% Ni and 0.7 wt% Cu. Li et al. (2004b, 2005) reported a U-Pb SHRIMP zircon age of  $827 \pm 8$  Ma and a U-Pb SHRIMP baddeleyite age of  $812 \pm 26$  Ma. Using the ID-TIMS method, Zhang et al. (2010) published more precise U-Pb ages of  $831.8 \pm 0.6$  Ma and  $832.2 \pm 0.9$  Ma for zircon and baddeleyite, respectively. The ages determined by the Re-Os method for massive ores are  $853 \pm 25$  Ma (Yang et al. 2005) and  $867 \pm 75$  Ma (Yang et al. 2008), similar to the U-Pb ages of the intrusion, which are considered to record the timing of crystallization of the intrusion and its main stage of ore formation.

The Jinchuan intrusion shows a tectonic contact with its immediate country rocks and is believed to have been thrust to its present location by a regional tectonic event (Tang et al. 1995; Zhou et al. 2002; de Waal et al. 2004; Lehmann et al. 2007; Song et al. 2012). Some authors think that this tectonic event may be related to the Qilian orogeny (Gao et al. 2009). However, there are no precise age data available to confirm this opinion.

One particular type of ore in the Jinchuan deposit can be distinguished from the main ore by its

highly sheared texture and elevated Cu and Pt contents (Gao et al. 2009; Chen et al. 2013). The sheared texture indicates that this ore type may have formed during deformation of the intrusion and related activity of hydrothermal fluids (Yang et al. 2006; Lehmann et al. 2007; Gao et al. 2009). The extremely high Pt contents and generally low common Os contents in these ore bodies make it possible to employ the  $^{190}\text{Pt}$ - $^{186}\text{Os}$  method as a tool for dating the hydrothermal enrichment event. Use of this isotopic system is complicated by the extremely long half-life of ca. 450 Ga of the parental nuclide and the low fraction of  $^{190}\text{Pt}$  in total Pt (Walker et al. 1997). Consequently, to generate resolvable differences in  $^{186}\text{Os}/^{188}\text{Os}$  and obtain useful geochronological information, samples need to be old and/or have very large differences in Pt/Os. PGE-bearing ore systems often meet these criteria and so are among the potential dating targets. Among the first attempts to apply the Pt-Os system to ore deposits were the studies of the Sudbury and Noril'sk deposits by Walker et al. (1991, 1997) and Morgan et al. (2002). Later, the Pt-Os system was successfully used to constrain the mantle source of komatiites (Puchtel et al. 2004, 2005, 2009, 2014), contribution of material from the Earth's core to certain hot spot magmas (Brandon et al., 1999, 2005), platinum mineralization in an ophiolite (Coggon et al. 2011), and the Bushveld PGE mineralization (Coggon et al. 2012), and to place time constraints on a Hadean mantle melting event (Coggon et al. 2013). In this study, we employ the  $^{190}\text{Pt}$ - $^{186}\text{Os}$  isotopic system to dating of the hydrothermal overprinting event affecting the Jinchuan Cu-Ni-(PGE) sulfide deposit and assess its relationship with the regional tectonic evolution.

## Geological Background

The Jinchuan intrusion is located in the Longshoushan thrust belt, which is a fault-bounded, NW-striking terrane between the Alax Block to the north and the northern Qilian Suture Zone to the south (Fig. 1a). The Alax Block is generally thought to represent the western part of the North China Craton (Zhao et al. 2005). It is composed of Paleoproterozoic high-grade gneisses, marbles and migmatites. The Qilian Suture Zone consists of early Paleozoic subduction complexes including ophiolitic mélanges, blueschists, and eclogites (Fig. 1). Further south is the North Qaidam Ultra-High Pressure (UHP) Belt, which consists of granitic and pelitic gneisses intercalated with blocks of eclogite and garnet peridotite and is considered to be a typical continental-type subduction complex (Fig. 1) (Yang et al. 2002; Song et al. 2003). Greenschist facies regional metamorphism related to the collisional event has affected the southern part of the Longshoushan Terrane including the Jinchuan

intrusion (Li and Ripley 2011).

The NW-SE-striking fault F1, dipping to the southwest at angles of  $>60^\circ$ , is a regional-scale thrust fault marking the northern boundary of the Longshoushan Terrane (Fig. 2a). The footwall rocks of fault F1 include Jurassic to Tertiary terrestrial clastic sedimentary rocks and sedimentary strata as young as Quaternary. Proterozoic metamorphic rocks and Paleozoic sedimentary rocks comprise the hanging wall of fault F1 (Song et al. 2012). A series of reverse faults parallel to fault F1 and dipping to the southwest with angles of  $70\text{--}80^\circ$  also occur in the region (Song et al. 2012).

The Jinchuan intrusion was emplaced into the Alax block (Fig. 1). It is about 6500 m long and from 20 m to  $>500$  m wide and dips steeply to the south or southwest (Fig. 2a, b). The main rock types include dunite, lherzolite, plagioclase lherzolite, troctolite, and olivine pyroxenite (Fig. 2a) (Chai et al. 1992a, b; Tang et al. 1993; Barnes and Tang 1999). All rocks are altered to different degrees. The intrusion displays tectonic contacts with its country rocks and has experienced extensive shearing along its southern marginal zone, resulting in greenschist-grade chlorite schists (Lehmann et al. 2007).

The Jinchuan intrusion and its sulfide ores are divided into four mining areas (from west to east, III, I, II and IV) by NE-trending faults F8, F16 and F17 (Fig. 2). The net-textured sulfide ores are hosted by dunite and to a lesser degree by lherzolite. They are commonly surrounded by disseminated ore zones, which are hosted in lherzolite and plagioclase lherzolite (Fig. 2b). Minor massive ores occur as veins cutting net-textured ores near the footwall side of the intrusion. Primary sulfide mineral assemblages consist of pentlandite, chalcopyrite, and pyrrhotite.

Sulfide ore rich in Cu and Pt occurs in sheared lherzolite and dunite and is termed sheared ore by Yang et al. (2006). The mineralization appears to be concentrated along fault F6 at the base of the concealed ore body No. 6 of the intrusion (Fig. 2b). Fault F6 strikes to the NE-E and dips to the NW with an angle of 70 degrees, varying in width from 1 to 2 m (Gao et al. 2009). A zone of pelitic schists and mylonite occurs in the F6 fault zone. Serpentine, chlorite, carbonate, and sulfide veins also occur widely within this fault zone.

The thickness of the Cu-Pt-rich ore body reaches 40 m. It has a sharp contact with Paleoproterozoic country rocks comprising gneisses, amphibolites, and marbles. Granophyre and lamprophyre xenoliths occur in the middle to upper part of the ore body. The original textures are replaced by a cataclastic breccia texture. The original silicate minerals were dominated by cumulus olivine and interstitial orthopyroxene, and 20% to 30% interstitial sulfide, with the primary magmatic

cumulus textures being well preserved (Fig. 3a). The rounded olivine grains have been extensively altered to serpentine, talc, and magnetite, with traces of chlorite, muscovite, phlogopite, tremolite, and actinolite (Li et al. 2004; Ripley et al. 2005; Yang et al. 2006; Gao et al. 2009).

The Cu-Pt-rich ores consist of disseminated or net-textured sulfides. In some samples (e.g., JCI-77, 79), the sulfides are dominated by pentlandite and minor pyrrhotite showing a primary coarse-grained interstitial texture (Fig. 3b). Minor chalcopyrite occurs as veinlets inside altered olivine grains (Fig. 3c). In some other samples (e.g., JCI-72, 82), the sulfide minerals are dominated by chalcopyrite with lesser amounts of pentlandite and pyrrhotite (Fig. 3d). In these samples, some chalcopyrite shows ductile deformation textures (Figs. 3e, f, g, h). It is worth noting that wherever a ductile texture of chalcopyrite is present, some spatially associated chlorite occurs in the vicinity (Figs. 3e, f, g, h). Later-stage pyrite veins occur in some samples.

During hydrothermal alteration, pyrrhotite, pentlandite, and chalcopyrite were replaced by mackinawite, pyrite, cubanite, vallerite, and violarite (Yang et al. 2006). In some Pt-rich samples, sperrylite grains from 10 to 30  $\mu\text{m}$  in size are found inside serpentinized olivine grains (Figs. 4a, b, c, d, e). Palladium-rich PGM grains are also encountered (Fig. 4f), which is consistent with previous studies (Yang et al. 2006; Prichard et al. 2013). In addition, abundant small grains (mostly  $<5 \mu\text{m}$ ) of PbTe(Se) were found both inside base metal sulfides (BMS) and altered silicates (Fig. 4f).

## **Sample preparation and analytical methods**

Most of our samples (codes starting with 04JCI) were collected from the 1185-m level along exploration line 6 (Fig. 2b). Samples GS-1 and GS-7 were collected from the same type of ore, but their detailed location is not available. Heavy mineral separates including mainly sulfide and minor PGM were obtained, with the sulfide minerals being mainly pyrrhotite, pentlandite, and chalcopyrite.

### *Whole-rock Cu and Ni analysis*

Nickel and Cu concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) at the National Research Center of Geoanalysis (NRCG), Chinese Academy of Geological Sciences, Beijing, China. Samples were digested with HCl, HNO<sub>3</sub>, HF, and HClO<sub>4</sub> in screw top, PTFE-lined, stainless steel bombs at 190 °C for 12 h. Indium was used as an internal standard. The precision of the analyses was generally better than 1%. Two national geochemical

standards, GBW07233 (sulfide) and GBW 07109 (granite), and an in-house standard Xinchao8 (sulfide) were used to monitor the reproducibility.

#### *Pt-Re-Os isotope analysis*

All Pt-Re-Os chemistry was performed at the NRCG. Platinum, Re and Os concentrations were measured using the isotope dilution method. The  $^{195}\text{Pt}$ ,  $^{187}\text{Re}$  and  $^{190}\text{Os}$  spikes were purchased from the Oak Ridge National Laboratory, USA, and calibrated at the NRCG. The samples were crushed and ground to less than 200 mesh using contaminant-free equipment. Approximately 4 g of whole-rock powder or 2g of each sulfide separate were weighed precisely and loaded into Carius tubes, together with  $^{195}\text{Pt}$ ,  $^{187}\text{Re}$  and  $^{190}\text{Os}$  mixed spikes, and digested by reverse aqua regia in the presence of a small amount of  $\text{H}_2\text{O}_2$  (Shirey and Walker 1995). The tubes were heated in an oven at 230 °C for about 24 h.

Osmium was separated as  $\text{OsO}_4$  by distillation at 105–110 °C and trapped by Milli-Q water. During distillation, the inverse aqua regia acted as the oxidizer. Half of the residual solution was used for Re extraction by acetone in 5 M NaOH solution (Du et al., 2001, 2004). The other half of the solution was used to pre-concentrate Pt by tellurium co-precipitation (Yang et al. 2003; Yang, 2005). Platinum and Re concentrations were measured by ICP-MS (PQ Excell) at the NRCG. The intensity of the  $^{190}\text{Os}$  signal was monitored to correct for traces of Os in Re. Hydrogen peroxide and 5% ammonia were alternately used to wash the Teflon injection tube in order to avoid cross-contamination between samples (Du et al. 2001, 2004). Using a negative thermal ionization mass spectrometer (N-TIMS, MAT-262), osmium concentrations and isotopic compositions were measured by peak jumping on an electron multiplier at the Laboratory of Crust–Mantle Materials and Environments, University of Science and Technology of China. All measured ratios were corrected for oxygen isotopic compositions (Sun et al. 1997), and iteration was used to correct mass fractionation and calculate Os concentrations and isotopic compositions based on a  $^{192}\text{Os}/^{188}\text{Os}$  ratio of 3.0827 (Yang 2005; Yang et al. 2008).

An in-house standard, HLP molybdenite, was used to monitor the reproducibility of the Re-Os measurements (Du et al. 2012). The Re and  $^{187}\text{Os}$  contents and Re–Os ages of HLP determined during the course of this work were  $276.3 \pm 2.0$  ppm,  $648.1 \pm 4.5$  ppb and  $221.0 \pm 4.6$  Ma ( $n=2$ ), respectively, which coincide within uncertainties with the reference values (Re =  $283.8 \pm 6.2$  ppm, Os =  $659 \pm 14$  ppb and  $t = 221.4 \pm 5.6$  Ma; Du et al. 2012). For Pt, three national standards, GBW07293, GBW07291 and GBW07102, were systematically analyzed (5 analyses for each). The measured values are  $407.0 \pm$

32 ppb,  $66 \pm 12$  ppb, and  $11.0 \pm 5.7$  ppb, consistent with the reference values of  $440 \pm 37$  ppb,  $58 \pm 5$  ppb, and  $6 \pm 1$  ppb, respectively (Yan et al. 1998). The generally large variations in the analyzed results are due to the smaller amounts of sample material analyzed in this study (1g) compared to the recommended amount (10g) (Yan et al. 1998). The results of standard GBW07293 with higher Pt content show a better reproducibility, and it is worth noting that our samples contain high Pt contents similar to that of this standard. Because we did not have reference material with certified  $^{186}\text{Os}/^{188}\text{Os}$  ratios to monitor the analytical accuracy of the  $^{186}\text{Os}/^{188}\text{Os}$  values of the samples, we measured one sample (04JCI-79S) with a low  $^{190}\text{Pt}/^{188}\text{Os}$  ratio of 0.03, as this sample should have insignificant amount of radiogenic  $^{186}\text{Os}$ , and thus a mantle like  $^{186}\text{Os}/^{188}\text{Os}$  ratio of about 0.11984 at 830 – 430 Ma (Puchtel et al. 2005). Five replicate analyses of this sample, without addition of spike, yield an average  $^{186}\text{Os}/^{188}\text{Os}$  ratio of  $0.1208 \pm 0.0012$ , consistent with the expected mantle value within error.

Platinum blanks varied from 0.4 to 1.3 ng, and are thus insignificant relative to the quantity of Pt obtained from most samples (160 to >100000 ng). Two whole rock samples (04JCI-77, 79) with relatively low amounts of Pt (4.6 to 15 ng) may be affected by blank, but the extremely low  $^{190}\text{Pt}/^{188}\text{Os}$  ratios of these two samples (0.0003, 0.0017) imply that the Pt blank had a negligible effect on the Pt-Os isochron age calculation. Rhenium blanks range from 8 to 30 pg, insignificant relative to the quantities of Re analyzed in the samples (2200–45,000 pg). Osmium blanks range from 0.7–3.4 pg, significantly lower than the amount of Os derived from the samples (170–15700 pg).

The age calculations were made using the  $^{187}\text{Re}$  decay constant ( $1.666 \times 10^{-12}$ ) from Smoliar et al. (1996), and  $^{190}\text{Pt}$  decay constant ( $1.542 \times 10^{-12}$ ) from Walker et al. (1997). In the Re-Os and Pt-Os isochron calculation performed using the ISOPLOT program (Ludwig 2003), the absolute errors used for  $^{187}\text{Re}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$ , and  $^{190}\text{Pt}/^{188}\text{Os}$  and  $^{186}\text{Os}/^{188}\text{Os}$  are those listed in Table 1.

#### *In-situ sulfur isotope analysis*

In-situ sulfur isotope analyses of pyrrhotite and chalcopyrite were conducted using a Nu Plasma HR multicollector ICPMS at the Geological Survey of Finland in Espoo together with a Photon Machine Analyte G2 laser microprobe (Molnar et al. 2016; Maier et al. 2016). Samples were ablated in He gas (gas flows = 0.4 and 0.1 l/min) within a HelEx ablation cell (Müller et al. 2009). During the ablation, the data were collected in static mode ( $^{32}\text{S}$ ,  $^{34}\text{S}$ ). Line spots of pyrrhotite and chalcopyrite were ablated at a spatial resolution of 30  $\mu\text{m}$  in diameter and about 150  $\mu\text{m}$  in length, using a fluence of



2.7 J/cm<sup>2</sup> and a repetition rate of 4 Hz. The total S signal obtained for chalcopyrite was generally below 3 V and for pyrrhotite, it was below 2 V. Under these conditions, after a 20 s baseline measurement, ~100 s of ablation is needed to obtain an internal precision of  $^{34}\text{S}/^{32}\text{S}$   $6 \pm 0.00001$  ( $2\sigma$ ). In-house pyrrhotite (Polopo) and chalcopyrite standards (Cpy1) were used for external standard bracketing and in-house pyrite (Py1) and chalcopyrite standards (Cpy2) were employed for quality control. An average  $\delta^{34}\text{S}$  (CDT) value of  $-1.02 \pm 0.32\text{‰}$  ( $2\sigma$ ,  $n = 3$ ) was obtained for Py1, which is consistent with the value of  $-0.6 \pm 1.2\text{‰}$  ( $2\sigma$ ) measured by gas mass spectrometry. For Cpy2, we obtained an average value of  $-0.57 \pm 0.28\text{‰}$  ( $2\sigma$ ,  $n = 3$ ), which is consistent with the gas mass spectrometry value of  $-0.7 \pm 1.0\text{‰}$  ( $2\sigma$ ).

## **Analytical results**

Concentrations of Pt, Re, Os, Ni, and Cu, Re-Os and Pt-Os isotopic data for whole-rock samples and sulfide separates are presented in Table 1. The sulfide separates generally have much higher Pt contents than the whole-rock samples, ranging from 4 to 40 times, indicating a dominant control of Pt by sulfide minerals. The sulfide separates also show higher Re and Os contents than the whole-rock samples, but generally less than 8 times, indicating that part of Re and Os is also contained in the silicate fraction. This results in higher Pt/Os ratios for the sulfide separates than for the bulk-rock samples, but the contrast of Re/Os ratios between sulfide separates are much less. One group of our Cu-Pt rich ore samples (04JCI-77, 79) have the highest Ni contents (25,000–48,000 ppm) and a relatively low Cu contents (8000–21000 ppm) with the lowest Cu/Ni ratios (0.2 to 0.8 in whole-rock samples). These two samples have the highest Os contents, of 80 and 8 ppb respectively, and relatively low Pt/Os ratios of <56. Another group of samples (04JCI-72, 74, 75, 81, 82) contains lower Ni contents (<13,000 ppm) and clearly higher Cu contents (20,000 to 60,000 ppm) with higher Cu/Ni ratios ranging from 3.1 to 5.4. These samples show extremely high Pt concentrations (up to 13000 ppb in whole rock), low Os concentrations (mainly <0.4 ppb in whole rock), and high Pt/Os ratios up to 120000 (whole rock). Two samples (73, 86) have a composition between the two groups (Fig. 5). Compared to the large variation of Pt/Os, the Cu and Pt-rich samples only show several times higher Re/Os ratios than the Ni-rich samples.

The samples show poor linearity on the  $^{187}\text{Re}/^{188}\text{Os}$  vs.  $^{187}\text{Os}/^{188}\text{Os}$  isochron diagram, yielding an  
 errorchron age of  $519 \pm 130$  Ma, with an initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio of  $0.41 \pm 0.13$  (MSDW=3417). The  
 samples have a large spread in  $^{190}\text{Pt}/^{188}\text{Os}$ , with maximum ratios reaching values of ca. 350 (Fig. 7). On  
 the  $^{190}\text{Pt}/^{188}\text{Os}$  vs.  $^{186}\text{Os}/^{188}\text{Os}$  isochron diagram, the samples show better linearity than the Re-Os  
 isotope system, yielding an isochron age of  $433 \pm 40$  Ma and an initial  $^{186}\text{Os}/^{188}\text{Os}$  ratio of  $0.1291 \pm$   
 $0.0074$  (MSWD=168) (Fig. 7). Two replicates of sulfide separates and one whole-rock analysis of  
 sample 04JCI-81 plot quite far from the isochron (Fig. 7). If the obvious outliers (sample 04JCI-81) are  
 neglected, the refined isochron age becomes  $436 \pm 23$  Ma and the initial  $^{186}\text{Os}/^{188}\text{Os}$  ratio  $0.1242 \pm$   
 $0.0047$  (MSWD = 41) (Fig. 8a). For most samples, the whole-rock and sulfide separate compositions  
 generally plot close to the isochron trend, though only one whole rock and four sulfide separates  
 overlap with this trend within their uncertainty limits (Fig. 7). If calculated using only the sulfide  
 separate samples (without sample 04JCI-81), the isochron age becomes  $432 \pm 28$  Ma and the initial  
 $^{186}\text{Os}/^{188}\text{Os}$  ratio  $0.1253 \pm 0.0069$  (MSWD = 24) (Fig. 8b), which is indistinguishable from the results  
 calculated using both sulfide separate and whole rock samples (Fig. 8a). Nevertheless, regardless of  
 whether all samples or sulfides alone are considered, the MSWD value calculated for the Pt/Os  
 isochron greatly exceeds one. This implies that the one or both of the conditions required for  
 development of a true isochron (complete isotopic equilibration at the time of the event of interest and  
 lack of disturbance of the Pt/Os systematics since that time) is not fulfilled. This must be borne in mind  
 when making tectonic interpretations of the apparent age. The results listed above are based on the  
 isotope abundance and decay constant of  $^{190}\text{Pt}$  from Walker et al. (1997). A similar age is obtained if  
 the recommended values of Begemann et al. (2001) are used.

Pyrrhotite and chalcopyrite of 7 samples from the Cu-Pt-rich ores were analyzed for in-situ S isotope composition (Table 2). Pyrrhotite from Ni-rich ore (04JCI-77, 79) has  $\delta^{34}\text{S}$  (CDT) values ranging from  $-0.67 \pm 0.18\text{‰}$  to  $+0.10 \pm 0.14\text{‰}$ , indistinguishable from the values of  $-0.128 \pm 0.12\text{‰}$  to  $+0.38 \pm 0.15\text{‰}$  obtained for pyrrhotite and chalcopyrite of Cu-Pt-rich ores. There is no difference between coarse-grained pyrrhotite and chalcopyrite and fine-grained veinlet-like chalcopyrite, which is disseminated in serpentine (Fig. 9). All analyses form a peak from -1.0 to +0.5‰ (Fig. 10).

## Discussion

### *Magmatic and hydrothermal enrichment*

The genesis of Ni-Cu-(PGE) sulfide deposits are generally attributed to segregation of an immiscible sulfide liquid from a mafic-ultramafic magma (Naldrett 1980). Late-stage magmatic or hydrothermal fluids may also have played some role in redistribution of the metals to variable degrees (Boudreau et al. 1986; Le Vaillant et al. 2015). The generally good positive correlation between chalcophile metal and sulfur contents in the main ore bodies (No.1, 2, 24) of the Jinchuan intrusion indicates that the major mineralization is controlled by magmatic sulfides (Chai and Naldrett 1992b). This is supported by a very good positive correlation between metal tenors of iridium group PGEs (IPGE: Os, Ir, Ru, not shown, data from Chai and Naldrett 1992b). For the Cu-Pt-rich ores of this study, the magmatic enrichment is evidenced by the well-preserved interstitial sulfide textures (Fig. 3a).

The main ore bodies in the Jinchuan intrusion have Cu/Ni ratios of around 0.5, and Pt/Ir ratios of around 50, which are consistent with a high-Mg basaltic parental magma composition (Chai and Naldrett 1992a; Yang et al. 2006; Song et al. 2006). Hydrothermal fluid process has also been proposed to play some role in the redistribution of metals to variable degrees, especially in the Cu-Pt rich ore as supported by several lines of evidence (Chai et al. 1999b; Yang et al. 2006; this study). The silicate minerals have been extensively altered (Yang et al. 2006; this study). One important feature of this ore type is that abundant Pt-Pd-bearing platinum group minerals (PGM) occur in altered silicates (e.g., serpentine), associated with other hydrous minerals (e.g., chlorite) or fractures of base metal sulfide (BMS). This is clearly different from the main ore bodies where PGM mainly occur as small inclusions

enclosed in BMS (Yang et al. 2006; this study). Silver-bearing PGM was identified in the Cu-Pt-rich ore hosted in altered silicates, whereas this type of PGM is absent in the main ore bodies (Yang et al. 2006). Compared with the main ore bodies, the Cu-Pt-rich ore shows clearly elevated Cu, Pt, Pd and Au concentrations on the primitive mantle normalized chalcophile element patterns, with the (Pt+Pd)/(Os+Ir+Ru+Rh) ratio increasing from <7 in the main ore bodies to 240-710 in the Cu-Pt-rich ore (Pt up to 80 ppm; Fig. 7 in Yang et al. 2006). All these features suggest that a hydrothermal fluid has significantly changed the metal composition in the Cu-Pt-rich mineralization.

In our study, two samples (04JCI-77, 79) have similar Cu/Ni and Pt/Os ratios to those of the nearby main ore body (Fig. 3). These two samples also show relatively high whole-rock Os contents (8.5–79.6 ppb), also similar to those of the nearby ore body (Fig. 3). Another group of samples (04JCI-72, 74, 75, 81, 82, 86) show high Cu/Ni and Pt/Os ratios. The two sample groups have different sulfide mineral assemblages, with that of the first group being dominated by pentlandite and pyrrhotite (Fig. 3b) and that of the second group by chalcopyrite with minor pentlandite (Fig. 3c). This may indicate that monosulfide solid solution (MSS) fractionation played some role in the distribution of metals, which has also been proposed for the metal content variations in the main ore bodies (Su et al. 2008; Chen et al. 2013). However, we have observed abundant small veinlets of chalcopyrite within altered silicates (Fig. 3c), and some chalcopyrite associated with chlorite shows ductile textures (Figs. 3e, f, g, h). In addition, sperrylite occurs mainly in serpentine (Fig. 4). These features support the interpretation of previous studies that a later-stage fluid may have redistributed metals in the Cu-Pt-rich ores (Yang et al. 2006; Gao et al. 2009).

Though both Pt and Pd are high in the Cu-Pt rich ore, Pt is generally more enriched over Pd resulting in high Pt/Pd ratios ranging from 7 to 50 (Yang et al. 2006; Chen et al. 2013). On the other hand, it has been reported that negative Pt anomalies occur in net-textured and massive ores in some of the Nos. 1 and 2 main ore bodies, which show variable Pt/Pd ratios, with the lowest values being as low as 0.02 (Su et al. 2008; Song et al. 2009; Chen et al. 2013). Song et al. (2009) suggest that the fractionation of sulfide liquid may not differentiate Pt and Pd, as the two elements have similar partition coefficients between MSS and sulfide melt (Barnes et al., 1997; Mungall and Brenan, 2014). It is proposed that the Pt depletion probably resulted from precipitation of Pt-Fe alloys together with chromite prior to sulfide saturation (Song et al. 2009). However, disseminated ores in these ore bodies do not show a negative Pt anomaly (Song et al. 2009; Chen et al. 2013). Another possible mechanism is

hydrothermal fluid redistribution of metals (Chai et al. 1992b; de Waal et al. 2004; Ripley et al. 2005; Yang et al. 2006; Gao et al. 2009; Su et al. 2008; Song et al. 2009). A recent paper summarized all the published PGE data of the Jinchuan deposit, the primitive mantle normalized PGE patterns of the main ore bodies exhibit both positive and negative Pt anomalies (Fig. 8 in Duan et al. 2016), in agreement with a hydrothermal fluid redistribution of Pt.

The solubility of Pt and Pd in hydrothermal fluid is dependent on several factors, including oxidation condition, PH and salinity (Barnes and Liu 2012). Under oxidized conditions, the predominant Pt and Pd species are chloride complexes. In contrast, under more reduced conditions, bisulfide complexes predominate (Barnes and Liu 2012). Fluid inclusions in hydrous minerals (e.g., tremolite) in the Cu-Pt-rich ore of Jinchuan have been studied in detail by (Yang et al. 2006). The fluid phases include chlorine as well as CO<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>S, with homogenization temperature being in the range of 235-365 °C (Yang et al. 2006). This indicates that the fluid is under a relatively reduced condition, and Pt and Pd occur mainly as bisulfide in fluid. Meanwhile, the high sulfide content of the Jinchuan ore samples makes Pt and Pd highly soluble in hydrothermal fluid (Barnes and Liu 2012). However, in any conditions, Pd is more soluble in hydrothermal fluids than Pt and therefore is easier to dissolve and remobilize by hydrothermal fluids (Keays et al. 1981; Wood et al. 1992; Xiong and Wood 2000; Seabrook et al. 2004; Barnes and Liu 2012). Hence, later hydrothermal alteration is more likely to remove more Pd than Pt, giving rise to positive and negative Pd anomalies rather than those of Pt (Prichard et al. 2013). The Pt-Os age of the Cu-Pt-rich ore is about 430 Ma, significantly younger than the main magmatic stage of about 830 Ma (see later discussion), indicating the major Pt enrichment is clearly not magmatic but related to a post-magmatic hydrothermal fluid event. However, the reason for the enrichment of Pt over Pd is difficult to explain. During the cooling of sulfide melt, about half of Pd is hosted in BMS, mainly in pentlandite, and a lesser amount in pyrrhotite and chalcopyrite, while the majority of Pt is hosted in PGM inside BMS, or at the contact between BMS and silicates (Godel et al. 2007; Holwell and McDonald 2007; Chen et al., 2014). It may be possible that leaching of Pd from BMS is less efficient than Pt from small Pt-bearing PGM grains. The sulfur isotope compositions of the Cu-Pt-rich ore are indistinguishable from the compositions of the main ore bodies obtained previously by Ripley et al. (2003), consistent with mobilization of sulfur from the main ore body to the Cu-Pt-rich mineralization.

We suggest that the high Pt/Os and Cu/Ni ratios of some Cu-Pt-rich ores are produced firstly by

fractionation of sulfide liquid in a magmatic stage, which was followed by overprinting via a hydrothermal fluid process, elevating further the Cu, Pt, Pd and Au contents. Probably in a similar way to the metal redistribution in the Sarah's Find deposit in Western Australia, circulation of As-rich hydrothermal fluids dissolved base metals, Pd, and Pt from the main orebodies and redeposited them along a sheared footwall contact (Le Vaillant et al. 2016).

#### *Age of Pt enrichment*

The Re-Os isochron show poor linearity with an errorchron age of  $519 \pm 130$  Ma, with an initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio of  $0.41 \pm 0.13$  (MSDW=3417). The poor linearity could be explained by inhomogeneity of initial  $^{187}\text{Os}/^{188}\text{Os}$  ratio which will be discussed later. On the Pt-Os isochron diagram, duplicate analyses of two sulfide separates and one whole-rock analyses of sample 04JCI-81 plot above the isochron (Fig. 7). This could potentially be explained by mobility of Pt during a late-stage disturbance after the main hydrothermal fluid event. However, in most cases, the analyses of sulfide separates and whole-rock samples plot along the isochron line, especially for those samples with high Pt/Os ratios that dominate the age result (04JCI-72, 74, 75, 82) (Fig. 7). This indicates that the later-stage disturbance may be local and the main system has preserved the original isotopic composition. Samples without the outliers of samples 04JCI-81 yield an isochron age of  $436 \pm 23$  Ma (Fig. 8a). This age is quite similar to the isochron age ( $433 \pm 40$  Ma) obtained from all samples (including 04JCI-81). If we only consider the isochron obtained from the sulfide separates of these samples (without 04JCI-81), the isochron age will be  $432 \pm 28$  Ma, similar to the isochron age defined by whole rock and sulfide separates. The initial  $^{186}\text{Os}/^{188}\text{Os}$  ratio ( $0.1242 \pm 0.0047$ , or  $0.1253 \pm 0.0069$  sulfide only) is comparable to the mantle value at ca. 430 Ma ( $\sim 0.11984$ , Puchtel et al. 2005; Brandon et al. 2006; Coggon et al. 2013), confirming the possibility of a  $\sim 435$  Ma age. This age is significantly younger than that of the main magmatic and ore-forming processes of the Jinchuan intrusion, which occurred at ca. 830 Ma (Li et al. 2004, 2005; Yang et al. 2005; 2008; Zhang et al. 2010). Regarding the disturbance of samples 04JCI-81, one potential possibility is the effect of the Indo and Eurasian collision in Cenozoic (Zhang et al. 2009).

The Jinchuan main ore body contains a considerable amount of Pt, which could have generated radiogenic  $^{186}\text{Os}$  between crystallization of the primary ore and the time of the proposed hydrothermal

event. The main ore bodies of the Jinchuan intrusion generally have Pt/Os ratios lower than 50 (Chai and Naldrett 1992b; Su et al. 2008; Song et al. 2009; Li and Ripley 2011; Chen et al. 2013). Assuming that the crystallization of the intrusion and the main ore formation took place at 830 Ma (Li et al. 2005; Zhang et al. 2010; Yang et al. 2005; Yang et al. 2008), the radiogenic  $^{186}\text{Os}$  produced within the following 400 Ma would yield a  $^{186}\text{Os}/^{188}\text{Os}$  ratio lower than 0.000035. This value will be elevated to 0.0007 if a higher Pt/Os ratio of 1000 is assumed. In any case, the radiogenic  $^{186}\text{Os}/^{188}\text{Os}$  ratio is extremely low at about 400 Ma and has a negligible impact on the homogeneity of initial  $^{186}\text{Os}/^{188}\text{Os}$  ratios of our samples on the isochron diagram. This is an advantage of the Pt-Os isotope system compared to the Re-Os system in dating later-stage hydrothermal enrichments in Ni-Cu-PGE sulfide deposits, because the Re-Os system has clearly higher inherited radiogenic  $^{187}\text{Os}$  due to both the much higher abundance of  $^{187}\text{Re}$  and its shorter half-life relative to that of  $^{190}\text{Pt}$ . These could produce large heterogeneities in initial  $^{187}\text{Os}/^{188}\text{Os}$  at the time of a hydrothermal event if the fluid enrichment event is significantly younger than the intrusion, and thus could explain the poor linearity of the Re-Os isochron of the Jinchuan Cu-Pt rich ore samples (Fig. 6).

#### *Link to the regional tectonic evolution*

To the south of the Longshoushan Group are the North Qilian high-pressure (HP) belt and the North Qaidam ultra-high-pressure (UHP) belt (Fig. 1a), which are juxtaposed 250 km apart from each other. Eclogites from both belts, with protoliths of MORB and OIB affinities, have yielded similar metamorphic ages (464 vs. 500–457 Ma; Song et al. 2006; Zhang et al. 2006). These eclogites are interpreted to result from subduction of cold oceanic crust from the south to the north (Song et al. 2003, 2006; Cao et al. 2011). The closure of the Qilian Ocean and subduction cessation took place at ~446 Ma. This inference is based on several lines of evidences, including the  $446\pm3$  Ma age of the latest arc volcanic rocks (Wang et al., 2005), and the 446–454 Ma Ar–Ar ages of phengitic mica from the blueschist belt (Liou et al. 1989; Liu et al. 2006). Ultra-high pressure metamorphic ages of the North Qaidam belt are constrained at c. 423 Ma by U–Pb SHRIMP dating of zircon from garnet peridotites (Song et al. 2005) and coesite-bearing metapelites (Song et al. 2006), and are proposed to result from continental subduction (Song et al. 2005, 2006, 2014). Intensive uplift during the Qilian orogeny is marked by the Lower Devonian intermontane molasse well developed throughout the North Qilian orogenic belt, which is interpreted to result from continental collision between the Alax Block and

Qilian–Qaidam Block. The age of the molasse formation is dated at 417 Ma by employing the Ar–Ar method of to blue schists (Lin et al. 2010) and at 404–424 Ma by using U–Pb zircon retrograde ages of eclogite samples (Song et al. 2014). These ages are consistent with those of the syn-collisional felsic intrusions, including the Jinfosi intrusion in the northwestern part of the North Qilian orogenic belt ( $424 \pm 3$  Ma, Wu et al. 2010) and the Laohushan intrusion in the eastern part of the North Qilian orogenic belt ( $423.5 \pm 3$  Ma, Qian et al. 1998).

The collision between the Alax Block and Qilian–Qaidam Block is also recorded by the regional-scale ductile shear zone striking NW–SE at the southern margin of the North Qilian suture zone (Fig. 1, Qi et al. 2004). The lower age limit of the shear zone is estimated to be 440 Ma, as represented by the youngest felsic volcanic rocks which have experienced intensive shearing (502–440 Ma, Yin et al. 1998; Guo et al. 2001), whereas the upper age limit is constrained by a number of felsic intrusions with ages of 388 to 403 Ma which cut the shear zone (Yin et al. 1998; Guo et al. 2001). Qi et al. (2004) reported Ar–Ar ages of biotite and K–feldspar separated from mylonite of the shear zone, ranging from 395–380 Ma, which also define the upper age limit for the shear zone.

In the Jinchuan intrusion area, a high degree of alteration near the contact zone is evidenced by the occurrence of actinolite replacing olivine (Li et al. 2004) and tremolite replacing clinopyroxene (Ripley et al. 2005). Based on the lithological observations, de Waal et al. (2003) suggested that the current dip of the Jinchuan intrusion is due to a counterclockwise rotation after emplacement, with the original intrusion being a sub-horizontal sill instead of a vertical dike-like body. Through geochemical and structural studies, Song et al. (2012) suggested that the four ultramafic segments at Jinchuan were originally portions of two separate subhorizontal intrusions, which emplaced at different stratigraphic levels and were subsequently rotated and dismembered. Lehmann et al. (2007) performed detailed mapping of the contact zone between the intrusion and its country rocks and found several lines of evidence supporting the model in which the emplacement of the intrusion is ‘tectonic’: 1) The contacts at the north and south of the intrusion are clearly discordant and the gneiss–intrusion contact is highly sheared in the south; 2) lenses of peridotite up to 30 m in length occur in the country rock, with cores of olivine–pyroxene cumulate and margins of schist and chlorite schist, and 3) the southern contact is gently curved and its orientation follows that of the foliation of the gneisses. A ductile shear zone parallel to the F1 fault at Jinchuan occurs 10 km to the south of the Jinchuan intrusion, striking NW to SE with a width of several meters to tens of meters. This shear zone is recorded by mylonite foliation



and stretching lineation, shearing folds (Ma 2012; Yang et al. 2013). Based on cross-cutting relationship between intrusions and the ductile shear zone, the age of the ductile shear zone in this region is estimated to be between 570 Ma and 410 Ma (Yang et al. 2013). This age is similar to that of the regional-scale ductile shear zone on the southern margin of the North Qilian subduction zone, which is located tens of kilometers to the SW (440–403 Ma, Qi et al. 2004). The similar age and similar NW-SW foliation direction indicates that they may belong to the same system.

The presence of a ductile texture of chalcopyrite in the Cu-Pt-rich ores of Jinchuan clearly indicates deformation related to the shearing of the intrusion, and hydrothermal fluid enrichment of Cu and Pt may have occurred during this process (Figs. 3F, H, Yang et al. 2006; Gao et al. 2009). The Pt-Os isotopic age of the Cu-Pt-rich ores in the Jinchuan intrusion is identical to the continental subduction stage between the Qaidam-Qilian Block and Alax Block. It is possible that the related regional compressional forces uplifted the Longshoushan Terrane from deeper crust.

#### *Implications for sulfide mineralization*

To form sulfide-rich magmatic Ni sulfide deposits, addition of external crustal sulfur to a mantle-derived magma is often considered a critical factor (Keays and Lightfoot 2010; Ripley et al. 2013). In most major Ni-Cu sulfide deposits, e.g., Noril'sk, Pechenga, and Voisey's Bay, sulfide-/or sulfate-rich country rocks have provided sulfur to the magma (Hannah and Stein 2002; Li et al. 2003, 2009; Hanski et al. 2011; Ripley et al. 2002). Among the rare important Ni sulfide deposits without associated sulfide-rich country rocks are the Jinchuan and Nebo Babel (Australia) deposits. In Nebo Babel, it is suggested that no crustal sulfur was assimilated by the magma based on the homogeneous and mantle-like sulfur isotope compositions (Seat et al. 2009). The country rocks of the Jinchuan intrusion are dominated by gneisses, marbles, and migmatites with a very limited amount of sulfide. Based on the potential interaction between the magma and marbles, Lehmann et al. (2007) suggest that assimilation of marble may have oxidized the magma, facilitating sulfide saturation. However, an important difference between Jinchuan and Nebo Babel is the much higher sulfide abundance at Jinchuan, with the domination of sulfide rich net-textured ores. Our new obtained sulfur isotope data from the Cu-Pt-rich ore exhibit  $\delta^{34}\text{S}$  (CDT) values mainly from -1.0 to +1.0‰ with mantle-like signature, similar to the values of most samples analyzed by Ripley et al. (2005). However, a few samples show higher  $\delta^{34}\text{S}$  (CDT) ranging from +3.0 to +8.3‰ (Ripley et al. 2005). Recently, multiple

sulfur isotope ( $\Delta^{33}\text{S}$ ) anomaly has been reported in the Jinchuan sulfide ores, though these samples also show mantle like  $\delta^{34}\text{S}$  (-1 - +2‰). This is interpreted as evidence for a contribution of Archean crustal sulfur from country rocks in ore formation (Duan et al. 2016). The situation is similar to some other magmatic Ni sulfide deposits showing  $\Delta^{33}\text{S}$  anomaly but mantle like  $\delta^{34}\text{S}$  (CDT) (Fiorentini et al. 2012; Konnunaho et al. 2013).

#### *Implications for dating of hydrothermal fluid process*

During hydrothermal enrichment, Pt is generally much more mobile than Os, and hence ores with extremely high Pt/Os ratios could be generated, such as we suggest to have happened at Jinchuan. Resulting in high Pt/Os ratios will facilitate the acquisition of high-quality Pt-Os ages. The Jinchuan case suggests that the Pt-Os isotope system is potentially a powerful tool for dating hydrothermal fluid overprinting of Cu-Ni-(PGE) sulfide deposits and could be applied to other Cu-Ni-(PGE) deposits worldwide. For example, in the Sudbury Igneous Complex (SIC), magmatic-segregation is the main process accounting for the massive sulfides in the Sublayer and Footwall Breccia (Naldrett 1989). Nevertheless, the effects of hydrothermal overprinting are observed in the foot-wall rocks, especially in the southern range, and this process may have enriched Cu and PGE (Mukwakwami et al. 2014a, b). The hydrothermal alteration may be related to deformation triggered by the Penokean Orogeny. U-Pb dating of titanite yield has yielded an age of  $1849 \pm 6$  Ma, suggesting that the deformation occurred immediately after crystallization of the SIC during the Penokean Orogeny (Mukwakwami et al. 2014a). However, most titanite grains are discordant, and the timing of hydrothermal fluid overprinting could potentially be confirmed using the Pt-Os isotope system. In the Portimo complex in Finland, the origin of the PGE enrichment in the off-set type PGE mineralization in the footwall rocks is not clear, The debate centers on whether this mineralization formed in the in a late magmatic stage at ca. 2.44 Ga or in a later hydrothermal fluid episode during the Svecofennian orogeny at 1.9-1.8 Ga (Lahtinen et al. 2005) . Anderson and Thalhhammer (2006) attempted to date the Portimo off-set ores using the Re-Os isotope system, but it turned out that this system may have been disturbed by a fluid process as it did not yield a reasonable age. Therefore, it would be worthwhile to try to date the Portimo PGE-rich ores could be using the Pt-Os isotopic system, as a further test on the ability of the Pt-Os system to date hydrothermal overprints.

## Conclusions

The Jinchuan Cu-Pt-rich ore exhibits extensive alteration, consistent with an enrichment of Cu and Pt in a late hydrothermal fluid process. The Pt-Os isochron age of the Cu-Pt-rich ore body is about 430 Ma, clearly younger than the main ore formation episode at about 825 Ma but similar to the age of the regional collision event between the Qiamdam-Qilian and Alax Blocks. We suggest that the Cu-Pt-rich ore formed during the uplift of the Longshoushan Terrane from depth due to the regional tectonic compression during the Paleozoic orogenic processes. The Jinchuan case suggests that the Pt-Os isotope system is potentially a powerful tool for dating hydrothermal overprinting of Ni-Cu-(PGE) sulfide deposits.

## Acknowledgements

We are grateful to Tongyou Liu, Fugui Qiao, Jiapu Jiang, Lizhong Xiao, and Rongqi Sun of the Jinchuan Nonferrous Metal Cooperation for assistance with the fieldwork. We thank Yulong Tian and Yalin Gao of the Jinchuan Nonferrous Metal Cooperation, Zongli Tang and Jiangang Jiao of Chang'an University, and Li Chusi of Indiana University for enlightening discussions. We thank Wang Ruiting of Northwest Mining and Geology Group Cooperation Limited for providing two samples. We are grateful to Fagang Zeng and Li Li for assistance in chemistry related to Pt, Os, Cu and Ni analyses and Fengjiao Li for assistance in sample preparation for N-TIMS measurements. Holly Stein and Laurie Reisberg are thanked for their constructive and helpful reviews. This work is supported by the NSFC (grants 40373010, 40534020 and 40972070) and Academy of Finland (No. 276614, 281859).

## References

- Andersen JCQ, Thalhhammer OAR (2006) Platinum-Group Element and Re-Os Isotope Variations of the High-Grade Kilvenjärvi Platinum-Group Element Deposit, Portimo Layered Igneous Complex, Finland. *Econ Geol* 101:159–177
- Barnes Sarah-J, Makovicky E, Makovicky M, Rose-Hansen J, Karupmoller S (1997) Partition coefficients for Ni, Cu, Pd, Pt, Rh, And Ir between monosulfide solid solution and sulfide liquid and the formation of compositionally zoned Ni–Cu Sulfide bodies by fractional crystallization of sulfide liquid. *Can J Earth Sci* 34:366–374

558 Barnes SJ, Tang ZL (1999) Chrome spinel from the Jinchuan Ni-Cu sulfide deposit, Gansu province,  
559 People's Republic of China. *Econ Geol* 94:343–356

560 Barnes SJ, Liu W (2012) Pt and Pd mobility in hydrothermal fluids: Evidence from komatiites and  
561 from thermodynamic modelling. *Ore Geol Rev* 44:49–58

562 Begemann F, Ludwig KR, Lugmair GW, Min K, Nyquist LE, Patchett PJ, Renne PR, Shih CY, Villa IM,  
563 Walker RJ (2001) Call for an improved set of decay constants for geochronological use. *Geochim*  
564 *Cosmochi Acta* 65:111–121

565 Boudreau AE, Mathez EA, Mccallum IS (1986) Halogen geochemistry of the Stillwater and Bushveld  
566 Complexes: evidence for transport of the platinum-group elements by Cl-rich fluids. *J Petrol*  
567 27:967–986

568 Brandon AD, Walker RJ, Puchtel IS (2006) Platinum osmium isotope evolution of the Earth's mantle:  
569 constraints from chondrites and Os-rich alloys. *Geochim Cosmochim Acta* 70:2093–2103

570 Bursztyn NE, Olivo GB (2010) PGE-Rich Ni-Cu sulfide mineralization in the Flin Flon Greenstone  
571 Belt, Manitoba, Canada: Implications for hydrothermal remobilization of platinum group elements  
572 in basic-ultrabasic sequences. *Econ Geol* 105:1469–1490

573 Cao Y, Song SG, Niu YL, Jung H, Jin ZM (2011) Variation of mineral composition, fabric and oxygen  
574 fugacity from massive to foliated eclogites during exhumation of subducted ocean crust in the  
575 North Qilian suture zone, NW China. *J Metamorph Geol* 29:699–720

576 Chai G, Naldrett AJ (1992a) The Jinchuan ultramafic intrusion: cumulate of a high-MgO basaltic  
577 magma. *J Petrol* 33:277–303

578 Chai G, Naldrett AJ (1992b) Characteristics of Ni–Cu–PGE mineralization and genesis of the Jinchuan  
579 deposit, northwest China. *Econ Geol* 87:1475–1495

580 Chen LM, Song XY, Keays RR, Tian YL, Wang YS, Deng YF, Xiao JF (2013) Segregation and  
581 fractionation of magmatic Ni-Cu-PGE sulfides in the Western Jinchuan intrusion, northwestern  
582 China: Insights from platinum group element geochemistry. *Econ Geol* 108: 1793–1811

583 Chen LM, Song XY, Danyushevsky LV, Wang YS, Tian YL, Xiao JF (2015) A laser ablation ICP-MS  
584 study of platinum-group and chalcophile elements in base metal sulfide minerals of the Jinchuan  
585 Ni–Cu sulfide deposit, NW China. *Ore Geol Rev* 65:955–967

586 Coggon JA, Luguet A, Nowell GM, Appel PWU (2013) Hadean mantle melting recorded by southwest  
587 Greenland chromitite  $^{186}\text{Os}$  signatures. *Nat Geosci* 6:871–874

588 Coggon JA, Nowell GM, Pearson DG, Parman SW (2011) Application of the  $^{190}\text{Pt}$ – $^{186}\text{Os}$  isotope system  
589 to dating platinum mineralization and ophiolite formation – An example from the Meratus  
590 Mountains, Borneo. *Econ Geol* 106:93–111

591 Coggon JA, Nowell GM, Pearson DG, Oberthür T, Lorand JP, Melcher F, Parman SW (2012) The  
592  $^{190}\text{Pt}$ – $^{186}\text{Os}$  decay system applied to dating platinum-group element mineralization of the Bushveld  
593 Complex, South Africa. *Chem Geol* 302–303:48–60

594 de Waal SA, Xu ZH, Li C, Mouri H (2004) Emplacement of viscous mushes in the Jinchuan  
595 ultramafic intrusion, western China. *Canad Mineral* 42:371–392

596 Du AD, Zhao DM, Wang SX, Sun DZ, Liu DY (2001) Precise Re–Os dating for molybdenite by  
597 ID-NTIMS with Carius Tube sample preparation. *Rock Miner Anal* 20:247–252 (in Chinese with  
598 English abstract)

599 Du AD, Wu SQ, Sun DZ, Wang SX, Qu WJ, Markey R, Stein H, Morgan J, Malinovskiy D (2004)  
600 Preparation and certification of Re–Os dating reference materials: molybdenite HLP and JDC.  
601 *Geostand Geoanal Res* 28:41–52

602 Duan J, Li C, Qian ZZ, Jiao JG, Ripley EM, Feng YQ (2016) Multiple S isotopes, zircon Hf isotopes,  
603 whole-rock Sr–Nd isotopes, and spatial variations of PGE tenors in the Jinchuan Ni–Cu–PGE  
604 deposit, NW China. *Mineral Depos* 51:557–574

605 Farrow CEG, Watkinson DH, Jones PC (1994) Fluid inclusions in sulfides from North and South  
606 Range Cu–Ni–PGE deposits, Sudbury structure, Ontario. *Econ Geol* 89:647–655

607 Fiorentini M, Beresford S, Barley M, Duuring P, Bekker A, Rosengren N, Cas R, Hronsky J (2012)  
608 Sulfide deposits, Agnew–Wiluna greenstone belt, western Australia: insights from the multiple  
609 sulfur isotopes. *Econ Geol* 107:781–796

610 Gál B, Molnár F, Guzmics T, Mogessie A, Szabó C, Peterson DM (2013) Segregation of magmatic  
611 fluids and their potential in the mobilization of platinum-group elements in the South Kawishiwi

612 Intrusion, Duluth Complex, Minnesota – Evidence from petrography, apatite geochemistry and  
613 coexisting fluid and melt inclusions. *Ore Geol Rev* 54:59–80

614 Gao YL, Tang ZL, Song XY, Tian YL, Meng YZ (2009) Study on genesis of the concealed Cu-rich ore  
615 body in the Jinchuan Cu-Ni deposit and its prospecting in depth. *Acta Petrol Sinica* 25:3379–3395  
616 (in Chinese with English abstract)

617 Gammons CH, Bloom MS, Yu Y (1992) Experimental investigation of the hydrothermal geochemistry  
618 of platinum and palladium: I. Solubility of platinum and palladium sulfide minerals in  
619 NaCl/H<sub>2</sub>SO<sub>4</sub> solutions at 300°C. *Geochim Cosmochim Acta* 56:3881–3894

620 Gammons CH (1995) Experimental investigations of the hydrothermal geochemistry of platinum and  
621 palladium: IV. The stoichiometry of Pt(IV) and Pd(II) chloride complexes at 100 to 300°C.  
622 *Geochim Cosmochim Acta* 59:1655–67

623 Godel B, Barnes S-J, Maier WD (2007) Platinum-group elements in sulfide minerals, platinum-group  
624 minerals, and whole-rocks of the Merensky Reef (Bushveld Complex, South Africa): implications  
625 for the formation of the reef. *J Petrol* 48:1569–1604

626 Hannah JL, Stein HJ (2002) Re-Os model for the origin of sulfide deposits in anorthosite-associated  
627 intrusive complexes. *Econ Geol* 97: 371–383

628 Hanski E, Luo ZY, Oduro H, Walker RJ (2011) The Pechenga Ni-Cu sulfide deposits, northwestern  
629 Russia: A review with new constraints from the feeder dikes. *Econ Geol* 17:145–162

630 Hinchey JG, Hattori KH (2005) Magmatic mineralization and hydrothermal enrichment of the High  
631 Grade Zone at the Lac des Iles palladium mine, northern Ontario. *Canad Mineral Depos* 40:13–23

632 Holwell DA, McDonald I (2007) Distribution of platinum-group elements in the Platreef at Overysel,  
633 northern Bushveld complex: a combined PGM and LA-ICP-MS study. *Contrib Mineral Petrol*  
634 154:171–190

635 Iljina M (1994) The Portimo Layered Igneous Complex. *Acta Universitatis Ouluensis, Series A*,  
636 258:1–158

637 Iljina M, Hanski E (2005). Layered mafic intrusions of the Tornio-Näränkäväära belt. In: M. Lehtinen,

638 P. Nurmi, T. Rämö (eds) Precambrian bedrock of Finland – Key to the evolution of the  
 639 Fennoscandian Shield. Elsevier, Amsterdam pp 103–138  
 640 Keay RR, Lightfoot PC (2010) Crustal sulfur is required to form magmatic Ni-Cu sulfide deposits:  
 641 Evidence from chalcophile element signatures of Siberian and Deccan Trap basalts. *Mineral*  
 642 *Depos* 45:241–257  
 643 Konnunaho JP, Hanski EJ, Bekker A, Halkoaho TAA, Hiebert RS, Wing BA (2013) The Archaean  
 644 komatiite-hosted, PGE-bearing Ni-Cu sulphide deposit at Vaara, eastern Finland: evidence for  
 645 assimilation of external sulphur and post-depositional desulphurization. *Mineralium Deposita* 48:  
 646 967–989  
 647 Lahtinen R, Korja A, Nironen M (2005) Paleoproterozoic tectonic evolution. In: Lehtinen M, Nurmi  
 648 PA, Rämö OT (eds) Precambrian geology of Finland – Key to the evolution of the Fennoscandian  
 649 Shield. Elsevier BV, Amsterdam, pp 481–532  
 650 Lehmann J, Arndt N, Windley B, Zhou M-F, Wang CY, Harris C (2007) Field relationships and  
 651 geochemical constraints on the emplacement of the Jinchuan intrusion and its Ni-Cu-PGE sulfide  
 652 deposit, Gansu, China. *Econ Geol* 102:75–94  
 653 Le Vaillant M, Barnes SJ, Fiorentini ML, Miller J, McCuaig TC, Muccilli P (2015) A hydrothermal  
 654 Ni-As-PGE geochemical halo around the Miitel komatiite-hosted nickel sulfide deposit, Yilgarn  
 655 Craton, Western Australia. *Econ Geol* 110:505–530  
 656 Le Vaillant M, Saleem M, Barnes SJ, Fiorentini ML, Miller J, Beresford S, Perring C (2016)  
 657 Hydrothermal remobilisation around a deformed and remobilized komatiite-hosted Ni-Cu-(PGE)  
 658 deposit, Sarah's Find, Agnew Wiluna greenstone belt, Yilgarn Craton, Western Australia. *Mineral*  
 659 *Depos* 51:369–388  
 660 Li C, Ripley EM, Naldrett AJ (2003) Compositional variation of olivine and sulfur isotopes in the  
 661 Noril'sk and Talnakh intrusions, Siberia: Implications for ore-forming processes in dynamic  
 662 magma conduits. *Econ Geol* 98:69–86  
 663 Li C, Ripley EM, Naldrett AJ (2009) A new genetic model for the giant Ni-Cu-PGE sulfide deposits  
 664 associated with Siberian flood basalts. *Econ Geol* 104:291–301  
 665 Li C, Xu ZH, de Waal SA, Ripley EM, Maier WD (2004a) Compositional variations of olivine from

the Jinchuan Ni-Cu sulfide deposit, western China: implications for ore genesis. *Mineral Depos*  
39:159–172

Li C, Ripley EM (2011) The giant Jinchuan Ni-Cu-(PGE) deposit: Tectonic setting, magma evolution,  
ore genesis, and exploration implications. *Rev Econ Geol* 17:163–180

Li XH, Su L, Song B, Liu DY (2004) SHRIMP zircon U–Pb age of the Jinchuan ultramafic intrusion  
and its geological significance. *Chin Sci Bull* 49:420–422 (in Chinese)

Li XH, Su L, Chung SL, Li ZX, Liu Y, Song B, Liu DY (2005) Formation of the Jinchuan ultramafic  
intrusion and the world’s third largest Ni-Cu sulfide deposit: Associated with the ~825 Ma south  
China mantle plume? *Geochem Geophys Geosyst* 6:1–16

Lin YH, Zhang LF, Ji JQ, Song SG (2010)  $^{40}\text{Ar}/^{39}\text{Ar}$  age of Jiugequan lawsonite blueschists in northern  
Qilian Mountains and its petrologic significance. *Chin Sci Bull* 55:2021–2027

Liu JG, Pearson DG (2014) Rapid, precise and accurate Os isotope ratio measurements of nanogram to  
sub-nanogram amounts using multiple Faraday collectors and amplifiers equipped with  $10^{12}\ \Omega$   
resistors by N-TIMS. *Chem Geol* 363:301–311

Liu YJ, Neubauer F, Genser J, Takasu A, Ge XH, Handler R (2006)  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of blueschist facies  
pelitic schists from Qingshuigou in the Northern Qilian Mountains, western China. *Island Arc*  
15:87–198

Liou JG, Wang X, Coleman RG (1989) Blueschists in major suture zones of China. *Tectonics*  
8:609–619

Ludwig KR (2003) User’s manual for Isoplot 3.00: a geochronological toolkit for Microsoft Excel.  
Berkeley Geochronology Center Special Publ.

Ma JH (2012) Jinchuan mining ductile shear zone characteristics and its significance. PhD thesis,  
Chang’an Univ.

Maier WD, Rasmussen B, Fletcher I, Godel B, Barnes S, Fisher I, Yang SH, Huhma H, Lahaye Y (2015)  
Petrogenesis of the 2.765–2.775 Ga Monts de Cristal Complex, Gabon: evidence for direct  
precipitation of Pt-rich phases from basaltic magma. *J Petrol* 56:1285–1308

Maier WD, Smithies RH, Spaggiari CV, Barnes SJ, Kirkland CL, Yang SH, Lahaye Y (2016)



693 Petrogenesis and Ni-Cu sulphide potential of mafic-ultramafic rocks in the Mesoproterozoic  
694 Fraser Zone within the Albany-Fraser Orogen, Western Australia. *Precambrian Res* 281:27–46

695 Mogessie, A. Stumpfl, E.F. Weiblen, P.W. 1991. The role of fluids in the formation of  
696 platinum-group-minerals, Duluth Complex, Minnesota; mineralogic, textural and chemical  
697 evidence. *Econ Geol* 86: 1506–1518

698 Molnár F, Watkinson DH, Jones PC, Gatter I (1997) Fluid inclusion evidence for hydrothermal  
699 enrichment of magmatic ore at the contact zone of the Ni–Cu–platinum group element 4b deposit,  
700 Lindsley mine, Sudbury, Canada. *Econ Geol* 92:674–685

701 Molnár F, Mänttari I, O'Brien H, Lahaye Y, Pakkanen L, Johanson B, Käpyaho A, Sorjonen-Ward P,  
702 Whitehouse M, Sakellaris G (2016) Boron, sulphur and copper isotope systematics in the orogenic  
703 gold deposits of the Archaean Hattu schist belt, eastern Finland. *Ore Geol Rev* 77:133–162

704 Morgan JW, Walker RJ, Horan MF, Ellyn SB, Naldrett AT (2002)  $^{190}\text{Pt}$ – $^{186}\text{Os}$  and  $^{187}\text{Re}$ – $^{187}\text{Os}$   
705 systematics of the Sudbury Igneous Complex, Ontario. *Geochim Cosmochim Acta* 66:273–290

706 Mukwakwami J, Lafrance B, Leshner CM, Tinkham DK, Rayner NM, Ames DE (2014a) Deformation,  
707 metamorphism and mobilization of Ni-Cu-PGE sulfide ores at Garson mine, Sudbury. *Mineral*  
708 *Depos* 49:175–198

709 Mukwakwami J, Leshner CM, Lafrance B (2014b) Geochemistry of deformed and  
710 hydrothermally-mobilized magmatic Ni–Cu–PGE ores at the Garson Mine, Sudbury. *Econ Geol*  
711 109:367–386

712 Mungall JE, Brenan JM (2014) Partitioning of platinum-group elements and Au between sulfide liquid  
713 and basalt and the origins of mantle crust fractionation of the chalcophile elements. *Geochim*  
714 *Cosmochim Acta* 125:265–289

715 Naldrett AJ, Duke J (1980) Platinum metals magmatic sulfide ores. *Sci* 208:1417–1424

716 Naldrett AJ, Asif M, Schandl E, Searcy T, Morrison CG, Binney WP, Moore C (1999) Platinum-group  
717 elements in the Sudbury ores: Significance with respect to the origin of different ore zones and to  
718 the exploration for footwall orebodies. *Econ Geol* 94:185–210

719 Olivo GR, Theyer P (2004) Platinum group minerals from the McBratney PGE-Au prospect in the Flin  
720 Flon greenstone belt, Manitoba, Canada. *Canad Mineral* 42:667–681

721 Prichard HM, Knight RD, Fisher PC, McDonald I, Zhou M-F, Wang CY (2013) Distribution of  
722 platinum-group elements in magmatic and altered ores in the Jinchuan intrusion, China: an

723 example of selenium remobilization by postmagmatic fluids. *Mineral Depos* 48:767–786  
 724 Puchtel IS, Brandon AD, Humayun M (2004) Precise Pt–Re–Os isotope systematics of the mantle  
 725 from 2.7-Ga komatiites. *Earth Planet Sci Lett* 224:157–174  
 726 Puchtel IS, Brandon AD, Humayun M, Walker RJ (2005) Evidence for the early differentiation of the  
 727 core from Pt–Re–Os isotope systematics of 2.8-Ga komatiites. *Earth Planet Sci Lett* 237:118–134  
 728 Puchtel IS, Walker RJ, Brandon AD, Nisbet EG (2009) Pt–Re–Os and Sm–Nd isotope and HSE and  
 729 REE systematics of the 2.7 Ga Belingwe and Abitibi komatiites. *Geochim Cosmochim Acta*  
 730 73:6367–6389  
 731 Puchtel IS, Walker RJ, Mathieu T, Nisbet EG, Byerly GR (2014) Insights into early Earth from the  
 732 Pt–Re–Os isotope and highly siderophile element abundance systematics of Barberton komatiites.  
 733 *Geochim Cosmochim Acta* 125:394–413  
 734 Qi XQ, Zhang JX, Li HB, Cai JL (2004) Geochronology of the dextral strike ductile shear zone in  
 735 south margin of the Northern Qilian Mountains and its geological significance. *Earth Sci Front*  
 736 11:469–479 (in Chinese with English abstract)  
 737 Qian Q, Wang YM, Li HM, Jia XQ, Han S, Zhang Q (1998) Geochemical characteristics and genesis of  
 738 diorites from Laohushan. Gansu Province. *Acta Petrol Sinica* 14:520–528 (in Chinese with  
 739 English abstract)  
 740 Ripley EM (1986) Application of stable isotopic studies to problems of magmatic sulfide ore genesis  
 741 with special reference to the Duluth Complex, Minnesota. In: Friedrich GH, Genkin AD, Naldrett  
 742 AJ et al. (eds) *Geology and metallogeny of copper deposits*, Springer-Verlag, Berlin, pp 8–24  
 743 Ripley EM (1990) Platinum-group element geochemistry of Cu–Ni mineralization in the basal zone of  
 744 the Babbitt Deposit, Duluth, Complex, Minnesota. *Econ Geol* 85:830–841  
 745 Ripley EM, Butler BK, Taib NI, Lee I (1993) Hydrothermal alteration in the Babbitt Cu–Ni deposit,  
 746 Duluth Complex; mineralogy and hydrogen isotope systematics. *Econ Geol* 88:679–696  
 747 Ripley EM, Park YR, Lambert DD, Frick LR (2001) Re–Os isotopic variations in carbonaceous pelites  
 748 hosting the Duluth Complex: implications for metamorphic and metasomatic processes associated

749 with mafic magma chambers. *Geochim Cosmochim Acta* 65:2965–2978

750 Ripley EM, Li C, Shin D (2002) Paragneiss assimilation in the genesis of magmatic Ni-Cu-Co sulfide  
751 mineralization at Voisey's Bay, Labrador:  $^{34}\text{S}$ ,  $\delta^{13}\text{C}$ , and Se/S evidence. *Econ Geol* 97:1307–1318

752 Ripley EM, Sarkar A, Li C (2005) Mineralogic and stable isotope studies of hydrothermal alteration at  
753 the Jinchuan Ni–Cu deposit, China. *Econ Geol* 100:1349–1361

754 Ripley EM, Li C (2013) Sulfide saturation in mafic magmas: Is external sulfur required for magmatic  
755 Ni-Cu-(PGE) ore genesis? *Econ Geol* 108:45–58

756 Rowell WF, Edgar AD (1986) Platinum-group element mineralization in a hydrothermal Cu–Ni sulfide  
757 occurrence, Rathbun Lake, northeastern Ontario. *Econ Geol* 81:1272–1277

758 Seat Z, Beresford SW, Grguric BA, Gee MAM, Grassineau NV (2009) Reevaluation of the role of  
759 external sulfur addition in the genesis of Ni-Cu-PGE deposits: Evidence from the Nebo-Babel  
760 Ni-Cu-PGE deposit, West Musgrave, Western Australia. *Econ Geol* 104:521–538

761 SGU (the Sixth Geological Unit of the Geological Survey of Gansu Province) (1984). *Geology of the*  
762 *Baijiaozuizi Cu–Ni sulfide deposit*. Geol Publ House, Beijing (in Chinese)

763 Shirey SB, Walker RJ (1995) Carius tube digestion for low-blank rhenium-osmium analysis. *Anal*  
764 *Chem* 67:2136–2141

765 Smoliar, M.I., Walker, R.J., Morgan, J.W., 1996. Re-Os ages of group IIA, IIIA, IVA, and IVB iron  
766 meteorites. *Sci* 271:1099–1102

767 Song SG, Yang JS, Xu ZQ, Liou JG, Wu CL, Shi RD (2003) Metamorphic evolution of coesite-bearing  
768 UHP terrane in the North Qaidam, northern Tibet, NW China. *J Metamorph Geol* 21:631–644

769 Song SG, Zhang LF, Niu YL, Su L, Jian P, Liu DY (2005) Geochronology of diamond bearing zircons  
770 from garnet peridotite in the North Qaidam UHPM belt, Northern Tibetan Plateau: a record of  
771 complex histories from oceanic lithosphere subduction to continental collision. *Earth Planet Sci*  
772 *Lett* 234:99–118

773 Song SG, Zhang LF, Niu YL, Su L, Song B, Liu DY (2006) Evolution from oceanic subduction to  
774 continental collision: a case study for the northern Tibetan Plateau based on geochemical and  
775 geochronological data. *J Petrol* 47:435–455

776 Song SG, Niu Y, Zhang LF, Wei CJ, Liou JG, Su L (2009) Tectonic evolution of Early Paleozoic HP

777 metamorphic rocks in the North Qilian Mountains, NW China: new perspectives. *J Asian Earth*  
778 *Sci* 35:334–353

779 Song SG, Niu YL, Su L, Zhang C, Zhang LF (2014) Continental orogenesis from ocean subduction,  
780 continent collision/subduction, to orogen collapse, and orogen recycling: The example of the  
781 North Qaidam UHPM belt, NW China. *Earth Sci Rev* 129:59–84

782 Song XY, Keays RR, Zhou M-F, Qi L, Ihlenfeld C, Xiao JF (2009) Siderophile and chalcophile  
783 elemental constraints on the origin of the Jinchuan Ni-Cu-(PGE) sulfide deposit, NW China.  
784 *Geochim Cosmochim Acta* 73:404–424

785 Song XY, Danyushevsky LV, Keays RR, Chen LM, Wang YS, Tian YL, Xiao JF (2012) Structural,  
786 lithological, and geochemical constraints on the dynamic magma plumbing system of the Jinchuan  
787 Ni-Cu sulfide deposit, NW China. *Mineral Depos* 47:277–297

788 Stumpfl EF, Rucklidge J (1982) The platiniferous dunite piped of the eastern Bushveld. *Econ Geol*  
789 77:1419–1431

790 Su S, Li C, Zhou M-F, Ripley E, Qi L (2008) Controls on variations of platinum-group element  
791 concentrations in the sulfide ores of the Jinchuan Ni-Cu deposit, western China. *Mineral Depos*  
792 43:609–622

793 Sun WD, Peng ZC, Wang ZR, Yin QZ (1997) Oxygen corrections in negative thermal ionization mass  
794 spectrometry determination of rhenium and osmium. *J Chin Mass Spectrom Soc* 18:1–6 (in  
795 Chinese with English abstract)

796 Tang ZL (1993) Genetic model of the Jinchuan nickel–copper deposit. *Geol. Association Canada Spec*  
797 *Paper* 40:389–401 (in Chinese)

798 Tang ZL, Li WY (1995) The metallogenetic model and geological contrast of the Jinchuan platinum  
799 bearing Cu–Ni sulfide deposit. Geological Publish House, Beijing (in Chinese)

800 Tang ZL, Bai YL, Li ZL (2002) Geotectonic settings of large and superlarge mineral deposits on the  
801 southwestern margin of the North China Plate. *Acta Geol Sinica* 76:367–377 (in Chinese with  
802 English abstract)

803 Walker RJ, Morgan JW, Naldrett AJ, Li C, Fassett JD (1991) Re–Os systematics of Ni–Cu sulfide ores,  
804 Sudbury Igneous Complex, Ontario: Evidence for a major crustal component. *Earth Planet Sci*  
805 *Lett* 105:416–429

806 Walker RJ, Morgan JW, Beary ES, Smoliar MI, Czamanske GK, Horan MF (1997) Applications of the

807  $^{190}\text{Pt}$ – $^{186}\text{Os}$  isotope system to geochemistry and cosmochemistry. *Geochim Cosmochim Acta*  
 808 61:4799–4807

809 Wang CY, Zhang Q, Qian Q (2005) Geochemistry of the Early Paleozoic Baiyin volcanic rocks (NW  
 810 China): implications for the tectonic evolution of the North Qilian Orogenic Belt. *J Geol*  
 811 113:83–94

812 Wood SA (2002) The aqueous geochemistry of the platinum group elements with applications to ore  
 813 deposits. *Can Inst Min Metal Petrol* 54:211–249

814 Wu CL, Xu XY, Gao QM, Li XM, Lei M, Gao YH, Frost RB, Wooden JL (2010) Early Palaeozoic  
 815 granitoid magmatism and tectonic evolution in North Qilian, NW China. *Acta Petrol Sinica*  
 816 26:1027–1044 (in Chinese with English abstract)

817 Yan HQ, Su SG, Jiao JG, Tang H (2005) Metallogenetic epoch of Jinchuan Cu–Ni (PGE) magmatic  
 818 sulfide deposit. *Earth Sci Front* 12:309–315 (in Chinese with English abstract)

819 Yan MC, Wang CS, Gu TX, Chi QH, Yan WD (1998) Preparation of geochemical certified reference  
 820 materials for platinum group elements. *Rock Miner Anal* 17:1–21 (in Chinese with English  
 821 abstract)

822 Yang G, Du AD, Chen JF, Qu WJ (2003) The measurement of Pt in rocks by isotope dilution ICP-MS.  
 823 *Rock Miner Anal* 22:5–9 (in Chinese with English abstract)

824 Yang G, Du AD, Lu J, Qu WJ, Chen JF (2005) Re–Os dating of massive sulfide ores of the Jinchuan  
 825 Ni–Cu deposit by ICP-MS. *Sci China (D)* 35:241–245 (in Chinese)

826 Yang G (2005) Applications of Re–Os and Pt–Os isotopic systems in the ore deposit. Doctoral  
 827 Dissertation of University of Science and Technology of China. (in Chinese with English  
 828 abstract).

829 Yang JS, Xu ZQ, Zhang JX, Song SG, Wu CL, Shi RD, Li HB, Brunel M (2002) Early Palaeozoic  
 830 North Qaidam UHP metamorphic belt on the north-eastern Tibetan plateau and a paired  
 831 subduction model. *Terra Nova* 14: 397–404

832 Yang SH, Qu WJ, Tian YL, Chen JF, Yang G, Du AD (2008) Origin of the inconsistent apparent  
 833 Re–Os ages of the Jinchuan Ni–Cu sulfide ore deposit, China: post-segregation diffusion of Os.

Chem Geol 247:401–418

Yang WT, Duan LZ, Zhang Y (2013) Studying in middle-tectonic level and rock deformation characteristic in Longshoushan area. Northwest Geol 46:44–53 (in Chinese with English abstract)

Yang XZ, Ishihara S, Zhao DH (2006) Genesis of the Jinchuan PGE deposit, China: evidence from fluid inclusions, mineralogy and geochemistry of precious elements. Mineral Petrol 86:109–128

Zhao GC, Sun M, Wilde SA, Li SZ (2005) Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. Precambrian Res 136:177–202

Zhou M-F, Yang ZX, Song XY, Leshner CM, Keays RR (2002) Magmatic Ni–Cu–(PGE) sulfide deposits in China. In: Cabri LJ (ed) The geology, geochemistry, mineralogy, mineral beneficiation of the platinum-group elements, Can Inst Mining Metall Petrol, Spec Vol 54:619–636

Zhang J, Li JY, Li YF, Ma ZJ (2009) How did the Alax Block respond to the Indo-Eurasian collision ? Int J Earth Sci 98:1511–1527

Zhang JX, Yang JS, Meng FC, Wan YS, Li HM, Wu CL (2006) U–Pb isotopic studies of eclogites and their host gneisses in the Xitieshan area of the North Qaidam Mountains, western China: new evidence for an early Paleozoic HP-UHP metamorphic belt. J Asian Earth Sci 28: 143–150

Zhang MJ, Kamo S, Li C, Hu PE, Ripley EM (2010) Precise U–Pb zircon-baddeleyite age of the Jinchuan sulfide ore-bearing ultramafic intrusion, western China: Mineral Depos 45:3–9

## Figure captions

Fig. 1. Regional geological map showing the location of the Jinchuan intrusion (after Song et al. 2006, 2014; Duan et al., 2016). LSS indicates Longshoushan.

Fig. 2 a) Map showing the Jinchuan intrusion and country rocks. I, II, III, IV represent mining district defined the mining company. b) Vertical cross sections of ore bodies 1 and 6 of the Jinchuan intrusion, and an expanded view at three different elevation levels of the horizontal distribution of the hydrothermal ore (modified after SGU, 1984; Tang et al. 2002; Gao et al. 2009; Zhang et al. 2010).

Fig. 3. Photomicrographs of Cu-Pt-rich ores. a, Densely disseminated sulfide with serpentinized olivine; b, Sulfide mineral aggregate dominated by pentlandite and pyrrhotite; c, Sulfide minerals dominated by chalcopyrite with minor pentlandite; d, Chalcopyrite vein in serpentinized olivine; e–f, chlorite associated with ductile sulfide; g–h, another example of chlorite associated with ductile sulfide. Chl, Serp, Mag, Sul, Po, Pn, Cp indicate chlorite, serpentine, magnetite, sulfide, pyrrhotite, pentlandite, and chalcopyrite, respectively. Figures a, e and g taken in transmitted light with crossed polars and figures b, c, d, f and h taken in reflected light.

Fig. 4. Photomicrographs of Cu-Pt-rich ores. a–c, Serpentine containing  $\text{PtAs}_2$ ; d, serpentine containing  $\text{PtAs}_2$ ; e,  $\text{PtAs}_2$  in serpentine; f,  $\text{PdTeBi}$  and  $\text{PbTe(Se)}$  in the margin of chalcopyrite. Serp, Mag, Cp indicate serpentine, magnetite, and chalcopyrite, respectively. Figure a taken in transmitted light with crossed polars, figures b–d taken in reflected light, and figures e–f are back-scattered electron images.

Fig. 5. a) Cu/Ni vs. Pt/Os ratios of sulfide separate (S) and whole-rock samples (W) from Cu-Pt-rich ore; b) Pt vs. Os diagram for sulfide separates and whole-rock samples from Cu-Pt-rich ore. The combination of these figures argues for Cu and Pt mobility in hydrothermal event.

Fig. 6. Re-Os isochron of sulfide separates and whole-rock samples from a Cu-Pt-rich ore body in the Jinchuan intrusion. Note the poor linearity of the isochron.

Fig. 7. Pt-Os isochron of sulfide separates and whole-rock samples from a Cu-Pt-rich ore body in the Jinchuan intrusion. The numbers are part of sample number, for example, 82S and 82W indicate sulfide separate and whole-rock analyses of sample 04JCI-82. Sulfide separates of sample 04JCI-74, 04JCI-81, GS7 and whole-rock sample 04JC-81 have replicate analyses labeled as 74S-2, 81S-2, GS7-2 and 81W-2, and they are linked using thin dashed line.

Fig. 8. a, Pt-Os isochron of sulfide separates and whole-rock samples from a Cu-Pt-rich ore body in the Jinchuan intrusion, excluding the obvious outlier sample 04JCI-81. b, Pt-Os isochron of only sulfide separates of samples from a Cu-Pt-rich ore body in the Jinchuan intrusion, excluding the obvious

outlier sample 04JCI-81.

Fig. 9. In-situ sulfur isotope compositions of pyrrhotite and chalcopyrite grains of samples from a Cu-Pt-rich ore body. a) fine-grained veinlet chalcopyrite from Cu-Pt-rich ore sample 04JCI-72; b) coarse-grained chalcopyrite and pyrrhotite from sample 04JCI-72; c) coarse-grained chalcopyrite and pyrrhotite from another Cu-Pt-rich sample 04JCI-74; d) a fine-grained veinlet chalcopyrite from sample 04JCI-74; e) coarse-grained pyrrhotite from a Ni-rich sample 04JCI-77; f) coarse-grained pyrrhotite from another Ni-rich sample 04JCI-79. Po, Pn, Cp, Serp and Mag indicate pyrrhotite, pentlandite, chalcopyrite, serpentinite and magnetite, respectively.

Fig. 10.  $\delta^{34}\text{S}$  (CDT, ‰) distribution of sulfide grains from the Cu-Pt-rich ore body. Note that almost all grains have values within the range of -1.0 to +1.0.

#### **Table Captions**

Table 1. Platinum Re and Os concentrations (ppb), and Pt-Os and Re-Os isotope data for sulfide separates and whole-rock samples and Ni and Cu concentrations (ppm) for whole-rock samples from a Cu-Pt-rich ore body of the Jinchuan intrusion.

Table 2. In-situ sulfur isotope composition of pyrrhotite and chalcopyrite grains of samples from a Cu-Pt-rich ore body in the Jinchuan intrusion.