Re–Os Pyrite Geochronological Evidence of Three Mineralization Styles within the Jinchang Gold Deposit, Yanji–Dongning Metallogenic Belt, Northeast China

Shun-Da Li 1, Zhi-Gao Wang 2, Ke-Yong Wang 1,*, Wen-Yan Cai 1, Da-Wei Peng 1, Li Xiao 3 and Jie Li 4

1 College of Earth Sciences, Jilin University, Changchun 130061, China; sdli16@mails.jlu.edu.cn (S.-D.L.); wenyang_1025@126.com (W.-Y.C.); pdw308zy@163.com (D.-W.P.)
2 College of Exploration and Surveying Engineering, Changchun Institute of Technology, Changchun 130061, China; xiaoli18930163.com
3 Gold Geological Institute of CAPF, Langfang 065000, China; xiaoli18930163.com
4 State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China; jieli@gig.ac.cn
* Correspondence: wangky@jlu.edu.cn; Tel.: +86-130-6900-4095

Received: 11 September 2018; Accepted: 1 October 2018; Published: 12 October 2018

Abstract: The Jinchang gold deposit is located in the eastern Yanji–Dongning Metallogenic Belt in Northeast China. The orebodies of the deposit are hosted within granite, diorite, and granodiorite, and are associated with gold-mineralized breccia pipes, disseminated gold in ores, and fault-controlled gold-bearing veins. Three paragenetic stages were identified: (1) early quartz–pyrite–arsenopyrite (stage 1); (2) quartz–pyrite–chalcopyrite (stage 2); and (3) late quartz–pyrite–galena–sphalerite (stage 3). Gold is hosted predominantly within pyrite. Pyrite crystals from the quartz–pyrite–chalcopyrite veinlets (Py1) yield a Re–Os isochron age of 102.9 ± 2.7 Ma (MSWD = 0.17). Pyrite crystals from the quartz–pyrite–chalcopyrite veinlets (Py2) yield a Re–Os isochron age of 102.0 ± 3.4 Ma (MSWD = 0.2). Pyrite separated from quartz–pyrite–galena–sphalerite veins (Py3) yield a Re–Os isochron age of 100.9 ± 3.1 Ma (MSWD = 0.019). Re–Os isotopic analyses of the three types of auriferous pyrite suggest that gold mineralization in the Jinchang Deposit occurred at 105.6–97.8 Ma (includes uncertainty). The initial 187Os/188Os values of the pyrites range between 0.04 and 0.60, suggesting that Os in the pyrite crystals was derived from both crust and mantle sources.

Keywords: Re–Os isotopes; geochronology; Jinchang gold deposit; Yanji–Dongning Metallogenic Belt

1. Introduction

Studies investigating the genesis of hydrothermal gold deposits are commonly limited by a lack of suitable minerals to directly date the age of mineralization. The age of metallogenesis is commonly inferred from the timing of magmatism, deformation, metamorphism, and alteration; however, it is still difficult to determine the age of mineralization within a deposit that records evidence for multiple tectonic and magmatic events. Accurately dating the age of mineralization is crucial in determining the genesis and prospectivity of the deposit.

Recent advances in Re–Os isotopic systematics have seen an increase in the use of this technique to directly date the age of metal deposits. These developments have included improved capability to undertake Re–Os dating of molybdenite as well as more common minerals with lower Re and Os concentrations such as pyrite and arsenopyrite [1–3]. Many studies have undertaken Re–Os geochronology work on auriferous pyrites to date the age of gold deposits [4,5].
The Jinchang Deposit is a large gold deposit located in Heilongjiang Province, Northeast China. This deposit was discovered by the Chinese Armed Police Force in the 1990s. Exploration, which continues today, has involved 96,725 m of drilling of >200 holes, and 6339 m of underground tunnel development, revealing an estimated 80.4 t gold resource with a grade of 8 g/t Au.

Previous studies of the deposit have focused on its geological features, alteration, geochemistry, fluid inclusion systematics, and geochronology [6–9]. These studies have suggested that the Jinchang Deposit is a typical magmatic–hydrothermal deposit. The interpreted age of gold mineralization in the deposit is based on the U–Pb, Rb–Sr, and Ar–Ar ages of host rocks and alteration minerals [6,10,11]. Ore formation is interpreted to have occurred between ca. 130 and 100 Ma, but the causative mechanism and timing of gold mineralization remain unclear within the context of the complex geological and magmatic evolution of the region.

We present Re–Os pyrite age data to constrain the timing of the various stages of mineralization within the Jinchang gold deposit. The results demonstrate that sulfide minerals can be used to determine the age of different types of mineralization, provide information on the origin of metals, and further our understanding of the genesis of the Jinchang gold deposit.

2. Geological Background

2.1. Geological Setting

Northeast China is located between the Siberian and North China cratons, and forms the eastern part of the Central Asian Orogenic Belt, which is the largest Phanerozoic accretionary orogen in the world [12]. Northeast China is subdivided by the Tayuan–Xiguitu, Nenjiang, and Mudanjing faults into, from east to west, the Erguna, Xinan, Songnen, and Jiamusi–Xingkai blocks (Figure 1A). The region records a prolonged geological evolution involving the emplacement of Archean–Paleoproterozoic rocks, mid–late Proterozoic rifting and subduction–collision related to the closure of the Paleo-Asian Ocean and Mesozoic subduction of the Pacific Plate and pervasive tectonomagmatic events [13,14].

The Yanji–Dongning area is located in the eastern part of Jilin and Heilongjiang provinces, within the Xingkai Block, which is bounded by the Dunhua–Mishan and Xar Moron–Changchun faults to the northwest and southeast, respectively (Figure 1B). The Yanji–Dongning area comprises Precambrian basement rocks that are overlain by Silurian–Quaternary sedimentary successions. The crystalline basement rocks were formed in high temperature and pressure environments and exposed to the surface due to the regional crustal uplift. These rocks comprise mica schists, granulites, and amphibolites. Silurian–Quaternary sedimentary successions are formed by subsequent weathering, erosion, sedimentation, and volcanic eruption. The Silurian metasedimentary rocks are overlain by Permian sandstones and greywackes, Triassic pyroclastic rocks, Jurassic intermediate–acidic pyroclastic volcanics, and Cretaceous siltstones, pelites, and tuffs. Unconsolidated Tertiary and Quaternary sediments cover the region. The main groups of faults trend NE–SW, NW–SE, and E–W. Intrusive rocks comprise Paleoproterozoic–Paleozoic granodiorites and Mesozoic granodiorites, monzogranites, and granites.

Gold mineralization occurs in the Yanji–Dongning area. The main deposits are the Nongping and Xiaoxinancha porphyry gold deposits, the mesothermal vein-hosted Naozhi Gold Deposit, and the epithermal vein-hosted Jiusangou, Wufeng–Wuxing, and Duhuangling gold deposits [15,16] (Figure 1B).
Figure 1. (A) Simplified tectonic map of Northeast China (modified after Wu et al. [17]). (B) Regional geological map of the Yanji–Dongning Metallogenic Belt, Northeast China (modified after Sun [18]), showing the location of the Jinchang gold deposit and other deposits discussed in this study.

2.2. Jinchang Gold Deposit

The Jinchang Deposit is located to the southeast of Jinchang Village (Figure 2). Outcrops are limited in this area, with exposures of andesitic–dacitic tuff restricted largely to the southeastern part of the mineralized area.

Crosscutting relationships suggest that the faults in this area can be classified into three groups with respect to the timing of mineralization. Early NE–SW, NW–SE, N–S, and E–W trending faults are widely distributed. Although they pre-date the mineralization, the intersections of these early faults facilitated fluid transport, leading to brecciation. Dome structures, and ring and radial faults in the central part of the ore field were contemporaneous with mineralization, with some orebodies occurring along these faults. Post-mineralization deformation was limited to the reactivation of early faults, which locally displaced the orebodies.
The variable characteristics of magmatic rocks within the ore field, their intrusive contact relationships, and age indicate a multi-stage emplacement history. The intrusive rocks comprise diorite, granite, graphic granite, granodiorite, and diorite and granite porphyries. The granitoids are calc-alkaline and high-K calc-alkaline with geochemical affinities to typical island-arc intrusive rocks [20,21]. The diorites and diorite porphyries are calc-alkaline and have geochemical affinities to adakites [20].

Diorite, graphic granite, and granite are widely exposed within the Jinchang Deposit and yield U–Pb ages of 209–185 Ma, indicating that they were emplaced after collision of the North China Craton and the Jiamusi–Xingkai Block [19,20,22,23]. These rocks are the main hosts of the ore body and are extensively altered adjacent to the mineralization. The granodiorite, diorite porphyry, and granite porphyry yield U–Pb ages of 118–106 Ma, indicating that these rocks were emplaced during subduction of the Pacific Plate beneath the Eurasian Plate [19–21,23,24]. Several diorite porphyry and granite porphyry dikes are crosscut by the ore body and are therefore interpreted to have formed prior to mineralization. Granodiorite is widespread, was emplaced in the deepest parts of the area (J11, J14, J17, and No. 18 orebodies), is extensively altered, and contains disseminated pyrite, suggesting a causal link between granodiorite emplacement and mineralization.

3. Mineralization

Exploration of the Jinchang Deposit prior to 2017 resulted in the discovery of 23 orebodies and three mineralization types (i.e., breccia pipes, disseminated veinlets, and fault-controlled veins).

3.1. Breccia Pipe Mineralization

Breccia pipe mineralization is the dominant source of gold within the deposit, accounting for >41% of the total resources in the ore field. Eight large breccia pipes are presently documented (J-0, J-1, J-8, J-9, J-10, J-11, J-14, and J-17), extending in a rough line from east to west, controlled by a major NW–SE-striking fault (Figure 2). The largest breccia pipe (J-1) is located at the intersection of N–S, NW–SE, and E–W striking faults, and occurs primarily within graphic granite. J-1 is pipe-like in form, with 5–15 m of diorite occurring above the orebody. Dikes comprising diorite porphyries
occur at a deeper structural level (Figure 3A). The orebody is 46 m long and 30 m wide at the surface, with an average thickness of 21 m and an average grade of 8.1 g/t Au. It plunges 80°–82° toward 155°–160° to a depth of 540 m. The ore rock comprises primarily cement and breccia (Figure 4A–D), the latter constituting up to 50%–80% of the total rock by volume. The breccia consists of clasts of diorite, granite, and diorite and granite porphyries that are lenticular or angular in shape and 10–25 cm in size. The breccias are cemented mainly by sulfides (i.e., pyrite, arsenopyrite, and chalcopyrite) and alteration minerals (i.e., feldspar, sericite, and quartz). Pyrite alteration is extensive in the cement, but is not observed within the breccias.

![Figure 3](image-url)  
**Figure 3.** Geological sections and alteration patterns of the ore bodies (modified after Zhang et al. [19]); (A) geological cross-section of the J-1 ore body; (B) geological cross-section of the No. 18 ore body; (C) geological cross-section of the XII ore body; (D) alteration patterns of the J-1 ore body; (E) alteration patterns of the No. 18 ore body; (F) alteration patterns of the XII ore body.

Alteration of the wall rock is variable external to the mineralized pipe (Figure 3D). K-feldspar alteration, silicification, and sericitization are observed adjacent to the mineralized breccia pipe, whereas sericite–kaolinite and propylitic alteration occurs farther from the mineralized domain, in the outermost part of the northern breccia pipe [25].
3.2. Veinlet Disseminated Mineralization

The No. 18 orebody is a typical example of veinlet disseminated mineralization, accounting for ~20% of the total resources in the ore field. The orebody is hosted within graphic granite and several diorite porphyry dikes beneath a dome structure. The orebody appears to be layered and is divided into four sub-bodies that are labeled 18-1 to 18-4, from top to bottom (Figure 3B). These sub-bodies are 0.6–7.9 m thick, ~800 m long, and have an average grade of 11.23 g/t Au. They strike toward 138°, dip ~47° to the SW, and extend to depths of 160–490 m. Drill holes have intersected granodiorite at depth. The ore minerals are mainly pyrite and chalcopyrite, and lesser molybdenite, chalcocite, bornite, azurite, sphalerite, galena, and gold. Quartz is the main gangue mineral, with minor sericite, chlorite, and epidote.

The wall rock and concealed granodiorite observed in the drill holes are both altered. From depth to the surface, the alteration varies from K-feldspar alteration and silicification to beresitization and finally propylitic alteration [25] (Figure 3D).

3.3. Fault-Controlled Vein Mineralization

Fault-controlled vein mineralization accounts for 39% of the total Au resources in the ore field, including within ore belts II, III, and XII. Vein development was controlled primarily by ring and radial
faults associated with a dome. The forming of the dome is resulted from intrusion of magma. Ore belt XII is typical of this type of mineralization, as it comprises a swarm of veins within graphic granite that are controlled by E–W-trending radial faults in the northeastern part of the lava dome (Figure 2). This ore belt is 460 m long, 0.2–1.78 m thick, and has an average grade of 9.34 g/t Au. The orebodies plunge 70°–80° toward 001°–005° and extend to depths of 190–510 m. The ore minerals include pyrite, sphalerite, galena, and minor chalcopyrite. The gangue minerals are predominantly quartz and minor carbonate (Figure 4H).

Wall rock alteration occurs over several meters from the fault-controlled veins, is symmetrical about the veins, and is more extensive than alteration associated with the other mineralization styles (Figure 3F). With increasing distance from the ore body, the wall rock is affected by quartz–sericite, sericite–kaolinite, and subsequently K-feldspar alteration, although the boundaries between these domains are gradational [25].

The Jinchang Deposit comprises a number of hydrothermal veins and mineral assemblages. The mineral assemblages and their crosscutting relationships indicate three mineralization stages (Figures 4–6). Stage 1 mineralization occurred primarily within the cement of the breccia-hosted ore. This was the most important ore-forming stage as it involved the deposition of abundant native gold (Figure 5A). Stage 1 mineralization is also characterized by milky white quartz, pyrite, and lesser arsenopyrite, K-feldspar, and sericite (Figure 4A–D). Pyrite is the most abundant ore mineral, commonly occurring within the cement as coarse-grained pentagonal dodecahedra and tetragonal trisoctahedra crystals (Figure 4A,B), and locally as fine- to medium-grained aggregates (Figure 4C).

Figure 5. Photomicrographs of key mineral assemblages in the Jinchang Deposit. (A) Native gold in pyrite; (B) coexisting pyrite and arsenopyrite; (C) pyrite–chalcopyrite–chalcocite–bornite assemblage; (D) chalcopyrite–molybdenite assemblage; (E) coexisting pyrite and galena; (F) pyrite–sphalerite veinlet; (G) beresitization of the wall-rock; (H,I) chloritization and K-feldspar alteration of wall-rock. Abbreviations: Qz, quartz; Ser, sericite; Chl, chlorite; Kf, K-feldspar; S, sulfide; Py, pyrite; Ccp, chalcopyrite; Gn, galena; Sp, sphalerite; Apy, arsenopyrite; Mot, molybdenite; Bn, bornite; Cc, chalcocite.
Stage 2 mineralization involved the formation of economic quartz–pyrite–chalcopyrite veins and widespread in veinlet disseminated ores (Figure 4H). These veins also comprise small amounts of molybdenite, chalcolite, bornite, azurite, gold, chlorite, and epidote. Chalcopyrite is the dominant sulfide and occurs as anhedral crystals intergrown with pyrite in quartz veins (Figure 5C). Molybdenite is rare, typically exhibits a hexagonal shape, and occurs as aggregates that are intergrown with chalcopyrite (Figure 5D). The breccia-hosted ore is crosscut by the quartz–pyrite–chalcopyrite veins and is observed in the tunnel at the 30 m level (Figure 4K).

Stage 3 mineralization involved the formation of quartz–pyrite–galena–sphalerite veins (Figure 4LJ) that also contain minor gold, chlorite, epidote, kaolinite, and calcite. Pyrite commonly occurs as hypidiomorphic or xenomorphic crystals that are intergrown with galena and sphalerite in quartz veinlets (Figure 5E,F). These veins have a limited distribution and commonly cut across quartz–pyrite–chalcopyrite veins, suggesting that they formed relatively late (Figure 4L). These veins are associated with fault-controlled vein mineralization and are not observed in the breccia.

4. Sample Selection and Analytical Methods

Fifteen samples of auriferous pyrite were collected from five drill holes (ZKE01, ZK05, ZK11, ZK14, and ZK4702) and underground tunnels for Re–Os analysis (Table 1). Re–Os isotopic analyses were undertaken on pyrites from the cement of breccia-hosted ore (Py1), within quartz–pyrite–chalcopyrite veins (Py2), and within quartz–pyrite–galena–sphalerite veins (Py3). These three types of pyrite are representative of the observed breccia pipe, veinlet disseminated, and fault-controlled vein mineralization styles, respectively. Samples that displayed late-stage sulfide replacement were not analyzed to avoid the influence of late-stage hydrothermal alteration on the results.

We employed the Carius tube digestion technique commonly used in our lab for Re–Os chemistry [26]. About 0.5–2 g of each powdered sample was digested and equilibrated with $^{185}$Re- and $^{190}$Os-enriched spikes in reverse aqua regia (7.5 mL concentrated HNO$_3$ + 2.5 mL concentrated HCl) for 24 h at 240 °C in sealed Carius tubes. Osmium was extracted by solvent extraction into CCl$_4$ and back-extraction into concentrated HBr [27,28], with subsequent cleanup by microdistillation [29]. The Re fraction was separated and purified using anion column chromatography.

Mass spectrometry procedures for the Os are given in Li et al. [30]. Os was loaded onto Pt filaments and measured as OsO$_3^-$ ions by negative-thermal ionization mass spectrometry (N-TIMS) using the electron multiplier mode on a Thermo-Finnigan Triton [31,32] at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China. Repeated analyses of the Os standard solution (Merck Chemical AA standard solution) yield a mean $^{187}$Os/$^{188}$Os value of 0.12052 ± 0.00032 (2 SD, $n = 5$) for the period of analysis. These values are in good agreement with a value of 0.12022 ± 0.00020 (2 SD, $n = 14$) measured on the same mass spectrometer in Faraday cup mode [33].
Table 1. Re–Os isotopic data for auriferous pyrites from various locations in the Jinchang gold deposit.

<table>
<thead>
<tr>
<th>Pyrite</th>
<th>Sample</th>
<th>Location</th>
<th>Re Conc (ppt)</th>
<th>2SE</th>
<th>Os Conc (ppt)</th>
<th>2SE</th>
<th>$^{187}$Os/$^{188}$Os</th>
<th>2σ</th>
<th>$^{187}$Re/$^{188}$Os</th>
<th>2SE</th>
<th>Initial $^{187}$Os/$^{188}$Os</th>
</tr>
</thead>
<tbody>
<tr>
<td>Py1</td>
<td>J1-1</td>
<td>ZKE01 at 84 m level</td>
<td>9906</td>
<td>268.75</td>
<td>11.30</td>
<td>0.21</td>
<td>70.72</td>
<td>0.79</td>
<td>42,853</td>
<td>1408.28</td>
<td>−2.80</td>
</tr>
<tr>
<td></td>
<td>J1-2</td>
<td>ZKE01 at 64 m level</td>
<td>9643</td>
<td>147.37</td>
<td>11.78</td>
<td>0.21</td>
<td>52.22</td>
<td>0.47</td>
<td>31,501</td>
<td>748.43</td>
<td>−1.82</td>
</tr>
<tr>
<td></td>
<td>J1-3</td>
<td>30 m level middle section</td>
<td>10,475</td>
<td>159.15</td>
<td>14.61</td>
<td>0.36</td>
<td>16.48</td>
<td>0.40</td>
<td>10,855</td>
<td>314.64</td>
<td>−2.14</td>
</tr>
<tr>
<td></td>
<td>J1-4</td>
<td>30 m level middle section</td>
<td>9908</td>
<td>104.95</td>
<td>11.82</td>
<td>0.37</td>
<td>68.68</td>
<td>0.93</td>
<td>41,376</td>
<td>1354.88</td>
<td>−2.31</td>
</tr>
<tr>
<td></td>
<td>J1-5</td>
<td>30 m level middle section</td>
<td>9856</td>
<td>121.56</td>
<td>11.66</td>
<td>0.24</td>
<td>58.53</td>
<td>0.71</td>
<td>35,295</td>
<td>1024.55</td>
<td>−2.02</td>
</tr>
<tr>
<td>Py2</td>
<td>J18-1</td>
<td>ZK05 at 280 m level</td>
<td>4194</td>
<td>76.99</td>
<td>5.09</td>
<td>0.09</td>
<td>50.28</td>
<td>0.38</td>
<td>31,074</td>
<td>804.77</td>
<td>−2.57</td>
</tr>
<tr>
<td></td>
<td>J18-2</td>
<td>ZK05 at 362 m level</td>
<td>4087</td>
<td>61.62</td>
<td>6.12</td>
<td>0.05</td>
<td>19.04</td>
<td>0.16</td>
<td>11,203</td>
<td>196.09</td>
<td>−0.01</td>
</tr>
<tr>
<td></td>
<td>J18-3</td>
<td>ZK11 at 235 m level</td>
<td>4224</td>
<td>153.08</td>
<td>6.20</td>
<td>0.05</td>
<td>21.30</td>
<td>0.17</td>
<td>12,395</td>
<td>460.54</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>J18-4</td>
<td>ZK11 at 342 m level</td>
<td>4541</td>
<td>96.97</td>
<td>5.95</td>
<td>0.05</td>
<td>36.70</td>
<td>0.23</td>
<td>21,496</td>
<td>498.65</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>J18-5</td>
<td>ZK14 at 166 m level</td>
<td>4125</td>
<td>73.58</td>
<td>5.55</td>
<td>0.05</td>
<td>52.36</td>
<td>0.43</td>
<td>30,856</td>
<td>706.91</td>
<td>−0.12</td>
</tr>
<tr>
<td>Py3</td>
<td>Jh-1</td>
<td>374 m level middle section</td>
<td>1437</td>
<td>26.20</td>
<td>3.12</td>
<td>0.05</td>
<td>7.36</td>
<td>0.10</td>
<td>4054</td>
<td>96.79</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Jh-2</td>
<td>374 m level middle section</td>
<td>1255</td>
<td>36.95</td>
<td>2.94</td>
<td>0.02</td>
<td>7.19</td>
<td>0.08</td>
<td>3957</td>
<td>119.94</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Jh-3</td>
<td>374 m level middle section</td>
<td>1346</td>
<td>20.85</td>
<td>3.57</td>
<td>0.02</td>
<td>6.47</td>
<td>0.05</td>
<td>3527</td>
<td>56.64</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Jh-4</td>
<td>ZK4702 at 186 m level</td>
<td>1735</td>
<td>13.05</td>
<td>3.21</td>
<td>0.03</td>
<td>11.39</td>
<td>0.13</td>
<td>6443</td>
<td>76.36</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Jh-5</td>
<td>ZK4702 at 287 m level</td>
<td>1185</td>
<td>20.46</td>
<td>3.02</td>
<td>0.02</td>
<td>11.21</td>
<td>0.06</td>
<td>6354</td>
<td>83.55</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Rhenium mass fraction was analyzed by inductively coupled plasma mass spectrometry (Thermo Elemental X2 Series). A conventional low volume quartz impact bead spray chamber with a Peltier cooled (3 °C) and a 0.4 mL·min⁻¹ borosilicate nebulizer (MicroMist GE) was used in the determinations. Ion lens settings, nebulizer gas flow rate and torch position were optimized daily using a 10 ng·mL⁻¹ tuning In–Ce mixture standard solution in order to obtain the high instrumental sensitivity and low oxide production levels. A peristaltic pump was not used, as free aspiration of the nebulizer provided better signal stability. The details of measurements are described elsewhere [34].

Total procedural blanks (TPBs) were 0.72 ± 0.44 pg (1SE, n = 2) with an 187Os/188Os ratio of 0.67 ± 0.55 (1SE, n = 2) on average for Os and 4.0 ± 0.1 pg (1SE, n = 2) for Re. All data were corrected for the procedural blank for each analytical batch. Blank contributions for mafic-ultramafic rock samples were generally insignificant. The average values (187Os/188Os = 0.13369 ± 0.00014, Os = 0.340 ± 0.032 ppb, Re = 0.691 ± 0.002 ppb, 1SE, n = 2) are in good agreement with published data for basaltic reference material BIR-1 [35–37].

Errors for Re and Os concentration and 187Re/188Os and 187Os/188Os isotopic ratios were determined by numerical error propagation and include spike calibration uncertainties an in-run determination. Ion lens settings, nebulizer gas flow rate and torch position were optimized daily using a 10 ng·mL⁻¹ tuning In–Ce mixture standard solution in order to obtain the high instrumental sensitivity and low oxide production levels. A peristaltic pump was not used, as free aspiration of the nebulizer provided better signal stability. The details of measurements are described elsewhere [34].

Total procedural blanks (TPBs) were 0.72 ± 0.44 pg (1SE, n = 2) with an 187Os/188Os ratio of 0.67 ± 0.55 (1SE, n = 2) on average for Os and 4.0 ± 0.1 pg (1SE, n = 2) for Re. All data were corrected for the procedural blank for each analytical batch. Blank contributions for mafic-ultramafic rock samples were generally insignificant. The average values (187Os/188Os = 0.13369 ± 0.00014, Os = 0.340 ± 0.032 ppb, Re = 0.691 ± 0.002 ppb, 1SE, n = 2) are in good agreement with published data for basaltic reference material BIR-1 [35–37].

Errors for Re and Os concentration and 187Re/188Os and 187Os/188Os isotopic ratios were determined by numerical error propagation and include spike calibration uncertainties an in-run precision during mass-spectrometry measurements for both Re and Os.

5. Results

The blank-corrected Re and Os data for 15 pyrite samples from the Jinchang Deposit are provided in Table 1. Isochrons for these samples were calculated using ISOPLOT software [38] and employing a 187Re decay constant of 1.666 × 10⁻¹¹ year⁻¹ [39].

Total Re and Os concentrations in Py range between 9643 and 10,475, and 11.50 and 14.61 ppt, respectively, corresponding to 187Re/188Os ratios between 10,855 and 42,853, and 187Os/188Os ratios of 16.48–70.72. Py yielded an individual model 3 Re–Os isochron age of 102.9 ± 2.7 Ma (2SE (Standard error); mean square weighted deviation (MSWD) = 0.17; initial 187Os/188Os (IOs) = −2.1 ± 1.0; Figure 7A).

**Figure 7.** Re–Os isochron plots of stage 1–3 pyrites from the Jinchang Gold Deposit. (A) Isochron age of five analyses of Py1; (B) isochron age of five analyses of Py2; (C) isochron age of five analyses of Py3; (D) isochron age of four analyses (excluding J18–4) of Py2.
Rhenium (Re) and Osmium (Os) concentrations in Py$_2$ range between 4087 and 4541, and 5.09 and 6.20 ppt, respectively. The $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios of Py$_2$ range between 11,203 and 31,074, and 19.04 and 52.36, respectively. Five samples yielded an isochron age of 99.3 ± 7.9 Ma (MSWD = 3.2) and $I_{\text{Os}}$ of 0.6 ± 2.1; however, the MSWD is indicative of a relatively large degree of scatter in the data. The results indicate a 0.02 probability of the data fitting the criteria for a model 3 isochron calculated using the ISOPLOT software (Figure 7B), which may be a result of Os loss. Excluding sample J18-4 from the calculation yielded a more precise individual model 3 Re–Os isochron age of 102.0 ± 3.4 Ma (2SE; MSWD = 0.2; $I_{\text{Os}} = 0.04 ± 0.82$; Figure 7D).

The Py$_3$ crystals yielded Re and Os concentrations of 1185–1735 and 2.94–3.20 ppt, respectively, corresponding to $^{187}\text{Re}/^{188}\text{Os}$ ratios of 3957–6443 and $^{187}\text{Os}/^{188}\text{Os}$ ratios of 6.47–11.39. Py$_3$ yielded an individual model 3 Re–Os isochron age of 100.9 ± 3.1 Ma (2SE; MSWD = 0.019; $I_{\text{Os}} = 0.54 ± 0.25$; Figure 7C).

6. Discussion

6.1. Timing of Metallogenesis

To establish the ore genesis of the Jinchang Deposit, it is necessary to obtain precise geochronological data. Previous geochronological studies established that the Jinchang gold deposit formed during the Cretaceous (Table 2). $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of quartz from quartz–pyrite veins in orebody J-1 yielded an age of 122.53 ± 0.88 Ma [10] and an $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 122 Ma [6]. Quartz from quartz–pyrite veins in orebody XII yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age of 119 ± 5 Ma [11]. Sphalerite from orebody J-9 yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age of 129 ± 0.8 Ma [11]. The specific age of mineralization, however, remains unclear. This is firstly due to the fact that quartz and sphalerite are not Au-bearing minerals within the Jinchang Deposit, so the analyses of these minerals define the age of alteration rather than gold mineralization. Secondly, the Jinchang Deposit records evidence of multiple phases of hydrothermal activity, adding further complexity. Even monomineralic quartz samples may contain inclusions of K-feldspar and sericite which, due to their relatively high K concentrations, may influence the $^{40}\text{Ar}/^{39}\text{Ar}$ results. The relatively low precision of the $^{40}\text{Ar}/^{39}\text{Ar}$ fast neutron activation method means that a spread of ages may be observed between the actual ages of different hydrothermal events, further limiting our ability to constrain the nature of the evolving system [40].

The Re–Os radiogenic system in pyrite can be used as a high-precision geochronometer. This dating method has the advantage of an isotopic closure temperature of >500 °C, meaning that the results are not easily disturbed by subsequent metamorphism or deformation and therefore are likely to record the timing of primary crystallization [26,41–43]. Since pyrite is the dominant host of gold in the Jinchang Deposit, the age of pyrite formation will likely record the age of gold mineralization. Five Re–Os isotopic analyses of pyrite reported by Zhang et al. [44] yielded an isochron age of 114 ± 22 Ma; however, the uncertainty on the age is large, probably owing to two factors. First, it is unclear which of the mineralization stages the analyzed pyrite relates to. Pyrite from different ore veins and mineralization stages were analyzed together, resulting in a low degree of confidence in the isochron age and a large age uncertainty [45]. Second, impure separates may yield Re–Os mixed ages of both the pyrite and other material, rather than solely the age of the pyrite [26].

In the present study, three types of pyrite (Py$_1$, Py$_2$, and Py$_3$), reflecting three styles of mineralization, were analyzed. Each stage yields sufficient representative pyrite samples to enable a robust interpretation of the age data. Py$_1$, Py$_2$, and Py$_3$ yield similar metallogenic ages that are sequentially younger from Py$_1$ to Py$_3$, indicating that the ages are representative and accurate. Sericite from altered granite in drill holes ZK14 and ZK04 in the No. 18 orebody yields a Rb–Sr age of 107 ± 5 Ma. Together, the sericite and pyrite yield a Rb–Sr age of 104 ± 6 Ma [19]. This alteration is considered to reflect the initial stage of mineralization in the deposit. The age of gold mineralization should therefore be slightly younger than these ages. The age of gold mineralization is consistent with the Re–Os pyrite age (105.6–97.8 Ma) obtained in this study. A sample of granodiorite was collected...
from a depth of 380 m in drill hole ZK1001 and yielded a $^{206}\text{Pb}/^{238}\text{U}$ age of 106.8 ± 2.0 Ma [21], which is broadly similar to the age of ore formation. Crystallization of a large intrusion and the main stage of mineralization in the development of a gold deposit may occur over several million years [46]. Similarities in the timing of granodiorite emplacement and mineralization within the Jinchang Deposit suggest that the former is the likely source and driver of the latter. The occurrence of granodiorite at depth suggests that mineralization may also extend to deeper structural levels.

### Table 2. Isotopic ages of rocks and minerals from the Jinchang gold deposit.

<table>
<thead>
<tr>
<th>Test object</th>
<th>Method</th>
<th>Age</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diorite</td>
<td>U–Pb</td>
<td>209 ± 1.4 Ma</td>
<td>[23]</td>
</tr>
<tr>
<td>Granite</td>
<td>U–Pb</td>
<td>203.62 ± 0.86 Ma</td>
<td>[20]</td>
</tr>
<tr>
<td>Granite</td>
<td>U–Pb</td>
<td>202.1 ± 3.0 Ma</td>
<td>[22]</td>
</tr>
<tr>
<td>Granite</td>
<td>U–Pb</td>
<td>201 ± 3 Ma</td>
<td>[19]</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>U–Pb</td>
<td>184.69 ± 0.98 Ma</td>
<td>[20]</td>
</tr>
<tr>
<td>Dioritic porphyrite</td>
<td>U–Pb</td>
<td>118.4 ± 1.6 Ma</td>
<td>[9]</td>
</tr>
<tr>
<td>Dioritic porphyrite</td>
<td>U–Pb</td>
<td>116 ± 2 Ma</td>
<td>[23]</td>
</tr>
<tr>
<td>Dioritic porphyrite</td>
<td>U–Pb</td>
<td>115.7 ± 2.0 Ma</td>
<td>[9]</td>
</tr>
<tr>
<td>Dioritic porphyrite</td>
<td>U–Pb</td>
<td>113.5 ± 3.6 Ma</td>
<td>[24]</td>
</tr>
<tr>
<td>Granite porphyry</td>
<td>U–Pb</td>
<td>112.62 ± 0.85 Ma</td>
<td>[23]</td>
</tr>
<tr>
<td>Granite porphyry</td>
<td>U–Pb</td>
<td>110 ± 3 Ma</td>
<td>[19]</td>
</tr>
<tr>
<td>Granodiorite</td>
<td>U–Pb</td>
<td>106.8 ± 2.0 Ma</td>
<td>[21]</td>
</tr>
<tr>
<td>Quartz–pyrite veins in the J-1 orebody</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$ plateau</td>
<td>122.53 ± 0.88 Ma</td>
<td>[10]</td>
</tr>
<tr>
<td>Quartz–pyrite veins in the J-2 orebody</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$ plateau</td>
<td>122 Ma</td>
<td>[6]</td>
</tr>
<tr>
<td>Quartz from quartz–pyrite veins of orebody XII</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$</td>
<td>119 ± 5 Ma</td>
<td>[11]</td>
</tr>
<tr>
<td>Sericite from altered granite</td>
<td>Rb–Sr</td>
<td>107 ± 5 Ma</td>
<td>[19]</td>
</tr>
<tr>
<td>Sericite and pyrite from altered granite</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$</td>
<td>104 ± 6 Ma</td>
<td>[19]</td>
</tr>
<tr>
<td>Sphalerite from J-9 orebody</td>
<td>$^{40}\text{Ar}/^{39}\text{Ar}$</td>
<td>129 ± 0.8 Ma</td>
<td>[11]</td>
</tr>
<tr>
<td>Pyrite from J1 orebody</td>
<td>Re–Os</td>
<td>114 ± 22 Ma</td>
<td>[44]</td>
</tr>
<tr>
<td>Py1</td>
<td>Re–Os</td>
<td>102.9 ± 2.7 Ma</td>
<td>This study</td>
</tr>
<tr>
<td>Py2</td>
<td>Re–Os</td>
<td>102.0 ± 3.4 Ma</td>
<td>This study</td>
</tr>
<tr>
<td>Py3</td>
<td>Re–Os</td>
<td>100.9 ± 3.1 Ma</td>
<td>This study</td>
</tr>
</tbody>
</table>

### 6.2. Re–Os Isotopic Compositions and Implications for the Ore Source

In addition to constraining the age of ore formation, the Re–Os isotopic system can be used to identify the source of the ore-forming material [3,26]. Excluding negative values that are inferred to be erroneous or indicative of systematic disturbance, the $\text{I}_{\text{Os}}$ values derived from Re–Os pyrite isochrons in this study range from 0.04 to 0.60 (Figure 7). The $\text{I}_{\text{Os}}$ values calculated for individual samples range from 0.14 to 0.54 (Table 1), assuming that Py1, Py2, and Py3 formed at 102.9, 102.0, and 100.9 Ma, respectively. In both instances, the $\text{I}_{\text{Os}}$ values are lower than the upper crustal $^{187}\text{Os}/^{188}\text{Os}$ average value of 1.9256 [47]. The $\text{I}_{\text{Os}}$ values lie between the $^{187}\text{Os}/^{188}\text{Os}$ values of chondrite (0.1263), which is representative of the mantle composition at 102 Ma, and those of the lower crust (0.64–0.96) [48]. These observations suggest that the ore-forming materials in this deposit were derived from a mixed crust–mantle source. In the Re–Os versus common Os diagram (Figure 8; after Lambert et al. [1]), the compositions of the auriferous pyrites are approximately consistent with those of mantle melts and the lower crust, suggesting that the ore-forming materials were derived from a mixed crust–mantle source, with the largest contribution being from the lower crust.
6.3. Genesis and Metallogenic Setting of the Jinchang Deposit

The study area records evidence for collision, deformation, and extension associated with subduction of the west Pacific Plate during the late and early stages of the Indosinian and Yanshanian orogenies, respectively [15]. During the early stages of collision (210–190 Ma), I-type granites intruded the Yanji–Dongning area as a result of upper crustal melting [13,16,49]. At ca. 140 Ma, the tectonic setting changed from compression to extension due to closure of the Pacific Ocean during continent–continent collision [50]. During the Early Cretaceous (130–100 Ma), northeast China was undergoing extension, as indicated by bimodal volcanic rocks in the Xiaoxing’anling–Zhangguangcailing region [51–53] and the widespread development of metamorphic core complexes in the Songliao Basin [54].

The timing of mineralization in the various ore deposits within the Yanbian–Dongning area has been investigated by Ar–Ar, Rb–Sr, Re–Os, and U–Pb geochronology of quartz and muscovite, sericite, sulfides, and zircon, respectively [18,40,54–56]. These analyses yielded ages between 126 and 95 Ma, indicating that an important mineralization event took place at this time in the Yanbian–Dongning area. Previous studies have suggested that the ore deposits formed due to regional-scale lithospheric thinning [13,15,16,57].

In the Jinchang Deposit, granodiorite is extensively altered and mineralized, and yields a U–Pb age of 106.8 ± 2.0 Ma (MSWD = 0.65, n = 20) [21]. Re–Os dating of pyrites from the ore body yields ages of 105.6–97.8 Ma (This study), which are interpreted as the timing of ore formation. The ages of diagenesis and metallogenesis are within error of each other, suggesting that mineralization was related to granodiorite emplacement. Upwelling mantle-derived magmas would have provided heat to partially melt the lower crust as well as fluids that extracted metals from the lower crust and facilitated their migration to shallower levels (i.e., toward the upper crust). The Re–Os isotopic analyses of pyrites in this study, and the S and Pb isotopic compositions of ores analyzed previously, also suggest that
the ore-forming components were derived from both crust and mantle sources [19]. The ore-forming fluids are interpreted to have contained abundant volatiles that migrated to the intersections of faults. When the fluid pressure exceeded the pressure of the overlying rocks, cryptoexplosions and thereby breccia pipe mineralization occurred. Vein-disseminated mineralization occurred adjacent to the intrusive body, within the surrounding rock. Magma intrusion caused ring and radial faults to form around the magma dome, creating space for hydrothermal migration, fluid mixing, metal precipitation, and thus fault-controlled vein mineralization.

7. Conclusions
1. Re–Os isotopic analyses of auriferous pyrites from the Jinchang Deposit yielded ages of 102.9–100.9 Ma, which are interpreted to reflect the age of gold mineralization.
2. Re–Os isotopic compositions suggest that the ore-forming material was derived from lower crustal and mantle sources.
3. Three types of mineralization were contemporaneous, but occurred at different structural locations. Granodiorite emplacement is considered the most likely cause of mineralization.

Author Contributions: Conceptualization, S.-D.L. and K.-Y.W.; Methodology, J.L.; Software, W.-Y.C.; Validation, K.-Y.W., S.-D.L. and L.X.; Formal Analysis, Z.-G.W.; Investigation, S.-D.L.; Resources, K.-Y.W.; Data Curation, S.-D.L.; Writing—Original Draft Preparation, S.-D.L.; Writing—Review & Editing, K.-Y.W.; Visualization, S.-D.L.; Supervision, D.-W.P.; Project Administration, L.X.; Funding Acquisition, K.-Y.W.

Funding: This work was supported by China Geological Survey, Chinese Ministry of Science and Technology (2017YFC0601304).

Acknowledgments: We are grateful to the staff of the No. 1 Party of Gold Geology, China People’s Armed Force, for field work in the Jinchang Mine. Two anonymous reviewers and editor are thanked for their constructive comments and reviews, which have significantly improved this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Lambert, D.D.; Foster, J.G.; Frick, L.R. Re-Os isotopic systematics of the Voisey’s Bay Ni-Cu-Co magmatic ore system, Labrador, Canada. Lithos 1999, 47, 69–88. [CrossRef]
3. Stein, H.J.; Morgan, J.W.; Schersten, A. Re-Os dating of low-level highly radiogenic (LLHR) sulfides: The Harnas gold deposit, southwest Sweden, records continental-scale tectonic events. Econ. Geol. 2000, 95, 1657–1671. [CrossRef]


Han, S.J.; Yang, Y.C.; Ye, S.Q.; Khomich, V.G.; Boriskina, N.G.; Wang, X.Y. U-Pb zircon and geochemical constraints on age and genesis of granitoids from the Jinchang Au deposit in Heilongjiang, NE China. Geol. J. 2017. [CrossRef]


Qian, Y.; Sun, F.Y.; Li, B.L.; Chen, J.; Diwu, C.R. Geochemistry and U-Pb geochrony of zircon from granite Samples. Geostand. Geoanal. Res. 2015, 39, 17–30. [CrossRef]


48. Han, S.J.; Sun, J.G.; Bai, L.A.; Xing, S.W.; Chai, P.; Zhang, Y.; Yang, F.; Men, L.J.; Li, Y.X. Geology and ages of porphyry and medium- to high-sulphidation epithermal gold deposits of the continental margin of northeast China. *Int. Geol. Rev.* 2013, 55, 287–310. [CrossRef]


