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Anomalously silver-rich vein-hosted mineralisation in disseminated-style gold deposits, Jiaodong gold district, China

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ABSTRACT

Structural measurements and geochemical analyses, including bulk and in situ pyrite geochemistry, sulfur isotopes, and whole-rock geochemistry, are presented for the No. 3 orebody of the Jiaojia gold deposit (JJ3), located in the Jiaodong district of northeast China. The JJ3 orebody is distinct from the main orebody of the Jiaojia deposit (JJ1) because it is characterised by steeply dipping sub-metric quartz-pyrite veins with up to 300 ppm of gold, whereas the JJ1 orebody represents an archetypal example of the disseminated and veinlet style mineralisation characteristic of regional faults in the Jiaodong district. Measurements on JJ3 veins and the host Jiaojia-Xincheng regional fault are consistent with development of mineralised, steeply dipping extension fractures during normal faulting, which produced the fault-hosted disseminated-style JJ1 orebody. Trace element geochemistry of pyrite in these veins shows that JJ3 pyrite is geochemically distinct from those of the main Jiaojia and Xincheng orebodies, being relatively enriched in Ag and Pb, as well as Ba, Bi, Te and Au, and relatively depleted in Cu and As. Enrichment in Ag and Pb is possibly related to infiltration of a saline hydrothermal fluid, as both are effectively transported as chloride complexes; however, depletion of Cu, which is also mobile as chloride complexes, requires a low temperature saline fluid where Cu is no longer soluble. The textural setting of the ore minerals suggests that these cooler fluids likely infiltrated during the waning stages of the hydrothermal system. The relative abundance of barite in the JJ3 orebody, which formed from late-stage oxidised magmatic–hydrothermal fluids, also supports the interpretation that the JJ3 orebody represents a late mineralisation event. The pervasive alteration surrounding the JJ3 orebody is K-feldspathic with a minor sericitic overprint, indicating an earlier higher temperature pervasive fluid flow event that was followed by low-temperature mineralising fluids. This interpretation implies that fracture dilation post-dated the earliest alteration, and that mineralisation and pervasive alteration in the JJ3 orebody are geochemically disconnected. Thus structural analysis is expected to be the most effective targeting method in future exploration for similar ore bodies.

1. Introduction

Located in the northeast Shandong Province, the Jiaodong gold district is responsible for more than 25% of China's annual gold production, at a time when China is the world leader in gold production (Goldfarb et al., 2014). Given that the Jiaodong district covers only ~20,000 km^2 (representing 0.2% of China's land area) and yet hosts 30% of China's total gold reserves (Guo et al., 2013), this region is one of the most important gold producing regions globally and has been the focus of much modern research (e.g. Li et al., 2015; Song et al., 2015; Q. Yang et al., 2014). Within the district, over 95% of mineralisation is hosted in Mesozoic granitoids, which intrude Archean and Proterozoic cratonic basement of the North China Craton (Qiu et al., 2002).

Among the gold deposits in the Jiaodong district, there are two world-class gold fields, the Jiaojia-Xincheng and the Linglong fields, each containing over 150 t of Au (Qiu et al., 2002; C. Wang et al, 2015). The Jiaojia-Xincheng and Linglong fields contain many individual deposits within broader areas of related mineralisation. These two gold fields, in addition to being the largest gold concentrations in the Jiaodong district, are considered to be the archetypal examples of the two most common styles of mineralisation in the Jiaodong district. 'Jiaojia-style' mineralisation is typified by disseminated and veinlet mineralisation forming tabular orebodies in the brecciated footwall of regional faults (Fan et al., 2007; Qiu et al., 2002). 'Linglong-style' mineralisation is characterised by centimetre to metre wide quartz-pyrite veins (lodes) developed along subsidiary fracture networks associated with regional faults (Fan et al., 2007; Qiu et al., 2002). Although distinguishing between these main styles of mineralisation can be helpful for a brief description, presenting 'Jiaojia-' and 'Linglong-styles' as endmember mineralisation styles indicates they are exclusive to

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one another, while in fact both styles can be locally important within a single deposit.

In this study, we show that steeply dipping quartz-pyrite veins, a similar structural style of mineralisation to that found in the Linglong gold field, are an important feature of the Jiaojia-Xincheng gold field. They contain geochemical anomalies that, when combined with an analysis of the structural setting, provide insights into variations in the evolution of the hydrothermal fluids that formed the world-class Jiaojia-Xincheng gold field.

2. Jiaojia-Xincheng gold field

2.1. Regional geology

The Jiaodong gold district is located on the eastern margin of the North China Craton, which has experienced multiple significant Phanerozoic reactivations since cratonisation at 1.8 Ga. One of the most unique aspects of the North China Craton is that it represents the best known example worldwide of a craton that has become 'decratonised' through destruction of its stabilising lithospheric keel (Griffin et al., 1998). The destruction of the sub-continental lithospheric mantle (SCLM) took place mainly during the Cretaceous and was limited to the eastern portion of the craton, with some areas losing up to 100 km of lithospheric root (Griffin et al., 1998; Zhu et al., 2012). This drastic thinning of the lithosphere occurred coevally with extensional tectonics, mantle upwelling, widespread magmatism, and development of gold mineralisation along the margins of the eastern North China Craton (Li et al., 2012; Wu et al., 2005).

In addition to loss of lithosphere, all margins of the North China Craton experienced significant orogenesis during the late Paleozoic to Mesozoic. Of particular importance to the basement architecture of the Jiaodong district was the Triassic (~240 Ma) continental collision between the southern margin of the North China Craton and the Yangtze Craton, which saw continental material from the Yangtze craton subducted beneath the North China Craton (Hacker et al., 2006). The collision also resulted in formation of the Sulu ultrahigh pressure (UHP) terrane, which forms the basement of the eastern Jiaodong district. Subduction of the Pacific Plate beneath the margin of east Asia was also initiated in the Cretaceous, and is commonly suggested to have been a far-field control on lithospheric destruction and consequent processes (e.g. Goldfarb et al., 2014). The Tan Lu fault zone, which is a regional transcrustal fault that parallels the eastern margin of the North China Craton, was also active during the Cretaceous and has been shown to be a corridor for mantle upwelling (Guo et al., 2013; Xiao et al., 2010). The Tan Lu fault is located only ~30 km from the westernmost extent of the Jiaodong district (Fig. 1).

The basement of the Jiaodong district is comprised of two terranes: 1) the aforementioned Sulu UHP terrane in the east, typically considered to bear affinity to the Yangtze Craton, and 2) the Archean to Paleoproterozoic Jiaobei terrane in the west, which is part of the North China Craton (Jahn et al., 2008; Tang et al., 2008; Fig. 1). The two terranes are separated by the Wulian-Yantai fault. There is no evidence for the existence of Paleozoic to middle Jurassic aged rocks in the Jiaodong district, likely indicating intensive uplift and erosion during this period (Guo et al., 2013). The earliest preserved units deposited after cratonisation are late Cretaceous volcano-sedimentary sequences hosted in the Jiaolai basin, which opened as a result of extensional tectonics (L. Zhang et al., 2003). These rocks are distributed throughout the southern portion of the Jiaodong district.

Despite the lack of Paleozoic and early Mesozoic strata, intrusive magmatism was active starting in the Jurassic. Magmatism in the Jiaodong district is typically divided into Jurassic, early Cretaceous, and late Cretaceous periods. Magmatism in the Jurassic was active at ~160 Ma and resulted in the Linglong, Luanjiahe, and Kunyushan

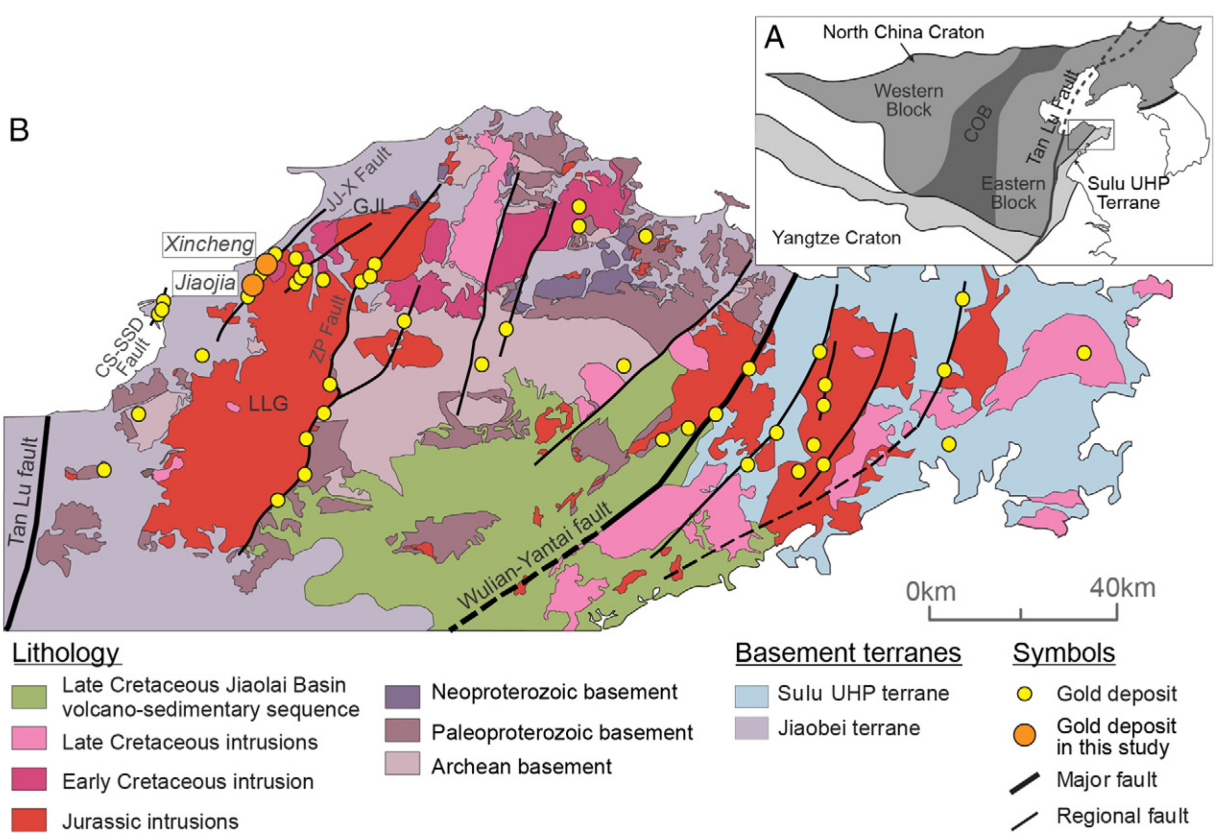

Fig. 1. (A) Regional map of the North China Craton, and (B) geologic map of the Jiaodong gold district. Major gold mineralisation belts and the deposits sampled for and referred to in this study are indicated (after Fan et al., 2003; Goss et al., 2010; Hacker et al., 2006; Li et al., 2012; Liu et al., 2013; Zhang et al., 2010; Yang et al., 2012). JJ-X fault = Jiaojia-Xincheng fault, CS-SSD fault = Cangshang-Sanshandao fault, ZP fault = Zhaoping fault, LLG = Linglong granite, GJL = Guojialing granodiorite.