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Tectonic transition from a compressional to extensional metallogenic environment at ~120 Ma revealed in the Hushan gold deposit, Jiaodong, North China Craton

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ABSTRACT

The world-class giant gold province (> 4000 t) in the Jiaodong Peninsula has attracted global attention and extensive studies for decades. However, most of the works have been focused on the western Zhaoyuan-Laizhou and eastern Muping-Rushan gold metallogenic belt, leaving the middle Penglai-Qixia belt largely unexplored. The Hushan gold deposit in the Penglai-Qixia belt shows a unique two-stage gold mineralization, i.e., an early-stage pyrite-sericite-quartz altered-rock type mineralization and a late-stage pyrite-pyrrhotite vein type mineralization. Hydrothermal monazite coexisting with Au-bearing pyrite is observed in the early-stage mineralization. The widespread "circular zoned" metasomatic relict structures indicate that monazite was formed by the strong interaction between (Ca, P, REE)-rich fluids and feldspars (plagioclase and K-feldspar). Therefore obtained *in-situ* U-Pb age of 120.0 ± 3.1 Ma for the "pure" monazite without mineral inclusions (such as feldspars) can represent the timing of the early-stage gold mineralization. The *in-situ* monazite ε_{Nd} (t) (t = 120 Ma) values vary from −20.6 to −18.4, well corresponding to Nd isotopes of the late Jurassic Linglong granite. It is inferred that the REE-rich components in the ore-forming fluids were extracted during the process of primary mineralizing fluids passing through the lower Linglong granite body, and that the Nd isotopic compositions were altered due to the strong fluid-rock interaction. In this regard, Linglong granite contributes some ore-forming materials to the mineralizing fluids during fluid-rock interaction.

The early-stage altered-rock type gold mineralization indicates a compressional (closed) ore-forming system, whereas the late-stage pyrite-pyrrhotite vein type mineralization and the occurrences of fracture, geode and hole in the ore samples reflect an extensional (open) ore-forming system. The presence of barite and magnetite in the late-stage mineralization also suggests an increase of oxidation state during the process. Furthermore, pyrites in the late stage generally have lower $\delta^{34}S$ values (5.69–6.98‰, av. = 6.47‰) than pyrites in the early stage ($\delta^{34}S$ values = 7.06–7.85‰, av. = 7.42‰), which can also be well explained by the increase of oxidation state. Therefore, the Hushan gold deposit uniquely records a metallogenic environmental transition from compressional, reduced to extensional, oxidized at ~120 Ma. In addition, the mineralizing fluids with higher oxidation state in the late-stage is supposed to superimpose on the early-stage mineralization, dissolve and rework previously crystalized pyrite to form the high-grade gold mineralization. Unlike the gold deposits in the western and eastern belts, the Hushan gold deposit temporally preserves two types of mineralization in one single deposit, as a response to regional stress field transition.

1. Introduction

The gold deposits in the Jiaodong Peninsula constitute one of the richest gold mineralization class in the world (Santosh and Pirajno, 2015) and the entire Jiaodong gold prospective resources have now exceeded 4000 metric tons with the two new super-large gold deposits discovered at Sanshandao and Shaling areas (with 470 and 389 tons, respectively) in 2015 (Hao et al., 2016). The Jiaodong gold deposits own some unique tectonic settings and gold mineralization origins that cannot be fully explained by conventional orogenic or intrusion-related gold deposits (e.g., Goldfarb and Santosh, 2014; Li et al., 2015; Wen et al., 2016; Ma et al., 2017), which thus have attracted continuous

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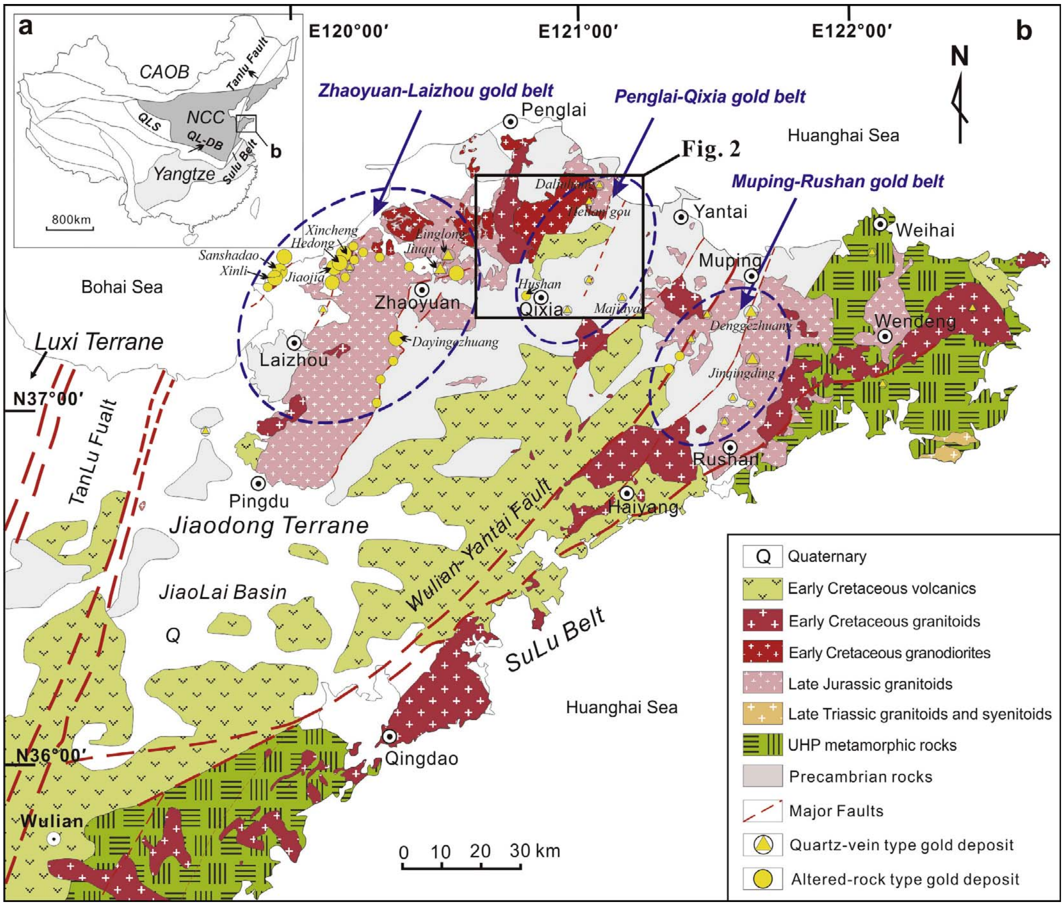

Fig. 1. Simplified geological map of the Jiaodong Peninsula showing location of the major gold deposits. (a) The location of NCC in China; QLS, QL-DB represents Qilianshan and Qinling-Dabie orogenic belt respectively. (b) The distribution of Precambrian basement, Triassic igneous rocks and UHP metamorphic rocks, Late Mesozoic igneous rocks, and the three gold metallogenic belts in the Jiaodong Peninsula. (Modified after Jiang et al., 2016). The size of the symbols of the gold deposits indicates the gold reserves, small (< 50 t), large (> 50 t).

global attention and intensive studies. During the past decades, a mass of researches have been conducted to constrain the timing of gold mineralization (e.g., Yang and Zhou, 2001; Li et al., 2003, 2006; Bi and Zhao, 2017; Ma et al., 2017), fluid inclusions and their implications for ore fluid evolution (e.g., Fan et al., 2003; Hu et al., 2013; Wen et al., 2015, 2016), ore-forming fluid and material sources (e.g., Yang and Zhou, 2001; Zhang et al., 2008; Mao et al., 2008; Tan et al., 2012, 2015), hydrothermal alteration and gold precipitation processes through geology and geochemical modeling (Li et al., 2013; Xu et al., 2016), and geodynamic settings and metallogenic models for the Jiaodong gold deposits (e.g., Qiu et al., 2002; Song et al., 2012; Guo et al., 2013; Yang and Santosh, 2015; Zhu et al., 2015; Groves and Santosh, 2016; Fan et al., 2016; Lan et al., 2017; Yang et al., 2017a).

However, most of the attentions have been paid to the Zhaoyuan-Laizhou and Muping-Rushan gold metallogenic belt which are located in the western and eastern Jiaodong, respectively, whereas the works regarding the Penglai-Qixia belt in the Central Jiaodong is rather limited, mainly including the works on the fluid/metal sources, fluid inclusions and mechanisms for gold precipitation (e.g., Hou et al., 2004, 2006, 2007a; Yan et al., 2014; Wang et al., 2013, 2016). The detailed mineralogical and *in-situ* geochemical works, and discussion on the delicate ore-forming process are lacked. In addition, the obtained pyrite Rb-Sr isochron ages (117.8 ± 6.5 Ma, MSWD = 17) for the Heilan'gou and Daliuhang gold deposits (Hou et al., 2006) and hydrous muscovite (sericite) Rb-Sr and K-Ar ages (135.1 ± 5.2 Ma and 120 ± 2 Ma, respectively) for the Majiayao gold deposits (Luo and Wu, 1987) all revealed large uncertainties. Therefore, precise constraints on the mineralization ages of the gold deposits in the Penglai-Qixia belt are in strongly required. Furthermore, comparisons of timing, ore-forming processes and metallogenic environments among the Penglai-Qixia, Zhaoyuan-Laizhou and Muping-Rushan gold belts needs to be made in order to have a better and more complete understanding of the gold metallogenesis in the Jiaodong region.

The Hushan gold deposit is a newly discovered (2011–2012) large gold deposit at the Penglai-Qixia metallogenic belt (Fig. 1b), with a gold reservoir of over 30 tons (Liao et al., 2014). Up to now, no more studies have been investigated on this deposit. What signifies the importance of this deposit is its occurrence of pyrrhotite-vein mineralization with high grade gold mineralization (~20 g/t) and hydrothermal monazite coexisting with Au-bearing pyrite. Although many gold deposits in Jiaodong show occurrences of pyrrhotite (e.g., Li et al., 2013; Wen et al., 2015, 2016; Ma et al., 2017), but it does not occur as ore veins to form a single mineralization stage. In addition, with a high closure temperature (700–750 °C) (e.g., Smith and Giletti, 1997; Suzuki and Adachi, 1994), hydrothermal monazite can be an ideal mineral to date mineralization events (Schandl and Gorton, 2004; Janots et al., 2014). One the latest and first report of *in-situ* monazite U-Pb dating for the Xiadian gold deposit in the western Jiaodong has been reported by Ma et al. (2017), which obtains a well-constrained age of ~120 Ma. However, such a study does not present further implications from monazite for the fluid-rock interaction process. Monazite has shown its robust fingerprints on geological processes with its textures, geochemical and isotopic compositions (e.g., Poitrasson et al., 1996, 2000; Harlov et al., 2002; Williams et al., 2007; Holder et al., 2015; Fisher et al., 2017). Furthermore, the Hushan gold deposit is unique by revealing two distinct mineralization types, i.e., an early-stage altered-rock type (pyrite-sericite-quartz) mineralization, and a late-stage pyrite-pyrrhotite vein type gold mineralization. Currently, no studies have been reported on