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Geodynamics of gold metallogeny in the Shandong Province, NE China: An integrated geological, geophysical and geochemical perspective

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ABSTRACT

The Shandong Province along the southeastern margin of the North China Craton is the largest gold producing region in China. The nature and extent of gold metallogeny between the Western Shandong (Luxi) and Eastern Shandong (Jiaodong) sectors display marked contrast. In this paper, we synthesize the information on mineralization and magmatism, S–Pb–H–O–C–He–Ar isotopic data of the ores and Sr–Nd–Pb–Hf isotopic data of the Mesozoic plutons from the Shandong region. Combined with the salient regional geophysical data, we discuss the geodynamic setting of the gold mineralization in Shandong. The age data converge to indicate that the peak of gold metallogeny in this region occurred at ca. 120 ± 10 Ma. The mineralization in Luxi area shows links with sources in the Tongjing and Yinan complexes. The ore-forming materials in the Jiaodong area were derived from multiple sources and show clear evidence for crust–mantle mixing. The Moho depth on both sides of the Tan–Lu fault is broadly similar with only a minor variation across the Tan–Lu fault. The LAB (lithosphere–asthenosphere boundary) in the Jiaodong region is shallower than that in the Luxi area. The Tan–Lu fault is identified as a major corridor for asthenosphere upwelling. Geochemical features show that the mantle beneath the Luxi area is mainly of EM1 type, whereas the mantle in the eastern part, close to the Tan–Lu fault shows mixed EM1 and EM2 features. In contrast, the mantle beneath the Jiaodong area is mainly of EM2 type, suggesting the existence of more ancient lithospheric mantle beneath the Luxi area, in comparison to the extensively modified lithospheric mantle and asthenosphere beneath the Jiaodong area. The gold metallogeny in Shandong Province occurred in the geodynamic setting of lithospheric thinning. The differences in the character and intensity of gold mineralization between the Western and Eastern Shandong regions might be a reflection of the contrasting tectonic histories. The Western Shandong region preserves imprints of destruction through the Yangtze plate collision which probably marks the prelude for gold metallogeny in Jiaodong area. Subsequent magmatic input and cratonic destruction through Pacific plate subduction provided the settings for the later widespread mineralization in multiple phases.

1. Introduction

The geological settings, host rocks, nature of mineralization and geochemical signatures have been used as important parameters to classify gold deposits over the globe into various categories (e.g., Robert et al., 1997). Among these, the intrusion-related vein gold deposits have been further classified into a number of sub-types (Sillitoe and Thompson, 1998). Gold deposits over the globe have also been classified based on their geodynamic setting, such as the convergent margin orogenic gold deposits, continental margin to intracratonic Carlin and Carlin-like gold deposits, arc-related epithermal gold–silver deposits, oceanic arc to continental arc copper–gold porphyry deposits, anorogenic to late orogenic iron-oxide copper–gold deposits, and gold-rich submarine volcanic hosted massive sulfide (VMS) to sedimentary exhalative (SEDEX) deposits (Kerrich et al., 2000). The circum Pacific metallogenic belt and surrounding regions to the East and West sides of the Eurasian plate and the Variscan–Tethyan metallogenic belts are among the major gold producers of the globe (e.g., Deng et al., 2002). Goldfarb et al. (2007) considered the Early Cretaceous “orogenic gold deposits” in eastern Asia as globally unique in that large Phanerozoic lode gold deposits occur in this region within Archean–Paleoproterozoic cratons. They correlated the gold deposits in northern Pacific region, the ca. 125 Ma orogenic gold deposits in the North China, Yangtze, and Siberian craton margins, as well as in young terranes in California, to a giant Cretaceous mantle plume in the southern Pacific basin and the relatively rapid tectonic consequences along both continental margins resulting from Pacific plate reconfigurations. Chen et al. (1992) divided the gold deposits in China into several genetic types based on the nature of mineralization, main ore controlling factors, the composition and structure of the ores and the nature of the host rock types. Liu et al. (2000) classified the major gold deposits of China

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into medium-deep vein type, hypabyssal vein type, porphyry type, skarn type and placer (alluvial) type. Lu (2002) further refined the classification into magmatic–hydrothermal type, volcanic–subvolcanic type, sedimentary–metamorphic type, metamorphic–hydrothermal type, sub-surface thermal brine leaching type, weathering crust type and sedimentary type.

The Shandong Province along the southeastern margin of the North China craton is the largest gold producing region in China, yielding about 30 t bullions per year. The gold reserves occupy more than 25% of the total reserve of the country, with 90% of the gold deposits concentrated in the Jiaodong area (Zhai et al., 2001; Zhou et al., 2002; Fan et al., 2005; Li et al., 2006). The reserves identified so far, the concentration of large deposits and the scales of individual deposits in the area are the largest among the various gold metallogenic belts in China (Li et al., 2006). At present, the Shandong Province has 159 gold mines, including 39 large and medium mines and 120 small mines. According to statistics, 13 of the 17 towns in Shandong Province have gold deposits. The proved reserves are mainly concentrated in Yantai, Weihai, and Qingdao, which account for 93% of the gold reserves of Shandong. Among the various deposits in this region, the Linglong gold deposit in Zhaoyuan area and the Jiaojia–Xincheng gold deposit in Laizhou area are the two super large gold fields in East Shandong. The second largest reserve occurs in the Pingyi area in southwest Shandong (Liu, 2004).

The major metallogenic belt of Shandong Province belongs to the region bordering the Western Pacific domain. The second belt occurs in the North China Platform and Taishan Dabie orogenic belt. The third set of occurrences include the East Shandong metallogenic belt, Tan–Lu fault metallogenic belt, West Shandong metallogenic belt, North China Basin and Jiaonan orogenic metallogenic belt (Liu and Chen, 2002; Song et al., 2007). The gold reserves in the Shandong Province are mainly distributed in East Shandong metallogenic zone, Jiaonan metallogenic zone and West Shandong (Chen et al., 1998).

The gold deposits in the Jiaodong gold belt are genetically separated into Zhaoyuan–Laizhou–Changyi belt, Qixia–Daotou–Pingdu belt, Muping–Rushan belt, Weihai–Wendeng belt, and Taocun–Haiyang–Laiyang belt, largely based on the gold distribution, nature of magmatic rocks, tectonic settings, geophysical and geochemical prospecting anomalies, and placer deposits (Wang et al., 2003; G.Z. Xu et al., 2004; Y.G. Xu et al., 2004a). X.P. Qiu et al. (2008) divided the Jiaodong gold region into 4 metallogenic belts: (1) the first gold ore belt located in western Sanshandao–Cangshang fault shear zone, including the sea domain; (2) the second gold ore belt located between Jiaojia–Huangxian arc shear zone and Zhaoping curved shear zone representing the largest gold metallogenic belt in Jiaodong as well is in China; (3) the third gold ore belt comprising the Muping–Rushan metallogenic belt; and (4) the fourth gold ore belt named Muping–Jimo metallogenic belt (also known as the Guocheng metallogenic belt). The Luxi area has much less gold deposits as compared to those in the Jiaodong area, both in their quantity and size. Several scattered and small deposits also occur in the region, such as those in the Pingyi and Yinan areas. Based on the spatial distribution of gold deposits, ore-controlling structures, and metallogenic features, Song et al. (2007) divided the Shandong gold deposits into 7 metallogenic zones: Sanshandao–Cangshang metallogenic belt, Loukou–Laizhou metallogenic belt, Zhaoyuan–Pingdu metallogenic belt, Muping-Rushan metallogenic belt, Qixia–Penglai–Fushan metallogenic area, the margins of Jiaolai Basin and Mesozoic complex in western Shandong.

The main structural feature of these gold belts is the strong fault-controlled nature of the mineralization, particularly the relationship with the secondary fracture systems associated with the major Tan–Lu fault (Zhao et al., 1996; Ren et al., 1997; Shen et al., 2003; Song et al., 2007). The super large and large gold deposits in Jiaodong such as the Linglong, Jiaojia, Taishang, and Sansandao deposits are distributed in Zhaoyuan–Yexian belt in northwest Jiaodong. Except the Denggezhuang, Jinqingding, and Pengjiakuang gold deposits, the rest are mostly in small scale. Thus, the gold mineralization in West Jiaodong shows much higher intensity as compared with that in East Jiaodong (Fan et al., 2005).

In this paper, we integrate the geological, geochronological, geochemical and geophysical information from published literature relating to the gold mineralization in the Shandong Province in an attempt to evaluate the mechanism and processes of gold metallogeny within a regional tectonic perspective.

2. Geological framework

2.1. Precambrian geological and tectonic framework of the North China Craton

The North China Craton (NCC), composed of the Western Block, Eastern Block and Trans-North China Orogen (TNCO), is one of the world's oldest Archean cratons with crustal remnants as old as 3800 Ma (Jahn et al., 1987; Liu et al., 1992; Zhai and Santosh, 2011). The NCC was figured prominently in recent discussions on the paleogeographic reconstructions of the Paleoproterozoic supercontinent Columbia (Kusky and Santosh, 2009; Santosh et al., 2010; Kusky, 2011). The basement of the Eastern Block includes Archean tonalitic–trondhjemitic–granodioritic (TTG) gneisses, syntectonic granitoids and minor Archean supracrustal rocks. The Western Block is an amalgam of the Archean Yinshan Block to the north and the Proterozoic Ordos Block to the south. The TNCO which is considered as the collisional suture between the Eastern and Western Blocks exposes Neoarchean to Paleoproterozoic TTG gneisses and granitoids (Zhao et al., 1998, 1999, 2001). Zhai and Santosh (2011) evaluated the early Precambrian crustal evolution history of the NCC and identified a major continental growth at ca. 2.7 Ga, and the amalgamation of micro-blocks and building of the craton at ca. 2.5 Ga. This was followed by rifting–subduction–accretion–collision during Paleoproterozoic accompanied by high and ultrahigh-temperature granulite facies metamorphism and granitoid magmatism during ca. 2.0–1.82. The NCC was finally stabilized in late Paleoproterozoic at 1.85 Ga, and much of the craton remained stable up to Triassic (B. Chen et al., 2008a). During Mesozoic, extensive magmatism destroyed a significant portion of the eastern part of the craton and several magmatic intrusions are widely distributed in the eastern NCC and part of the TNCO (Fig. 1). The magmatism and craton destruction coincided with the formation of gold deposits such as those in the northern NCC gold district, the Jiapigou gold district, the Liaodong gold district, the Jiaodong gold district, the Linyi gold belt, the Xiaoqinling gold belt and the Xiong'ershan gold district. Recent studies clearly identify the contribution of the Mesozoic magmatism to large scale gold metallogeny in this region (e.g., J.W. Li et al., 2012; S.R. Li et al., 2012a; Li et al., 2013).

2.2. Mesozoic magmatism and craton destruction

The tectonic framework and continental geodynamic milieu during Mesozoic and Cenozoic in East Asia, including the NCC lithosphere witnessed a unique transformation and destruction process. In the eastern part, the old, cold, thick and refractory cratonic lithosphere mantle was replaced by young, hot, thin and relatively fresh oceanic lithosphere mantle, accompanied by extensive magmatic activity, increased surface heat flux, leading to large-scale tectonic extension and the formation of large intracratonic basins (Chen et al., 2010; Tang et al., 2013). The timing, mechanism and geodynamic setting of the thinning of the NCC lithosphere have been topics of interesting debate (e.g., Zhang et al., 2013, and references therein).

Various views exist regarding the timing of onset of lithospheric thinning including late Triassic (Menzies and Xu, 1998; Lu et al., 2000; Gao et al., 2002), Late Mesozoic (Deng et al., 1994; Lu et al., 2006; F.Y. Wu et al., 2008), Cenozoic (Menzies et al., 1993; Griffin et