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Decratonic gold deposits

ZHU RiXiang[1*], FAN HongRui[1], LI JianWei[2], MENG QingRen[1], LI ShengRong[3] & ZENG QingDong[1]

[1] *State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;*
[2] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China;*
[3] *State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China*

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The North China Craton (NCC) hosts numerous gold deposits and is known as the most gold-productive region of China. The gold deposits were mostly formed within a few million years in the Early Cretaceous (130–120 Ma), coeval with widespread occurrences of bimodal magmatism, rift basins and metamorphic core complexes that marked the peak of lithospheric thinning and destruction of the NCC. Stable isotope data and geological evidence indicate that ore-forming fluids and other components were largely exsolved from cooling magma and/or derived from mantle degassing during the period of lithospheric extension. Gold mineralization in the NCC contrasts strikingly with that of other cratons where gold ore-forming fluids were sourced mostly from metamorphic devolatization in compressional or transpressional regimes. In this paper, we present a summary and discussion on time-space distribution and ore genesis of gold deposits in the NCC in the context of the timing, spatial variation, and decratonic processes. Compared with orogenic gold deposits in other cratonic blocks, the Early Cretaceous gold deposits in the NCC are quite distinct in that they were deposited from magma-derived fluids under extensional settings and associated closely with destruction of cratonic lithosphere. We argue that Early Cretaceous gold deposits in the NCC cannot be classified as orogenic gold deposits as previously suggested, rather, they are a new type of gold deposits, termed as "decratonic gold deposits" in this study. The westward subduction of the paleo-West Pacific plate (the Izanagi plate) beneath the eastern China continent gave rise to an optimal tectonic setting for large-scale gold mineralization in the Early Cretaceous. Dehydration of the subducted and stagnant slab in the mantle transition zone led to continuous hydration and considerable metasomatism of the mantle wedge beneath the NCC. As a consequence, the refractory mantle became oxidized and highly enriched in large ion lithophile elements and chalcophile elements (e.g., Cu, Au, Ag and Te). Partial melting of such a mantle would have produced voluminous hydrous, Au- and S-bearing basaltic magma, which, together with crust-derived melts induced by underplating of basaltic magma, served as an important source for ore-forming fluids. It is suggested that the Eocene Carlin-type gold deposits in Nevada, occurring geologically in the deformed western margin of the North America Craton, are comparable with the Early Cretaceous gold deposits of the NCC because they share similar tectonic settings and auriferous fluids. The NCC gold deposits are characterized by gold-bearing quartz veins in the Archean amphibolite facies rocks, whereas the Nevada gold deposits are featured by fine-grained sulfide dissemination in Paleozoic marine sedimentary rocks. Their main differences in gold mineralization are the different host rocks, ore-controlling structures, and ore-forming depth. The similar tectonic setting and ore-forming fluid source, however, indicate that the Carlin-type gold deposits in Nevada are actually analogous to decratonic gold deposits in the NCC. Gold deposits in both the NCC and Nevada were formed in a relatively short time interval (<10 Myr) and become progressively younger toward the subduction zone. Younging of gold mineralization toward subduction zone might have been attributed to retreat of subduction zone and rollback of subducted slab. According to the ages of gold deposits on inland and marginal zones, the retreat rates of the Izanagi plate in the western Pacific in the Early Cretaceous and the Farallon plate of the eastern Pacific in the Eocene are estimated at 8.8 cm/yr and 3.3 cm/yr, respectively.

Early Cretaceous, craton destruction, decratonic gold deposit, ore deposit model

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*Corresponding author (email: rxzhu@mail.iggcas.ac.cn)

Cratons are the crustal domains that have remained stable since their formation in the early Precambrian, and are typified by a thick lithospheric root (>150 km), weak tectonism (lacking intense crustal deformation, large-scale magmatism and strong seismicity), existence of a refractory lithospheric mantle (harzburgite of $Mg^{\#}$>92, high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$), and strong mechanical and chemical coupling between the crust and mantle (Pollack, 1986; Hieronymus et al., 2007; Zhang et al., 2008; Wu et al., 2014). Decratonization is thus defined as the complete loss of the fundamental characters of a craton (Zhu et al., 2011).

On the basis of geological, geophysical, and geochemical data, the North China Craton (NCC) can be divided into the eastern block (east of the Taihang Mountains), central zone (along the Taihang-Lüliang Mountains), and western block (Ordos block) (Figure 1). The eastern block has completely been decratonized, whereas the western block remains largely unaffected. The central zone, however, experienced modification to various degrees. Decratonization of the eastern block and modification of the central zone culminated at ca. 125 Ma (Zhu et al., 2012a), which are thought to be the result of unsteady mantle flow induced by the west-dipping subduction of the paleo-West Pacific plate (the Izanagi plate) (Zhu and Zheng, 2009). Subduction of the paleo-West Pacific plate is believed to have exerted three major influences on the mantle lithosphere beneath East Asia: (1) metasomatism and weakening of subcontinental lithospheric mantle (SCLM) due to unsteady mantle flow, upwelling of the asthenosphere, and marked increase in slab-derived fluids and/or melts (Zheng et al., 2008a); (2) whole-scale lithospheric extension in the eastern NCC due to unsteady mantle flow in conjunction with slab rollback and trench retreat (Zhu et al., 2012b), and (3) the ancient SCLM was largely replaced with young oceanic mantle as a result of the peridotite-melt interaction (Zhang et al., 2009; Tang Y J et al., 2013 and references therein), implying that the NCC was no longer a stable craton at all (Zhu et al., 2011). Similar observations have also been made in the Wyoming (Lee et al., 2001; Carlson et al., 2005) and Brazilian cratons (Beck and Zandt, 2002) that have been already modified due to rollback of a subducted flat slab. We here suggest an integrated driving mechanism for decratonization involving the following processes: (1) subduction of oceanic plate; (2) rollback of the subducted slab and trench retreat; (3) stagnation and dehydration of the subducted slab in mantle transition zone; (4) partial melting of the lithospheric mantle above the mantle transition zone owing to dehydration of stagnant slab; (5) weakening and unsteady flow of the hydrated mantle wedge and its adiabatic melting; (6) changing of tectonic regime of lithosphere mantle (i.e. decratonization) triggered by unsteady mantle flow. Subduction of oceanic plate alone is unable to cause craton destruction.

Most cratons are well endowed with a large variety of ore deposits that were emplaced in the process of craton formation. However, few endogenic ore deposits were formed after the formation or stabilization of cratonic blocks owing to the lack of significant deformation and magmatism (Groves and Bierlein, 2007). The NCC is an exception because it experienced extensive hydrothermal mineralization in the late Mesozoic, as manifested by numerous Mo, Au, Fe, and Ag-Pb-Zn deposits. This unusual mineralization is best illustrated in the southern and northern margins of the NCC, which contain the world's largest Mo resources of Mesozoic ages (Mao et al., 2011; Li et al., 2012; Zeng et al., 2013) and in the eastern margin that hosts giant gold resources. Gold deposits cluster in several ore- concentrated districts in the NCC, such as the Jiaodong district in the easternmost NCC and the Xiaoqinling district in the southernmost NCC. The two districts have a total gold reserve of ~4000–5000 t and are among the largest gold producing districts in the world (Goldfarb and Santosh, 2014). These gold deposits were formed in the Early Cretaceous (130–120 Ma; Li J W et al., 2003, 2012a; Yang et al., 2003) when destruction of the NCC culminated (Zhu et al. 2011).

The temporal and spatial coincidence between gold mineralization and craton destruction indicates that there exists a genetic linkage between them. Stable isotope and noble gas geochemistry provides evidence that gold and ore-forming fluids were largely from mantle- and crust-derived magmas (Mao et al., 2008; Li J W et al., 2012a), contrasting with orogenic gold deposits of other cratons, which precipitated from metamorphism-related fluids. Some gold deposits in the northern and southern margins of the NCC were formed in the Late Triassic and Early Jurassic (e.g., Jinchangyu, Jiapigou, Shanggong, Dianfang), and are interpreted to have resulted from tectonic processes of the Qinling orogen to the south and the central Asian orogen to the north of the NCC. In this paper, we present an overview of geology, mineralization characteristics, spatio-temporal distribution, and sources of gold and ore-forming fluids of the Early Cretaceous gold deposits in the NCC to demonstrate a causal linkage between large-scale gold mineralization and craton destruction. On the basis of a comparative analysis of gold deposits in the NCC and typical orogenic gold deposits elsewhere, we argue that the Early Cretaceous gold deposits in the NCC is a new type of gold deposits, termed as "decratonic gold deposits" in this study.

1 Age and spatial distribution of gold deposits

Gold deposits cluster in a few major gold ore-concentrated districts in the NCC, such as the Liaodong-Ji'nan, Jiaodong, Xiaoqinling, Xiong'ershan, central Taihangshan, Jibei-Jidong, and Chifeng-Chaoyang districts (Chen et al., 1998; Yang et al., 2003), which form two roughly NNE-striking gold belts (Figure 1). The Eastern Belt consists of the Jiaodong, Liaodong, and Ji'nan districts, which mainly occur to the east of the Tanlu strike-slip fault. The Western Belt comprises the Xiaoqinling, Xiong'ershan, central Taihangshan, and Jibei-

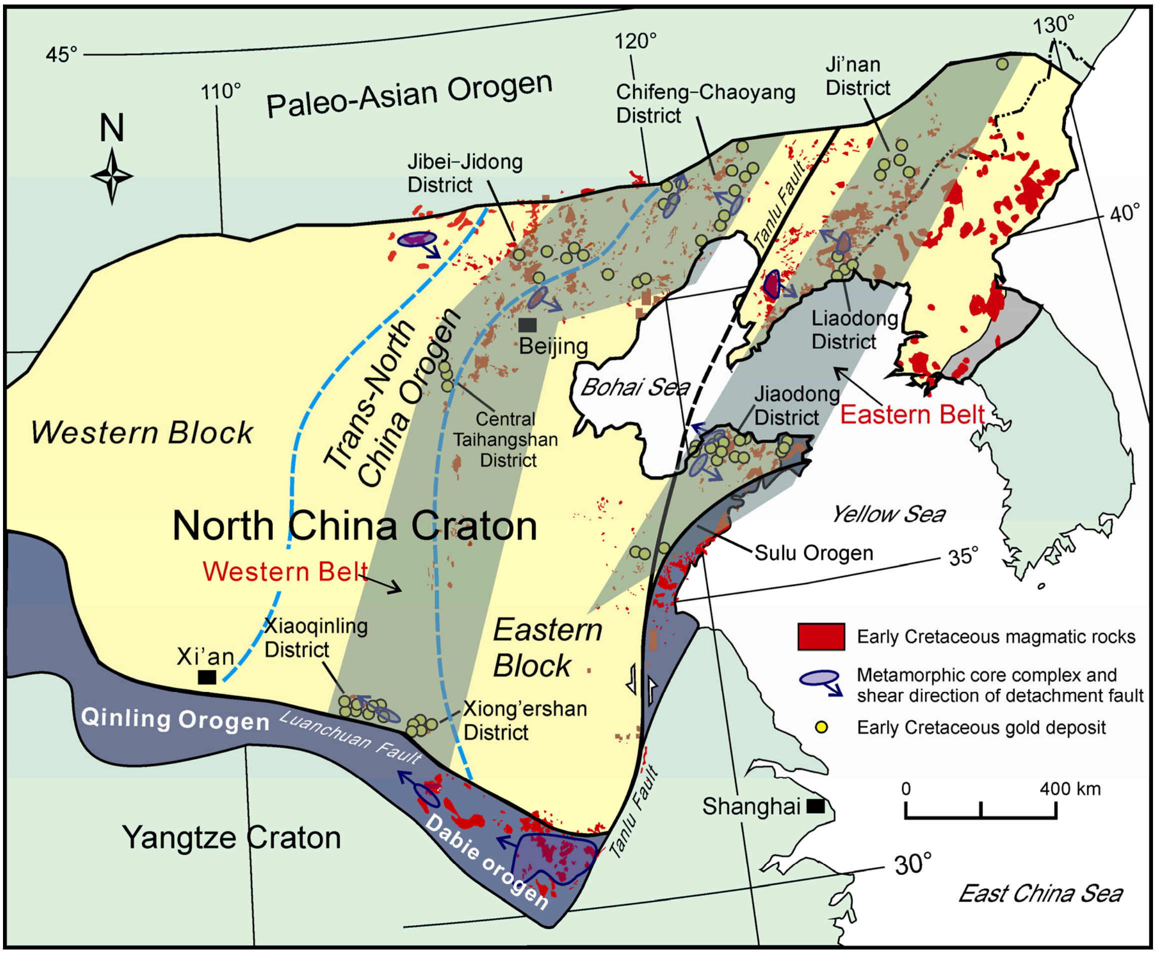

Figure 1 Map of the North China Craton (NCC) and distribution of major gold deposits in several gold districts. The tectonic divisions of the NCC is after Zhao et al. (2005), whereas the northern extension of the Tanlu Fault is based on Xu et al. (1987) and Sun et al. (2010).

Jidong districts (Figure 1).

The Jiaodong district is defined by the Tanlu Fault and the Sulu orogen, and is lithologically dominated by Neoarchean to Paleoproterozoic amphibolite facies metamorphic rocks that are intruded by a large volume of Mesozoic granitoid intrusions (Appendix 1, available at http://link.springer.com, http://earth.scichina.com). Brittle faults and ductile-brittle shear zones are well developed in Jiaodong, and are considered as subsidiary structures of the Tanlu Fault (Li J W et al., 2003, 2006). More than 100 gold deposits, including 7 world-class giants, have been discovered and explored (Appendix 1; Fan et al., 2003; Wen et al., 2015). These deposits have a total proven gold reserve of >4000 t (Yang et al., 2014), thus making Jiaodong the largest gold producer of China. The Liaodong district is geologically similar to Jiaodong, marked by strong Mesozoic tectonic and magmatic activities. Typical large gold deposits in Liaodong include Wulong, Sidaogou, and Jinchangyu (Zeng et al., 2001). The Ji'nan district also has some major gold deposits like Huanggoushan, Nancha, and Baishan, which are hosted in the Liaonan metamorphic core complex.

The Western Belt, consisting of the Xiaoqinling, Xiong'ershan, central Taihangshan, and Jibei-Jidong districts from south to north (Figure 1), is roughly parallel to the Trans-North China orogen that originated from the collision between the Western and Eastern blocks at ca. 1.85 Ga, and unified the whole NCC (Figure 1; Zhao et al., 2005). The Xiaoqinling-Xiong'ershan district (Appendix 1) in the southernmost portion of the Western Belt is the second largest gold producer of China (Chen and Fu, 1992; Mao et al., 2002; Li J W et al., 2012a). In the central of the Western Belt is the Taihangshan district that contains several medium- to small-scale gold deposits, including Shihu, Xishimen, Yixingzhai, Xinzhuang, Chafangtie, and Houyu (Li Q et al., 2013, Li et al., 2014). Along the northern margin of the NCC and northern portion of the Western Belt are the Jidong-Jibei and Chifeng-Chaoyang districts that contain some major gold deposits, such as Baizhangzi, Jinchanggouliang, Paishanlou, Erdaogou, and Anjiayingzi (Zhang et al., 2005). These deposits and other equivalents in the northern NCC are less investigated compared with those of the Jiaodong and Xiaoqinling districts.

In the last two decades, most gold deposits, particularly those in the eastern and southern margins of the NCC, have been dated using a variety of techniques. The main methods include $^{40}Ar/^{39}Ar$ dating of hydrothermal K-bearing alteration minerals (sericite, K-feldspar, muscovite, biotite) and fluid inclusions extracted from ore-related quartz, Re-Os dating of molybdenite coexisting with auriferous pyrite, Rb-Sr isochron dating of gold-bearing pyrite and fluid inclusions extracted from ore-related quartz, and U-Pb dating of U-bearing accessory minerals precipitated from ore-forming fluids (Ye et al., 1999; Yang and Zhou, 2000, 2001; Yang et al., 2000; Wei et al., 2001; Li J W et al., 2003, 2006, 2012a, 2012b; Li Q et al., 2008; Li H M et al., 2003; Miao et al., 2003; Hu et al., 2004, 2013; Hou et al., 2006; Yao et al., 2009; Cai et al., 2011; Li S R et al., 2013, 2014; Tang K F et al., 2013; Yang et al., 2014). The results show that gold deposits in different districts of the NCC were in general formed in a time interval from 130–120 Ma (Figure 2).

The Eastern and Western Belts coincide well with two tectono-magmatic belts marked by extensive late Mesozoic magmatism and extensional deformation. Except for a short-term contractional event in the Early Cretaceous (140–138 Ma) in the northern NCC, as evidenced by an unconformity beneath the Zhangjiakou volcanic rocks (ca. 136 Ma) (Zhang et al., 2004), the Eastern Block of the NCC was dominated by large-scale extension during most of the Early Cretaceous (135–100 Ma), as implied by widespread rift basins and metamorphic core complexes (Liu et al., 2005; Wang et al., 2011; Charles et al., 2012). Timing of the extension is perfectly consistent with ages of most gold deposits of the NCC. It is worth noting that gold deposits in the Western Belt are generally older than those in the Eastern Belt (Figure 2). The temporal and spatial coincidence between the gold mineralization and the craton destruction indicates a causal link between the two events. Below we summarize the gold mineralization features, sources of gold and fluids, and ore genesis to better understand the genetic linkage between large-scale gold veining and decratonization.

2 Early Cretaceous gold deposits in the NCC

2.1 Types of gold deposits

Gold deposits in the NCC can be divided into two types, "altered rock" and "quartz vein" types. The altered rock type gold deposits are represented by the Sanshandao, Jiaojia, Xincheng, and Dayingezhuang gold deposits in the Jiaodong District of the Eastern Belt, the Paishanlou gold deposit in the Chifeng-Chaoyang District and the Qianhe gold deposit in the Xiong'ershan District of the Western Belt. Orebodies, characterized by disseminated and stockwork gold mineralization, are usually controlled by ductile to brittle or brittle fault zones with low dip angles (Chen et al., 1998; Fan et al., 2003; Yang et al., 2003, 2014; Li J W et al., 2003, 2012a; Li Q L et al., 2008; Li S R et al., 2013). Overprinting of hydrothermal alteration and late-stage brittle deformation led to the modifications of early ductile fabrics and the brecciation of altered mylonite. The quartz vein type gold deposits are represented by the Linglong, Taishang, Denggezhuang, Jinqingding gold deposits in the Jiaodong District, the Wulong gold deposit in the Liaodong District of the Eastern Belt, the Haigou gold deposit in the Ji'nan District of the Eastern Belt, the Wenyu, Dongchuang, Qiangma gold deposits in the Xiaoqinling District, and the Shihu, Yixingzhai gold deposits in the Central Taihangshan District of the Western Belt. Auriferous quartz veins commonly occur in the second-order structures relevant to adjacent main faults, and are distributed in groups or belts. Individual auriferous quartz veins are usually slightly wave-like, showing the characteristics of pinch-out and branch combination along strike and dip. Orebodies normally display various-degree silicification, sericitization, pyritization, and potash feldspathization along their edges with different widths.

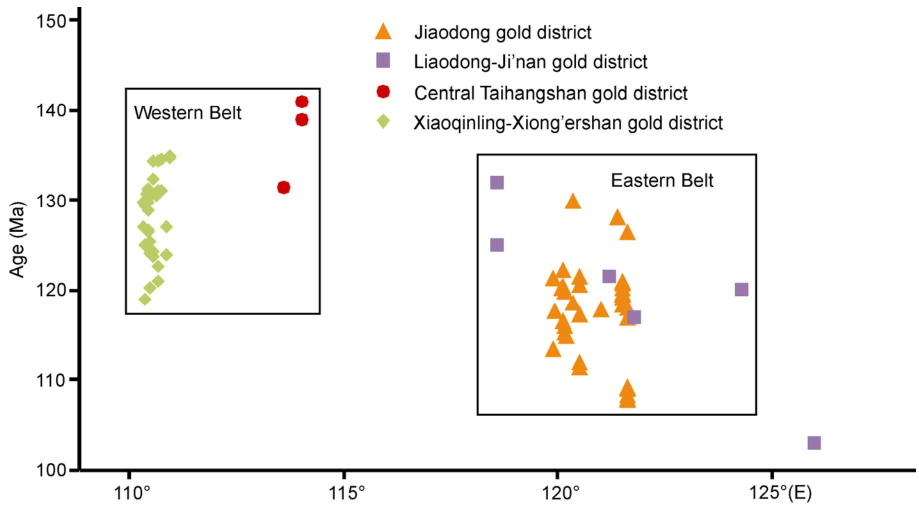

Figure 2 Age distribution of gold deposits in the Eastern and Western Belts of the NCC.

2.2 Properties of ore-forming fluids

Ore-forming fluids of gold deposits in the Eastern Belt have similar chemical and physical properties. In the early mineralization stage, ore-forming fluids belongs to the H_2O-CO_2-NaCl system, which is characterized by medium to high temperatures (250–410°C), enrichment of CO_2, and low salinities (<9 wt% NaCl eq.). The fluids evolved into a H_2O-CO_2-NaCl system with medium-low temperatures (200–330°C), decreased amounts of CO_2, and variable salinities (0.5–15 wt% NaCl eq.) in the middle mineralization stage. In the late mineralization stage, ore-forming fluids are transformed into the H_2O-NaCl system with low temperatures (<100–230°C), low salinities (<5 wt% NaCl eq.) and no CO_2 (Fan et al., 2003; Yang et al., 2009; Hu et al., 2013; Wang et al., 2015; Wen et al., 2015). The properties of ore-forming fluids in the Xiaoqinling, Xiong'ershan and Central Taihangshan of the Western Belt are similar to those of the Eastern Belt (Jiang et al., 1999; Fan et al., 2000; Ni et al., 2008). However, some gold deposits are unique, such as the Qiyugou gold deposit in the Xiong'ershan District, and the Yixingzhai gold deposit in the central Taihangshan District, which are controlled by cryptoexplosive breccia pipes. The salinities of ore-forming fluids vary from 6 wt% NaCl eq. to 22 wt% NaCl eq., with the highest salinity up to 35 wt% NaCl eq. and the peak salinities being less than or close to 10 wt% NaCl eq. (Chen et al., 2009; Fan et al., 2011; Lu et al., 2012). This phenomenon might have been attributed to the influence of deep-seated magmatic activity.

Although there are similarities in fluid properties and evolution between altered rock type and quartz vein type gold deposits, their ore-forming mechanisms might be different. The mineralization of the altered rock type gold deposits resulted from intense water-rock interaction between ore-forming fluids and wallrocks, whereas precipitation of gold was possibly a consequence of phase separation or boiling of ore-forming fluids in response to pressure and temperature fluctuations within the quartz vein type gold deposits (Fan et al., 2003; Wen et al., 2015).

2.3 Sources of ore-forming fluids and materials

The Early Cretaceous gold deposits in different regions of the NCC possess similar hydrogen and oxygen isotope compositions (Figure 3). Most of the data are lie between the magmatic field and the global meteoric water line, suggesting that ore-forming fluids could have a magmatic origin. Meteoric water might have be involved in the ore-forming fluids in the process of fluid circulation and evolution. By comparison, quartz in hydrothermal veins of orogenic gold deposits of different ages has the following fluid hydrogen and oxygen isotope composition: $\delta^{18}O$=6‰ to 14‰ and δD=−105‰ to 0 (Figure 3), indicating that the ore- forming fluids of orogenic gold deposits are mainly of metamorphic origin, contrasting strikingly with the Early Cretaceous gold deposits in the NCC.

The Early Cretaceous gold deposits in the NCC have $\delta^{13}C$ values between −7‰ and −3‰ (Figure 4(a)), which are consistent with high-temperature carbon isotopic values of granitoids and basalt (Hoefs, 2009) and thus indicate that the ore- forming fluids might have originated from degassing or devolatilization of mantle-derived magmas. Sulfur isotopes of the Au deposits are highly variable. $\delta^{34}S$ values of the Jiaodong gold deposits range from −5.6‰ to 14.1‰ (Figure 4(b)), which are distinct from those of chondrite or mantle-derived rocks, thereby indicating the presence of enriched sources from ^{34}S-rich magmas (Hoefs, 2009) or degassing of mantle wedges that were metasomatised by slab fluids. During the Early Cretaceous, the East Asia continent was affected by westward subduction of the paleo-West Pacific plate, and the parts of the subducted slab became stagnant in the mantle transition zone. These processes are thought to have led to partial melting, unstable flow of the upper mantle, intense metasomatism of the lithospheric mantle, and an increase in oxygen fugacity. The processes also gave rise to ^{34}S-rich magmas (Ionove et al., 1992), which

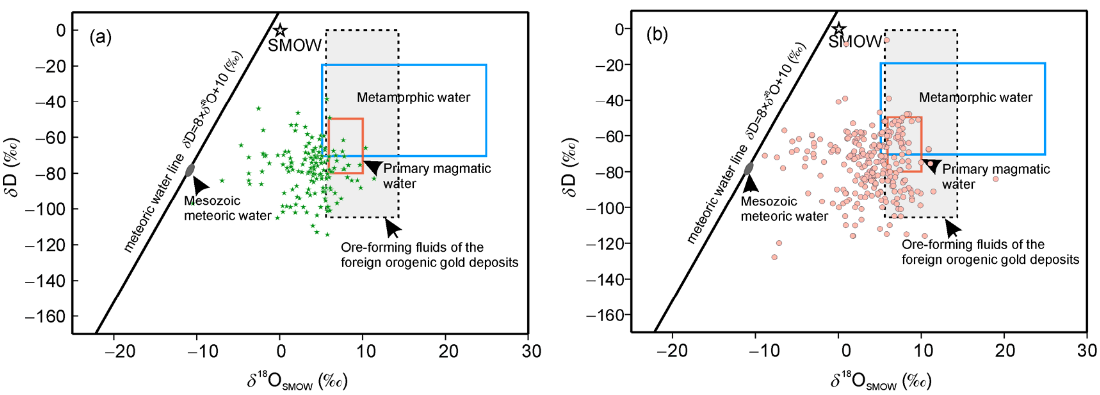

Figure 3 Hydrogen and oxygen isotope composition of Early Cretaceous gold deposits in NCC. (a) the Western Belt; (b) the Eastern Belt. Shadow regions represent hydrogen and oxygen isotope composition of typical orogenic gold deposits. After Bierlein et al. (2000); Hagemann et al. (2000); Partington et al. (2000).

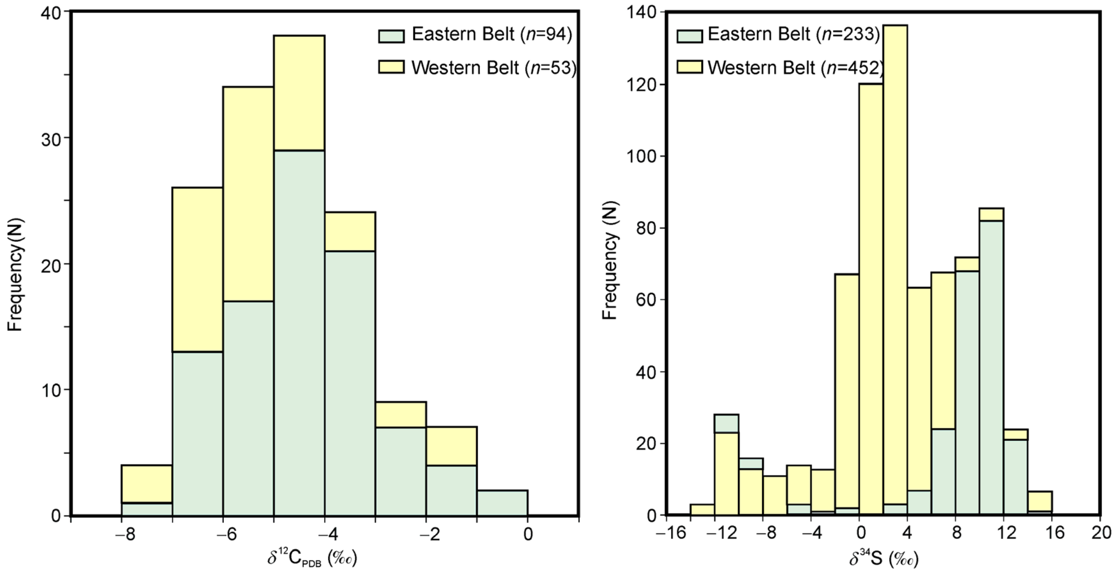

Figure 4 Carbon (a) and sulfur (b) isotopic compositions of the Early Cretaceous gold deposits in the NCC.

could account for the high sulfur content of the Jiaodong gold deposits. Alternatively, fluid mixing could be another mechanism for the enrichment of ^{34}S. Gold deposits in the Xiaoqingling and central Taihangshan Districts have ^{34}S values of –2‰ to 6‰ (Figure 4(b)). The enrichment of ^{34}S may have formed through oxidizing magmas or incorporation of evaporates during magma/fluid migration. Gold deposits in the Ji'nan District have variable sulfur composition (with large negative $\delta^{34}S$ values), suggesting a contribution from organic matter or magma oxidation (Tang Y J et al., 2013).

On a $^3He/^4He$-$^{40}Ar^*/^4He$ diagram (Figure 5(a)), all Early Cretaceous gold deposits in the NCC plot between the crust and mantle sources, but closer to mantle component. On a ^3He-^4He diagram (Figure 5(b)), most deposits lie between crustal and mantle helium, although closer to mantle helium. A small number of gold deposits plot in the area of mantle helium, implying that mantle-derived fluids played a key role in their formation.

The Early Cretaceous gold deposits in the NCC are closely associated with intermediate to mafic dykes. These dykes are dated at 130–110 Ma (Tan et al., 2012; Cai et al., 2013; Ma et al., 2013), synchronous with gold metallogenesis. The temporal coincidence indicates that mafic magma may have been a source for ore materials and fluids. In addition, the Western Belt contains abundant calaverite, petzite, tellurobismuthite, altaite, native tellurium and native bismuth. Some of these deposits were enclosed in metamorphosed volcanic rocks. Related studies indicate that telluride-rich ore deposits are closely related to magmatism, suggesting that the telluride-rich gold deposits in the NCC might have obtain auriferous fluids from the Early Cretaceous magmatic

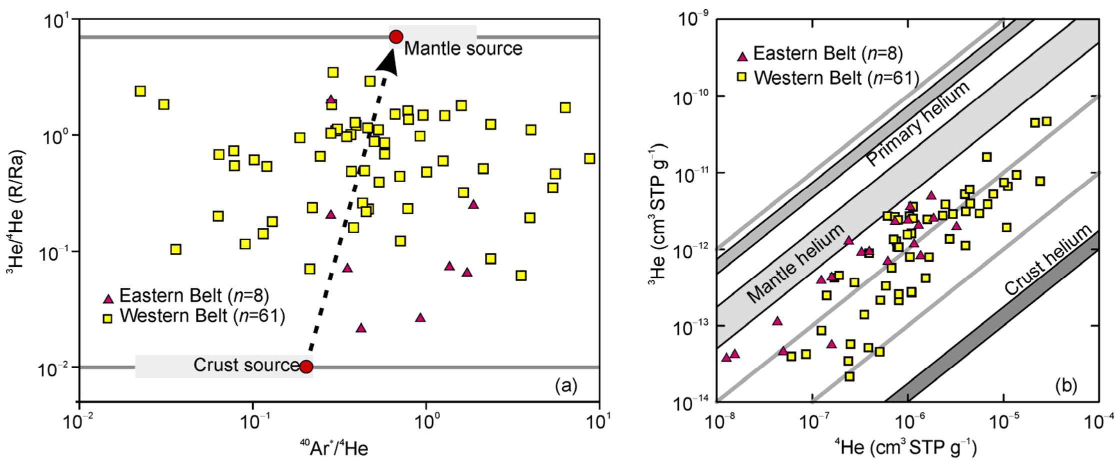

Figure 5 Diagrams of noble gas composition of Early Cretaceous gold deposits in the NCC.

or volcanic rocks.

3 Decratonic gold deposits and geneses

3.1 Decratonic gold deposits

Gold resources in the world are dominated by porphyry, epithermal, orogenic, Carlin-type, skarn, VMS, and conglomerate-hosted gold deposits. Orogenic gold deposits are widely recognized in both Phanerozoic mobile belts and older cratonic blocks, and thought to have resulted from accretionary and collisional orogenesis (Goldfarb et al., 2001). The ore-controlling structures are commonly compressional or transpressional in nature, and gold formation is not necessarily coeval with peak metamorphism in the orogenic processes. The ore-forming fluids have compositions similar to that of host rocks and are regarded as crustal metamorphic fluids sourced from devolatilization process during regional metamorphism (Groves et al., 1998; Goldfarb et al., 2001). The lode gold deposits in cratons over the world are grouped as orogenic gold deposits, such as the lode gold deposits in the Yilgarn Craton of western Australian and the Superior Craton of northern America (Goldfarb et al., 2001; Robert et al., 2005). According to the geological characteristics, mineralization features, metallogenic ages, sources of ore-forming fluids and metallogenic materials, and tectonic settings, we argue that Early Cretaceous gold deposits in the NCC are distinct from orogenic gold deposits except for the style of hydrothermal alteration. The primary controlling factors for large-scale gold mineralization are the melts and/or fluids from metasomatism of the enriched mantle and interaction between the mantle and crust, all of which were related to destruction of the NCC. Given that the NCC gold mineralization has a close linkage with craton destruction in the Early Cretaceous, we therefore define the NCC gold deposits as the decratonic gold deposits. The main distinctions between decratonic and orogenic gold deposits are highlighted below:

(1) The Early Cretaceous gold deposits in the NCC have much lower hydrothermal carbonate content than that in typical orogenic gold deposits. They are mainly composed of auriferous quartz vein and altered rock type deposits in the early and middle stages of fluid evolution. Decratonic gold deposits lack quartz-carbonate veins, which, however, are the main gold producer in orogenic gold deposits. Furthermore, carbonate is predominant in orogenic gold deposits throughout the early to late stages of fluid evolution, with a total proportion of 5%–15% (Groves et al., 1998). Because ore-forming fluids of orogenic gold deposits are mainly derived from regional metamorphism, large quantities of CO_2 can be produced due to carbonate decomposition and oxidization of organic carbon. The CO_2 is then transformed to hydrothermal carbonate. By contrast, hydrothermal carbonate occurs only at the late stage of gold mineralization in the Early Cretaceous gold deposits in the NCC, indicating that ore-forming fluids were not sourced from metamorphic devolatilization.

(2) The element assemblage of the ores in the Early Cretaceous gold deposits in the NCC is commonly Au-Ag-Te-Pb-Zn-Cu, with minor As content (Mills et al., 2015). Arsenic in orogenic gold deposits, however, is often enriched and occurs as arsenopyrite, as best illustrated in the Yindongpo gold deposit (Zhang et al., 2013) and the Yangshan gold deposit in the western Qinling orogen of China (Qi et al., 2003), the Sawaya'erdun gold deposit (Yang et al., 2005) and the Muruntau gold deposit in Kazakhstan (Drew et al., 1996) of the central Asian orogen, and the Bendigo gold deposit in Australia (Li X et al., 1998), among others. Arsenic enrichment in these deposits indicates that the metamorphic devolatilization process of sedimentary rocks or volcano-sedimentary rocks is essential for mineralization of orogenic gold deposits.

(3) The elemental, stable isotope and noble gas isotope studies have shown that mantle-derived fluids and other components are important for gold mineralization in the NCC (Mao et al., 2008; Li S R et al., 2013) (Figures 3–5). In contrast, the ore-forming fluids of orogenic gold deposits are mainly derived from devolatilization processes associated with regional metamorphism (Phillips and Powell, 2010).

(4) The Early Cretaceous gold deposits in the NCC emerged in a short period, with the Eastern and Western Belts having mineralization ages of 130 and 120 Ma, respectively (Yang et al., 2003; Sun et al., 2007, 2013). Orogenic gold deposits usually have a prolonged mineralization history, lasting up to 50–70 Ma or even longer as revealed from the Cordillera orogenic belt and the Abitibi greenstone belt (Goldfarb et al., 2001; Robert et al., 2005).

(5) The Early Cretaceous gold deposits in the NCC developed in an extensional setting in contrast to contractional tectonics for orogenic gold deposits.

In summary, decratonic gold deposits, as represented by the Early Cretaceous lode gold deposits of the NCC, exhibit a number of unique features, which are clearly distinct from orogenic gold deposits in both Precambrian cratons and Phanerozoic orogenic belts around the world. The decratonic gold deposits was once named as "Jiaodong-type" gold deposits (Li S et al., 2015), but "decratonic" gold deposits should be a more suitable term for all gold deposits that resulted from decratonic processes.

3.2 Geneses of decratonic gold deposits

Subduction of the paleo-West Pacific plate and dehydration of the stagnant slab in the mantle transition zone (Niu, 2005, 2014) might have triggered unstable mantle flows, which is thought to be the driving force for destruction of the eastern NCC (Zhu and Zheng, 2009). The mantle temperature increased during the Early Cretaceous (Machetel, 2003) and, under these thermal circumstances, the unstable mantle flows brought about a marked increase in melts/fluids and a striking decrease in viscosity of the lithospheric mantle of the eastern NCC. Consequently, the original ancient mantle evolved into a highly metasomatic and enriched mantle after extensive melting and fluid metasomatism. It is thought that auriferous magma and the resultant aurous fluids resulted from direct contact between the lower crust and the highly metasomatic and enriched mantle containing abundant melts and fluids in conjunction with the interaction between melts/fluids and crust-derived felsic magma (Figure 6(a)).

The stagnant slab beneath the eastern Asian continent, with a length up to 2000 km from the Japan Trench to the mantle transition zone, was thought to have resulted from Cenozoic subduction of the paleo-West Pacific plate, as revealed by tomographic images (Huang and Zhao, 2006). On the basis of observations of magnetic anomaly of the oceanic crust, reconstruction of global plates, and numerical modeling of oceanic basin dynamics (Funiciello et al., 2003; Seton et al., 2012; Müller et al., 2008a, 2008b; Bird, 2003), the modern West Pacific plate at the Japan Trench is ca. 130 Ma old, and its subduction rate is estimated as ca. 10 cm/yr. If it was the case, about 20 Ma was required for the paleo-West Pacific plate to move from the Japan Trench to the westernmost part of the stagnant slab. It is worth noting that, although it is as old as 130–110 Ma, the stagnant slab did not reach the mantle transition zone until 20 Ma. Therefore, subduction of the observed stagnant slab should have nothing to do with the Early Cretaceous destruction of the eastern NCC. The true cause for destruction of the NCC should be the combined effect of subduction and stagnancy of the paleo-West Pacific plate during the Early Cretaceous (Figure 6(a)). A relatively high-velocity body exists west of the stagnant West Pacific plate, which extends westwards to longitude 100°E. Two other high-velocity bodies are present below the stagnant Pacific slab (Figure 6(b)). These relatively high velocity bodies are assumed to be remnants of the subducted paleo-West Pacific plate during the Early Cretaceous (Figure 6(a)), which either survived in the mantle transition zone of East Asia or foundered into the lower mantle.

The ages of gold deposits in the Eastern and Western Belts cluster at ca.120 Ma and ca. 130 Ma, respectively, with an age difference of 10 Ma (Figure 2). The age difference in gold deposits between the Eastern and Western Belts might have originated from retreating of the paleo-West Pacific plate in the Early Cretaceous. It is inferred that the frontal portion of the paleo-West Pacific plate began stagnating in the mantle transition zone beneath the western margin of the eastern NCC around 130 Ma. Considering retreat of the subducted plate and eastward movement of the East Asia continent, the western edge of the eastern NCC should be located more westward at 130 Ma than its present-day position, at least at longitude 100°E, as shown in Figure 6(b). In other words, the subduction zone of the paleo-West Pacific plate should be located to the west of the present-day West Pacific plate. It is thought that dehydration of the stagnated paleo-West Pacific plate in the mantle transition zone had significantly changed the physical properties and viscosity of the overlying mantle, thus leading to the occurrence of unstable mantle flow. The dehydration of the stagnated slab and the unstable mantle flows further resulted in rapid increase of melts and fluids in the lithospheric mantle, gradually making the lithospheric mantle become more metasomatic and enriched. Auriferous fluids were generated as a result of interactions between the enriched mantle and the lower crust. Auriferous fluids then rose along tectonically weak zones in the crust at the western edge of the eastern NCC, thus forming gold deposits of the Eastern Belt. The paleo-West Pacific plate became stagnant beneath the Eastern Belt around 120 Ma due to continued retreat of subducting plate. The lithospheric mantle of the eastern NCC then changed completely into intensely metasomatic and enriched mantle The mantle-derived melts and the lower crust-derived fluids moved upwards along major faults, like the Tanlu and Yalujiang faults, as well as some secondary faults, leading to the formation of the eastern gold-mineralization belt. The longitude difference of the Eastern and Western Belts is ca. 10°, and the distance between the two belts is about 880 km along latitude line of 38°N. If it migrated eastward for about 880 km during a time interval of 10 Ma, the paleo-West Pacific plate should had a retreat rate of ~8.8 cm/a in the Early Cretaceous. The estimate of retreat rate is nearly identical with that of the modern West Pacific plate based on present-day magnetic anomaly of the oceanic crust and dynamic modeling (10 cm/a, Funiciello et al., 2003).

Some other cratons also underwent destruction or deformation similar to the NCC. The crust thickness of the Basin and Range provinces in the west of the North America Craton varies from 30 to 35 km (Mooney and Braile, 1989) and the lithosphere thickness is from 60 to 70 km (Zandt et al., 1995), similar to those of the eastern NCC. It is regarded that the western margin of the North America Craton had been deformed in the Eocene (Figure 7(a)), although the mechanism for the destruction remains unclear. On the basis of the study of destruction of the NCC, we propose that destruction of the North America Craton might have also resulted from subduction, retreat, and transient stagnancy of the paleo-East Pacific plate (the Farallon plate) as well as the induced unstable mantle flows, which could be the main force for destruction of the western North America Craton. It is suggested that the unstable flow system in the upper mantle led to intense metasomatism and enrichment of the lithospheric mantle of the western North America Craton, accompanied by strong crustal and lithospheric extension that gave rise to the Basin and Range provinces. Interaction of melts from the highly metasomatic and enriched mantle with the lower crust led to the generation of magma rich in auriferous fluids. The ascending auriferous fluids were rich in H_2S and experienced phase transition and mixing of atmospheric water. These fluids could bring about solution

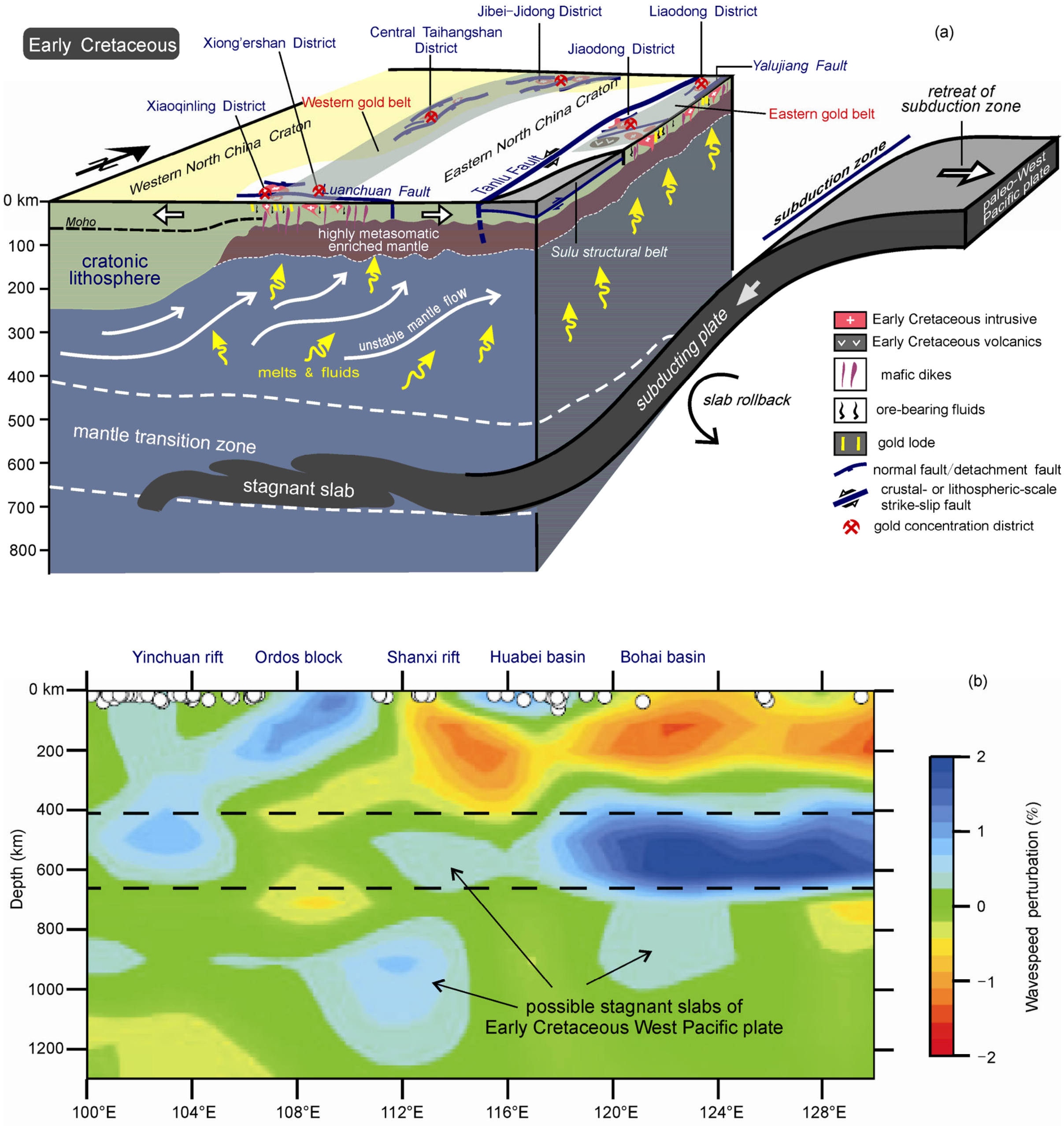

Figure 6 Deep tectonic processes of the NCC and relationship between decratonization and gold mineralization in the Early Cretaceous (a), Velocity structures of the mantle transition zone of the NCC (b). The eastward-subducted plate beneath East Asia is the inferred paleo-West Pacific (Izanagi) plate. Present-day observations do not reveal the Early Cretaceous subduction process of the paleo-West Pacific plate, but the modern subduction state of the West Pacific plate (Huang and Zhao, 2006) can be used as a reference to reconstruct Early Cretaceous subduction of the paleo-West Pacific plate on the basis of reconstruction of global plates and studies of oceanic-basin dynamics (Seton et al, 2012; Müller et al., 2008a, 2008b; Bird, 2003). Accordingly, the total length of subducted paleo-West Pacific plate beneath East Asia is about 2000 km (the sum of subducted and stagnant portions). According to the model of global plate reconstruction by Seton et al. (2012), the age of the subducting plate at the trench is about 160 Ma and the subduction rate was 60–120 km/Ma. Based on subduction rate of 80 km/Ma, ages of the paleo-West Pacific plate beneath East Asia are 135–160 Ma from west to east. (b) after Huang et al. (2006).

and sulfuration of carbonate rocks at the depth of several kilometers beneath the surface, and resulted in the formation of gold-bearing pyrite and Carlin-type gold deposits (Muntean et al., 2011). The Carlin-type gold deposits were thus formed as a result of interaction of mantle-derived melts/fluids and the lower crust during the processes of craton destruction. The main distinctions between the Carlin-type gold deposit in Nevada and the gold deposits related to destruction of the eastern NCC are the differing host rocks into which ore-forming fluids penetrated. The host rocks of the NCC gold deposits are the Archean and Paleoproterozoic metamorphic rocks, Mid-Neoproterozic volcanics, and Phan-

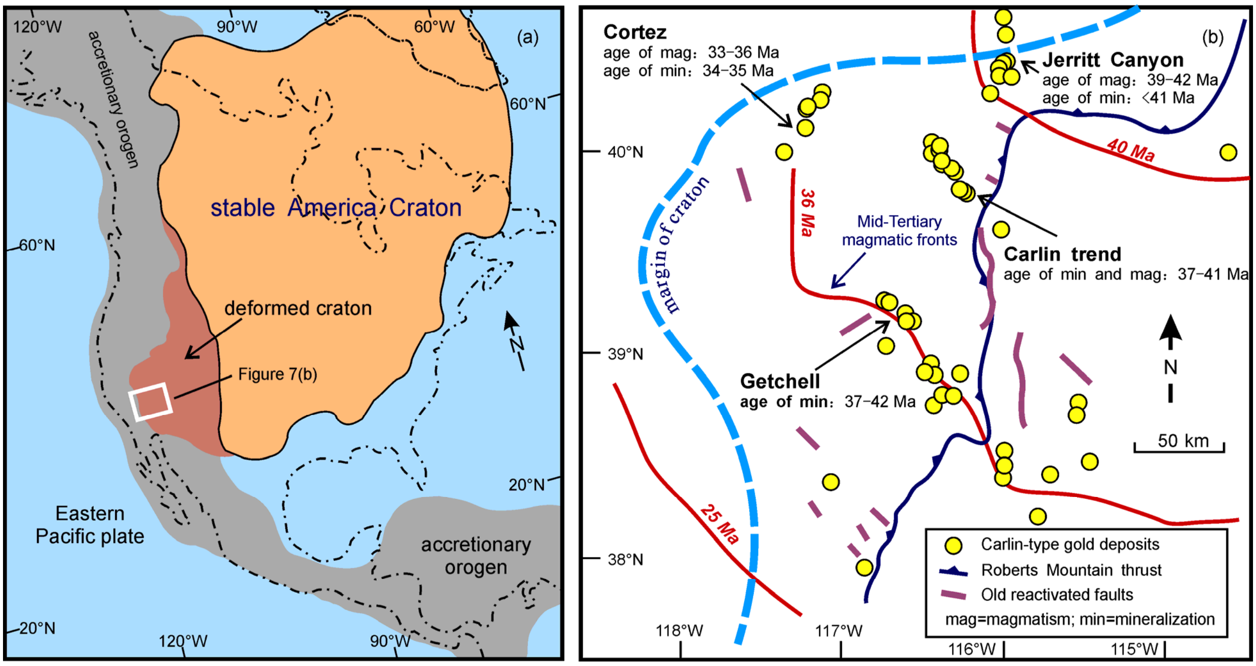

Figure 7 Diagram showing the North America Craton and the deformed area (a) (modified from North America Craton nps.gif); time-space distribution of gold deposits in Nevada (b). Modified from Muntean et al. (2011).

erozoic granitoids, whereas the wallrocks hosting the Carlin-type gold deposits are dominantly carbonate rocks. Similar origin of ore-forming magma and fluids could account for the relatively rapid gold mineralization in North China and Nevada. The differences in the host rocks could explain why gold deposits in the eastern NCC are characterized by high-grade ores and limited distribution. Low-grade ores and extensive distribution are characteristic of the Carlin-type gold deposits in Nevada.

Gold deposits in the eastern and western gold mineralization belts in Nevada are 40 and 36 Ma, respectively (Muntean et al., 2011), with a time difference of 4 Ma (Figure 7(b)). The difference in the mineralization ages can also be attributed to retreating of the paleo-East Pacific plate. The distance between the eastern and western gold mineralization belts in Nevada is about 130 km. Given the age difference of the two mineralization belts, retreat rate of the Farallon plate is about 3.3 cm/a during the Eocene, which corresponds to ~40% of the Early Cretaceous retreat rate of the paleo-West Pacific plate. The lower retreat rate implies that the paleo-East Pacific plate might have only stagnated in the mantle transition zone for a relatively short time. Implicitly, subduction of the paleo-East Pacific plate exerted less impact on the North America Craton, whereas the paleo-West Pacific plate strongly influenced the NCC. Both the West and East Pacific plates experienced retreating in the late Cenozoic, but their retreat rate are quite different, with the paleo-West Pacific plate retreating at the rate of ca. 100 km/Ma (Bird, 2003) and got stagnant in the mantle transition zone (Huang and Zhao, 2006; Li et al., 2008). The paleo-East Pacific plate retreated at a low rate, about 20 km/Ma (Bird, 2003), which is broadly consistent with our estimate (~33 km/Ma). Low-rate retreat of the paleo-East Pacific plate might be one of the reasons for absence of stagnant slab in the mantle transition zone of the North America Craton. Consequently, whether or not a subducting plate stagnates in the mantle transition zone will depend upon its age and retreat rate (van der Hilst, 1995; Niu, 2014).

To understand decratonic gold deposits, it is important to investigate the origin of ore-forming fluids, gold mineralization, and their relation to craton destruction. Our studies show that mantle derived magma is the main source of auriferous fluids for decratonic gold deposits, and gold mineralization took place in the extensional tectonic settings. Therefore, mantle-derived magma and extensional tectonics are two basic geologic requirements for the formation of decratonic gold deposits. The main controls of mantle- derived magma on mineralization of decratonic gold deposits can be summarized as follows: (1) mantle magma partially provides gold element and volatiles. (2) mantle magma could underplate or intrude the lower crust and cause extensive partial melting of the lower crust. Subsequently, the magma ascended and may have formed transitory magma chambers in the various crustal depths where sulfide may have fractionated to form Au-rich sulfide accumulations in the magma chambers (Muntean et al, 2011). New fluxes of more mafic magma into the magma chamber would have melted the sulfide accumulations to form more Au-prolific magma (Botcharnikov et al., 2011). (3) Metal sulfides accumulated locally in the magma chamber can be dissolved by the exsolved fluids from magma, or can be injected into mafic melts evolved within magma chamber, which forms gold-rich magma. Auriferous fluid phases would be separated during the ascent into the upper crust and rapid decompression of the magma. These magma fluids commonly migrate along faults for a long distance, precipitate ore materials in a short time interval, and are characterized by low gradients in temperature and salinity (Muntean et al., 2011). The ore-forming fluids of the Jiaodong gold district revealed by deep drilling resemble these characteristics (Hu et al., 2013). The magmatic characteristics exhibited by decratonic gold deposits in Sanshandao, Jiaodong and Nevada, are indistinguishable from metamorphic fluids, which led some researchers to suggest metamorphic models. (4) Mafic magma can provide heat sources for metallogenesis and circulation of crustal fluids as well. Some Au in metamorphosed mafic volcanic rocks of the NCC was leached out by the existing fluid circulation (Sun et al., 2013). The mineralization process is depicted in Figure 8. Following the peak of the NCC decratonization, the volatile-rich, low melting-point components were exhausted, which was followed by cessation of Au mineralization. Therefore, the decratonic gold deposits in the NCC were formed in a short time interval.

Craton destruction is marked by following processes: large-scale magmatism, strong extensional ductile deformation, and rift-basin formation, all of which indicate that the cratonic lithosphere has been destabilized (Zhu et al., 2011). Widespread occurrences of metamorphic core complexes and rift basins imply that the eastern NCC was in an extensional setting during the Early Cretaceous. Both basic and medium-acidic magma in the lower-middle crust experienced strong liquid resolution due to rapid pressure reduction, which generated auriferous fluids. When intruding to shallower levels at rapid rates, magma will soon become saturated, leading to the formation of auriferous fluids. The resulted cryptoexplosive emplacement will bring about the formation of cryptoexplosive breccia type gold deposits, such as the Qiyugou gold deposit in the Xiong'ershan gold concentration district. Abundant lamprophyre dikes occur in both the Jiaodong and Xiaoqinling gold concentration districts, which indicate that the lithospheric mantle of the eastern NCC contained abundant water in the Early Cretaceous. Strong extension would have caused water-rich lithospheric mantle to partially melt and degas, and the resultant mantle fluids would have migrated upwards into the metallogenic systems along lithospheric-scale faults like the Tanlu and Luanchuan faults. This model explains why Early Cretaceous gold deposits occur in the eastern margin of the NCC, such as the Jiaodong and Xiaoqinling gold districts and the cyclic mineralization of the decratonic gold deposits. Lithospheric extension could also cause development of secondary fractures in the middle-upper crust, thereby governing the spatial distribution of gold ore-bearing dikes, deposits and fields. For instance, gold deposits in the Jiaodong district are clearly controlled by secondary faults related to the Tanlu Fault. In addition, subduction of the paleo-West Pacific plate could have led to reactivation of early major and secondary faults, which either served as channels for auriferous fluids or preferentially formed gold deposits. Atmospheric water could infiltrate downward or migrate laterally along extensional fault systems formed during the craton destruction processes, and eventually mix with mineralizing fluids derived mainly from mantle melts. Fluid mixing should, therefore, be another important mechanism for gold deposition.

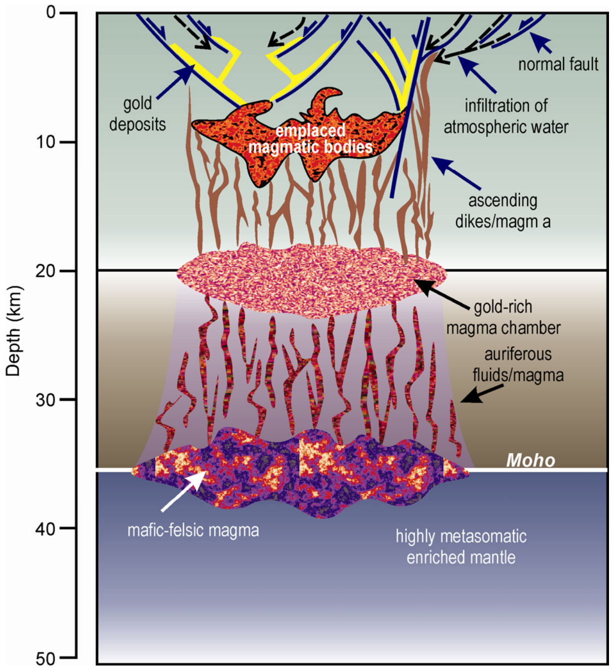

Figure 8 A diagram showing possible mineralization processes of decratonic gold deposits. Depth of Moho and internal structures of the crust are from Zheng et al. (2008a, 2008b, 2009) and Wang et al. (2014).

4 Metallogenic prospecting

The rapidly developing economy of China has led to an increasing shortage of mineral resources and severely inadequate resources. Recognition and development of deep resources have therefore become strategically significant. Techniques to explore and develop the deeply buried resources face the challenges of lack of mineralization data, poor geological information, and requirements of adequate investment in exploration and development. For example, in the gold concentration districts of Jiaodong and Xiaoqinling, shallow gold reserves (<500 m) are being exhausted and the demand to explore and develop new large and rich deposits is increasing. Previous studies have shown that the major parts of the gold deposits in the NCC are related to the decratonization processes, generated by interaction between melts and fluids derived from the mantle with the crust. Thus, the gold mineralizing belts extending approximately NNE in the eastern and the western edges of the eastern block of the NCC are most favourable for the exploration for large, deep-seated gold deposits. Recently, Shandong Gold Ltd. implemented a "First Deep Drilling Exploration Project for Gold in China" (4006.17 m deep) in the Xiling ore field at Sanshandao camp in the Jiaodong gold district, and discovered a 20-m-thick gold ore body with 3.5 g/t average grade at the depth of 2600 m. In the Xiaoqinling gold concentration district, 0.9–1.2-m-thick gold ore bodies with 6–8 g/t average grade was found at the depth of 1470 m and 836 m, respectively (Feng et al., 2009). These discoveries prove the potential for the deep-seated gold concentrations in the Jiaodong and Xiaoqinling Districts.

The Liaodong gold-concentration District in the Eastern Belt and the central Taihangshan District in the Western Belt display geological characteristics similar to those of the Jiaodong and Xiaoqinling districts. However, the Liaodong gold reserve is considered less important because no large and super-large gold deposits have been discovered.

On the basis of the comparison of Precambrian geology, tectonic deformation, magmatic activities, metallogenic and ore-controlling conditions, and gold-deposit features, it is revealed that the Liaodong and Jiaodong areas share many similarities, including: (1) existence of the Archean basement composed of gneiss and greenstone belts and the Paleoproterozoic metamorphic volcanic and sedimentary series; (2) similar tectonic features recording intense Early Cretaceous extension; (3) widespread Early Cretaceous magmatic intrusions; (4) gold deposits are mainly quartz vein, alteration rock and breccia types; (5) mineralizing fluids are largely sourced from the mantle, with intense interaction between the mantle-sourced magmas and the crust; (6) large and super-large gold deposits are adjacent to large faults. For instance, the Sanshandao super-large gold deposit occurs near the Tanlu fault, and the Wulong gold deposit is close to the Yalujiang Fault. Based on the above analyses, the Liaodong area is considered as a potential region for exploration of large/super-large gold deposits. In particular, the Wulong gold deposits to the west of Yalujiang Fault and its surrounding area are likely the most favourable area for gold mineralization associated with craton destruction.

The central Taihangshan region, in particular, the Fuping-Hengshan area, is located at the junction of three micro-continents, the Ordos, Xuchang, and Qianhuai microcontinents, where the lithosphere is about 70 km thick (Li S R and Santosh, 2014). The area displays the following tectonic, magmatic, and gold-deposit characteristics: (1) occurrences of I-type intermediate to acidic granites and basic dike swarms coeval with gold metallogenic events (Li Q et al., 2015); (2) gold mineralization was simultaneous with the destruction event of the NCC (Li S R et al., 2014); (3) a number of large gold deposits, like Shihu and Yixingzhai, have been discovered (Dong et al., 2013; Li S R et al., 2014; Sun et al., 2014; Wang et al., 2014), indicating that this region must have been extensively mineralized; (4) drilling has proven the existence of deep gold resources in the Yixingzhai and Shihu. Consequently, the Fuping-Hengshan area is regarded as an important prospect for new gold deposits related to decratonization of the NCC.

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