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Gold metallogeny associated with craton destruction: A geophysical perspective from the North China Craton

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ABSTRACT

Currently ranking as the largest producer of gold in the world, China's gold reserves are spread over 200 major gold deposits and several minor deposits. A large part of these belong to the late Mesozoic gold deposits in the North China Craton (NCC) that occur along craton margins, as well as within the cratonic interior in reactivated paleo sutures, and show a close spatio-temporal relationship with zones of lithospheric thinning and craton destruction. Here we integrate and evaluate geophysical information from the NCC through an analysis of receiver function and tomography that suggest mantle upwelling accompanied by lower crustal or lithospheric delamination. Our results identify that the major gold belts in the NCC are largely located above zones of mantle upwelling and craton destruction. The faults and paleo sutures provided the pathways for migration of ore-bearing fluids, with the granitoids offering favorable conditions for gold deposition.

1. Introduction

The major cratons on the globe are characterized by ancient crustal material overlying thick lithospheric keel. The thickness of the cratonic lithosphere ranges up to 200–250 km such as in the case of the Kaapvaal, Siberia and Slave cratons (Gung et al., 2003; Mather et al., 2011; Wang et al., 2014). Due to the low geotherms in the 'tectospheric' keel composed of thick sub-continental lithospheric mantle, most cratons are typically dormant except for some eruptions of kimberlites (Tang et al., 2013a, 2013b, 2013c). A major exception is the North China Craton (NCC), one of the ancient cratonic fragments in the Asian continental collage, the base of which has been differentially eroded and destroyed resulting in the loss of the typical features of other Archean cratons (Menzies et al., 1993; Griffin et al., 1998; Menzies and Xu, 1998; Fan et al., 2000; Xu, 2001; Gao et al., 2002; Qiu et al., 2002; Zhai and Santosh, 2013).

It is well accepted that the old, thick and refractory lithospheric keel beneath the eastern part of the NCC was largely replaced by young and fertile lithospheric mantle during the Mesozoic and Cenozoic (Menzies et al., 1993; Santosh et al., 2010; Li and Santosh, 2013; Zhai and Santosh, 2013). However, the mechanism of the Mesozoic lithospheric thinning beneath the NCC is debated (Xu, 2001, 2004, 2007; Xu et al., 2009; Gao et al., 2004; Niu, 2005; Wu et al., 2008; Deng et al., 2007; Menzies et al., 2007; Zhai et al., 2007; Menzies et al., 1993; Griffin et al., 1998; Zhang et al., 2012a, 2012b; Chen, 2010; Tang et al., 2013a; Huang et al., 2012). Models on craton destruction in the NCC revolve around two schools of thought: one proposing the upwelling asthenosphere leading to thermal or mechanical erosion beneath the lithosphere and craton destruction (Menzies et al., 1993; Zheng et al., 1998; H.F. Zhang et al., 2002; Tian et al., 2009; Tian and Zhao, 2011; Guo et al., 2013; He et al., 2015) and the other favoring lower crustal and (or) lithospheric delamination resulting in decratonization (Gao et al., 1998; Xu et al., 2002; Wu and Sun, 1999; Gao et al., 2004, 2009; Deng et al., 2004a, 2004b; Xu and Zhao, 2009; He et al., 2015). The erosion model considers destruction of the lithospheric mantle by hydrous melts derived either from subducting oceanic lithosphere, or plumes rising from the asthenosphere (Menzies et al., 1993; Zheng et al., 1998; H.F. Zhang et al., 2002), whereas the delamination model envisages foundering of eclogitic lower crust followed by upwelling mantle (Ling et al., 2009; He et al., 2015).

While previous studies of mantle upwelling were largely based on speculative tectonic models and indirect geochemical and isotopic evidence, He et al. (2015) used geophysical data to image an upwelling mantle plume beneath the northern part of the Trans-North China Orogen and the eastern NCC. They suggested that westward subduction of the Pacific Plate and resultant compression led to lower crustal and (or) lithospheric delamination in the central and southern part of the eastern NCC. Eventually, both upwelling mantle plume and lower crustal and (or) lithospheric delamination resulted in considerable lithospheric thinning and craton destruction in the eastern NCC (He et al., 2015).

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Importantly, the lithospheric thinning and cratonic destruction which accompanied widespread magmatism and deformation also resulted in the formation of abundant gold deposits, launching China as the largest producer of gold in the world (Yang et al., 2003; Li et al., 2013; Tang et al., 2013c; Li and Santosh, 2014; Goldfarb and Santosh, 2014; Groves and Santosh, 2015; Yang and Santosh, 2015a; Zhang et al., 2015). At least six major gold metallogenic belts have been identified in the NCC (Fig. 1). Based on the consistency between the ages of most of the gold ores and the time of lithospheric thinning in the NCC, craton destruction is inferred to have exerted a major control on gold metallogeny, particularly in the Late Mesozoic (Li and Santosh, 2014; Li et al., 2013). Several investigations have been carried out on the Chinese gold deposits (see Deng and Wang, 2015 for a recent review), suggesting the potential link between metallogeny and craton destruction in the NCC (Li and Santosh, 2014). However, the tectonic setting of these deposits and the role of mantle dynamics remain poorly understood.

In this paper, we apply geophysical techniques involving interpretation of results from recent receiver function analysis (He et al., 2015) and tomographic study to evaluate the relationship between the distribution of the major gold mineralized belts and mantle dynamics in the NCC.

2. Geological setting and gold metallogeny

2.1. Tectonic framework of the NCC

The North China Craton (Fig. 1) is composed of several Archean micro-continents which were amalgamated within the three major crustal units of Yinshan, Ordos and Eastern Blocks (Zhai and Santosh, 2011; Yang et al., 2015). The Yinshan and Ordos Blocks were welded along the Inner Mongolia Suture Zone (IMSZ, Santosh, 2010; incorporating the Khondalite Belt, Zhao et al., 2005) into the unified Western Block, and the Eastern and Western Blocks collided along the Trans-North China Orogen (TNCO), both during the Paleoproterozoic between 1.92 and 1.85 Ga (Zhao and Zhai, 2013; Yang and Santosh, 2015b, and references therein). The NCC is bounded by the early Paleozoic Qilian orogen in the west, the late Paleozoic to Mesozoic Central Asian Orogen in the north, and the Mesozoic Qinling–Dabie–Sulu orogen in the south (Zhao et al., 2001; Xu et al., 2012; Dong and Santosh, 2016).

The major tectonic events associated with the evolution of the NCC have been summarized in previous studies as follows (Zhai and Santosh, 2011; Zhao and Zhai, 2013): (1) Crustal growth and stabilization during Neoarchean; (2) rifting–subduction–accretion–collision from early to late Paleoproterozoic; (3) multistage rifting during Late Paleoproterozoic–Neoproterozoic; (4) craton margin orogenesis during Paleozoic, and (5) Mesozoic extensional tectonics associated with lithosphere thinning and decratonization. Zhai and Santosh (2013) traced the correlation between secular changes in tectonic regimes were with the formation of at least five major metallogenic systems: Archean Banded Iron Formation (BIF), Paleoproterozoic Cu–Pb–Zn and Mg–B, Mesoproterozoic REE–Fe–Pb–Zn, Paleozoic orogenic Cu–Mo, and Mesozoic intracontinental Au and Ag–Pb–Zn and Mo. Among these, major gold mineralization is associated with the large-scale Mesozoic magmatism, considered to be related to mantle dynamics and crust–mantle interaction leading to the lithospheric thinning and craton destruction in the NCC.

Currently ranking as the largest producer of gold in the world, China's gold reserves are spread over 200 major gold deposits and several minor deposits, and those in the NCC are mainly clustered into three major domains: the northern margin, the northeastern part of the NCC (including Jiaodong and Luxi areas and the western part of the Tan-Lu fault), and the southern margin (including Xiaoqinling and Xiong'ershan areas). The timing of gold mineralization in this region mostly constrained as Early Cretaceous (Goldfarb and Santosh, 2014). Although previous studies correlated many of the gold deposits located within the craton as greenstone belt-type (Zhai et al., 2002; Deng et al., 2003), this notion has recently been challenged because the host rocks of these deposits are high-grade metamorphic rocks, and the age of the mineralization is considerably younger than that of the Archean greenstone belts. In a recent review, Deng and Wang (2015) compiled the geochronological data on these gold deposits and showed that most of them belong to Phanerozoic, which they attributed to the orogenic overprinting, such as the Permian closure of Paleo-Asian Ocean

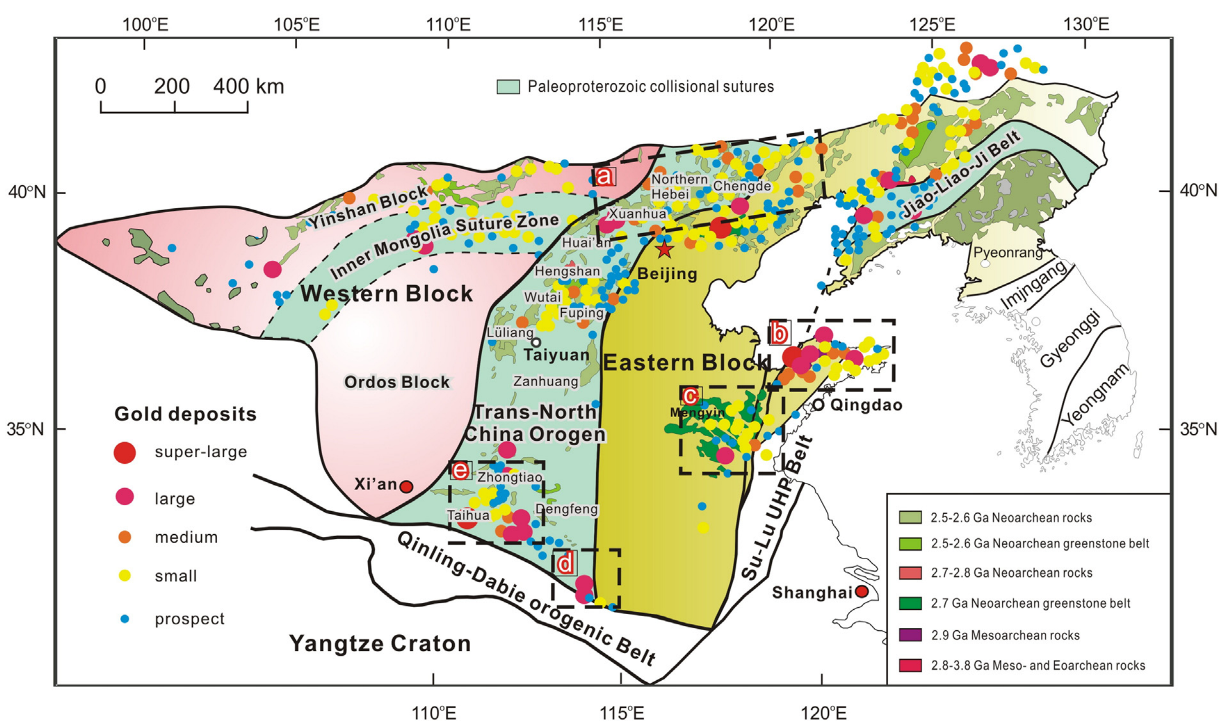


Fig. 1. General tectonic framework and distribution of the major gold mineralized belts (shown as boxes with dotted lines) of the North China Craton (modified after Zhao et al., 2005; Santosh, 2010; Li and Santosh, 2014; Yang et al., 2015). a: North NCC gold district, b: Jiaodong gold district, c Linyi gold district, d: Xiong ershan gold district, e: Xiaoqiling gold district (Yang et al., 2013).

between the NCC and the Siberian Craton, the Triassic collision between the NCC and Yangtze Craton, and the Jurassic–Cretaceous subduction of the Pacific Ocean beneath the Eurasian continent.

2.2. Major gold metallogenic belts of the NCC

2.2.1. Northern margin of North China Craton

A 1500 km-long EW-trending gold belt in the northern margin of the NCC hosts a gold resource of around 1000 t Au (Hart et al., 2002). The major deposits in this belt include those in the Daqingshan, Zhangjiakou, Yanshan, West Liaoning and Changbaishan areas from west to east (Deng and Wang, 2015). Several hundred deposits and occurrences formed in this region, through multiple orogenic events (Wang et al., 2015). The major proportion of deposits are hosted within Precambrian metamorphic rocks, with subordinate (~30%) ones within Paleozoic or Mesozoic intrusions (Cook et al., 2009). In the Daqingshan gold area, Nie et al. (2005) reported $^{40}Ar/^{39}Ar$ sericite plateau age of 240 Ma for auriferous quartz veins. In the Zhangjiakou area, Bao et al. (2014) reported U–Pb age of 389 $\pm$ 1.0 Ma from hydrothermal zircons in the Dongping deposit. Results from fluid inclusion and noble gas analyses of the Dongping deposit led Mao et al. (2003) to invoke a mantle connection for the ore fluids. The Jinchangyu and Yuerya large gold deposits occur in the Yanshan area, along with some medium to small deposits. Re–Os dating of molybdenites from Jinchangyu show weighted mean age of 225 $\pm$ 4 Ma and an isochron age of 223 $\pm$ 5 Ma (Song et al., 2014). The zircon fission-track age of the Yuerya deposit is in the range of 200–115 Ma (Tang et al., 2003). The formation ages of the Jinchangyu and Yuerya gold deposits are similar to those of the Qingshankou and Yuerya granitic plutons (Deng and Wang, 2015). The gold deposits in West Liaoning include the Jinchanggouliang and Paishanlou large deposits and many smaller gold deposits including the Honghuagou, Lianhuashan, and Shuiquan. The regional magmatism here lasted from Triassic to Cretaceous (Miao et al., 2003; Luo et al., 2001). The $^{40}Ar/^{39}Ar$ ages of biotite from the NNE-trending ductile shear zone and K-feldspar from gold-bearing altered rocks in the Paishanlou deposit are 126.6 $\pm$ 1.1 Ma (Zhang et al., 2005) and 116.7 $\pm$ 1.2 Ma (Wang et al., 2008) respectively, suggesting coeval mineralization in Cretaceous. The Changbaishan gold area, located in eastern Liaoning and southern Jilin provinces, includes the Jiapigou super-large goldfield, as well as the large Maoling, Wulong and Xiaotongjiapuzi gold deposits. Luo et al. (2002) reported $^{40}Ar/^{39}Ar$ plateau age of 204.0 $\pm$ 0.5 Ma from sericite in Jiapigou. The ages obtained from Wulong and Xiaotongjiapuzi are 112.2 $\pm$ 3.2 Ma (quartz Rb–Sr) and (167 $\pm$ 2 Ma sericite Ar–Ar) (Deng and Wang, 2015).

Among the four pulses of magmatism along the northern margin of the NCC, the 143–125 Ma magmatic event represented by the Shangshuiquan monzogranite in Dongping, which temporally coincide with the widespread Cretaceous magmatism in eastern China, has been considered to be related to lithosphere thinning (Miao et al., 2002; Deng et al., 2004a, 2004b; Deng et al., 2009). The three pulses of gold mineralization at 240–204 Ma, 192–167 Ma, 127–112 Ma in this region have been correlated to post-collisional stage, post-orogenic stage, and lithospheric thinning stage respectively (Deng and Wang, 2015).

2.2.2. Northeastern NCC

2.2.2.1. Jiaodong Peninsula. The Jiaodong Peninsula in eastern Shandong Province along the eastern margin of the NCC is bordered by the Tan-Lu Fault to the west and the Su–Lu ultrahigh-pressure metamorphic belt to the east. The Precambrian basement in this region is dominantly composed of Neoarchean–Paleoproterozoic TTG (tonalite–trondhjemite–granodiorite) gneisses, felsic and mafic volcanic and volcano-sedimentary successions, all metamorphosed under upper amphibolite to granulite facies conditions and variously reworked during the Mesozoic orogeny (Qiu, 1989; Wang et al., 1998; Yang et al., 2003, 2013, 2014; Guo et al., 2013). The Mesozoic intrusions have been classified into three suites: the Linglong, Kunyushan and Guojialing. The Linglong and Kunyushan suites show ages of 160 to 156 Ma, whereas the Guojialing suite is dated as 130 to 126 Ma (Guan et al., 1998; Wang et al., 1998; Zhang et al., 2003a, 2003b). Numerous Cretaceous mafic-intermediate dikes are also widespread in Jiaodong Peninsula. A major magmatic event of Early Cretaceous age has been recorded in the Jiaodong Peninsula (Wu et al., 2005c; Guo et al., 2013). Yang and Santosh (2015a) identified a remarkable overlap between the peak timing of gold mineralization and the peak of volcanism in the Jiaodong area at ca. 125–120 Ma.

Previous studies broadly classified the gold mineralization in Jiaodong into two types: the Linglong-type and the Jiaojia-type (Goldfarb and Santosh, 2014 and references therein). The Linglong type gold vein mineralization is typically represented in the Linglong, Jinqingding and Denggezhuang deposits (Yang et al., 2003). The Jiaojia type disseminated mineralization is mostly developed in the northwestern Jiaodong region, together with some Linglong type (Li and Santosh, 2014). These types of gold deposits are also found in the Xiaoqingling and the Luoning–Songxian regions in the southern margin of the NCC (Li and Santosh, 2014).

Goldfarb and Santosh (2014) noted that the ca. 126–120 Ma Au deposits of the Jiaodong Peninsula define the country's largest gold province with an overall endowment estimated as >3000 t Au. They emphasized that the Jiaodong deposits formed within two Precambrian blocks approximately 2 billion years after devolatilization of the country rocks. They invoked ore fluid focusing associated with sub-crustal thermal event, which they speculated to be a combination of coeval lithospheric thinning, asthenospheric upwelling, paleo-Pacific plate subduction, and seismicity along the continental-scale Tan-Lu fault. They envisaged that ore fluids were produced directly by the metamorphism of oceanic lithosphere and overlying sediment on the subducting paleo-Pacific slab, or by devolatilization of an enriched mantle wedge above the slab.

2.2.2.2. Luxi area (western part of the Tan-Lu fault). In the Luxi area, Mesozoic magmatic rocks comprise granitic intrusions, K-rich volcanic rocks and lamprophyre dikes (Lin et al., 1995). The gold belt in southwestern Luxi area which incorporates the Tongshi, Yinan and Cangshan domains are located in the western segment of the central region of the Tan-Lu Fault. The mineralization in southwestern Luxi area includes cryptoexplosive breccia type, skarn type, ancient karst type, layered disseminated limestone type, quartz vein type and porphyry altered rock type (Zeng et al., 1999). The granitoids from the Luxi area also show two age groups: the Tongshi complex with ages in the range of 175–190 Ma, and the Tongjing and Jinchang complexes with ages in the range of 113–135 Ma. The intermediate–mafic dikes in this region have ages in the range of 88 to 144 Ma. The ages of mineralization in Luxi area mainly include two stages: 180–170 Ma and 128–133 Ma (Guo et al., 2013).The gold metallogeny and the sources of ore-forming material in the Luxi gold belt are fairly defined and correlated to the Mesozoic intermediate–alkaline volcano-plutonic complexes (Lin et al., 1995; Wang and Gao, 2001).

2.2.3. Southern margin of NCC

The Xiaoqinling–Xiong'ershan gold province, with ca. 600 t of gold reserves, is located at the Qinling Mountains of eastern Shaanxi and western Henan provinces in the southern margin of the NCC, a region that witnessed the Mesozoic continental collision between the NCC and the Yangtze Craton. The gold deposits in this region cluster in three areas: the Xiaoqinling district to the west, the Xiaoshan district in the center, and the Xiong'ershan district to the east.

The basement rocks are mostly late Archean belonging to the Taihua Group and Middle Proterozoic belonging to the Xiong'er Group, intruded by several Mesozoic granitoid plutons. In the Xiaoqinling district, the gold deposits are associated with E-W folds, faults, and fold hinges in the metamorphic rocks of the Taihua Group and the volcanic rocks of the Xiong'er Group, whereas deposits in the Xiong'ershan district, they are dominantly controlled by NE-trending faults. The orebodies in the Xiaoqinling district dominantly occur in gold-bearing quartz veins and to subordinately in auriferous altered rocks hosted in the Taihua Group. The orebodies in the Xiong'ershan district are mainly concentrated in auriferous altered rocks hosted in volcanic rocks of the Xiong'er Group and to a lesser extent in gold-bearing quartz veins (Deng and Wang, 2015).

The $^{40}Ar/^{39}Ar$ geochronology of quartz from the Shanggong gold deposit in Xiong'ershan district shows an age of 223 ± 25 Ma (Ren and Li, 1996). The K–Ar age of sericite from the Tongyu gold deposit is 237.5 Ma, and the Re–Os age of molybdenite from the Dahu Au–Mo deposit is 218 ± 41–206.4 ± 3.9 Ma (Li et al., 2011; Jian et al., 2015). Re–Os modal ages of 130.8 ± 1.5 Ma and 129.1 ± 1.6 Ma were reported from the Quanjiayu Au–Mo deposit (Li et al., 2007b). Tang and Li (2009) reported $^{40}Ar/^{39}Ar$ age of 126.99 ± 1.56 Ma from sericite in the Qianhe gold deposit, which is similar to 135.6 ± 5.6 Ma age of the Qiyugou gold deposit in the Xiong'ershan district based on the Re-Os age of molybdenite (Yao et al., 2009). Li et al. (2002) reported $^{40}Ar/^{39}Ar$ age of 132.2 ± 2.6 Ma for sericite in the Dongchuang gold deposit. In a recent study, Li et al. (2012a, 2012b) obtained Re-Os and $^{40}Ar/^{39}Ar$ data between ca. 135 and 120 Ma for ten deposits in the Xiaoqinling district. The available age data show that the gold mineralization of the Xiaoqinling probably took place at 135–120 Ma, coeval with those of the Jiaodong Peninsula.

3. The stagnant slab enigma

The seismic images together with geological, petrological, geochemical, structural and mineral physics data have been used to suggest that the fundamental destruction of the eastern NCC lithosphere might have been triggered largely by the deep subduction of the Paleo-Pacific plate (northwestward subduction) or Pacific plate (westward subduction), especially during the Late Mesozoic (Zheng and Wu, 2009). Subducting slabs move down vertically until they reach the mantle transition zone (MTZ: bound by the 410 and 660 km discontinuities) where they are arrested and become stagnant. Through heat input from the surround mantle, the slab debris would begin to melt. Because of their buoyancy, the crustal materials dragged down and accumulated at the mantle transition zone would start melting and rising up triggering plume-like convective upwelling (Korenaga, 2004; Lustrino, 2005; Kawai et al., 2013). This process would also result in the disturbance of mantle convection, leading to intensified thermomechanical and chemical erosion (including mantle–melt interaction) at the base of the overlying continental lithosphere and/or triggering gravitational instability and delamination of the modified lithosphere. It is possible that both processes might have contributed to the destruction of the lithospheric root of the eastern NCC in the Late Mesozoic (Xu, 2001; Gao et al., 2004; Zhang, 2005; Tang et al., 2013a, 2013b). Thus, the weakening and destruction of the cratonic lithosphere has been correlated to the dehydration of subducting slabs (Tian et al., 2009).

Regional and global tomographic studies have investigated the 3-D mantle structure of the western Pacific subduction zone, revealing the general structure of the subducting slab (e.g., Zhou and Clayton, 1990; Zhao et al., 1994; Bijwaard et al., 1998; Fukao et al., 2001; Zhao, 2001, 2004). Recent geophysical studies also suggest that the transition zone under NE China is remarkably hydrous (Kuritani et al., 2013). Huang and Zhao (2006) reported a stagnant slab of the Pacific Plate subduction in the mantle transition zone between E108° and E136°, covering most part of the NCC.

However, He et al. (2015) used the depth domain receiver function to demonstrate a significant deepening of the 410 km discontinuity beneath the northern part of the Trans-North China Orogen and the eastern NCC (410 km discontinuity > 410 km) (Fig. 2-a). A similar feature is also observed for the 660 km discontinuity (Fig. 2-b) (660 km discontinuity > 655 km) in these regions. The average value for the depth of the 410 km and 660 km discontinuity in this area are around ~406 km and ~651 km respectively, both of which are lower than the global average values.

The deepening of both the 410 and 660 km discontinuities have been correlated with a phase transition from majorite garnet to perovskite at 660 km depth (Hirose, 2002; Deuss et al., 2006; Huerta et al., 2009; Yu et al., 2011; Farnetani et al., 2012) with the positive pressure-temperature gradients (the Clapeyron slope is positive). Thus, presence of an upwelling mantle plume can result in the deepening of the 410 and 660 km discontinuities (Fig. 3a). The major upper mantle phase transitions could also be through olivine to wadsleyite at the 410 km and ringwoodite to perovskite and magnesiowüustite at 660 km (Helffrich, 2000). The phase changes responsible for the 410 km have positive pressure-temperature gradients (Clapeyron slope), so that a decrease in temperature results in a decrease in pressure (depth) of the phase change. For the phase change responsible for the 660 km, the Clapeyron slope is negative and a decrease in temperature will lead to an increase in the pressure (depth) (Fig. 3b).

The results from tomography predict that if there is a stagnant slab, it should be a cold slab (Zorin et al., 2006), lying in the mantle transition zone, which would generate a shallower region of both the 410 and 660 km discontinuities (Fig. 3c) or lead to a decrease in the depth of the 410 km discontinuity and an increase of the depth of the 660 km discontinuity (Fig. 3d). The character of the deepening region of both the 410 and 660 km discontinuity is not consistent with a cold stagnant slab in the mantle transition zone. Additionally, the depth domain receiver function can effectively delineate the 410 and 660 km interfaces, and 410 and 660 km discontinuity topography, whose precision is higher than the tomography, which displays the thermal state of the upper mantle from which any upwelling plume from the lower mantle

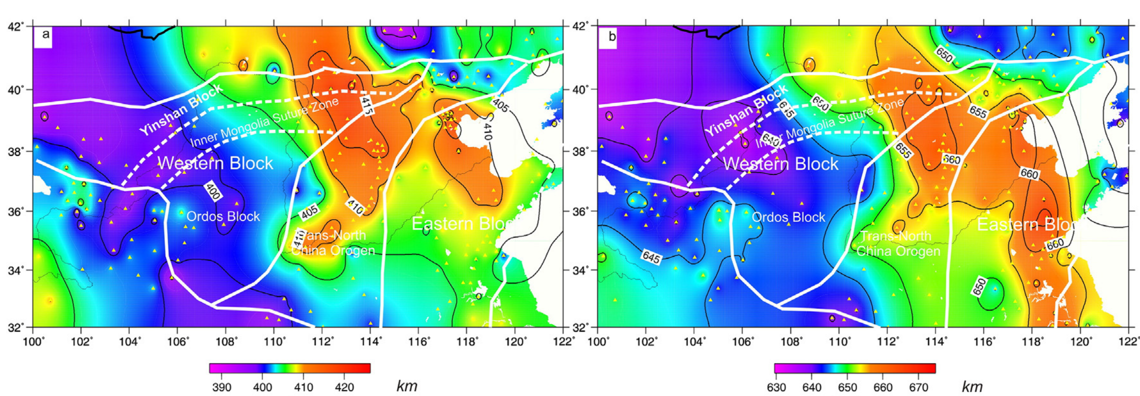


Fig. 2. Distribution of the 410 (a) and 660 (b) km discontinuities. An overlapping region of deepening region of both the 410 km (>410 km) and the 660 km (>655 km) discontinuities can be seen (after He et al., 2015).

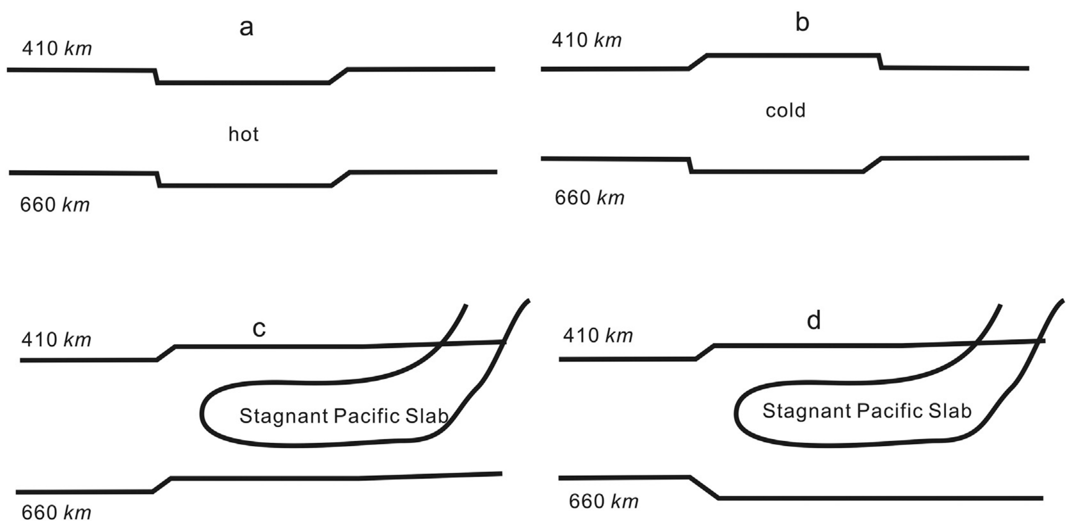


Fig. 3. Upper mantle discontinuity topography from thermal and chemical heterogeneity (a, b). The stagnant slab in the mantle transition zone resulting in the upper mantle discontinuity topography (c, d) is also shown.

can be tracked (e.g. Huerta et al., 2009; He, 2010).Thus, a stagnant slab in the mantle transition zone is not likely as the major trigger for lithospheric destruction.

4. Upwelling mantle plume, lower crustal and lithospheric delamination and gold mineralization

The final tectonic architecture of the NCC comprising the assembly of the major crustal blocks of Yinshan and Ordos into the unified Western Block and its amalgamation with the Eastern Block coincided with the global-scale collisional events that led to the assembly of the Columbia supercontinent in late Paleoproterozoic (Rogers and Santosh, 2009; Zhao et al., 2009; Santosh, 2010). The assembly of supercontinents severely disrupts the Earth's mantle flow at continental and planetary scales, promoting plume and superplume activity or upwelling mantle (Condie, 2004; Rino et al., 2008; Aitken et al., 2013). Such upwelling mantle plume can greatly impinge on the base of the lithosphere and promote cratonic or continental destruction (Cloetingh et al., 2013), which is an important process for consuming lithosphere (Replumaz et al., 2013; Aitken et al., 2013).

Wilson (1963) suggested that the Hawaiian Islands were produced by the oceanic lithosphere moving over a stationary 'hot spot' in the mantle. Mantle plumes play an important role in convection and material transfer (Morgan, 1971; Safonova and Santosh, 2014). In model experiments, mantle plumes, which originate either from the core–mantle boundary (one-layer mantle model) or from the 660 km discontinuity at the base of the upper mantle (two-layer mantle model) (Pirajno and Hoatson, 2012; Pirajno and Santosh, 2015), are generated by injection of a low-density and low-viscosity fluid into a high-density and high-viscosity fluid and the material in the lower boundary layer will be lighter than the overlying mantle (Dostal and Mueller, 2012; Campbell, 2005).

In the early history of the Earth, controlled by the gravitational contraction and thermal expansion, lighter elements migrated upwards, whereas heavier elements had a tendency of sinking to the Earth's core, so that the elements like iron, nickel, gold and silver are mainly concentrated in the Earth's core (Huo, 1991; Niu et al., 2003). Plumes rising from the core-mantle boundary act as pipes (Santosh et al., 2009), connecting the migration of deep-seated ore-forming material, and thus elements such as gold and silver concentrated in the core and on the core–mantle boundary migrate in gaseous stage together with the hot material flow of plumes into the base of the lithosphere. These are finally transferred through magmatic and fluid conduits to be concentrated in favorable structural zones, forming mineral deposits (Niu et al., 2002, 2003; Pirajno and Hoatson, 2012; Safonova and Santosh, 2014; Pirajno and Santosh, 2015). Evidence that that gold is present in mantle plumes lends support to the role of plume-related processes in generating gold deposits (Hames et al., 2009).

Some workers have correlated the craton destruction in the NCC to large-scale lithosphere–mantle interaction, which may have its origin in mantle plumes (Eggler et al., 1988; Griffin et al., 1998, 1999; Artemieva et al., 2002; Liu and Chang, 2001; Zhao and Zheng, 2005). The involvement of plumes in the re-activation/delamination of the NCC has been also been suggested by many investigators (Flower et al., 1998; Peng et al., 1986; Zhao et al., 2003, 2004; Wilde et al., 2003; Menzies et al., 2007; He et al., 2015).

Abundant gold deposits are distributed along craton margins and paleo suture zones in the NCC, most of which show Early Cretaceous ages (130–110 Ma) (Cai et al., 2013) (Fig. 1). Extensive magmatic activity with possible relation to mantle plume, defined as the "giant igneous event", occurred dominantly at 130–120 Ma, coeval with the lithospheric thinning in the NCC (Wu et al., 2005a, 2005b; Menzies et al., 2007). The timing of lithospheric thinning and craton destruction in the eastern and central NCC also coincided with the formation of a number of important ore deposits, particularly the extensive gold mineralization in the Jiaodong Peninsula (Guo et al., 2013; Li and Santosh, 2014; Zhai and Santosh, 2013; Goldfarb and Santosh, 2014).

A prominent upper mantle low velocity zone is present under east Shandong Province at 25, 40, 60, 90, 120 and 150 km depth sections. The low velocity zone correlates with mantle upwelling and have been cited as a potential reason for magmatism and gold metallogeny in the Shandong Province (Guo et al., 2013). Generally, the mantle plumes have a large head followed by a relatively narrow tail (Campbell, 2005; Cloetingh et al., 2013). Tomographic and receiver function images show that most plumes are not simple vertical structures (Pirajno and Hoatson, 2012; He et al., 2015) and the plume heads contribute huge volumes of lava to the Earth's surface over short periods of time (Weis et al., 2011). This implies that mantle plume may influence wider regions in the surface than deeper regions of the mantle transition zone.

Compared with other cratons in the world, the NCC is relatively small. Thus, it has been proposed that subduction and collision of adjacent blocks might have exerted considerable influence on the craton (Zheng, 2009; Lan et al., 2011; Zhang et al., 2005). Menzies et al. (1993) suggested that Pacific plate subduction acted as a geodynamic force for the destabilization and delamination of the cratonic lithosphere. The Mesozoic deep-seated tectonic processes in eastern China are considered to have triggered local delamination (Li et al., 2012a, 2012b). Several studies attribute delamination of thickened lithosphere accompanied by asthenosphere upwelling leading to lithospheric destruction and active magmatism in the continent margin of the NCC (Wu and Sun, 1999; Sun et al., 2007; Xu et al., 2009).

There is a marked distinction in the distribution of the younger magmatic rocks in the NCC, with Carboniferous to Triassic suites occurring in the craton margin, and Jurassic to Cenozoic suites extending gradually into the interior. This distribution probably suggests that the destruction of the NCC started from its margins to the interior (Li and Santosh, 2014), which might suggest delamination process from the margins to the interior.

Magmatic rocks with adakitic affinities have been correlated to melt generation in thickened lower crust or from lower crust that delaminated into the convecting mantle and subsequently melted and interacted with peridotite (Atherton and Petford, 1993; Wang et al., 2004; Zhao et al., 2012). Several Mesozoic granitoids with adakitic signature have been reported in the NCC (Ma et al., 2012; Xu et al., 2002). These adakitic rocks are considered to be related to lithospheric thinning and delamination in the Mesozoic (Yang and Wu, 2009; Wang et al., 2014). Gold provinces in some parts of the world are linked to lithospheric instabilities following the lower crustal and (or) lithospheric delamination (Leahy et al., 2005; Bierlein et al., 2006) as well as upwelling asthenosphere, which produce high-heat flow in the lithosphere which is connected with the peak gold mineralization events (Goldfarb et al., 2005; Kabete et al., 2012).

From geophysical point of view, receiver function analysis indicates the bulk *Vp*/*Vs* ratio is lower (mostly between 1.76 and 1.74 or < 1.74) at the central and southern part of the eastern NCC (He et al., 2015) (Fig. 4), suggesting an intermediate to felsic lower crust in this area based on interpretations and correlations in other studies (Zandt and Ammon, 1995; Chang and Baag, 2007; He et al., 2014a, 2014b). It is possible that the westward subduction of the Pacific Plate and resultant compression led to lower crustal and (or) lithospheric delamination in the central and southern parts of the eastern NCC (He et al., 2015).

Thus, a combination of delamination, mantle upwelling, subduction-related metasomatic enrichment and recycling of ancient components facilitated the gold metallogeny in the NCC as suggested by Guo et al. (2013). It has also been proposed that the strike-slip along the Tan-Lu fault occurred in a post-collisional setting following the collision between the NCC and Yangtze Craton, and coincided with a hypothesized mantle plume event, which initiated the gold mineralization in the Jiaodong Peninsula (Wang et al., 1998).

5. Tomography results

In order to further evaluate the various hypothetical models discussed in the previous sections, we carried out a 3-D teleseismic tomography analysis (Zhao et al., 1992, 1994, 2002) to image deep structures of the mantle following the principle that the body-wave tomography is an effective tool for the studies of deep mantle structures (Feng et al., 2010).

In this study, we collected 116350 P and 26231 S wave arrivals from 1081 teleseismic events (6.0 ≤M ≤8.0) with epicentral distances within the range of 30°-85° (Fig. 5: inset figure). These events were recorded by 561 seismic stations of the China national seismic network from 2007 to 2014 (Fig. 5). A 3-D grid was set up in the model and velocity perturbations at the grid nodes were taken as unknown parameters. The grid spacing of the model is 0.5° × 0.5° laterally and 25, 40, 60, 120, 150, 200, 250, 300, 350, 400, 500, 600 and 700 km in depth.

The results identified from our tomographic analyses show that all the major goldfields in the North China Craton are located above regions of low velocity perturbation anomaly in the 25 km, 40 km, 60 km, 90 km, 120 km, 150 km, and 200 km depth sections (Fig. 6: a-g). This finding strengthens the possible link between the upwelling mantle material and gold mineralization. In the 250–300 km depth section, the distribution of the lower velocity perturbation region is very similar (Fig. 6: h-i). In the 350 km and 400 km depth sections, a complex feature of the velocity perturbation is seen (Fig. 6: j-k), which might result from the influence of the lower crustal and (or) lithospheric delamination. In the 500 km depth zone (within the MTZ) (Fig. 6: l), there is a higher velocity perturbation region in the eastern NCC, which might be a result of the lower crustal and (or) lithospheric delamination and its sinking down into the MTZ. In the 600 km and 700 km depth (Fig. 6: m-n), which are located at the MTZ and lower mantle, respectively, lower

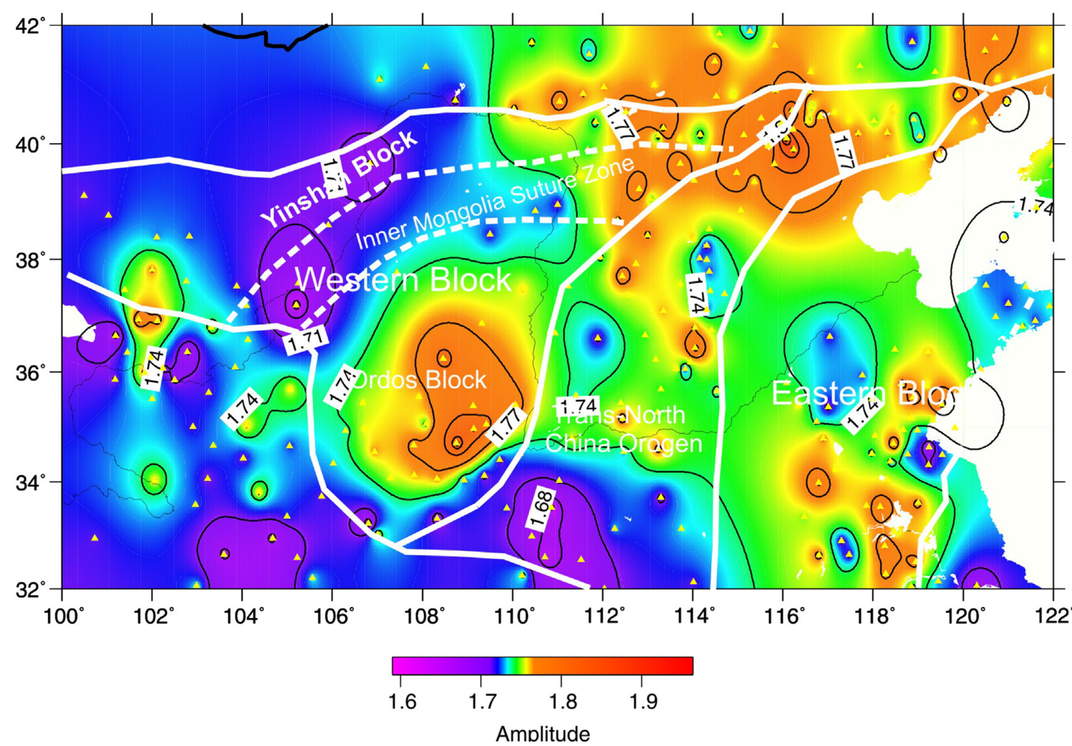


Fig. 4. Distribution of the *Vp*/*Vs* ratio in the NCC (after He et al., 2015).

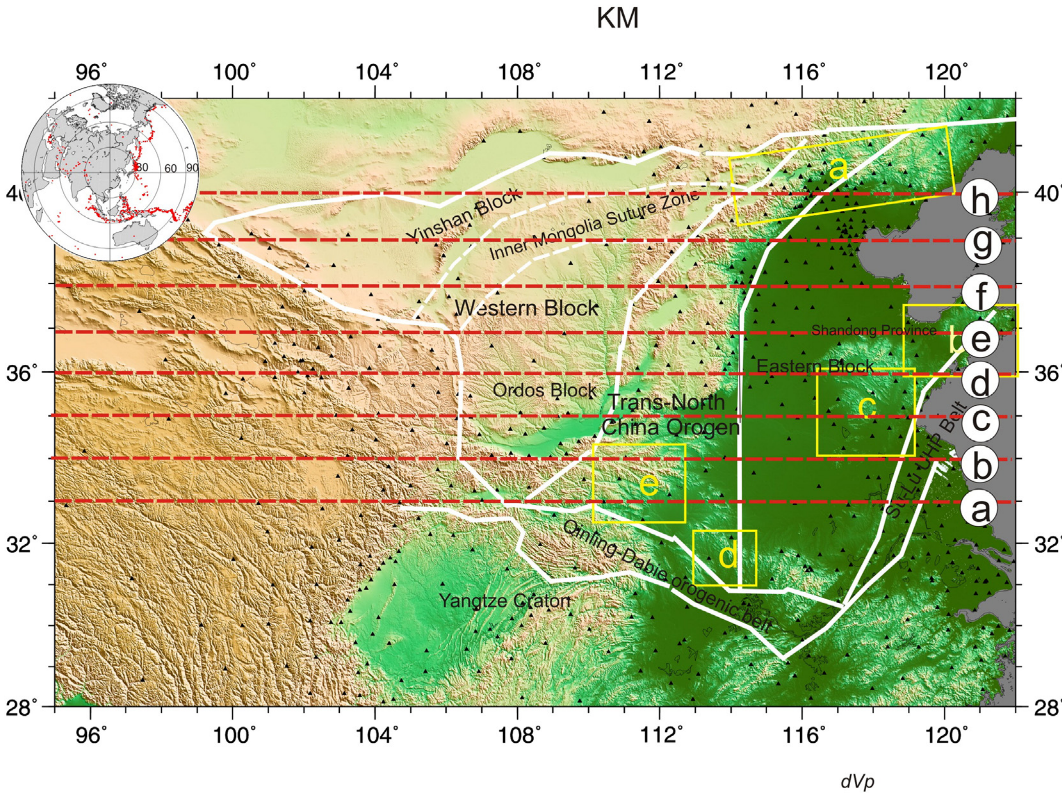


Fig. 5. The location of the seismic stations in the NCC used for tomography analyses and the velocity distribution profiles in this study.

velocity perturbation regions occur at the eastern part of the NCC, suggesting upwelling mantle plume beneath this area.

We also carried out analysis on 8 latitudinal profiles (Fig. 5, Fig. 7). In the 35–38° profiles, the outline of the upwelling mantle plume is characterized, which include some higher velocity material generated by the lower crust and (or) lithosphere delamination. Obviously, the velocity structure of the upwelling mantle plume was destroyed by the lower crustal and (or) lithospheric delamination.

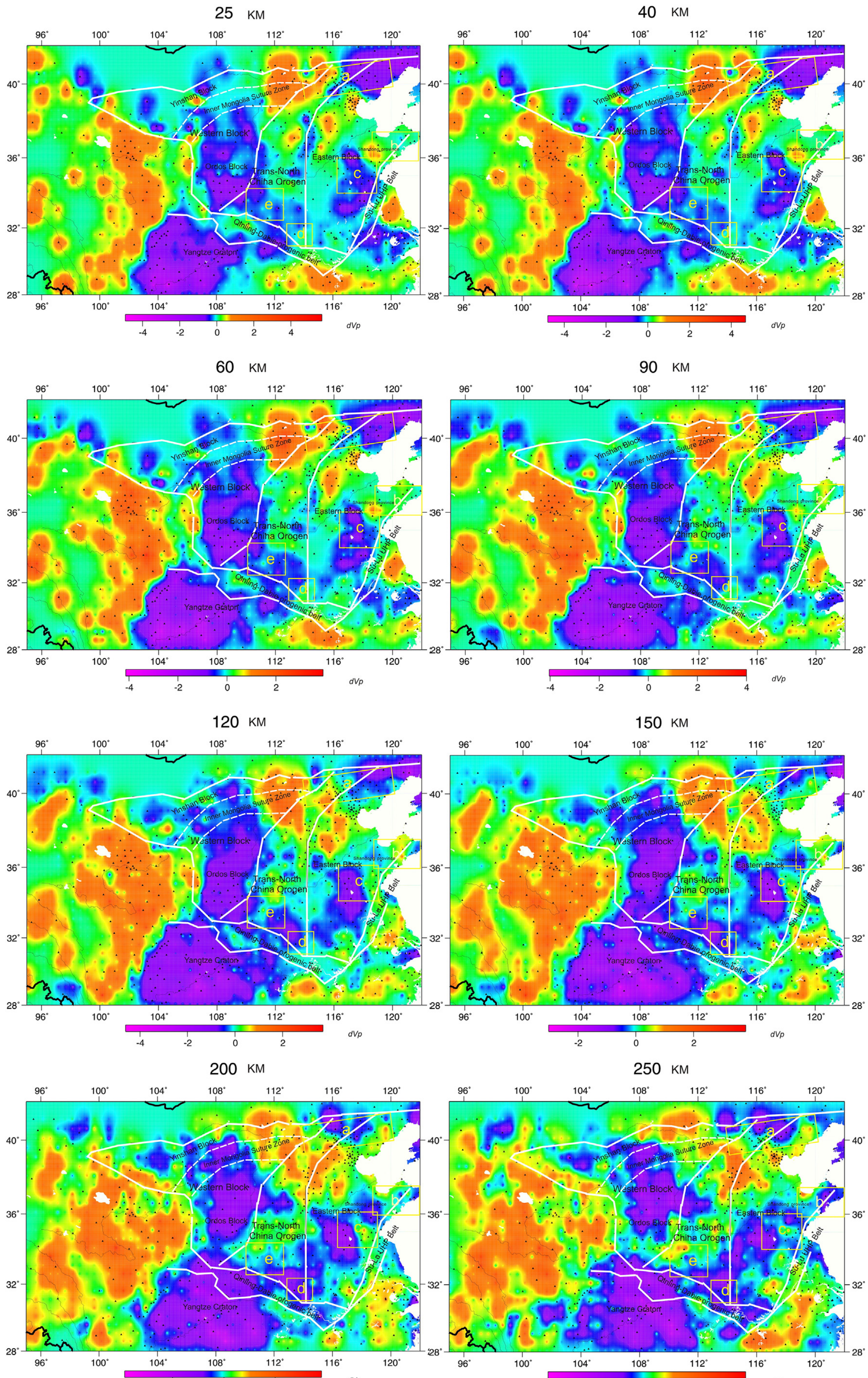
One of the potential magmatic proxies for the reaction between delaminated lower crust and the mantle is high-Mg adakitic rocks, whereas low-Mg adakitic rocks are probable products of melting from thickened lower crust. The characteristic spatial and temporal distributions of high-Mg adakitic rocks along the Tan-Lu fault with emplacement ages of 134–128 Ma suggest a strong structural control for the emplacement of these intrusions, whereas in the Dabie orogenic belt, most of the low-Mg adakitic rocks (143–129 Ma) were emplaced earlier than the high-Mg adakitic rocks (Gu et al., 2013). This suggests that the upwelling mantle plume generated the low-Mg adakitic rocks and the lower crustal and (or) lithospheric delamination generated the high-Mg adakitic rocks. Thus, the upwelling mantle plume is earlier than the lower crustal and (or) lithospheric delamination. We therefore interpret that the delaminated material was superimposed on the upwelling plume, as suggested by the velocity data in the tomographic images.

6. Discussion

Magmatism is a potential indicator of geodynamic processes (Pirajno et al., 2011; Zhang et al., 2011). Metallic mineralizations, including gold deposits, provide important constraints on magmatism and geodynamics (Yang et al., 2003; Li et al., 2014). Among the various processes that generate magmatism are slab windows in convergent margins (Eyuboglu, 2013), developed through ridge subduction. When a slab is subducted beneath the continent or plate, a slab window opens (Thorkelson and Taylor, 1989). The slab window marks the region of hot asthenospheric upwelling, which results in elevated temperatures causing the melting of overlying crustal rocks to generate intermediate to felsic magmas (Yang and Santosh, 2015b). Thus, among the several models proposed for the origin of gold mineralization in the NCC include ridge subduction associated with the convergence of the Pacific Plate (Zhou and Zhou, 2006; Li et al., 2007a, 2007b, 2012a, 2012b). However, geophysical studies show the slab of the Pacific plate subduction, characterized by a ~45° dipping Wadati–Benioff zone beneath the Kuril arc (Wei et al., 2012), arrived only at the eastern part of the Japanese sea or the eastern part of E135° (Miller et al., 2005; Kennett and Furumura, 2010; Heki and Mitsui, 2013). Thus, so far there is no geophysical evidence to indicate ridge subduction associated with the Pacific Plate beneath the Jiaodong Peninsula. The link invoked between the subduction of a ridge of the Pacific plate and gold mineralization therefore remains debatable.

Alkaline rocks associated with lithospheric thinning have been observed in the NCC (Zhang et al., 2005). The alkaline magmas can be generated by partial melting of the lower crust (Smith et al., 1988; Tchameni et al., 2001) or derived by partial melting of the lithospheric mantle (Miyazaki et al., 2003). Alkaline igneous rocks generally occur in extensional tectonic settings (Whalen et al., 1987), which provide a significant indication for the post-collisional or intraplate extensional magmatic processes within the continental lithosphere (Mushkin et al., 2003; Peng et al., 2008; Zhang et al., 2012c).

The Mesozoic metallogenic events in the northern, southern and eastern margins of the NCC have been correlated to a tectonic transition from shortening to extension (Zhai and Santosh, 2013). The gold deposits in the NCC are considered to be distributed along the margins of the craton, at the junctions of the microblocks that built the cratonic architecture, and within some of the reactivated paleo-suture zones (Li and Santosh, 2014; Zhai and Santosh, 2013). There is also a strong association between gold mineralization and regional faults or shear zones


25 KM
40 KM
60 KM
90 KM
120 KM
150 KM
200 KM
250 KM
Yinshan Block
Inner Mongolia Suture Zone
Western Block
Ordos Block
Trans-North China Orogen
Eastern Block
Shandong province
Su-Lu UHP Belt
Qinling-Dabie orogenic belt
Yangtze Craton
a
b
c
d
e
dVp
96° 100° 104° 108° 112° 116° 120°
28° 32° 36° 40°

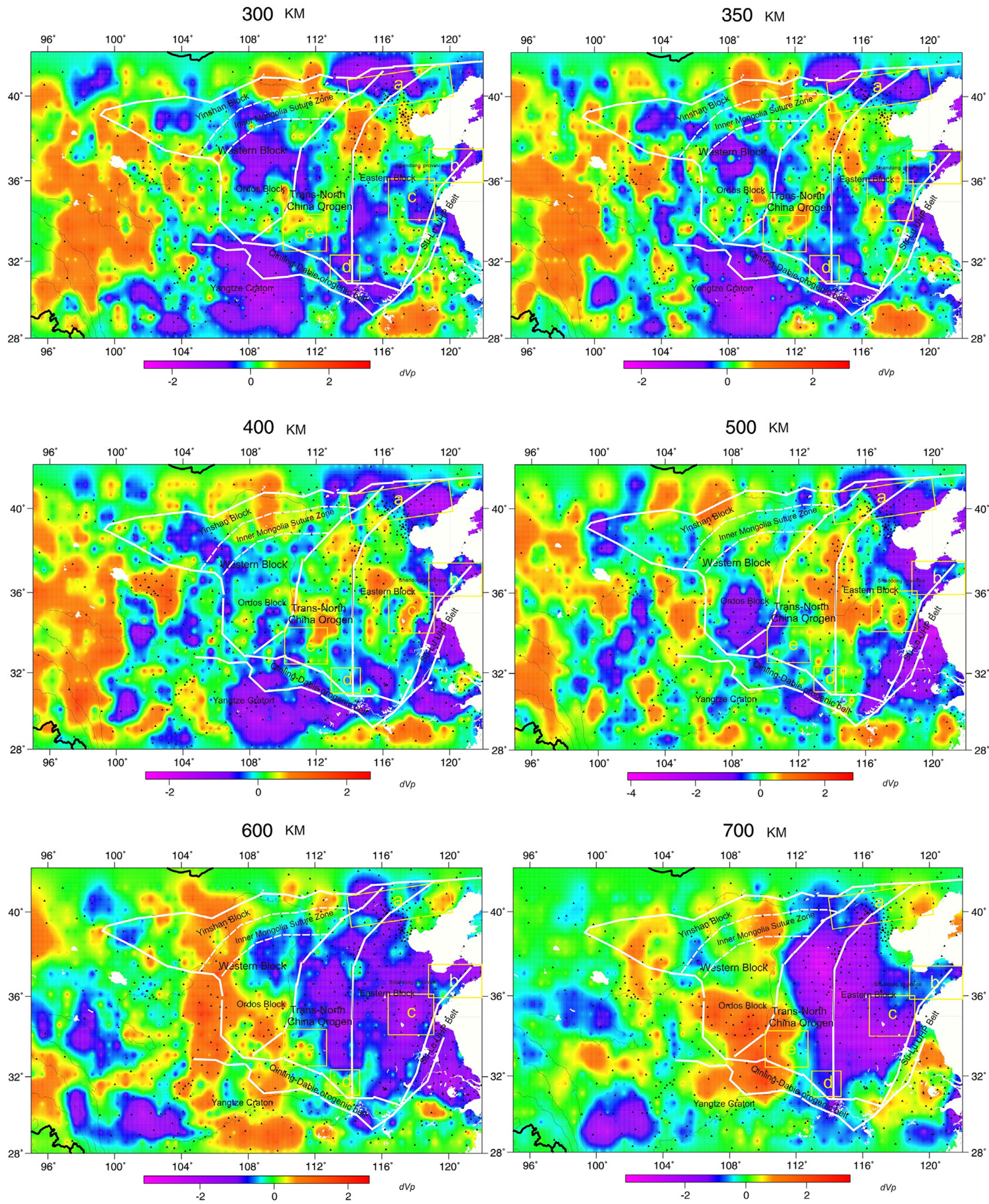


Fig. 6. Distribution of the P-wave velocity distribution at different depths in the NCC, 25 km depth, 40 km depth, 60 km depth, 90 km depth, 120 km depth, 150 km depth, 200 km depth, 250 km depth, 300 km depth, 350 km depth, 400 km depth, 500 km depth, 600 km depth and 700 km depth. a: North NCC gold district, b: Jiaodong gold district, c Linyi gold district, d: Xiong ershan gold district, e: Xiaoqiling gold district (Yang et al., 2013).

(Upton and Craw, 2014) in the NCC, with the faults, shear zones or paleo-sutures providing the pathway for the migration of mineralized fluids with the physico-chemical settings of metal precipitation aided by granitoids (Goldfarb and Santosh, 2014).

Recent studies indicate that mantle plume can generate some sub-plumes at the mantle transition zone (Koppers, 2011; Wang et al., 2013). Some workers suggest that the branch structure is a third-order tectonic unit of the mantle plume, and also an integrated manifestation of multi-stage evolution of the mantle plume at the shallow level of the lithosphere (Sun et al., 2006; Niu et al., 2009, 2012). Thus, the upwelling mantle material can also be controlled by tectonics such as fault or suture.

7. Conclusion

Mantle plumes rising from the core-mantle boundary, and generated through the melting of 'slab graveyards' accumulated through large-scale subduction associated with supercontinent building opens passageways for the migration of metals like gold concentrated in the

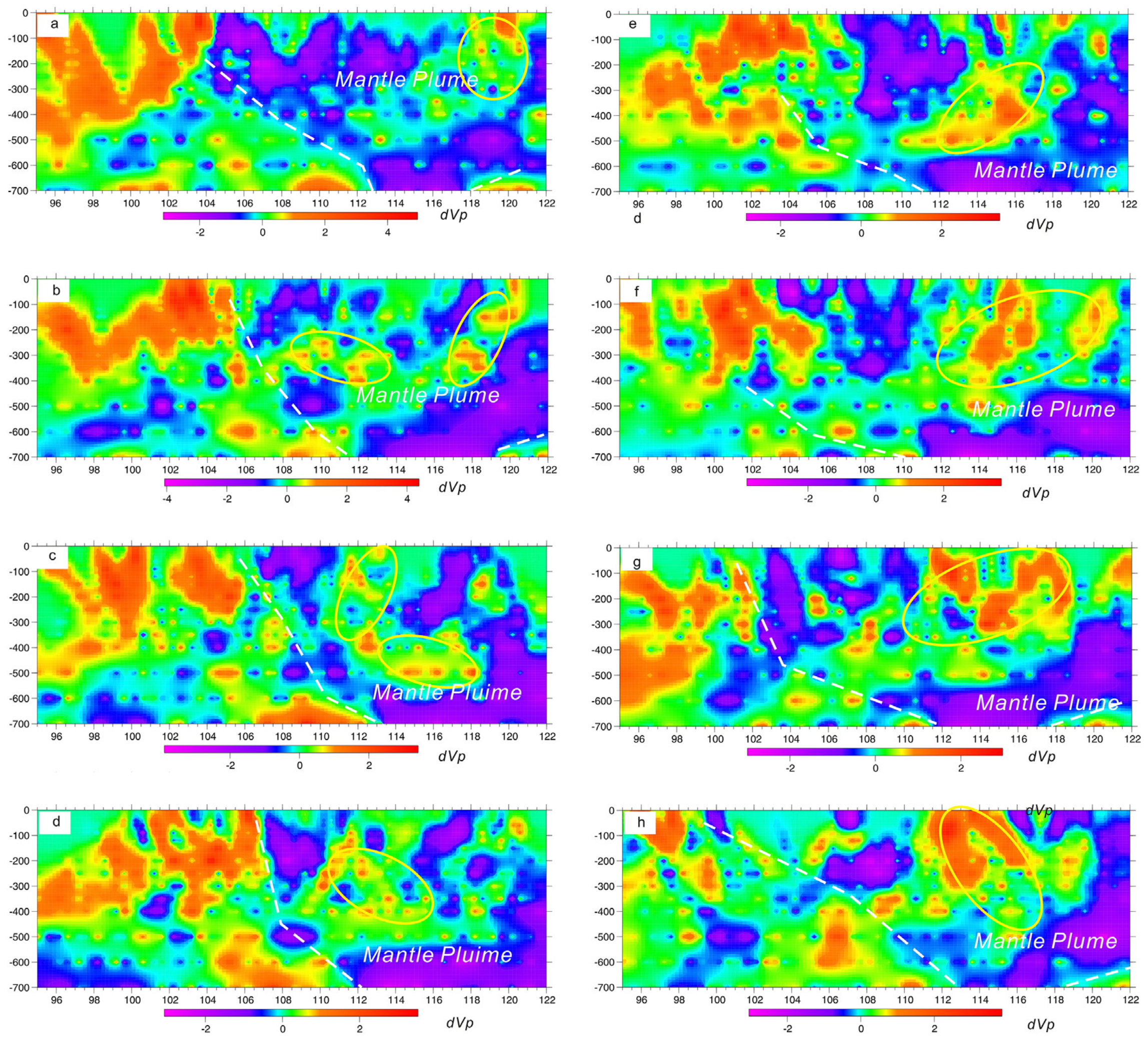


Fig. 7. Latitudinal profiles of velocity perturbation. Yellow ellipse: higher velocity region which might be generated by the lower crustal and (or) lithospheric delamination. White dotted lines mark the outline of the possible upwelling mantle plume. The velocity distribution profiles are: a: 33°, b: 34°, c: 35°, d: 36°, e: 37°, f: 38°, g: 39° and h: 40°.

core. Plumes act as large pipes that enable material transfer from core and deep mantle to lithosphere. Sub-plumes from the mantle transition zone transfer the materials into magmas and fluids and from there to structural pathways. In the North China Craton, the distribution of major gold fields shows close correspondence with zones of mantle upwelling at various depth domains, as revealed from the analysis of seismic tomographic data. These regions also coincide with the domains of intense lithospheric erosion and craton destruction. We propose that lower crustal and (or) lithospheric delamination, upwelling mantle and extension along faults and paleo sutures provided favorable conditions for gold mineralization at shallow depths.

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References

Aitken, A.R.A., Raimondo, T., Capitanio, F.A., 2013. The intraplate character of supercontinent tectonics. Gondwana Res. 24, 807–814.
Artemieva, I.M., Mooney, W.D., Perchuck, E., Thybo, H., 2002. Processes of lithosphere evolution: new evidence on the structure of the continental crust and uppermost mantle. Tectonophysics 358, 1–15.
Atherton, M.P., Petford, N., 1993. Generation of sodium-rich magmas from newly underplated basaltic crust. Nature 362, 144–146.
Bao, Z.W., Sun, W.D., Li, C.J., Zhao, Z.H., 2014. U–Pb dating of hydrothermal zircon from the Dongping gold deposit in North China: constraints on the mineralization processes. Ore Geol. Rev. 61, 107–119.
Bierlein, F.P., Groves, D.I., Goldfarb, R.J., Dubé, B., 2006. Lithospheric controls on the formation of provinces hosting giant orogenic gold deposits. Mineral. Deposita 40, 874–886.
Bijwaard, H., Spakman, W., Engdahl, E.R., 1998. Closing the gap between regional and global travel time tomography. J. Geophys. Res. 103, 30,055–30,078.
Cai, Y.C., Fan, H.R., Santosh, M., Liu, X., Hu, F.F., Yang, K.F., Lan, T.G., Yang, Y.H., Liu, Y.S., 2013. Evolution of the lithospheric mantle beneath the southeastern North China Craton: constraints from mafic dikes in the Jiaobei terrain. Gondwana Res. 24, 601–621.
Campbell, I.H., 2005. Large igneous provinces and the mantle plume hypothesis. Elements 1, 256–269.
Chang, S.J., Baag, C.E., 2007. Moho depth and crustal Vp/Vs variation in Southern Korea from teleseismic receiver functions: implication for tectonic affinity. Bull. Seismol. Soc. Am. 97, 1621–1631.
Chen, L., 2010. Concordant structural variations from the surface to the base of the upper mantle in the North China Craton and its tectonic implications. Lithos 120, 96–115.
Cloetingh, S., Burov, E., Francois, T., 2013. Thermo-mechanical controls on intra-plate deformation and the role of plume-folding interactions in continental topography. Gondwana Res. http://dx.doi.org/10.1016/j.gr.2012.11.012.
Condie, K.C., 2004. Supercontinents and superplume events: distinguishing signals in the geologic record. Phys. Earth Planet. Inter. 146, 319–332.

Cook, N.J., Ciobanu, C.L., Mao, J.W., 2009. Textural control on gold distribution in As-free pyrite from the Dongping, Huangtuliang and Hougou gold deposits, North China Craton (Hebei Province, China). Chem. Geol. 264 (1), 101–121.
Deng, J., Wang, Q.F., 2015. Gold metallogenesis in China: metallogenic provinces, deposit types and tectonic framework. Gondwana Res. (submitted for publication).
Deng, J., Yang, L.Q., Sun, Z.S., Wang, J.P., Wang, Q.F., Xin, H.B., Li, X.J., 2003. A metallogenic model of gold deposits of the Jiaodong granite-greenstone belt. Acta Geol. Sin. 77 (4), 537–546 (English-Edition).
Deng, J., Wang, Q.F., Yang, L.Q., Wang, J.P., Gao, B.F., Liu, Y., 2004a. The geological settings of the gold metallogeny in northwestern Jiaodong peninsula, Shandong province. Earth Sci. Front. 11, 527–533 (in Chinese with English abstract).
Deng, J.F., Mo, X.X., Zhao, H.L., Wu, Z.X., Luo, Z.H., Su, S.G., 2004b. A new model for the dynamic evolution of Chinese lithosphere: "continental roots-plume tectonics". Earth-Sci. Rev. 65, 223–275. http://dx.doi.org/10.1016/j.earscirev.2003.08.001.
Deng, J.F., Su, S.G., Niu, Y.L., Liu, C., Zhao, G.C., Zhao, X.G., Zhou, S., Wu, Z.X., 2007. A possible model for the lithospheric thinning of North China Craton: evidence from the Yanshanian (Jura-Cretaceous) magmatism and tectonism. Lithos 96, 22–35.
Deng, J., Yang, L.Q., Gao, B.F., Sun, Z.S., Guo, C.Y., Wang, Q.F., Wang, J.P., 2009. Fluid evolution and metallogenic dynamics during tectonic regime transition: an example from the Jiapigou gold belt in Northeast China. Resour. Geol. 59 (2), 140–153.
Deuss, A., Redfern, S.A.T., Chambers, K., Woodhouse, J.H., 2006. The nature of the 660-kilometer discontinuity in earth's mantle from global seismic observations of PP precursors. Science 311, 198–201.
Dong, Y.P., Santosh, M., 2016. Tectonic architecture and multiple orogeny of the Qinling Orogenic Belt, Central China. Gondwana Res. 29, 1–40. http://dx.doi.org/10.1016/j.gr.2015.06.009.
Dostal, J., Mueller, W.U., 2012. Deciphering an Archean mantle plume: Abitibi greenstone belt, Canada. Gondwana Res. 23, 493–505.
Eggler, D.H., Meen, J.K., Welt, F., Dudas, F.O., Furlong, K.P., McCallum, M.E., Carlson, R.W., 1988. Tectonomagmatism of the Wyoming Province. Cenozoic volcanism in the southern rocky mountains revisited; a tribute to Rudy C. Epis. Part 3. Colo. Sch. Mines Q. 83 (2), 25–40.
Eyuboglu, Y., 2013. Slab window magmatism and convergent margin tectonics. Geosci. Front. 4, 349–351.
Fan, W.M., Zhang, H.F., Baker, J., Javis, K.E., Mason, P.R.D., Menzies, M.A., 2000. On and off the North China craton: where is the Archean keel? J. Petrol. 41, 933–950.
Farnetani, C.G., Hofmann, A.W., Class, C., 2012. How double volcanic chains sample geochemical anomalies from the lowermost mantle. Earth Planet. Sci. Lett. 359–360, 240-24.
Feng, M., van der Lee, S., An, M., Zhao, Y., 2010. Lithospheric thickness, thinning, subduction, and interaction with the asthenosphere beneath China from the joint inversion of seismic S-wave train fits and Rayleigh-wave dispersion curves. Lithos 120, 116–130.
Flower, M.F.J., Tamaki, K., Hoang, N., 1998. Mantle extrusion: a model for dispersed volcanism and DUPAL-Like Asthenosphere in East Asia and the Western Pacific. In: Flower, M., Ching, S.L., Lo, C.H., Lee, T.Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. AGU Geodynamics Series 27, pp. 67–88.
Fukao, Y., Widiyantoro, S., Obayashi, M., 2001. Stagnant slabs in the upper and lower mantle transition region. Rev. Geophys. 39, 291–323.
Gao, S., Zhang, B.R., Jin, Z.M., Kern, H., Luo, T.C., Zhao, Z.D., 1998. How mafic is the lower continental crust? Earth Planet. Sci. Lett. 161, 101–117.
Gao, S., Rudnick, R.L., Carlson, R.W., McDonough, W.F., Lin, Y.S., 2002. Re–Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton. Earth Planet. Sci. Lett. 198, 307–322.
Gao, S., Rundnick, R.L., Yuan, H.L., Liu, X.M., Liu, W.S., Xu, L.W., Ling, L.W., Ayers, H., Wang, X.C., Wang, Q.H., 2004. Recycling lower continent crust in the North China. Nature 432, 892–897. http://dx.doi.org/10.1038/nature03162.
Gao, S., Zhang, J.F., Xu, W.L., Liu, Y.S., 2009. Delamination and destruction of the North China Craton. Chin. Sci. Bull. 54, 3367–3378. http://dx.doi.org/10.1007/s11434-009-0395-9.
Goldfarb, R., Santosh, M., 2014. The dilemma of the Jiaodong gold deposits: are they unique? Geosci. Front. 5, 139–153. http://dx.doi.org/10.1016/j.gsf.2013.11.001.
Goldfarb, R.J., Baker, T., Dubé, B., Groves, D.I., Hart, C.J.R., Gosselin, P., 2005. Distribution, character and genesis of gold deposits in metamorphic terranes. Econ. Geol. 407–450 (100th Anniv. Vol.).
Griffin, W.L., Zhang, A.D., O'Reilly, S.Y., Ryan, C.G., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean Craton. In: Flower, M.F.J., Chung, S.L., Lo, C.H., Lee, T.Y. (Eds.), Mantle Dynamics and Plate Interactions in East AsiaGeodynamics Series 27. American Geophysical Union, Washington DC, pp. 107–126.
Griffin, W.L., O'Reilly, S.Y., Ryan, C.G., 1999. The composition and origin of sub-continental lithospheric mantle. In: Fei, Y., Bertka, C.M., Mysen, B.O. (Eds.), Mantle Petrology: Field Observations and High Pressure ExperimentationGeochem. Soc. Spec. Publ. vol. 6. Univ. Houston, Dept. Chemistry, Houston, TX, pp. 13–45.
Groves, D.I., Santosh, M., 2015. The giant Jiaodong gold province: the key to a unified model for orogenic gold deposits? Geosci. Front. http://dx.doi.org/10.1016/j.gsf.2015.08.002.
Gu, H.O., Xiao, Y., Santosh, M., Li, W.Y., Yang, X., Pack, A., Hou, Z., 2013. Spatial and temporal distribution of Mesozoic adakitic rocks along the Tan-Lu fault, Eastern China: constraints on the initiation of lithospheric thinning. Lithos 177, 352–365.
Guan, K., Luo, Z.K., Miao, L.C., Huang, J.Z., 1998. SHRIMP zircon chronology for Guojialing suite granite in Jiaodong Zhaoye district. Sci. Geol. Sin. 33, 318–328 (in Chinese with English abstract).
Gung, Y., Panning, M., Romanowicz, B., 2003. Global anisotropy and the thickness of continents. Nature 422, 707–711.
Guo, P., Santosh, M., Li, S., 2013. Geodynamics of gold metallogeny in the Shandong Province, NE China: an integrated geological, geophysical and geochemical perspective. Gondwana Res. 24, 1172–1202.
Hames, W., Unger, D., Saunders, J., 2009. George Kamenov Early Yellowstone hotspot magmatism and gold metallogeny. J. Volcanol. Geotherm. Res. 188, 214–224.
Hart, C.J.R., Goldfarb, R.J., Qiu, Y.M., Snee, L., Miller, L.D., Miller, M.L., 2002. Gold deposits of the northern margin of the North China Craton multiple late Paleozoic–Mesozoic mineralizing events. Mineral. Deposita 37, 326–351.
He, C.S., 2010. Seismic evidence for plume and subducting slab in West Yunnan, Southwestern China. Acta Petrol. Sin. 85, 801–840 (English Edition).
He, C.S., Dong, S.W., Chen, X.H., Santosh, M., Li, Q.S., 2014a. Seismic evidence for plume-induced rifting in the Songliao basin of Northeast China. Tectonophysics 627, 171–181. http://dx.doi.org/10.1016/j.tecto.2013.07.015.
He, C.S., Dong, S.W., Chen, X.H., Santosh, M., Li, Q.S., 2014b. Crustal structure and continental dynamics of Central China: a receiver function study and implications for ultrahigh-pressure metamorphism. Tectonophysics 600, 172–181. http://dx.doi.org/10.1016/j.tecto.2013.11.012.
He, C.S., Dong, S.W., Santosh, M., Li, Q.S., Chen, X.H., 2015. Destruction of the north China Craton: a perspective based on receiver function analysis. Geol. J. 50, 93–103. http://dx.doi.org/10.1002/gj.2530.
Heki, K., Mitsui, Y., 2013. Accelerated Pacific plate subduction following interplate thrust earthquakes at the Japan Trench. Earth Planet. Sci. Lett. 363, 44–49. http://dx.doi.org/10.1016/j.epsl.2012.12.031.
Helffrich, G., 2000. Topography of the transition zone seismic discontinuities. Rev. Geophys. 38, 141–158.
Hirose, K., 2002. Phase transitions in pyrolitic mantle around 670-km depth: implications for upwelling of plumes from the lower mantle. J. Geophys. Res. 107. http://dx.doi.org/10.1029/2001JB000597.
Huang, J.L., Zhao, D., 2006. High-resolution mantle tomography of China and surrounding regions. J. Geophys. Res. 111, B09305. http://dx.doi.org/10.1029/2005JB004066.
Huang, X.L., Zhong, J.W., Xu, Y.G., 2012. Two tales of the continental lithospheric mantle prior to the destruction of the North China Craton: insights from Early Cretaceous mafic intrusions in western Shandong, East China. Geochim. Cosmochim. Acta 96, 193–214.
Huerta, A.D., Nyblade, A.A., Reusch, A.M., 2009. Mantle transition zone structure beneath Kenya and Tanzania: more evidence for a deep-seated thermal upwelling in the mantle. Geophys. J. Int. 177, 1249–1255. http://dx.doi.org/10.1111/j.1365-246X.2009.04092.x.
Huo, M.Y., 1991. Atomic structure model of gold and its mineralization mode1. In: Guangchi, T. (Ed.), Gold Economics, l-7. Science Press, Beijing (in Chinese).
Jian, W., Lehmann, B., Mao, J.W., Ye, H.S., Li, Z.Y., He, H.J., Zhang, J.G., Zhang, H., Feng, J.W., 2015. Mineralogy, fluid characteristics, and Re–Os age of the late Triassic Dahu Au–Mo deposit, Xiaoqinling region, central China: evidence for a magmatic–hydrothermal origin. Econ. Geol. 110 (1), 119–145.
Kabete, J.M., Groves, D.I., McNaughton, N.J., Mruma, A.H., 2012. A new tectonic and temporal framework for the Tanzanian shield: implications for gold metallogeny and undiscovered endowment. Ore Geol. Rev. 48, 88–124.
Kawai, K., Yamamoto, S., Tsuchiya, T., Maruyama, S., 2013. The second continent: existence of granitic continental materials around the bottom of the mantle transition zone. Geosci. Front. 4, 1–6.
Kennett, B.L.N., Furumura, T., 2010. Tears or thinning? Subduction structures in the Pacific plate beneath the Japanese Islands. Phys. Earth Planet. Inter. 180, 52–58.
Koppers, A.A.P., 2011. Mantle plumes persevere. Nat. Geosci. 4, 816–817.
Korenaga, J., 2004. Mantle mixing and continental breakup magmatism. Earth Planet. Sci. Lett. 218, 463–473.
Kuritani, T., Kimura, J.I., Ohtani, E., Miyamoto, H., Furuyama, K., 2013. Transition zone origin of potassic basalts from Wudalianchi volcano, northeast China. Lithos 156–159, 1–12.
Lan, T.G., Fan, H.R., Hu, F.F., Tomkins, A.G., Yang, K.F., Liu, Y.S., 2011. Multiple crust–mantle interactions for the destruction of the North China Craton: geochemical and Sr–Nd–Pb–Hf isotopic evidence from the Longbaoshan alkaline complex. Lithos 122, 87–106.
Leahy, A., Barnicoat, A.C., Foster, R.P., Lawrence, S.R., Napier, R.W., 2005. Geodynamic processes that control the global distribution of gold deposits. In: McDonald, I., Boyce, I., Butler, I.B., Herrington, R.J., Polya, D.A. (Eds.), Mineral deposits and Earth Evolution: Geol. Soc. London, Spec. Publ. 248, pp. 119–132
Li, S.R., Santosh, M., 2013. Metallogeny and craton destruction: records from the North China Craton. Ore Geol. Rev. http://dx.doi.org/10.1016/j.oregeorev.2013.03.002.
Li, S.R., Santosh, M., 2014. Metallogeny and craton destruction: records from the North China Craton. Ore Geol. Rev. 56, 376–414.
Li, Q.Z., Chen, Y.J., Zhong, Z.Q., Li, W.L., Li, S.R., Gou, X.D., Jin, B.Y., 2002. Ar–Ar dating on the metallogenesis of the Dongchuang gold deposit in the Xiaoqinling area. Acta Geol. Sin. 76 (4), 488–493.
Li, S.Z., Kusky, T.M., Wang, L., Zhang, G.W., Lai, S.C., Liu, X.C., Dong, S.W., Zhao, G.C., 2007a. Collision leading to multiple-stage large-scale extrusion in the Qinling Orogen: insights from the Mianlue Suture. Gondwana Res. 12 (1–2), 121–143.
Li, H.M., Ye, H.S., Mao, J.W., Wang, D.H., Chen, Y.C., Qu, W.J., Du, A.D., 2007b. Re–Os dating of molybdenites from Au (Mo) deposits in Xiaoqinling Gold ore district and its geological significance. Mineral Deposits 26 (4), 417–424 (in Chinese with English abstract).
Li, N., Chen, Y.J., Fletcher, I.R., Zeng, Q.T., 2011. Triassic mineralization with Cretaceous overprint in the Dahu Au–Mo deposit, Xiaoqinling gold province: constraints from SHRIMP monazite U–Th–Pb geochronology. Gondwana Res. 20, 543–552.
Li, J.W., Bi, S.J., Selby, D., Chen, L., Vasconcelos, P., Thiede, D., Zhou, M.F., Zhao, X.F., Li, Z.K., Qiu, H.N., 2012a. Giant Mesozoic gold provinces related to the destruction of the North China craton. Earth Planet. Sci. Lett. 349-350, 26–37.
Li, S.Z., Zhao, G.C., Dai, L.M., Zhou, L.H., Liu, X., Suo, Y.H., Santosh, M., 2012b. Cenozoic faulting of the Bohai Bay Basin and its bearing on the destruction of the eastern North China Craton. J. Asian Earth Sci. 47, 80–93.
Li, S.R., Santosh, M., Zhang, H.F., Shen, J.F., Dong, G.C., Wang, J.Z., Zhang, J.Q., 2013. Inhomogeneous lithospheric thinning in the central North China Craton: zircon U–Pb and S–

He–Ar isotopic record from magmatism and metallogeny in the Taihang Mountains. Gondwana Res. 23, 141–160.
Li, S.R., Santosh, M., Zhang, H.F., Luo, J.Y., Zhang, J.Q., Li, C.L., Song, J.Y., Zhang, X.B., 2014. Metallogeny in response to lithospheric thinning and craton destruction: geochemistry and U–Pb zircon chronology of the Yixingzhai gold deposit, central North China Craton. Ore Geol. Rev. 56, 457–471.
Lin, J.Q., Tan, D.J., Yu, X.F., Xu, W.L., Li, B.R., Li, Y., 1995. Genesis and metallogeny model of Guilaizhuang gold deposit. J. Changchun Univ. Earth Sci. 25, 286–293 (in Chinese with English abstract).
Ling, W.L., Duan, R.C., Xie, X.J., Zhang, Y.Q., Zhang, J.B., Cheng, J.P., Liu, X.M., Yang, H.M., 2009. Contrasting geochemistry of the Cretaceous volcanic suites in Shandong province and its implications for the Mesozoic lower crust delamination in the eastern North China craton. Lithos 113, 640–658.
Liu, Y.K., Chang, X., 2001. 3-D tomographic images and deep ore-control in northern margin of the North China plate. Resour. Geol. 51, 401–406.
Luo, Z.K., Qiu, Y.S., Guan, K., Miao, L.C., Qiu, Y.M., McNaughton, N.J., Groves, D.I., 2001. SHRIMP U–Pb dating on Zircon from Yu'erya and Niuxinshan granite intrusions in Eastern Hebei Provence. Bull. Mineral. Petrol. Geochem. 20, 278–285 (In Chinese with English abstract).
Luo, Z.K., Guan, K., Miao, L.C., 2002. Dating of the dykes and altered sericite in Jiapigou gold ore belt, Jilin province and its gold ore formation age. Geoscience 16, 19–25 (In Chinese with English abstract).
Lustrino, M., 2005. How the delamination and detachment of lower crust can influence basaltic magmatism. Earth Sci. Rev. 72, 21–38.
Ma, Q., Zheng, J.P., Griffin, W.L., Zhang, M., Tang, H.Y., Su, Y.P., Ping, X.Q., 2012. Triassic "adakitic" rocks in an extensional setting (North China): melts from the cratonic lower crust. Lithos 149, 159–173.
Mao, J.W., Li, Y.Q., Goldfarb, R., He, Y., Zaw, K., 2003. Fluid inclusion and noble gas studies of the Dongping gold deposit, Hebei Province, China: a mantle connection for mineralization? Econ. Geol. 98, 517–534.
Mather, K.A., Pearson, D.G., McKenzie, D., Kjarsgaard, B.A., Priestley, K., 2011. Constraints on the depth and thermal history of cratonic lithosphere from peridotite xenoliths, xenocrysts and seismology. Lithos 125, 729–742.
Menzies, M.A., Xu, Y.G., 1998. Geodynamics of the North China Craton. In: Flower, M.F.J., Chung, S.L., Lo, C.H., Lee, T.Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. AGU, Geodynamics Series 27, pp. 155–165.
Menzies, M.A., Fan, W.M., Zhang, M., 1993. Palaeozoic and Cenozoic lithoprobes and the loss of >120 km of Archaean lithosphere Sino-Korean Craton, China. Magmatic Processes and Plate Tectonics 76. Geological Society London, pp. 71–81.
Menzies, M.A., Xu, Y., Zhang, H., Fan, W., 2007. Integration of geology, geophysics and geochemistry: a key to understanding the North China Craton. Lithos 96, 1–21.
Miao, L.C., Qiu, Y.M., McNaughton, N.J., Groves, D.I., Zhai, Y.S., Fan, W.M., Zhai, M.G., Guan, K., 2002. SHRIMP U–Pb zircon geochronology of granitoids from Dongping area, Hebei Province, China: constraints on tectonic evolution and geodynamic setting for gold metallogeny. Ore Geol. Rev. 19, 187–204.
Miao, L.C., Fan, W.M., Zhai, M.G., Qiu, Y.M., McNaught, N.J., Groves, D.I., 2003. Zircon SHRIMP U–Pb geochronology of the granitoid intrusions from Jinchanggouliang-Erdaogou gold orefield and its significance. Acta Petrol. Sin. 19, 71–80 (In Chinese with English abstract).
Miller, M.S., Gorbatov, A., Kennett, B.L.N., 2005. Heterogeneity within the subducting Pacific slab beneath the Izu–Bonin–Mariana arc: evidence from tomography using 3D ray tracing inversion techniques. Earth Planet. Sci. Lett. 235, 331–342.
Miyazaki, T., Kagami, H., Mohan, V.R., Shuto, K., Morikiyo, T., 2003. Enriched subcontinental lithospheric mantle in the northern part of the South Indian Granulite Terrain: evidence from Yelagiri and Sevattur syenite plutons, Tamil Nadu, South India. Gondwana Res. 6, 585–594.
Morgan, W.J., 1971. Convection plumes in the lower mantle. Nature 230, 42–43.
Mushkin, A., Navon, O., Halicz, L., Hartmann, G., Stein, M., 2003. The petrogenesis of Atype magmas from the Amram Massif, Southern Israel. J. Petrol. 44, 815–832.
Nie, F.J., Jiang, S.H., Liu, Y., Hu, P., 2005. Re-discussion on the time limitation of gold mineralization occurring within the Hadamenggou deposit, south-central Inner Mongolia autonomous region. Acta Petrol. Sin. 21, 1719–1728 (In Chinese with English abstract).
Niu, Y.L., 2005. Generation and evolution of basaltic magmas: some basic concepts and a new view on the origin of Mesozoic–Cenozoic basaltic volcanism in Eastern China. Geol. J. China Univ. 11, 9–46.
Niu, S.Y., Li, H.Y., Sun, A.Q., Wang, B.D., Xu, C.S., Xie, R.B., Yang, Z.H., Bi, F.K., 2002. Theory on Mantle-Branch Structures and Mineral Prospecting Practice. Geological Publishing House, Beijing, p. 243 (Chinese).
Niu, S.Y., Hou, Q.L., Hou, Z.Q., Sun, A.Q., Wang, B.D., Li, H.Y., Xu, C.S., 2003. Cascaded evolution of mantle plumes and metallogenesis of core- and mantle-derived elements. Acta Geol. Sin. 77, 522–536.
Niu, S.Y., Sun, A.Q., Wang, B.D., Nie, F.J., Jiang, S.H., Shao, J.A., Guo, L.J., Liu, J.M., 2009. Mantle branch structure in the South-Central segment of the Da Hinggan Mts., Inner Mongolia and its ore-controlling role. Acta Geol. Sin. 83, 1148–1162.
Niu, S.Y., Sun, A.Q., Zhang, J.Z., Ma, B.J., Wang, B.D., Chen, C., Zhang, F.X., Liu, C., Zhang, X.F., 2012. Analysis of the ore-controlling role of Guojiadian mantle branch structure, Northwest Shandong Peninsula, China. Chin. J. Geochem. 31, 414–423.
Peng, Z.C., Zartman, R.E., Futa, K., Chen, D., 1986. Pb, Sr and Nd isotopic systematics and chemical characteristics of Cenozoic basalts eastern China. Chem. Geol. 59, 3–33.
Peng, P., Zhai, M.G., Guo, J.H., Zhang, H.F., Zhang, Y.B., 2008. Petrogenesis of Triassic post-collisional syenite plutons in the Sino-Korean Craton: an example from North Korea. Geol. Mag. 145, 637–647.
Pirajno, F., Hoatson, D.M., 2012. A review of Australia's large igneous provinces and associated mineral systems: implications for mantle dynamics through geological time. Ore Geol. Rev. 48, 2–54.
Pirajno, F., Santosh, M., 2015. Mantle plumes, supercontinents, intracontinental rifting and mineral systems. Precambrian Res. 259, 243–261.
Pirajno, F., Seltmann, R., Yang, Y., 2011. A review of mineral systems and associated tectonic settings of northern Xinjiang, NW China. Geosci. Front. 2, 157–185.
Qiu, Y.S., 1989. Regional geological setting of gold deposits in the Zhaoye gold belt in Shandong ProvinceLiaoning Science and Technology Publishing House, Shenyang. p. 153 (in Chinese with English abstract).
Qiu, Y., Groves, D.I., McNaughton, N.G., Wang, L., Zhou, T., 2002. Nature, age and tectonic setting of granitoid-hosted, orogenic gold deposits of the Jiaodong peninsula, eastern North China Craton. Mineral. Deposita 37, 283–309.
Ren, F.G., Li, W.M., 1996. Ore-Forming Geological Conditions and Models for ore Searching and ore Evolution of Gold Deposit in Xiong'Ershan-Xiaoshan Areas. Geological Publishing House, Beijing, pp. 1–136 (In Chinese).
Replumaz, A., Guillot, S., Villaseñor, A., Negredo, A.M., 2013. Amount of Asian lithospheric mantle subducted during the India/Asia collision. Gondwana Res. 24, 936–945.
Rino, S., Kon, Y., Sato, W., Maruyama, S., Santosh, M., Zhao, D., 2008. The Grenvillian and Pan-African orogens: world's largest orogenies through geologic time, and their implications on the origin of superplume. Gondwana Res. 14, 51–72.
Rogers, J.J.W., Santosh, M., 2009. Tectonics and surface effects of the supercontinent Columbia. Gondwana Res. 15, 373–380.
Safonova, I.Y., Santosh, M., 2014. Accretionary complexes in the Asia-Pacific region: tracing archives of ocean plate stratigraphy and tracking mantle plumes. Gondwana Res. 25, 126–158.
Santosh, M., 2010. Assembling North China Craton within the Columbia supercontinent: the role of double-sided subduction. Precambrian Res. 178, 149–167.
Santosh, M., Maruyama, S., Omori, S., 2009. A fluid factory in solid Earth. Lithosphere 1, 29–33.
Santosh, M., Zhao, D.P., Kusky, T.M., 2010. Mantle dynamics of the Paleoproterozoic North China Craton: a perspective based on seismic tomography. J. Geodyn. 49, 39–53.
Smith, I.E.M., White, A.J.R., Chappell, B.W., Eggleton, R.A., 1988. Fractionation in a zoned monzonite pluton: Mount Dromedary, southeastern Australia. Geol. Mag. 125, 273–284.
Song, Y., Jiang, S.H., Bagas, L., Li, C., Hu, J.Z., Zhang, Q., Zhou, W., Ding, H.Y., 2014. The geology and geochemistry of Jinchangyu gold deposit, North China Craton: implications for metallogenesis and geodynamic setting. Ore Geol. Rev. http://dx.doi.org/10.1016/j.oregeorev.2014.10.031.
Sun, A.Q., Hu, H.B., Niu, S.Y., Mao, J.W., Wang, B.D., Li, Y.P., Wang, L.M., 2006. Characteristics of mantle branch structure in western Shandong and its roles in minerogenesis and ore-controlling. Chin. J. Geochem. 25, 340–353.
Sun, W.D., Ding, X., Hu, Y.H., Li, X.H., 2007. The golden transformation of the Cretaceous plate subduction in the west Pacific. Earth Planet. Sci. Lett. 262, 533–542.
Tang, K.F., Li, J.W., 2009. Mineralization characteristics, age, and genesis of the Qianhe gold deposit in the Songxian city, Henan province. Acta Mineral. Sin. S1, 136–137 (In Chinese).
Tang, Y.H., Yuan, W.M., Han, C.M., Dong, J.Q., Wang, S.C., 2003. Fission track age of the Yuerya gold deposit. Acta Geosci. Sin. 24 (6), 573–578 (in Chinese with English abstract).
Tang, Y.J., Zhang, H.F., Ying, J.F., Su, B.X., Chu, Z.Y., Xiao, Y., Zhao, X.M., 2013a. Highly heterogeneous lithospheric mantle beneath the Central Zone of the North China Craton evolved from Archean mantle through diverse melt refertilization. Gondwana Res. 23, 130–140.
Tang, Y.J., Zhang, H.F., Santosh, M., Ying, J.F., 2013b. Differential destruction of the North China Craton: a tectonic perspective. J. Asian Earth Sci. http://dx.doi.org/10.1016/j.jseaes.2012.11.047.
Tang, Y.J., Zhang, H.F., Santosh, M., Ying, J.F., 2013c. Differential destruction of the North China Craton: a tectonic perspective. J. Asian Earth Sci. 78, 71–82.
Tchameni, R., Mezger, K., Nsifa, N.E., Pouclet, A., 2001. Crustal origin of Early Proterozoic syenites in the Congo Craton (NTEM Complex), south Cameroon. Lithos 57, 23–42.
Thorkelson, D.J., Taylor, R.P., 1989. Cordilleran slab windows. Geology 17, 833–836.
Tian, Y., Zhao, D.P., 2011. Destruction mechanismof the North China Craton: insight from P and S wave mantle tomography. J. Asian Earth Sci. 42, 1132–1145.
Tian, Y., Zhao, D.P., Sun, R.M., Teng, J.W., 2009. Seismic imaging of the crust and upper mantle beneath the North China Craton. Phys. Earth Planet. Inter. 172, 169–182.
Upton, P., Craw, D., 2014. Extension and gold mineralisation in the hanging walls of active convergent continental shear zones. J. Struct. Geol. 64, 135–148.
Wang, Z.B., Gao, C.B., 2001. Luxi Guilaizhuang gold deposits genesis. Contrib. Geol. Miner. Resour. Res. 16, 247–251 (in Chinese with English abstract).
Wang, L.G., Qiu, Y.M., McNaughton, N.J., Groves, D.I., Luo, Z.K., Huang, J.Z., Miao, L.C., Liu, Y.K., 1998. Constraints on crustal evolution and gold metallogeny in the northwestern Jiaodong peninsula, China, from SHRIMP U–Pb zircon studies of granitoids. Ore Geol. Rev. 13, 275–291.
Wang, Q., Xu, J.F., Zhao, Z.H., Bao, Z.W., Xu, W., Xiong, X.L., 2004. Cretaceous highpotassium intrusive rocks in the Yueshan–Hongzhen area of east China: adakites in an extensional tectonic regime within a continent. Geochem. J. 38, 417–434.
Wang, R.H., Jing, C.Z., Li, J.C., 2008. ^{40}Ar–^{39}Ar isotopic dating for Paishanlou gold deposit and its geological implication. J. Northeast. Univ. Nat. Sci. 29, 1482–1485.
Wang, H., Wu, Y.B., Gao, S., Liu, X.C., Liu, Q., Qin, Z.W., Xie, S.W., Zhou, L., Yang, S.H., 2013. Continental origin of eclogites in the North Qinling terrane and its tectonic implications. Precambrian Res. 230, 13–30.
Wang, H.L., van Hunen, J., Pearson, D.G., Allen, M.B., 2014. Craton stability and longevity: the roles of composition-dependent rheology and buoyancy. Earth Planet. Sci. Lett. 391, 224–233.
Wang, W., Liu, S.W., Santosh, M., Deng, Z.B., Guo, B., Zhao, Y., 2015. Shuanhong Zhang, Pengtao Yang, Xiang Bai, Rongrong Guo, Late Paleoproterozoic geodynamics of the North China Craton: geochemical and zircon U–Pb–Hf records from a volcanic suite in the Yanliao rift. Gondwana Res. 27, 300–325.

Wei, W., Xu, J.D., Zhao, D.P., Shi, Y.L., 2012. East Asia mantle tomography: new insight into plate subduction and intraplate volcanism. J. Asian Earth Sci. 60, 88–103.
Weis, D., Garcia, M.O., Rhodes, J.M., Jellinek, M., Scoates, J.S., 2011. Role of the deep mantle in generating the compositional asymmetry of the Hawaiian mantle plume. Nat. Geosci. 4, 831–838.
Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. Contrib. Mineral. Petrol. 95, 407–419.
Wilde, S., Zhou, X., Nemchin, A.A., Sun, M., 2003. Mesozoic crust–mantle interaction beneath the North China Craton: a consequence of the dispersal of Gondwanaland and accretion of Asia. Geology 31, 817–820.
Wilson, J.T., 1963. A possible origin of the Hawaiian Islands. Can. J. Phys. 41, 863–870.
Wu, F.Y., Sun, D.Y., 1999. The Mesozoic magmatism and lithospheric thinning in Eastern China. J. Changchun Univ. Sci. Technol. 29, 313–318 (in Chinese with English abstract).
Wu, F.Y., Lin, J.Q., Wilde, S.A., Zhang, X.O., Yang, J.H., 2005a. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth Planet. Sci. Lett. 233, 103–119.
Wu, F.Y., Yang, J.H., Wilde, S.A., Zhang, X.O., 2005b. Geochronology, petrogenesis and tectonic implications of Jurassic granites in the Liaodong Peninsula, NE China. Chem. Geol. 221, 127–156.
Wu, F.Y., Lin, J.Q., Wilde, S.A., Zhang, X.O., Yang, J.H., 2005c. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth Planet. Sci. Lett. 103–119.
Wu, F.Y., Xu, Y.G., Gao, S., Zheng, J.P., 2008. Lithospheric thinning and destruction of the North China Craton. Acta Petrol. Sin. 24, 1145–1174.
Xu, Y.G., 2001. Thermo-tectonic destruction of the Archaean lithospheric keel beneath eastern China: evidence, timing and mechanism. Phys. Chem. Earth 26, 747–757.
Xu, Y.G., 2004. Lithospheric thinning beneath North China: a temporal and spatial perspective. Geol. J. China Univ. 10, 324–331.
Xu, Y.G., 2007. Diachronous lithospheric thinning of the North China Craton and formation of the Daxin'anling–Taihangshan gravity lineament. Lithos 96, 281–298.
Xu, P.F., Zhao, D.P., 2009. Upper-mantle velocity structure beneath the North China Craton: implications for lithospheric thinning. Geophys. J. 177, 1279–1283. http://dx.doi.org/10.1111/j.1365-246X.2009.04120.x.
Xu, J.F., Shinjo, R., Defant, M.C., Wang, Q., Rapp, R.P., 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust? Geology 30, 1111–1114.
Xu, Y.G., Li, H.Y., Pang, C.J., He, B., 2009. The timing and duration of the destruction of the North China Craton. Chin. Sci. Bull. 54, 3379–3396.
Xu, Z., Zhao, Z.F., Zheng, Y.F., 2012. Slab–mantle interaction for thinning of cratonic lithospheric mantle in North China: geochemical evidence from Cenozoic continental basalts in central Shandong. Lithos 146-147, 202–217.
Yang, Q.Y., Santosh, M., 2015a. Early Cretaceous magma flare-up and its implications on gold mineralization in the Jiaodong Peninsula, China. Ore Geol. Rev. 65, 626–642.
Yang, Q.Y., Santosh, M., 2015b. Charnockite magmatism during a transitional phase: implications for late Paleoproterozoic ridge subduction in the North China Craton. Precambrian Res. 261, 188–216.
Yang, J.H., Wu, F.Y., 2009. Triassic magmatism and its relation to decratonization in the eastern North China Craton. Sci. China Earth Sci. 52, 1319–1330.
Yang, J.H., Wu, F.Y., Wilde, S.A., 2003. A review of the geodynamic setting of large-scale Late Mesozoic gold mineralization in the North China Craton: an association with lithospheric thinning. Ore Geol. Rev. 23, 125–152.
Yang, Q.Y., Santosh, M., Shen, J.F., Li, S.R., 2014. Juvenile vs. recycled crust in NE China: Zircon U–Pb geochronology, Hf isotope and an integrated model for Mesozoic gold mineralization in the Jiaodong Peninsula. Gondwana Res. 25, 1445–1468. http://dx.doi.org/10.1016/j.gr.2013.06.003.
Yang, Q.Y., Santosh, M., Collins, A.S., Teng, X.M., 2015. Microblock amalgamation in the North China Craton: Evidence from Neoarchaean magmatic suite in the western margin of the Jiaoliao Block. Gondwana Res. http://dx.doi.org/10.1016/j.gr.2015.04.002.
Yao, J.M., Zhao, T.P., LI, J., Sun, Y.L., Yuan, Z.L., Chen, W., Han, J., 2009. Molybdenite Re–Os age and Zircon U–Pb age and Hf Isotope Geochemistry of the Qiyugou Gold System, Henan.
Yu, Y.G., Wentzcovitch, R.M., Vinograd, V.L., Angel, R.J., 2011. Thermodynamic properties of $MgSiO_3$ majorite and phase transitions near 660 km depth in $MgSiO_3$ and Mg_2SiO_4: a first principles study. J. Geophys. Res. 116. http://dx.doi.org/10.1029/2010JB007912.
Zandt, G., Ammon, C.J., 1995. Continental crust composition constrained by measurements of crustal Poisssons ratio. Nature 374, 152–154.
Zeng, Q.D., Shen, Y.C., Liu, T.B., Li, G.M., Zhang, Q.R., Sun, X.Y., 1999. Subvolcanic complex and gold metallogenic series in western region of Linyi, Shandong Province. Geol. Rev. 45, 572–576 (in Chinese with English abstract).
Zhai, M.G., Santosh, M., 2011. The early Precambrian odyssey of the North China Craton: a synoptic overview. Gondwana Res. 20, 6–25.
Zhai, M.G., Santosh, M., 2013. Metallogeny of the North China Craton: link with secular changes in the evolving Earth. Gondwana Res. 275–297.
Zhai, Y.S., Miao, L.C., Xiang, Y.C., Deng, J., Wang, J.P., 2002. Preliminary discussion on gold ore forming system in greenstone belt-type of North China Craton. Earth Sci. 27 (5), 522–531 (In Chinese with English abstract).
Zhai, M.G., Fan, Q.C., Zhang, H.F., Sui, J.L., Shao, J.A., 2007. Lower crustal processes leading to Mesozoic lithospheric thinning beneath eastern North China: underplating, replacement and delamination. Lithos 96, 36–54.
Zhang, H.F., 2005. Transformation of lithosphericmantle through peridotite-melt reaction: a case of Sino-Korean craton. Earth Planet. Sci. Lett. 237, 768–780.
Zhang, H.F., Sun, M., Zhou, X.H., Fan, W.M., Zhai, M.G., Yin, J.F., 2002. Mesozoic lithosphere destruction beneath the North China Craton: evidence from major-trace element and Sr–Nd–Pb isotope studies of Fang Cheng basalts. Contrib. Mineral. Petrol. 144, 241–253.
Zhang, X.O., Cawood, P., Wilde, S., Liu, R., Song, H., Li, W., Snee, L., 2003a. Geology and timing of mineralization at the Cangshang gold deposit, north-western Jiaodong Peninsula, China. Mineral. Deposita 141–153.
Zhang, L.C., Shen, Y.C., Lin, T.B., Zeng, Q.D., Li, G.M., Li, H.M., 2003b. ^{40}Ar–^{39}Ar and Rb–Sr isochron dating of the gold deposits on northern margin of the Jiaolai Basin, Shandong, China. Sci. China Ser. D Earth Sci. 46, 708–718 (in Chinese with English abstract).
Zhang, X.H., Liu, Q., Ma, Y.J., Wang, H., 2005. Geology, fluid inclusions, isotope geochemistry, and geochronology of the Paishanlou shear zone-hosted gold deposit, North China Craton. Ore Geol. Rev. 26, 325–348.
Zhang, H.F., Ying, J.F., Tang, Y.J., Li, X.H., Feng, C., Santosh, M., 2011. Phanerozoic reactivation of the Archean North China Craton through episodic magmatism: evidence from zircon U–Pb geochronology and Hf isotopes from the Liaodong Peninsula. Gondwana Res. 19, 446–459.
Zhang, H.F., Chen, L., Santosh, M., Menzies, A., 2012a. Construction and destruction of cratons: preface. Gondwana Res. 23, 1–3.
Zhang, H.F., Sun, Y.L., Tang, Y.J., Xiao, Y., Zhang, W.H., Zhao, X.M., Santosh, M., Menzies, M.A., 2012b. Melt–peridotite interaction in the Pre-Cambrian mantle beneath the western North China Craton: petrology, geochemistry and Sr, Nd and Re isotopes. Lithos 149, 100–114.
Zhang, H.F., Yang, Y.H., Santosh, M., Zhao, X.M., Ying, J.F., Xiao, Y., 2012c. Evolution of the Archean and Paleoproterozoic lower crust beneath the Trans-North China Orogen and the Western Block of the North China Craton. Gondwana Res. 22, 73–85.
Zhang, R., Pian, H., Santosh, M., Zhang, S., 2015. The history and economics of gold mining in China. Ore Geol. Rev. 65, 718–727.
Zhao, D., 2001. Seismic structure and origin of hotspots and mantle plumes. Earth Planet. Sci. Lett. 192, 251–265.
Zhao, D., 2004. Global tomographic images of mantle plumes and subducting slabs: insight into deep earth dynamics. Phys. Earth Planet. Inter. 146, 3–34.
Zhao, G.C., Zhai, M.G., 2013. Lithotectonic elements of Precambrian basement in the North China Craton: review and tectonic implications. Gondwana Res. 23, 1207–1240.
Zhao, L., Zheng, T.Y., 2005. Using shear wave splitting measurement to investigate the upper mantle anisotropy beneath the North China Craton: distinct variation from east to west. Geophys. Res. Lett. 32, L1039. http://dx.doi.org/10.1029/2005GL022585.
Zhao, D., Hasegawa, A., Horiuchi, S., 1992. Tomographic imaging of P and S wave velocity structure beneath northeastern Japan. J. Geophys. Res. 97, 19,909–19,928. http://dx.doi.org/10.1029/92JB00603.
Zhao, D., Hasegawa, A., Kanamori, H., 1994. Deep structure of Japan subduction zone as derived from local, regional and teleseismic events. J. Geophys. Res. 99, 22,313–22,329.
Zhao, G.C., Wilde, S.A., Cawood, P.A., Sun, M., 2001. Archean blocks and their boundaries in the North China Craton: lithological, geochemical, structural and P–T path constraints and tectonic evolution. Precambrian Res. 107, 45–73.
Zhao, D., Mishra, O., Sanda, R., 2002. Influence of fluids and magma on earthquakes: seismological evidence. Phys. Earth Planet. In. 132, 249–267. http://dx.doi.org/10.1016/S0031-9201(02)00082–1.
Zhao, Z.F., Zheng, Y.F., Zhao, Z.F., 2003. Zircon U–Pb age, element and isotope geochemistry of Mesozoic mafic–ultramafic rocks at Shacun and Jiaziyan in north Dabie (in Chinese with English abstract). Geol. J. China Univ. 9, 139–162.
Zhao, Z.F., Zheng, Y.F., Wei, C.S., Wu, Y.B., 2004. Zircon isotope evidence for recycling of subducted continental crust in postcollisional granitoids from the Dabie terrane in China. Geophys. Res. Lett. 31, L226020. http://dx.doi.org/10.1029/2004GL021061.
Zhao, G.C., Sun, M., Wilde, S.A., Li, S.Z., 2005. Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. Precambrian Res. 136, 177–202.
Zhao, G.C., He, Y., Sun, M., 2009. The Xiong'er volcanic belt at the southern margin of the North China Craton: petrographic and geochemical evidence for its outboard position in the Paleo-Mesoproterozoic Columbia Supercontinent. Gondwana Res. 16, 170–181.
Zhao, H.X., Jiang, S.Y., Frimmel, H.E., Dai, B.Z., Ma, L., 2012. Geochemistry, geochronology and Sr–Nd–Hf isotopes of two Mesozoic granitoids in the Xiaoqinling gold district: implication for large-scale lithospheric thinning in the North China Craton. Chem. Geol. 294-295, 173–189.
Zheng, J.P., 2009. Comparison of mantle-derived materials from different spatiotemporal settings: implications for destructive and accretional processes of the North China Craton. Chin. Sci. Bull. 54, 3397–3416.
Zheng, Y.F., Wu, F.Y., 2009. Growth and reworking of cratonic lithosphere. Chin. Sci. Bull. 54, 3347–3353.
Zheng, J.P., O'Reilly, S.Y., Griffin, W.L., Lu, F.X., Zhang, M., 1998. Nature and evolution of Cenozoic lithospheric mantle beneath Shandong peninsula, Sino-Korean craton, eastern China. Int. Geol. Rev. 40, 471–499.
Zheng, X.F., Yao, Z.X., Liang, J.H., Zheng, J., 2010. The role played and opportunities provided by IGP DMC of China National Seismic Network in Wenchuan earthquake disaster relief and researches. Bull. Seismol. Soc. Am. 100 (5B), 2866–2872.
Zhou, H., Clayton, R., 1990. P and S wave travel-time inversions for subducting slab under the island arcs of the northwest Pacific. J. Geophys. Res. 95, 6829–6851.
Zhou, J.X., Zhou, J.S., 2006. Cenozoic deformational regimes of Bohai Bay Basin: physical modelling and discussion. Sci. China Ser. D 36 (6), 507–519.
Zorin, Y.A., Turutanov, E.K., Kozhevnikov, V.M., Rasskazov, S.V., Ivanov, A.V., 2006. Cenozoic upper mantle plumes in East Siberia and Central Mongolia and subduction of the Pacific Plate. Geology 409, 723–726.