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Focus paper

The dilemma of the Jiaodong gold deposits: Are they unique?

Richard J. Goldfarb [a,b,c], M. Santosh [b,*]

[a] U.S. Geological Survey, Box 25046, MS 973, Denver Federal Center, Denver, CO 80225-0046, USA
[b] State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
[c] Centre for Exploration Targeting, School of Earth and Geographical Sciences, University of Western Australia, Crawley, Western Australia 60094, Australia

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ABSTRACT

The ca. 126–120 Ma Au deposits of the Jiaodong Peninsula, eastern China, define the country's largest gold province with an overall endowment estimated as >3000 t Au. The vein and disseminated ores are hosted by NE- to NNE-trending brittle normal faults that parallel the margins of ca. 165–150 Ma, deeply emplaced, lower crustal melt granites. The deposits are sited along the faults for many tens of kilometers and the larger orebodies are associated with dilatational jogs. Country rocks to the granites are Precambrian high-grade metamorphic rocks located on both sides of a Triassic suture between the North and South China blocks. During early Mesozoic convergent deformation, the ore-hosting structures developed as ductile thrust faults that were subsequently reactivated during Early Cretaceous "Yanshanian" intracontinental extensional deformation and associated gold formation.

Classification of the gold deposits remains problematic. Many features resemble those typical of orogenic Au including the linear structural distribution of the deposits, mineralization style, ore and alteration assemblages, and ore fluid chemistry. However, Phanerozoic orogenic Au deposits are formed by prograde metamorphism of accreted oceanic rocks in Cordilleran-style orogens. The Jiaodong deposits, in contrast, formed within two Precambrian blocks approximately 2 billion years after devolatilization of the country rocks, and thus require a model that involves alternative fluid and metal sources for the ores. A widespread suite of ca. 130–123 Ma granodiorites overlaps temporally with the ores, but shows a poor spatial association with the deposits. Furthermore, the deposit distribution and mineralization style is atypical of ores formed from nearby magmas. The ore concentration requires fluid focusing during some type of sub-crustal thermal event, which could be broadly related to a combination of coeval lithospheric thinning, asthenospheric upwelling, paleo-Pacific plate subduction, and seismicity along the continental-scale Tan-Lu fault. Possible ore genesis scenarios include those where 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. Both the sulfur and gold could be sourced from either the oceanic sediments or the serpentinized mantle. A better understanding of the architecture of the paleo-Pacific slab during Early Cretaceous below the eastern margin of China is essential to determination of the validity of possible models.

1. Introduction

The Early Cretaceous gold deposits of the Jiaodong Peninsula, on the eastern side of the North China block, define China's largest gold province (Figs. 1 and 2). Their origin continues to be problematic and controversial (Goldfarb et al., 2013). Based upon their structural setting, mineralization style, and ore fluid geochemistry, one of us classified these as orogenic gold deposits (e.g., Goldfarb et al., 2001, 2005, 2007), as also was emphasized by Zhou and Lu (2000). However, the tectonic environment and metamorphic

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[*] Corresponding author. China University of Geosciences, School of Earth Sciences and Resources, State Key Laboratory of Geological Processes and Mineral Resources, Beijing 100083, China. Tel.: +86 10 82322283.
E-mail addresses: santosh@cugb.edu.cn, msantosh.gr@gmail.com (M. Santosh).

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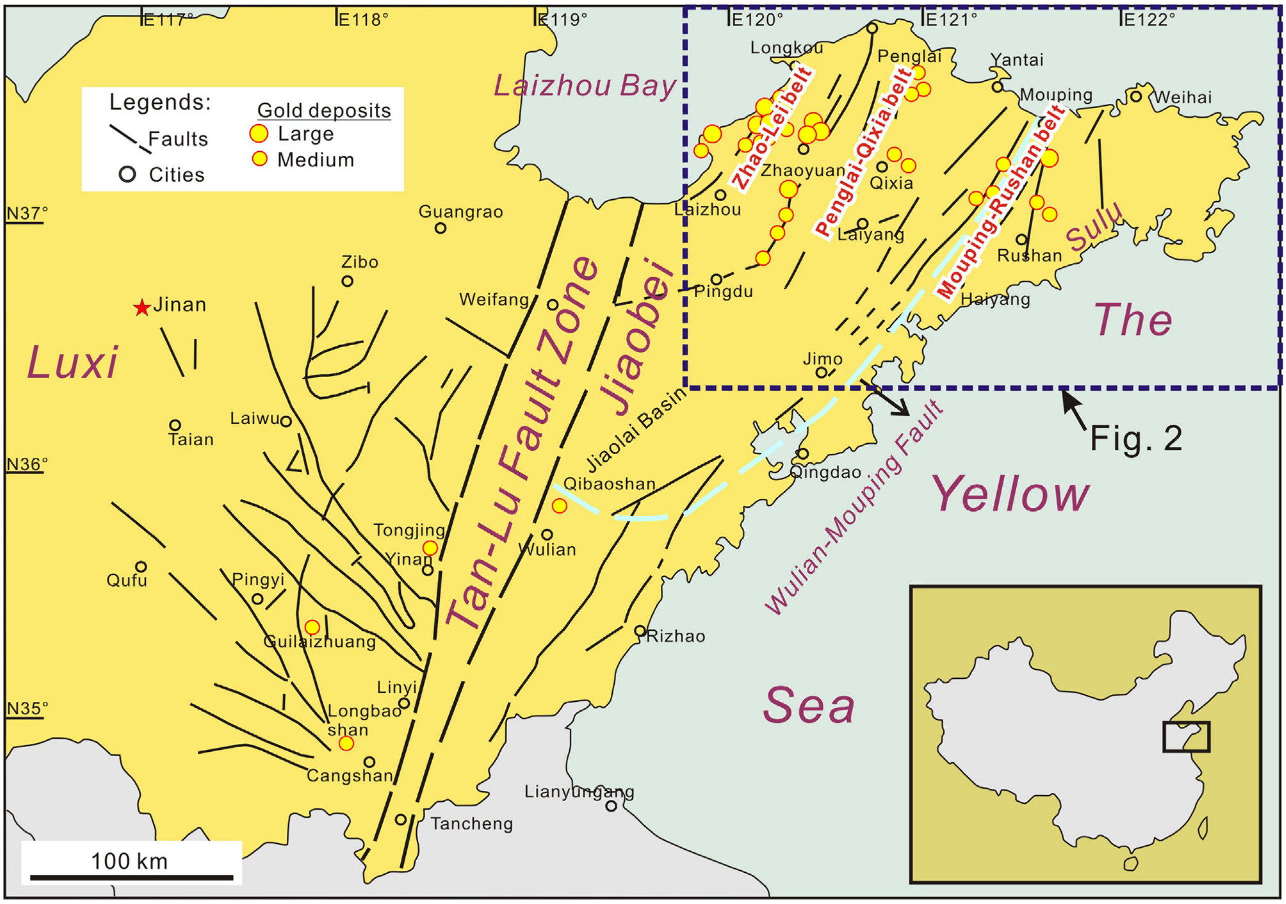

Figure 1. The eastern side of the North China block, as well as part of the South China block that was translated east of the Wulian-Mouping fault, and the distribution of the main gold deposits. The majority of the deposits are hosted by NNE-trending faults on the western side of the Jiaodong fault zone. The faults were originally Jurassic compressive thrust zones that were reactivated as normal faults during widespread Late Jurassic–Early Cretaceous extension. Modified after Gu et al. (2013).

setting of the Jiaodong deposits are unique relative to the accepted model for orogenic gold deposits (e.g., Groves et al., 1998), such that the other one of us considers these world-class gold deposits as a class of unique "Jiaodong-type" gold deposits (e.g., Zhai et al., 2004; Zhai and Santosh, 2013).

In this overview, we try to address and resolve the opposing models by first stating the basic and well-accepted geological and geochemical features of the Jiaodong gold deposits. We attempt to point out what conclusions related to ore genesis can and cannot be drawn from the existing data. The results of this approach will better constrain the plausible models for ore formation and help guide future research and exploration directions. From detailed studies in the fields of economic geology and related disciplines, we recognize that most ore deposits form from well-explained geological processes and therefore they can be classified by mineral deposit models into common ore deposit types (e.g., Cox et al., 1986). Nevertheless, the genesis of some relatively unique giant gold systems remain controversial, including the great conglomerate-hosted gold ores of the Witwatersrand basin in South Africa (Frimmel et al., 2005; Law and Phillips, 2005) and those deposits along the North American craton margin of the Carlin gold province in Nevada, USA (Cline et al., 2005). The giant gold deposits of Jiaodong in China appear to be another such example.

2. Resource and goldfields

Reliable resource and reserve data for the Jiaodong gold province in eastern Shandong province are lacking. The mining history of the Jiaodong lodes dates back to at least the early Sui dynasty, more than 1400 years ago. Various reports and papers have suggested that gold mined from Jiaodong may have accounted for 40% of China's annual production in the mid 1990s, about 30% in 2005, and perhaps 25% today. Guo et al. (2013) reported that there are 159 active mines in the gold province and they produce, at a minimum, a combined 30 tonnes (t) Au per year. Annual production could be significantly more, however, because Shandong Gold Corp. alone has current production of about 28 t Au per year from its three mines in the province, with total reserves of the province now estimated at 2300 t Au (China Daily, October, 28, 2012). At least seven of the active mines in the province contain reserves of >100 t Au. Shandong Gold Corp. plans to increase annual production from its operations to 100 t Au by the end of the decade. We estimate that perhaps 500 t Au have been recovered to-date, assuming about 30–50 t of production per year since the early 2000s when an estimated 180–200 t Au past production was reported. The overall endowment of at least 3000 t Au ranks Jiaodong as the largest granitoid-hosted "gold-only" deposit type (e.g., Phillips and Powell, 1993) province in the world.

Historically, production had solely been from vein style gold lodes (e.g., Linglong-type ores), but beginning with new discoveries in the late 1970s and associated production in the early 1980s, more disseminated style gold lodes have been developed (e.g., Jiaojia-type deposits). More than 95% of the gold resource, in both vein and disseminated ores, is hosted by Mesozoic granitoids. Most of the resource in the Jiaodong gold province lies in its western part within what is known as the Zhao-Lai belt (Fig. 1; Wang et al., 1998;

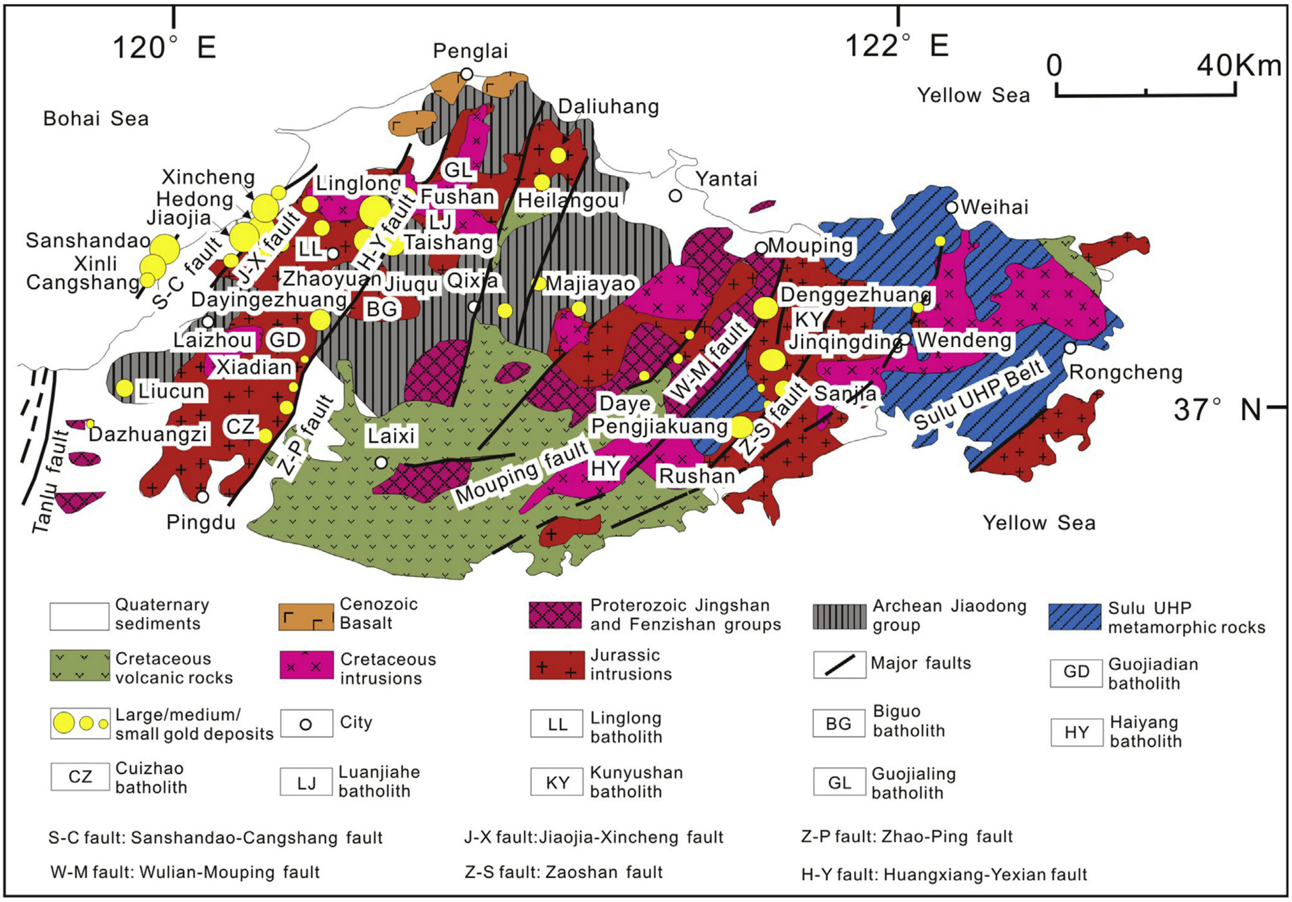

Figure 2. Geology of the Jiaodong gold province sglowing locations of large (>20 t Au), medium (5–20 t Au), and small (<5 t Au) gold deposits. Most deposits are located along NNE-trending normal faults that follow the margins of Jurassic batholiths and intrusions. Total endowment likely exceeds 3000 t Au and the more than 150 mines in the province yield approximately 25% of China's annual gold production. Modified after compilations by Charles et al. (2011) and Q.Y. Yang et al. (2013).

Zhou and Lu, 2000; Qiu et al., 2002). This "belt" comprises essentially five distinct goldfields (largest deposits are shown on Fig. 2) as listed below:

1) Cang-San goldfield including the Sanshandao, Xinli, and Cangshang deposits,
2) Jiao-Xin goldfield including the Jiaojia, Xincheng, Hedong, Hexi, Hongbu, Wangershan, Shangzhuang, and Jiehe deposits,
3) Ling-Bei goldfield including the Lingshangou, Beijie, and Huangpuling deposits,
4) Linglong goldfield including the Eastern Linglong, Western Linglong, Taishang, Lingnan, and Dongfeng deposits,
5) Dayingezhuang-Xiadian goldfield including the Dayingezhuang, Caojiawa, Jiangjiayao, and Xiadian deposits.

The latter two goldfields follow the linear Zhao-Ping (or Zhaoyuan-Pingdu, see Fig. 2) fault system that is >80 km in length and 4- to 7-km-wide; the other three goldfields occur along parallel fault zones, the Sanshandao-Cangshang, Jiaojia-Xincheng, and Huangxian-Yexian faults (Fig. 2), farther to the west (e.g., Qiu et al., 2002; Lu et al., 2007). Drilling results suggest that ore zones in the larger deposits continue to depths of at least 800–1000 m. Most deposits are developed by underground workings. The NE-striking ore-hosting faults and the ores of these goldfields are mainly spatially associated with the margins of widespread granitoid batholiths. The Xinli gold deposit, hosted by the Sanshandao-Cangshang fault, is mined below the waters of Laizhou Bay, where geologists have followed the ore-hosting structure offshore.

The Penglai-Qixia gold belt is located in the center of the gold province (Fig. 1). All gold occurrences here are small; the largest of perhaps twelve deposits, including Qixia and Majiayao (Fig. 2), each contain a resource of no more than a few hundred thousand ounces of gold. In contrast to the Zhao-Lai belt, the smaller deposits of the Penglai-Qixia belt all occur in metamorphic basement rocks. Farther to the east on the Jiaodong Peninsula are the deposits of the Mouping-Rushan belt (Fig. 1) that are hosted along faults within and adjacent to igneous rocks that intrude ultra-high pressure metamorphic rocks. The largest deposits (Fig. 2), including Mouping (Denggezhuang), Rushan (Jinqingding), and Pengjiakuang, occur along a series of NE-trending faults.

Grade and tonnage estimates for individual deposits are extremely contradictory; typically, different estimates are even provided by different geologists at the same mine. Most commonly, both the Jiaojia and Linglong style ores are reported to range in grade between 4 and 15 g/t Au, although locally higher grade ore shoots are present within most of the deposits. The most significant single resource is the Linglong goldfield, with perhaps 300 t Au over an area of about 100 km^2 and at an average grade of 9.7 g/t Au. Although developed by many small active and mined out underground workings, and lesser small surface pits, the density of auriferous veins throughout this goldfield could define a favorable target for future development by a large open pit operation, if more efficient western-style mining is considered here. Other large resources of approximately 100 t Au include Taishang and Lingnan on the edges of the Linglong goldfield, and Sanshandao, Jiaojia, and Xincheng to the west of Linglong. The two largest deposits in the

Mouping-Rushan belt, at Denggezhuang and Jinqingding, each contain >50 t Au and are also highly variable in reported ore grades.

3. Regional setting

3.1. Jiaodong basement geology

The Jiaodong region in the Shandong Peninsula (Fig. 2), which hosts the deposits of the Jiaodong gold province, is bordered to the north and east by the Bohai and Yellow Seas. The northwestern to north-central part to the peninsula, sometimes referred to as the Jiaobei terrane, is underlain by Archean to Paleoproterozoic basement rocks of the North China block, which in eastern China are locally as old as 3.8 Ga. The Archean rocks in the Jiaodong gold province are dominated by 2.9–2.6 Ga granulites, TTG (tonalite-trondhjemite-granodiorite) gneisses, and amphibolites of the Jiaodong Group (e.g., Jahn et al., 2008; Fig. 2), although older rocks are also locally recognized. The Jiaodong Group rocks are unconformably overlain by Paleoproterozoic ultramafic rocks, granulites, amphibolite, marble, and schist. Deformation and metamorphic events at ca. 2.5 and 1.8 Ga impacted these rocks prior to a ≥1.3-b.y.-long period of cratonization. Neoproterozoic slate, phyllite, and carbonates overlie the basement rocks. Although other parts of the North China block experienced Caledonian (Middle Ordovician to Silurian) deformation, it is unclear as to whether the Precambrian rocks of the Jiaobei terrane were deformed during the Paleozoic.

The NE-trending Wulian-Yantai or Wulian-Mouping thrust fault system (Fig. 1), bisecting the peninsula from Wulian in the southwest to Mouping in the northeast, separates rocks of the Jiaobei terrane in the north from ultra-high pressure rocks of the Sulu terrane of the South China block to the south (Figs. 1 and 2). The latter rocks are the easternmost segment of the Dabie-Sulu metamorphic belt that was offset 500 km in the Triassic by the left-lateral Tan-Lu fault system (Xu and Zhu, 1994). Early Paleoproterozoic (ca. 2.48–2.38 Ga) country rocks of the Sulu terrane include gneiss, amphibolite, schist, marble, and quartzite that comprise the Jinshan Group, which were metamorphosed to high grade facies between ca. 2.22 and 1.85 Ga (e.g., Q.Y. Yang et al., 2013). In addition, ca. 240–210 Ma eclogite pods and layers that formed at pressures of 30 kb commonly overprint the older metamorphic units (Liou et al., 1996). It is widely accepted that this indicates passive margin Proterozoic rocks at the leading edge of the South China block were subducted to great depths during the Triassic collision between the North China and South China blocks.

3.2. Mesozoic “Yanshanian” orogeny

Following cratonization in the late Paleoproterozoic, the interior part of the North China block remained largely quiescent until the Mesozoic when extensive reactivation, erosion of the cratonic keel, and differential destruction of the lithosphere occurred (Zhai and Santosh, 2011, 2013); hence, in this paper, we define it as a block, rather than as a present-day craton. This pre-Yanshanian decratonization was driven by convergence from the north, south, and east that was dominant in the Triassic and Jurassic. Events included the southward indentation of the Siberian block into the North China block following the closure of the Mongol-Okhotsk Ocean (Metelkin et al., 2010), the collision of the North China block with the South China block, and the oblique subduction of the paleo-Pacific plate from the east, which together generated a superconvergent regime (S.Z. Li et al., 2013, and references therein). Under such a regime, large volumes of fluid may have induced melting, magmatism, and erosion of mantle lithosphere (Windley et al., 2010).

The dominant compressive tectonic regime switched to an extensional one likely in the Early Cretaceous, a regime that is widely referred to as Yanshanian intracontinental orogeny. The extension is considered to have had a major control on the formation of detachment faults and exhumation of metamorphic core complexes (Zhai et al., 2004; Davis and Darby, 2010; Zhai and Santosh, 2011, 2013). Two Yanshanian orogenic belts lie along the northern part of the North China block, the Yinshan orogen in the west and the Yanshan orogen in the east (Davis and Darby, 2010; Lin et al., 2013), both of which underwent the tectonic transformation to the late Mesozoic Yanshanian extension (Davis and Darby, 2010). These two orogens developed in areas where earlier Mesozoic convergence included terrane accretion to the northern margin of the North China block and the westward subduction of the Pacific plate, which resulted in early Mesozoic crustal thickening and the development of fold-and-thrust belts (Meng, 2003; Lin et al., 2013; Zhao et al., 2013). The Mesozoic basins in the block also show significant diversity with regard to their tectonic origin. Whereas compressive-flexure associated with NEE-trending thrust zones characterize the pre-Late Jurassic basins in the Yanshan area, the Late Jurassic NE- to N-trending rift basins are associated with zones of uplift (Zhai and Santosh, 2011). The post-Late Jurassic basins trend NE to NNE, developed coevally with the active uplift zones, and are controlled by the existing NEE-trending thrust zones.

Although there is a general consensus on the Mesozoic tectonic inversion in the eastern NCC, its timing is debated, with some workers proposing a complex and multi-stage inversion during the period from 150–140 Ma to 110–100 Ma, with a peak at 120–110 Ma (Zhai et al., 2004). However, spatial-temporal variations are noted between the margins and interior of the North China block. For example, in the southeastern part of the block, where the compressive event occurred mainly at 230–210 Ma, the peak stage of Yanshanian extensional tectonic inversion was at 130–110 Ma. In the north, compressive events occurred at 230–210 Ma and ca. 175–155 Ma, with a peak stage of extensional tectonic inversion at 130–110 Ma (Zhai and Santosh, 2011, 2013). Recent models, however, identify the transition from compression to extension in the North China block to have occurred at a slightly older time, generally from 145 Ma to 135 Ma (S.Z. Li et al., 2013), although this is still debated with some workers claiming the transition was as young as 125 Ma (Zhu et al., 2012; Lin et al., 2013). Faure et al. (2012) favor a specific age of 136 Ma as best defining the transition.

The Mesozoic tectonic inversion regime in the North China block is distinct from the processes and features associated with typical subduction-accretion-collision orogens (e.g., Santosh et al., 2010). The Yanshanian extension, and associated transpression, during the Early Cretaceous in eastern China were dominantly intraplate tectonic events, which included the evolution of the Tan-Lu fault (Fig. 1). Mercier et al. (2007) suggested that the Tan-Lu fault and its subsidiary structures became zones of sinistral transcurrent motion at ca. 127 Ma, which seemingly relates to shifting circum-Pacific plate motions (e.g., Goldfarb et al., 2007). The ca. 165–90 Ma magmatism in the eastern North China block (see below) was triggered by mantle dynamics and resulting crust-mantle interaction, which were controlled by the subduction of the Pacific plate. It involved the chemical and thermal erosion and hydration of the sub-continental lithospheric mantle (SCLM; Santosh, 2010), as well as delamination (Gao et al., 2004).

3.3. Igneous rocks

Approximately two-thirds of the area of the Jiaodong Peninsula is characterized by felsic to intermediate calc-alkaline intrusions that were emplaced into the Precambrian basement blocks (Fig. 2). These have most commonly been divided into the Linglong (or Linglong/Luanjiahe) and Guojialing intrusive suites (Wang et al., 1998; Zhou and Lu, 2000; Qiu et al., 2002; Yang et al., 2012; Q.Y. Yang et al., 2013). The former is ca. 165–150 Ma medium- to coarse-grained, equigranular to porphyritic granite and granodiorite that form a series of NNE- to NE-trending batholith-sized intrusive complexes emplaced into basement of both blocks across the peninsula. Bodies of the Linglong suite are commonly deformed, with gneissic textures developed along their margins, defined by the preferred orientation of well-developed biotite grains. The Linglong granitoids were formed by Late Jurassic partial melting of thickened lower crust (Gao et al., 2008; Zhu et al., 2012). The intrusions are adakite-like bodies that are thought to have developed from the eclogitic delaminated mafic lower crust, which subsequently sank into the less dense mantle and melted and interacted with peridotite (Gao et al., 2008; Windey et al., 2010). Most of the gold mineralization in the Jiaodong province is hosted by intrusions of the Linglong suite, although those of the Guojialing suite host some of the most western ores of the Zhao-Lai belt. Unlike much of eastern China, the more voluminous magmatism in Jiaodong is Late Jurassic, and not Early Cretaceous, in age.

The much less extensive Early Cretaceous Guojialing intrusive suite (ca. 130–123 Ma) is dominated by porphyritic hornblende-biotite granodiorite. Bodies were emplaced at depths of 5–13 km (L.Q. Yang et al., 2013) within the gold-rich northwestern and northern margins to the westernmost of the Linglong suite of batholiths. They were also emplaced throughout much of the Sulu terrane to the east and south (e.g., Yang et al., 2012). The Guojialing intrusions may reflect, in part, partial melting of enriched SCLM (Zhou et al. (2003) that mixed with peridotitic mantle material as it descended to the base of the lithosphere (e.g., Gao et al., 2004). Based on isotopic data for rocks on the Liaodong Peninsula to the north of the Bohai Sea, the younger period of Guojialing magmatism was locally dominated by the mantle contribution, relative to the crustal-melt signature that is the dominant component of the Late Jurassic magmas (J.H. Yang et al., 2008).

During uplift of the westernmost Linglong batholith, small masses of ca. 120–118 Ma granodiorite were emplaced into the center of the batholith (e.g., the PRG intrusions of Charles et al., 2013). Mafic dikes cut all felsic to intermediate igneous bodies on the Jiaodong Peninsula. Q.Y. Yang et al. (2013) note that these cluster into two main age groups at 117–116 Ma and 95–87 Ma. The former shows a derivation from melting of the North China block's SCLM and subducted lower crust of the South China block. The younger dikes formed through the melting of depleted SCLM that was added below the Jiaodong peninsula in Late Cretaceous.

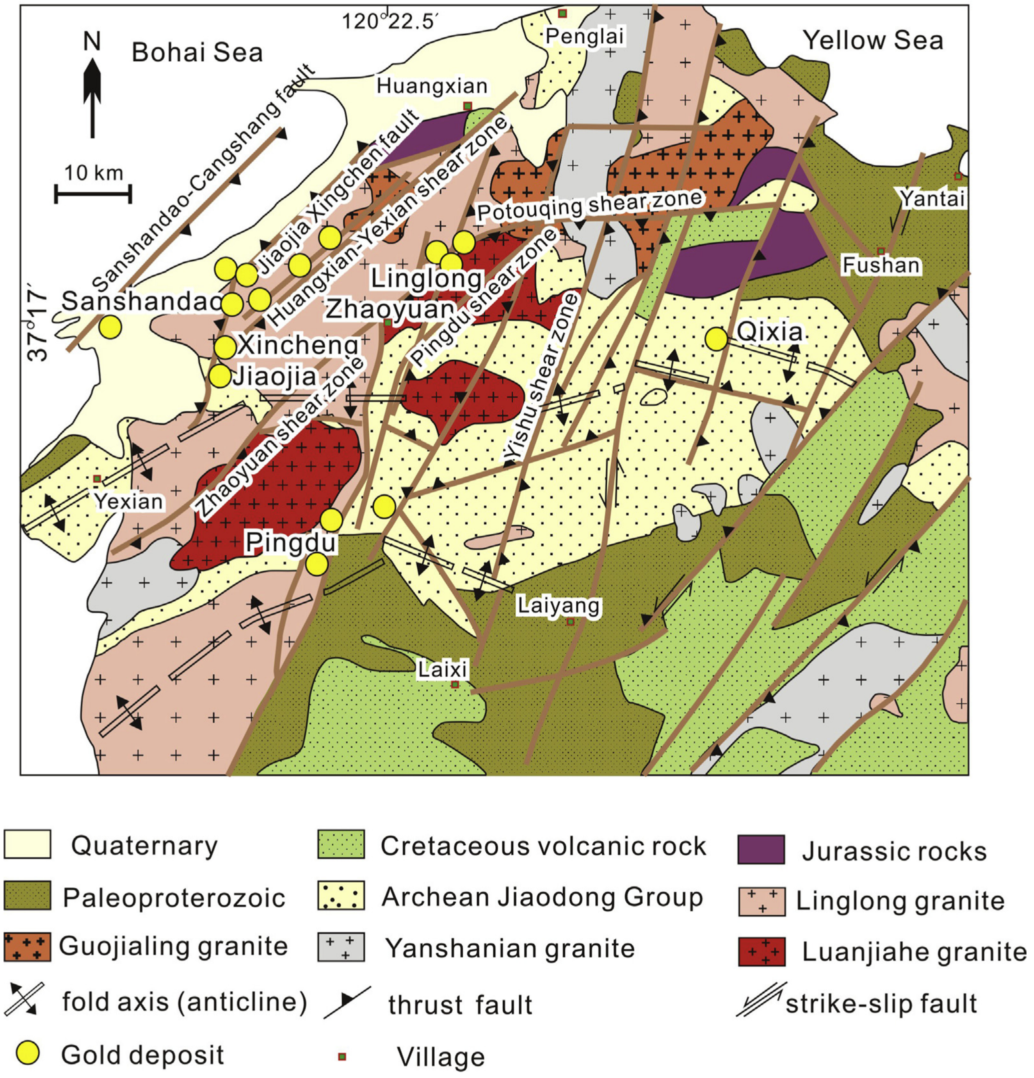

Figure 3. Detailed structural map of the Zhao-Lai gold belt generalized after Lu et al. (2007). Gold deposits are hosted in mainly brittle fractures along NE- to NNE-trending middle Mesozoic brittle-ductile thrust faults and oblique slip shear zones, which were reactivated with normal displacement during late Mesozoic uplift and extension. The east-west ductile shears and regional folds are older Mesozoic features related to initial collision between the North and South China blocks.

The NNE-trending, continental-scale Tan-Lu fault system occurs about 20–30 km west of the westernmost gold deposits of the Zhao-Lai gold belt. Northeast-trending brittle-ductile shear zones (Figs. 2 and 3), which are commonly suggested to be splays off the Tan-Lu fault, localize much of the gold mineralization. These 2nd-order faults are best developed along the margins of the large batholiths and define the productive Zhao-Lai and Mouping-Rushan gold belts. Jurassic–Cretaceous transtensional motion along the Tan-Lu fault is likely responsible for opening of the NE-striking Jiaolai basin (Fig. 1) within rocks of the southern part of the Jiaobei terrane, between the Tan-Lu fault to the west and Wulian-Mouping fault to the south and east. The basin is filled with sedimentary rocks, which are greater than 7 km in thickness, as well as volcanic rocks of mainly andesitic composition. The andesites are dated at ca. 124 Ma and possess a similar adakite-like signature to the Late Jurassic and Early Cretaceous intrusions (e.g., Liu et al., 2009).

4. Current state of knowledge of the control on and characteristics of the Jiaodong gold ores

4.1. Tectonometamorphic setting

The Jiaodong gold deposits, all Early Cretaceous in age (see below), are hosted in Precambrian basement rocks of high metamorphic grades as discussed above. Whereas the North China block was an integral part of the Paleoproterozoic Columbia supercontinent (Zhao et al., 2004; Santosh, 2010; Meert, 2012), the South China block was likely first assembled within the Gondwana supercontinent through the end of the Neoproterozoic (Metcalfe, 2013). South China began to subduct below the North China block in the Carboniferous or Permian, with final collision of the blocks in Triassic. The Wulian-Mouping thrust fault system is probably a part of the suture.

Most orogenic gold deposits form in rocks that are tens to a few hundred million years older than the deposits. Thus, Late Archean gold resources in metamorphic rocks are generally hosted by Late Archean rocks, Paleoproterozoic deposits by Paleoproterozoic rocks, and Phanerozoic deposits by Phanerozoic rocks (e.g., Goldfarb et al., 2001, 2005; Groves et al., 2005). The Jiaodong gold deposits are the most notable global exception. The gold ores formed approximately two billion years after protolith formation and high-grade metamorphism of the rocks in both Precambrian blocks. Also, in contrast to typical Phanerozoic orogenic gold deposits that formed in accretionary orogens surrounding Precambrian cratons, the Phanerozoic Jiaodong gold deposits formed in reactivated Precambrian terranes.

Both the typical Cordilleran-style orogens and the areas affected by the Yanshanian intracontinental orogeny in eastern China contain giant gold deposits in metamorphic rocks. In the former, orogenic gold deposits are preferentially hosted in greenschist facies rocks of Barrovian metamorphic sequences (Groves et al., 1998; Goldfarb et al., 2005). They generally form on the retrograde metamorphic path during regional uplift of the orogen (e.g., Stuwe, 1998), with fluid and metals being derived from the prograde zones of the host Cordilleran terranes at depth (e.g., Pitcairn et al., 2006). There are some exceptions, mainly Precambrian in age (e.g., Hemlo, Big Bell, Challenger), where orogenic gold deposits are

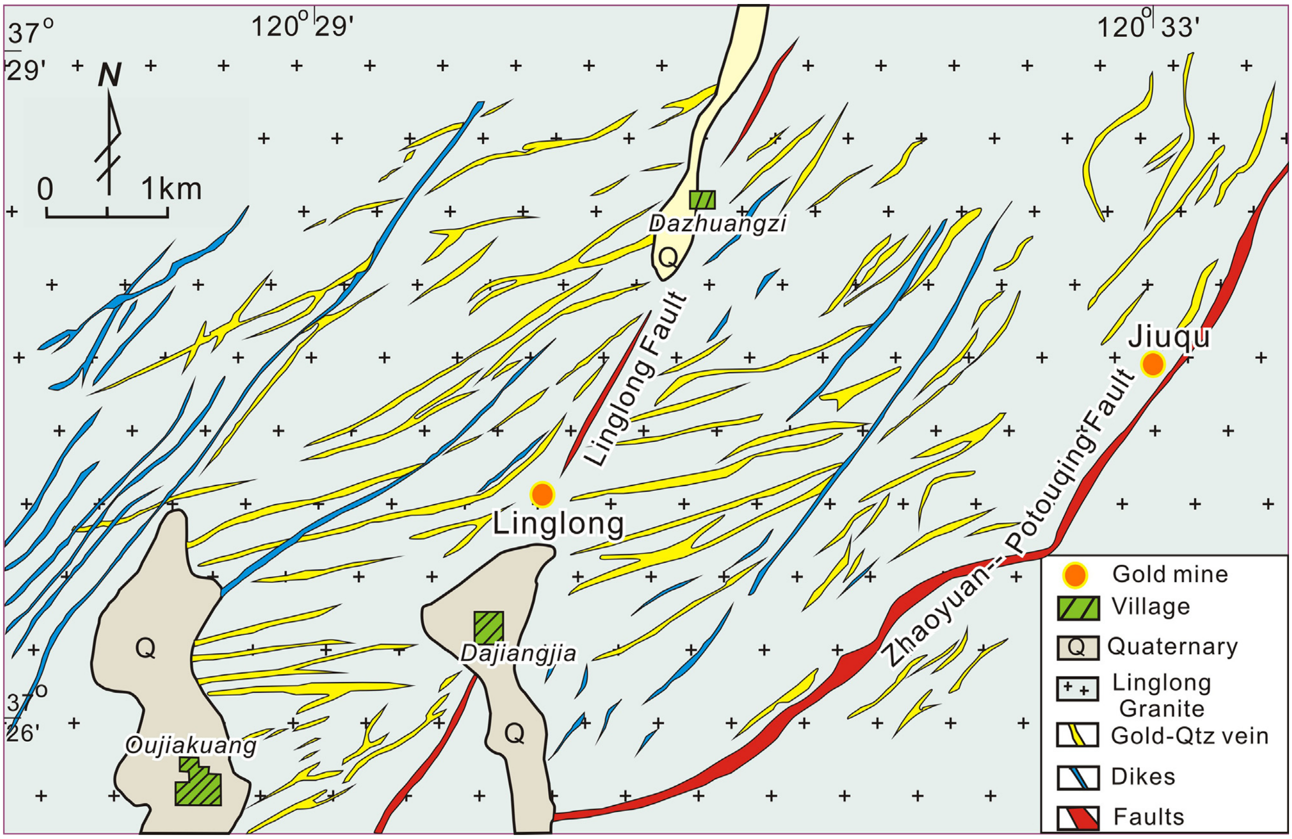

Figure 4. Detail structural map of the Linglong goldfield after Zhuang and Wang (2009) showing the extensive vein system presently being mined by a number of underground operations. The major ore controlling structure in the goldfield is the NE-striking Zhaoyuan-Potouqing ductile-brittle reverse shear zone, with NE-trending gold-bearing extensional veins being continuous along strike for as much as 5 km within a series of *en-echelon* brittle faults. The NNE-striking Linglong normal fault is a late- to post-gold feature that cuts through the goldfield.

subsequently metamorphosed (e.g., Phillips and Powell, 2009), but these are few in number. In contrast, the host terranes for the Jiaodong gold deposits are upper amphibolite and granulite facies rocks that have been uplifted to the near surface during Yanshanian orogeny. These older crustal rocks could not be a source of fluids and metals for the Jiaodong deposits because they were metamorphosed and devolatilized at least two billion years earlier.

4.2. Structural setting

There is little argument that the Jiaodong gold deposits are strongly structurally controlled ore deposits. The gold deposits, particularly those in the Zhao-Lai belt, follow NE–NNE linear trends along the margins of intrusions and between intrusions of the different ages (e.g., Qiu et al., 2002; Chen et al., 2005; Figs. 2 and 4). Many of the deposits are located along obvious fault jogs in these trends, indicating some control on the ores by zones of dilation and hydrothermal fluid focusing. Several workers have assumed that the NNE- to NE-trending zones of faults and fractures are secondary faults of the main Tan-Lu fault (e.g., Shen et al., 2003; Qiu et al., 2008), a regional fault that extends to mantle depths (Z. Zhao et al., 2012) and is considered a major conduit for melts and hydrothermal fluids (Guo et al., 2013). Although it is uncertain whether this assumption is correct, the abundance of lamprophyre dikes along the auriferous secondary faults indicates that these too extend to great depth.

Not only do the gold-bearing faults show a NNE–NE trend, but the Late Jurassic granitoids also are elongated in the same direction across both the Jiaobei and Sulu terranes (Fig. 2). This is consistent with the pre-Yanshanian (i.e., Late Jurassic) NW–SE extension east of the Tan-Lu fault zone (Faure et al., 2012), which thus controlled emplacement of the lower crustal melts. The brittle and ductile-brittle normal faults define sites of pre-existing ductile shears, perhaps related to the extensive Triassic–Jurassic sinistral shear along the Tan-Lu fault zone (e.g., Gilder et al., 1999; Zhang et al., 2007), which could relate in some manner to the North China—South China block collision. Wang et al. (1998) stated that these were originally ductile-brittle shear zones with sinistral oblique reverse movement, which underwent later brittle deformation and normal movement during the Early Cretaceous gold deposition. However, such normal fault motion likely could indicate a Late Jurassic initiation of extension that localized the Linglong/Luanjiahe granite suite bodies. Extensional faults are commonly sites of magma migration (e.g., de Voogd et al., 1988; Milia and Torrente, 2011) and zones of pre-existing compressional structures could have been the sites of most extensive Late Jurassic normal faulting.

The distribution of the Jiaodong gold deposits shows a definite spatial association to the extensional faults bounding and cutting the Late Jurassic intrusions, but not with the Early Cretaceous granites and granodiorites. The Zhao-Lai belt lodes are predominantly hosted within or near the NNE- to NE-striking faults that define the margins of the Late Jurassic granitoids (Fig. 2). The Linglong and Dayingezhuang-Xiadian goldfields are located along the NNE-trending eastern margin of the Linglong batholith, the Ling-Bei goldfield is along a NE-striking fault cutting the northern part to the batholith, and the NNE-trending Jiao-Xin goldfield is along the northwestern margin. The NNE-striking Cang-San goldfield occurs in a poorly exposed area about 10 km west of the batholith. The NNE-trending structures are ancient fault zones that parallel the Tan-Lu fault and were reworked to show a component of normal faulting during Yanshanian extension (e.g., Faure et al., 2012).

The SE-dipping Zhaoping fault (or sometimes mapped as distinct Zhaoyuan-Potouqing and Pingdu shear zones as on Figs. 3 and 4) defines the eastern margin of the Linglong batholith. Charles et al. (2011) described the Linglong batholith of Late Jurassic plutons as a metamorphic core complex that was uplifted between 150 and 130 Ma below the Zhaoping normal fault or so-called Linglong detachment fault along its southern extent. The large Dayingezhuang gold deposit is located in the footwall at the northernmost part of the Linglong detachment fault, notably at the boundary between ductile deformation to the south and brittle deformation to the north (L.Q. Yang et al., 2013). The smaller deposits of the Dayingezhuang-Xiadian goldfield stretch along the mylonitic detachment fault between hangingwall metamorphic rocks and footwall granite to the south of Dayingezhuang. To the north, the Linglong goldfield (Fig. 4) is defined by a 5 km × 3 km area of massive NE-striking, and steeply SE- and NW-dipping veins in brittle shear fractures in the Zhaoping fault footwall. The Zhaoping fault here is about 100- to 300-m-wide and shows evidence of originally being a reverse ductile shear zone (Lu et al., 2007). The oblique-slip Linglong fault in the center of the goldfield is a NNE-trending late brittle fault that post-dates formation of the gold deposits (Poulsen et al., 1990).

The NW-dipping Jiaojia-Xincheng fault zone (Fig. 2) localizes the orebodies of the Jiao-Xin goldfield within a 2-km-wide zone (e.g., Fig. 7 in Qiu et al., 2002). The ores are generally localized in areas of lithologic contacts or of dilational jogs along the fault zone. The hangingwall includes both Precambrian basement rocks and Late Jurassic granite, whereas the footwall includes both Late Jurassic and Early Cretaceous intrusive rocks. The latter Guojialing granodiorite pluton intrudes the northern margin of the Linglong batholith along an E–W extensional shear zone (Charles et al., 2011), and hosts mineralization in the footwall of the Jiaojia-Xincheng fault at the Hedong deposit. As with the Zhaoping fault, the hangingwall at the large Jiaojia deposit is mainly barren Precambrian metamorphic rocks and the footwall is mineralized Late Jurassic granite. Linglong granite is exposed on both walls of the fault at the Xincheng deposit. The subparallel and smaller Lingshangou-Beijie or Huangxian-Yexian fault zone (Fig. 3), a few kilometers east of the Jiaojia-Xincheng fault zone, is not well studied, but also cuts the Linglong batholith and is associated with the deposits of the Ling-Bei goldfield.

The Cang-San goldfield occurs along the length of the moderately southeast-dipping Sanshandao-Cangshang fault zone (Fig. 2) that extends into the Bohai Sea to the northeast and southwest. At the Cangshang deposit, this fault separates Paleoproterozoic metamorphic rocks in the hangingwall to the southeast from Late Jurassic Linglong suite granite in the footwall to the northwest, and shows evidence of reverse and dextral movement (X. Zhang et al., 2003). The fault zone in the deposit varies in strike from 20° to 85° (X. Zhang et al., 2003), reflecting significant complexity and dilation; the mined area is centered over a very distinct jog along the fault zone (e.g., see Fig. 3 in H.J. Zhao et al., 2012). The Sanshandao deposit, 8 km to the northeast along the fault, is characterized by a 50- to 200-m-wide zone of brittle fracturing striking 35°, with a hangingwall to the SE comprised of Linglong granite and a footwall to the northwest of both Linglong granite and Early Cretaceous Guojialing suite granodiorite (X.C. Li et al., 2013). Between the Sanshandao and Cangshang deposits, the Xinli deposit is being mined offshore in the Bohai Sea at the site of a 2nd major jog along the Sanshandao-Cangshang fault zone, where the strike changes from a regional trend of approximately 40° to a local more easterly orientation of 62° (H.J. Zhao et al., 2012). The fault at the deposit again separates hangingwall metamorphic rocks from footwall granite.

Smaller gold resources are structurally controlled further east on the Jiaodong Peninsula (Fig. 2), also by reworked normal faults that originally were reverse strike-slip structures (e.g., Zhang et al., 2007; Hou et al., 2012). In the Penglai-Qixia gold belt, the Fayunkuang and Pengjiakuang deposits are hosted by shallowly-dipping brittle-ductile normal faults along the margin of the Early Cretaceous Jaolai extensional basin, adjacent to the Late Jurassic Queshan granite. Regional control by a series of NE-trending shear zones and associated cross faults that host the ores (X. Zhang et al., 2003), could reflect a part of the regional Muping shear zone of Zhang et al. (2007). The Denggezhuang and Jinqingding deposits occur with many smaller deposits along the NNE-striking faults parallel to the west side of the Late Jurassic Kunyushan granite (e.g., Xu and Zhu, 1994; Zeng et al., 2006), whereas even further to the east in the Sulu terrane, the Fanjiafu and Wendeng deposits parallel the west side of the Wendeng granite.

In summary, the Jiaodong gold deposits are controlled by NE- to NNE-striking faults across the entire Jiaodong Peninsula, although the majority of hydrothermal activity was within the western side of the peninsula. Subsequent to suturing of the North China and South China blocks, deformation was dominated by sinistral strike-slip along ductile thrust faults, which was then overprinted by brittle normal faulting (e.g., Lu and Kong, 1993; Qiu et al., 2002; Lu et al., 2007; Zhang et al., 2007). Faure et al. (2012) defined the early deformation as pre-Yanshanian contractional deformation and the later extensional tectonics as ca. 136–110 Ma Yanshanian intracontinental orogeny. The gold deposits formed in brittle fractures along the faults during the middle of the orogeny (see discussion on age data below) and thus mark a period of NW–SE extension. If the faults also controlled emplacement of the older granites, then the shift to extensional tectonics on Jiaodong and Yanshanian orogeny may be considered to be as early as ca. 160 Ma.

4.3. *Description of the lodes*

Historically, workers have distinguished two styles of mineralization in the Jiaodong gold province – Linglong-type and Jiaojia-type ores. The former represents typically large quartz vein-hosted deposits, whereas the latter defines ores that occur as stockwork veinlets and wallrock disseminations in cataclastic zones in granitoids, both in and along pre-existing faults (Qiu et al., 2002; Li and Santosh, 2013). Ore zones with one or both types of the mineralization are hundreds of meters to 1–2 km both in length and down-dip, and tens of meters wide. In some cases, individual veins as long as 5 km and as wide as 12 m are observed (Lu et al., 2007), and some orebodies have been proven by drilling to continue down-dip for at least 2 km. Arguments have been made that the Jiaojia-type deposits occur along the NE-trending second-order faults, and the Linglong-type deposits are restricted to the lower-order tensile fractures and shears (Qiu et al., 2002). However, in many locations, the two mineralization styles are often gradational and thus commonly are present within a single deposit. The Linglong-type ores tend to be more common along the more steeply dipping parts of the ore zones (e.g., ≥60°) and the gold-bearing veins are often brecciated and fractured. Changes in strike of the hosting faults may be critical for localization of ores along the major structures, as is particularly obvious in the westernmost deposits along the Sanshandao-Cangshang fault system and in the Mouping-Rushan belt to the east. Hall (2002) indicated that the steeper parts of the NE-trending faults are more highly mineralized, where there was dilation during normal faulting, and changes of just a few degrees in fault dip may be quite significant in defining high-grade zones.

Gold mainly occurs in pyrite and in fractures in quartz. The gold is particularly associated with fine-grained pyrite; better grades are recorded with fine pyrite and often sub-ore grades characterize zones of coarsest pyrite. Gold, electrum, native silver, pyrite, chalcopyrite, sphalerite, galena, and pyrrhotite are commonly associated with the ore zones, but pyrite is by far the most voluminous sulfide mineral phase (Qiu et al., 2002). In fact, in many orebodies of Linglong-style mineralization there are widespread zones of massive pyrite, both fine and coarse, which themselves are locally boudinaged or fractured. The ore zones are also typically anomalous in Ag, As, Au, Bi, Cu, Hg, Mo, Pb, Sb, W, and Zn. Although concentrations of as much as 2500 ppm As characterize some deposits (R. Goldfarb, unpub. data), arsenopyrite is not common in the orebodies. Trace amounts, however, of marcasite, hematite, magnetite, sulfosalts, and barite are reported. At the Jinqingding deposit, Te- and Bi-bearing minerals are characteristic of the orebodies (Li et al., 2006). It is commonly interpreted that the gold and base metals were deposited during a second paragenetic stage, subsequent to the voluminous pyrite, but some such observations could reflect remobilization of gold into fractures in pyrite during post-ore deformation.

Granitoid host rocks where highly sulfidized, rather than hosting Linglong-type vertical veins, are commonly defined as the Jiaojia-type orebodies. With recent higher gold prices, much more of this “alteration” has become part of the ore. Sericitically-altered and silicified rocks are also common in and adjacent to ores, whereas secondary K-feldspar, epidote, and chlorite are located more distally. The K-feldspar often produces a broad reddish zone surrounding the orebodies, which is a useful exploration tool. Carbonate alteration (e.g. calcite, siderite) is present, but is not abundant, nor widespread, which is uncommon for orebodies formed from CO_2-rich hydrothermal fluids. However, the abundant pyrite and limited carbonate formation is typical of a fluid interacting with rocks with relatively high Fe/(Fe-Mg) ratios, as is common of many granites (e.g., Bohlke, 1988).

4.4. *Hydrothermal geochemistry*

Fluid inclusion and isotope data are consistent between the many studied deposits in Jiaodong; there are no notable differences between the Jiaojia- and Linglong-style orebodies. Furthermore, Hu et al. (2012) reported consistent ore fluid chemistry over a vertical extent of >2 km for the Sanshandao deposit. Despite the many consistencies in fluid chemistry, interpretation of these data remains problematic (see Section 5 below). As a result, fluids of a felsic magmatic, mafic magmatic, enriched SCLM, and shallow crustal origin are all sometimes cumulatively implicated within the ore-forming process at a single Jiaodong deposit (e.g., X.C. Li et al., 2013).

Qiu et al. (2002) indicated that most deposits in the Jiaodong gold province formed at 250–350 °C from low to moderate salinity (6–14 wt.% NaCl equiv.), CO_2–H_2O fluids. Homogenization temperatures for fluid inclusions from ore-bearing quartz typically range from 170 to 370 °C, but with a mode at approximately 300 °C (e.g., Qiu et al., 2002; Yao et al., 2002; Hu et al., 2006; Fan et al., 2007). Much of the broad range reflects reliability issues of some published fluid inclusion studies, particularly probable measurement of post-ore stage fluid inclusions of secondary nature. Data for samples from many of the deposits at Linglong show significant amounts of CO_2 and CH_4, and low to moderate salinity (He et al., 1989; Fan et al., 2003, 2007). Similar gas-rich fluids are found at the Qixia deposit within the Penglai-Qixia belt (Xu, 1998). Estimates of trapping pressures for the gold deposits are stated as 0.7–2.5 kb (Fan et al., 2007), with the extreme variability due, at least in part to, extreme pressure fluctuations associated with deposition of quartz and metals during fracturing of the rocks.

Many stable isotope measurements have been carried out on ore-related minerals in the Jiaodong gold deposits. Qiu et al. (2002) summarize $\delta^{18}O_{quartz}$ values from numerous deposits of the province as generally +9.4 to +13.1 per mil; measurements for the Hubazhuang deposit near Rushan are between +8 and +9 per mil

(Cai et al., 2011). Exceptionally light fluid $\delta^{18}O$ values were calculated for the Denggezhuang deposit by Zeng et al. (2006), but it is impossible to know the significance of these anomalies without knowledge of the measured values for the hydrothermal quartz. The reported $\delta D_{\text{fluid inclusion waters}}$ vary significantly between -100 and -30 per mil (Yao et al., 2002). Compilations of $\delta^{34}S_{\text{sulfides}}$ data show ranges from about $+3$ to $+14$ per mil (Qiu et al., 2002), $+4$ to $+12$ per mil (Yao et al., 2002), and $+6.8$ to $+12.5$ per mil (Mao et al., 2008). Zhang et al. (2008) examined He and Ar isotopes of fluid inclusion waters to suggest a mantle fluid source for many of the Jiaodong deposits.

4.5. Relative and absolute timing constraints

Absolute ages reported in the literature for the Jiaodong gold deposits broadly span more than 100 m.y. (see summary in Chen et al., 2005), but this time range reflects many questionable dating approaches (e.g., K-Ar on a variety of materials, ^{40}Ar-^{39}Ar on quartz, Rb-Sr on altered granite) and measurements in some unreliable laboratories. Relative timing relationships indicate that gold deposition was younger than the crystallization of the 124 Ma Guojialing intrusion that hosts some of the ores in the northwestern part of the Jiaodong Peninsula (Charles et al., 2011). Lamprophyre dikes, dated at ca. 124–120 Ma, both cut the gold mineralization and are themselves mineralized (Yang and Zhou, 2001; Cai et al., 2013). A post-mineralization dike in the Linglong goldfield was dated by U-Pb at 120 ± 2 Ma (Wang et al., 1998). Thus, relative timing relationships have shown much of the gold deposition was probably restricted to the earliest Aptian age.

During the past decade, many well-documented isotopic dating studies, mainly applying $^{40}Ar/^{39}Ar$ dating techniques to hydrothermal white mica and biotite, have precisely defined deposition of the gold resource in Jiaodong to a remarkably brief time span during the Early Cretaceous. Reliable dates for almost all deposits in the Jiaobei terrane cluster between 126 and 120 Ma (Chen et al., 2005; Li et al., 2008; Guo et al., 2013; L.Q. Yang et al., 2013). Argon dating at the Dayingezhuang deposit, however, suggests some gold was deposited between 134 and 126 Ma (L.Q. Yang et al., 2013). There is also evidence that mineralization in the Sulu terrane is a few million years younger than that of the Jiaobei terrane (see Fig. 3 in Mao et al., 2008). However, the reported dates for the Sulu deposits are from unreliable argon analysis of quartz samples or old K-Ar determinations with poor precision. Li et al. (2006) provided $^{40}Ar/^{39}Ar$ dates on hydrothermal sericite of ca. 120 Ma from Pengjiakuang, but ca. 110–107 Ma for the Rushan deposit. Nevertheless, Hu et al. (2004) reported an age of 117 ± 3 Ma for hydrothermal zircon from Jinqingding by U-Pb SHRIMP methods, so the age of the Sulu deposits remains unclear. For the most part, although the possibility exists for some gold formation between 134 and 107 Ma, we conclude that the vast majority of the gold ore was deposited over a relatively short time interval between ca. 126 and 120 Ma.

5. Critical constraints from deposit characteristics

The geological and geochemical characteristics of the Jiaodong gold deposits place important constraints on ore formation that must be considered for any ore deposit model. In large part due to the voluminous Mesozoic magmatism on the Jiaodong Peninsula, many workers have suggested that the main source of the ore fluids and metals was exsolution from a magma (e.g., Wang and Yan, 2002; Fan et al., 2003, 2007). In some cases, these were specifically stated to be “mantle fluids” that were exsolved from a rising melt with a large mantle component (e.g., Zhang et al., 2008).

There are, however, problems with widespread fluid release from a specific group of Yanshanian granitoids. The exposed granitoids in the Jiaodong region lack any obvious genetic connection with the gold ores. There is a spatial association between the linear belts of gold deposits and the similarly NE- to NNE-oriented Linglong/Luanjiahe granitoids. However, these crustal melts pre-date the gold event by approximately 25–40 m.y. The younger Guojialing suite of granitoids does have temporal overlap with the gold event, however an obvious spatial association between these mantle-crustal melts and the gold ores and their hosting structures is lacking. Furthermore, numerous linear belts of giant gold deposits along regional fault zones are not typical of the geohydrology that is associated with most classic magmatic types of ores deposits. Rather, adjacent stockworks and veinlet networks are produced when fluids exsolve in the roof zones of porphyry deposits and sheeted vein networks in the roof zones of the more deeply formed reduced intrusion-related gold systems. Furthermore, when fluids exsolve from a granite to form epithermal gold deposits, some type of zoning is typically evident in association with the larger systems. The lack of such features and the fact that the Jiaodong ores can extend down-dip for more than 2 km with no notable change in mineralogy, alteration, and ore fluid chemistry suggests a regional ore fluid in relative thermal equilibrium with host rocks, rather than one released from a proximal granite intrusion. Although brittle features dominate in most lodes, some show well-developed ductile crack-seal textures that are consistent with multiple seismic events along large fault systems, rather than much briefer fluid flow events related to magmatic hydrothermal systems. Finally, the Early Cretaceous granitoids have a strong mantle component, whereas the sulfur isotope compositions of the ore-related sulfides are clearly much heavier than accepted mantle sulfur values. If the ore deposits have a magmatic origin, then such an origin certainly cannot belong to the two well-recognized groups of intrusions exposed on the Jiaodong Peninsula.

Metamorphic fluids are widely accepted to have formed most of the world’s orogenic gold deposits, at least of Phanerozoic age. In accretionary orogens, 3–4% of the rock may convert to a fluid phase as it passes through greenschist and amphibolite facies conditions. The release of a low to moderate salinity H_2O-$CO_2 \pm CH_4 \pm N_2 \pm H_2S$ fluid, focusing of the fluid into major fault zones, and its upward migration during seismic events combine to form gold ores in the retrograded and actively exhuming parts of accretionary orogens. The gold is carried by the H_2S, with both components being released during the metamorphic conversion of pyrite to pyrrhotite. The H_2O-CO_2-rich fluid composition for Jiaodong ores is identified in most fluid inclusion studies (e.g., He et al., 1989; Fan et al., 2003, 2007). In addition, Jiaodong deposit mineralogy, alteration, and the linear distribution of ores along lengthy fault zones are very characteristic of orogenic gold (Zhou and Lu, 2000; Zhou et al., 2002).

Nevertheless, such a classic metamorphic model, widely accepted for the orogenic gold deposit type (e.g., Goldfarb et al., 2005), cannot be applied to the Jiaodong gold deposits. The rocks of the Jiaobei and Sulu terranes were metamorphosed through greenschist and amphibolite conditions about two billion years before Yanshanian tectonism and Jiaodong gold deposition. Under such conditions, most volatiles and gold would have been lost from the Jiaodong Archean and Paleoproterozoic country rocks. In a recent zircon U-Pb and Hf isotope study of Late Jurassic and Early Cretaceous magmatic rocks from Jiaodong, Q.Y. Yang et al. (2013) reported zircon data from multiple magmatic pulses that showed evidence of extensive mixing of crustal, lithospheric mantle, and asthenospheric components. They correlated these data to a combination of processes including delamination, mantle upwelling, subduction-related metasomatic enrichment, and recycling of ancient components. However, none of the zircon grains from the magmatic suites possess any metamorphic overgrowth, or neoformed metamorphic grains, suggesting that the tectonothermal events during this period were mostly related to intraplate magmatism. Thus, it is clear that the formation of the Early Cretaceous gold is most likely associated with intracontinental extensional tectonics along the edge of an ancient Precambrian block, rather than typical Phanerozoic orogenic gold deposits that form during accretionary orogenesis in rocks no more than a couple of hundred million years older than the ores.

Another intriguing factor is the contrast in the nature and extent of gold mineralization between the western (Luxi) and eastern (Jiaodong) parts of Shandong province (Fig. 1; Guo et al., 2013). The Moho depth on both sides of the Tan-Lu fault is broadly similar with only a minor variation across the fault zone. The lithosphere-asthenosphere boundary in the Jiaodong region is shallower than that in the Luxi area. A synthesis of the available geochemical and isotopic characteristics shows that the mantle beneath the Luxi area is mainly of EM1 (enriched mantle 1) type, close to the Tan-Lu fault it shows mixed EM1 and EM2 features, and beneath the Jiaodong area it is mainly of EM2 type. Thus the Luxi area is dominated by a more ancient lithospheric mantle compared to the extensively modified lithospheric mantle and shallower asthenosphere beneath the Jiaodong area. Guo et al. (2013) interpreted the distinct contrast in gold endowment across the Tan-Lu fault, with abundant gold mineralization in the Jiaodong region, to be a clear reflection of the contrasting tectonic histories that are defined by the distinct mantle types.

Some type of mantle fluid associated with the gold mineralization has been implicated by many workers. This conclusion has most commonly been supported by data on rare gas isotope ratios for fluids extracted from inclusions in ore-bearing quartz veins (e.g., Zhang et al., 2002, 2008; Mao et al., 2008). However, the gas data only suggest the source of species such as Ar and He, and not the source of the major fluid components and the metals; these may or may not be quite different, and therefore such data alone are not definitive of source region(s) for the main ore components. The ore-hosting faults may be deep, as supported by their probable association with the mantle tapping Tan-Lu fault system and the association of lamprophyre dikes along many of the faults that are exposed in the gold mines, and thus they will focus both gases from the mantle and fluids and melts from shallower crustal levels (Guo et al., 2013). Along the San Andreas fault system, for example, both mantle and metamorphic fluids are identified (Pili et al., 2011). In general, mantle rare gas data are reported for many important mineral deposits along major faults, whereas most components in the ore deposits are commonly of a crustal origin. In Jiaodong, for example, the heavy sulfur isotope data for the gold deposits are inconsistent with a simple mantle source for the sulfur.

Although many workers have suggested that meteoric waters were important in ore formation (Yao et al., 2002; L.C. Zhang et al., 2003; J.H. Yang et al., 2008; L.Q. Yang et al., 2008), arguments may be made against such meteoric water involvement. The proposed meteoric water source is typically solely based upon stable isotope data from bulk extraction of fluid inclusions from vein quartz in structurally controlled ore deposits. Such measurements are typically not definitive because they will contain fluid from both ore-related inclusions and many later generations of inclusions that are unrelated to ore and were trapped during uplift from formation depths to the surface. This explains the range of δD from about -100 to -30 per mil (Yao et al., 2002) for the Jiaodong gold deposits, which is commonly used to suggest that downward convection of surface waters was significant in the ore-forming process. Also, some δ^{18}O values measured for quartz are as light as $+11$ per mil, which yield calculated fluid values lower than those characteristic of deep crustal fluids. The low δ^{18}O fluid values have additionally led to suggestions of meteoric water input. However, quartz from many lode gold deposits hosted by granitoids is typically slightly depleted in ^{18}O due to the minor amount of isotopic exchange between a relatively enriched fluid and depleted igneous rock at the site of auriferous quartz vein formation.

Therefore, in summary, certain straightforward and commonly applied models for ore formation in the Jaiodong region can be ruled out based on the following observations:

1) The source of metals and fluid components, including, O, H, and S, cannot be the Late Archean and Paleoproterozoic basement rocks because these components would have been lost from the rocks when they were metamorphosed 2 b.y. before the gold event.
2) A significant meteoric water component to ore formation is not definitive based on the hydrogen isotope data because bulk extraction analyses of fluid inclusion waters reflect multiple sources (e.g., Pickthorn et al., 1987). Furthermore, the isotopically heavy oxygen isotope data of the ore fluids cannot reflect a significant meteoric water component except under very low water:rock ratios, which are atypical of structurally controlled ore deposits.
3) The heavy sulfur isotope data are not permissive of an original mantle source for the ore-transporting sulfur in the hydrothermal fluids.
4) The Late Jurassic granitoids, with a significant lower crustal component, are at least 25 m.y. older than the gold deposits, although both are associated with the NE-trending fault systems. There can be no genetic association.
5) The Early Cretaceous Gouojialing granitoids, with a significant mantle component, overlap in age with the ca. 126–120 Ma gold event. However, because the spatial association of these granitoids with the regional distribution of the gold ores and controlling structures is poor, a genetic association is unlikely.

6. Permissive scenarios for gold formation

The above-described constraints prevent the application of the more typical ore deposit genetic models in defining the formation of the Jiaodong gold deposits. The structural setting of the ores, mineralization style, ore and alteration assemblages, and fluid chemistry suggest a regional fluid flow event that generally characterizes the metamorphic model for orogenic gold (Groves et al., 1998; Goldfarb et al., 2005). But, in contrast to the model for Phanerozoic orogenic gold, the Precambrian host rocks were metamorphosed to high-grade conditions at least a couple of billion years before ore formation. Other genetic models have emphasized a combination of meteoric and/or magmatic fluids in ore formation (Yao et al., 2002; Fan et al., 2007; Mao et al., 2008). But the deposit distribution and mineralization styles are atypical of such proximal magmatically driven hydrothermal systems, there is a poor spatial or temporal correlation between the ores and coeval igneous rocks, and the stable isotope data do not support such a scenario. Clearly a distinct model for ore formation is required for this unique setting for the gold lodes, irrespective of whether one wants to classify the Jiaodong ores as orogenic gold deposits or, alternatively, label these as a distinct deposit type. Or, in other words, how does one produce a hydrothermal fluid that is identical to a typical ore-forming fluid well proven to be released via Barrovian metamorphism (e.g., Pitcairn et al., 2006), but, at least in the case of Jiaodong, cannot be sourced in the upper crust?

6.1. Metamorphic fluid expulsion within a subduction zone

If the ore-forming fluids and metals were not derived from the basement rocks or Guojialing suite of intrusions in the Jiaodong area, then the most logical source is new material added below the basement rocks. An exceptionally large transient fluid flux is required, which is eventually focused into the deep-seated Jiaodong fault zones, with a mixed H_2O-CO_2±CH_4 composition and significant H_2S for the transport of enormous amounts of gold. Such a source could be associated with the dehydration and decarbonization of a subducting paleo-Pacific plate with its underthrusted oceanic lithosphere and overlying marine sediments (Fig. 5). Dehydration of such subducted material generally occurs at depths between 30 and 150 km and as the slab reaches temperatures in excess of 400 °C, at distances a few hundred kilometers landward of the trench (Saffer and Tobin, 2011; Grove et al., 2012). Such fluids may migrate up-dip, either along faults, within permeable strata, or at the slab-mantle wedge interface (Kawano et al., 2011; Saffer and Tobin, 2011). They may (1) interact with and hydrate a narrow corner of the mantle wedge (Peacock, 2009 and see below Section 6.2), (2) remain as a free phase in a compressional regime as observed in the Cascadia subduction zone (e.g., Hyndman, 1995), or (3) enter directly into deep-seated fault zones and move upward to the shallow crust (e.g., Manning, 2004). If present as a free phase, then these fluids would be trapped in pore spaces until changes in stress enhance hydrofracturing and fluid focusing, perhaps causing significant seismic slip and a massive fluid flux in a brief time window, such as at ca. 126–120 Ma in Jiaodong. If flow is directly into the Tan-Lu fault system, then a major and distinct thermal event was needed to have locally heated a part of the slab and cause devolatilization of the oceanic lithosphere and sediments at ca. 125 Ma. A more localized asthenospheric upwelling, perhaps enhanced by a shift from the broad NW–SE extensional stress regime to the more NE-oriented extension and resulting transcurrent motion along the Tan-Lu fault system (e.g., Mercier et al., 2007), is one possible mechanism for a rapid breakdown of volatile phases within the subducting oceanic crust.

The CO_2 and CH_4 in fluid inclusion from the Jiaodong deposits could have been derived from breakdown of organic matter or metamorphism of carbonate sediments, both of which were possible carbon reservoirs. Guo et al. (2013) indicated an EM2 enriched mantle below the gold-rich part of eastern Shandong province, which is a type of mantle that is widely interpreted to reflect the presence of subducted continental sediments entering a trench (Condie, 2005). Gorman et al. (2006) showed that the loss of CO_2 from the sediments, and to a lesser degree from metabasalt at the top to the slab, is expected at depths <100 km in a forearc region. They note that much of the decarbonization may take place where the slab intersects the nose of the mantle wedge. Any water released by associated dehydration can further enhance the decarbonation reactions (e.g., Rumble et al., 1982). Carbonate-rich platform rocks that occur along the leading edge of the subducted Yangtze plate comprise some of the Mesozoic lithosphere added to the base of the Jiaodong area crust (Gao et al., 2013). An abnormally hot late Mesozoic thermal event below Jiaodong may not have only enhanced devolatilization in shallow parts of the paleo-Pacific subduction zone, but also led to substantial decarbonization of any limestone in the hangingwall to the downgoing slab.

There is also no reason why such metamorphosed subducted material cannot also release significant H_2S due to the desulfidization breakdown of marine pyrite; as stated above, a large part of the sulfur must have had a non-mantle origin. Because the basement rocks of the crust have lost most of their mobile sulfur during Precambrian high-grade metamorphism, the only feasible source for ^{34}S-enriched sulfur must be the subducted sediments. A possible source for the gold itself would also be the devolatilization of subducting material, with the gold being initially released from the marine pyrite and carried upward by the H_2S.

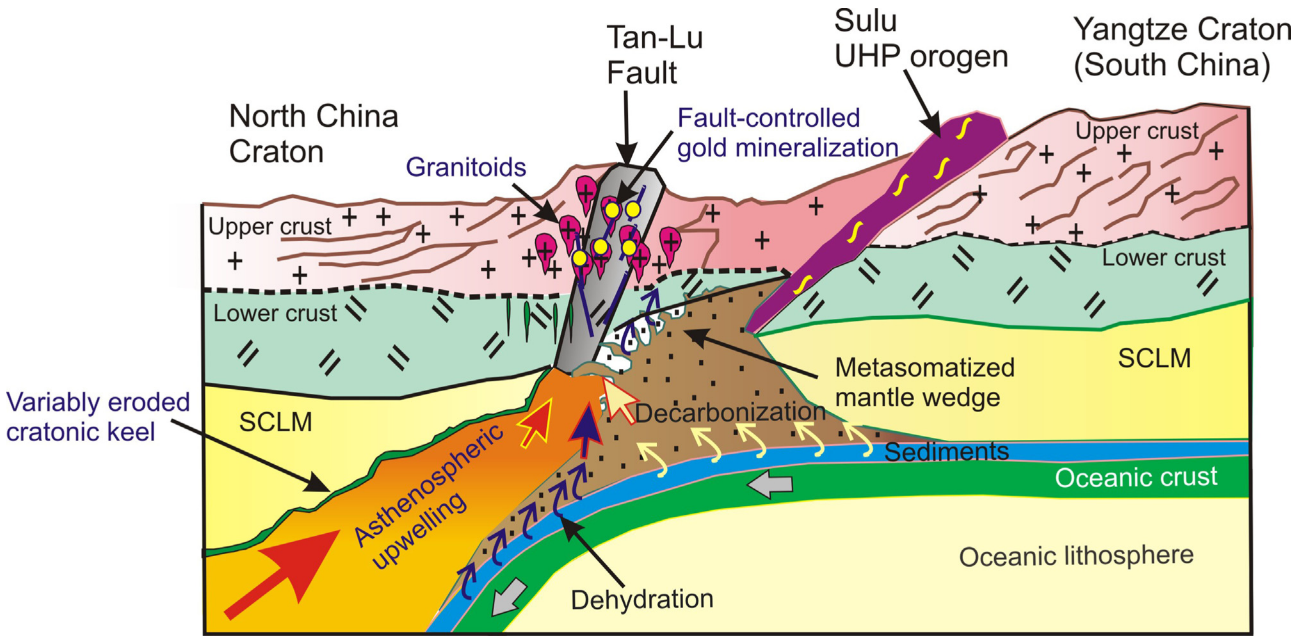

Figure 5. Cartoon showing the most permissive scenarios for Early Cretaceous gold formation in the Jiaodong gold province. Gold formation post-dated the initial delamination of the subcontinental lithospheric mantle (SCLM), Yanshanian deformation, and Jurassic magmatism in the Jiaodong region by 30–50 m.y. The source of the fluids and metal may have been from a ca. 125 Ma dehydration, decarbonization, and desulfidation of subducting sediment and/or the underlying basalt of the subducting paleo-Pacific plate, particularly if a relatively low slab angle characterized late Mesozoic subduction. Fluids would have been channeled into the continental-scale Tan-Lu fault system, which is rooted in the asthenospheric mantle below the greatly thinned lithosphere. Alternatively, released fluid and metal may have been temporarily stored in the fertilized mantle wedge for tens of millions of years and subsequently released into the Tan-Lu fault system by some type of heating event in the wedge at ca. 125 Ma.

6.2. Devolatilization of enriched mantle wedge

An equally permissive alternative to a metamorphic ore-forming fluid sourced from a downgoing paleo-Pacific plate would be a regional fluid derived from devolatilization of the paleo-Pacific mantle wedge (Fig. 5). The subduction process delivers volatiles and incompatible trace elements to the mantle (Hermann et al., 2013), and these commonly are stored in serpentinite minerals in a mantle wedge (e.g., Audet et al., 2009). Devolatilization of a mantle wedge that has been hydrated and serpentinized during subduction can release in excess of 10% H_2O (Peacock, 2001; Fulton and Saffer, 2009). If a significant amount of the fluids expelled from the down-going paleo-Pacific slab migrates upward towards the mantle wedge, then a relative small area of highly serpentinized mantle will form in a narrow area near the top of the down-going slab.

This metamorphic fertilization of a small domain of the mantle is also possible by fluids moving directly upward into the asthenospheric mantle (e.g., Manning, 2004), but as pressures increase down-dip along the subduction zone, rather than hydrating the mantle wedge, much of the fluid may be miscible with melts being produced. Thus, at temperatures of only about 750 °C, but with slab pressures of about 3–3.5 GPa, any melt formed from subducting metapelites or gneiss will be totally miscible with aqueous fluid (Hermann et al., 2006); in other words, once a slab is subducted below a few hundred kilometers, it no longer could be a direct fluid source for the Jiaodong gold deposits. Also, as temperatures rise to approximately 800–900 °C, hydrous minerals are no longer stable (Grove et al., 2012) and fluid will be released into a mantle wedge. Therefore, at depths between about 50 and 200 km, devolatilization of serpentinized mantle rocks in subducting oceanic crust forms an immiscible hydrothermal fluid (Peacock, 2001). Part of this mantle fluid could be released into the Tan-Lu fault system that continues downward into the asthenosphere (e.g., Deng et al., 1999). Under very hot conditions, such as those in a mantle wedge at abnormally shallow depths below the decratonized eastern part of the North China block, a large fluid volume may have been released from a small area of the mantle wedge above the subducting paleo-Pacific plate and channeled into the nearby Tan-Lu fault zone.

The other volatile species noted in the ore-forming fluids, in addition to the H_2O, also must be consistent with a mantle fluid model. Ascending mantle fluids along zones of active seismicity are characterized by a high CO_2 concentration (e.g., Weinlich et al., 2013). Data from deep drill holes along the San Andreas fault system indicate with little doubt that many mantle fluids are indeed enriched in CO_2 (Fulton and Saffer, 2009). Santosh et al. (2009) noted that such SCLM may be an important CO_2 reservoir, rather than just the asthenospheric mantle wedge. There is a significant enrichment of volatiles in mantle lherzolite xenoliths from Cenozoic basalts throughout the eastern half of the North China block, suggesting significant volatile loss into the young SCLM from the paleo-Pacific slab (Zhang et al., 2007; Tang et al., 2013). Thus either the mantle wedge or overlying SCLM may be potential ore fluid sources.

If the mantle is the source of the H-O-C-rich fluid in Jiaodong, then the isotopically heavy sulfur must nevertheless have a significant crustal contribution. Thus as in the above subduction zone model for the fluids, the sulfur in the Jiaodong sulfide minerals would be that which is initially released from subducting marine sediments. Serpentinization of the overlying mantle would include formation of Ni- and Fe-rich sulfide minerals that contain elevated gold released with the H_2S from the marine pyrite. Eventual heating of the mantle wedge or SCLM would release sulfur and gold from this “enriched mantle”, with a sulfur isotope signature that is consistent with pyrite formed in a marine environment, rather than of direct mantle origin.

6.3. Constraints on subduction-related models for Jiaodong

One point of concern regarding a model of fluid release from a subducted slab or hydrated mantle is that presently the top to the stagnant slab below the Jiaodong area is located at about 400 km depth (e.g., Huang and Zhao, 2006). At such a depth, it would be unlikely that fluids could directly metasomatize a new lithospheric mantle or directly enter into the deep-seated Tan-Lu fault system. Any released fluid would instead lead to melting of the overlying asthenosphere and ascending mafic magmas.

Slab geometry, however, likely was different 100–200 m.y. ago during subduction. The slab originally was subducted through much shallower levels of the asthenosphere and eventually rolled back and sank to its present depth, which might be correlated with the Late Jurassic–Early Cretaceous shift to E–W extension. Unfortunately, it is impossible to be certain about the slab depth below the Jiaodong area in late Mesozoic and the location of forearc mantle serpentinization. Whether it was at 50 km or 200 km depends on the past slab subduction angle that is poorly defined. In support of a shallower depth and perhaps some type of flat slab subduction is the fact that (1) a voluminous amount of fluid was channeled into the Tan-Lu fault system, rather than forming melts and (2) no well-defined subduction-related arc developed, although there was nevertheless significant coeval magmatism.

7. Classification and conclusions

The available geological, geochronological, and tectonic information from Jiaodong indicates that the gold metallogeny in the Shandong province occurred in an extensional tectonic regime within a Precambrian continental block that was cratonized nearly 2 b.y. prior to the main mineralization event. Some workers have attempted to correlate the metallogeny with processes of craton destruction and thinning, commencing with the collision between the North China block and the Yangtze “craton” in the South China block and intensifying through Pacific plate subduction from the east (e.g., Li and Santosh, 2013; Guo et al., 2013). Although the various magmatic suites with a wide range of ages in Jiaodong might correlate with this tectonic milieu, the narrow timespan during which the bulk of the gold mineralization occurred (ca. 120–125 Ma) requires mechanisms that account for intense fluid activity over a restricted time interval that mobilized and concentrated the gold both in veins (Linglong-type) and in alteration halos associated with fracture systems (Jiaojia-type). Obviously, the broad range of ages obtained from the magmatic suites in Jiaodong, as well as the considerably large spread in the time range proposed for the lithospheric destruction, do not directly correlate with the focused fluid activity within a restricted time range that generated these unique gold deposits. Although some of the conventional features of orogenic-type gold deposits are associated with the Jiaodong mineralization, it is clear that the major subduction-accretion-collision orogeny in the region had already culminated by the end of the Paleoproterozoic, when North China was finally cratonized (Zhai and Santosh, 2011, 2013), several billion years before the gold event on the Shandong Peninsula.

Thus, the giant gold deposits of Jiaodong open up further discussions and the possibility that they represent a different, unique, and not yet fully characterized class of gold deposits. The North China block provides a rare example of an Archean craton that underwent differential destruction during the Phanerozoic, and was caught up within the zone of a series of tectonic disturbances and over a highly perturbed mantle. Continental collision and deep subduction, delamination, slab dehydration, and lithospheric thinning are among the various geodynamic processes recorded in this region. They are all broadly part of the gold event, but do not address a specific fluid/metal source or reason for voluminous fluid flux across the Jiaodong region over a few million years of time.

Potential fluid and metal reservoirs include metamorphism of the subducted paleo-Pacific lithosphere and its overlying sediments, as well as devolatilization of a hydrated mantle wedge or SCLM. Either process could theoretically provide the required fluid production, fluid chemistry, and metal. Tectonic inversion and mantle upwelling in the Early Cretaceous (e.g., Zhai and Santosh, 2013) would have provided the heat at shallow levels required by the two scenarios. The protracted nature of the structurally controlled gold event, particularly in contrast to the more temporally and spatially extensive Early Cretaceous "great igneous event" (Wu et al., 2005), suggests a very specific trigger for fluid migration. Such a cause may well have been major changes in the stress regime along the Tan-Lu fault system relating to reorganization of the paleo-Pacific plate configuration at ca. 125 Ma (Goldfarb et al., 2007).

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References

Audet, P., Bostock, M.G., Christensen, N.I., Peacock, S.M., 2009. Seismic evidence for overpressured subducted oceanic crust and megathrust fault sealing. Nature 457, 76–78.

Bohlke, J.K., 1988. Carbonate-sulfide equilibria and "stratabound" disseminated epigenetic gold mineralization: a proposal based on examples from Allegheny, California, U.S.A. Applied Geochemistry 3, 499–516.

Cai, Y.C., Fan, H.R., Hu, F.F., Yang, K.F., Lan, T.G., Yu, H., Liu, Y.M., 2011. Ore forming fluids, stable isotope and mineralizing age of the Hubazhuang gold deposit, Jiaodong Peninsula of eastern China. Acta Petrolei Sinica 27 (5), 1341–1351 (in Chinese with English abstract).

Cai, Y.C., Fan, H.R., Santosh, M., Liu, X., Hu, F.F., Yang, K.F., Lan, T.G., Yang, Y.H., Liu, Y., 2013. Evolution of the lithospheric mantle beneath the southeastern North China Craton: Constraints from mafic dykes in the Jiaobei terrain. Gondwana Research 24, 601–621.

Charles, N., Augier, R., Gumiaux, C., Monie, P., Chen, Y., Faure, M., Zhu, R.X., 2013. Timing, duration and role of magmatism in wide rift systems: Insights from the Jiaodong Peninsula (China, East Asia). Gondwana Research 24, 412–428.

Charles, N., Gumiaux, C., Augier, R., Chen, Y., Zhu, R.X., Lin, W., 2011. Metamorphic core complexes vs. synkinematic plutons in continental extension setting: Insights from key structures (Shandong Province, eastern China). Journal of Asian Earth Sciences 40, 261–278.

Chen, Y.J., Pirajno, F., Qi, J.P., 2005. Origin of gold metallogeny and sources of ore-forming fluids, Jiaodong Province, eastern China. International Geology Review 47, 530–549.

Cline, J.S., Hofstra, A.H., Muntean, J.L., Tosdal, R.M., Hickey, K.A., 2005. Carlin type gold deposits in Nevada: critical geologic characteristics and viable models. In: Economic Geology 100th Anniversary Volume, pp. 451–484.

Condie, K.C., 2005. Earth as an Evolving Planetary System. Elsevier Academic Press, Burlington, MA, 447 pp.

Cox, D.P., Singer, D.A., Barton Jr., P.B., 1986. Mineral deposit models. In: Cox, D.P., Singer, D.A. (Eds.), Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, pp. 1–10.

Davis, G.A., Darby, B.J., 2010. Early Cretaceous overprinting of the Mesozoic Daqing Shan fold-and-thrust belt by the Hohhot metamorphic core complex, Inner Mongolia, China. Geoscience Frontiers 1, 1–20.

Deng, J., Yang, L.Q., Zhai, Y.S., Wang, J.P., Fang, Y., 1999. Crust-mantle interaction an dynamics of ore metallogenic system of Jiaodong gold ore concentrating area, China. Journal of China University of Geosciences 1, 39–46.

de Voogd, B., Serpa, L., Brown, L., 1988. Crustal extension and magmatic processes: COCORP profiles from Death Valley and the Rio Grande rift. Geological Society of America Bulletin 100, 1550–1567.

Fan, H.R., Hu, F.F., Yang, J.H., Zhai, M.G., 2007. Fluid evolution and large-scale gold metallogeny during Mesozoic tectonic transition in the Jiaodong Peninsula, eastern China. In: Geological Society London Special Publication 280, pp. 303–316.

Fan, H.R., Zhai, M.G., Xie, Y.H., Yang, J.H., 2003. Ore-forming fluids associated with granite-hosted gold mineralization at the Sanshandao deposit, Jiaodong gold province, China. Mineralium Deposita 38, 739–750.

Faure, M., Lin, W., Chen, Y., 2012. Is the Jurassic (Yanshanian) intraplate tectonics of North China due to westward indentation of the North China block? Terra Nova 24, 456–466.

Frimmel, H.E., Groves, D.I., Kirk, J., Ruiz, J., Chesley, J., Minter, W.E.L., 2005. The formation and preservation of the Witwatersrand goldfields, the world's largest gold province. In: Economic Geology 100th Anniversary Volume, pp. 769–797.

Fulton, P.M., Saffer, D.M., 2009. Potential role of mantle-derived fluids in weakening the San Andreas Fault. Journal of Geophysical Research 114, B07408. http://dx.doi.org/10.1029/2008JB006087.

Gao, S., Rudnick, R.L., Xu, W.L., Yuan, H.L., Liu, Y.S., Waler, R.J., Puchtel, I.S., Liu, X.M., Huang, H., Wang, X.R., Yang, J., 2008. Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton. Earth and Planetary Science Letters 270, 41–53.

Gao, S., Rudnick, R.L., Yuan, H.L., Liu, X.M., Liu, Y.S., Xu, W.L., Ling, W.L., Ayers, J., Wang, X.C., Wang, Q.H., 2004. Recycling lower continental crust in the North China craton. Nature 432, 892–897.

Gilder, S.A., Leloup, P.H., Courtillot, V., Chen, Y., 1999. Tectonic evolution of the Tancheng-Lujiang (Tan-Lu) fault via Middle Triassic to Early Cenozoic paleomagnetic data. Journal of Geophysical Research B104, 15365–15390.

Goldfarb, R.J., Baker, T., Dube, B., Groves, D.I., Hart, C.J.R., Robert, F., Gosselin, P., 2005. Distribution, character, and genesis of gold deposits in metamorphic terranes. In: 100th Anniversary Volume of Economic Geology, pp. 407–450.

Goldfarb, R.J., Groves, D.I., Gardoll, S., 2001. Orogenic gold and geologic time: a synthesis. Ore Geology Reviews 18, 1–75.

Goldfarb, R.J., Hart, C.J.R., Davis, G., Groves, D.I., 2007. East Asian gold—Deciphering the anomaly of Phanerozoic gold in Precambrian cratons. Economic Geology 102, 341–346.

Goldfarb, R.J., Santosh, M., Deng, J., Yang, L.Q., 2013. The giant Jiaodong gold deposits, China: Orogenic gold in a unique tectonic setting or a unique gold deposit type?. In: Geological Society of America Abstracts with Programs, 118–8.

Gorman, P.J., Kerrick, D.M., Connolly, J.A.D., 2006. Modeling open system metamorphic decarbonation of subducting slabs. Geochemistry, Geophysics, Geosystems 7, Q04007. http://dx.doi.org/10.1029/2005GC001125.

Grove, T.L., Till, C.B., Crawczynski, M.J., 2012. The role of H_2O in subduction zone magmatism. Annual Review of Earth and Planetary Sciences 40, 413–439.

Groves, D.I., Condie, K.C., Goldfarb, R.J., Hronsky, J.M.A., Vielreicher, R.M., 2005. Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits. Economic Geology 100, 203–244.

Groves, D.I., Goldfarb, R.J., Gebre-Mariam, M., Hagemann, S.G., Robert, F., 1998. Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews 13, 7–27.

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.

Guo, P., Santosh, M., Li, S.R., 2013. Geodynamics of gold metallogeny in the Shandong Province, NE China: An integrated geological, geophysical and geochemical perspective. Gondwana Research 24, 1172–1202.

Hall, G., 2002. A Shandong exploration model. In: Wang, Y.W., Zhu, F.S. (Eds.), Proceedings of the Golden City International Symposium on Gold Geology and Exploration in Zhaoyuan. Shandong Zhaojin Group, Zhaoyuan, China, pp. 63–64.

He, Z., Yuan, H.Y., Xu, J.H., 1989. Fluid inclusion geochemistry in minerals obtained from Zhao-Ye gold metallogenic belt, Shandong Province. Journal of Geochemical Exploration 33, 121–133.

Hermann, J., Spandler, C., Hack, A., Korsakov, A.V., 2006. Aqueous fluids and hydrous melts in high-pressure and ultra-high pressure rocks: Implications for element transfer in subduction zones. Lithos 92, 399–417.

Hermann, J., Zheng, Y.F., Rubatto, D., 2013. Deep fluids in subducted continental crust. Elements 9, 281–287.

Hou, Q.L., Liu, Q., Zhang, H.Y., Zhang, X.H., Li, J., 2012. The Mesozoic tectonic dynamics and chronology in the eastern North China block. Journal of Geological Research http://dx.doi.org/10.1155/2012/291467. Article ID 291467, 11 pp.

Hu, F.F., Fan, H.R., Jiang, X.H., Yang, K.F., 2012. Fluid inclusions in different depths at Sanshandao gold deposit, Jiaodong Peninsula: Implication for ore genesis. In: Asian Current Research on Fluid Inclusions, ACROFI IV, Abstracts, Brisbane, Australia, pp. 37–38.

Hu, F.F., Fan, H.R., Yang, J.H., Wan, Y.S., Liu, D.Y., Zhai, M.G., Jin, C.W., 2004. Hydrothermal U-Pb zircon Shrimp dating ore-forming age of the lode gold-quartz-sulphide veins in Rushan, Jiaodong Peninsula. Chinese Science Bulletin 49, 1191–1198.

Hu, F.F., Fan, H.R., Zhai, M.G., Jin, C.W., 2006. Fluid evolution in the Rushan lode gold deposit of Jiaodong Peninsula, eastern China. Journal of Geochemical Exploration 89, 161–164.

Huang, J., Zhao, D., 2006. High-resolution mantle tomography of China and surrounding regions. J. Geophys. Res. 111. http://dx.doi.org/10.1029/2005JB004066.

Hyndman, R.D., 1995. The Lithoprobe corridor across the Vancouver Island continental margin: the structural and tectonic consequences of subduction. Canadian Journal of Earth Sciences 32, 1777–1802.

Jahn, B.M., Liu, D.Y., Wan, Y.S., Song, B., Wu, J.S., 2008. Archean crustal evolution of the Jiaodong Peninsula, China, as revealed by zircon SHRIMP geochronology, elemental and Nd-isotope geochemistry. American Journal of Science 308, 232–269.

Kawano, S., Katayama, I., Okazaki, K., 2011. Permeability anisotropy of serpentinite and fluid pathways in a subduction zone. Geology 39, 939–942.

Law, J.D.M., Phillips, G.N., 2005. Hydrothermal model for Witwatersrand gold. In: Economic Geology 100th Anniversary Volume, pp. 799–812.

Li, J.W., Vasconcelos, P.M., Zhou, M.F., Zhao, X.F., Ma, C.Q., 2006. Geochronology of the Pengjiakuang and Rushan gold deposits, Eastern Jiaodong gold province, Northeastern China: Implications for regional mineralization and geodynamic setting. Economic Geology 101, 1023–1038.

Li, Q.L., Chen, F.K., Yang, J.H., Fan, H.R., 2008. Single grain pyrite Rb–Sr dating of the Linglong gold deposit, Eastern China. Ore Geology Reviews 34, 263–270.

Li, S.R., Santosh, M., 2013. Metallogeny and craton destruction: records from the North China Craton. Ore Geology Reviews. http://dx.doi.org/10.1016/j.oregeorev.2013.03.002.

Li, S.Z., Suo, Y.H., Santosh, M., Dai, L.M., Liu, X., Yu, S., Zhao, S.J., Jin, C., 2013a. Mesozoic to Cenozoic intracontinental deformation and dynamics of the North China Craton. Geological Journal. http://dx.doi.org/10.1002/gj.2500.

Li, X.C., Fan, H.R., Santosh, M., Hu, F.F., Yang, K.F., Lan, T.G., 2013b. Hydrothermal alteration associated with Mesozoic granite-hosted gold mineralization at the Sanshandao deposit, Jiaodong Gold Province, China. Ore Geology Reviews 53, 403–421.

Lin, W., Faure, M., Chen, Y., Ji, W.B., Wang, F., Wu, L., Charles, N., Wang, J., Wang, Q.C., 2013. Late Mesozoic compressional to extensional tectonics in the Yiwulüshan massif, NE China and its bearing on the evolution of the Yinshan–Yanshan orogenic belt: Part I: Structural analyses and geochronological constraints. Gondwana Research 23, 54–77.

Liou, J.G., Zhang, R.Y., Wang, X., Ede, E.A., Ernst, W.G., Maruyama, S., 1996. Metamorphism and tectonics of high-pressure and ultrahigh-pressure belts in the Dabie-Sulu region, China. In: Yin, A., Harrison, M. (Eds.), The Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 300–344.

Liu, S., Hu, R.Z., Gao, S., Feng, C.X., Yu, B.B., Qi, Y.Q., Wang, T., Feng, G.Y., Coulson, I.M., 2009. Zircon U–Pb age, geochemistry and Sr–Nd–Pb isotopic compositions of adakitic volcanic rocks from Jiaodong, Shandong Province, Eastern China: constraints on petrogenesis and implications. Journal of Asian Earth Sciences 35, 445–458.

Lu, G.X., Kong, Q.C., 1993. Geology of Linglong-Jiaojia Type of Gold Deposits in Jiaodong Area. Science Press, Beijing, pp. 1–253 (in Chinese with English abstract).

Lu, H.Z., Archambault, G., Li, Y.S., Wei, J.X., 2007. Structural geochemistry of gold mineralization in the Linglong-Jiaojia district, Shandong Province, China. Chinese Journal of Geochemistry 26, 215–234.

Manning, C.E., 2004. The chemistry of subduction-zone fluids. Earth and Planetary Science Letters 223, 1–16.

Mao, J.W., Wang, Y.T., Li, H.M., Pirajno, F., Zhang, C.Q., Wang, R.T., 2008. The relationship of mantle-derived fluids to gold metallogenesis in the Jiaodong Peninsula: evidence from D-O-C-S isotope systematic. Ore Geology Reviews 33, 361–381.

Meert, J.G., 2012. What's in a name? The Columbia (Paleopangaea/Nuna) supercontinent. Gondwana Research 21, 987–993.

Meng, Q.R., 2003. What drove late Mesozoic extension of the northern China–Mongolia tract? Tectonophysics 369, 155–174.

Mercier, J.L., Hou, M.J., Vergely, P., Wang, Y.M., 2007. Structural and stratigraphical constraints on the kinematic history of the southern Tan-Lu fault zone during the Mesozoic, Anhui province, China. Tectonophysics 439, 33–66.

Metcalfe, I., 2013. Gondwana dispersion and Asian accretion: tectonic and palaeogeographic evolution of eastern Tethys. Journal of Asian Earth Sciences 66, 1–33.

Metelkin, D.V., Vernikovsky, V.A., Kazansky, A.Y., Wingate, M.T.D., 2010. Late Mesozoic tectonics of Central Asia based on paleomagnetic evidence. Gondwana Research 18, 400–419.

Milia, A., Torrente, M.M., 2011. The possible role of extensional faults in localizing magmatic activity: a crustal model for the Campanian Volcanic Zone (eastern Tyrrhenian Sea, Italy). Journal of the Geological Society 168, 471–484.

Peacock, S.M., 2001. Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle? Geology 29, 299–302.

Peacock, S.M., 2009. Thermal and metamorphic environment of subduction zone episodic tremor and slip. Journal of Geophysical Research 114, B00A07.

Phillips, G.N., Powell, R., 1993. Link between gold provinces. Economic Geology 88, 1084–1098.

Phillips, G.N., Powell, R., 2009. Formation of gold deposits: review and evaluation of the continuum model. Earth-Science Reviews 94, 1–21.

Pickthorn, W.J., Goldfarb, R.J., Leach, D.L., 1987. Comment and reply on "Dual origin of lode gold deposits in the Canadian Cordillera". Geology 15, 471–473.

Pili, E., Kennedy, B.M., Conrad, M.E., Gratier, J.-P., 2011. Isotopic evidence for the infiltration of mantle and metamorphic CO_2-H_2O fluids from below in faulted rocks from the San Andreas fault system. Chemical Geology 281, 242–252.

Pitcairn, I.K., Teagle, D.A.H., Craw, D., Olivo, G.K., Kerrich, R., Brewer, T.S., 2006. Sources of metals and fluids in orogenic gold deposits; Insights from the Otago and Alpine schists, New Zealand. Economic Geology 101, 1525–1546.

Poulsen, K.H., Taylor, B.E., Robert, F., Mortensen, J.K., 1990. Observations on gold deposits in North China Platform. In: Current Research, Part A: Geological Survey of Canada Paper 90–1A, pp. 33–44.

Qiu, X.P., Wang, S.H., Zou, Q., 2008. Metallogenetic effect of Tan–Lu fault on gold accumulation area in Shandong Peninsula, China. Anhui Geology 18, 16–19 (in Chinese with English abstract).

Qiu, Y.M., Groves, D.I., McNaughton, N.J., Wang, L.J., Zhou, T., 2002. Nature, age and tectonic setting of granitoid-hosted orogenic gold deposits of the Jiaodong Peninsula, eastern North China craton, China. Mineralium Deposita 37, 283–305.

Rumble, D., Ferry, J.M., Hoering, T.C., Boucot, A.J., 1982. Fluid flow during metamorphism at the Beaver Brook fossil locality, New Hampshire. American Journal of Science 282, 886–919.

Saffer, D.M., Tobin, H.J., 2011. Hydrogeology and mechanics of subduction zone forearcs: fluid flow and pore pressure. Annual Review of Earth and Planetary Sciences 39, 157–186.

Santosh, M., 2010. Assembling North China Craton within the Columbia supercontinent: the role of double-sided subduction. Precambrian Research 178, 149–167.

Santosh, M., Maruyama, S., Komiya, T., Yamamoto, S., 2010. Orogens in the evolving Earth: from surface continents to 'lost continents' at the core mantle boundary. In: Geological Society of London Special Publications 338, pp. 77–116.

Santosh, N., Maruyama, S., Omori, S., 2009. A fluid factory in solid Earth. Lithosphere 1, 29–33.

Shen, Y.C., Zeng, Q.D., Liu, T.B., Li, G.M., Shen, P., Sun, X.Y., 2003. The Tan–Lu fault zone and gold ore metallogenesis. Global Geology 22, 41–46.

Stuwe, K., 1998. Tectonic constraints on the timing relationships of metamorphism, fluid production and gold-bearing quartz vein emplacement. Ore Geology Reviews 13, 219–228.

Tang, Y.J., Zhang, H.F., Ying, J.F., Su, B.X., Chu, Z.Y., Xiao, Y., Zhao, X.M., 2013. Highly heterogeneous lithospheric mantle beneath the Central Zone of the North China Craton evolved from Archean mantle through diverse melt refertilization. Gondwana Research 23, 130–140.

Wang, L.G., Qiu, Y.M., McNaughton, N.J., Groves, D.I., Luo, Z.K., Huang, J.Z., 1998. Constraints on crustal evolution and gold metallogeny in the northwestern Jiaodong peninsula, China, from SHRIMP U-Pb zircon studies of granitoids. Ore Geology Reviews 13, 275–291.

Wang, T.J., Yan, F., 2002. Ore fluid evolution and ore prediction of magmatic hydrothermal gold deposits in the Jiaodong area. Journal of Geochemical Exploration 17, 169–174 (in Chinese with English abstract).

Weinlich, F.H., Stejskal, V., Teschner, M., Poggenburg, J., 2013. Geodynamic processes in the NW Bohemian swarm earthquake region, Czech Republic, identified by continuous gas monitoring. Geofluids 13, 305–330.

Windley, B.F., Maruyama, S., Xiao, W.J., 2010. Delamination/thinning of subcontinental lithospheric mantle under eastern China: the role of water and multiple subduction. American Journal of Science 310, 1250–1293.

Wu, F.Y., Lin, J.Q., Wilde, S.A., Zhang, X.O., Yang, J.H., 2005. Nature and significance of the Early Cretaceous giant igneous event in eastern China. Earth and Planetary Science Letters 233, 103–119.

Xu, H., 1998. Genesis and geological and geochemical characteristics of the Qixia gold deposit, Shandong, China. Chinese Journal of Geochemistry 17, 338–345.

Xu, J.W., Zhu, G., 1994. Tectonic models of the Tan–Lu fault zone, eastern China. International Geology Review 36, 771–784.

Yang, J.H., Wu, F.Y., Wilde, S.A., Belousova, E., Griffin, W.L., 2008. Mesozoic decratonization of the North China Block. Geology 36, 467–470.

Yang, J.H., Zhou, X.H., 2001. Rb-Sr, Sm-Nd, and Pb isotope systematics of pyrite: Implications for the age and genesis of lode gold deposits. Geology 29, 711–714.

Yang, K.F., Fan, H.R., Santosh, M., Hu, F.F., Wilde, S.A., Lan, T.G., Lu, L.N., Liu, Y.S., 2012. Reactivation of the Archean lower crust: implications for zircon geochronology, elemental and Sr–Nd–Hf isotopic geochemistry of late Mesozoic granitoids from northwestern Jiaodong Terrane, the North China Craton. Lithos 146–147, 112–127.

Yang, L.Q., Deng, J., Goldfarb, R.J., Zhang, J., Gao, B.F., Wang, Z.L., 2013. $^{40}Ar/^{39}Ar$ geochronological constraints on the formation of the Dayingezhuang gold deposit: new implications for timing and duration of hydrothermal activity in the Jiaodong gold province, China. Gondwana Research. http://dx.doi.org/10.1016/j.gr.2013.07.001.

Yang, L.Q., Deng, J., Zhang, J., Guo, C.Y., Gao, B.F., Gong, Q.J., Wang, Q.F., Jiang, S.Q., Yu, H.J., 2008. Decrepitation thermometry and compositions of fluid inclusions of the Damoqujia gold deposit, Jiaodong gold province, China: implications for metallogeny and exploration. Journal of China University of Geosciences 19, 378–390.

Yang, Q.Y., Santosh, M., Shen, J.F., Li, S.R., 2013. 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 Research. http://dx.doi.org/10.1016/j.gr.2013.06.003.

Yao, Y., Robb, L.J., Anhaeusser, C.R., Ying, H.L., Liu, B.G., Tu, G.Z., 2002. Mesozoic Gold Deposits in the Eastern Shandong Peninsula, P.R. China—Preliminary Geology, Geochemistry and Fluid Inclusion Investigations. In: University of Witwatersrand, Economic Geology Research Institute Information Circular 361, 11 pp.

Zeng, Q.D., Liu, J.M., Liu, H.T., Shen, P., Zhang, L.C., 2006. The ore forming fluid of the gold deposits of Muru gold belt in eastern Shanding, China—a Case Study of Denggezhuang gold deposit. Resource Geology 56, 375–384.

Zhai, M.G., Liu, J.M., Zhang, H.F., Liu, W., Zhu, R.X., 2004. Time-range of Mesozoic tectonic regime inversion in eastern north China block. Science China (D) 34 (2), 151–159.

Zhai, M.G., Santosh, M., 2011. The early Precambrian odyssey of North China Craton: A synoptic overview. Gondwana Research 20, 6–25.

Zhai, M.G., Santosh, M., 2013. Metallogeny of the North China Craton: Link with secular changes in the evolving Earth. Gondwana Research 24, 275–297.

Zhang, H.Y., Hou, Q.L., Cao, D.Y., 2007. Study of thrust and nappe tectonics in the eastern Jiaodong Peninsula, China. Science China D50, 161–171.

Zhang, L.C., Liu, T.B., Shen, Y.C., Zeng, Q.D., Li, G.M., 2003. Structure, isotopes, and 40Ar39Ar dating of the Pengjiakuang gold deposit, Mesozoic Jiaolai basin, eastern China. International Geology Review 45, 691–711.

Zhang, L.C., Sheng, Y.C., Li, H.M., Zeng, Q.D., Li, G.M., Liu, T.B., 2002. Helium and argon isotopic compositions of fluid inclusions and tracing to the source of ore-forming fluids for Jiaodong gold deposits. Acta Petrologica Sinica 18, 559–565.

Zhang, L.C., Zhou, X.H., Ding, S.J., 2008. Mantle-derived fluids involved in large-scale gold mineralization, Jiaodong District, China: constraints provided by the He–Ar and H–O isotopic systems. International Geology Review 50, 472–482.

Zhang, X., Cawood, P.A., Wilde, S.A., Liu, R., Song, H., Li, W., Snee, L.W., 2003b. Geology and timing of mineralization at the Cangshang gold deposit, northwestern Jiaodong Peninsula, China. Mineralium Deposita 38, 141–153.

Zhao, G.C., Sun, M., Wilde, S.A., Li, S., 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth Science Reviews 67, 91–123.

Zhao, H.J., Ma, F.S., Li, G.Q., Zhang, Y.M., Guo, J., 2012. Study of the hydrogeological characteristics and permeability of the Xinli Seabed Gold Mine in Laizhou Bay, Jiaodong Peninsula, China. Environmental Earth Sciences 65, 2003–2014.

Zhao, L., Zheng, T., Lu, G., 2013. Distinct upper mantle deformation of cratons in response to subduction: constraints from SKS wave splitting measurements in eastern China. Gondwana Research 23, 39–53.

Zhao, Z., Zhao, Z.X., Xu, J.R., 2012. Velocity structure heterogeneity and tectonic motion in and around the Tan–Lu fault of China. Journal of Asian Earth Sciences 57, 6–14.

Zhou, T.H., Goldfarb, R.J., Phillips, G.N., 2002. Tectonics and distribution of gold deposits in China—an overview. Mineralium Deposita 37, 249–282.

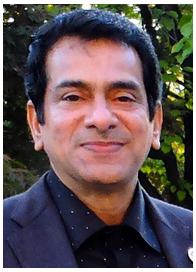
Zhou, T.H., Lu, G., 2000. Tectonics, granitoids, and Mesozoic gold deposits in East Shandong, China. Ore Geology Reviews 16, 71–90.

Zhou, X.H., Yang, J.H., Zhang, L.C., 2003. Metallogenesis of superlarge gold deposits in Jiaodong region and deep processes of subcontinental lithosphere beneath North China Craton in Mesozoic. Science China D46 (Suppl.), 14–25.

Zhu, R.X., Yang, J.H., Wu, F.Y., 2012. Timing of destruction of the North China Craton. Lithos 149, 51–60.

Zhuang, L.J., Wang, R.C., 2009. Temporal–spatial relationship between vein rock and gold mineralization and its indicative significance of Linglong gold field. Gold: Science, Technology 17 (1), 34–37 (in Chinese with English abstract).

Richard J. Goldfarb is a senior research geologist in the Minerals Program of the U.S. Geological Survey, as well as an adjunct professor with the China University of Geosciences Beijing, Colorado School of Mines, and University of Western Australia. He received a B.Sc. (1975) from Bucknell University, M. Sc. (1981) from MacKay School of Mines, and a Ph.D. from the University of Colorado (1989). He is past-President of the Society of Economic Geologists and present Vice President of the International Association for Gondwana Research. Research fields include the geology of gold and tectonics and ore deposits. He has published more than 200 papers in economic geology, is a past recipient of the SEG Silver Medal, past editor-in-chief of Mineralium Deposita, and is presently on the Editorial Boards of Economic Geology, Gondwana Research, GEEA, and Journal of the Geological Society of China.



M. Santosh is Professor at the China University of Geosciences Beijing (China), Specially Appointed Foreign Expert of China, and Emeritus Professor at the Faculty of Science, Kochi University, Japan. B.Sc. (1978) from Kerala University, M.Sc. (1981) from University of Roorkee, Ph.D. (1986) from Cochin University of Science and Technology, D.Sc. (1990) from Osaka City University and D.Sc. (2012) from University of Pretoria. Founding Editor of Gondwana Research as well as the founding Secretary General of the International Association for Gondwana Research. Research fields include petrology, fluid inclusions, geochemistry, geochronology and supercontinent tectonics. Published over 350 research papers, edited several memoir volumes and journal special issues, and co-author of the book ‘Continents and Supercontinents’ (Oxford University Press, 2004). Recipient of National Mineral Award, Outstanding Geologist Award, Thomson Reuters 2012 Research Front Award, Global Talent Award.