Structural control and genesis of gold deposits in the Liaodong Peninsula, northeastern North China Craton

Jianmin Liu, Guochun Zhao, Gang Xu, Deming Sha, Changhao Xiao, Xing Fang, Fuxing Liu, Qi Guo, Hua Yu

PII: S0169-1368(19)30951-5
DOI: https://doi.org/10.1016/j.oregeorev.2020.103672
Reference: OREGEO 103672

To appear in: Ore Geology Reviews

Received Date: 30 October 2019
Revised Date: 3 July 2020
Accepted Date: 7 July 2020

Please cite this article as: J. Liu, G. Zhao, G. Xu, D. Sha, C. Xiao, X. Fang, F. Liu, Q. Guo, H. Yu, Structural control and genesis of gold deposits in the Liaodong Peninsula, northeastern North China Craton, Ore Geology Reviews (2020), doi: https://doi.org/10.1016/j.oregeorev.2020.103672

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier B.V.
Structural control and genesis of gold deposits in the Liaodong Peninsula, northeastern North China Craton

Jianmin Liu\textsuperscript{a, b}, Guochun Zhao\textsuperscript{c}, Gang Xu\textsuperscript{a, b}, Deming Sha\textsuperscript{d}, Changhao Xiao\textsuperscript{a, b}, Xing Fang\textsuperscript{a, b, c}, Fuxing Liu\textsuperscript{e}, Qi Guo\textsuperscript{c}, Hua Yu\textsuperscript{c}

\textsuperscript{a} Laboratory of Dynamic Diagenesis and Metallogenesis, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing, 100081, China
\textsuperscript{b} Key Laboratory of Paleomagnetism and Tectonic Reconstruction, Ministry of Natural Resources, Beijing, 100081, China
\textsuperscript{c} China University of Geosciences, Beijing, 100083, China
\textsuperscript{d} Shenyang Geological Survey Center, China Geological Survey, Shenyang, 110034, China
\textsuperscript{e} 103 Brigade of Non-ferrous Geological Bureau of Liaoning Province, Dandong, 118008, Liaoning, China

Corresponding Author:
Jianmin Liu
Institute of Geomechanics, Chinese Academy of Geological Sciences,
No. 11, Minzudaxue South Road, Beijing 100081, P. R. China
E-mail address: liujianmin@vip.sina.com
Abstract

Two distinct styles of gold mineralization occurred in the Liaodong Peninsula, in the northeastern North China Craton. One formed an altered rock-type gold deposit in the west, and the other formed a quartz vein-type deposit in the east. Geological investigations and structural analysis show that these deposits may have originated from two distinct tectono-magmatic hydrothermal systems. The former is an E–W-trending contractional–extensional structural system formed in the Late Triassic, which includes the deposits in Baiyun, Jianshangou, and Maoling. The latter is related to high-angle strike-slip faults formed in the Early Cretaceous, and includes the Wulong gold deposit. Stress-induced tectonic analyses show that the principal stress in the western district was nearly N–S contractional stress initially, which subsequently changed to extensional stress; this might have been the result of the collision and subsequent extension of the Siberia Craton, North China Craton, and Yangzi Craton in the Late Triassic. The principal stress in the eastern district was nearly N–W contractional and sinistral shear stress initially, which subsequently changed to extensional stress, which may be the result of regional extension associated with the westward subduction of the Paleo Pacific Plate in the Early Cretaceous.

The structural control of the gold mineralization is manifested at all scales from regional to mines to orebodies; that is, the grading of the ores was controlled by different generations or orders of deformation. Gold ores were mainly formed under brittle or brittle-shear deformation conditions; in particular with extensive ore-bearing catalasite flows; which were generated by both the brittle or brittle-shear failure along major fault systems and related Late Triassic and Early Cretaceous magmatic hydrothermal activity. This genetic origin for gold mineralization and ore-bearing catalasite flows may provide support for the mechanism of flash vaporization in mineralization processes that form mesothermal gold systems.

Keywords: Structural control, ore-bearing catalasite flows, genesis, gold deposits, Liaodong Peninsula, northeastern North China Craton
1. Introduction

The Liaodong Peninsula (Fig. 1) was the location for one of the most important mining industry bases in China from the 1950s to the 1970s. The gold potential and prospects in the Peninsula have attracted a great deal of attention from geologists and exploration companies. Large-scale metal resource development included, for example, the Anshan-type metamorphic Fe deposits, the Qingchengzi hydrothermal Pb-Zn sulfide deposits, the Dashiqiao Mg deposits, and several precious metal deposits, including Au. The early history of gold mining in the Peninsula dates back to the 1940s (107GT, 1964) when some of the mesothermal gold-bearing quartz veins in the eastern region of the Peninsula had been mined at intervals. About 60 tons of gold were obtained from the Wulong deposit. It was not until the 1980s that there was a significant progress in gold exploration in the western region of the Peninsula, which resulted in the successive discoveries and profitable development of numerous major gold deposits, such as those at Baiyun, Maoling, Xiaotongjiapuzi. In contrast to the eastern region of the Peninsula, the gold in the western region is mainly located in stratiform, structurally controlled alteration belts in the Paleoproterozoic Liaohe Group.

An overview of the geology of the Liaodong Peninsula gold deposits is in the report by 103GT (2016). A great many previous studies have focused on the geochronology (Yang, 1997; Liu and Ai, 2000, 2002; Wei et al., 2001, 2003; Xue et al., 2003; Yu et al., 2005, 2009; Duan et al., 2012, 2017), and the ore-forming fluid and isotope geochemistry of the deposits (Dai et al., 2006; Yu et al., 2018; Liu et al., 2019a, 2019b; Zeng et al., 2019). However, many aspects concerning their mineralization processes remain to be answered, especially in regards to their genesis, the structural control of these deposits, the regional metallogenic processes, and the relationship between the eastern and western regions.

Based on the investigations over the years of 2016–2019 and published papers on the geology and geochronology of the gold deposits, we conducted a comprehensive analysis of microstructural deformation and geochronology of the ore-related rocks to discuss the genesis and structural control of the gold deposits in the Liaodong Peninsula.

2. Regional geologic setting and tectonic framework
The Liaodong Peninsula is tectonically located in the northeastern section of the eastern block of the North China Craton (as well as the middle and northern sections of the Jiao–Liao platform uplift). It is bounded by the Tancheng–Lujiang Fault Zone (TLF) to the west and the Yalujiang River Fault Zone (YRF) to the east (Fig. 1B; Zhao et al., 2009). The Peninsula consists of a basement composed of strongly folded gneissic rocks of Neoarchean- (2500 Ma) and Paleoproterozoic-aged (1800–2300 Ma) fold belts, which are covered by a series of Neoproterozoic and Cenozoic sedimentary rocks. In addition, this area contains an intrusive series of granitoids of different geological ages. According to the main lithologic components and deformation characteristics, the Liaodong Peninsula can be divided into three tectonic units from north to south: the Taizihe–Hunjiang platform Downwarp in the north (I in Fig. 1B), the Yingkou–Kuandian platform uplift in the center (II in Fig. 1B), and the Fuzhou Downwarp in the south (III in Fig. 1B). The different units are bounded by deep-seated fractured boundary zones (Fig. 1B; BGML, 1989).

The basement in the Liaodong Peninsula predominantly includes three sections, which correspond to the above two downwarps and one uplift: the Anshan–Fushun Archean complex in the Liaobei–Ji’nan Block in the north, the Jinzhou Archean complex in the Liaonan Block in the south, and the Paleoproterozoic Liaohe Group and Liaoji granites in the Jiao–Liao–Ji mobile belts in the central part (Wu et al., 2005c; Zhao et al., 2009).

The Archean basement is composed of a metamorphosed plutonic and the supracrustal rocks of the Anshan Group, which form enclaves in the plutonic rocks. These rocks have undergone high greenschist facies and low amphibolite facies metamorphism in the north and south, respectively.

The Paleoproterozoic metamorphic rocks, which mainly occur in the middle Yingkou-Kuandian platform uplift, are predominantly composed of schists, granulites, metavolcanic rocks, and marbles. They are generally divided into upper and lower parts, which are named the Yusulazi and Liaohe Groups, respectively. The Liaohe Group, which is developed along the regionally east–west-trending Liao–Ji rift (Chen, 1990), is up to 15 km thick, unconformably overlies the Archean Anshan complex, and is overlain by Neoproterozoic strata. It is subdivided into the Langzishan, Li’eryu, Gaojiayu, Dashiqiao, and Gaixian formations, and changes from a basal clastic-rich sequence (Langzishan formation) and a lower bimodal-volcanic succession (Li’eryu formation) to medial carbonate-dominated deposits (Gaojiayu and Dashiqiao formations) to an
upper pelite-rich sequence (Gaixian formation), which underwent low greenschist facies and low amphibolite facies metamorphism.

Neoproterozoic and Paleozoic sedimentary formations occur extensively and thickly in the downwarps in the north and south. Permian and Lower to Middle Triassic successions occur sporadically in the Benxi area in the north. Jurassic and Cretaceous terrestrial elasic and volcanic successions are mainly located within a series of small basins along the fault zones. Pliocene and Pleistocene olivine basalts and Holocene tillite and fluvioglacial deposits occur locally.

Archean–Paleoproterozoic and Mesozoic intrusive granitoids are widely distributed throughout the Peninsula. Lu et al. (2004) divided the early Precambrian granitic magmatism in the southern Liaodong Peninsula into three age groups: 2440–2500 Ma, 2160 Ma, and 1850 Ma, which correspond to three geological evolutionary stages of the Liaobei-Jinan Archean block and the Liaoji Paleoproterozoic orogenesis. Mesozoic intrusive rocks can be subdivided into three periods: Triassic (233–212 Ma), Jurassic (180–156 Ma), and Early Cretaceous (131–117 Ma; Wei et al., 2003; Wu et al., 2005a, 2005b, 2005c). They are generally felsic and occur as batholiths and stocks as well as a varying number of dikes. There are a few Late Triassic alkaline rocks (230–233 Ma), such as the alkali syenite plutons at Saima and Bolinchuan (Wu et al., 2005c). It is generally accepted that granites may form in the continental crust in various tectonic settings such as marginal arcs, collisional orogenies, and intraplate rifts (e.g., Barbarin, 1999), but they are mainly related to post-orogenic lithospheric delamination and extension events. The Triassic granitoid and alkaline intrusive rocks were formed either after the collision of the North China Craton with the Siberian Craton, or during the collision and extension of the South China Craton and the North China Craton during the Permian and Triassic (Yang et al., 2011). However, the Jurassic and Early Cretaceous intrusive granitoids are regionally distributed along NE- and NNE-trending tectonic magmatic belts and are the products of lithospheric thinning and extension that occurred after the westward subduction of the Paleo-Pacific Plate (Sun et al., 2012).

The tectonic systems can be divided into two major categories based on their regional trends and deformations (Fig. 1B):

(1) The E–W-trending basement uplift is mainly composed of late Archean–Paleoproterozoic metamorphic rocks. These are deformed by a series of compound folds, including the Yingkou–Caohekou Synclinorium, Hupiyu–Kuandian Anticlinorium, and Gaixian–Xiuyan–Gulouzi
Synclinorium, from north to south, as well as a number of corresponding faults in the contractional–extensional structural systems. The metamorphic rocks have a long history of geological evolution (Yang and Liu, 1989; Li et al., 1996; Liu et al., 2002) and are cut by a series of NE- and NW-trending, high-angle strike-slip fault zones.

(2) The second category contains extensive, intense, parallel, NE- and NNE-trending regional and local fault zones (Cathaysian and Neocathaysian tectonic systems; Lee, 1984), as well as Late Mesozoic intrusions and pull-apart basins. The main regional NE-trending faults include the Yalujiang River Fault Zone (YRF), Zhuanghe–Huanren Fault Zone (ZHF), and Fushun–Yingkou Fault Zone (part of the TLF) from east to west (BGML, 1989). They are major strike-slip crustal structures with a complex history of both sinistral and dextral movements from the Late Jurassic to the Cretaceous, and may have played a leading role in the tectonic evolution of the eastern district and associated gold mineralization. In addition, there are a series of extensional structural assemblages, that is, magmatic core complexes and detachment faults (Liu et al., 2011, 2015).

3. Geology of the representative gold deposits

The gold mineralization discovered in the Liaodong Peninsula is predominantly distributed along the medial Yingkou-Kuandian platform uplift. It is divided into the eastern and western districts, which have different mineralization styles, by the NE-trending lithospheric Zhuanhe–Huanren Fault Zone (ZHF in Fig. 1B). In this section, we give a basic description of the geology of the main gold deposits.

3.1. Gold mineralization in the eastern district

The eastern district is characterized by the presence of regional NE-trending faults (F₁–F₅) and voluminous Late Jurassic gneissic granites and Early Cretaceous granites (Fig. IC). Most of the fault zones experienced repeated tectonic events that mainly involved brittle deformation (Zhang et al., 2006). The gold mineralization in the eastern district is mainly quartz-vein type, for example, the Wulong and Xinfang gold deposits. However, there is also a minor amount of structural alteration type, for example, the Sidaogou deposit.
3.1.1. Wulong quartz vein-style gold deposit

The Wulong gold deposit, which is located about 20 km northwest of Dandong City (refer to No. 1 in Fig. 1B and C), is the largest mesothermal gold-bearing quartz vein deposit in the eastern district. An old mine was started in the 1940s, and more than 60 tons of gold have been obtained from this deposit since mining began. Based on decades of geological surveys, to date, about 460 quartz veins have been found within the deposit, of which more than 100 have been proven to be commercially profitable. The veins vary in density and have a generally restricted distribution within the NE-trending Dagudingzi (F$_2$) and Youpanling (F$_7$) regional fault zones (Fig. 1C). The gold-bearing quartz veins mainly strike NNE and NW. They are developed along a set of NNE- and NW-striking, steeply dipping shear zones and are accompanied by dike swarms (diorite, granite-porphyry, and lamprophyre) in the same tectonic system as the quartz veins. A few diorite dikes with brecciated irregular textures have been observed within the quartz veins (Fig. 2a), indicating that the dikes are older. The quartz veins are up to 1 km long, 2–3 m thick, and are rarely up to 20 m thick. They generally extend down dip from a few tens of meters to more than 1 km. In plan view, the NNE-trending set of veins tends to exhibit sinistral offsets, whereas the NW-trending veins exhibit dextral offsets, suggesting that they formed synchronously and are potentially a conjugate fault set. The quartz veins have an average grade of 5–10 g/t of gold with a maximum of up to 100 g/t.

Gold mineralization occurs along fractured quartz veins (Fig. 2b), with some in the contact zone between the quartz veins and the accompanying diorite and granite-porphyry dikes, which exhibit intense alteration assemblages of silicification, sericitization, and chloritization.

The NNE-trending No. 80 orebody and the NW-trending No. 163 orebody are typical of the main orebodies (Fig. 3). They extend for more than 1000 m down dip, and exhibit a trend of continued extension. The No. 163 orebody is much steeper than the No. 80 orebody, which shows undulating trends in attitude with depth.

3.1.2. Xinfang quartz vein-style gold deposit

The Xinfang gold deposit, which is located between Dalian City and Dandong City (refer to No.
3 in Fig. 1B), is tectonically located in the Fuzhou Downwarp at the junction of the southern E–W-trending Yingkou-Kuandian uplift and the NE-trending Zhuanghe deep-seated fault. Gold mineralization occurs within the contact zone between the Archean Anshan Group of biotite-plagioclase-gneiss and the Neoproterozoic Diaoyutai Formation of metasandstone, and sericite-quartz-schist rocks. The ore bodies are locally restricted to quartz vein-type in N–S- and NE-trending high-angle fracture zones. The characteristics of the alteration and the ore bodies are similar to those in the Wulong deposit. Extensive Mesozoic diorite and granitoid vein dikes occur within the deposit. Wei et al. (2007) reported a Rb–Sr isochron age of 143.0±5.8 Ma for the fluid inclusions in the quartz.

3.1.3. Sidaogou structural alteration-style gold deposit

The Sidaogou gold deposit, which is located next to Dandong City and 20 km southeast of the Wulong deposit (refer to No. 2 in Fig. 1B and C), was discovered in the 1960s. It is tectonically located at the junction of the regional E–W trending Yingkou-Kuandian uplift and the NE-trending Yalujiang River Fault Zone (Fig. 4). Folds in the Paleoproterozoic Gaixian Formation (Liaohe Group) in the deposit were affected by the Yalujiang River Fault Zone, resulting in a change in the trend of the folds from an early nearly E-W direction to a later NE direction. According to our investigation and previous studies (BGML, 1974; Zhao, 1984; Xiao et al., 2002), the gold mineralization in this deposit is a hybrid. It is mostly composed of structurally controlled alteration, but there are also some quartz veins in clastic sequences in the Gaixian Formation (Fig. 5). The gold-bearing alteration belts and the economic ore bodies occur between faults F₂ and F₃, and the closer they are to F₃, the higher their gold grade. The relationships between the ore-bearing alteration belt, the ore bodies, and the NE-trending Yalujiang River Fault Zone demonstrate the key role of the fault zone in the gold mineralization. Based on these tectonic relationships and the other characteristics of the deposit, we conclude that the Sidaogou deposit was formed by the Late Yanshanian (Early Cretaceous) tectono-magmatic activity, the same as the Wulong and Xinfang deposits.

3.2. Gold mineralization in the western district
The western district is a typical section of the Paleoproterozoic Liaohe Group in the Liaodong Peninsula. This area includes three nearly E–W-trending compound folds, each of which consists of a few secondary structures of varying sizes and styles: the Yingkou–Caohekou Synclinorium, Hupiyu–Kuandian Anticlinorium, and Gaixian–Xiu–Xiuyan–Gulouzi Synclinorium, from north to south. These E–W tectonic belts experienced two stages of deformation during Paleoproterozoic orogenic processes (Yang and Liu, 1989; Li et al., 1996; Liu et al., 2002; Liu, 1995). In addition, there are other sets of predominantly NE- and NW-trending fault zones that cut across the E–W-trending belts, as well as some NE-trending folds superimposed on the E–W-trending tectonics. A number of primarily Triassic (occasionally Jurassic and Cretaceous) granitoids accompanying mafic-intermediate and felsic dikes are distributed in the western district.

Compared with the style of gold mineralization in the eastern district, gold mineralization in the western district is mainly structurally controlled, largely along a series of low-angle fault zones, for example, the Baiyun, Jianshangou deposits (refer to Nos. 4 and 5 in Figs. 1B and 6), less commonly in high-angle fault zones, for example, the Maoling deposits (refer to No.6 in Fig. 1B).

Macroscopically, the gold mineralization appears to be located along the contact zone between the Dashiqiao carbonate and the Gaixian clastic formations of the Paleoproterozoic Liaohe Group. However, most of the orebodies in the deposits occur along local or secondary thrust or fault zones.

3.2.1. Baiyun gold deposit

The Baiyun gold deposit, which is located about 10 km north of Qingchengzi City (refer to No. 4 in Figs. 1B and 6A, B), is tectonically located in the Yaojiapuzi–Tianqiaoling–Lijiapuzi and Huangchagou reverse anticlines as well as the Baiyun Thrust Belt, which are part of the regional Yingkou–Caohekou Synclinorium. The E–W-trending Baiyun Nappe Tectonic Belt extends for more than 8 km, is 100–200 m wide, and dips to the south at an angle of 30°. Geological surveys have revealed that the Baiyun Thrust Belt appears to be located along the contact zone between clastic sequences of the Gaixian Formation and carbonate sequences of the Dashiqiao Formation. The upper and lower parts of the main belt have distinct structural attitudes; the schistosity of the lower part is sub-vertical, whereas the upper part is more gently dipping that is subparallel to the
main Thrust Belt (Fig. 6B). A series of secondary reverse folds and thrust structures occur near and within the belt and sets of intermediate and felsic dikes. Mineralization is mainly developed along the main and secondary structural planes. The Baiyun Thrust Belt is thought to be the key ore-controlling structure, although the relationship between the reverse anticlines and the Baiyun Nappe tectonic belt is not clear due to vegetation and sediment cover.

Macroscopically, the ore bodies appear to be stratiform, or nearly stratiform, and are lenticular. They generally have a variable strike and dip, with strikes of 110–290° and gentle dips to the NW at angles of 20–40°. A single representative ore-body has a strike length of 50–900 m, is 0.88–8 m thick, and extends from 70 m to 670 m deep. The grades of gold vary from $1.03 \times 10^{-6}$ g/t to $8.78 \times 10^{-6}$ g/t. The ores in the deposit are characterized by intense pyritization, silicification, sericitization, chloritization, and carbonatization.

3.2.2. Jianshangou gold deposit

The Jianshangou gold deposit is located about 8 km east of Qingchengzi Town (refer to No. 5 in Figs. 1B and 6A). It includes three areas, that is, the Xiaotongjiapuzi, Linjiasandaogou, and Taoyuan (Fig. 6A–C). Similar to the Baiyun deposit, mineralization in all three areas is restricted to the vicinity of the contact between the carbonate sequences of the Dashiqiao Formation and the clastic sequences of the Gaixian Formation. The ore bodies are stratiform, or nearly stratiform, and are lenticular, with various strikes and dips. The ore-bearing tectonic belt in Taoyuan generally strikes 290–310° and dips gently NE at angles of 10–30° (Fig. 6C), whereas the tectonic belt in Xiaotongjiapuzi strikes 80–100° and dips gently N–NE at angles of 25–40° (Fig. 6D). Extensive thrust-fold structures occur along the ore-bearing belt (see the photograph in Fig. 6D), which reveals the deformation features involved in the ore-formation processes. It should be noted that the ore-bearing structural belts around Qingchengzi Town are spatially consistent with the regional Haicheng–Caohekou Fault Zone, suggesting that this regional deep fault zone may be one of the more important ore controlling factors in the Liaodong Peninsula.

3.2.3. Maoling deposit

The Maoling major gold deposit in the southwestern part of the Liaodong Peninsula is
tectonically located at the junction of the E–W-trending Yingkou–Kuandian uplift in the north and the Fuzhou Downwarp in the south (refer to No. 6 in Fig. 1B and D). It was discovered in the 1980s, but has not yet been developed. The most distinctive feature of this deposit is the structural control on the distribution of the orebodies and the related alteration belts. According to an early report (5GT, 1987), the gold mineralization is controlled by local NNE-trending compressive or compression-shear fault zones (Fig. 1D).

The ore bodies are largely composed of auriferous quartz veins and disseminated altered rocks containing assemblages of native gold, arsenopyrite, pyrite, sericite phyllites, and chlorite schists. Several studies have focused on the genesis and ages of the mineralization, but the results are still inconclusive. Yu et al. (2005) and Liu et al. (2018) reported that Rb-Sr isochron ages of 2316 Ma and 2287 Ma respectively for arsenopyrite and arsenopyrite/pyrrhotite, suggesting that the gold mineralization was formed in the Paleoproterozoic. However, several studies have stressed the roles of late Mesozoic magmatic activity. Ren (1990) reported a K-Ar age of 245.9 Ma for the altered ore-bearing rocks (sericite and chlorite) and concluded that the mineralization formed in the Late Triassic.

4. Geochronology of granites and dikes related to the mineralization

Geological surveys have revealed the widespread development of voluminous Archean to Paleoproterozoic and Mesozoic intrusive granitoids throughout the Liaodong Peninsula. They mainly include batholiths and stocks, as well as varying numbers of mafic-intermediate and felsic dikes (BGML, 1989; Wu et al., 2005a, 2005b, 2005c). Some of the intrusive rocks exhibit a close spatial relationship with the gold mineralization, either as the host of the mineralization or as part of the same tectonic system, that is, as swarms within the ores. However, the detailed ages of the intrusive rocks in the different gold districts are not clear, resulting in debate over the relationship between the genesis of the gold mineralization and the intrusive rocks.

To define the genetic relationship between the gold mineralization and the granitic rocks, a number of granitic intrusive rocks and dikes were collected from the Wulong and Qingchengzi goldfields for laser ablation inductively coupled plasma mass spectroscopy (LA–ICP–MS) U–Pb zircon dating. The location of the samples and their relationships with the mineralization are
shown in Table 1. Cathodoluminescence (CL) images and U–Pb dating analyses were conducted at Beijing Geoanalysis Co. Ltd. CL images of analyzed zircons are shown in Figure 7.

The zircon grains are mainly euhedral with well-preserved pyramidal faces and have elongation ratios of 2:1 to 3:1. CL images show that most of the zircons exhibit oscillatory zoning, indicating a magmatic origin. The U–Pb zircon isotopic results of 12 representative samples are presented in Figure 8 and Table 1, and the data is reported in Table S1.

The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages obtained for the collected samples can be divided into two groups corresponding to the Wulong goldfield in the eastern district and the Qingchengzi goldfield in the western district.

The ages for the Wulong goldfield can be subdivided into three groups: 1846.3±9.8 Ma (Paleoproterozoic) (Fig. 8a); 162.0 ± 2.6 Ma and 163.2 ± 2.2 Ma (Jurassic) (Fig. 8b and c); and 125.8 ± 1.3 Ma to 120.4 ± 1.3 Ma (Early Cretaceous (Fig. 8d–f). The first group might be the indicator of presence of the Paleoproterozoic plutonic rocks. The second group for the Jurassic ages of 162.0 ± 2.6 Ma and 163.2 ± 2.2 Ma is from the gneissic granites that host the Wulong Au-bearing quartz veins. The younger 125.8 ± 1.3 Ma to 120.4 ± 1.3 Ma ages are predominantly from the swarms of mafic-intermediate and felsic dikes, including diorite and granite porphyry rocks. These dikes mainly occur within the NNE- and NW-trending sets of faults in the Wulong deposit. Although they are in the same tectonic system as the ore-bearing quartz veins, the diorite dikes are interpreted to have formed earlier than the quartz veins, which often contain diorite breccia. Most of the granite porphyry rocks are located in the region containing the NNE-trending set of faults and were emplaced later than the diorite and quartz veins, although they also contain some mineralization.

The samples from the Qingchengzi goldfield in the western district are mostly Triassic in age, in the range 207.3 ± 1.5 Ma to 217.0 ± 1.9 Ma (Fig. 8g–l). They are mainly from mafic-intermediate and felsic dikes, including lamprophyre, granite porphyry, and aplite. These dikes mainly occur in the region containing the NE- and NW-trending set of faults in the Baiyun and Jianshangou deposits. Most of the dikes developed next to the structurally controlled orebodies, and some of the dikes contain mineralization. The newly obtained ages of these dikes are the same as those of some of the intrusions outside the gold deposits, such as the Xinling granitic intrusion (Sun et al., 2019a). A few studies have reported Cretaceous ages for some of the
dikes in the Qingchengzi goldfield (Sun et al., 2019b), which suggests that there must be a Cretaceous source somewhere (maybe buried or distal). However, the newly obtained ages of this paper reveals that the Triassic magmatic event might predominate in the Qingchengzi goldfield.

5. Microstructural features of ore-related rocks

It has been well established that the fault-related rock assemblages record a history of progressive uplift during the deformation and formation of fault zones and the genesis of the structurally controlled ore bodies in both the eastern and western districts of the Liaodong Peninsula (Sibson, 1977; Sibson et al., 1988; Liu et al., 2015). The microscopic structures of the ores and the related fault rocks from the Wulong, Baiyun, and Jianshangou gold deposits were analyzed in order to determine the deformation characteristics and genesis of the ores and the related fault rocks.

5.1. Microstructures of the ore-related rocks in the Wulong goldfield

The host rocks for ore-bearing quartz veins in the Wulong deposit in the eastern district are mainly Jurassic gneissic granite (Fig. 1B and C). They are predominantly composed of plagioclase (30–50%), K–feldspar (30–40%), quartz (25–30%), biotite (5–10%) and minor muscovite. The rocks are characterized by gneissic or banded structures with nearly E–W-trending elongation of biotite and quartz. They contain augen structures that are composed of a plagioclase core and mantled quartz deformed bands; these formed in response to dextral shear (Fig. 9a). Locally, proto-mylonitic and mylonitic textures with quartz ribbons and mica fish are observed (Fig. 9B–D), which suggest that the rocks were formed at the ductile-brittle transition at crustal depths of 10–15km (Sibson et al., 1988) at about 162.0–163.2 Ma and were later exposed by uplift and erosion.

Samples of the ore-bearing quartz are characterized by the presence of well-developed foliations of separated, parallel light- and dark-colored bands (Fig. 2b), composed of quartz and ore-bearing altered rock fragments, respectively. At outcrop scale, the foliations are generally NNE-and NW-trending and dip steeply along a set of conjugate shear zones. Microscopically, the foliations can be divided into four different deformation domains, ranging from a weak domain (I
in Fig.10) to strongly deformed quartz ribbons (II and III in Fig.10) to an altered ore-bearing domain (IV in Fig.10). The presence of undulating extinction and subgrains in the quartz ribbons suggests that the quartz veins have undergone ductile deformation. The alteration domain is predominantly composed of aggregates of felsic minerals with sericite, calcite, pyrite, and minor other metals, where the high-grade gold is located (Fig. 11a–f). The grades of gold in samples with different deformations are listed in Table 2. This shows that the gold mineralization in the Wulong deposit appears to have a positive correlation with cataclasite flows resulting from late-stage brittle deformation along the ore-bearing fault zones.

5.2. Samples from the Baiyun and Jianshangou gold deposits

The host rocks from the Baiyun and Jianshangou deposits in the western district are predominantly composed of the carbonate and clastic rocks of the Dashiqiao and Gaixian formations, respectively, in the Paleoproterozoic Liaohe Group. These rocks experienced low greenschist facies and low amphibolite facies metamorphism. They are generally schists and marbles with lepido- and granular crystalloblastic textures. Microstructurally, the schists have well-developed foliations or schistosity, or crumple structures. Some schists have plenty of disseminated or veinlet pyrite along foliations or schistosity. In the Linjiasandaogou mineralizing segment, some of the pyrite veinlets (Py₁ in Fig. 12a–d) are crumpled along the schistosity (Fig. 12a–b), suggesting that this kind of pyrite may have formed prior to or synchronously with metamorphism and deformation. There is almost no gold mineralization in such pyrites (Fig. 12a, b; Table 2).

Another kind of ore-bearing structure that generally cuts the foliations or schistosity consists of pulverized schists or cataclasite flows with intense silica-sericite-ankerite alteration mineral assemblages. These kinds of cataclasite flows have the highest gold grades (Fig. 12e–h; Table 2). Samples from the Baiyun deposit exhibit similar characteristics to those from the Linjiasandaogou segment (Fig. 13a–f; Table 2).

Microstructural characteristics show that there are generally well-developed cataclasite flows in the ore-bearing fault rocks from the Wulong, Baiyun and Jianshangou gold deposits. Most of them occur along pre-existing shear zones, either the high-angle strike-slip fault in the Wulong deposit,
or the low-angle thrust system in the Baiyun and Jianshangou deposits. The cataclasites are predominantly composed of a mixture of pulverized wall rocks and were mineralized by ore-bearing hydrothermal fluids with a range of gold and trace elements. The textural characteristics are consistent with a mechanism of flash vaporization during the hydrothermal eruption by abrupt drops in fluid pressure along seismogenic zones (e.g., Sibson, 1987; Sibson et al., 1988; Weatherley and Henley, 2013).

6. Discussion

The presence of ore deposits in various parts of the crust is broadly determined by the presence of a number of favorable conditions (e.g., see Lee, 1984; Groves et al., 2016; Sibson, 2001; Goldfarb et al., 2005; Cox et al., 2001; Weinberg et al., 2004; Oliver et al., 2001; Jaireth, et al., 2010; Richards, 2013; Qiu et al., 2016; Yu et al., 2020a). Fault structures and hydrothermal fluids are undoubtedly the two most inseparable important factors for the formation of hydrothermal mineral deposits. Faults, shear zones, and associated fracture arrays play a key role in controlling the distribution of local permeability and the macroscopic architecture of fluid pathways in hydrothermal systems, which can develop either in the brittle upper crust or in the more ductile deeper crust (Sibson et al., 1987, 1988; Cox et al., 2010; Yu et al, 2019; Qiu et al., 2020). During the mineralizing processes, dynamic stress change (Sibson, 1987; Sibson et al., 1988; Wilkinson and Johnston, 1996; Parry, 1998; Yu et al., 2020b) or flash vaporization (Weatherley and Henley, 2013; Qiu et al., 2017) from fault-valve behavior often occur along the seismogenic zone. The gold mineralizing systems in the Liaodong Peninsula are an excellent example to illustrate the relationships between fault systems and magmatic hydrothermal fluids.

6.1. Mineralization ages

The quartz vein-style mineralization in the Wulong deposit in the eastern district evidently formed after the fracturing and lamination of the quartz veins. Newly obtained U–Pb zircon ages for the host rocks of the quartz veins are in the range 162.0–163.2 Ma, whereas the swarms of diorite dikes and granite porphyry vein rocks are 125.8–120.4 Ma in age. Wei et al. (2001, 2003)
reported Rb–Sr ages of 110–120 Ma for the ores. Thus, the gold mineralization related to the quartz veins is Early Cretaceous in age, which is consistent with the age of the large clusters of gold mineralization in the Jiaodong Peninsula in eastern China (Zhai et al., 2001; Yang et al., 2007; Deng et al., 2020).

The gold mineralization in the western district is predominantly hosted in Paleoproterozoic metamorphic rocks, either as stratiform and nearly stratiform orebodies along low-angle fault zones, or in quartz veins and disseminated altered rocks. Previous studies have concluded that this mineralization has stratabound (Tu, 1984) or metamorphic-hydrothermal origins (Xue et al., 2003; Yu et al., 2009). Several studies have been conducted on the Mesozoic magmatic-hydrothermal activity and its effect on mineralization (Liu and Ai, 2000, 2002; Duan et al., 2012; Liu et al., 2019; Zeng et al., 2019; Sun et al., 2019a, 2019b). Based on our analyses and geologic mapping, we have determined that most of the gold deposits in the Baiyun, Jianshangou, and Maoling areas are distributed adjacent to a series of Triassic granite batholiths and/or stocks, which intruded into Liaohe Group metamorphic rocks. However, there is no structural deformation, alteration, and mineralization inside the granites. There are numerous dike swarms within the ore-bearing tectonic belt and within the ore bodies themselves. Some of the dikes are altered and contain disseminated pyrite with low grades of gold.

The newly obtained U–Pb zircon ages of most of the dikes are in the range 207.3 to 217.0 Ma (Table 2); this is consistent with the ages of the ore-related porphyries reported by Liu et al. (2019a) and is slightly younger than a series of Rb–Sr and Ar–Ar isochron ages (233–234 Ma and 239.5–240.4 Ma) for the ores reported by Liu and Ai (Liu and Ai, 2000, 2002). In view of the temporal and spatial relationships between the mineralizing dikes and the orebodies, we conclude that the gold mineralization in the western district formed in the Late Triassic.

6.2. Structural controls on and genesis of the gold mineralization

In the Liaodong Peninsula, the structural control on the gold mineralization is manifested on all scales from regional to mines to orebodies. The distribution of the mineralization is uneven rather than being restricted along specific structural belts, which are often secondary or lower orders of a major tectonic system.
As can be seen from Figure 1B, the Yingkou-Kuandian platform uplift in the Liaodong Peninsula is surrounded by E–W- and NE-trending (or NNE) regional boundary faults, which belong to two distinct tectonic systems. In the western district, the mineralization in the Baiyun, Jianshangou, and Maoling deposits is distributed within the Paleoproterozoic Liaohe Group along the northern and southern boundaries between the medial platform uplift and the downwarps on both sides, which is consistent with the regional E–W-trending boundary fault zones. However, the mineralization in the Baiyun and Jianshangou deposits occurs at the junction of three different fault zones, that is, the E–W-trending Caohekou Fault Zone, the NW-trending Jianshanzi Fault Zone, and a few NE-trending Fault Zones. At mine scale, the ore bodies are all present along gently-dipping thrust belts or fold belts and have strikes consistent with the strikes of the regional E–W-trending faults and compound folds. Similarly, the Maoling gold deposit is also located at the junction of an E–W-trending fault zone and a NE-trending fault zone, and the ore bodies are controlled by the local NNE-trending compressive or compression-shear fault zones. Thus, the E–W-trending tectonic system is the first-order factor controlling the gold belts; whereas the gently-dipping thrust belts and fold belts in the Baiyun and Jianshangou deposits and the local NNE-trending ore-bearing fault zones in the Maoling deposit, which control the locations of the orebodies, are secondary features of a major tectonic system.

Compared with those in the western district, the deposits in the Wulong, Xinfang, and Sidaogou areas in the eastern district are predominantly distributed along NE-trending strike-slip fault zones. At mine scale, the ore bodies in the Wulong deposit are controlled by a set of NNE-trending and NW-trending ore-bearing conjugate quartz veins, which were previously thought to be related to the shearing movement of the NE-trending fault zones. Gold mineralization in the Xinfang deposit occurs within the contact zone between the Archean Anshan Group and the Neoproterozoic Sinian System. The ore bodies are restricted to quartz vein-type mineralization in NS- and NE-trending high-angle fracture zones. The gold-bearing alteration belts and the economic ore bodies in the Sidaogou deposit occur along NE-trending faults, which are secondary structures of the NE-trending Yalujiang River Fault Zone. Thus, NE-trending strike-slip fault zones are the first-order features controlling the NE-trending gold belts; whereas the NNE-trending and NW-trending, ore-bearing conjugate quartz veins in the Wulong deposit, the N–S and NE-trending high-angle fracture zones in the Xinfang deposit, and the NE-trending
faults in the Sidaogou deposit, which control the locations of the orebodies, are all subsidiary structures of the NE-trending strike-slip tectonic system.

Microscopically, most of the ore-bearing structures from the two goldfields included multiple episodes of deformation. In the Wulong deposit, gold mineralization was evidently inside foliations along the ore-bearing fault zones. The ore-bearing quartz veins were subjected to early ductile and late brittle deformations along NNE- and NW-trending conjugate set faults. The high-grade gold is located in the cataclasite flows of aggregates of felsic minerals, along with sericite, calcite, pyrite, and minor other metals, generated during brittle deformation.

Similar early ductile and late brittle deformation occurred in the Baiyun and Jianshangou deposits along ore-controlling structural belts. The early ductile deformation is characterized by foliations or schistosity and crumple structures in schists. Abundant disseminated or veinlet pyrite occurs along the foliation or schistosity which remains barren of gold mineralization. Late brittle deformation cross-cuts the foliations or schistosity and is mainly represented by cataclasite flows consisting of aggregates of felsic minerals, with sericite, calcite, pyrite, and minor other metals. The cataclasite flows are similar to those in the Wulong deposit and hosts the high-grade gold.

Microstructural evidence from the ore-related rocks shows that the mineralization in both the western and eastern districts was probably formed under brittle-ductile conditions. The gold mineralization is closely associated with late-stage cataclasite flows, which occurred along pre-existing fracture zones. These characteristics demonstrate that the main factors in the genesis of the gold deposits were late-stage cataclasite flows and mineralized hydrothermal fluid resulting from abrupt rupturing along the fault systems.

6.3. Genetic model for the gold mineralization

We propose a genetic model for gold mineralization in the Liaodong Peninsula, based on the metallogenic characteristics of the orebodies (Fig. 14). There are two distinct styles of gold mineralization, both of which are structurally controlled and mesothermal. Mineralization is associated with structurally controlled alteration rocks in the western district and with quartz-veins in the eastern district. The mineralization events were most likely related to two distinct tectono-magmatic hydrothermal systems, in the Late Triassic in the western district and in the
Early Cretaceous in the eastern district, respectively. Almost all of the gold mineralization is temporally and spatially related to the mineralizing dikes, which were emplaced at these times.

Stress-induced tectonic analysis indicates that the principal stresses in the western district consisted of an early-stage, nearly N–S-oriented contractional stress and a late-stage extensional stress, which may have originated from the collision and subsequent extension of either the North China Craton and the Siberian Craton or the South China Craton and the North China Craton during the Permian and Triassic. The principal stress in the eastern district consisted of early-stage, nearly NW-oriented contractional and sinistral shear stress followed by late-stage extensional stress, which can be attributed to the regional extension associated with the westward subduction of the Paleo-Pacific Plate in the Early Cretaceous. Gold ores in both districts were mainly formed under late-stage brittle or brittle-shear deformation conditions that generated extensive ore-bearing cataclasites by repetitive brittle or brittle-shear failure along major fault systems in association with magmatic hydrothermal activity.

The interpreted tectonic setting for gold mineralization in the Liaodong Peninsula is the same as that of the large clusters of gold mineralization in the Jiaodong Peninsula in eastern China (e.g., Zhai et al., 2001; Yang et al., 2007; Sai et al., 2020).

7. Conclusions

Based on structural relationships, the ages of mineralization and microstructural characteristics, we draw the following main conclusions on the genesis of and structural controls of gold deposits in the Liaodong Peninsula, northeastern North China Craton.

(1) There are two styles of gold deposits in the Liaodong Peninsula, both of which are structurally controlled and mesothermal. In the western district, mineralization is associated with structurally controlled alteration rocks, whereas in the eastern district, it is associated with quartz-veins. These contrasting styles of mineralization may have originated from two distinct tectono-magmatic hydrothermal systems. The former is related to the E–W-trending contractional-extensional structural system formed in the Late Triassic, and includes the deposits at Baiyun, Xiaotongjiapuzi, Linjiasandaogou, and Maoling. The latter is related to high-angle strike-slip faults formed in the Early Cretaceous, and includes the Wulong gold deposit. Structural
controls on the gold mineralization are manifested at all scales from regional to mines to orebodies.

(2) Most of the ore-bearing structures from the two goldfields went through multiple episodes of deformation, ranging from early-stage ductile to late-stage brittle. Higher grades of gold are associated with cataclasite flows consisting of aggregates of felsic minerals with sericite, calcite, pyrite, and minor other metals, which were formed during late-stage brittle deformation.

(3) The association of gold mineralization with cataclasite flows may support the concept of flash vaporization as a genetic process in mesothermal gold systems along seismogenic zones.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this study.

Acknowledgments

This study was supported by the National Key R&D Program of China (Grant Nos. 2016YFC0600108 and 2018YFC0603802), the Special Program for the International Cooperation of the Ministry of Science and Technology of China (Grant No. 2014DFR21270), and the Presidential Foundation of the Chinese Academy of Geological Sciences (Grant No. JYYWF20180602). We are also grateful for the helpful editorial review of the Editor-in-Chief Professor Franco Pirajno, the managing editor, Professor Santosh, the guest editor, Professor Yang Liqiang, and two reviewers for making critical comments and valuable suggestions, which have significantly improved the manuscript. The text has benefited from a critical review by Tim Munson (Northern Territory Geological Survey, Australia). We thank the local mines for their cooperation and willingness to share information during our field investigation.

We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

References


Liu, J., 1995. Tectonic deformation texture and ore-controlling features of Qingchengzi orefield, Liaoning


Wilkinson, J. J. & Johnston, J. D., 1996. Pressure fluctuations, phase separation, and gold precipitation during...


Table captions

Table 1. U–Pb zircon ages of granite and dike samples from the Wulong and Qingchengzi goldfields in the eastern and western districts, respectively.

Table 2. Gold grades of samples with different deformations from the eastern and western districts.

Figure captions

Fig. 1. Geologic map of the Liaodong Peninsula showing the tectonic framework and distribution of major gold deposits in the Liaodong Peninsula (A–after Goldfarb et al., 2019; B–after BGML, 1989 and Liu et al., 2019).

The numbers of the tectonic units in Fig. 1B are defined as follows: I–Taizhe–Hunjiang platform Downwarp, II–Yingkou–Kuandian platform uplift, III–Fuzhou Downwarp. YRF–Yalujiang River Fault Zone, ZHF–Zhuanghe-Huanren Fault Zone, TLF–Tancheng–Lujiang Fault Zone.

(C) Geologic map of the Wulong goldfield showing the distribution of the Liaohu Group (Pt), Paleoproterozoic and Mesozoic granitoids, main faults, and significant gold deposits (modified after Yang, 1997). The names of the faults are abbreviated as follows:

F₁—Yuanlujiang River Fault Zone, F₂—Heigou reservoir Fault Zone, F₃—Dagudingzi Fault Zone, F₄—100th Ore vein Fault Zone,
F₅—Jixinling Ridge Fault Zone, F₆—Yangjia Fault Zone, F₇—Hongshila Fault Zone.

(D) Geologic map of the Maoling deposit (modified after Ren, 1990).

Fig. 2. Photomicrographs of brecciated and fractured textures of an ore-bearing quartz vein in the Wulong deposit.
(a) Photomicrograph of brecciated textures and irregular breccia of diorite dikes (Di) in quartz veins (Qz) from the 80th ore-bearing quartz vein in the Wulong deposit; (b) Photograph of fractured quartz belt with altered mineralization along foliations, showing that gold mineralization was formed later than quartz veins.

Fig. 3. Vertical cross section of the No. 80 (left) and No. 163 (right) orebodies in the Wulong deposit (data from Wulong mine), showing horizontal and vertical variations in the orebodies.

Fig. 4. Geological map of the Sidaogou gold deposit (after Zhao, 1984).

Fig. 5. Cross-section of exploration line 300 in the Sidaogou gold deposit (after BGML, 1974).

Fig. 6. Geologic map of the Qingchengzi gold ore field (A) and several cross-sections of the orebodies (B-D, after 103GT, 2016; Liu, 1995).
(A) Geologic map of the Qingchengzi gold ore field; (B) Cross-section of the orebodies along exploration line 2 in the Baiyun gold deposit; (C) Cross-section of the orebodies along exploration line 195 in the Taoyuan section of the Jianshangou gold deposit; (D) Cross-section of the orebodies along exploration line 32 in the Xiaotongjiazi deposit. The ore-bearing thrust-fold structure in the photo shows the compressive deformation features created by the ore-formation process.

Fig. 7. Representative cathodoluminescence (CL) images of petrographic thin sections of analyzed zircon grains.
Red circles are presumably ablation pits

Fig. 8. U–Pb zircon age diagrams for the samples from the Wulong (a–f) and Qingchengzi (g–l) gold deposits.
Fig. 9. Microstructural aspects of host rocks in the Wulong gold deposit.

(a) Porphyroclasts of feldspar and S–C structures in the gneissic granite indicate dextral shear; (b)–(d) Proto–mylonitic and mylonitic textures with quartz ribbon and mica fish suggests that the rocks were formed under the conditions of ductile-brittle transition. Qz: Quartz, Kf: K–feldspar, Mi: Mica.

Fig. 10. Microstructures across foliations in the ore-bearing quartz veins (Qz) in the Wulong gold deposit.

I–IV: Four different deformation stages from ductile to brittle domain. (I) Weak ductile deformed quartz veins; (II and III) Strongly ductile deformed quartz ribbons; (IV) Brittle deformation domain with intense ore-bearing alteration. The presence of undulating extinction and subgrains in the quartz ribbons (II and III) suggests early ductile deformation in the quartz veins. The alteration ore-bearing domain (IV) is predominantly composed of cataclasite with the high-grade gold.

Fig. 11. Microstructures of cataclasite cross-cutting ore-bearing quartz veins (Qz) and occurrences of pyrite (Py) in the Wulong gold deposit.

Pyrite mainly occurs within the cataclasite flows. A positive correlation exists between gold content and rock cataclasite flow. Left images of a, c, and e are under transmitted light; right images of b, d, and f are under reflected light. (a) and (d) are from sample WL1816–2, (e) and (f) is from sample WL1830–6.

Fig. 12. Microstructures of the host rocks and ores of the Linjiasandaogou deposit.

Two kinds of structural deformation occur in schists and granulites from the Linjiasandaogou deposit. One is mainly ductile deformation along the schistosity. Abundant disseminated or veinlet pyrite (Py1) along foliations or schistosity (a–d), formed prior to or synchronously with metamorphism and deformation. The other is brittle deformation that cross-cuts schistosity. This is mainly composed of cataclasite flow textures with the presence of veinlet and massive pyrites (Py2) and high-grade gold (e–h ). Left images of a, c, e, and g are under transmitted light; right images of b, d, f, and h are under reflected light.

Fig. 13. Microstructures of host rocks and ores of Baiyun deposit.

(a–b) Veinlet pyrite (Py1) along foliations or schistosity with no gold. (c–f) Disseminated and veinlet pyrite (Py2) in cataclasite flows with high-grade gold. Left images of a, c, and e are under transmitted light; right images of b, d, and f are under reflected light.

Fig. 14. Genetic model of the gold mineralization in the Liaoning Peninsula.
There are two distinct styles of gold mineralization in the Liaoning Peninsula, one associated with structurally controlled alteration rocks in the western district and the other with quartz-veins in the eastern district. The mineralization events were most likely related to two distinct tectono-magmatic hydrothermal systems, in the Late Triassic and Early Cretaceous, respectively. Stress-induced tectonic analysis show that the principal stress in the western district was nearly N-S contractional stress initially, which subsequently changed to extensional stress; this might have been the result of the collision and subsequent extension of the Siberia Craton, North China Craton, and Yangzhi Craton in the Late Triassic. However, the principal stress in the eastern district was nearly N–W contractional and sinistral shear stress initially, which subsequently changed to extensional stress, which may be the result of regional extension associated with the westward subduction of the Paleo Pacific Plate in the Early Cretaceous. Gold ores in both districts were mainly formed under late-stage brittle or brittle-shear deformation conditions that generated extensive ore-bearing cataclasites by repetitive brittle or brittle-shear failure along major fault systems in association with magmatic hydrothermal activity.

Table 1. U-Pb zircon ages of the granite and dike samples from the Wulong and Qingchengzi gold fields in the eastern and western districts, respectively

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Rock type</th>
<th>Ages (Ma)</th>
<th>Relationship with mineralization</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL1805B02</td>
<td>Mica gneissic granite</td>
<td>1846.3±9.8</td>
<td>Host rocks in the Wulong gold deposit</td>
</tr>
<tr>
<td>WL1807B02</td>
<td>Mylonitic gneissic granite</td>
<td>162.0±2.6</td>
<td>Host rocks of the Au-bearing quartz veins</td>
</tr>
<tr>
<td>WL1809B01</td>
<td>Gneissic granite</td>
<td>163.2±2.2</td>
<td>the Wulong gold deposit</td>
</tr>
<tr>
<td>WL1813B02</td>
<td>Diorite</td>
<td>125.8±1.3</td>
<td>Cut by the Au-bearing quartz veins</td>
</tr>
<tr>
<td>WL1823B01</td>
<td>Post mineralization dike</td>
<td>122.5±1.5</td>
<td>Cut or cut by the Au-bearing quartz veins</td>
</tr>
<tr>
<td>WL1818B01</td>
<td>Granite porphyry</td>
<td>120.4±1.3</td>
<td></td>
</tr>
<tr>
<td>QC1801B01</td>
<td>Aplite</td>
<td>217.0±1.9</td>
<td>Wall rocks of the Au-bearing alteration belt in</td>
</tr>
<tr>
<td>QC1805B01</td>
<td>Lamprophyry</td>
<td>214.0±1.1</td>
<td>the Jianshangou gold deposit</td>
</tr>
<tr>
<td>QC1805B02</td>
<td>Granite porphyry</td>
<td>210.8±0.9</td>
<td></td>
</tr>
<tr>
<td>QC1818B01</td>
<td>Granite porphyry</td>
<td>207.3±1.5</td>
<td>Wall rocks of the Au-bearing alteration belt in</td>
</tr>
<tr>
<td>QC1818B02</td>
<td>Granite porphyry</td>
<td>212.9±1.9</td>
<td>the Baiyun gold deposit</td>
</tr>
<tr>
<td>QC1817B01</td>
<td>Lamprophyry</td>
<td>215.6±1.1</td>
<td></td>
</tr>
</tbody>
</table>

Notes: the U-Pb zircon ages were carried out by LA-MC-ICP-MS at the Beijing Geoanalysis company, Ltd.

Table 2. Grades of gold in samples with different deformations from the eastern and western districts

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Rock type</th>
<th>Microstructures</th>
<th>Au(x10^-9)</th>
<th>Locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>WL1808-1</td>
<td>Granitic mylonite</td>
<td>Proto-mylonite</td>
<td>0.89</td>
<td>Jixinlin Rudge</td>
</tr>
<tr>
<td>WL1808-2</td>
<td></td>
<td></td>
<td>1.66</td>
<td>fault, Wulong</td>
</tr>
<tr>
<td>Sample Code</td>
<td>Description</td>
<td>Alteration</td>
<td>Site</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
<td>---------------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>WL1808-3</td>
<td>Diorite</td>
<td>Chlorite alteration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WL1808-4</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>14890</td>
<td></td>
</tr>
<tr>
<td>WL1808-5</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>9107</td>
<td></td>
</tr>
<tr>
<td>WL1808-6</td>
<td>Diorite</td>
<td>Chlorite alteration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WL1808-7</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>2818</td>
<td></td>
</tr>
<tr>
<td>WL1808-8</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>2227</td>
<td></td>
</tr>
<tr>
<td>WL1808-9</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>WL1813-2</td>
<td>Diorite</td>
<td>Chlorite alteration</td>
<td>152</td>
<td></td>
</tr>
<tr>
<td>WL1816-2</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>WL1816-4</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>29475</td>
<td></td>
</tr>
<tr>
<td>WL1816-5</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>WL1821-2</td>
<td>Diorite</td>
<td>Chlorite alteration</td>
<td>5.93</td>
<td></td>
</tr>
<tr>
<td>WL1822-1</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>9107</td>
<td></td>
</tr>
<tr>
<td>WL1822-2</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>2227</td>
<td></td>
</tr>
<tr>
<td>WL1830-1</td>
<td>Diorite</td>
<td>Chlorite alteration</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>WL1830-2</td>
<td>Faulted chlorite schist</td>
<td>Chlorite alteration</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>WL1830-6</td>
<td>Laminated quartz vein with alteration</td>
<td>Cataclasite flow</td>
<td>29475</td>
<td></td>
</tr>
<tr>
<td>WL1832-1</td>
<td>Diorite</td>
<td>Mylonitize</td>
<td>8.01</td>
<td></td>
</tr>
<tr>
<td>WL1842-1</td>
<td>Granitic gneiss</td>
<td>Mylonitize</td>
<td>1.59</td>
<td></td>
</tr>
<tr>
<td>QC1811-2</td>
<td>Si-K-altered rocks</td>
<td>Cataclasite flow</td>
<td>12147</td>
<td></td>
</tr>
<tr>
<td>QC1811-3</td>
<td>Si-K-altered rocks</td>
<td>Cataclasite flow</td>
<td>9478</td>
<td></td>
</tr>
<tr>
<td>QC1811-4</td>
<td>Si-K-altered rocks</td>
<td>Cataclasite flow</td>
<td>53484</td>
<td></td>
</tr>
<tr>
<td>QC1811-5</td>
<td>Si-K-altered rocks</td>
<td>Cataclasite flow</td>
<td>6401</td>
<td></td>
</tr>
<tr>
<td>QC1811-6</td>
<td>Si-K-altered rocks</td>
<td>Cataclasite flow</td>
<td>8.01</td>
<td></td>
</tr>
<tr>
<td>QC1806-1</td>
<td>Mica schist</td>
<td>The pyrite is folded with schistosity</td>
<td>4.41</td>
<td></td>
</tr>
<tr>
<td>QC1806-2</td>
<td>Quartz mica schist</td>
<td>Bedded pyrite veins</td>
<td>2.77</td>
<td></td>
</tr>
<tr>
<td>QC1802-1</td>
<td>Si-k-altered granulite</td>
<td>Quartz veins cut by cataclasite flow</td>
<td>16450</td>
<td></td>
</tr>
<tr>
<td>QC1802-3</td>
<td>Mica schist</td>
<td>Quartz veins cut by cataclasite flow</td>
<td>1777</td>
<td></td>
</tr>
<tr>
<td>QC1807-1</td>
<td>Granulite</td>
<td>Bedded pyrite veins</td>
<td>51.5</td>
<td></td>
</tr>
</tbody>
</table>

Notes: The data were obtained at the National Research Center for Geoanalysis, Chinese academy of Geological Sciences.

**Research Highlights**

- There are two styles of gold mineralization in the Liaodong Peninsula.
● The gold ores formed under brittle or brittle-shear deformation conditions.
● The association of gold mineralization with catalasite flows may support the concept of flash vaporization as a genetic process in mesothermal gold systems along seismogenic zones.