40Ar/39Ar 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

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Abstract

China's largest gold resource is located in the highly endowed northwestern part of the Jiaodong gold province. Most gold deposits in this area are associated with the NE- to NNE-trending shear zones on the margins of the 130–126 Ma Guojialing granite. These deposits collectively formed at ca. 120 ± 5 Ma during rapid uplift of the granite. The Dayingezhuang deposit is a large (>120 t Au) orogenic gold deposit in the same area, but located along the eastern margin of the Late Jurassic Linglong Metamorphic Core Complex. New 40Ar/39Ar geochronology on hydrothermal sericite and muscovite from the Dayingezhuang deposit indicate the gold event is related to evolution of the core complex at 130 ± 4 Ma and is the earliest important gold event that is well-documented in the province. The Dayingezhuang deposit occurs along the Linglong detachment fault, which defines the eastern edge of the ca. 160–150 Ma Linglong granite–granodiorite massif. The anatectic rocks of the massif were rapidly uplifted, at rates of at least 1 km/m.y. from depths of 25–30 km, to form the metamorphic core complex. The detachment fault, with Precambrian metamorphic basement rocks in the hangingwall and the Linglong granitoids and migmatites in the footwall, is characterized by early mylonitization and a local brittle overprinting in the footwall. Gold is associated with quartz-sericite–pyrite–K-feldspar altered footwall cataclasites at the southernmost area of the brittle deformation along the detachment fault. Our results indicate that there were two successive, yet distinct gold-forming tectonic episodes in northwestern Jiaodong. One event first reactivated the detachment fault along the edge of the Linglong massif between 134 and 126 Ma, and then a second reactivated the shears along the margins of the Guojialing granite. Both events may relate to a component of northwest compression after a middle Early Cretaceous shift from regional NW extension to a NE–SW extensional regime.

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1. Introduction

Understanding temporal relationships within metallogenic epochs has been a key issue of interest to economic geologists during the past few decades. Determination of the duration of ore-forming events is of major importance for a thorough understanding of the genesis of ore deposits and for identifying associated geological events, such as defining the relationship between ore formation and evolving continental dynamics. Reconstruction of the spatial and temporal patterns of the geologic evolution of many large metallogenic provinces can be complex when characterized by relatively long-lived hydrothermal activity.

The Jiaodong gold province is the area of the most extensive past gold mining and largest recognized gold resources in China. The majority of the production and resources for the province is located in the Zhaoyuan region in the northwestern part of the peninsula (Qiu et al., 2002). Reliable production and resource data for the province, as with gold districts throughout China, are lacking. Based upon various reported accounts, it is likely that the Zhaoyuan region originally contained in excess of 1000 tonnes of Au (t Au). Dozens of operations now produce about 3–5 t Au/year from underground operations. Future large-scale mining development, perhaps with significant open-pit operations, is likely to highlight the brownfields potential that still remains in the region for even a larger resource. Despite the unique tectonic setting of the Jiaodong gold deposits...
that has led some workers to define these as a new type of gold deposit (e.g., Zhai and Santosh, 2013), the spatial association with large fault zones, local structural controls, temporal association with uplift, mineral assemblages, alteration, and ore fluid chemistries suggest these are best classified as orogenic gold deposits.

The geochronology of gold mineralization in the Jiaodong gold province has been addressed in many detailed studies during the past decade. A relatively young age for these gold deposits hosted in Precambrian terranes has been recognized for many years now. However, debate still exists (e.g., Li et al., 2006) as to whether these formed during a single event during the Yanshanian (Early Cretaceous) orogen (Wang et al., 1998; Zhou and Lu, 2000; Qiu et al., 2002), or as multiple, late Mesozoic hydrothermal episodes (Deng et al., 1999, 2003; Mao et al., 2003). There are, furthermore, still significant controversies regarding the overall duration of the main orogenic gold deposition event(s) (Wang et al., 2002; Deng et al., 2003; Chen et al., 2005).

Numerous published absolute age constraints of variable quality characterize the gold deposits of the Jiaodong Peninsula. Abundant existing age data for the Zoneyu region deposits include Rb–Sr (Luo and Wu, 1987; Zhang et al., 1994), K–Ar (Lu and Kong, 1993; Sun et al., 1995), and 40Ar/39Ar measurements on alteration minerals (Li et al., 2003; X.O. Zhang et al., 2003; Li et al., 2006), Rb–Sr on fluid inclusion waters (Yang and Zhou, 2001), 40Ar/39Ar for quartz (Zhang et al., 1994, 2003; Mao et al., 2003). There are, furthermore, still significant controversies regarding the overall duration of the main orogenic gold deposition event(s) (Wang et al., 2002; Deng et al., 2003; Chen et al., 2005).

Prior to our work, existing absolute age data for the Dazhangshan gold deposit were solely determined by whole rock K–Ar methods on auriferous sericitized granite and K-feldspar-altered granite, and both groups of analyses range imprecisely from 132 to 120 Ma (Xu, 1984; Chen et al., 1996). SHRIMP and LA-ICP-MS zircon U–Pb ages can be in part explored by judicious choice of samples for measurement, but can be much more fully exploited using the 40Ar/39Ar dating technique to decipher the detailed thermal history of a given region (McDougall and Harrison, 1999), which led us to initially conduct this study. We have combined high-precision, step-heating 40Ar/39Ar geochronology on white micas with field observations to help resolve the chronology and duration of the ore-forming hydrothermal activity at the deposit. Combining these new data, with the existing geochronology for structural events, intrusive activity, and gold mineralization in the area, we discuss the timing of gold mineralization in the Dazhangshan gold deposit and the duration of ore-forming hydrothermal activity during late Mesozoic in the Jiaodong gold province.

2. Regional geology

2.1. Terranes and lithologies

The eastern block of the North China Craton in Shandong Province is divided into two parts by the Tan–Lu (Tancheng–Lujiang) Fault, with the Jiaodong Peninsula to the east and the Luxi area to the west. The Jiaodong Peninsula is underlain by two Precambrian tectonic units, the Jiaobei terrane in the west and Sulu terrane in the east (Fig. 1). The Sulu terrane is the eastern end of the Dabie–Sulu ultra-high-pressure metamorphic belt, which developed along the southern side of the North China Craton during ca. 240–220 Ma metamorphism of Proterozoic rocks (Hacker et al., 1998; Ayers et al., 2002). Paleoproterozoic amphibolite and granitic gneiss are exposed in the area of Haiyangsu, which is located at the southernmost margin of the Sulu terrane (Li and Chen, 1994; Ye et al., 1999; Guo et al., 2002; Liou et al., 2006). In addition, ca. 800–700 Ma granitic gneiss is widely exposed in the Weihe, Rongcheng, and Wendeng areas (Ames et al., 1996; Wang and An, 1996).

The Jiaobei terrane, which hosts the vast majority of the gold deposits, consists of the Jiaobei uplift in the north and the Jialai basin in the south. Precambrian basement rocks exposed in the Jiaobei uplift are composed mainly of Neorarchean and younger tonalite–trondhjemite–granodiorite (TTG) gneisses (Jiaodong Group), and Paleoproterozoic (Fenzishan/Jinshan Group) and Neoproterozoic (Penglai Group) metamorphic sequences (Lu, 1998; Wallis et al., 1999; Tang et al., 2007). The TTG gneisses are exposed in the center of the Jiaobei uplift. Protolith ages of the TTG gneisses are 2.9–1.9 Ga (Wang and An, 1996; Lu, 1998; Tang et al., 2007, 2008; Jahn et al., 2008), with metamorphic ages for the amphibolite–granulite-facies rocks of ca.1.8–1.7 Ga (Zhai et al., 2000; Faure et al., 2003). The Jialai basin is a Cretaceous extensional basin, which is underlain by rocks of the middle Early Cretaceous Liayang Group (sandstone conglomerate and carbon-rich shale), late Early Cretaceous Qingshan Group (basalt, andesite, and trachyte tuff), and Late Cretaceous Wangshizi Group (sandstone conglomerate and siltstone; Lu and Dai, 1994; Ren et al., 2008).

2.2. Mesozoic granitoids

Mesozoic igneous rocks that intruded the Precambrian basement in Jiaodong cluster into four groups: Late Triassic syn-collisional granitoids, Late Jurassic calc-alkaline granitoids, Early Cretaceous high-K calc-alkaline granitoids, and late Early Cretaceous alkaline granitoids. The gold deposits are spatially associated with Late Jurassic and/or Early Cretaceous calc-alkaline granitoids, which are described in detail below.

Late Triassic syn-collisional granitoids, including the Shidao syenite–granitic complex (Chen et al., 2003; Yang et al., 2005), were emplaced into rocks of the Sulu terrane. The granitoids are mantle-derived (Song et al., 2003; Guo et al., 2005), and the syenitic bodies were emplaced at ~15 km depth (Zeng et al., 2007). These intrusions formed during the collision of North China and Yangtze Cratons at ca. 225–205 Ma (Chen et al., 2003; Guo et al., 2005).

Late Jurassic calc-alkaline granitoids are E-W trending across uplifted parts of both terranes. Most of the granites were intruded as components of a large batholith and include the Linglong, Kunyushan, Duogushan, and Wendeng bodies; the former two are widely deformed into gneissic rocks (Li and Yang, 1993). Compositions include biotite monzonitic granite, monzonitic diorite, quartz diorite, and granodiorite. However, there are different viewpoints as to whether the magmas are crustal melts (Hu et al., 1987; Wang et al., 1999), or are a type of hybrid system (Yao et al., 1990; Yang et al., 2013). These various opinions partly resulted from different views about the spatial relation between the granite and the Precambrian high-grade metamorphic rocks (Yang et al., 2007a). Application of high-precision dating, coupled with interpretation of detailed petrological and geochemical data, have led to a widely accepted understanding on the genesis of the Linglong granitoids in more recent years. These data indicate that the Linglong suite was derived by partial melting of Neorarchean lower-crustal rocks (Hou et al., 2007), with emplacement depths of 25–30 km (Zen and Hammarstrom, 1984; Chen et al., 1996). SHRIMP and LA-ICP-MS zircon U–Pb ages of the granitoids in the batholith are mainly between 160 and 150 Ma, although a few range from 147 to 142 Ma (Wang et al., 1998; Hu et al., 2004; Guo et al., 2005). Many Cretaceous felsic to mafic dikes, which have a broad range of reported ages (Wang et
Fig. 1. Simplified geological map of the Jiaodong Peninsula showing location of the major gold deposits (modified from Deng et al., 2003; Chen et al., 2005; Yang et al., 2006). The Dayingezhuang gold deposit is located in the southeast part of the Jiaoxibei uplift, and along the part of the fault to the south of Zhaoyuan City, defined by Charles et al. (2011) as the Linglong detachment fault.

3. Regional structure

Regional structures include E-, NE–NNE-, and NW–NNW-trending fault systems (Fig. 1). The gold mineralization is mainly controlled by the NE- to NNE-trending set of faults (Deng et al., 1996), as is described below.

The E-trending set of faults is the earliest of the Mesozoic structures. Their formation has been linked to the north–south compression associated with early Mesozoic collision between the North China and Yangtze cratons, and was synchronous with the formation of the Dabies–Sulu ultrahigh-pressure metamorphic rocks (Zhang et al., 2006). The E-trending faults are relatively poorly preserved throughout the region, but could have provided a basement control on the belt of east–west Jurassic plutons (Fig. 1). Furthermore, some workers have suggested a high density of gold deposits where the E-striking faults intersect the NE- to NNE-striking structures (e.g., Wang et al., 1984; Teng, 1985; Zhou, 1995; Deng et al., 2010).

The NE- to NNE-trending set of faults form the principal ore-controlling structures (Goldfarb et al., 2001; Qiu et al., 2002). These are argued to be subsidiary faults to the regional Tan–Lu Fault system, initially developed in eastern China as Late Jurassic sinistral faults that transect the Zhaoyuan area and as Early Cretaceous dextral faults that formed pull-part basins, such as the jialai basin (Fig. 1; Xu et al., 1987; Y.Q. Zhang et al., 2003; Zhu et al., 2010). These faults are evenly distributed, at a spacing of about 35 km, and are parallel to each other across the peninsula. From west to east, these are defined as the Sanshandao, Jiaojia, Zhaoping, Qixia, Muping–Jimo, and Mouru faults (Fig. 1), which are associated with nearly 90% of the defined gold resource on the jiaodong Peninsula (Lu and Kong, 1993; Qiu et al., 2002; Deng et al., 2006). Previous studies have shown that movements along all of these faults are long-lived, and that the Mesozoic deformation along these is complex and can be divided into four stages (Li and Yang, 1993; Deng et al., 2003). For example, the Muping–Jimo Fault experienced left-slip transpression during the Late Jurassic, extension or transtension during the Early Cretaceous gold event, transpression at the end of the Early Cretaceous, and right-slip transtension during the Late Cretaceous and Paleogene (Zhang et al., 2007).

The NW-trending set of faults, which are locally associated with late, minor silver mineralization (see below), developed during compressional events after the main gold mineralization. This is well recognized because they cut the NE- to NNE-trending set of faults (Deng et al., 1996, 2010). The Dayingezhuang Fault, which offsets the Dayingezhuang gold deposit (see below), is a prominent example of one of these NW-striking faults.

4. Dayingezhuang deposit geology

The Dayingezhuang gold deposit is located about 18 km southwest of Zhaoyuan City, in the southeastern part of the Jiaobei uplift, near the center of the Zhaoping Fault zone (Fig. 1). The pre-mining reserves were about 125 t Au at the end of 2011, including more than 35 t that had already been produced, with an estimated annual production slightly greater than 2.6 t Au. The deposit is a typical Jiaojia-style gold deposit (e.g., Qiu et al., 2002), and is therefore characterized by most high-grade orebodies being dominated by auriferous quartz–sulfide veinlets and stockworks. Wallrocks comprise both highly metamorphosed Precambrian sequences to the east and Mesozoic granitoid to the west. Precambrian sequences are composed of rocks of the Neoarchean Jiaodong Group and Paleoproterozoic Jingshan Group. Late Jurassic intrusions are composed of Linglong-type granites cut by numerous dikes of varied composition.

At the Dayingezhuang deposit, the gold mineralization is confined to the major NNE-trending Zhaoping Fault, which is cut by the post-ore NW-trending Dayingezhuang Fault (Fig. 2). The part of the Zhaoping Fault to the south of Zhaoyuan City, where it forms the eastern margin of the Linglong massif, has been termed the Linglong detachment fault (Fig. 1) by Charles et al. (2011). The Precambrian basement rocks form the hangingwall and the Linglong granitoids define the mineralized footwall of an uplifted dome that is recognized as a type of metamorphic core complex. Partial exhumation of the core complex took place at ca. 150–130 Ma (Charles et al., 2011), during a major period of Mesozoic extension along the eastern margin of China (e.g., Lin et al., 2008). Estimated maximum depths of gold deposition, as defined by above Guojialing-type pluton emplacement constraints, are 5–13 km within the Zhaoyuan area. This suggests that the Linglong granitoids were being uplifted at rates of at least 1 km/m.y. from emplacement depths of 25–30 km prior to the time of gold deposition because many of the ores are along the contact between the two groups of granitoids, as well as being hosted within or along the edges of the Linglong-type plutons.

The high-angle Dayingezhuang Fault zone cuts the main gold lode into two sections with 260–300 m of lateral offset (Figs. 2 and 3). The Dayingezhuang Fault is located at the southernmost area of widespread brittle deformation along the Linglong detachment fault, with cataclasites dominant locally on both sides of the Dayingezhuang Fault.
and also to the north, reflecting a late overprint to the ductile deformation. The earlier mylonitic features remain dominant at the granite’s eastern margin along the length of the detachment to the south (Charles et al., 2011). The Dayingezhuang Fault may have developed post-ore because of the very different strain intensities (e.g., Charles et al., 2011) between the mylonitized rocks to the south and the brittle rocks to the north along the Linglong detachment fault. Alternatively, it may have originally been a pre-ore or syn-ore structure developed during the core complex exhumation.

Orebodies are hosted in quartz–sericite–pyrite altered and cataclastically deformed Linglong granite located in the footwall of the Linglong detachment fault zone, which dips to the southeast 21° to 58°. The variable dip is consistent with the well-accepted model of Spencer (1984) that indicates many low-angle “detachments” were originally moderately dipping normal faults and that some segments subsequently rotated to shallower angles during unloading of the footwall during doming. The barren hangingwall of the Linglong detachment fault is composed of rocks of the Precambrian Jiaodong Group. The NNE- to NE-trending Linglong detachment fault and the brecciated zones in the footwall control the occurrence of the orebodies (Fig. 2), with joints and fissures controlling local zones of high-grade gold mineralization (Zhai et al., 2002).

The No. I and II orebodies are the most important parts of the resource. They represent 85% of the proven reserves in the Dayingezhuang deposit, located south and north of the Dayingezhuang Fault, respectively (Fig. 3), and are described in detail below.

The No. I orebodies are composed of 18 ore lenses, including both continuous lodes and parallel ore zones, and they are mainly concentrated for about 60 m into the altered footwall rocks (Fig. 3). These individual orebodies are NE-trending (20°) and dip to the southeast from 27° to 40°, with an average length of 740 m and an average ore grade of 4.03 g/t Au. The thickness of these individual orebodies is mainly 2–10 m, with a maximum of 20 m (Fig. 3). Ores are dominated by pyrite–sericite–quartz altered rock (Fig. 4). Ore-bearing pyrite is mainly in veinlets cutting the cataclasite and disseminated in the intrusion, although some larger vein networks are present.

The No. I orebodies are different from the No. II orebodies based on higher silver grades and the presence of associated Pb- and Zn-bearing sulfides. The silver content in the ores gradually increases with depth, from 2 g/t at shallow (−140 m) to 50 g/t at the deeper levels (−380 m), with an average grade of 14.78 g/t; silver enrichment is associated with more abundant galena. Although silver grades are exceptionally high for gold orebodies in the Jiaodong province, silver is not of high enough grade to be recovered in the mining. There are no obvious reasons as to why the deeper parts of the No. I orebodies contain an abundance of silver-rich base metal sulfides.

The No. II orebodies are composed of 73 ore lenses, occurring as more irregular lodes and pods. They are mainly concentrated for about 60 m into the footwall and strike 20° (Fig. 3), and dip to the southeast from 28° to 53°, with an average length of 930 m and an average ore grade of 4.01 g/t Au. The thickness of these individual orebodies is mainly 10–30 m and the maximum width reaches 100 m. The orebodies are anastomosing and branching, and pinch-and-swell throughout most of their length (Fig. 3), suggesting ongoing high-strain ductile deformation. Because this is not observed in the No. I orebodies, this suggests the No. II orebodies are older. Ores are dominated by pyrite–sericite–quartz altered rock. Ore-bearing pyrite is mainly in veinlets cutting the cataclasite and disseminated in the intrusion, although some larger vein networks are present.

Gold in the No. I and No. II orebodies is present as silver-bearing native gold and electrum. It occurs as free gold (75%), gold in fissures (20%), and gold inclusions in sulfides (5%), and is most closely associated with pyrite, and lesser chalcopyrite, galena, and sphalerite (Fig. 4E and F). Identified silver-bearing minerals in the...
No. I orebodies include native silver, küstelite, hessite, argentite, acanthite, polybasite, and pearceite, with lesser freibergite and argentobismutite. These are mainly hosted in quartz, with rare inclusions in sulfides (Fig. 4G). Microscopic studies show gold-bearing phases were deposited before the silver minerals. The presence of a large number of silver minerals in the No. I orebodies of the Dayingezhuang gold deposit makes this deposit unique from other Jiaodong deposits. Other sulfides in the deposit include pyrrhotite and bismuthinite.

The bulk of the ore is within and surrounded by zones of strong silicification, sericitization, sulfidation, and K-feldspar alteration; the K-feldspar and sericite extend beyond the limits of the pyrite and silicification. Although the ore fluids were CO₂-rich (Yang et al., 2009), the very limited carbonate alteration and typically...
Fig. 4 (continued).
massive pyrite are consistent with a fluid in equilibrium with a high Fe/(Fe + Mg) rock, as is common with many granitoids (e.g., Bohlke, 1988). The Precambrian metamorphic rocks in the hangingwall of the Linglong detachment fault zone are only very weakly altered, and are characterized by carbonatization and chloritization, weak silicification, and slightly anomalous gold (<0.1 ppm).

5. Geochronology of gold mineralization

5.1. Sample collection

To investigate the timing of gold mineralization, and resulting implications for both ore genesis and for late Mesozoic tectonic evolution, three sericite and one muscovite samples for 40Ar/39Ar geochronology were collected from three widely spaced locations in orebodies I and II (Fig. 3). These sites are described below.

Sample y61250k was collected from the center of the No. I orebodies at the −250 m level (Fig. 3), in an area dominated by quartz–sulfide veinlets (Fig. 4B). The altered granite is gray-white in color, generally massive, and with a granoblastic texture (Fig. 4H). The rock is composed of quartz (about 45%), sericite (about 25%), plagioclase (about 5%), K-feldspar (about 10%), pyrite (about 10%), and traces of chlorite, epidote, and graphite (Fig. 4E and F). Sericite grains are about 0.01–0.2 mm in length, formed from the hydrothermal alteration of feldspar, are closely associated with the euhedral and subhedral pyrite (Fig. 4L), and show almost colorless to very pale green birefringence and the same interference color of Level 3. Scanning electron microscope (SEM) images show the sericite occurs as subhedral hexagonal plates or anhedral grains (Fig. 4M and N).

Sample y725245k from the No. II orebodies was collected from a zone of gold mineralization at the −245 m level (Fig. 3), dominated by chlorite pyrite veinlets and disseminated pyrite (Fig. 4C). All features of the sampled zone (Fig. 4I) and collected sericite are identical to those of sample y61250k, although the massive granite here consists of quartz (about 35%), sericite (about 35%), plagioclase (about 5%), K-feldspar (about 10%), pyrite (about 10%), and traces of chlorite, epidote, and graphite (Fig. 4E and F). Sericite grains are about 0.01–0.2 mm in length, formed from the hydrothermal alteration of feldspar, are closely associated with the euhedral and subhedral pyrite (Fig. 4L), and show almost colorless to very pale green birefringence and the same interference color of Level 3. Scanning electron microscope (SEM) images show the sericite occurs as subhedral hexagonal plates or anhedral grains (Fig. 4M and N).

At a third site, both hydrothermal sericite and coarser muscovite were visible in the ores. Sample y745380kl and Sample y745380ki from the No. II orebodies were collected from the same site in a zone of gold mineralization at the −400 m level (Fig. 3). The zone contains quartz (about 50%), sericite (about 15%), muscovite (about 10%), plagioclase (about 10%), K-feldspar (about 10%), pyrite and chlorite (about 5%), and minor calcite (Fig. 4I). The sericite is the same size as that from the other two locations and is closely associated with the euhedral and subhedral pyrite (Fig. 4K). Muscovite in the sample shows similar interference colors and polychroism, but is distinguished because it is distinctly larger (about 0.05–0.5 mm) and has brighter interference colors than the sericite (Fig. 4I). Nevertheless, both phases of white mica were formed from the hydrothermal alteration of feldspar and are associated with the euhedral and subhedral pyrite (Fig. 4L). The SEM images show that both the sericite and muscovite (Fig. 4O and P) occur as subhedral hexagonal plates or anhedral grains.

5.2. Experimental method

Muscovite and sericite grains were crushed and sieved to 125 to 250 μm and separated from the other phases in the altered granites by conventional heavy-liquid, magnetic, and hand separation techniques to achieve >99% purity at the Langfang Regional Geological Survey, Hebei Province, China. The mineral separate, Fish Canyon Tuff sandstone and ZBH-25 biotite (standard sample in China) flux monitors were irradiated in the atomic reactor of Research Institute of Atomic Energy (Beijing, China) and set in the H8 hole for fast neutron irradiation. The irradiation duration and neutron dose were 10.7 h and 2.45 × 1017 n/cm² for the analyzed minerals, respectively. The J factor was estimated by replicate analysis of Fish Canyon Tuff sandstone, with an age of 27.55 ± 0.08 Ma (Lanphere and Baadsgaard, 1997), and the ZBH-25 biotite standard with an age of 133.3 ± 0.24 Ma (Fu et al., 1987) with 1% relative standard deviation (1σ). The J-values for individual samples were determined by a second-order polynomial interpolation. The Ca and K correction factors were calculated from co-irradiation of pure salts of CaF₂ and K₂SO₄ [e.g., (40Ar/39Ar)₀ = 0.004782, (39Ar/37Ar)₀ = 0.00081, (39Ar/37Ar)₀/CA = 0.0002398].

The 40Ar/39Ar analyses were performed at the Geologic Laboratories Center, China University of Geosciences, Beijing, on a MM5400 Micromass spectrometer operating in a static mode. Samples were loaded in aluminum packets into a Christmas tree sample holder and dagessed at low temperature (250–300 °C) for 20–30 min before being incrementally heated in a double-vacuum furnace. The gases released during each step were purified by means of Ti and Al–Zr getters. Once cleaned, the gas was introduced into a MM-5400 Micromass spectrometer, and 4–5 min were allowed for equilibration before static analysis was done.

The 40Ar/39Ar analyses are listed in Table 1, and released spectra are shown in Fig. 6. Weighted mean plateau ages are reported where >50% of the released 39Ar in contiguous steps is within 1σ error. The closure temperature of argon diffusion of muscovite has been generally assumed to be about 400 ± 50 °C for a relatively rapid cooling rate, 360 °C to 350 °C for a moderate cooling rate (Hames and Bowring, 1994; McDougall and Harrison, 1999), and 270 °C during slow cooling or extended reheating (Snee et al., 1988). More recently, Harrison et al. (2009) suggested muscovite closure temperatures in excess of 400 °C for slow cooling.

5.3. 40Ar/39Ar results

The three sericite samples and one muscovite yield well-defined 40Ar/39Ar plateau ages. The 40Ar/39Ar plateau age of muscovite (y745380kl) and sericite (y745380kl, y725245k) from the No. II orebodies, and sericite (y61250k), from the No. I orebodies, at the two sigma level and calculated from about 93.5 to 98.4% of the released 39Ar, are 128.67 ± 0.50 Ma, 130.52 ± 0.52 Ma, 133.37 ± 0.56 Ma, and 126.8 ± 0.59 Ma (Fig. 5), respectively. The isochron ages are similar to the plateau age, agreeing within error (Fig. 5).

In order to discuss the difference among the age data for these four samples, we have recalculated the 40Ar/39Ar plateau ages to include the error in the J-value. The 40Ar/39Ar plateau age of muscovite (y745380kl) and sericite (y745380kl, y725245k) from the No. II orebodies, and sericite (y61250k) from the No. I orebodies, at the two sigma level and calculated from about 91.5, 96.4, and 81.3% of the released 39Ar, are 128.38 ± 0.69 Ma, 130.71 ± 0.70 Ma, and 132.74 ± 0.83 Ma (Fig. 6), respectively, showing they are statistically indistinguishable. Because we were unable to collect >50% of the released 39Ar in contiguous steps within 2σ error in the age spectra of sericite (y61250k), the 40Ar/39Ar plateau age within error at the two sigma level could not be obtained.
6. Discussion

6.1. Timing of gold mineralization at the Dayingezhuang gold deposit

Well-defined plateau ages of four mica samples indicate that they are reliable estimates of the timing of hydrothermal alteration. The minimum temperature of gold deposition in the investigated deposit, estimated from homogenization temperature of fluid inclusions in auriferous quartz, ranges from 240 °C to 360 °C (Yang et al., 2009), although trapping temperature of the ore fluids could be slightly higher if pressure corrections were required. Coexistence of ductile deformation of the quartz associated with pyrite (Fig. 4H and I) and brittle

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<td>97.01</td>
<td>132.28</td>
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</table>

Table 1

40Ar/39Ar step-heating geochronology data for sericite and muscovite from Dayingezhuang gold deposit in Jiaodong gold province.

Note: Time of each step-heating is 10 min.

* Radiogenic.
Fig. 5. $^{40}$Ar/$^{39}$Ar plateau and isochron ages ($\pm$) for sericite and muscovite from the Dayingezhuang gold deposit. The following abbreviations are used: Ser, sericite; Mus, muscovite; PA, preferred age.
deformation of sericitized feldspar (Fig. 4J) in the ores at the Dayingezhuang gold deposit could also indicate that deformation, and thus gold deposition, occurred under temperature conditions of ~300–400 °C (e.g., Passchier and Trouw, 2005). This relationship would hold true if the secondary feldspar was coeval with the main mineralization; a consistent spatial association between the orebodies and large clots of the feldspar in surrounding wallrock suggest this is a likely scenario. Given that the location of the deposit along the Linglong detachment fault zone is at the boundary between brittle and ductile deformation of the footwall granitoids (e.g., Charles et al., 2011), and such a transition is commonly observed in the 300–450 °C temperature interval in the upper crust, the above ore-forming temperature estimate of 300–400 °C seems very realistic.

The previously stated muscovite blocking temperatures, coupled with the above estimated ore formation temperatures, indicate that the ages of the argon plateaus represent the approximate mineralization age, irrespective of whether the hydrothermally altered rocks were undergoing slow or rapid cooling subsequent to the gold event. The weighted mean plateau 40Ar/39Ar data (2σ) from the Dayingezhuang deposit are indistinguishable from each other, and the weighted mean plateau 40Ar/39Ar data (1σ) range from 126.8 ± 0.59 Ma to 133.37 ± 0.56 Ma, indicating that they were formed contemporaneously in the middle Early Cretaceous (Figs. 5 and 6).

Thus, our study provides the first precise age data on the Dayingezhuang gold mineralization. More significantly, it unequivocally extends the oldest bound of the period of hydrothermal activity in the gold province to between 126.8 ± 0.59 Ma and 133.37 ± 0.56 Ma.

In contrast to the Dayingezhuang gold deposit, many of the other large gold deposits in the northwestern part of Jiaodong gold province, such as Cangshang, Jiaojia, Xincheng and Wang’ershan, located adjacent to the NE- to NNE-trending shear zones on the margins of Guojialing granite, formed between 125 and 115 Ma (Li et al., 2003; X.O. Zhang et al., 2003; Y.Q. Zhang et al., 2003) when using the most precise geochronology in the literature. The muscovite 40Ar/39Ar plateau age within error at the two sigma of Cangshang is 121.3 ± 0.2 Ma (X.O. Zhang et al., 2003). The sericite 40Ar/39Ar plateau ages within error at the two sigma of Jiaojia, Xincheng and Wang’ershan are 120.5 ± 0.6 Ma, 120.9 ± 0.3 Ma, and 119.8 ± 0.2 Ma, (Li et al., 2003), respectively.

6.2. Comparison with previous geochronological data

Existing K–Ar data for the Dayingezhuang deposit overlap our relatively narrow range of new ages, but are less precise. The whole-rock K–Ar dates of K-feldspar-altered granite and sericite-altered granite are both 126 ± 6 Ma (Xu, 1999). The poorer precision of the K–Ar dating left a great deal of uncertainty in defining the absolute age, particularly as to whether some gold in Jiaodong may have been older than previously determined for most of the other deposits. The whole-rock K–Ar age for the unaltered Linglong granite at the Dayingezhuang deposit is 144 ± 7 Ma (Table 2; Xu, 1999), which, within error, overlaps the younger part of the ca. 160–150 Ma U–Pb crystallization age of the majority of the Linglong granites (Wang et al., 1998; Hu et al., 2004; Guo et al., 2005). Furthermore, K–Ar dates on granites often underestimate the age of the granites due to incomplete degassing of polymerized melts and argon loss effects. So there is little doubt that the gold ores are 20–30 m.y. younger than their immediate igneous host rocks. Based on cross-cutting relationships, pre-mineralization pegmatites (Fig. 4A) at the Dayingezhuang deposit yielded a whole-rock K–Ar date of 129 ± 6 Ma (Xu, 1999), and this indicates that the gold has a maximum age of 135 Ma. Similarly, the whole-rock K–Ar age for post-mineralization diorite porphyry dike
emplacement along the Zhaoping Fault zone is 129 ± 2 Ma (Guo et al., 1990), which places a minimum age constraint of 127 Ma on the gold event. Thus, although less precise, the existing K–Ar constraints bracket the time of mineralization to a relatively older time period than the other reliable ages for the mineralization in the Zhaoyuan region. Again, if the K–Ar dates are minimum age estimates, ore formation would be even older. Our new 40Ar/39Ar ages, however, more precisely confirm that the gold mineralization at Dayingezhuang occurred between 134 and 126 Ma (Fig. 7), which is a period nevertheless nearly identical to that suggested by the less dependable K–Ar studies of the pre- and post-ore dikes.

6.3. Duration of ore-forming hydrothermal activity

Our study of the 40Ar/39Ar systematics of the mineralization of the Dayingezhuang deposit shows that the main phase of gold mineralization there is constrained to the period 130 ± 4 Ma, which is older than 120 ± 5 Ma, the widely accepted main ore-forming period of the other major gold deposits in the northwestern part of the Jiaodong gold province (Yang et al., 2000; Yang and Zhou, 2001; Li et al., 2003; X.O. Zhang et al., 2003; Li et al., 2006, 2008; Guo et al., 2013; Yang et al., 2013). Some workers have broadly indicated that the gold event in the Zhaoyuan area was ca. 130–110 Ma (e.g., Qiu et al., 2002; Chen et al., 2005), but evaluation of only the most reliable geochronology among the existing data, as described above, has led to the general conclusion of a 120 ± 5 Ma gold event. However, our new data now suggest a significant older gold pulse did occur in the Zhaoyuan area. Although it is still uncertain as to whether gold formation is best defined as one continuous and evolving event or multiple and distinct episodes of a gold-forming period, when we consider the most precise dates from other workers and our new dates, the duration of ore formation in this giant gold province was at least 15–20 million years.

The duration of this older gold pulse itself is difficult to define. The fact that our youngest new date of 126.8 Ma characterizes the No. I orebodies hints at an evolution to the more Ag–Pb–Zn-rich gold ore during the latter stages of the hydrothermal pulse. This is supported by the fact that the pinch-and-swell nature of the ores is restricted to the more northerly No. II orebodies, whereas no such strain seems to have impacted the No. I orebodies. In addition, we interpret the four dates, with well-defined plateaus and small errors, as a whole to indicate fluid movement and gold deposition during reactivation of the Linglong detachment fault occurred over as period of at least six to eight million years.

Charles et al. (2013) indicate that ductile deformation along the Linglong detachment fault continued until at least ca. 135.5–132.5 Ma and brittle overprinting was ongoing between ca. 129.5 Ma and 126.3 Ma. These data are consistent with our new deposit data that indicate gold was deposited during brittle deformation at this time and the oldest gold may have been deposited towards the end of the older ductile event. Many smaller gold deposits occur along the detachment further to the south (Fig. 1), but the transition to a more brittle regime may have been critical for localization of large orebodies, such as at the Dayingezhuang gold deposit.

6.4. Tectonic significance of new age data

The Dayingezhuang gold deposit is the only significant gold deposit (>100 t Au) along the Linglong detachment fault. Other undated deposits to the south along the structure are smaller and within areas of ductile deformation within the footwall to the fault. The larger Dayingezhuang deposit suggests a major hydrothermal event near the section of the fault zone that was characterized by a brittle–ductile transition at ca. 130 Ma. The association of gold with the cataclasites indicates brittle deformation and ore formation along the margin of the rapidly uplifting Linglong massif as it passed through a depth somewhere between 5 and 13 km. The hydrothermal activity is clearly responsible for brittle deformation and the resulting brecciation (e.g., see fig. 4H of Charles et al., 2011). Brecciated rocks along the detachment for about 20 km to the north may define other targets for large ca. 130 Ma gold deposits.

In contrast to the Dayingezhuang gold deposit, many of the other large gold deposits, such as Taishang and Damoqujia (Yang et al., 2007b, 2008), in the Zhaoyuan area are located adjacent to the NE- to NNE-trending faults along the margins of the Guojialing plutons that intruded the Linglong massif at 130–126 Ma. An 40Ar/39Ar date on biotite from the Guojialing pluton of 124 Ma (Charles et al., 2011) indicates very rapid uplift was ongoing immediately after crystallization of the Guojialing suite of plutons and during widespread gold formation. The brittle reactivation of these faults at ca. 120 ± 5 Ma, during the uplift, represents a subsequent episode of mineralization that is temporally distinct from that along the Linglong detachment fault. It may reflect successive periods of ductile to brittle transition along the uplifting margins of first the southeastern side of the Linglong massif and secondly the younger intrusions. Such mylonitization followed by cataclastic reactivation, as is characteristic of the Dayingezhuang gold deposit.

Table 2
Summary of direct 40Ar/39Ar and indirect K–Ar ages constrains on gold mineralization of Dayingezhuang gold deposit in jiaodong gold province.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock name</th>
<th>Mineral</th>
<th>Method</th>
<th>Age (Ma)</th>
<th>References</th>
</tr>
</thead>
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<tr>
<td>Y745380K</td>
<td>Pyrite-sericite-quartz gold ore</td>
<td>Sericite</td>
<td>Ar-Ar</td>
<td>130.52 ± 0.52 (P)</td>
<td>This paper</td>
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<tr>
<td>Y745380KI</td>
<td>Pyrite-sericite-quartz gold ore</td>
<td>Sericite</td>
<td>Ar-Ar</td>
<td>128.67 ± 0.50 (P)</td>
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<td>Y725245K</td>
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<td>Sericite</td>
<td>Ar-Ar</td>
<td>133.37 ± 0.56 (P)</td>
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</tr>
<tr>
<td>Y61250K</td>
<td>Pyrite-sericite-quartz silver-polymetallic ore</td>
<td>Sericite</td>
<td>Ar-Ar</td>
<td>126.8 ± 0.59 (P)</td>
<td>This paper</td>
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<td>9880304</td>
<td>Fresh unaltered granite</td>
<td>Whole rock</td>
<td>K–Ar</td>
<td>129 ± 6</td>
<td>Xu (1999)</td>
</tr>
<tr>
<td>9880302</td>
<td>Pegmatite vein</td>
<td>Whole rock</td>
<td>K–Ar</td>
<td>126 ± 6</td>
<td>Xu (1999)</td>
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<tr>
<td>9880303</td>
<td>K-feldspar altered granite</td>
<td>Whole rock</td>
<td>K–Ar</td>
<td>125 ± 6</td>
<td>Xu (1999)</td>
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<td>9692611</td>
<td>Sericite quartzite altered granite</td>
<td>Whole rock</td>
<td>K–Ar</td>
<td>126 ± 6</td>
<td>Xu (1999)</td>
</tr>
<tr>
<td>86-j-6</td>
<td>Fault gouge of Zhaoping Fault</td>
<td>Chlorite</td>
<td>Ar-Ar</td>
<td>136.86 ± 8.35</td>
<td>Deng et al. (1996)</td>
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<td>   </td>
<td>Post-mineralization K-feldspar altered granite vein</td>
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<td>114.18 ± 16.7</td>
<td>Guo et al. (1990)</td>
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<tr>
<td>   </td>
<td>Post-mineralization diorite porphyrite intruding the Zhaoping Fault and orebody</td>
<td>Whole rock</td>
<td>K–Ar</td>
<td>129.25 ± 2.25</td>
<td>Guo et al. (1990)</td>
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</tbody>
</table>

Fig. 7. Diagram indicating the ages determined for minerals and whole rocks from Dayingezhuang deposit. The ±1 analytical uncertainties are indicated by a solid line. The shaded interval indicates the ca. 130 ± 4 Ma period of gold mineralization in the Dayingezhuang gold deposit.
of the Linglong detachment fault and the NE- and NNE-trending faults, typically characterizes the evolution of many core complexes (e.g., Davis and Lister, 1988).

The North China Craton represents an atypical example where lode gold deposits are hosted in terranes that are billions of years older than ore formation. The gold event on the Jiaodong Peninsula lode gold deposits are hosted in terranes that are billions of years (e.g., Davis and Lister, 1988).

Previous workers have shown that most of the important gold deposits in the Zhaoyuan area of the Jiaodong gold province formed at ca. 120 ± 5 Ma. The \(^{40}\)Ar/\(^{39}\)Ar dating results from this study provide the first precise age data on the Dayingezhuang gold deposit. The deposit is located along the Linglong detachment fault on the eastern margin to the Linglong metamorphic core complex. The data extend the oldest bound of the period of hydrothermal activity in the Jiaodong gold province to between 134 and 126 Ma. The older gold mineralization at Dayingezhuang suggests zones of brittle deformation along the southeastern margin of the massif may be equally prospective for large gold resources in the Zhaoyuan area.

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**References**


