$^{40}Ar/^{39}Ar$ Constraints on a Temporal Link between Gold Mineralization, Magmatism, and Continental Margin Transtension in the Jiaodong Gold Province, Eastern China

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ABSTRACT

The Jiaodong gold province is the largest gold repository in China. Both mineralization and granitoid hosts are spatially related to the crustal-scale Tan-Lu strike-slip fault system, which developed along the Mesozoic continental margin in eastern China. A series of $^{40}Ar/^{39}Ar$ laser incremental heating analyses of hydrothermal sericite/muscovite from three major gold deposits (Jiaojia, Xincheng, and Wangershan) and igneous biotite from the granodiorite hosts were performed to establish a possible temporal link between gold mineralization, magmatism, and movement along the Tan-Lu fault zone. Magmatic biotite crystals yield well-defined and concordant plateau ages between 124.5 ± 0.4 Ma and 124.0 ± 0.4 Ma (2σ), whereas sericite and muscovite samples (a total of 30 single separates) give reproducible plateau ages ranging from 121.0 ± 0.4 Ma to 119.2 ± 0.2 Ma (2σ). An integration of our $^{40}Ar/^{39}Ar$ results with age data from other major gold deposits in Jiaodong demonstrates that widespread gold mineralization occurred contemporaneously during a 2–3-m.yr. period. Most gold deposits show intimate spatial associations with abundant mafic to intermediate dikes. The mafic dikes have K-Ar ages of 123.5–119.6 Ma, in excellent agreement with those of the gold deposits. These newly obtained $^{40}Ar/^{39}Ar$ ages, in combination with other independent geological and geochronological data on granodioritic intrusions (130–126 Ma), volcanic rocks (1243.6–114.7 Ma), and deformed rocks within strike-slip faults (132–120 Ma) in Jiaodong or adjacent areas, also support the idea that gold mineralization postdated the granodioritic magmatism but was contemporaneous with mafic magmatism and volcanism, all controlled by the transtensional motion along the Tan-Lu fault in the Early Cretaceous.

Introduction

Strike-slip faults, important structural features in many orogenic belts and a major form of intracontinental deformation, have played a positive role in the formation and distribution of granitoid intrusion and related hydrothermal deposits (Sylvester 1988; Henley and Adams 1992; White et al. 1995; Kocyigit and Beyhan 1998). Although a causal connection between strike-slip tectonism and magmatism/mineralization is commonly assumed (Henley and Adams 1992; White et al. 1995), only a few examples exist in which precisely defined temporal relations among all three have been well established.

The gold deposits from the Jiaodong gold province, eastern China, provide an opportunity to test such relations. This large gold concentration region is bounded to the west by the continental-scale north-northeast-striking Tan-Lu strike-slip fault zone. Gold deposits are dominantly hosted in the widespread Mesozoic granitoid intrusions, and both are apparently controlled by subsidiary strike-slip faults (Lü and Kong 1993; Goldfarb et al. 1998; Lu et al. 1999). Recent SHRIMP U-Pb zircon dating suggests that these Mesozoic intrusions were formed at 165–150 Ma and 130–126 Ma, respectively (Wang et al. 1998; Qiu et al. 2002; Zhang

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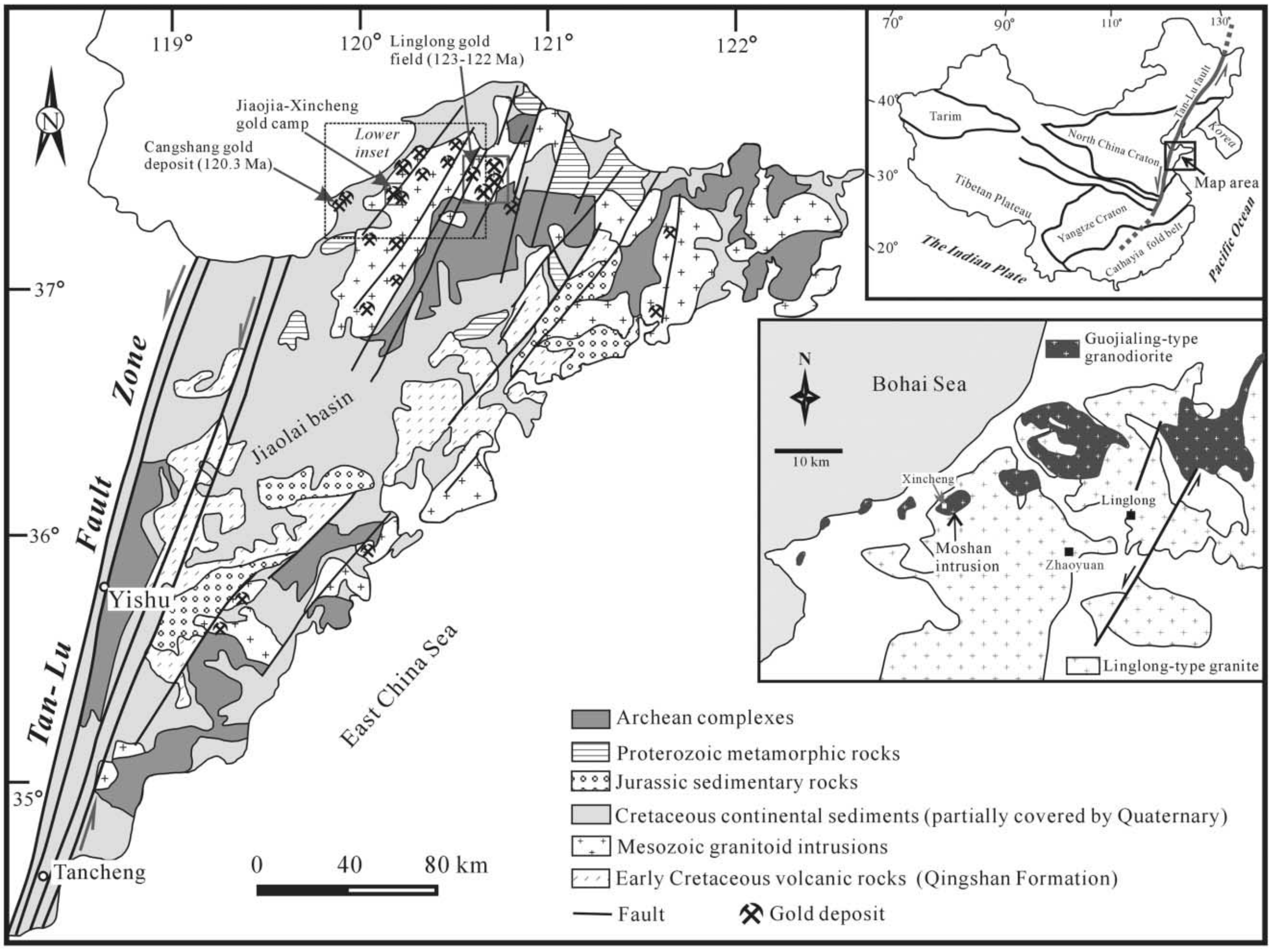

Figure 1. Simplified geological map of the Jiaodong gold province showing the spatial relationships of primary gold deposits to the Mesozoic intrusions and the Tan-Lu strike-slip fault (modified from SBGMR 1991). The lower inset map shows the distribution of the Guojialing granodiorites and the Linglong granites (modified from Guan et al. 1998). The upper inset is the map of China and its major tectonic units, with the location of Jiaodong.

2002). Field relations and previous geochronological measurements have led to the conclusion that the Early Cretaceous magmatism (130–126 Ma) was genetically related to gold mineralization, whereas the Late Jurassic intrusions (165–150 Ma) clearly predated, and merely provided the hosts to, gold deposits (e.g., Wang et al. 1998; Qiu et al. 2002). However, considering the extent of this gold province, direct dating of gold deposits has been inadequate, and the timing of gold deposition at most deposits has only been indirectly constrained through crosscutting relationships. In addition, many aspects regarding the genesis, tectonic control, and any magmatic affinity of these gold deposits remain controversial (Yang and Lü 1996; Wang et al. 1998; Zhai et al. 2002).

In this article, we present the first high-precision laser incremental heating $^{40}Ar/^{39}Ar$ data from three large-scale gold deposits within the economically important Jiaojia-Xincheng gold camp (fig. 1) and from their granodiorite hosts. These new data, coupled with available geologic and geochronological constraints on regional intrusions, volcanic rocks, and deformed rocks within the Tan-Lu fault zone, link gold mineralization, magmatism, and volcanism to the transtensional movement of the Tan-Lu fault system in the Early Cretaceous.

Regional Geology

The Jiaodong gold province is located in the southeastern margin of the Precambrian North China craton (fig. 1). The geology of the area can be divided into four main lithologic groups: (1) Archean granulite, gneiss, amphibolite, and biotite-bearing schist; (2) Early-Middle Proterozoic metamorphosed mafic igneous and sedimentary rocks; (3) Mesozoic granitoids mainly emplaced in the Archean rocks; and (4) Jurassic-Cretaceous continental sedimentary rocks and the Early Cretaceous volcanic sequences.

The northeast-directed Tan-Lu fault zone (fig. 1), more than 5000 km in strike length, is the most prominent strike-slip fault system in eastern Asia, extending from south China northeastward into the Russian Far East (Kimura et al. 1990; Xu 1993; Gilder et al. 1999). In Jiaodong, this fault system is marked by four major strike-slip faults and a group of subsidiary structures (fig. 1). The Tan-Lu fault zone has been active since the Late Jurassic and is thought to have played a major role in the Mesozoic geologic evolution of Jiaodong (SBGMR 1991; Xu 1993).

Mesozoic intrusions in the Archean metamorphic complexes in the northwestern part of Jiaodong consist of granites, granodiorites, and lesser monzonites. These rocks are traditionally classified as the Linglong and the Guojialing suites (fig. 1; Sang 1984; SBGMR 1991). The Linglong suite is mainly composed of medium-grained metaluminous to slightly peraluminous biotite-granites (Sang 1984). The Guojialing suite in the northern region of Jiaodong was emplaced in the Linglong granites and is composed of typically porphyritic biotite-hornblende granodiorites containing mafic enclaves (fig. 1; SBGMR 1991; Yang and Lü 1996). Both granites and granodiorites are significant hosts of gold mineralization (fig. 1). These granitoids themselves have been intruded by hundreds of dikes of lamprophyre, diabase, dioritie, and dacite, which are commonly fault controlled and distributed along the 30°–50° northeast and partially 300°–320° northwest directions (Sun et al. 1995, 2000; Yang 2000). Most dikes are characterized by high K_2O contents (2.08 wt%–5.17 wt%), a high Mg number ($=$molar [Mg/{Mg + Fe}]; 0.56–0.89), significant enrichments of large ion lithophile elements (LILE: Ba, Sr, Rb, K, LREE [light rare earth elements]), and depletions in Cr, Ni, Nb, and Y (Sun et al. 2000).

The Jiaolai basin, which is defined and likely controlled by the Tan-Lu fault and associated subsidiary structures, hosts extremely thick (~11,000 m) and rapidly deposited (200 m/m.yr.) continental volcano–sedimentary rocks (fig. 1). The Early Cretaceous volcanic rocks, namely the Qingshan Formation, are ~1500 m thick and consist of latibasalt, shoshonite, andesite, and potassic rhyolite containing abundant pyrolite xenoliths (SBGMR 1991; Qiu et al. 1996, 2001*a*). They occur in the Jiaolai basin as well as within or west of the Tan-Lu fault zone (SBGMR 1991). Commonly volcanic rocks of the Qingshan Formation are characterized by high contents of Na_2O and K_2O coupled with high Na_2O/K_2O ratios (>1), strongly fractionated rare earth element patterns with $(La/Yb)_N$ values of 14–31 but without an obvious Eu anomaly, and significant enrichments of LILE and incompatible elements (e.g., Rb, Ba, Sr, K; SBGMR 1991; Qiu et al. 1996).

Mineralization

The Jiaodong gold province hosts the most important historical and presently active centers of gold mining in China, in terms of both annual gold production (55 t Au in 2000) and gold reserves (>900 t Au; Qiu et al. 2002). Several world-class (>100 t Au) gold deposits have been discovered and mined in the last 2 decades. Gold deposits are mostly hosted by the Linglong and Guojialing granitoid intrusions and are spatially associated with the Tan-Lu fault system (Lü and Kong 1993; Yang and Lü 1996; Qiu et al. 2002). These deposits are traditionally grouped into a massive quartz vein style and a disseminated/stockwork style, locally termed as the Linglong-type and the Jiaojia-type ores, respectively (Yang and Lü 1996). The Linglong-type deposits are hosted by subsidiary northeast-trending strike-slip faults that cut the Mesozoic granitoids, and mineralization occurs as continuous auriferous quartz veins generally 1000–5000 m long, several meters wide, and extending for a few hundred meters downdip (Yang and Lü 1996; Yang 2000; Zhou and Lü 2000). The Jiaojia-type deposits are characterized by intensely altered rocks along northeast-striking brittle-to-ductile shear zones, largely composed of disseminated, fine-grained to medium-grained, pyrite and quartz-sericite-pyrite stockworks (Zhou and Lü 2000; Zhang et al. 2002). The latter style of mineralization has become the most important part of the gold resource in Jiaodong since its recognition in the early 1980s.

The Jiaojia-Xincheng gold camp comprises 13 Jiaojia-type gold deposits, including the Jiaojia, Xincheng, and Wangershan deposits investigated in this study (figs. 1, 2). These combined are currently the most important gold producers in the Jiaodong gold province, each containing >60 t of gold source at an average grade of 7–8 g/t (cf. Qiu et al. 2002). Orebodies are spatially related to a Guojialing-type granodiorite, the Moshan intrusion, and developed along the northeast-striking Jiaojia-Xincheng fault (JXF) and the Wangershan-Hedong fault (WHF; fig. 2). The JXF and WHF, both striking 40°–60° northeast with moderate to steep dip angles of 40°–70°

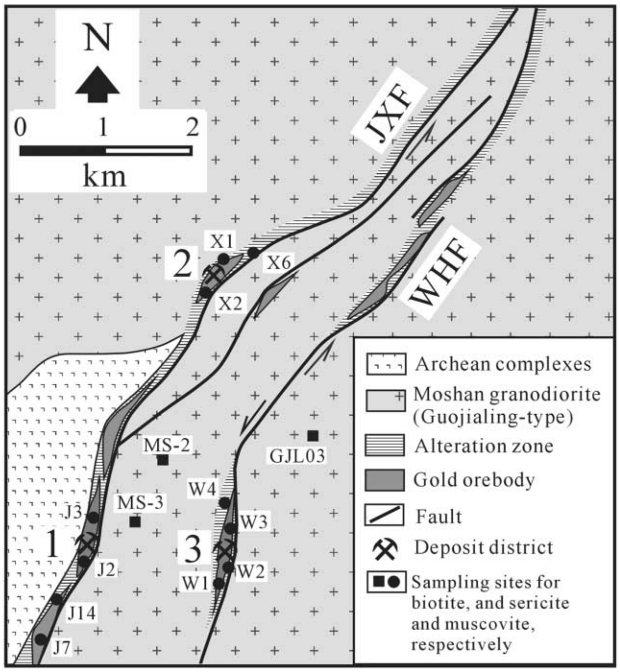

Figure 2. Schematic map of the Jiaojia-Xincheng gold camp showing the sample locations and the structural controls of secondary strike-slip faults on the granodiorite-hosted gold deposits and associated alterations zones (after Yang 1998); *1*, *2*, and *3* represent the Jiaojia, Xincheng, and Wangershan deposits, respectively. *JXF* = Jiaojia-Xincheng Fault; *WHF* = Wangershan-Hedong Fault.

northwest, converge into a single left-lateral strike-slip fault to the north of the gold camp. The faults become steeper with increasing depth (Lu et al. 1999). Auriferous alteration zones are commonly 500–1200 m long, several to a few hundred meters wide, and continuous for 400–1200 m downdip (fig. 2).

Hydrothermal alteration is dominated by sericitization, silicification, pyritization, and carbonation. Sericite is generally present as well-defined selvedges surrounding pyrite and quartz veins/aggregates, as a pervasive replacement in broad zones enclosing closely spaced pyrite grains, and in a few samples as veinlets filling fissures within early pyrite (fig. 3*a*). Veins and aggregates in association with sericitic alteration are composed predominantly of pyrite, quartz, and white mica, with minor amounts of chalcopyrite, calcite, galena, sphalerite, and trace anhydrite. The most important gold-bearing minerals are pyrite, quartz, and white mica.

Samples and Techniques

Isotopic dating was conducted on three samples of biotite, each from fresh granite, and 11 samples of sericite and muscovite from auriferous zones within the three deposits. Sample locations are shown in figure 2, and more details in the hydrothermal samples are reported in appendix 2, available from *The Journal of Geology*'s Data Depository free of charge on request. All samples were subjected to petrographic examination, scanning electron microprobe (SEM) observation, and electron microprobe (EMP) analysis. Suitable samples were crushed and then washed in distilled water in an ultrasonic bath for 1 h and dried. Biotite grains, sericite aggregates, and muscovite flakes (0.1–2.5 mm; >99% purity) were handpicked under a binocular microscope. For samples containing sericite and muscovite, separation of the two types of white mica was achieved by virtue of the generally platy nature of muscovite. From each sample, seven to 15 grains were irradiated along with the Fish Canyon standards (28.02 Ma; Renne et al. 1998) for 14 h at the B-1 CLICIT facility at the Radiation Center, Oregon State University. Sample and flux monitor irradiation geometry followed that of Vasconcelos (1999). After a 2-mo cooling period, one biotite grain and two or three sericite/muscovite separates from each sample were analyzed by the laser incremental-heating $^{40}Ar/^{39}Ar$ method using a MAP 215–50 noble gas mass spectrometer following the experimental procedures in Vasconcelos (1999).

Results

Petrographic analyses, SEM observations, and EMP analyses reveal that gold mainly occurs as gold and electrum within quartz and pyrite crystals (not shown) and on sericite and muscovite grains (fig. 3*b*, 3*c*), indicating that sericite and muscovite are genetically associated with gold precipitation. Sericite and muscovite are geochemically characterized by high potassium (9.92–10.70 wt% K_2O), low iron and magnesium concentrations, and scarcity of calcium (table 1), compositions close to the ideal formula of white mica. Such compositional characteristics indicate the monomineralic nature of these potassium mica minerals. The extreme purity and high potassium contents of the white mica and its genetic association with gold suggest that this mineral is amenable to $^{40}Ar/^{39}Ar$ dating and ensure that the resulting $^{40}Ar/^{39}Ar$ ages can be reliable chronological estimates for gold mineralization.

Because of the large number of analyses, it is im-

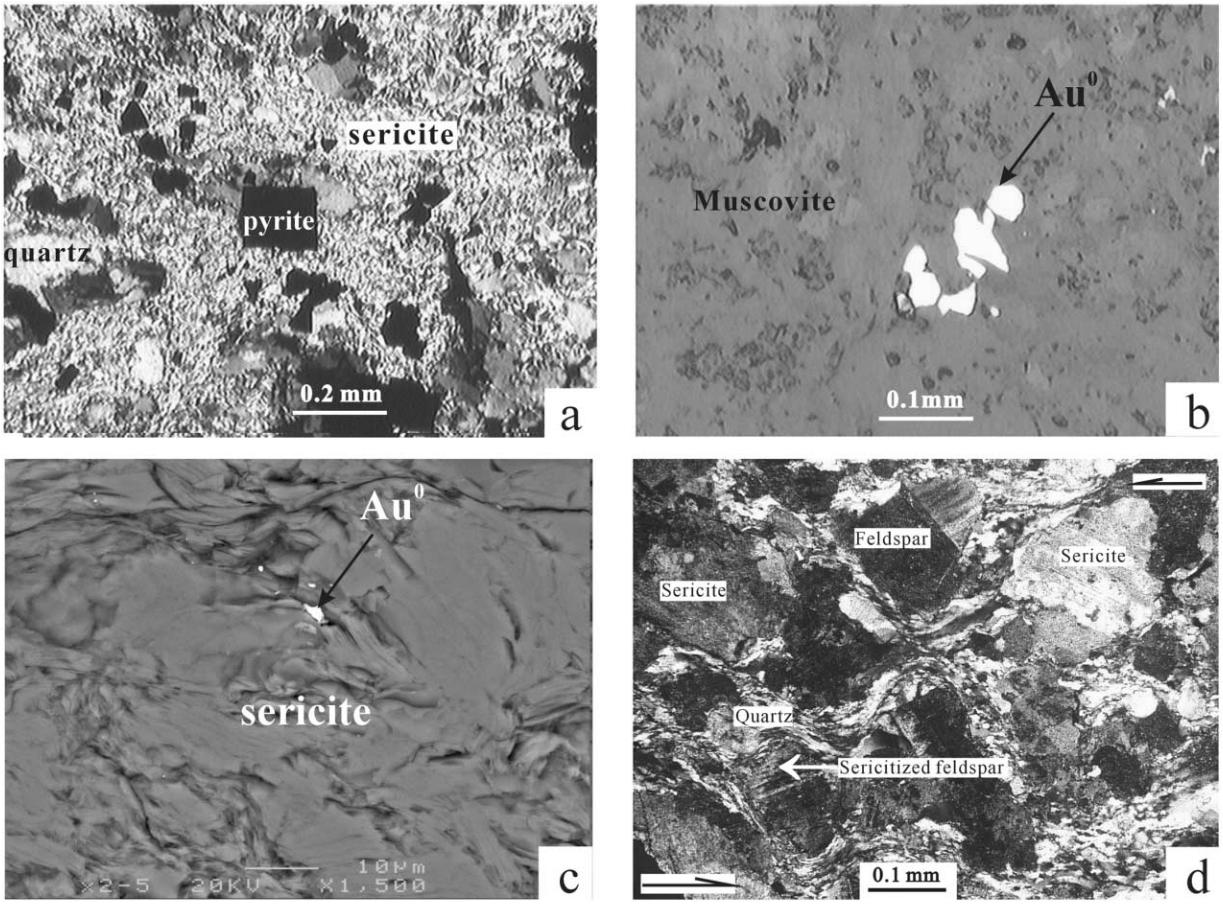

Figure 3. *a*, Photomicrograph illustrating the typical alteration assemblages in sample J14 from the Jiaojia deposit that are also common in the Xincheng and Wangershan deposits. *b*, Gold grains on muscovite (sample X1). *c*, SEM images of sample W1 showing occurrences of the sericite and gold. These textural relationships indicate that sericite/muscovite is genetically related to gold mineralization, thus $^{40}Ar/^{39}Ar$ dating on these white mica minerals can provide direct constraints on the timing of mineralization. *d*, Coexistence of ductile deformation of quartz and brittle deformation of sericitized feldspar (sample X6 from the Xincheng gold deposit) suggests the temperature conditions between 300° and 400°C (Scholz 1988), under which deformation and alteration took place. The black arrow pair denotes direction of left-lateral shear.

possible to present all the $^{40}Ar/^{39}Ar$ analytical results for each grain. These results are tabulated in appendix 1, also available from *The Journal of Geology*'s Data Depository. Representative age spectra from the granodiorite and each gold deposit are illustrated in figures 4 and 5, respectively. A summary of $^{40}Ar/^{39}Ar$ plateau ages for all samples and grains is shown in figure 6. All data are quoted at the 95% confidence interval (2σ).

All grains yield well-defined, reproducible, and high-precision plateau ages (figs. 4, 5). The shapes of the spectra indicate that excess argon, ^{39}Ar loss by recoil, and mixing of multiple phases (McDougall and Harrison 1999) do not occur in our samples. Some samples, however, show relatively low apparent ages and large uncertainties in the initial step(s) (figs. 4, 5*d*, 5*e*, 5*k*, 5*l*), suggesting minor argon loss in the dated minerals. This is supported by the integrated ages of these samples, which are consistently ca. 1–3 m.yr. younger than the corresponding plateau ages (figs. 4, 5*d*, 5*e*, 5*k*, 5*l*).

The $^{40}Ar/^{39}Ar$ ages of pristine biotite crystals range between 124.5 ± 0.4 Ma and 124.0 ± 0.4 Ma (figs. 4, 6). Sericite/muscovite separates from the Jiaojia, Xincheng, and Wangershan deposits yield $^{40}Ar/^{39}Ar$ ages of 120.5 ± 0.6 Ma to 119.2 ± 0.2 Ma, 120.7 ± 0.2 Ma to 120.2 ± 0.3 Ma, and 121.0 ± 0.4 Ma to 119.4 ± 0.2 Ma, respectively (figs. 5, 6). Remarkable concordance among plateau ages obtained by multiple sericite or muscovite grains

Table 1. Average Results of Sericite and Muscovite by Electron Microprobe Analyses (%)

Deposit	Jiaojia				Xincheng			Wangershan			
Samples[a]	J2 (21)	J3 (12)	J7 (15)	J14 (9)	X1 (9)	X2 (30)	X3 (13)	W1 (17)	W2 (10)	W3 (26)	W4 (8)
SiO_2	49.17	48.41	49.37	49.56	48.79	49.23	49.98	50.00	47.95	48.80	48.77
Al_2O_3	32.95	31.96	32.40	31.70	30.97	31.80	32.29	35.38	33.24	32.20	32.30
TiO_2	.13	.16	.04	.13	.20	.11	.13	.15	.15	.13	.17
FeO	1.95	2.96	2.73	3.10	3.57	3.03	3.20	2.12	2.88	2.78	2.81
MnO	.02	.00	.00	.01	.04	.01	.00	.02	.04	.00	.00
MgO	1.13	1.24	1.60	1.36	1.26	1.23	.98	.71	.73	.82	.84
CaO	.00	.01	.07	.07	.01	.04	.04	.03	.04	.06	.02
Na_2O	.12	.09	.15	.17	.17	.20	.17	.09	.12	.15	.10
K_2O	10.04	10.64	10.37	9.97	10.70	10.51	10.36	10.37	10.09	10.20	9.92
P_2O_5	.01	.06	.06	.05	.01	.05	.04	.00	.05	.1	.04
Total	95.52	95.53	96.79	96.12	95.72	96.21	97.19	98.87	95.29	95.24	94.97

Note. Standards and unknowns were analyzed with 0.5 mm of the probe diameter at 15 kV and 15 nA current using a JEOL JXA 8800L Superprobe at the CMM of the University of Queensland. Oxygen was analyzed as an unknown, and the following standards were used: MnO (Mn and O), Cl-apatite (P), Al_2O_3 (Al), Fe_2SiO_4 (Fe, Si), MgO (Mg), $CaSO_4$ (Ca), $NaAlSi_3O_8$ (Na), and $KAlSi_3O_8$ (K).
[a] Numbers in parentheses denote points analyzed.

from the same sample and by multiple samples from the same deposit suggests that the $^{40}Ar/^{39}Ar$ results reliably measure a single hydrothermal event. Samples from different localities in the same intrusion also yield similar plateau ages (figs. 4, 6), suggesting that the biotite plateau ages represent the time at which the granodiorite cooled below ~350°C (McDougall and Harrison 1999).

Discussion

Timing of Mineralization and Magmatism. Well-defined, high-precision, and reproducible plateau ages of 30 sericite and muscovite grains (figs. 5, 6) indicate that these are reliable estimates for the timing of sericitic hydrothermal alteration. The temperature of gold deposition in the three investigated deposits, estimated from homogenization temperature of fluid inclusions in auriferous quartz, range from 250°C to 350°C (Yang 1998). These values are below the closure temperature for Ar diffusion (350°C) in muscovite and sericite at moderate cooling rates (McDougall and Harrison 1999). The temperature of trapping of ore fluids would be higher if pressure corrections were considered. Coexistence of ductile deformation of quartz and brittle deformation of the feldspar in the altered rocks (fig. 3*d*) from the Xincheng deposit indicates that deformation, and thus gold deposition, occurred under temperature conditions of ~300°–400°C (Scholz 1988). We therefore suggest that the true temperature of mineralization fluids approximates the closure temperature of argon in sericite and muscovite, and we accordingly interpret the $^{40}Ar/^{39}Ar$ ages to represent the true age of gold mineralization. Plateau $^{40}Ar/^{39}Ar$ age data of the Jiaojia, Xincheng, and Wangershan deposits are

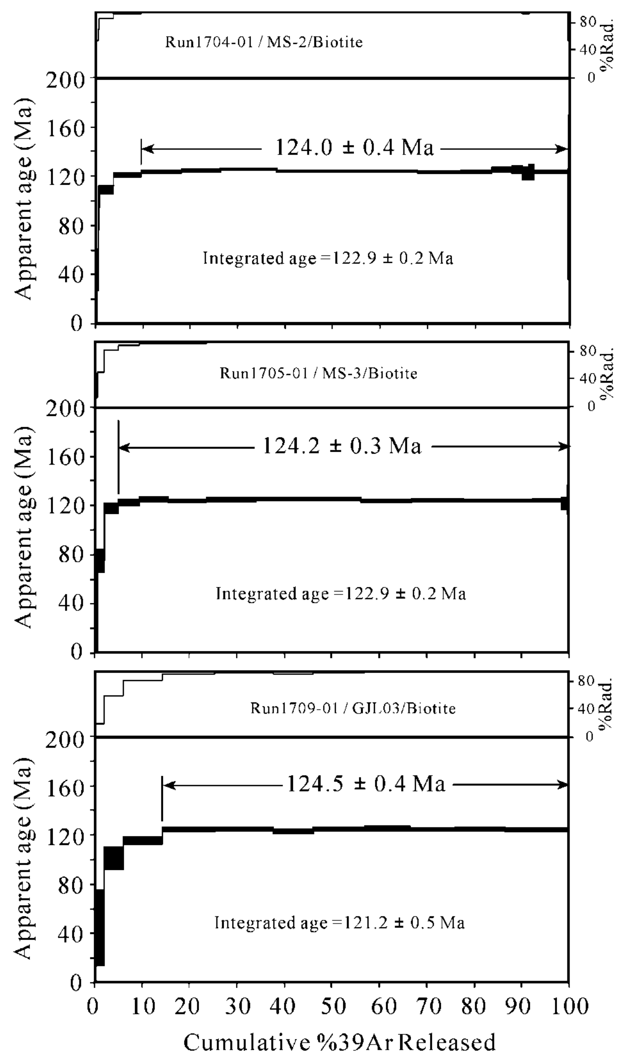

Figure 4. Apparent age spectra of igneous biotite crystals.

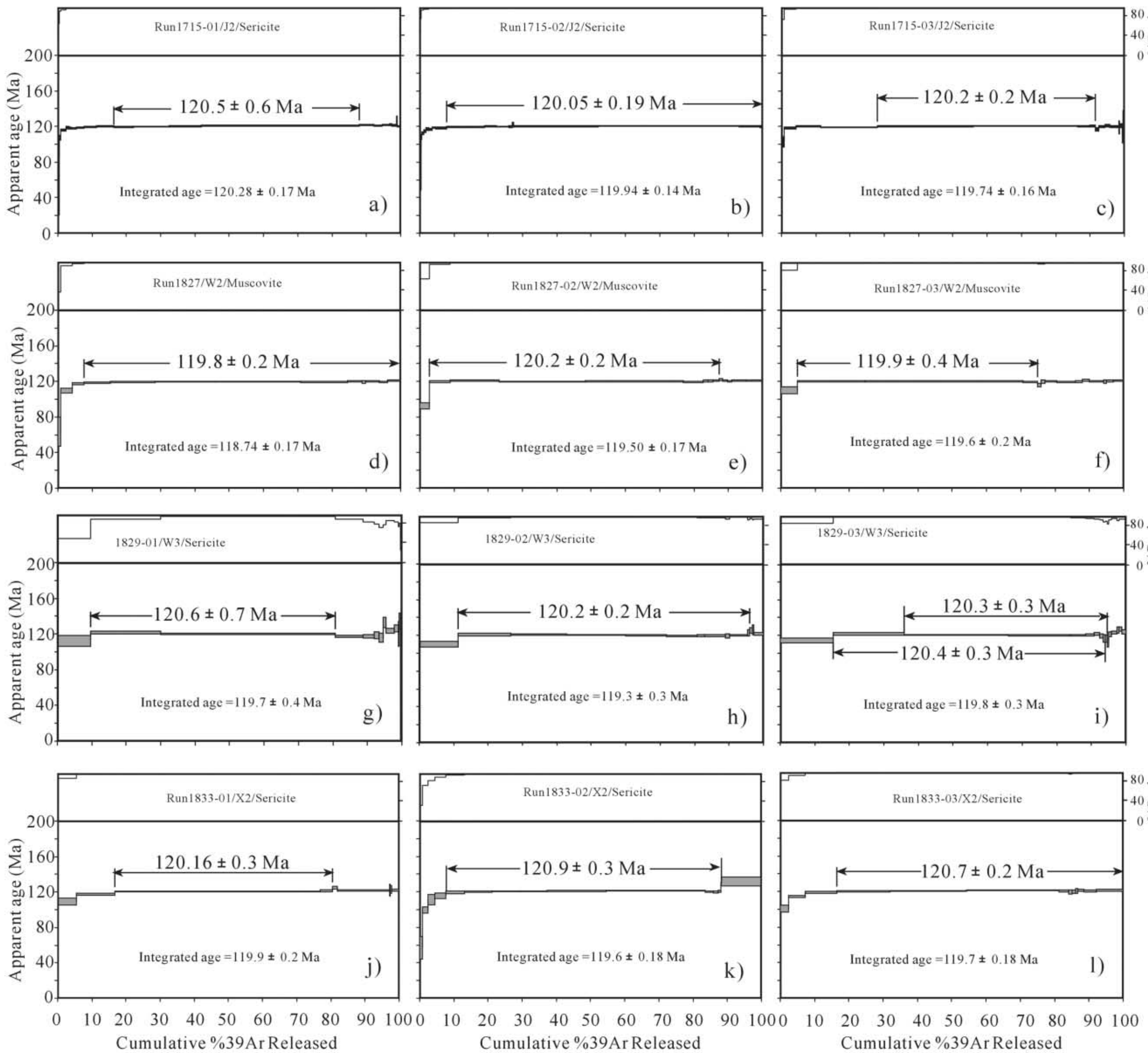

Figure 5. Well-defined plateau ages of representative sericite and muscovite separates, indicating the extreme reproducibility of $^{40}Ar/^{39}Ar$ ages obtained from different separates of the same sample, and the concordance among different deposits.

indistinguishable from each other, indicating that they were formed contemporaneously in the middle Early Cretaceous (fig. 6).

Timing of Jiaodong gold deposition has also been constrained directly or indirectly on other important gold deposits. SHRIMP zircon U-Pb dating on the Guojialing-type granodiorites and a postmineralization feldspar porphyry dike in the Linglong gold field, which host and displace mineralized quartz veins, respectively, show that they were formed at 130–126 Ma and 120 Ma (Guan et al. 1998; Wang et al. 1998). These indirectly constrain mineralization at 126–120 Ma. Rb-Sr dating of auriferous pyrite from three Linglong-type gold deposits (fig. 1) yields isochron ages of 123–122 Ma (Yang and Zhou 2001). More recently, Zhang et al. (2003) obtained a 121.3 Ma $^{40}Ar/^{39}Ar$ plateau age on sericite from the Jiaojia-type Cangshang gold deposit (fig. 1). These results further support the idea that our $^{40}Ar/^{39}Ar$ ages represent the true formation ages of the gold deposits, and they substantiate a regional gold mineralization event on the western side of the Jiaodong gold province (fig. 1), within a 2–3-m.yr. period in the middle Early Cretaceous.

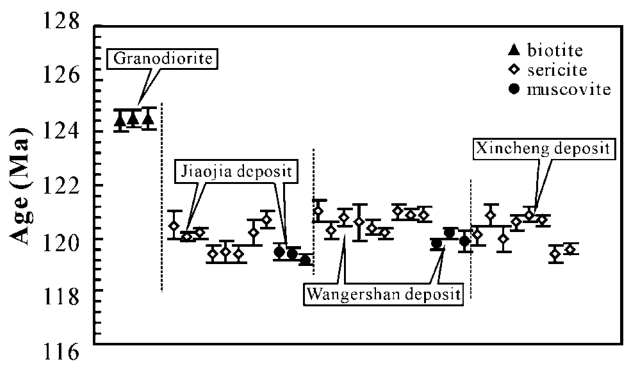

Figure 6. $^{40}Ar/^{39}Ar$ ages for mineral separates from the fresh granodiorite and the three gold deposits investigated. Analytical uncertainties at 2σ level are indicated with the error bars.

Whether or not gold mineralization is genetically related to magmatism has been a matter of controversy (Zhang et al. 1994; Yang and Lü 1996; Wang et al. 1998; Qiu et al. 2002). The apparent time gap (30–45 Ma) between the gold deposits and the Linglong granites precludes a temporal link between these two, and most Chinese workers agree that gold deposits have a genetic association with the Guojialing-type granodiorites (Luo and Wu 1988; Yang and Lü 1996; Guan et al. 1998; Wang et al. 1998). However, our $^{40}Ar/^{39}Ar$ data suggest that gold deposition did not take place until the Guojialing-type granodiorites cooled below ~350°C at 124.5–124.0 Ma. Mineralized fault zones cutting through the granodiorites (fig. 2; figs. 4, 6 in Qiu et al. 2002) further confirmed the fact that gold emplacement must have formed after the granodioritic magma solidification. SHRIMP zircon U-Pb ages for five Guojialing-type intrusions hosting gold deposits also demonstrate that they were emplaced before 126 Ma (Guan et al. 1998; Wang et al. 1998; Qiu et al. 2002). In this context, we suggest that gold deposition postdated granodioritic magmatism, and no causal relations could be established between these two events.

As mentioned earlier, widespread mafic to intermediate dikes occur in many gold mines, preferentially in mineralized zones, and some dikes themselves were mineralized (Sun et al. 1995; Yang and Lü 1996; Yang 2000). In many cases, these dikes are parallel to gold veins or occupy the same structure as the veins (Sun et al. 1995; Yang 2000; Yang and Zhou 2001). Geochemical and isotopic data indicate an enriched mantle source for their origin (Sun et al. 2000). Mafic dikes from the Linglong gold field have a whole-rock K-Ar age between 123.5 and 122.6 Ma, the same as the coexisting gold lodes (Yang 2000; Yang and Zhou 2001). Phlogopite crystals extracted from mafic dikes within, and 20–30 km west of, the Tan-Lu fault zone yield $^{40}Ar/^{39}Ar$ ages of 120.3–119.2 Ma. These ages indicate that regional mafic magmatism was a few million years later than Guojialing granodiorite emplacement but coincident with gold mineralization. We therefore suggest a genetic association between mineralization and dike formation.

Continental Transtension Control. The Tan-Lu fault system has long been considered to have played an important role in the formation and distribution of gold deposits in Jiaodong (Wang et al. 1998; Lu et al. 1999; Zhou and Lü 2000; Qiu et al. 2002). Gold veins of both the Linglong and Jiaojia types are generally hosted in the northeast- to north-northeast-trending subsidiary faults, and common loci for gold deposition are pull-apart step-overs, releasing bends or jogs, and splay structures in the terminal segments (Yang and Lü 1996; Lu et al. 1999; Zhou and Lü 2000).

Xu (1993) and Kimura et al. (1990) related the generation of the Tan-Lu fault system to the northwestward oblique subduction of the Izanagi-Pacific plate beneath eastern China starting in the Late Jurassic. Geologic evidence documents three distinct tectonic regimes during the evolution of the Tan-Lu fault: Late Jurassic transpression, Early Cretaceous transtension, and Tertiary compression. The Early Cretaceous transtension is well manifested by the Jiaolai basin, the Qingshan Formation volcanic rocks, and the mafic to intermediate dikes emplaced in many gold mines. The transtensional movement is directly evidenced by the many en-echelon brittle or brittle-to-ductile shear zones cutting the Linglong and Guojialing suites, and resulting fault breccias (Lü and Kong 1993; Xu 1993; Yang and Lü 1996; Lu et al. 1999; Zhai et al. 2002). Fault orientations and kinematic data show these shear zones to be dipping steeply southeastward or northwestward and to contain gently plunging slickenlines in the fault plane and left-lateral kinematic indicators within the 100–300-m-wide fault zones (Lü and Kong 1993; Lu et al. 1999). Timing of this tectonism was documented by Zhu et al. (2001), who measured $^{40}Ar/^{39}Ar$ ages between 132 and 120 Ma on whole-rock mylonite samples from five localities within the Tan-Lu fault zone.

Petrographic and geochemical studies on the Linglong suite granites indicate their origin by partial remelting of the Archean metamorphic complexes (Sang 1984). In contrast, the petrographic and geochemical characteristics of the Guojialing-type granodiorites led Yang (2000) to propose that these rocks were most likely derived from partial melting of basalt-underplated lower crust (Petford and Atherton 1996). The distinct structural, petrographic, and geochemical features of the Guojialing suite from the Linglong suite indicate a profound change of tectonic regime and the onset of mantle upwelling and lithospheric thinning in Early Cretaceous time (Wang et al. 1998; Yang 2000; Zhai et al. 2002). Mantle upwelling and resulting crustal extension may have significantly facilitated the tectonic regime change from transpression to transtension (Wang et al. 1998), although slab rollback and changes in the angle and rate of westward subduction of the Izanagi-Pacific plate underneath eat China remain possible (Xu 1993; Goldfarb et al. 1998; Bierlein et al. 2001*b*).

Following the emplacement of the Guojialing-type granodiorite, widespread mafic to intermediate dikes and volcanic rocks were likely formed in response to increasing extent of lithospheric thinning and crustal extension (Qiu et al. 1996, 2001*a*, 2001*b*; Sun et al. 2000; Yang 2000; Zhai et al. 2002). Geochemical and isotopic signatures suggest that these rocks were derived from metasomatized mantle (Qiu et al. 1996, 2001*a*; Sun et al. 2000). Whole-rock Rb-Sr and $^{40}Ar/^{39}Ar$ dating for several fresh rocks of the Qingshan Formation in the Jiaolai basin and ~20 km west to the Tan-Lu fault yielded two age groups (124.3–114.7 Ma and 109.9–108.2 Ma), with the first group overlapping our mineralization ages (Qiu et al. 1996, 2001*a*, 2001*b*).

Seismic data image the Tan-Lu fault continuing into the mantle depths (Teng et al. 1983). This translithospheric fault system must have acted as a set of efficient pathways for mafic magma and mantle-derived fluids (Sun et al. 1995; Yang 1998; Bierlein et al. 2001*a*). Such an idea is well supported by stable isotopic signatures of mineralizing fluids ($\delta D_{SMOW} = -57$ to -74 per mil, $\delta^{18}O_{SMOW} = 4.118$ to 5.6 per mil), determined and calculated from auriferous quartz both in the Jiaojia and Linglong gold camps (Zhang 1985; Yang 1998; Mao et al. 2002). More recently, noble gas isotopic determinations on the Jiaojia deposit show that the auriferous pyrite has $^3He/^4He$ ratios ranging from 2.0×10^{-6} to 3.5×10^{-6} (Zhang et al. 2003), 40–60 times higher than that in the earth's crust and indicating the presence of mantle components in the ore fluids (Stuart et al. 1995). The Sr-Nd-Pb isotopic systematics of auriferous pyrite from the Linglong gold deposits also suggest that ore fluids were derived from the mixing of fluids degassing from mafic magmas or directly from mantle, with meteoric waters (Yang and Zhou 2001).

Conclusions

Laser microprobe $^{40}Ar/^{39}Ar$ dating of hydrothermal sericite and muscovite associated with gold mineralization reveals an important mineralization event at 121.0 ± 0.4 Ma to 119.2 ± 0.2 Ma in the Jiaodong gold province, eastern China. The Guojialing-type granodiorites, hosts to the gold deposits, have $^{40}Ar/^{39}Ar$ biotite ages from 124.5 ± 0.4 Ma to 124.0 ± 0.4 Ma, leading us to suggest that gold deposition postdated the granodioritic magmatism. In conjunction with field relations and other reported geochronological data (SBGMR 1991; Qiu et al. 1996, 2001*b*; Yang 2000; Zhu et al. 2001), our $^{40}Ar/^{39}Ar$ age data also indicate that widespread gold mineralization in the western side of the province took place contemporaneously within a 2–3-m.yr. period in the middle Early Cretaceous. This extensive mineralization event was coincident with emplacement of the mafic to intermediate dikes occurring in most deposit areas, an early stage of mantle-derived magma eruption, and formation of the Jiaolai basin, all controlled by the transtensional movement along the Tan-Lu fault zone that might have facilitated rapid ascent of both mantle-derived magmas and fluids.

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