

# Geological and S–Pb–He–Ar isotope constraints on the origin of the Muping–Rushan gold belt, Jiaodong Peninsula, eastern China

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**Abstract** – The Muping–Rushan gold belt is one of three gold mineralization belts in Jiaodong Peninsula, eastern China, comprising between the Sulu ultrahigh-pressure metamorphic belt and North China Craton. This study investigates the source of gold and ore-forming fluids in the Muping–Rushan gold belt, based on a detailed analyses of typical gold deposits. Electron microprobe elemental mapping of pyrite and pyrrhotite shows that gold and silver occur mainly as thin veins in cracks in stage I pyrite (Py1) or around stage II pyrite (Py2). The arsenic contents are higher at the rims and in cracks of stage I pyrite (Py1) and around stage II pyrite (Py2), and are positively correlated with gold contents. *In situ* sulphur isotope data for sulphides in the study area range between 5.8‰ and 10.1‰. The sulphides in the belt are generally characterised by  $\delta^{34}\text{S}_{\text{Py}} > \delta^{34}\text{S}_{\text{Sp}} > \delta^{34}\text{S}_{\text{Ccp}}$  and  $\delta^{34}\text{S}_{\text{Py4}} > \delta^{34}\text{S}_{\text{Py2}} > \delta^{34}\text{S}_{\text{Py1}}$ . The  $\delta^{34}\text{S}$  values of mineralization stages II and III are similar to those of the Jiaodong and Jingshan Groups and the Kunyushan Complex. Lead isotopic compositions are consistent with those of the lower crust and orogenic belts.  $^3\text{He}/^4\text{He}$ ,  $^{40}\text{Ar}/^{36}\text{Ar}$ , and  $^{40}\text{Ar}^*/^4\text{He}$  ratios of the gold deposits in the study area are 0.01–5.06 Ra, 389.8–4674.7, and 0.03–2.78, respectively, indicating that the ore-forming fluids were derived mainly from the crust, with a minor mantle contribution.

**Keywords:** Jiaodong Peninsula / Muping–Rushan gold belt / Elemental mapping / *In situ* sulphur isotopes / Lead isotopes / Helium and argon isotopes

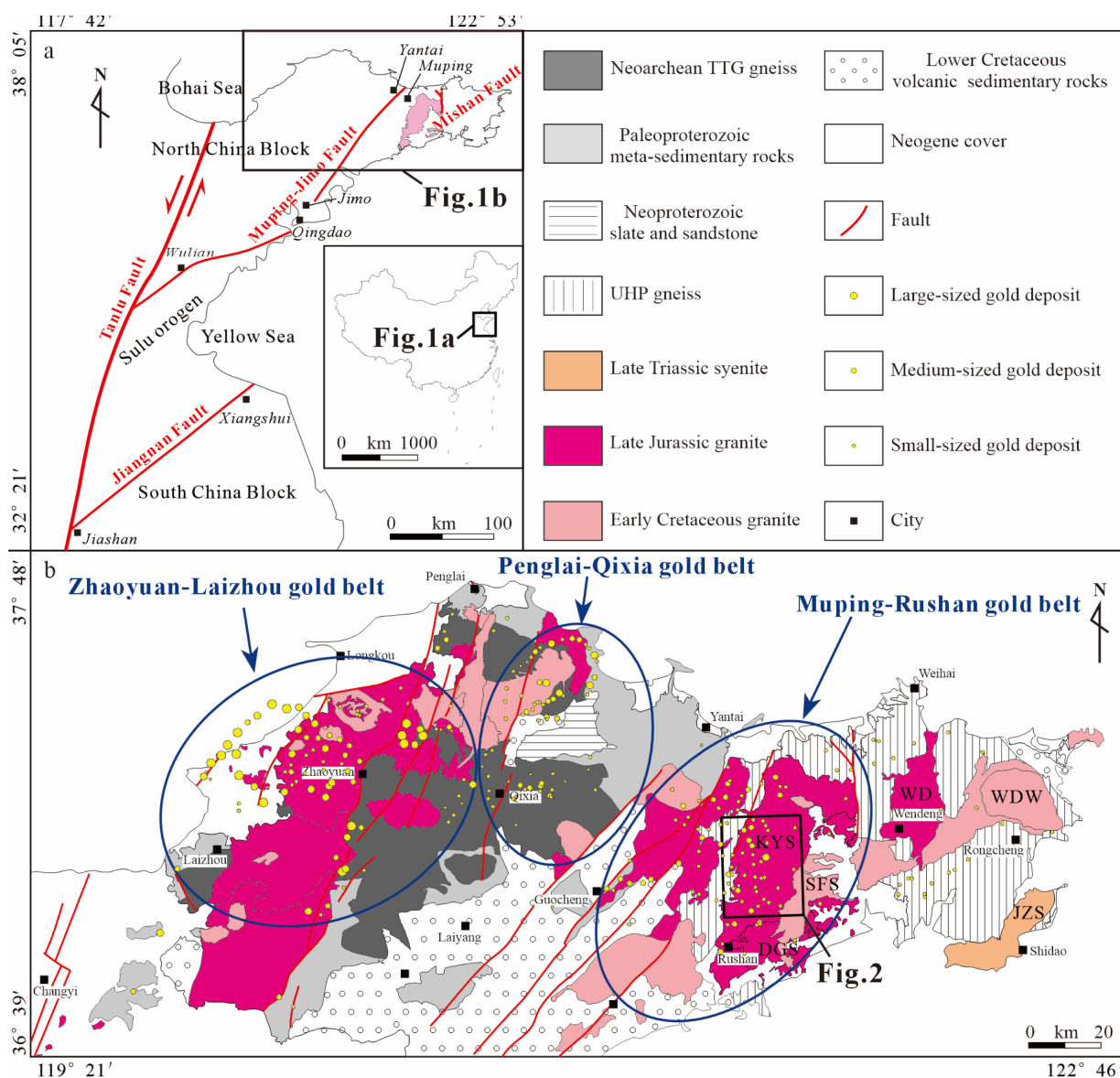
## 1 Introduction

Jiaodong Peninsula is the largest gold producing province in China (Deng *et al.*, 2018; Goldfarb and Groves, 2015). The proven gold reserves exceeded 5500 tons in 2023, and these reserves and production account for ~25% of the total reserves and production in China (Deng *et al.*, 2023; Song *et al.*, 2023; Yang *et al.*, 2019). The Muping–Rushan gold belt is one of three gold mineralization belts on Jiaodong Peninsula (Figs. 1–2), with >80 gold deposits (Fan *et al.*, 2016; Song, 2012). The single-vein gold reserves in the Jinqingding gold deposit are >40 tons.

Globally, the distribution of orogenic and magmatic-hydrothermal gold deposits is mainly controlled by the continental or oceanic arc system (Groves *et al.*, 2019). The Jiaodong gold province is hosted by a Precambrian metamorphic basement that originated in the Paleoproterozoic and was

metamorphosed by continental collision in the Triassic. Afterward, it entered an intracontinental setting that underwent anatectically-induced reworking from the Jurassic to the Cretaceous, with peak reworking ages between 120 and 130 Ma (Zheng *et al.*, 2013; Zheng and Wu, 2018; Zheng *et al.*, 2019). This led to a superimposed metallogenic environment and current metallogenic models related to plate theory have not fully interpreted it (Deng *et al.*, 2023; Zheng *et al.*, 2013; Zheng, 2023). Unlike other typical gold deposits, such as Mother Lode in the USA, Olympiada and Sukhoi Log in Russia, Timmins in Canada, Golden Mile and Bendigo in Australia, and Yangshan and Huachanggou in China, which typically exhibit close temporal and spatial relationships with regional metamorphism (Deng *et al.*, 2020a; Gebre-Mariam *et al.*, 1995; Goldfarb *et al.*, 2001; Goldfarb *et al.*, 2005; Goldfarb and Groves, 2015; Groves *et al.*, 1987; Groves *et al.*, 2000; Kerrich *et al.*, 2005; Li *et al.*, 2006; Phillips and Powell, 2010), the Jiaodong gold province was formed at ca. 120 Ma (Chen, 2017; Deng *et al.*, 2022; Hu *et al.*, 2004; Li *et al.*, 2006;

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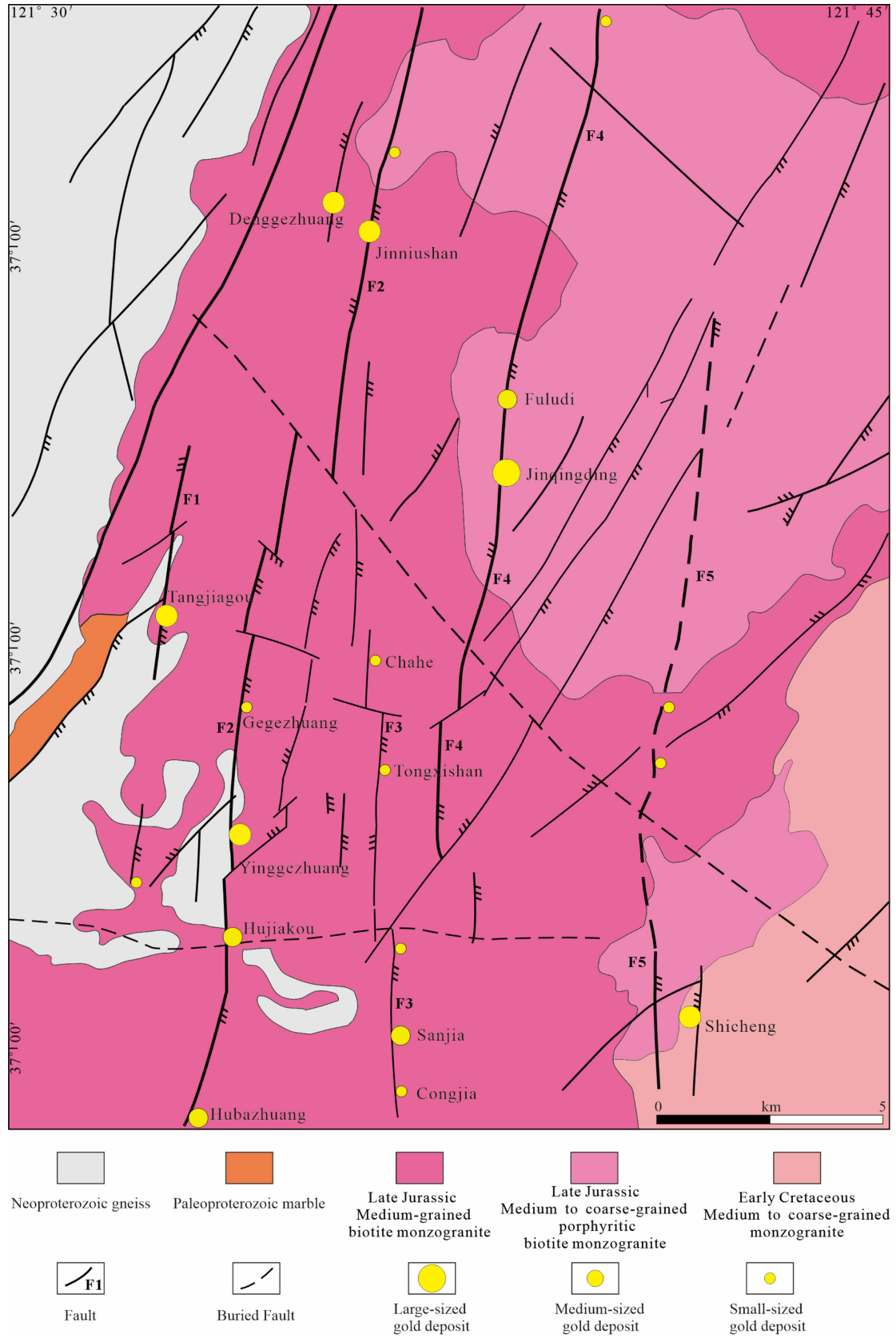


**Fig. 1.** Regional distribution of Muping–Rushan gold belt and simplified geological map of the Jiaodong area. (a) Tectonic subdivision of the Shandong Peninsula (modified after (He *et al.*, 2021; Tang *et al.*, 2008)); (b) Simplified geological map of the Jiaodong area (modified after (Fan *et al.*, 2016; Song, 2012)). KYS-Kunyushan granitic complex, SFS-Sanfoshan granite, DGS-Duogushan granodiorite, WD-Wendeng granite, WDS-Weideshan granite, JZS-Jiazishan complex.

Sai *et al.*, 2020; Yang and Zhou, 2001), with a significant time gap following the previous Precambrian regional metamorphic events. Given these unique features and other metallogenic attributes, the gold deposits in this region have been referred to as the “Jiaodong-type” (Deng *et al.*, 2015; Li and Santosh, 2014; Zhai *et al.*, 2004; Zhai and Santosh, 2013), atypical orogenic gold deposits (Goldfarb *et al.*, 2001; Goldfarb *et al.*, 2005; Yang *et al.*, 2014; Yang *et al.*, 2016), or as a unique orogenic gold deposit type (Goldfarb and Santosh, 2014).

Fluids are important in ore-forming processes, which enabling energy transfer and the transport and exchange of ore materials. Fluid migration can also expand the ore-forming space. The formation, migration, and evolution of fluids, as well as the deposition from fluids, reflect the entire ore-

forming process (Mao *et al.*, 1999; Xu *et al.*, 1999). According to the scale of gold reserves, the Muping–Rushan gold belt contains both large- and medium-sized gold deposits, such as the Tangjiagou, Dengezhuang, Jinniushan, Yinggezhuang, Jinqingding, Fuludi, Hubazhuang, Sanjia, Shicheng, Hujiakou, Gegezhuang, Chahe, Tongxishan, and Congjia gold deposits, along with tens of smaller deposits (Figs. 1–2). Previous research in the study area (Chen, 2010; Cui, 2012; Li, 2011; Zhang *et al.*, 2002; Zhang *et al.*, 2012; Zhou, 2010), has focused mainly on the Jinqingding, Dengezhuang, and Yinggezhuang gold deposits, while little attention was given to the Tangjiagou, Jinniushan and Shicheng gold deposits, which are controlled by nearly NE-trending faults. A paucity of systematic studies on the characteristics of ore fluids,



**Fig. 2.** Geological sketch map of the Muping–Rushan gold belt. F1 Qinghushan–Tangjiagou Fault, F2 Jinniushan Fault, F3 Chahe–Sanjia Fault, F4 Jiangjunshi–Quhezhuang Fault, F5 Majiazhuang–Gekou Fault.

isotope geochemistry, and timing of metallogenesis in Muping–Rushan gold belt has resulted in controversy/uncertainty regarding the age of mineralization, the source of the ore-forming fluids, and the genesis of the ore deposits. Moreover, conventional bulk analysis yields unusual sulphur isotope compositions, complicating genetic modeling. Due to the limited constraints on the pyrite paragenesis in isotope analysis and the pronounced fluid–rock interaction observed in the Muping–Rushan gold belt, current stable isotope investigations do not provide sufficient evidence for metal and fluid sources or genesis.

Considering the absence of electron microprobe elemental mapping for the Jinqingding, Denggezhuang, Yinggezhuang gold deposits and the lack of *in situ* sulphur isotope analysis for the Yinggezhuang gold deposit, even though previous research has been carried out. The source of the metals and the generation of auriferous fluids remain unclear. These factors significantly restrict the systematic study of the Muping–Rushan gold belt. To match the diverse geological facts, it is necessary to analyse the regional tectono-metallogenic background, lithospheric architecture, and gold mineralization processes in detail. Therefore, this study investigated typical gold deposits in the Muping–Rushan gold belt (Tangjiagou, Denggezhuang, Jinniushan, Yinggezhuang, Jinqingding, and Shicheng) using elemental mapping, and *in situ* sulphur, lead, and helium–argon isotope analysis. These data, combined with previous studies, are used to constrain the source of the ore-forming materials and the origins of the Muping–Rushan gold belt.

## 2 Regional geological and mineralization setting

Jiaodong Peninsula, located on the southeastern margin of the North China Craton (Fig. 1a), is bounded to the south by the Sulu ultrahigh-pressure (UHP) metamorphic belt and to the west by the Tanlu Fault (Fig. 1b). The Jiaodong Peninsula is geologically divided into two distinct terranes by the Muping–Jimo Fault which marks the suture the Yangtze and North China cratons (He *et al.*, 2021; Li *et al.*, 2013; Song, 2012; Zhang *et al.*, 2008): the Jiaodong terrane, located to the southeast, and the Jiaobei terrane, situated to the northwest. The southeastern Jiaodong terrane is composed of Mesozoic igneous rocks, Lower Cretaceous volcanic and sedimentary rocks, and UHP gneisses. These UHP gneisses are primarily amphibolite-facies granitic gneisses, with subordinate occurrences of eclogites and mafic rocks (He *et al.*, 2021; Yang *et al.*, 2005). The Mesozoic igneous rocks include the Kunyushan granitic complex, Sanfoshan granite, Duogushan granodiorite, Wendeng granite, Weideshan granite, and Jiazishan complex, which were intruded into the UHP gneisses (He *et al.*, 2021).

The study area is part of the Qinling–Dabie mineralization province (II-2), Tongbai–Dabie–Sulu mineralization region (III-3), southeast Shandong mineralization sub-region (IV-6), Wendeng–Weihai small mineralization region (V-13), and Muping–Rushan gold–silver–molybdenum–iron mineralization belt (VI-50) (Song *et al.*, 2015). The Muping–Rushan gold belt primarily refers to the zone bounded by the Muping–Jimo and Mishan faults. There are three mineralization types in the Jiaodong area: Jiaojia-type (altered rock-type), Linglong-type

(quartz–sulphide vein-type), and Pengjiakuang-type (breccia-type) (Mao *et al.*, 2008; Yang *et al.*, 2014). The Muping–Rushan gold belt contains Linglong-type gold deposits, which are vein-like or lenticular and hosted in high-angle brittle faults that developed within Late Jurassic granites. These ore bodies are strictly controlled by NE–SW-trending faults. The main ore-bearing wall rocks of the Muping–Rushan gold belt are the Kunyushan granitic complex, along with the western margins of the Queshan and Sanfoshan granites.

A series of NE–SW-trending faults control the gold deposits of the Muping–Rushan gold belt, which are the Qinghushan–Tangjiagou (F1), Jinniushan (F2), Jiangjunshi–Quhezhuang (F3), Chahe–Sanjia (F4), and Gekou (F5) faults from west to east. These faults are subparallel, nearly equidistant, with strikes of 005°–025° and dips of 75°–90°SE (Fig. 2). The ore bodies are vein-like or lenticular, parallel to the faults, and locally have an *en echelon* form.

## 3 Ore deposit geology

The representative gold deposits examined in this study are the Tangjiagou, Denggezhuang, Jinniushan, Yinggezhuang, Jinqingding, and Shicheng deposits. The geological features of these deposits are provided in Supplementary Table 1. The Jinqingding gold deposit controlled by the Jiangjunshi–Quhezhuang Fault, is the largest single-vein gold deposit in China, and the most intensively studied among those considered here. The Denggezhuang gold deposit is controlled by a secondary fault of the Jinniushan Fault and holds the second largest reserves in the region. The Jinniushan and Yinggezhuang gold deposits are located along the southern and northern sections, respectively of the Jinniushan Fault. The Qinghushan–Tangjiagou and Majiazhuang–Gekou faults, located on the western and eastern margins of the study area, respectively, controlled the locations of the Tangjiagou and Shicheng gold deposits. The deposits examined in this research occur in both the eastern and western parts of the gold belt and are associated with various primary and secondary faults.

The Muping–Rushan ores are dominated by pyrite, followed by native gold, electrum, pyrrhotite, galena, chalcopyrite, sphalerite, and secondary hematite. The principal gangue mineral is quartz, followed by sericite and calcite. The gold ores are primary in origin. The ores have panidiomorphic–hypidiomorphic granular, brecciated, interstitial, and mosaic textures, and blocky, vein, network, disseminated, and brecciated forms.

Due to the steepness of the ore-controlling faults, zoning of alteration related to mineralization is relatively obvious. The zoning is centred on the ore bodies, and comprises pyrite–phyllitic alteration → sericite–K-feldspar granite → K-feldspar granite → granite. There are gradual transitions between the altered rock zones.

The mineral assemblage of typical gold deposits in the Muping–Rushan gold belt is relatively consistent, and the differences are mainly in the polymetallic sulphide stage and the carbonate stage. For example, pyrrhotite is more abundant in the polymetallic sulphide stage of the Tangjiagou gold deposit, galena is more abundant in the polymetallic sulphide stage of the Denggezhuang and Jinniushan gold deposits, chalcopyrite is more abundant in the polymetallic sulphide



| Mineral assemblages of the Tangjiagou gold belt  |                                 |                                         |                             | Formula<br>Mineral | Mineral assemblages of the Denggezhuang gold belt |                                 |                                         |                             |
|--------------------------------------------------|---------------------------------|-----------------------------------------|-----------------------------|--------------------|---------------------------------------------------|---------------------------------|-----------------------------------------|-----------------------------|
| Pyrite-quartz stage<br>Stage I                   | Quartz-pyrite stage<br>Stage II | Polymetallic sulfide stage<br>Stage III | Carbonate stage<br>Stage IV |                    | Pyrite-quartz stage<br>Stage I                    | Quartz-pyrite stage<br>Stage II | Polymetallic sulfide stage<br>Stage III | Carbonate stage<br>Stage IV |
| Q1                                               | Q2                              |                                         | Q3                          |                    | Q1                                                | Q2                              |                                         | Q3                          |
|                                                  |                                 |                                         |                             | Quartz             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Sericite           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Pyrite             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Monazite           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Native gold        |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Electrum           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Pyrrhotite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Arsonpyrite        |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Chalcopyrite       |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Galena             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Sphalerite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Calaverite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Petzite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Hessite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Tellurbimuth       |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Calcite            |                                                   |                                 |                                         |                             |
| Mineral assemblages of the Jinniushan gold belt  |                                 |                                         |                             | Formula<br>Mineral | Mineral assemblages of the Yinggezhuang gold belt |                                 |                                         |                             |
| Pyrite-quartz stage<br>Stage I                   | Quartz-pyrite stage<br>Stage II | Polymetallic sulfide stage<br>Stage III | Carbonate stage<br>Stage IV |                    | Pyrite-quartz stage<br>Stage I                    | Quartz-pyrite stage<br>Stage II | Polymetallic sulfide stage<br>Stage III | Carbonate stage<br>Stage IV |
| Q1                                               | Q2                              |                                         | Q3                          |                    | Q1                                                | Q2                              |                                         | Q3                          |
|                                                  |                                 |                                         |                             | Quartz             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Sericite           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Pyrite             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Monazite           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Native gold        |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Electrum           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Pyrrhotite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Arsonpyrite        |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Chalcopyrite       |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Galena             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Sphalerite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Calaverite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Petzite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Hessite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Tellurbimuth       |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Calcite            |                                                   |                                 |                                         |                             |
| Mineral assemblages of the Jinjingding gold belt |                                 |                                         |                             | Formula<br>Mineral | Mineral assemblages of the Shicheng gold belt     |                                 |                                         |                             |
| Pyrite-quartz stage<br>Stage I                   | Quartz-pyrite stage<br>Stage II | Polymetallic sulfide stage<br>Stage III | Carbonate stage<br>Stage IV |                    | Pyrite-quartz stage<br>Stage I                    | Quartz-pyrite stage<br>Stage II | Polymetallic sulfide stage<br>Stage III | Carbonate stage<br>Stage IV |
| Q1                                               | Q2                              |                                         | Q3                          |                    | Q1                                                | Q2                              |                                         | Q3                          |
|                                                  |                                 |                                         |                             | Quartz             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Sericite           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Pyrite             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Monazite           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Native gold        |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Electrum           |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Pyrrhotite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Arsonpyrite        |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Chalcopyrite       |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Galena             |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Sphalerite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Calaverite         |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Petzite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Hessite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Tellurbimuth       |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Calcite            |                                                   |                                 |                                         |                             |
|                                                  |                                 |                                         |                             | Siderite           |                                                   |                                 |                                         |                             |

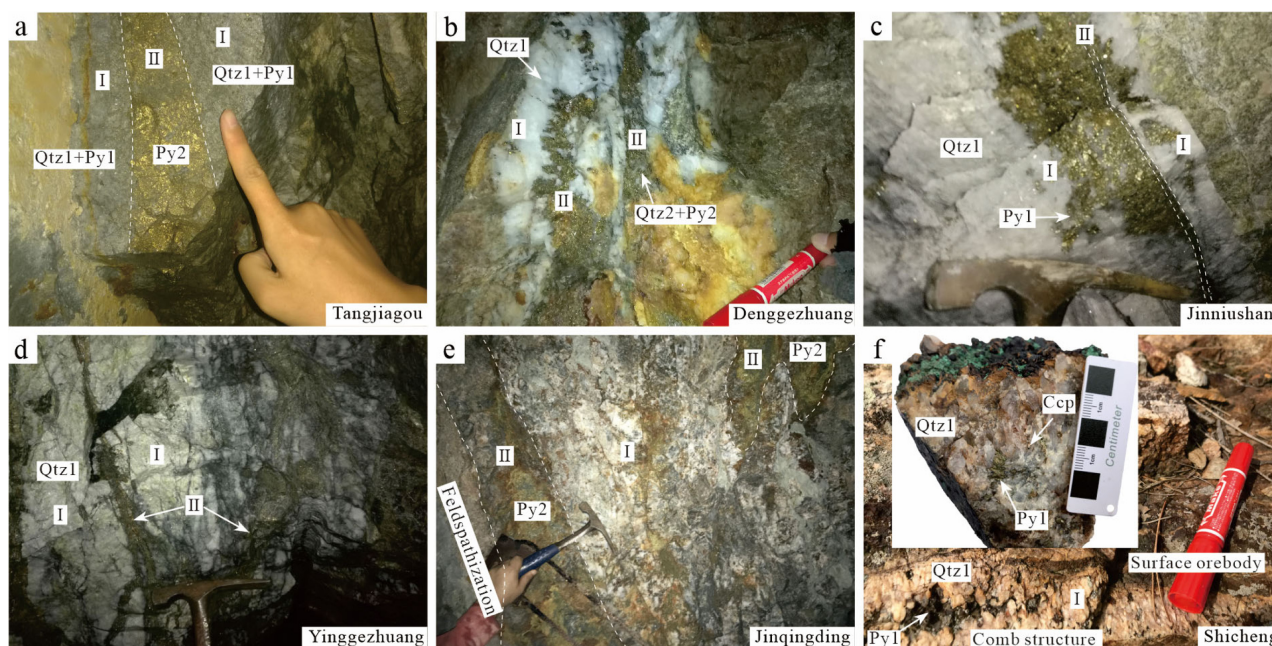
**Fig. 3.** Paragenetic sequence of hydrothermal minerals in the Muping–Rushan gold belt. Minerals' relative abundance is represented by the thickness of solid lines (thick = abundant, thin = less abundant, dashed = least abundant).

stage of the Shicheng gold deposit, and the characteristic siderite is found in the carbonate stage of the Shicheng gold deposit. Based on the mineral assemblages, four mineralisation stages are identified for the gold deposits in the study, as follows (Fig. 3):

**Stage I (pyrite–milky quartz stage):** Hand specimens show milky panidiomorphic–hypidiomorphic, coarse-grained quartz–pyrite veins with comb-like and miarolitic textures (Fig. 4e). This stage was characterised by coarse-grained milky quartz (Fig. 5d, h, n; Fig. 6d, i) and a small amount of panidiomorphic, cubic, coarse-grained pyrite (Fig. 5a, c, e, g, i, j, m; Fig. 6a, e, g, j, k, l). The mineralization is extensive, but the gold content and grade are low.

**Stage II (dark quartz–pyrite stage):** Hand specimens contain dark quartz–pyrite veins that cut the earlier milky quartz–pyrite veins (Fig. 4a, d). This stage was dominated by pyrite formation, which appears as hypidiomorphic–allomorphic fine-grained aggregates and single pentagonal–dodecahedral crystals (Fig. 5a, g, m; Fig. 6a, e, h). Locally, stage I pyrite (Py1) is cut and/or transformed into stage II pyrite (Py2) (Fig. 5m). The dark quartz occurs as allomorphic aggregates along the rims and in cracks of stage I milky quartz (Fig. 5d, h, n; Fig. 6d, f, i). In this stage, the quartz is less abundant, whereas gold is more concentrated than stage I.

**Stage III (polymetallic sulphide stage):** The mineral assemblage at this stage consists mainly of pyrite, galena,



**Fig. 4.** Representative photographs showing mineral paragenesis of the ore from the Muping–Rushan gold belt.

sphalerite, chalcopyrite, pyrrhotite, and quartz (Fig. 5b, c, k; Fig. 6a, g). The pyrite is anhedral (Fig. 5b) and fine-grained, and forms massive to banded ores with associated sulphides. Sphalerite includes chalcopyrite exsolution blebs (Fig. 5c). Compared with stage II, the contents of precious metal contents are significantly lower, and the mineralization intensity and spatial extent are also lower. However, it was also an important stage for gold formation, which is mainly found in the shallow parts of ore bodies and has no obvious boundary with the stage II mineralization.

Stage IV (pyrite–calcite stage): As fluid temperatures declined, calcite was precipitated, marking the end of mineralisation. This stage was dominated by the formation of panidiomorphic calcite, along with small amounts of panidiomorphic quartz and pyrite (Fig. 4c, f). The pyrite has a cubic form and quartz–calcite aggregates filling fractures (Fig. 5f, o; Fig. 6c, f, i).

## 4 Samples and analytical methods

### 4.1 Sample preparation

All studied samples ( $n=21$ ) are fresh ores from different mineralisation stages of the Tangjiagou, Denggezhuang, Jinniushan, Yinggezhuang, Jinqingding, and Shicheng gold deposits. Detailed sample information is provided in [Supplementary Table 2](#). The selected ore samples were prepared as double-sided polished sections (300–900  $\mu\text{m}$  thick) for microscopic observations, and target minerals (*i.e.*, sulphides) for electron microprobe analysis and elemental mapping and *in situ* sulphur isotope analysis were identified. Seven samples were used for electron microprobe elemental mapping, 16 samples for *in situ* sulphur isotope analysis, 8 samples for lead isotope analysis, and 9 samples for helium–argon isotope analysis.

### 4.2 Electron microprobe analysis

Electron microprobe analysis was conducted at the Tianjin Geological Survey Center, China Geological Survey, Tianjin, China, using a Shimadzu EPMA-1600 instrument. Experimental conditions were: accelerating voltage = 15 kV, primary beam current = 60 nA, secondary beam current = 40 nA, and beam diameter = 2  $\mu\text{m}$ . The detection limits were: Ag = 80 ppm, Au = 350 ppm, As = 250 ppm, Fe = 200 ppm, and S = 70 ppm.

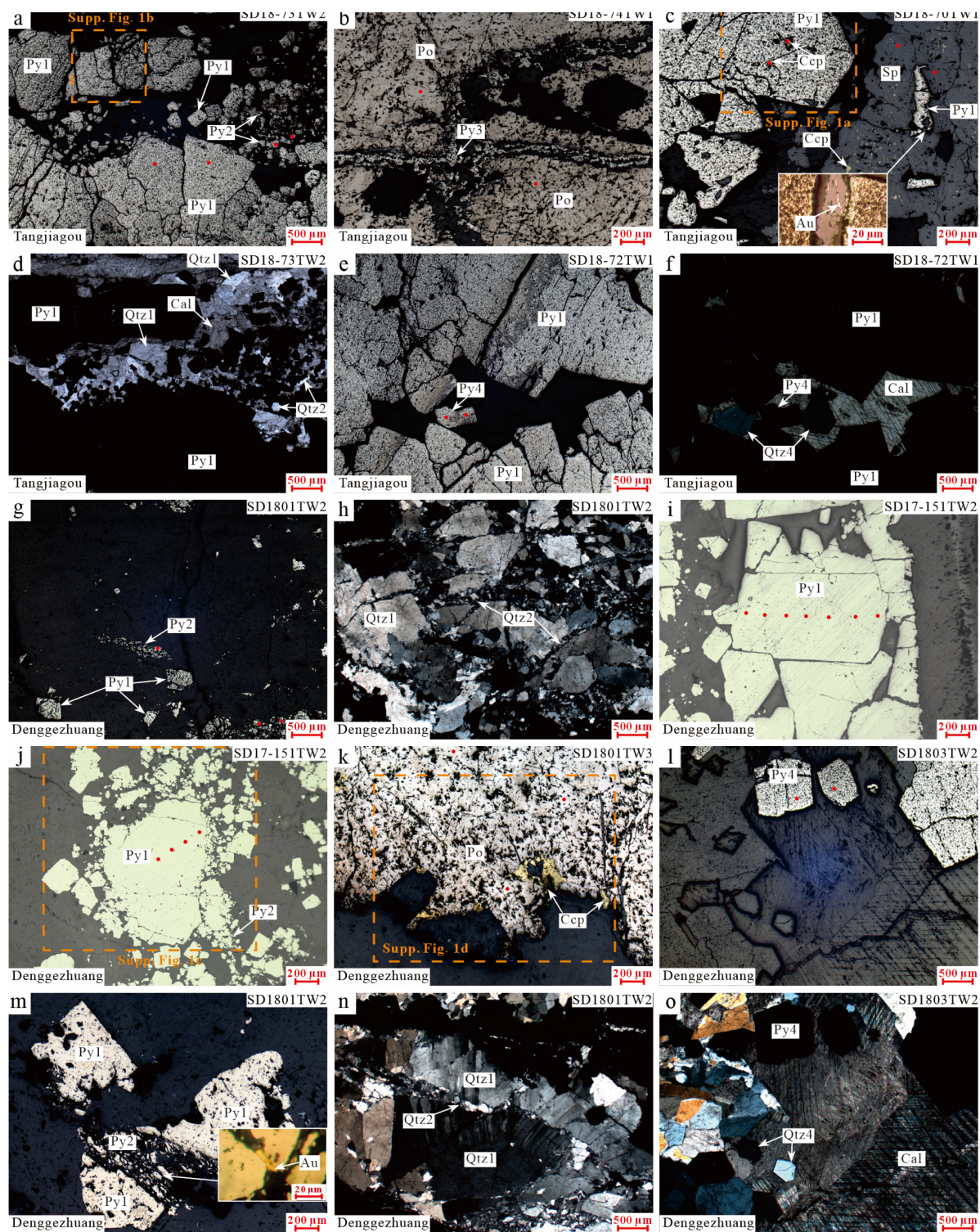
### 4.3 *In situ* sulphur isotope analysis

*In situ* sulphur isotopic compositions were determined with a 193nm ArF excimer laser ablation system (RESolution S-155) coupled to an MC–ICP–MS (Nu Plasma II) at the State Key Laboratory for Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, China. The analyses were conducted with a laser spot size of 33  $\mu\text{m}$ , a repetition rate of 8 Hz, and an energy density of 3–5 J/cm<sup>2</sup>. An in-house pyrite standard (WS-1) and United States Geological Survey standard (sphalerite NBS-123) were used to correct mass bias of the S isotopes. The  $\delta^{34}\text{S}_{\text{V-CDT}}$  value obtained for WS-1 was  $0.3\text{‰} \pm 0.1\text{‰}$  (Zhu *et al.*, 2017). The  $\delta^{34}\text{S}_{\text{V-CDT}}$  value obtained for NBS-1 was  $18.2\text{‰} \pm 0.2\text{‰}$  (Hu *et al.*, 2003). The analytical procedures were described by Liu *et al.* (2018).

### 4.4 Lead isotope analysis

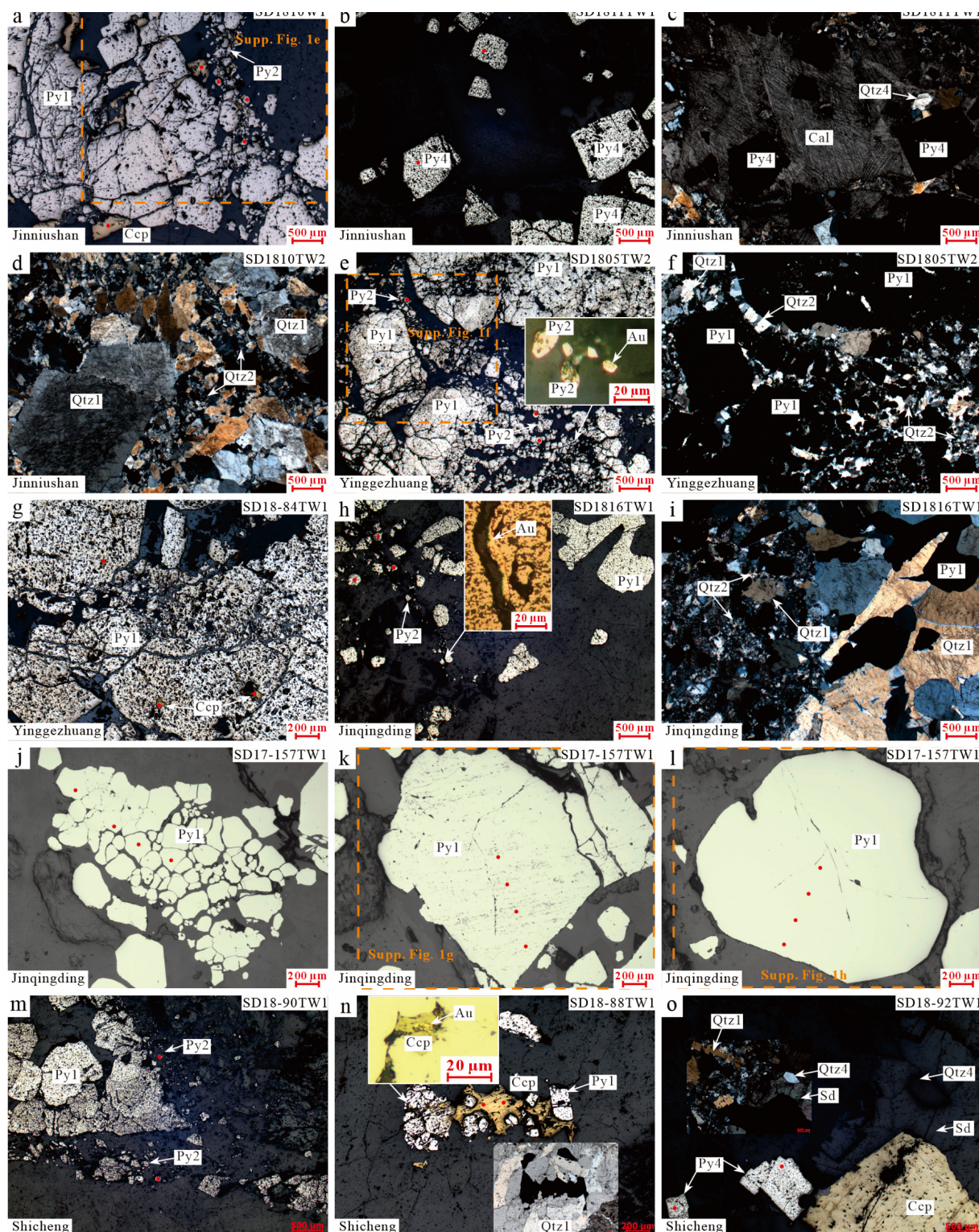
Lead isotope analysis was performed at the Analytical Laboratory, Beijing Research Institute of Uranium Geology, Beijing, China. Samples of 0.1–0.2 g of pyrite (60–80 mesh) were precisely weighed and dissolved in low-pressure, closed Teflon beakers in  $\text{HF} + \text{HNO}_3 + \text{HClO}_4$ . The lead was separated by anion exchange methods, and analysed by





**Fig. 5.** Representative photomicrographs of samples from the Tangjiagou and Denggezhuang gold deposits. (a) Assemblage of pyrite (Py1+Py2) (RPPL); (b) Pyrrhotite (Po) was cut by pyrite (Py3) (RPPL); (c) Sphalerite (Sp) contained pyrite (Py1) and chalcopyrite (Ccp) blebs were distributed along the pyrite (Py1) boundaries and fractures (RPPL); (d) Quartz (Qtz1) was cut by an aggregate of quartz (Qtz2) and calcite (Cal) filling fractures (TXPL); (e) Assemblage of pyrite (Py1+Py4) (RPPL); (f) Calcite (Cal) and quartz (Qtz4) filling fractures (TXPL); (g) Cube pyrite (Py1) and pyritohedron pyrite (Py2) (RPPL); (h) Quartz (Qtz2) was distributed along the quartz (Qtz1) boundaries and fractures (TXPL); (i) and (j) Large pyrite crystal (Py1) (RPPL); (k) Pyrrhotite (Po) is replaced by chalcopyrite (Ccp) (RPPL); (l) Euhedral cube pyrite (Py4) (RPPL); (m) Py1 was cut by Py2 (RPPL); (n) Quartz (Qtz2) was distributed along the quartz (Qtz1) boundaries and fractures (TXPL); (o) Assemblage of quartz (Qtz4) and calcite (Cal) (TXPL). Red circle points show the locations of *in situ* sulphur isotope spots. The orange dotted frame show the locations of EPMA mapping. RPPL: reflected plane-polar ised light, TXPL: transmitted crossed-polar ised light.





**Fig. 6.** Representative photomicrographs of samples from the Yinggezhuang, Jinniushan, Jinqingding and Shicheng gold deposits. (a) Chalcopyrite (Ccp) filling the fractures of cube pyrite (Py1) and pyritohedron pyrite (Py2) (RPPL); (b) Euhedral cube pyrite (Py4) (RPPL); (c) Assemblage of quartz (Qtz4) and calcite (Cal) (TXPL); (d) Quartz (Qtz2) was distributed along the quartz (Qtz1) boundaries and fractures (TXPL); (e) Cube pyrite (Py1) and pyritohedron pyrite (Py2) (RPPL); (f) Quartz (Qtz2) was distributed along the quartz (Qtz1) boundaries and fractures (TXPL); (g) Pyrite (Py1) is replaced by chalcopyrite (Ccp) (RPPL); (h) Large pyrite crystal (Py1) and fine-grain pyrite (Py2) (RPPL); (i) The boundary between quartz (Qtz2, left) was distributed along the quartz (Qtz1, right) (TXPL); (j), (k), (l) Large pyrite crystal (Py1) (RPPL); (m) Cube pyrite (Py1) and pyritohedron pyrite (Py2) (RPPL); (n) Pyrite (Py1) is replaced by chalcopyrite (Ccp) (RPPL+TXPL); (o) Siderite (Sd), Pyrite (Py4) and quartz (Qtz4) filling fractures (RPPL+TXPL). Red circle points show the locations of *in situ* sulphur isotope spots. The orange dotted frame show the locations of EPMA mapping. RPPL: reflected plane-polarised light, TXPL: transmitted crossed-polarised light.



thermal ionisation mass spectrometry with an accuracy of better than  $\pm 0.005\%$ . The lead isotope ratios were corrected for mass fractionation by the NIST SRM 981 lead standard.

#### 4.5 Helium and argon isotope analysis

Helium and argon isotope analysis was conducted using an inert gas isotope ratio mass spectrometer (MI-1201IG; Ukraine) at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, China. The pyrite was crushed to 20–60 mesh and handpicked under a binocular microscope to a purity exceeding 99%.  $^3\text{He}$  ions were measured with an electron multiplier, and  $^4\text{He}$  ions were measured with a Faraday collector. Beijing air was used as the standard ( $^3\text{He}/^4\text{He} = 1.399 \times 10^{-6}$ ). The He blank (at  $1600^\circ\text{C}$ ) is  $^4\text{He} = 2 \times 10^{-11} \text{ cm}^3 \text{ STP}$ , with  $^3\text{He}/^4\text{He} = 1 \times 10^{-6}$ . The standard yielded an accuracy of  $\pm 1\%$ . Analytical procedures followed those of Li *et al.* (2002).

## 5 Results

### 5.1 Elemental mapping

The Ag, Au, As, Fe, and S elemental maps for pyrite and pyrrhotite in seven samples are presented in [Supplementary Figure 1](#).

### 5.2 *In situ* sulphur isotopes

Fourteen samples (66 analyses) were chosen for *in situ* sulphur isotope analysis. The data are shown in [Figs 5–6](#) and summarised in [Supplementary Table 3](#).

$\delta^{34}\text{S}_{\text{V-CDT}}$  values of the Tangjiagou gold deposit are  $8.2\text{‰}$ – $9.5\text{‰}$  ( $n=2$ ) for stage I pyrite,  $9.2\text{‰}$ – $9.3\text{‰}$  ( $n=2$ ) for stage II pyrite,  $6.6\text{‰}$ – $7.1\text{‰}$  ( $n=2$ ) for stage III chalcopyrite,  $5.3\text{‰}$ – $7.7\text{‰}$  ( $n=3$ ) for stage III sphalerite,  $6.8\text{‰}$ – $6.9\text{‰}$  ( $n=3$ ) for stage III pyrrhotite, and  $7.0\text{‰}$ – $7.2\text{‰}$  ( $n=2$ ) for stage IV pyrite.  $\delta^{34}\text{S}_{\text{V-CDT}}$  values of the Denggezhuang gold deposit are  $4.9\text{‰}$ – $9.4\text{‰}$  ( $n=12$ ) for stage I pyrite,  $6.9\text{‰}$ – $9.8\text{‰}$  ( $n=2$ ) for stage II pyrite,  $6.6\text{‰}$ – $7.1\text{‰}$  ( $n=3$ ) for stage III pyrrhotite, and  $11.6\text{‰}$ – $11.9\text{‰}$  ( $n=2$ ) for stage IV pyrite.  $\delta^{34}\text{S}_{\text{V-CDT}}$  values of the Jinniushan gold deposit are  $8.8\text{‰}$ – $9.0\text{‰}$  ( $n=3$ ) for stage II pyrite,  $4.0\text{‰}$ – $5.7\text{‰}$  ( $n=3$ ) for stage III chalcopyrite, and  $9.7\text{‰}$ – $12.5\text{‰}$  ( $n=2$ ) for stage IV pyrite.  $\delta^{34}\text{S}_{\text{V-CDT}}$  values of the Yinggezhuang gold deposit are  $9.6\text{‰}$ – $10.3\text{‰}$  ( $n=3$ ) for stage II pyrite and  $8.1\text{‰}$ – $9.6\text{‰}$  ( $n=3$ ) for stage III chalcopyrite.  $\delta^{34}\text{S}_{\text{V-CDT}}$  values of the Jinqingding gold deposit are  $9.6\text{‰}$ – $10.2\text{‰}$  ( $n=12$ ) for stage I pyrite and  $7.6\text{‰}$ – $8.1\text{‰}$  ( $n=3$ ) for stage II pyrite.  $\delta^{34}\text{S}_{\text{V-CDT}}$  values of the Shicheng gold deposit are  $4.1\text{‰}$ – $4.8\text{‰}$  ( $n=2$ ) for stage II pyrite and  $6.0\text{‰}$ – $7.7\text{‰}$  ( $n=2$ ) for stage IV pyrite.

### 5.3 Lead isotopes

Lead isotope data for eight samples from the Tangjiagou and Jinniushan gold deposits are summarised in [Supplementary Table 4](#). The Tangjiagou gold deposit has  $^{206}\text{Pb}/^{204}\text{Pb} = 17.056$ – $17.354$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.404$ – $15.580$ , and  $^{208}\text{Pb}/^{204}\text{Pb} = 37.457$ – $38.107$ . The Jinniushan gold deposit has  $^{206}\text{Pb}/^{204}\text{Pb} = 17.015$ – $17.025$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.430$ – $15.437$ , and

$^{208}\text{Pb}/^{204}\text{Pb} = 37.385$ – $37.434$ . Lead isotopic compositions are relatively homogeneous. Model ages of the Tangjiagou and Jinniushan gold deposits are 758–1010 and 962–976 Ma, respectively. The  $\mu$  and  $\omega$  values derived from a single-stage model for normal lead are 9.27–9.62 and 38.02–40.05 for the Tangjiagou gold deposit, and 9.33–9.35 and 38.65–38.97 for the Jinniushan gold deposit, respectively.

### 5.4 Helium and argon isotopes

Helium–argon isotope data for nine samples of the Tangjiagou, Jinniushan, and Shicheng gold deposits are summarised in [Supplementary Table 5](#). The Tangjiagou gold deposit has  $^3\text{He} = 6.96$ – $14.2 \text{ cm}^3 \text{ STP}$ ,  $^4\text{He} = 2.29$ – $5.17 \text{ cm}^3 \text{ STP}$ ,  $^3\text{He}/^4\text{He} = 1.24$ – $2.17 \text{ Ra}$ ,  $^{40}\text{Ar}/^{36}\text{Ar} = 389.8$ – $685.7$ , and  $^{40}\text{Ar} = 0.316$ – $1.170 \text{ cm}^3 \text{ STP}$ . The Jinniushan gold deposit has  $^3\text{He} = 1.34$ – $11.61 \text{ cm}^3 \text{ STP}$ ,  $^4\text{He} = 0.69$ – $3.99 \text{ cm}^3 \text{ STP}$ ,  $^3\text{He}/^4\text{He} = 1.39$ – $2.08 \text{ Ra}$ ,  $^{40}\text{Ar}/^{36}\text{Ar} = 455.3$ – $587.43$ , and  $^{40}\text{Ar} = 3.504$ – $10.494 \text{ cm}^3 \text{ STP}$ . The Shicheng gold deposit has  $^3\text{He} = 28.15$ – $90.44 \text{ cm}^3 \text{ STP}$ ,  $^4\text{He} = 13.72$ – $27.87 \text{ cm}^3 \text{ STP}$ ,  $^3\text{He}/^4\text{He} = 1.47$ – $2.45 \text{ Ra}$ ,  $^{40}\text{Ar}/^{36}\text{Ar} = 836.9$ – $869.6$ , and  $^{40}\text{Ar} = 0.951$ – $2.507 \text{ cm}^3 \text{ STP}$ . The Tangjiagou, Jinniushan, and Shicheng gold deposits contain 18.82%–33.35%, 21.09%–31.79%, and 22.33%–35.49% mantle helium, respectively.

## 6 Discussion

### 6.1 Sphide features

In the Muping–Rushan gold belt, the ore minerals are mainly pyrite, followed by native gold, electrum, chalcopyrite, pyrrhotite, sphalerite, galena, and secondary hematite. The gangue minerals are mainly quartz, followed by sericite and calcite. Chalcopyrite is most common in the Shicheng gold deposit. The ores of the Muping–Rushan gold belt have panidiomorphic–hypidiomorphic granular, brecciated, interstitial, and mosaic textures, and blocky, vein, network, disseminated, and brecciated forms.

Different mineral assemblages in the various types of ores formed by hydrothermal activity define four mineralisation stages: the pyrite–milky quartz stage (stage I), dark quartz–pyrite stage (stage II), polymetallic sulphide stage (stage III), and pyrite–calcite stage (stage IV). Based on cross-cutting relationships between minerals, the formation sequence is quartz (Qtz1)  $\rightarrow$  pyrite (Py1)  $\rightarrow$  quartz (Qtz2)  $\rightarrow$  pyrite (Py2)  $\rightarrow$  polymetallic sulphides (pyrite [Py3]–sphalerite–chalcopyrite–galena)  $\rightarrow$  pyrite (Py4)  $\rightarrow$  quartz (Qtz4)  $\rightarrow$  calcite–siderite.

The As elemental maps for the Tangjiagou gold deposit ([Supp. Fig. 1a, b](#)) show the crystal rims and cracks in Py1, and rims of stage II and III sulphides are enriched in As. High As contents characterise the rims of Py1 in the Tangjiagou and Denggezhuang gold deposits. Some pyrite grains exhibit arsenic zoning ([Supp. Fig. 1a, c](#)). Silver and gold in samples of the Jinniushan, Yinggezhuang, and Jinqingding gold deposits occur mainly in cracks in Py1 or at the rims of stage II and III sulphides ([Supp. Fig. 1e, f, g, h](#)). This indicates that pyrite with high As contents formed mainly between late stage I to III, and that As and Au contents are positively correlated. There are no significant differences in the pyrite Fe and S contents in the different mineralization stages. However, the Fe–S elemental

maps for the Denggezhuang, Jinniushan, and Jinqingding gold deposits (Supp. Fig. 1d, e, h) show that the pyrite rims are Fe–S-poor, which is probably resulting from oxidative leaching of these elements.

## 6.2 Sources of the ore-forming materials

The migration and precipitation of gold is closely related to  $H_2S$ , and S is eventually incorporated into metallic sulphides. As such, sulphide sulphur isotope data can trace the gold source(s).  $\delta^{34}S$  values of the Muping–Rushan gold belt are mainly 5.8‰–10.1‰ (Supp. Table 3). The sulphides are generally characterised by  $\delta^{34}S_{Py} > \delta^{34}S_{Sp} > \delta^{34}S_{Ccp}$  and  $\delta^{34}S_{Py4} > \delta^{34}S_{Py2} > \delta^{34}S_{Py1}$  (Fig. 7). These patterns indicate isotopic equilibrium with regard to sulphur isotope composition in the Muping–Rushan gold belt, and that the  $\delta^{34}S$  values closely approximate those of the ore-forming fluids (Ohmoto and Goldhaber, 1997).

$\delta^{34}S$  values of the Kunyushan granitic complex and Jingshan and Jiaodong groups are 3.8‰–15.3‰, 8.2‰–12.0‰, and 6.1‰–7.8‰, respectively (An *et al.*, 1988; Li and Yang, 1993; Wang *et al.*, 2002; Xu, 1986; Yang *et al.*, 1998; Zhang and Chen, 1999).  $\delta^{34}S$  values of Py1, Py2, and the stage III polymetallic sulphides overlap those of the Kunyushan granitic complex and Jingshan and Jiaodong groups (Fig. 7).  $\delta^{34}S$  values of Py4 are elevated and resemble those of those of the Jingshan Group.

$\delta^{34}S$  values of the main mineralization period (*i.e.*, stages II and III) are as follows: Tangjiagou gold deposit = 5.3‰–9.3‰; Denggezhuang gold deposit = 2.1‰–9.8‰; Jinniushan gold deposit = 4.0‰–9.0‰; Yinggezhuang gold deposit = 8.1‰–10.2‰; Jinqingding gold deposit = 5.0‰–8.1‰; and Shicheng gold deposit = 4.1‰–4.8‰. The  $\delta^{34}S$  values are relatively uniform, and differ from mantle-derived sulphur (0‰), but are similar to sulphur in intermediate to silicic igneous rocks (–13.4‰ to 26.7‰) (Zhang *et al.*, 2013). The  $\delta^{34}S$  values of the gold deposits are slightly higher than values in mafic basement rocks (–4.0‰ to 4.0‰) and the Jiaodong Group (Department Of Geochemistry, 1979). This shows the ore-forming materials in the Muping–Rushan gold belt are of mixed source. Following sulphur dissolution in the strata, homogenization of sulphur isotopes and ore formation occurred, which resulted in higher  $\delta^{34}S$  values. The ore-forming processes involved multi-stage enrichment. Therefore, it is inferred that during the main mineralization period (stages II and III), sulphur was derived from the Kunyushan granitic complex and the Jingshan and Jiaodong groups. With fluid evolution,  $\delta^{34}S$  values increased. This indicates that the Kunyushan granitic complex and the Jingshan and Jiaodong groups could have provided the ore-forming material, and had different contributions to the different generations of sulphide. The variable sulphur isotopic compositions of the sulphide minerals may reflect sulphur isotope fractionation.

Lead isotopes can be used to constrain magma sources, but for ore deposits indicate the source of ore-forming materials (Ding *et al.*, 2013; Zhang, 1988; Zhao *et al.*, 2007; Zhu *et al.*, 1998). Ore minerals, include pyrite, galena, and sphalerite, typically contain little or no U and Th and there is no apparent accumulation of radiogenic lead after mineralization. The lead isotopic composition of ores is mainly a function of the  $\mu$

( $^{238}U/^{204}Pb$ ),  $\omega$  ( $^{232}Th/^{204}Pb$ ), Th/U ratios and the age of the source(s) of ore-forming materials (An *et al.*, 1988; Wu *et al.*, 2002; Zhang, 1988).

Lead isotope data for the Denggezhuang, Yinggezhuang, Jinqingding, and Shicheng gold deposits were compiled from earlier studies (Chen, 2010; Cui, 2012; Li, 1992; Li, 2011; Yang, 2000; Yang and Lv, 1996; Zhou, 2010). Lead isotope data for the Kunyushan granitic complex and Jiaodong Group were also compiled from the literature (Chen, 1989; Hu, 2006; Wang, 1988; Xu, 1986; Yang and Lv, 1996). All lead isotope data are summarised in Supplementary Table 4.

The sulphide lead isotopic compositions in the Muping–Rushan gold belt are relatively homogeneous, showing consistent variations for each deposit (Fig. 8), reflecting a common lead source. The gold deposits in the study area have  $^{206}Pb/^{204}Pb = 16.939$ – $17.920$ ,  $^{207}Pb/^{204}Pb = 15.305$ – $15.838$ , and  $^{208}Pb/^{204}Pb = 37.050$ – $38.736$ . The calculated source  $\mu$  value is 9.07–10.12, which is much higher than average crustal lead ( $8.99 \pm 0.07$ ), and the  $\omega$  value is 36.07–46.49, which is also higher than average crustal lead ( $35.55 \pm 0.59$ ). The Th/U ratio is 3.79–4.47, exceeding typical mantle values (3.45), but similar to that of the crust ( $3.92 \pm 0.09$ ) (Stacey and Kramers, 1975).

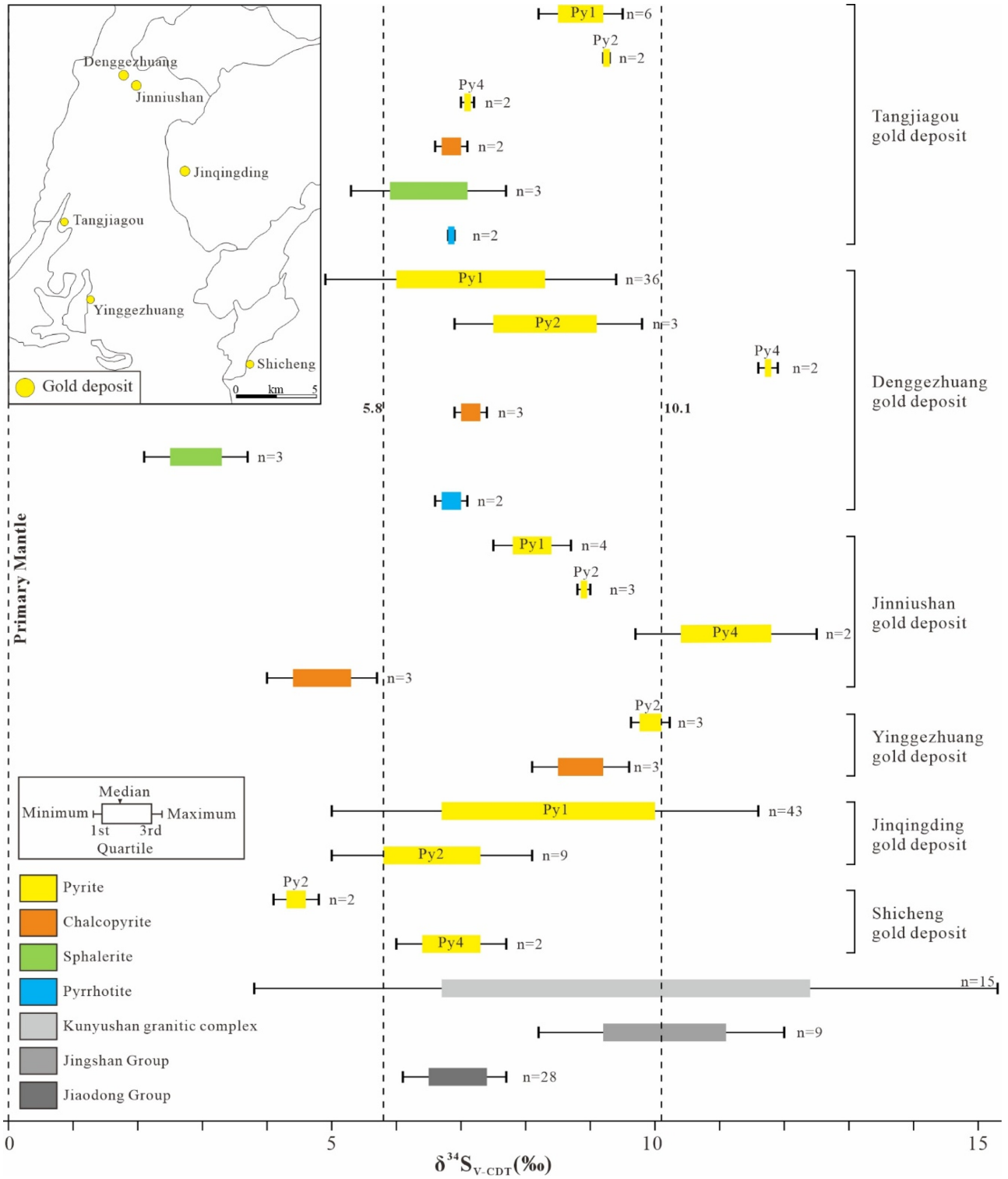
In a tectonic discrimination diagram based on lead isotopes (Fig. 8a, b), the Muping–Rushan gold belt falls predominantly within the lower crust field. In a  $^{206}Pb/^{204}Pb$ – $^{208}Pb/^{204}Pb$  diagram (Fig. 8c), the samples from the study area plot above the orogenic belt field and mantle evolution curve, and near the lower crustal evolution curve. On a  $\Delta\beta$ – $\Delta\gamma$  classification diagram (Fig. 8d), the Muping–Rushan gold belt plots mostly in the orogenic lead field, consistent with indicative of a genetic relationship the tectonic setting of the study area. The Kunyushan granitic complex and Jiaodong Group have similar Pb isotopic compositions as the Muping–Rushan gold belt (Fig. 8), indicative of a genetic relationship between these rocks and the gold deposits.

## 6.3 Source of the ore-forming fluids

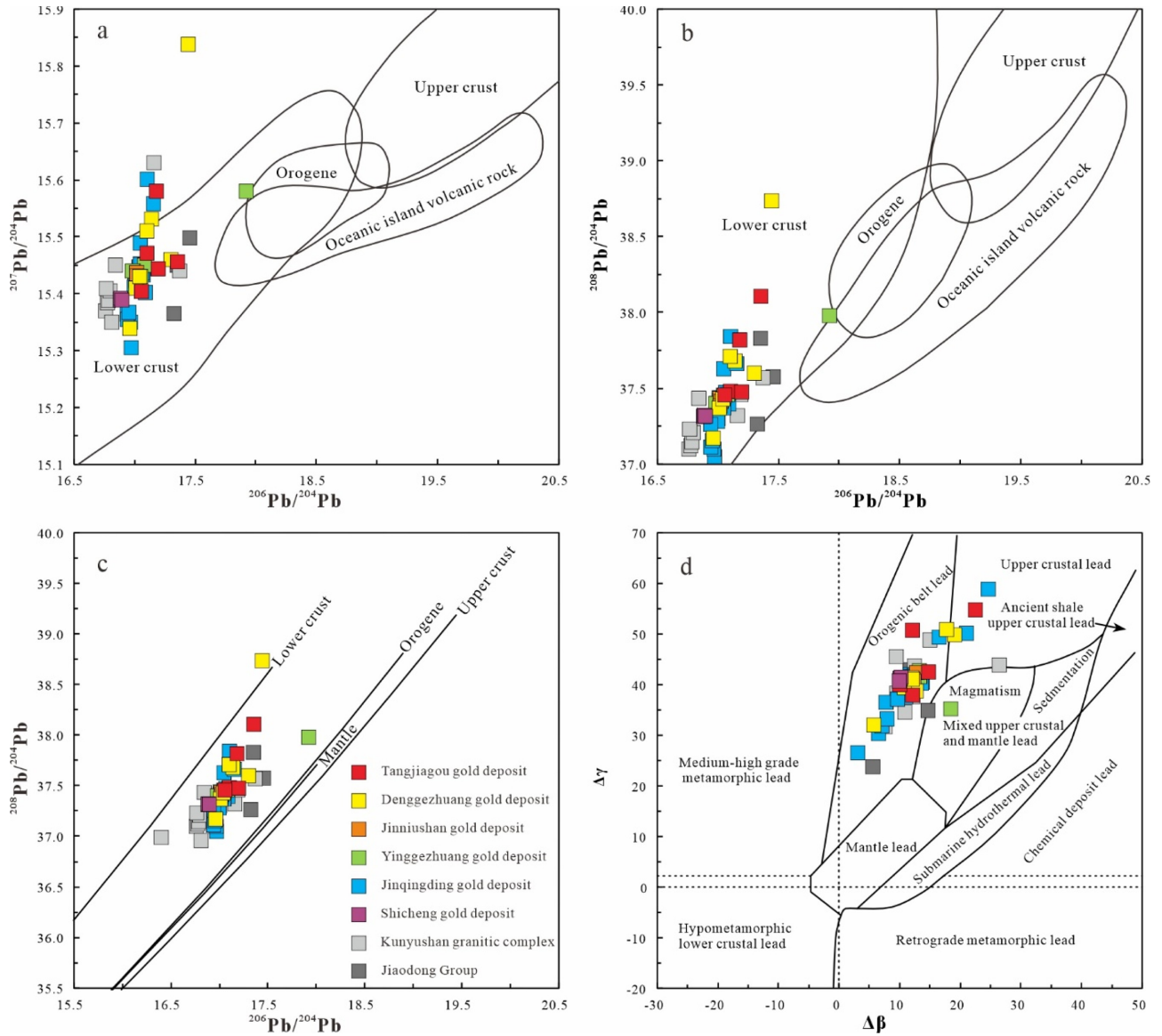
Due to the chemical inertness of the noble gases, they can remain unchanged during geological processes. Sources of geological fluids can be inferred from the noble gases. Helium isotope ratios of fluids from different sources exhibit relatively large differences, especially the  $^3He/^4He$  ratios of crustal helium ( $^3He/^4He = 0.01$ – $0.05$  Ra; average =  $0.02$  Ra) and mantle helium ( $^3He/^4He = 6$ – $9$  Ra; average =  $6.5$  Ra). Given that pyrite and other sulphides have a low diffusion coefficient for helium, the helium in pyrite inclusions will not be lost after being captured (Ballentine and Burnard, 2002; Burnard and Polya, 2004). Therefore, helium and argon isotopes can trace the fluid source(s).

Helium and argon isotope data for the Denggezhuang, Yinggezhuang, and Jinqingding gold deposits were compiled from previous studies (Xue *et al.*, 2013; Zhang *et al.*, 2002; Zhang *et al.*, 2012; Zhou, 2010). The helium and argon isotope data are summarised in Supplementary Table 5.  $^3He/^4He$  ratios of the Muping–Rushan gold belt are 0.01–5.06 Ra,  $^{40}Ar/^{36}Ar$  ratios are 389.8–4674.7, and  $^{40}Ar^*/^4He$  ratios are 0.03–2.78. Compared with air-saturated water, crustal fluids and mantle fluids, the fluid composition is intermediate between crust- and





**Fig. 7.** Compilation of  $\delta^{34}\text{S}$  isotope data for sulphides from the Muping–Rushan gold belt. The Kunyushan granitic complex  $\delta^{34}\text{S}$  data from (An *et al.*, 1988; Li and Yang, 1993; Yang *et al.*, 1998). The Jingshan group  $\delta^{34}\text{S}$  data from (Zhang and Chen, 1999). The Jiaodong group  $\delta^{34}\text{S}$  data from (Li and Yang, 1993; Wang *et al.*, 2002; Xu, 1986; Yang *et al.*, 1998).



**Fig. 8.** Diagrams of lead isotope ratios for sulphides from Muping–Rushan gold belt. (a)  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{207}\text{Pb}/^{204}\text{Pb}$ ; (b)  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{208}\text{Pb}/^{204}\text{Pb}$ ; (c)  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{208}\text{Pb}/^{204}\text{Pb}$  Pb isotope evolution diagram; (d)  $\Delta\beta$  vs.  $\Delta\gamma$  genetic classification diagram. Boundaries in diagrams of (a), (b), (c) are after Zartman and Doe (1981). Boundaries in diagrams of (d) are after Zhu *et al.* (1998). Denggezhuang gold deposit lead isotope data from (Cui, 2012; Yang and Lv, 1996). Yinggezhuang gold deposit lead isotope data from (Zhou, 2010). Jinqingding gold deposit lead isotope data from (Chen, 2010; Li, 1992; Li, 2011; Yang, 2000). The Kunyushan granitic complex lead isotope data from (Hu, 2006; Wang, 1988; Xu, 1986; Yang and Lv, 1996). The Jiaodong group lead isotope data from (Chen, 1989; Wang, 1988).  $\Delta\beta = 1000 \times \beta / (\beta_M - 1)$ ,  $\Delta\gamma = 1000 \times \gamma / (\gamma_M - 1)$ .  $\beta$ ,  $\gamma$ ,  $\beta_M$ ,  $\gamma_M$  are  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  for sample and mantle, respectively.

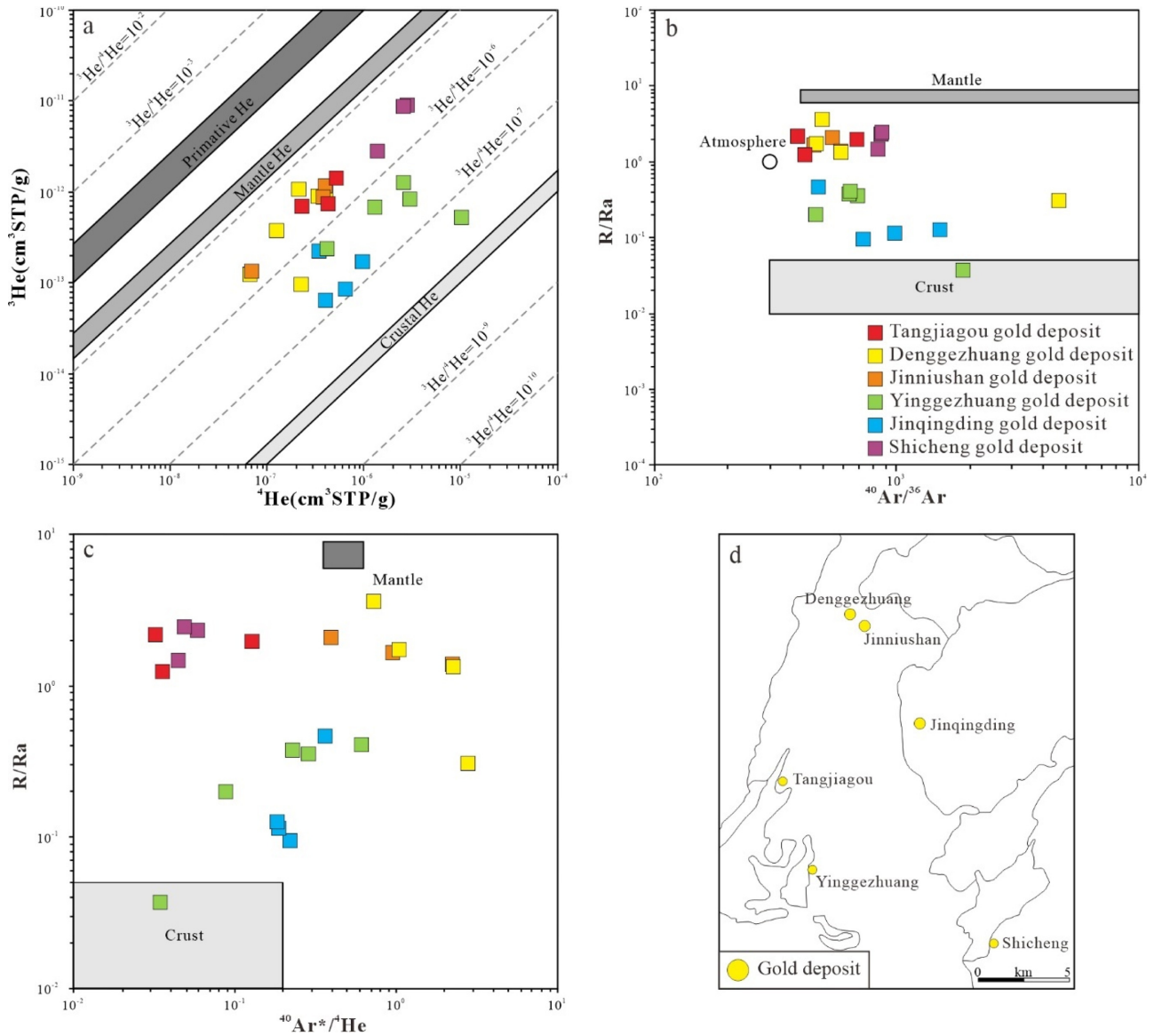
mantle-derived fluid, and the  $^{40}\text{Ar}/^{36}\text{Ar}$  values of some samples approach atmospheric values. Argon from the mantle and radiogenic argon have high  $^{40}\text{Ar}/^{36}\text{Ar}$  ratios.

Prior studies indicate that mantle-derived fluid has  $^{40}\text{Ar}^*/^4\text{He} = 0.33\text{--}0.56$  (Dunai and Baur, 1995; Patterson *et al.*, 1994; Porcelli *et al.*, 1992; Reid and Graham, 1996), and crust-derived fluid has  $^{40}\text{Ar}^*/^4\text{He} = 0.2$  (Andrews, 1985; Fontes *et al.*, 1991). However, the  $^{40}\text{Ar}^*/^4\text{He}$  values of some samples from the Denggezhuang, Jinniushan, Yinggezhuang, and Jinqingding gold deposits are above those of the mantle and crust. Therefore, the radiogenic argon of these samples

with high  $^{40}\text{Ar}/^{36}\text{Ar}$  and  $^{40}\text{Ar}^*/^4\text{He}$  ratios is mainly of atmospheric origin.

In a  $^4\text{He}\text{--}^3\text{He}$  diagram (Fig. 9a), the Muping–Rushan gold belt lies between the crustal and mantle helium fields, but closer to the crustal field, reflecting a mixed source for the ore-forming fluids. In a  $^{40}\text{Ar}/^{36}\text{Ar}\text{--}R/R_a$  diagram (Fig. 9b), further supporting a mixed fluid origin. The ratio of  $^3\text{He}/^4\text{He}$  in the ore-forming fluid is as high as 3.61  $R_a$ , which reflects mantle-derived He. Data for the Tangjiagou, Denggezhuang, and Jinniushan gold deposits has characteristics indicative of involvement of meteoric waters. In a  $^{40}\text{Ar}^*/^4\text{He}\text{--}R/R_a$  diagram



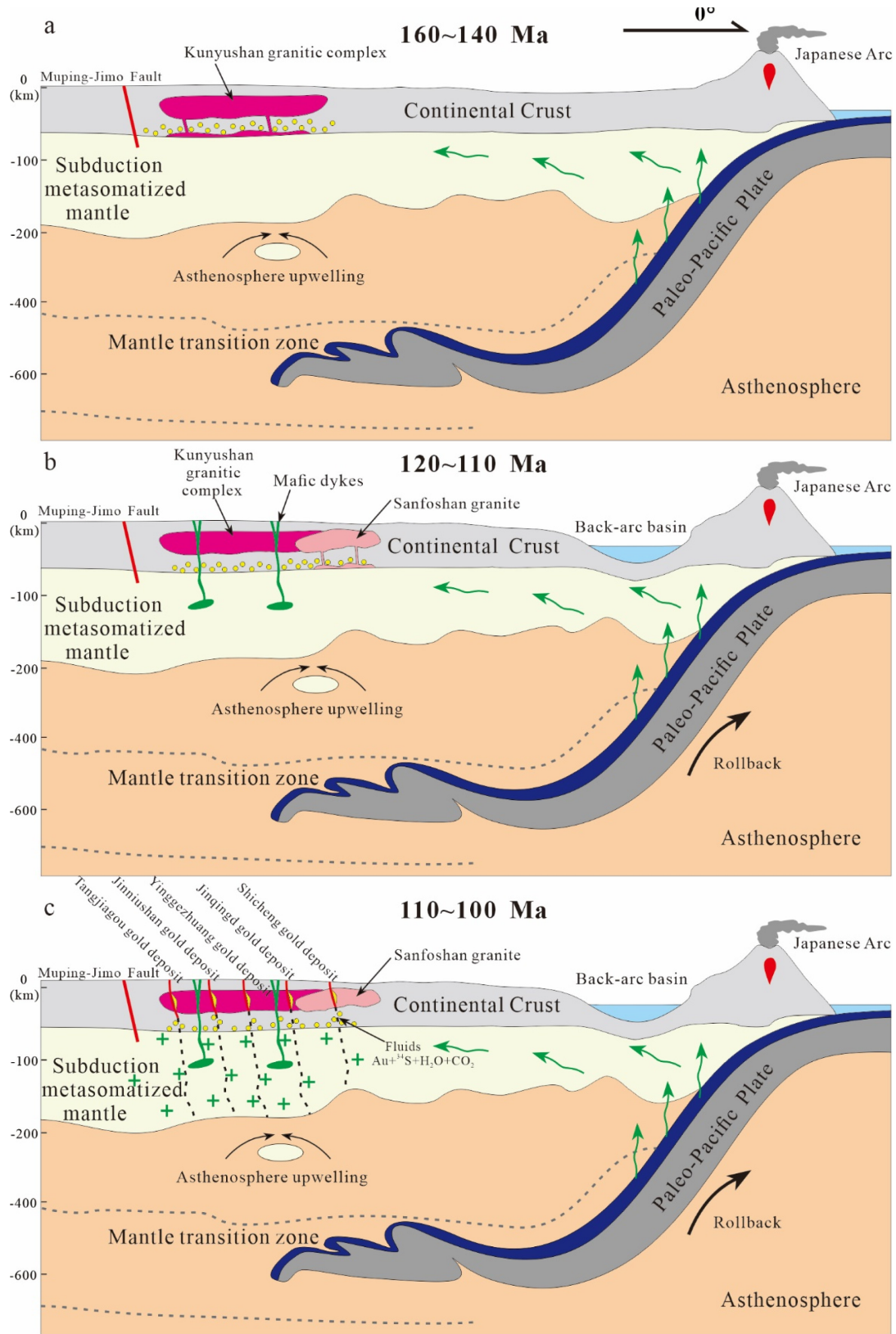


**Fig. 9.** Helium and argon isotope diagrams of fluid inclusions from the Muping–Rushan gold belt. (a)  $^4\text{He}$  vs.  $^3\text{He}$  diagram (modified after (Mamyrin and Tolstikhin, 1984)); (b)  $^{40}\text{Ar}/^{36}\text{Ar}$  vs.  $R/R_a$  diagram (modified after (Burnard *et al.*, 1999)); (c)  $^{40}\text{Ar}^*/^4\text{He}$  vs.  $R/R_a$  diagram (modified after (Hu *et al.*, 1997)); (d) Location of typical gold deposits. Denggezhuang gold deposit He–Ar isotope data from (Xue *et al.*, 2013; Zhang *et al.*, 2002). Yinggezhuang gold deposit He–Ar isotope data from (Zhou, 2010). Jinqingding gold deposit He–Ar isotope data from (Zhang *et al.*, 2012).  $R$  is the  $^3\text{He}/^4\text{He}$  ratio of sample;  $R_a$  is the  $^3\text{He}/^4\text{He}$  ratio of atmosphere ( $R_a=1.399\times 10^{-6}$ ) (Mamyrin *et al.*, 1970). The magmatic field is summarised by Goodwin *et al.* (2017). (d) Simple map of the Muping–Rushan gold belt showing deposit localities.

(Fig. 9c), the data also plot between the crust- and mantle-derived fields.

According to a binary mixing model, the proportion of mantle-derived He in the Tangjiagou, Denggezhuang, Jinniushan, Yinggezhuang, Jinqingding, and Shicheng gold deposits is 18.82%–33.25% (average = 27.35%), 4.43%–55.47% (average = 28.15%), 21.09%–31.79% (average = 26.05%), 0.26%–5.99% (average = 3.93%), 1.16%–6.87% (average = 2.78%), and 22.33%–35.49% (average = 31.78%), respectively (Supp. Table 5). These results

(Fig. 9) demonstrate that the proportions of mantle-derived He in the Yinggezhuang and Jinqingding gold deposits are much lower than in the Tangjiagou, Denggezhuang, Jinniushan, and Shicheng gold deposits. The lower proportions of mantle-derived He are probably related to fluids sourced from the deep part of faults, and crustal thickening and extrusion in the study area. They may also result from mixing with high contents of crust-derived He in the fluid, which results in dilution of the mantle-derived component (Zhao *et al.*, 2010).



**Fig. 10.** Genetic model of the Muping–Rushan gold belt (modified from (Deng *et al.*, 2020a; Deng *et al.*, 2020b; Lei *et al.*, 2018)). (a) Late Jurassic (160~140 Ma) magmatic activity, Kunyushan granitic complex emplacement; (b) Early Cretaceous (120~110 Ma) magmatic activity, emplacement of the Sanfoshan granite and arc-related mafic dyke; (c) Subsequently (110~100 Ma), the gold mineralization process of Muping–Rushan gold belt.



## 6.4 Mineralization model for the Muping–Rushan gold belt

Gold deposits in the Jiaodong area are similar to orogenic gold deposits (Goldfarb *et al.*, 2001; Zhou *et al.*, 2002), but exhibit some clear differences (Goldfarb and Santosh, 2014; Guo *et al.*, 2013). The host rocks of the Muping–Rushan gold belt in the Jiaodong area are the Late Jurassic Kunyushan granitic complex. The vein ore bodies have developed upon NE–SW-trending faults.

Sulphur and lead isotope data for stage I and II sulphides in the Muping–Rushan gold belt are consistent with the Kunyushan granitic complex, and Jingshan and Jiaodong groups, and the data for stage III polymetallic sulphides are more similar to those of the Jiaodong Group. Stage IV pyrite is more similar to the Jingshan Group. The data are indicative of lower crustal and orogenic belt sources (Figs. 7, 8). The Muping–Rushan gold belt is mainly situated at the transition between the North China Craton and Sulu UHP metamorphic belt, consistent with the sulphur and lead isotope data. In addition, a Hf–Nd isotope study showed that the average crustal model age of the Kunyushan granitic complex is consistent with that of Archean TTGs in the North China Craton. The source rocks of the Kunyushan granitic complex are mainly the Archean Jiaodong Group (Wu *et al.*, 2005; Yang *et al.*, 2006) and mafic lower crust of the Yangtze Craton (Hu, 2006). Due to the gold deposition process, the effects of redox reactions and other processes on the sulphur isotopic compositions is  $\leq 1\%$  (Goldfarb and Groves, 2015). Therefore, it is inferred that the ore-forming materials in the study area were principally derived from the Jingshan and Jiaodong groups.

Helium and argon isotope data indicate that the ore-forming fluids in the study area were mainly derived from the crust, and partly from the mantle (Fig. 9), which is consistent with the lead isotope data (Fig. 8). Geochemical and geological data indicate that the boundary between the North China and Yangtze cratons is the NE–SW-trending Muping–Jimo fault system that cuts the basement rocks (Zhang *et al.*, 2008). These deep faults likely acted as conduits for the crust- and mantle-derived ore-forming fluids in the Muping–Rushan gold belt.

Due to the subduction of the Paleo-Pacific Plate in the Middle Jurassic, the tectonic setting in eastern China experienced a major tectonic shift (Isozaki, 1997; Maruyama *et al.*, 1997; Quan *et al.*, 2020; Zhu *et al.*, 2016). Localised extension and large-scale magmatism occurred in the study area during the Late Jurassic, reflecting weak back-arc extension (Dang *et al.*, 2022; Zhu *et al.*, 2016; Zhu and Xu, 2019). Evidence for the local tectonic indicators suggest that N–S extension persisted from the Late Cretaceous to Paleocene (Zhang *et al.*, 2008). The mineralization ages of the Muping–Rushan gold belt are mainly concentrated between 113.3 and 104.8 Ma, and thus it is inferred that the gold deposits originated in an extensional back-arc setting linked to subduction of the Palaeo-Pacific Plate.

Enrichment of the lithospheric mantle by ore metals and fluids can be achieved by a number of processes: (1) released from the subducting slab and overlying sediments (Deng *et al.*, 2020a; Goldfarb and Santosh, 2014; Groves *et al.*, 2020); and (2) retention of metals in previously fertilised and hydrated lithospheric mantle (Wang *et al.*, 2020; Zhao *et al.*, 2019).

Sulphur isotope data for gold-related sulphide minerals may be able to help differentiate between the two mechanisms.

Based on the results and the regional geological evolution, the formation of the Muping–Rushan gold belt is inferred to have occurred as follows (Fig. 10). Firstly, in the Late Jurassic, subduction of the Palaeo-Pacific Plate released water and other volatiles from the plate and overlying sediments, resulting in hydration of the lithospheric mantle. Due to oceanic slab subduction, the Kunyushan granitic complex formed between 160 and 140 Ma (He *et al.*, 2021). Secondly, during the Early Cretaceous (120–100 Ma), the Sanfoshan granite intruded the crust and the Kunyushan granitic complex (Guo *et al.*, 2005; Li *et al.*, 2018; Tang, 2008; Zhang *et al.*, 2010) and, at the same time, arc-like mafic magmas were formed (Guo *et al.*, 2005; Hu, 2006). Thirdly, from 110 to 100 Ma, a back-arc extensional regime developed due to subduction of the Paleo-Pacific Plate. The metasomatised and previously fertilised lithospheric mantle underwent devolatilisation due to asthenospheric upwelling, which released auriferous  $\text{H}_2\text{O}$ – $\text{CO}_2$  fluids with positive  $\delta^{34}\text{S}$  values (Botcharnikov *et al.*, 2011; Zhai and Santosh, 2013). The ore-forming fluids from the mantle migrated upward through deep NNE–SSW-trending faults, and reacted with and metasomatised surrounding crustal rocks (*i.e.*, the Jiaodong and Jingshan groups, and Kunyushan granitic complex). Significant volumes of crustal fluid migrated upwards to shallow levels. Meteoric waters progressively contributed to the mineralisation process, which finally formed the Muping–Rushan gold belt.

## 7 Conclusions

(1) Elemental mapping of pyrite and pyrrhotite in typical gold deposits in the Muping–Rushan gold belt showed that silver and gold are mainly hosted in infilled cracks in Py1 or occur at the rims of stage II and III sulphides. The arsenic contents are higher in the rims and cracks of Py1 and around Py2, and are positively correlated with gold contents. Arsenic displays zoning in some pyrite grains.

(2) The sulphides have  $\delta^{34}\text{S} = 5.8\text{‰}$ – $10.1\text{‰}$ , suggesting that sulphur in the mineralization stages II and III was derived from the Jiaodong and Jingshan Groups and the Kunyushan granitic complex. The lead isotope data suggest derivation from lower crustal and orogenic sources.

(3)  $^3\text{He}/^4\text{He}$ ,  $^{40}\text{Ar}/^{36}\text{Ar}$ , and  $^{40}\text{Ar}^*/^4\text{He}$  ratios of the gold deposits are 0.01–5.06 Ra, 389.8–4674.7, and 0.03–2.78, respectively, indicating the ore-forming fluids in the Muping–Rushan gold belt were mainly derived from the crust, but with some involvement of mantle-derived fluids.

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## Supplementary material

**Fig. 1.** Element mapping shows the texture of the pyrites and pyrrhotites from Muping-Rushan gold belt. BEI=Backscattered electron imaging. Py=pyrite, Po= pyrrhotite.

**Table 1.** Metallogenetic geologic characteristics of typical ore deposits.

**Table 2.** Samples description and location presented in this study

**Table 3.** In situ sulfur isotope analyses in Muping-Rushan gold belt.

**Table 4.** Lead isotope composition for Muping-Rushan gold belt, Kunyushan granitic complex and Jiaodong group.

**Table 5.** Helium and argon data for fluids extracted from Muping-Rushan gold belt.

The Supplementary Material is available at <https://www.bsgf.fr/10.1051/bsgf/2025007/olm>.

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