**Mantle-derived fingerprints in hydrothermal gold deposits unraveled by** **interpretable machine learning**

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## 1 Ore district geology

The gold deposits in the NCC are mainly distributed in two belts: the east belt, including Ji’nan District, Liaodong Peninsula, and Jiaodong Peninsula districts, and the west belt, consisting of Chifeng-Chaoyang, Jibei-Jidong, central Taihangshan, Xiaoqinling, and Xiong’ershan districts (Fig. 1). In this study, four important districts (Jiaodong Peninsula, Liaodong Peninsula, central Taihangshan, and Xiaoqinling) are selected to analyze and their pyrite trace element contents are collected. The geology of these four districts is described as follows.

### 1.1 Jiaodong Peninsula

The Jiaodong Peninsula, located in the east of the NCC, is the largest gold district in China, containing over 240 gold deposits and 5500 tons of gold (Deng et al., 2023; Yang et al., 2024). The Jiaodong Peninsula comprises Precambrian metamorphic basement and Mesozoic igneous rocks. The Precambrian basement consists of Neoarchean tonalite-trondhjemite-granodiorite (TTG) gneisses, and volcanic and sedimentary rocks that experienced amphibolite to granulite facies metamorphism. Mesozoic igneous rocks dominantly formed during the late Jurassic (160–156 Ma) and early Cretaceous (130–126 Ma).

The gold deposits are predominantly distributed along the Zhaoyuan-Laizhou and Rushan-Muping belts. Gold mineralization is structurally controlled by faults trending NNE and NE. Mineralization is classified into two types: the quartz-vein type, primarily consisting of Au-bearing quartz veins, and the altered rock type, characterized by disseminated mineralization with minor associated quartz veins. Most deposits are hosted in the Jurassic granite, with minor deposits in the Precambrian basement (Yang et al., 2003).

### 1.2 Liaodong Peninsula

The Liaodong Peninsula is located in the northeast region of the NCC and is an important gold province. The Liaodong Peninsula’s basement comprises Neoarchean TTG gneisses (~3.4–2.5 Ga), overlain by Paleoproterozoic metasedimentary and volcanic sequences of the Liaohe Group (~2.2–1.9 Ga), which underwent greenschist to amphibolite facies metamorphism during the ~1.85 Ga orogeny. During the Mesozoic, three major phases of magmatism are recognized: 1) Late Triassic syenites, dolerites, and monzogranites (220–212 Ma); 2) Jurassic hornblende-bearing tonalite-granodiorite and two-mica monzogranite (179–156 Ma; Wu et al., 2005b). Early Cretaceous extensive granodiorite, dolerites, diorites, A-type granites, and syenites (131–117 Ma; Wu et al., 2005a). Tectonically, the peninsula records a Late Jurassic–Early Cretaceous transition from compression to extension. NW-SE-directed compression during the Jurassic formed thrust systems and volcanic-sedimentary basins, while Early Cretaceous extension led to metamorphic core complexes, half-graben basins, and detachment faults (Wu et al., 2005b, 2005a).

Gold deposits are mainly distributed in the Maoling, Wulong, and Qingchengzi districts. The quartz-vein type includes the Wulong, Zhuanghe, Wangjiawaizi, and Xindian, whereas the altered rock type comprises Baiyun, Linjiasandaogou, Qiuguobi, Maoling, and Dadongou. Most gold deposits, such as the Maoling, Dadonggou, Baiyun, and Linjiasandaogou, are hosted in the Paleoproterozoic metamorphic rocks. Minor deposits like the Wulong deposit are hosted in the granite (Sun et al., 2020b; Sun et al., 2022b).

### 1.3 Central Taihangshan

The central Taihangshan district is located in the northern part of the Trans-North China orogen, which comprises Archean to Paleoproterozoic TTG, amphibolite, schist, marble, and banded iron formation. The basement is overlain by the Proterozoic to Paleozoic carbonate rocks. Zircon U-Pb ages reveal that the ages of intrusions in this region are between 142 and 130 Ma (Li et al., 2013; Zhang et al., 2015).

Gold mineralization mostly occurs as auriferous quartz veins within the Archean to Paleoproterozoic metamorphic basement. Some breccia orebodies are also found in some deposits, such as Yixingzhai. Gold orebodies are dominantly controlled by NW- and NE-trending faults.

### 1.4 Xiaoqinling

The Xiaoqinling district, located along the southern margin of the NCC, is the second largest gold district in China, with over 100 gold deposits and 800 t of gold (Liu et al., 2022; Mao et al., 2010; Yang et al., 2003). The basement comprises the Archean Taihua Group, comprising gneiss, quartzite, and marble, overlain by the Neoproterozoic Xiong’er Group, which consists of metamorphosed volcanic rocks. The early Paleozoic sedimentary rocks are distributed in the southern parts of the district. The Mesozoic magmatic events mainly occurred in the late Jurassic (158–136 Ma) and early Cretaceous (134–108 Ma; Li et al., 2012; Mao et al., 2010).

Gold mineralization dominantly clusters in three WNW-trending gold belts and occurs as pyrite-vein type with minor altered rock type. Gold mineralization mainly occurs along the NW- to EW-trending faults in the limbs or axes of the EW-trending folds. Most gold mineralization is hosted in the Archean and Proterozoic metamorphic rocks.

2. Deposit geology

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| District | Deposit | Au reserve | Average grade | Host rocks | Mineralization type | Controlling Faults | Ore minerals | Age | Reference |
| Liaodong | Wulong | >80 t | 5.35 g/t | gneissic two-mica granite and granodiorite | Auriferous quartz veins | NNE and NW-trending faults | Pyrite and pyrrhotite, with minor chalcopyrite, sphalerite, galena, bismuthinite, native bismuth, molybdenite, arsenopyrite, chalcocite, bornite, tellurobismuthite, electrum, and native gold | 127 Ma (Molybdenite Re-Os; Monazite U-Pb) | Yu et al., 2020 |
| Sidaogou | >18 t | 7.0 g/t | Paleoproterozoic metamorphic rocks | Alteration type | Interstratified faults | Pyrite, with minor pyrrhotite, chalcopyrite, galena, Bi-minerals | Early Cretaceous (infered) | Feng et al., 2019 |
| Zhuanghe | >20 t | 2.85 g/t | Archean gneiss and Neoproterozoic metasandstone | Auriferous quartz veins and alteration type | The NS-striking faults, diping east at 45-60 ◦ | Pyrite and galena, with minor sphalerite, chalcopyrite, and native gold | 121 Ma (Pyrite Re-Os) | Zhang et al., 2022 |
| Jiaodong | Zhaoxian | >105 t | - | Late Jurassic granite | Auriferous quartz veins | NNE-trending Jiaojia fault, dipping NW at 10-30 ◦ | Pyrite, galena, sphalerite, chalcopyrite, pyrrhotite, with minor native gold | Early Cretaceous (infered) | Li et al., 2021 |
| Xiadian | >200 t | - | Late Jurassic granite | Auriferous quartz veins | Zhaoyuan–Pingdu fault | Pyrite, chalcopyrite, galena, sphalerite, electrum, and native Au | 120 Ma (Monazite U-Pb) | Ma et al., 2017 |
| Muping | >50 t | - | Late Jurassic granite | Auriferous quartz veins | Muping-Rushan fault | Pyrite, chalcopyrite, galena, sphalerite, magnetite, pyrrhotite, arsenopyrite, and native gold | 123-120 Ma (Monazite U-Pb) | Zhang et al., 2022 |
| Sanshandao | >260 t | 3.13 g/t | Late Jurassic granite | Auriferous quartz veins | Sanshandao fault | Pyrite, arsenopyrite, sphalerite, galena, and native gold | Early Cretaceous (infered) | Liu et al., 2019 |
| Dayingezhuang | >283 t | 4.03 g/t | Late Jurassic granite | Auriferous quartz veins | Zhaoping fault | Pyrite, chalcopyrite, galena, sphalerite, hessite, and native gold | 134-126 Ma (Sericite Ar-Ar) | Yang et al., 2014 |
| Xiaoqinling | Dahu | >42 t | 2.1 g/t | Archean amphibolite, gneisses, and migmatite | Auriferous quartz veins | EW- trending faults | Pyrite, galena, native gold, tellurides, and Bi-sulfosalt minerals | 125 Ma (rutile U-Pb) | Liu et al., 2022 |
| Fancha | >13 t | 11.4 g/t | Archean biotite plagiogneiss, amphibole plagiogneiss, migmatite, and amphibolite | Auriferous quartz veins | E-W- to NW-striking faults | Pyrite, chalcopyrite, galena, sphalerite, and complex Au(Ag)-Te-Bi assemblages | 130-124 Ma (Pyrite Re-Os) | Liu et al., 2020; 2022 |
| Qiangma | >50 t | 8.9 g/t | Paleoproterozoic metamorphic rocks | Auriferous quartz veins | NW, NNW, and EW-trending faults | Pyrite, with minor chalcopyrite, galena, sphalerite, native gold, and electrum | 128 Ma (rutile U-Pb) | Zhao et al., 2022 |
| central Taihangshan | Shihu | >20 t | 7.85 g/t | TTG genesis | Auriferous quartz veins | ENE-trending faults | Pyrite, with minor chalcopyrite, galena, sphalerite, and native gold | 129 Ma (pyrite Rb-Sr) | Zeng et al., 2020 |
| Yixingzhai | >70 t | - | TTG genesis | Auriferous quartz veins, breccia type | N-S-trending faults and breccia pipe | Pyrite, with minor chalcopyrite, galena, sphalerite, and native gold | 131 (quartz Ar-Ar) or 136 Ma (adularia Ar-Ar) | Li et al., 2014; Zhang et al., 2024 |

(Ma et al., 2017)

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