1 **Revision 2**

2 **Two discrete gold mineralization events recorded by hydrothermal xenotime and**

3 **monazite, Xiaoqinling gold district, central China**

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25                                    **ABSTRACT**

26      We present in situ LA-ICP-MS U-Pb dating of xenotime and monazite in assemblages with native

27      gold and Au (Ag) tellurides from the Xiaoqinling lode gold district in central China. Composite

28      xenotime and monazite grains formed through coupled dissolution–reprecipitation reactions reveal

29      two discrete gold mineralization events. The first gold mineralization event, recorded by monazite

30      (158.6 ± 3.3 Ma, Tera-Wasserburg lower intercept age) and xenotime cores (157.11 ± 0.83 Ma,

31      weighted mean $^{206}$Pb/$^{238}$U age), is characterized by the mineral assemblage of lingbaoite (AgTe$_3$)-

32      sylvanite ([Au,Ag]$_2$Te$_4$)-stützite (Ag$_5$−xTe$_3$)/native tellurium-sylvanite-stützite. The second gold

33      mineralization event, recorded in the rims of xenotime (135.46 ± 0.93 Ma, weighted mean $^{206}$Pb/$^{238}$U

34      age), is characterized by the mineral assemblage of native gold-calaverite (AuTe$_2$)-petzite

35      (AuAg$_3$Te$_2$)-tellurobismuthite (Bi$_2$Te$_3$). Our study implies that the large-scale Jurassic mineralization

36      event in eastern China, related to flat subduction of the paleo–Pacific plate beneath the eastern China

37      continent, also caused widespread gold mineralization in the Qinling–Dabie Orogen, in addition to

38      production of its world-class porphyry Mo deposits. The fact that only a few Jurassic gold

39      mineralization ages have been reported before, may be due to the lack of suitable geochronometers to

40      record the earlier Jurassic hydrothermal processes, which have been overprinted by the better-

41      recognized Early Cretaceous gold mineralization event. This study also presents a rare example of

42      xenotime compositional alterations and resetting of U–Pb ages induced by low to moderate salinity

43      carbono-aqueous fluids at low temperatures. The textural relationships between gold minerals in

44      contact with such composite xenotime crystals demonstrate that they could have precipitated before,

45      coeval with, or after the dated domains. Since low to moderate salinity carbono-aqueous fluids are

46   commonly involved in the formation of lode gold deposits, it's crucial to examine xenotime textures

47   and recognize potential alteration textures before carrying out isotopic dating of xenotime collected

48   from these deposits. Without prior compositional and textural characterization, attempts to date such

49   composite crystals could yield mixed dates and meaningless ages.

50   **Keywords:** Xenotime, monazite, gold deposit, LA-ICP-MS U-Pb dating, Xiaoqinling, central China

51                                                            **INTRODUCTION**

52       The formation of lode gold deposits commonly involves multiple hydrothermal stages or events

53   (e.g., Arne et al. 2001; Essarraj et al. 2001; Bateman and Hagemann, 2004; Meffre et al. 2016;

54   Fougerouse et al. 2017). The episodic nature of hydrothermal systems may be identified by well-

55   developed superimposed textures, such as breccias, ribbons, and a cross-cutting network of veinlets

56   (e.g., Dowling and Morrison, 1989; Goldfarb et al. 2005; Voisey et al. 2020; Jian et al. 2021).

57   However, it is challenging to determine whether vein systems result from the gradual cooling of a

58   single hydrothermal fluid or multiple hydrothermal events that occur millions of years apart. It is

59   especially difficult to accurately determine the timing of each individual hydrothermal event and the

60   timing of gold deposition. The difficulties mainly arise from the scarcity of suitable dating

61   minerals/mineral domains directly related to gold precipitation that remain closed to isotope re-

62   equilibration during subsequent hydrothermal events.

63       Monazite and xenotime are robust geochronometers that have low rates of Pb diffusion and low

64   susceptibility to Pb loss at high temperatures, with Pb closure temperatures of 890°C for xenotime

65   and 940°C for monazite (for a 10 μm grain with a cooling rate of 10°C/Ma: Cherniak et al. 2004;

66   Cherniak, 2006). However, the two minerals undergo coupled dissolution–reprecipitation reactions at

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67    temperatures <400°C (Townsend et al. 2000; Rasmussen and Muhling, 2007; Budzyń et al. 2015a,b),

68    leading to crystals that may have multiple, but discrete, age domains from which precise dates for

69    multiple hydrothermal events may be obtained (e.g., Fielding et al. 2017; Budzyń et al. 2018).

70    Although many lode gold deposits contain trace amounts of hydrothermal monazite or xenotime, the

71    size of most hydrothermal xenotime grains is typically <10 μm, and combined with its low

72    abundance make it difficult to find suitable crystals from which complex, multi-stage hydrothermal

73    histories may be reconstructed (e.g., McNaughton and Rasmussen, 2018).

74    This study presents detailed in situ LA-ICP-MS U-Pb dating of xenotime and monazite in

75    assemblages with native gold and Au (Ag) tellurides from the Xiaoqinling lode gold district, central

76    China. Composite xenotime and monazite crystals formed through coupled dissolution–

77    reprecipitation reactions reveal two discrete gold mineralization events, with an early Cretaceous

78    gold mineralization event preceded by a previously overlooked middle Jurassic gold mineralization

79    event.


80                                    GEOLOGICAL SETTING


81    Marginal parts of the North China Craton host hundreds of lode gold deposits of mainly Early

82    Cretaceous age (Mao et al. 2005; Li et al. 2012a; Deng et al. 2016), with a total gold resource

83    exceeding 3,600 tonnes Au (Li et al. 2012a; Deng et al. 2016). The Xiaoqinling gold district in the

84    southern margin of the North China Craton represents the second-largest gold production area in

85    China, with a proven gold reserve of more than 630 tonnes (Jian et al. 2015, 2022a).

86    **Mesozoic tectonomagmatic evolution of the Qinling-Dabie orogen**

87    The Xiaoqinling district is located at the southern margin of the North China craton and belongs to

88    the Qinling-Dabie orogen (Fig. 1). The WNW-trending Qinling-Dabie orogen delineates the

89    boundary between the North China craton and the Yangtze craton. This orogenic belt resulted from

90    multistage collisional events between the North China craton and the Yangtze craton; the final

91    collision between the two cratons occurred in the Triassic (Dong and Santosh, 2016). During the Late

92    Triassic, the Qinling-Dabie orogen evolved into a post-collisional extensional domain, which is

93    indicated by the emplacement of post-collisional intrusions, including alkaline intrusions (Wang et

94    al. 2007; Li et al. 2012a; Cao et al. 2015), carbonatites (Xu et al. 2010; Du et al. 2020; Zheng et al.

95    2020; Tang et al. 2021), and rapakivi-textured granitoids (Wang et al. 2011).

96    Since the Jurassic, eastern China, including the eastern part of the Qinling-Dabie orogen, became a

97    part of the circum-Pacific tectonic regime, with the subduction of the Izanagi plate (or paleo-Pacific

98    plate) beneath the Eurasian continental margin (Mao et al. 2021a). The subduction began with a steep

99    angle but changed to a flat angle in the Middle-Late Jurassic (Wu et al. 2019; Mao et al. 2021a).

100    Since the Early Cretaceous, eastern China evolved into an extensional setting (Mao et al. 2021a) due

101    to lithospheric thinning driven by the rollback of the paleo-Pacific plate (Wu et al. 2019; Ma et al.

102    2021). The flat subduction and subsequent rollback of the paleo-Pacific plate gave rise to widespread

103    magmatism and ore formation, making the Late Mesozoic the most important magmatic and

104    metallogenic period in eastern China.

105    **Geology of the Xiaoqinling gold district**

106    The strata exposed in the Xiaoqinling gold district are dominated by Archean amphibolite-facies

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107 metamorphic rocks of the Taihua Group (Fig. 1), which consists of biotite plagiogneiss, amphibolite

108 gneiss, amphibolite, quartzite, and marble (Cai and Su, 1985). These rocks probably formed in the

109 Neoarchean and have been subjected to amphibolite-facies metamorphism in the Paleoproterozoic

110 (Zhou et al. 1998; Ni et al. 2003; Li et al. 2007). The Archean rocks were intruded by

111 Paleoproterozoic pegmatite/granite (Li et al. 1996; Li et al. 2007), Proterozoic and Mesozoic granitic

112 intrusions (Wang et al. 2010; Hu et al. 2012; Li et al. 2012), and Paleoproterozoic and Early

113 Cretaceous mafic dikes (Wang et al. 2008; Bi et al. 2011). Jurassic magmatism, although widespread

114 in eastern China, has rarely been reported in the Xiaoqinling gold district. The Huashan granite

115 complex has a zircon age of $146 \pm 2$ Ma (Mao et al. 2010). Several Jurassic porphyritic stocks,

116 however, have been reported from the Xiong'ershan gold district, about 100 km east of the

117 Xiaoqinling district, and in a similar geologic setting (e.g., Niutougou, Miaoling, and Qiyugou gold

118 deposits: Wang et al. 2012; Li et al. 2014; Wang et al. 2020). However, these Jurassic porphyries do

119 not appear to be directly related to gold mineralization since they all postdate gold mineralization

120 (Wang et al. 2020). At the Qiyugou Au deposit, for instance, the quartz porphyries were emplaced at

121 $158.6 \pm 1.1$ to $157.3 \pm 1.1$ Ma (LA-ICP-MS zircon U–Pb age), while gold mineralization occurred at

122 $132.9 \pm 1.5$ Ma (molybdenite Re-Os age of gold ore samples) and is genetically related to the 130.9

123 $\pm 1.9$ Ma hornblende monzogranite (LA-ICP-MS zircon U–Pb age).

124 Early Cretaceous plutons are widely exposed across the gold district. These are, from east to west,

125 the Niangniangshan biotite monzogranite ($142 \pm 3$ to $129 \pm 2$ Ma: Wang et al. 2010; Li et al. 2012b),

126 the Wenyu biotite monzogranite ($141 \pm 2$ to $136 \pm 3$ Ma: Wang et al. 2010; Li et al. 2012b), and the

127 outer phase of the Huashan granite complex ($132 \pm 1$ Ma: Hu et al. 2012).

128 The nearly E-W–striking Taiyao and Xiaohe faults define the northern and southern boundaries of

129    the Xiaoqinling gold district. The two normal faults developed during the Cenozoic extension,

130    resulting in the exposure of the basement rocks (Li et al. 2020). The more than 1,200 gold-bearing

131    quartz veins concentrate along the axes of several EW-striking steep folds and are controlled by

132    small- to medium-size EW-striking faults. The S16 gold-bearing quartz vein, from which the studied

133    ore samples were collocated, is about 30 km southwest of Lingbao city, Henan province, central

134    China. The S16 gold-bearing quartz vein, from which the studied ore samples were collocated, is a

135    newly discovered concealed vein with an average gold grade of ~6 g/t. It is 0.1 to 2.5 m wide and

136    extends about 1.5 km in a roughly east-west direction, dipping to the south (Fig. 1). The S16 gold-

137    bearing quartz vein is about 30 km southwest of Lingbao city, Henan province, central China, and

138    belongs to the south ore belt of the Xiaoqinling gold district. The south ore belt hosts most of the

139    gold-bearing quartz veins, which concentrate along the Laoyacha anticline (Fig. 1).


140                  **SAMPLE MATERIAL AND METHODS**


141    **Sample selection**


142    The studied ore samples were collected underground from the S16 gold-bearing quartz vein. The

143    ore samples for geochronological study consist mainly of quartz and pyrite (Fig. 2). Other minerals

144    present in small or trace amounts include xenotime, monazite, scheelite, celestine, gold, native

145    tellurium, muscovite, as well as a variety of sulfides (e.g., chalcopyrite, bornite, sphalerite, and

146    galena) and tellurides (e.g., sylvanite, petzite, calaverite, stützite, hessite, altaite, rucklidgeite, and

147    tellurobismuthite).

**Analytical methods**

Xenotime and monazite in polished thick sections were first examined in reflected light and then by electron probe microanalysis (EPMA) and scanning electron microscopy (SEM). SEM investigation was carried out at the Institute of Geology, Chinese Academy of Geological Sciences, using a FEI NOVA nanoSEM equipped with an Oxford X-Max 50 detector. EPMA wavelength-dispersive X-ray spectrometry (WDS) analysis was carried out at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, using a JXA-iHP200F electron microprobe. Details on EPMA settings for WDS analysis are available in Table A1. EPMA X-ray mapping was carried out at the State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, China, using a JXA-8230 electron microprobe.

LA-ICP-MS U–Th–Pb isotope analysis of xenotime and monazite, as well as LA-ICP-MS trace element analysis of xenotime, were carried out at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. Analytical procedure for U–Th–Pb isotope analysis follows Wu et al. (2020). Analytical details are available in Tables A2, A3. LA-ICP-MS trace element analysis of monazite was carried out at the Yanduzhongshi Geological Analysis Laboratories Ltd., Beijing, using a New Wave NWR 193 laser ablation system coupled to an Analytikjena M90 quadrupole ICP-MS. Analytical details are available in Table A4.

<div align="center">

**RESULTS**

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**Vein mineralogy and paragenesis**

At least three hydrothermal stages, including two gold-mineralization stages, are recognized in the

168      studied ore samples (Figs. 2, 3, 4). The first hydrothermal stage (I) is characterized by the

169      precipitation of milky white quartz, which makes up more than 90% of the vein volume. The second

170      stage (II) is characterized by the growth of pyrite, scheelite, xenotime, monazite, and celestine on

171      fracture planes in quartz (Fig. 2). Pyrite contains composite mineral inclusions (<1–50 μm in

172      diameter) consisting mainly of lingbaoite (a recently named mineral with the chemical formula of

173      $AgTe_3$, Jian et al. 2020), sylvanite $[(Au,Ag)_2Te_4]$, stützite $[Ag_{5-x}Te3]$, native tellurium, and

174      chalcopyrite, with minor bornite, galena, and altaite (Figs. 3A–G). These inclusions outline the

175      primary growth zones in pyrite and generally display a negative crystal shape. They were interpreted

176      as primary melt inclusions, which were trapped as polymetallic melt droplets during the growth of

177      the host pyrite (Jian et al. 2021, 2022b). The third stage (III) is the main gold deposition stage. This

178      stage is characterized by native gold and tellurides (petzite $[AuAg_3Te_2]$, calaverite $[AuTe_2]$,

179      tellurobismuthite $[Bi_2Te_3]$, altaite $[PbTe]$, and rucklidgeite $[PbBi_2Te_4]$) as inclusions or fracture

180      fillings in early minerals (e.g., quartz, pyrite, and scheelite, Figs. 2–4). The stage III gold-bearing

181      mineral assemblages (e.g., native gold-calaverite-petzite-tellurobismuthite) commonly coexist with

182      low to moderate salinity $H_2O$-$CO_2$ fluid inclusions along healed fractures in quartz (Figs. 3I–K). The

183      total homogenization temperatures of these fluid inclusions have been investigated from many gold-

184      quartz veins in the Xiaoqinling gold district and cluster at 200 to 400°C (Fan et al. 2003; Li et al.

185      2012b; Xiong et al. 2013). The cross-cutting relation between stage II and stage III gold-bearing

186      minerals is illustrated in Figures 3A–B, in which stage II tellurides occur as inclusions in pyrite

187      while stage III gold and tellurobismuthite occur along quartz grain boundaries.

**Characterization of xenotime and monazite**

189    Xenotime and monazite crystals occur as inclusions in pyrite and scheelite, or along quartz

190    fractures (Figs. 2D, 4). Individual xenotime and monazite crystals are typically 10–80 μm in

191    diameter (Figs. 4–6), but large crystals (up to 350 μm in diameter, Figs. 4H, I) have also been

192    observed. The two minerals most commonly occur in contact with each other, and monazite has also

193    been observed as inclusions in xenotime. Cathodoluminescence (CL) imaging of xenotime reveals

194    that xenotime crystals have a dark, pristine core surrounded by bright altered domains, which

195    developed near grain rims or healed microfractures (Figs. 4I, 5). There is a sharp reaction front

196    between altered and pristine xenotime domains (Figs. 4D–I, 5). The xenotime cores display distinct

197    oscillatory zoning truncated at the boundary with the altered domains (Fig. 5). There is an epistatic

198    relationship between altered and pristine xenotime domains. For example, examination of the

199    xenotime crystals using polarized light shows that altered and pristine xenotime domains in each

200    grain are optically continuous (Figs. 4D, F, H). Altered xenotime also preserves the external

201    dimension of pristine xenotime. These textural features suggest that the altered xenotime domains in

202    our sample set formed through coupled dissolution-reprecipitation reactions (e.g., Putnis, 2002,

203    2009). Native gold and stage III tellurides have been observed as inclusions in the altered domains of

204    xenotime, or occur in contact with the altered domains (Figs. 4D–I).

205    Xenotime cores and rims show distinct major and trace element features (Tables A5, 6, Fig. A2).

206    EPMA analysis shows cores contain higher and more consistent Y concentrations (0.91–0.92 apfu,

207    atoms per formula unit on the basis of 4 oxygens) whereas Y concentrations in the altered rims vary

208    from 0.81 to 0.92 apfu. LA-ICP-MS trace element analysis reveals xenotime cores contain 1.4–4.1

209    wt% LREE (La to Eu), 9.0–13.0 wt% HREE (Gd to Lu,), 1000–2600 ppm Si, 730–4600 ppm Ca,

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210    12–19 ppm Rb, 5–19 ppm Sr, 29–220 ppm Zr, 240–620 ppm Pb, 1000–5800 ppm Th, and 1900–

211    5900 ppm U, while xenotime rims have higher concentrations of HREE (12.4–19.5 wt%), Si (0.1–2.1

212    wt%), and Rb (25–37 ppm), and lower concentrations of LREE (0.7–1.2 wt%), Zr (10–106 ppm), Pb

213    (84–256 ppm), Th (500–1900 ppm), and U (800–2400 ppm). In the chondrite-normalized REE

214    pattern (Fig. 7), neither the cores nor rims have an Eu anomaly. This differs from igneous xenotime,

215    which is commonly characterized by a pronounced negative Eu anomaly (e.g., Rasmussen, 2005;

216    Aleinikoff et al. 2015).

217    While xenotime crystals may show well-formed crystal faces, monazite occurs as subhedral-

218    anhedral grains, which form larger aggregates with irregular outlines (Fig. 6). Occasionally, elongate

219    monazite grains grow as radial, flower-shaped assemblages (Figs. 6, A3). Monazite shows a faint

220    core-rim texture under high-contrast SEM-BSE imaging (Fig. 6). The core has a heterogeneous

221    texture with chaotic, patchy zoning, and contains a dense population of mineral inclusions (≤10 μm,

222    mainly iron oxides) and smaller fluid inclusions. The rim is relatively homogenous and inclusion-

223    free, with faint patchy zoning. Like xenotime, the monazite rim may preserve the external dimension

224    of pristine monazite (e.g., the top right monazite grain in Fig. 6), suggesting the altered rim formed

225    through coupled dissolution-reprecipitation reactions. The heterogeneous core represents a mixture

226    of pristine and secondary monazite.

227    EPMA WDS analysis (Table A5) and X-ray mapping reveal that monazite rims contain 0.01–0.08

228    apfu Si, 0.007–0.014 apfu Th, 0.23–0.26 apfu La, 0.41–0.45 apfu Ce, 0.09–0.12 apfu Pr, and 0.12–

229    0.15 apfu Nd, while the partially altered cores have lower concentrations of Si (0.01–0.06 apfu), Th

230    (0.005–0.007 apfu), and La (0.21–0.23 apfu), and higher concentrations of Nd (0.15–0.16 apfu).

231    Other elements show little systematic variation between the core and rim. LA-ICP-MS trace element

232    data of monazite are available in Table A7. LA-ICP-MS analysis (a spot size of 10 μm) does not have

233    the spatial resolution to resolve the altered monazite rim and the partially altered monazite core.

234    Monazite shows an LREE-enriched smooth pattern in the chondrite-normalized REE diagram,

235    without a distinct Eu anomaly (Fig. 7).

236    **U-Th-Pb isotope data**

237    One hundred and thirteen U–Th–Pb isotopic analyses were carried out on ten xenotime crystals.

238    The locations of analyses, along with the analytical numbers and apparent $^{206}Pb/^{238}U$ ages, are

239    presented in Figure 5. U–Th–Pb isotope data are listed in Tables A8 and presented graphically in

240    Figure 9. Among them, 33 analyses are not considered geologically significant and are excluded

241    from the age analysis. The omitted analyses include 20 analyses with discordance values (1 -

242    $^{206}Pb/^{238}U/^{207}Pb/^{235}U) \times 100$) >5%  or <-5% and 13 analyses obtained from the incompletely altered

243    domains of xenotime. Explanations for the discordance and incompletely altered domains are

244    presented in the "Discussion" section.

245    After exclusion of the omitted analyses, the 46 analyses of pristine xenotime cores yield $^{206}Pb/^{238}U$

246    dates from 164.4 ± 6.1 to 153.2 ± 5.6 Ma, $^{207}Pb/^{235}U$ dates from 160.6 ± 6.9 to 152.2 ± 6.0 Ma, and

247    $^{208}Pb/^{232}Th$ dates from 168.2 ± 11 to 139.1 ± 7.6 Ma. These data define a weighted mean $^{206}Pb/^{238}U$

248    age of 157.11 ± 0.83 Ma (MSWD = 0.71), a weighted mean $^{207}Pb/^{235}U$ age of 155.93 ± 0.93 Ma

249    (MSWD = 0.60), and a Tera-Wasserburg lower intercept age of 156.49 ± 0.94 Ma (MSWD = 0.55).

250    The three ages overlap with each other within the margin of error. The remaining 41 analyses of

251    xenotime rims yield $^{206}Pb/^{238}U$ dates from 142.4 ± 5.8 to 128.5 ± 5.1 Ma, $^{207}Pb/^{235}U$ dates from 146.9

252    ± 9.4 to 129.4 ± 7.2 Ma, and $^{208}Pb/^{232}Th$ dates from 150.0 ± 21 to 121.5 ± 9.1 Ma. These data define

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253    a weighted mean $^{206}$Pb/$^{238}$U age of 135.46 ± 0.93 Ma (MSWD = 1.07), a weighted mean $^{207}$Pb/$^{235}$U

254    age of 135.2 ± 1.4 Ma (MSWD = 1.05), a Tera-Wasserburg lower intercept age of 135.5 ± 1.1 Ma

255    (MSWD = 1.05), and a Concordia age of 135.33 ± 0.91 Ma (MSWD = 0.41). The four ages overlap

256    with each other within the margin of error.

257    Thirty-eight  U–Th–Pb isotopic analyses were collected on 11 monazite crystals. The locations of

258    analyses and analytical numbers, along with the apparent $^{206}$Pb/$^{238}$U ages, $^{207}$Pb/$^{235}$U ages, and

259    $^{208}$Pb/$^{232}$Th ages, are shown in Figure 6. Results are listed in Table A9 and presented graphically in

260    Tera-Wasserburg Concordia diagram in Figure 8. Monazite shows large variations in $^{207}$Pb/$^{235}$U

261    (3730 ± 36 to 208 ± 8 Ma), $^{206}$Pb/$^{238}$U (1897 ± 61 to 161 ± 6 Ma), and $^{208}$Pb/$^{232}$Th dates (463 ± 15 to

262    141 ± 5 Ma). The U–Pb ages are highly discordant, with discordance values ranging from 23 to 79.

263    Nevertheless, the U-Pb isotope dataset forms a linear array in the Tera-Wasserburg Concordia

264    diagram, yielding an upper intercept age of >4.5 Ga and a lower intercept age of 158.6 ± 3.3 Ma

265    (MSWD = 3.7), which overlaps with the ages of xenotime cores within the margin of analytical error.

266                                    DISCUSSION

267    **Remarks on monazite and xenotime ages**

268    Although many monazite and xenotime dates are concordant or near concordant, the two minerals

269    may be affected by low-temperature hydrothermal alteration and yield discordant ages (e.g.,

270    Rasmussen et al. 2011; Seydoux-Guillaume et al. 2012; Didier et al. 2013; Budzyń et al. 2018, 2021,

271    2022; Budzyń and Sláma, 2019). Factors causing age discordance during hydrothermal alteration

272    include incomplete replacement of mineral domains (Grand'Homme et al. 2016; 2018) and

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273    incorporation of initial Pb in secondary monazite and xenotime (e.g., Seydoux-Guillaume et al. 2012;

274    Didier et al. 2013; Budzyń et al. 2022). For instance, altered monazite domains with apparently

275    homogeneous composition at a microscale may correspond to nanomixtures of primary and

276    secondary monazite, yielding discordant ages (Grand'Homme et al. 2016; 2018). During

277    hydrothermal alteration of monazite, initial Pb could accumulate in the monazite lattice along the

278    microcracks (e.g., Budzyń et al. 2022) or be incorporated as nanosized Pb-rich inclusions (Seydoux-

279    Guillaume et al. 2003; Fougerouse et al. 2018).

280    Twenty analyses of xenotime yield highly discordant dates with >5% or <-5% discordance,

281    suggesting the incorporation of common Pb. Among them, thirteen analyses were obtained from the

282    rims, two from the cores, and three from the incompletely altered domains. Eleven analyses

283    with >5% discordance were placed on micro-fracture or porous places (e.g., analytical points 1 and 7

284    in section V16-101A, see the top left xenotime grain in Figs. 5, A1). Common Pb could present as

285    nano-scale Pb-bearing minerals, such as altaite (Pb as an essential element) or tellurobismuthite (Pb

286    as a minor component), along monazite microcracks and grain boundaries. Two minerals are

287    commonly observed to occur in contact with xenotime and monazite (Fig. 4C). Accordingly, we

288    propose the source of common Pb can be attributed to micro-cracks or porous spaces, which are

289    more developed in xenotime rims. Quartz is another source of common Pb. Eight analyses designed

290    to analyze the thin xenotime rims are contaminated by the quartz matrix; it is visible from the laser

291    ablation pits that quartz was ablated (e.g., analytical points 19–21 in section V16-103A, see the

292    central right xenotime grain in Figs. 5, A1). Common Pb could be present within quartz-hosted fluid

293    inclusions or along the grain boundaries between quartz and xenotime. Thirteen analyses obtained

294    from the incompletely altered domains (i.e., mixture of pristine and secondary xenotime) of xenotime

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295    are also excluded from the age analysis. In Figure 5 (section V16-103A, the large grain in the top

296    right) and Figure A2 (xenotime in the third row), for instance, the incompletely altered domain in the

297    upper part of a xenotime grain partially preserves the oscillatory zoning of the pristine xenotime

298    core. Ages and U-Th concentrations of this domain fall between the pristine core and the completely

299    altered rim on the left.

300    Monazite shows highly discordant U–Pb ages (discordance values ranging from 23 to 79) and

301    large variations in $^{207}Pb/^{235}U$ (3730–208 Ma), $^{206}Pb/^{238}U$ (1897–161 Ma), and $^{208}Pb/^{232}Th$ ages (463–

302    141 Ma). Nevertheless, the U-Pb isotope dataset forms a linear array in the Tera-Wasserburg

303    Concordia diagram, with an upper intercept age of >4.5 Ga and a lower intercept age of 158.6 ± 3.3

304    Ma (MSWD = 3.7), suggesting the discordance is caused by the incorporation of common Pb (e.g.,

305    Schoene, 2004), which affected the more sensitive $^{207}Pb/^{235}U$ ratio (e.g., Budzyń et al. 2022).

306    The source of common Pb may be attributed to the extensive micro-cracks and grain boundaries,

307    which are not easily recognized under the optical microscope but become apparent under high-

308    contrast SEM-BSE imaging. Analytical spots placed within individual monazite grains without

309    visible micro-cracks (e.g., analytical spots 15–21 in section V16-103a, Fig. 6) show younger

310    $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ages than those placed in monazite aggregates with grain boundaries and

311    micro-cracks (e.g., analytical spots 1–14 in section V16-103a, Fig. 6). Common Pb could accumulate

312    in the monazite lattice along the microcracks (e.g., Budzyń et al. 2022). Similar to xenotime,

313    common Pb could also present as nano-scale Pb-bearing minerals, such as altaite or

314    tellurobismuthite, along monazite microcracks and grain boundaries. The abundant mineral

315    inclusions in monazite are less likely to the sources for common Pb, because X-ray mapping shows

316    that the inclusions contain lower Pb concentrations than the surrounding monazite (Fig. A3).

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317     Due to the limited width (i.e., <10 μm) of the altered rim (i.e., secondary monazite) and the

318     chaotic patchy zoning of the partially altered core (i.e., mixture of pristine and secondary monazite),

319     the laser spot size (i.e., 10 μm) does not have the spatial resolution to resolve pristine and secondary

320     monazite. Nevertheless, despite the mixture sampling of pristine and secondary monazite, monazite

321     U–Pb data form a linear array and yield a lower intercept age of 158.6 ± 3.3 Ma (MSWD = 3.7). One

322     possible explanation is that the alteration of monazite occurred shortly after the precipitation of

323     pristine monazite, less than the error of the lower intercept age. Accordingly, these altered (or

324     partially altered) monazite domains with high common Pb could yield geologically reasonable lower

325     intercept ages, which overlap with the ages of pristine monazite within the margin of error. Similar

326     results have been reported from the Sri Lanka monazite (Seydoux-Guillaume et al. 2012) and the

327     Montasset monazite, France (Didier et al. 2013).

328     While monazite and xenotime do occur in contact with each other, monazite ages do not reflect the

329     *ca.* 135 Ma hydrothermal event recorded by xenotime rims formed through coupled dissolution-

330     reprecipitation reactions. One possible explanation is that this hydrothermal event only induced

331     partial dissolution of monazite, but no compositional alteration. This is supported by the fact that

332     monazite contains abundant unhealed micro-cracks with little to no evidence of compositional

333     change along their edges, and shows a more anhedral shape than xenotime.

334     **Compositional alteration of monazite and xenotime**

335     One feature of the studied monazite is Th enrichment in the altered monazite rims. This contrasts

336     with many natural monazite samples, which normally form secondary monazite with lower Th

337     concentrations (e.g., Poitrasson et al. 2000; Rasmussen and Muhling, 2007; 2009; Seydoux-

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338    Guillaume et al. 2012) via dissolution-repreciptation reactions at low temperatures (i.e., ≤400°C).

339    For these natural samples, that decreasing Th content may be attributed to the high Th content in

340    pristine monazite (i.e., >4 wt% $ThO_2$) and limited structural incorporation of Th in secondary

341    monazite at lower temperatures. This is because the substitution of huttonite ($ThSiO_4$) into monazite

342    lattice is temperature-dependent (Hetherington et al. 2010; Seydoux-Guillaume et al. 2012), with

343    higher structural incorporation of Th at higher temperatures and vice versa. Accordingly, monazite

344    alteration experiments conducted at high temperatures (i.e., ≥600°C) form secondary monazite with

345    high Th contents (Seydoux-Guillaume et al. 2002; Hetherington et al. 2010; Harlov et al. 2011),

346    while low-temperature alteration experiments (i.e., ≤600°C) result in secondary monazite with low

347    Th contents (e.g., Williams et al. 2011; Budzyń et al. 2015a; Grand'Homme et al. 2018).

348      In our case, Th enrichment in the altered monazite is likely due to the relative low Th

349    concentrations (<4.5 wt% $ThO_2$, Tables A5, A7, A9). A low concentration of Th is typical for

350    hydrothermal monazite (Schandl and Gorton, 2004), which normally contains <4 wt% of $ThO_2$ (e.g.,

351    Schandl and Gorton, 2004, Catlos et al., 2013; Janots et al. 2012) and is frequently used to date

352    hydrothermal gold deposits (e.g., Rasmussen et al. 2006; Fielding et al. 2017; Zhao et al. 2019; Deng

353    et al. 2020; Liu et al. 2021). However, the mobility of Th during the alteration of hydrothermal

354    monazite has rarely been addressed, partially due to previous studies focused on isotopic dating and a

355    lack of careful examination to recognize potential alteration textures. This study demonstrates that

356    $^{208}Pb/^{232}Th$ ages, commonly overlooked in geochronological studies on hydrothermal monazite,

357    should be presented and discussed due to Th enrichment in the altered monazite.

358      In contrast to monazite, the mechanisms of xenotime alteration are less well-known and

359    understood due to its lower abundance in nature. Several works documented fluid-mediated

360      alteration of xenotime in nature. These studies demonstrate that xenotime may break down into

361      secondary phases such as apatite, epidote, and hingganite (Broska et al. 2005; Hetherington and

362      Harlov, 2008; Majka et al, 2011; Ondrejka et al. 2022). Xenotime could also undergo coupled

363      dissolution-reprecipitation reactions, resulting in compositional alterations that affected the age

364      record (e.g., Hetherington et al. 2008; Rasmussen et al. 2011; Fielding et al. 2017; Budzyń et al.

365      2018), but the fluids inducing the dissolution-reprecipitation reactions are not well characterized,

366      partially due to the lack of co-existing fluid inclusions. Experimental studies on xenotime alterations

367      focused on alkali-rich aqueous fluid conditions (e.g., Hetherington et al. 2010; Harlov and Wirth,

368      2012; Budzyń et al. 2015b, 2017; Budzyń and Sláma, 2019). Hetherington et al. (2010) reported

369      partial dissolution of xenotime in acid and brine fluids, but no compositional alteration. The recent

370      experimental work of Budzyń and Sláma (2019) confirms that xenotime may be affected by re-

371      equilibration induced by alkali-rich aqueous fluid via coupled dissolution-reprecipitation reactions

372      under temperature conditions of 550–650 °C, resulting in U–Pb age disturbance.

373      While it's widely accepted that $CO_2$ can promote the solubility of REE since $CO_3^{2-}$ forms strong

374      complexes with the REE (e.g., Wood, 1990; Williams-Jones et al. 2000; Hetherington et al. 2010;

375      Zhou et al. 2016), the role of $CO_2$ in xenotime alterations has been rarely addressed. This study

376      presents an example of xenotime compositional alteration and resetting of U–Pb ages caused by

377      coupled dissolution-reprecipitation reactions, which are induced by low to moderate salinity

378      carbono-aqueous fluids at low temperatures (i.e., <400°C). Since these fluids are commonly involved

379      in the formation of lode gold deposits (e.g., Groves et al. 1998; Goldfarb et al. 2005), it's crucial to

380      examine xenotime textures and recognize potential alteration textures before carrying out isotopic

381      dating of xenotime collected from these deposits.

### Two discrete gold mineralization events

The *ca.* 135 Ma hydrothermal event (Fig. 10), recorded by the altered rim of xenotime with a weighted mean $^{206}Pb/^{238}U$ age of 135.46 ± 0.93 Ma, is responsible for the deposition of native gold and stage III tellurides (i.e., petzite, calaverite, altaite, tellurobismuthite) because these minerals occur in contact with or as inclusions in xenotime rims (Figs. 4C–I). While abundant Early Cretaceous ages (144–120 Ma, Fig. 10 and Table A10) have been reported from the Xiaoqinling gold district, minerals directly in contact with gold have only been recently dated (i.e., a monazite U-Pb age of 127.5 ± 0.7 and a rutile U-Pb age of 129.7 ± 4.3 Ma: Liu et al. 2021). The paragenetic relationship between dated minerals and gold is unclear in many previous studies. For instance, dated minerals in gold-bearing quartz veins or altered wall rocks do not necessarily result from the same hydrothermal event responsible for gold deposition. This study presents robust textural and geochronological evidence to justify a *ca.* 135 Ma gold mineralization event in the Xiaoqinling gold district.

The *ca.* 157 Ma hydrothermal event, recorded by xenotime cores with a weighted mean $^{206}Pb/^{238}U$ age of 157.11 ± 0.83 Ma and monazite with a Tera-Wasserburg lower intercept age of 158.6 ± 3.3 Ma, is responsible for the earlier gold mineralization (i.e., lingbaoite-sylvanite-stützite/native tellurium-sylvanite-stützite), since xenotime, monazite, and stage II tellurides were all observed as primary inclusions in pyrite (Figs. 3, 4). The stage II tellurides, although they now appear much less abundant than stage III tellurides and gold, are merely remnants of the stage II gold mineralization (i.e., gold in the form of sylvanite ($[Au,Ag]_2Te_4$) after having been reworked by the later fluid event. The early-stage gold mineralization could have played an important role in the later gold enrichment process. For instance, recent studies (Jian et al. 2021, 2022b) reveal that stage II tellurides are

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404     primary melt inclusions trapped as polymetallic droplets that scavenged gold from aqueous fluids

405     with high efficiency. During later hydrothermal events, polymetallic melt inclusions could be

406     released from the host mineral and continue to scavenge gold from fluids, due to fracturing of the

407     host mineral or migration of the melt inclusions to the crystal surface. Aside from S16 gold-bearing

408     quartz vein, the characteristic lingbaoite-sylvanite-bearing mineral assemblage, and by analogy, the

409     earlier gold mineralization event has also been observed in other parts of the Xiaoqinling gold

410     district, such as the S60 gold-bearing quartz vein (Jian et al. 2020, 2021, 2022b) and the Jinqu gold

411     deposit (Chang et al. 2020). Our study, therefore, reveals a previously overlooked yet important Late

412     Jurassic gold mineralization event in the Xiaoqinling gold district.

413     Late Jurassic ages have been only reported from the Luzhougou gold deposit (two Re-Os

414     molybdenite model ages of $149 \pm 8.4$ Ma and $154 \pm 1.1$ Ma: Li et al. 2012a) in the Xiaoqinling gold

415     district. The lack of reported Late Jurassic ages likely results from the scarcity of geochronometers

416     that are able to preserve the Late Jurassic age information after the Early Cretaceous hydrothermal

417     overprint. Most of the Early Cretaceous ages in the Xiaoqinling gold district were obtained from

418     $^{40}Ar/^{39}Ar$ dating of micas, with a few Re-Os molybdenite and U-Pb monazite ages (Fig. 10 and Table

419     A10). The low $^{40}Ar/^{39}Ar$ closure temperatures of micas (e.g., ~300°C for biotite and ~400°C for

420     muscovite: Harrison et al. 1985, 2009; Schaen et al. 2021), suggest their isotopic system could be

421     easily reset during later hydrothermal events. For instance, our study reveals that the *ca.* 135 Ma gold

422     mineralization event is characterized by the mineral assemblage of native gold-calaverite-petzite-

423     tellurobismuthite, which coexists with low to moderate salinity $H_2O$-$CO_2$ fluid inclusions along

424     healed fractures in quartz (Figs. 3I–K). The total homogenization temperatures of these fluid

425     inclusions cluster at 200 to 400°C, a range that overlaps with the $^{40}Ar/^{39}Ar$ closure temperatures of

426    biotite and muscovite.

427    To the east of the Xiaoqinling gold district, abundant Late Jurassic ages have been reported in the

428    adjacent Xiong'ershan region. Examples include the Wuzhangshan monzogranite pluton (SHRIMP

429    zircon U–Pb age of 157 ± 1 Ma: Mao et al. 2010), granitic porphyries in the Shangfanggou Mo

430    deposit (SHRIMP zircon U–Pb age of 158 ± 3 Ma, Mao et al. 2010), Nannihu Mo deposit (SHRIMP

431    zircon U–Pb age of 157 ± 3 Ma, Mao et al. 2010), Balipo Mo deposit (LA-ICP-MS zircon U–Pb age

432    of 155.9 ± 2.3 Ma, Jiao et al. 2009), Qiyugou Au deposit (SIMS zircon U-Pb ages of 157.3 ± 1.1 and

433    158.7 ± 1.2 Ma, Wang et al. 2020), a Mo (Au?) mineralized vein in the Huaixiangwa Au deposit (Re-

434    Os molybdenite mean age of 155.0 ± 2.2 Ma, Gao et al. 2018), and a Au mineralized vein in the

435    Luanling Au deposit (Re-Os molybdenite isochron age of 163 ± 2 Ma, Chao et al. 2019).

436    Accordingly, the large-scale Jurassic magmatism and associated mineralization event in eastern

437    China (e.g., Mao et al. 2021a, b; Goldfarb et al. 2021), in relation to the subduction of the paleo–

438    Pacific plate beneath the eastern China continent (Mao et al. 2021a), might have also caused

439    widespread gold mineralization in the Xiaoqinling gold district.


440                                                           IMPLICATIONS


441    This study presents an example of xenotime compositional alteration and resetting of U–Pb ages

442    caused by coupled dissolution-reprecipitation reactions, which are induced by low to moderate

443    salinity carbono-aqueous fluids at low temperatures. Gold minerals in contact with such composite

444    xenotime crystals could precipitate before, coeval with, or after the dated domains, depending on the

445    relation between the gold minerals and the dated xenotime domains. Since low to moderate salinity

446    carbono-aqueous fluids are commonly involved in the formation of lode gold deposits, it's crucial to

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447 examine xenotime textures and recognize potential alteration textures before carrying out isotopic

448 dating of xenotime collected from these deposits. Without prior compositional and textural

449 characterization, attempts to date such composite crystals could yield mixed age information and

450 meaningless ages.

451 This study also demonstrates that monazite and xenotime could be affected by low-temperature

452 hydrothermal alteration and yield discordant ages, resulting from incomplete replacement of mineral

453 domains or incorporation of common Pb. Common Pb could accumulate in the monazite and

454 xenotime along microcracks and grain boundaries. These features may be identified under high-

455 contrast SEM-BSE images but are not always visible in reflected-light photomicrographs or CL

456 images. During the alteration of hydrothermal monazite that typically contains low Th

457 concentrations, Th may be enriched in secondary monazite through coupled dissolution-

458 reprecipitation reactions. Accordingly, $^{208}Pb/^{232}Th$ ages, sometimes neglected in geochronological

459 studies on hydrothermal monazite from ore deposits, should be presented and discussed. This study

460 also highlights the potential of utilizing highly discordant U-Pb age data, which can be discarded in

461 geochronology studies but could potentially be used to constrain the age of metasomatic events as

462 the lower intercept in the Tera-Wasserburg Concordia diagrams.

463        **ACKNOWLEDGMENTS**

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793                                    **FIGURE CAPTIONS**


794    Fig. 1. Geologic map of the Xiaoqinling gold district and its position in China (compiled from Jian et

795    al. 2015, 2021; Liu et al. 2021).

796

797    Fig. 2. Typical features of the S16 gold-bearing quartz vein shown by photographs. A. B.

798    Underground exposure. C. Hand specimen. D. Polished thick section showing the occurrences of

799    pyrite (euhedral large crystals), tellurides (black cloudy aggregates), and xenotime (very fine-grained

800    red cloudy aggregates).

801

802    Fig. 3. Two stages of gold mineralization shown by photomicrographs (A–I: plane-polarized

803    reflected light, J: reflected-transmitted light image created through focus stacking, K: reflected-

804    transmitted light). A–H. Distribution of two stages (II, III) of minerals within and near two pyrite

805    grains. I. Native gold and tellurides (stage III) occur as inclusions along a healed microfracture in

806    quartz. J–K. Native gold and telluride (stage III) coexist with low to moderate salinity $H_2O$-$CO_2$ fluid

807    inclusions along healed microfractures in quartz. Abbreviations: Alt = altaite, Au = gold, Bn =

808    bornite, Clv = calaverite, Ccp = chalcopyrite, Gn = galena, Lb = lingbaoite, Ptz = petzite, Py =

809    pyrite, Qz = quartz, Stz = stützite, Syv = sylvanite, Tbi = tellurobismuthite, Te = native tellurium.

810

811    Fig. 4. Occurrence of xenotime and monazite shown by photomicrographs (D, F, H: plane-polarized

812    reflected light), BSE images (A–C, E, G), and CL image (I). A–C. Xenotime and monazite occur as

813    inclusions in pyrite. D–G. Native gold and tellurides (stage III) occur in contact with xenotime. The

814    two xenotime grains were dated by LA-ICP-MS. Their CL images with analyzed spots and ages

815    labeled are shown in Fig.5. G. Xenotime rims are brighter than core zones in BSE images. H–I.

816    Native gold and tellurides (stage III) occur in contact with the rim of a xenotime grain or as

817    inclusions in the altered domains of the xenotime. Note that altered domains of xenotime are brighter

818     in CL image, while the unaltered domains are darker and show oscillatory zoning. Abbreviations: Alt

819     = altaite, Au = gold, Clv = calaverite, Mnz = monazite, Ptz = petzite, Py = pyrite, Qz = quartz, Xtm =

820     xenotime.

821

822     Fig. 5. Cathodoluminescence images of xenotime grains after LA-ICP-MS analysis. The 10 μm and

823     16 μm laser pits are for U-Th-Pb isotope and trace element analysis, respectively. SEM-BSE images

824     of the 10 xenotime grains before LA-ICP-MS analysis are shown in Figure A1. WDS X-ray maps (Y,

825     U, Th, Pb) of 6 xenotime grains before LA-ICP-MS analysis are shown in Figure A2.

826

827     Fig. 6. SEM-BSE images of monazite grains after LA-ICP-MS analysis. $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and

828     $^{208}Pb/^{232}Th$ ages of the analyzed spots are indicated.

829

830     Fig. 7. REE patterns of the xenotime and monazite. The data are normalized to C1 chondrite

831     composition as compiled in Sun and McDonough (1989).

832

833     Fig. 8. Tera-Wasserburg Concordia diagrams and weighted mean age diagrams for xenotime and

834     monazite.

835

836     Fig. 9. Two episodes of gold mineralization and growth of monazite and xenotime illustrated by

837     schematic drawing.

838

839    Fig. 10. Age distribution of gold deposits from the Xiaoqinling gold district. The age data, detailed in

840    the Appendix (Table A10), were compiled from Xu et al. (1998), Wang et al. (2002), Li et al. (2012a,

841    b), Qiang, 2012, Qiang et al. 2013, Zhao et al. (2019), and Liu et al. (2021).

842

843                                              **APPENDIX**

844    Fig. A1. SEM-BSE images of the 10 xenotime grains before LA-ICP-MS analysis.

845

846    Fig. A2. WDS X-ray maps of 6 xenotime grains before LA-ICP-MS analysis.

847

848    Fig. A3. Characterizations of the largest monazite grain before LA-ICP-MS analysis shown by BSE

849    image (A), photomicrographs (B: plane-polarized reflected light; C: plane-polarized reflected light

850    with gamma enhancement), and WDS X-ray maps (D–H).

851

852    Table A1. Analytical conditions of EPMA measurements of xenotime and monazite

853

854    Table A2. Analytical conditions of LA-ICP-MS U-Th-Pb analysis of xenotime and monazite

855

856    Table A3. Analytical conditions of LA-ICP-MS trace element analysis of xenotime

857

858    Table A4. Analytical conditions of LA-ICP-MS trace element analysis of monazite

859

860    Table A5. Electron microprobe data of xenotime and monazite

861

862    Table A6. LA-ICP-MS trace element data of xenotime

863

864    Table A7. LA-ICP-MS trace element data of monazite

865

866    Table A8. LA-ICP-MS U-Th-Pb data of xenotime

867

868    Table A9. LA-ICP-MS U-Th-Pb data of monazite

869

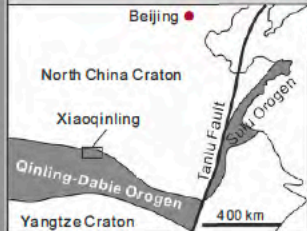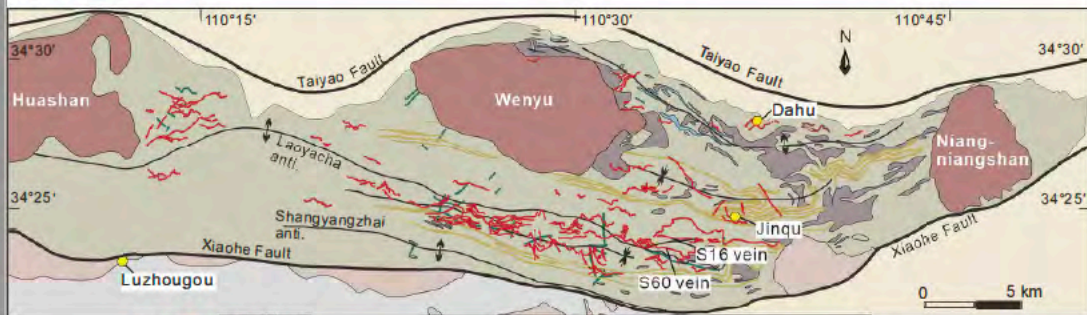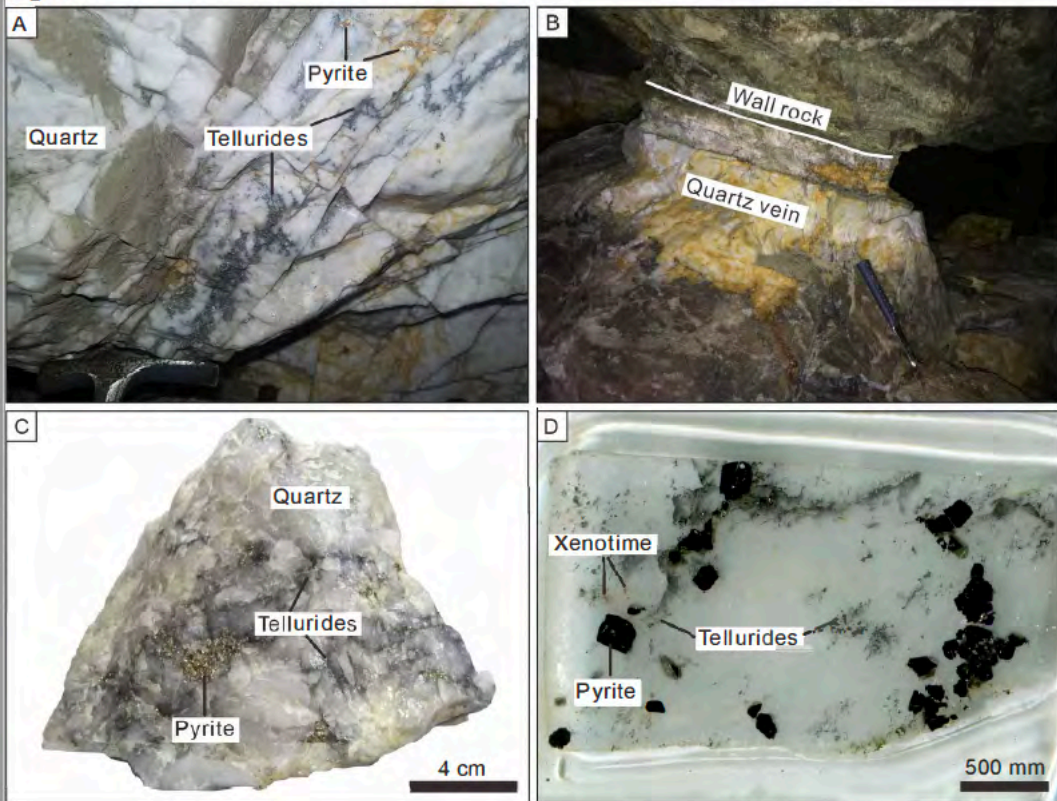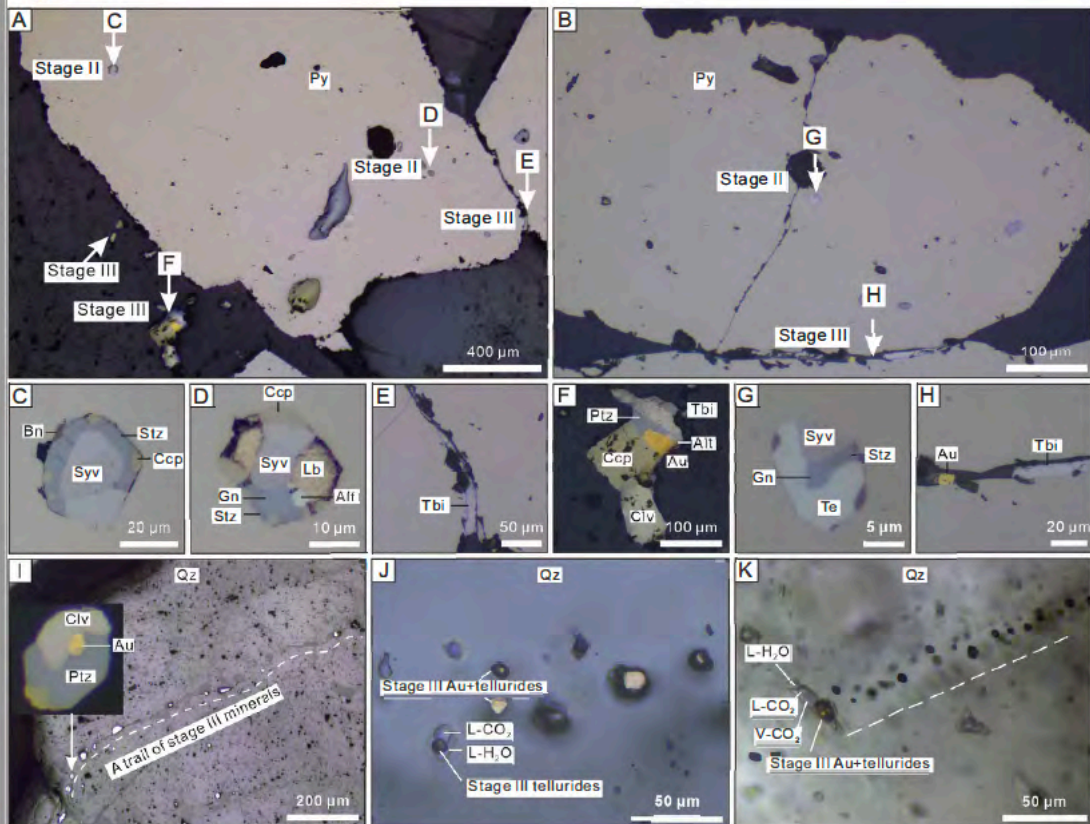870    Table A10. Age data of gold deposits from the Xiaoqinling gold district

871

Fig. 1

Legend:
- Neogene sediments
- Mesoproterozoic clastic rock and carbonate
- Neoarchean amphibolite and biotite plagiogneiss
- Neoarchean quartzite
- Neoarchean marble
- Mesozoic granite
- Paleo-Mesoproterozoic granite
- Paleoproterozoic granite pegmatite
- Mafic dike
- Syncline
- Fault
- Gold-bearing quartz vein
- Gold deposit
- Anticline

Map labels: Huashan, Wenyu, Dahu, Niangniangshan, Taiyao Fault, Laoyacha anti., Shangyangzhai anti., Xiaohe Fault, Luzhougou, Jinqu, S16 vein, S60 vein

Inset: Beijing, North China Craton, Xiaoqinling, Qinling-Dabie Orogen, Yangtze Craton, Tanlu Fault, Sulu Orogen, 400 km

**Fig. 2**

A — Quartz, Pyrite, Tellurides

B — Wall rock, Quartz vein

C — Quartz, Tellurides, Pyrite (scale 4 cm)

D — Xenotime, Tellurides, Pyrite (scale 500 mm)

Fig. 3

Fig. 4

**Fig. 5**

**Fig. 6**



## Section V16-103A

$^{208}Pb/^{232}Th$ age (Ma) ⟶ 187 ± 7
$^{206}Pb/^{238}U$ age (Ma) ⟶ 277 ± 11
$^{207}Pb/^{235}U$ age (Ma) ⟶ 1286 ± 29
Analytical number for Th-U-Pb isotopes

176 ± 6   180 ± 7
251 ± 10   269 ± 11
1104 ± 26   1181 ± 30

E23

Analytical number for EPMA

E28

200 ± 7
338 ± 13
1572 ± 31

1   2   3   4   5

375 ± 12
741 ± 26
2615 ± 35

167 ± 6
171 ± 7
364 ± 14

E25   E24

13   14   7

430 ± 14
968 ± 34
2935 ± 36

188 ± 6
240 ± 9
1040 ± 25

E18   E21

250 ± 8
486 ± 18
2072 ±33

12   E15   E16   E19   8   E22

159 ± 5
183 ± 7
486 ± 16

9

E17   11   10   E20

260 ± 10
379 ± 15
1734 ±33

261 ± 9
460 ± 17
1979 ± 33

193 ± 6
342 ± 13
1557 ± 31

19   20

141 ± 5
179 ± 8
349 ± 19

E27

163 ± 6
178 ± 7
280 ± 14

21   E26

163 ± 5
191 ± 7
520 ± 18

15

158 ± 6
178 ± 7
474 ± 18

16

166 ± 6
218 ± 8
907 ± 24

17

179 ± 6
233 ± 9
977 ± 24

18

171 ± 6
200 ± 8
769 ± 22

## Section V16-76

169 ± 6
161 ± 6
208 ± 8

8   9

196 ± 6
226 ± 9
959 ± 23

158 ± 5
174 ± 7
493 ± 15

7   10

1

171 ± 6
177 ± 7
287 ± 11

169 ± 6
181 ± 7
477 ± 14

6   11

2

314 ± 10
681 ± 24
2494 ± 34

325 ± 10
657 ± 24
2445 ±34

5   12

3   4

288 ± 10
519 ± 20
2169 ± 33

177 ± 6
230 ± 9
990 ± 24

389 ± 13
750 ± 27
2593 ± 34

190 ± 6
246 ± 10
1083 ± 25

13

463 ± 15
1897 ± 61
3730 ± 36

14

16

136 ± 4
189 ± 8
813 ± 22

20   19   18

230 ± 8
930 ± 34
2857 ± 35

15

17

302 ± 10
667 ± 23
2467 ± 34

168 ± 5
209 ± 8
707 ± 19

177 ± 6
219 ± 8
799 ± 20

197 ± 6
301 ± 11
1416 ± 28

50 μm

**Fig. 7**

**Fig. 8**

**Fig. 9**



*ca.* 157 Ma
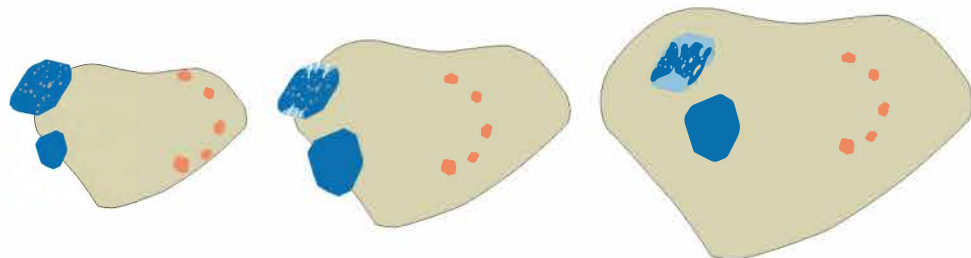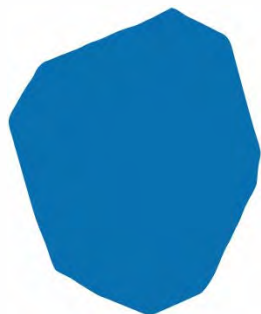
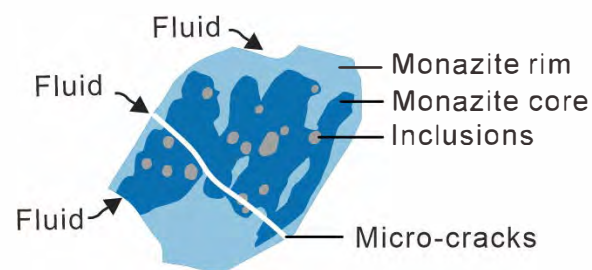Growth of pristine monazite  Dissolution–reprecipitation of monazite
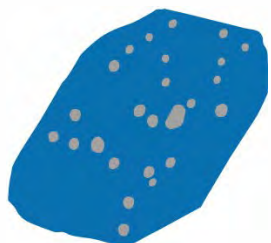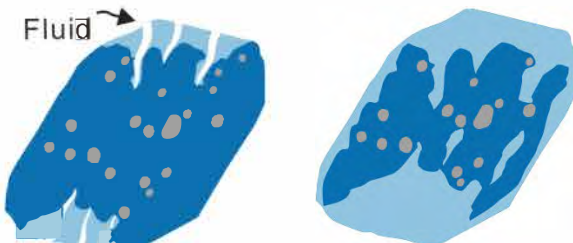
Growth of pristine xenotime
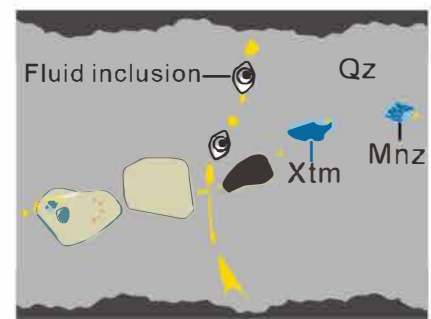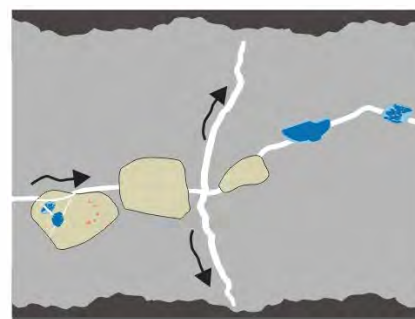
*ca.* 135 Ma

Dissolution of monazite

Fluid
Fluid
Fluid
Monazite rim
Monazite core
Inclusions
Micro-cracks

Dissolution–reprecipitation of xenotime

Fluid
Xenotime rim
Xenotime core
Fluid
Stage III Au minerals
Stage II Au minerals
Py

Fluid inclusion
Qz
Xtm
Mnz

Fig. 10