Two discrete gold mineralization events recorded by hydrothermal xenotime and monazite, Xiaoqinling gold district, central China

Wei Jian*, Jingwen Mao, Bernd Lehmann, Shiou Wu, Lei Chen, Shiwei Song, Jiandong Xu, Peng Wang, and Junchen Liu

1 MNR Key Laboratory for Exploration Theory & Technology of Critical Mineral Resources, School of Earth Sciences and Resources, China University of Geosciences (Beijing), Xueyuan Road 29, Beijing, 100083, China

2 Mineral Resources, Technische Universität Clausthal, Adolph-Roemer-Strasse 2A, Clausthal-Zellerfeld 38678, Germany

3 State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beitucheng Road 19, Beijing, 100029, China

4 State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, Ningda Road 251, Xining, 810016, China

5 School of Earth Sciences and Spatial Information Engineering, Hunan University of Science and Technology, Xiangtan 411201, China

*E-mail: weijian851@gmail.com
We present in situ LA-ICP-MS U-Pb dating of xenotime and monazite in assemblages with native gold and Au (Ag) tellurides from the Xiaoqinling lode gold district in central China. Composite xenotime and monazite grains formed through coupled dissolution–reprecipitation reactions reveal two discrete gold mineralization events. The first gold mineralization event, recorded by monazite (158.6 ± 3.3 Ma, Tera-Wasserburg lower intercept age) and xenotime cores (157.11 ± 0.83 Ma, weighted mean 206Pb/238U age), is characterized by the mineral assemblage of lingbaoite (AgTe3)-sylvanite ([Au,Ag]2Te4)-stützite (Ag5−xTe3)/native tellurium-sylvanite-stützite. The second gold mineralization event, recorded in the rims of xenotime (135.46 ± 0.93 Ma, weighted mean 206Pb/238U age), is characterized by the mineral assemblage of native gold-calaverite (AuTe2)-petzite (AuAg3Te2)-tellurobismuthite (Bi2Te3). Our study implies that the large-scale Jurassic mineralization event in eastern China, related to flat subduction of the paleo–Pacific plate beneath the eastern China continent, also caused widespread gold mineralization in the Qinling–Dabie Orogen, in addition to production of its world-class porphyry Mo deposits. The fact that only a few Jurassic gold mineralization ages have been reported before, may be due to the lack of suitable geochronometers to record the earlier Jurassic hydrothermal processes, which have been overprinted by the better-recognized Early Cretaceous gold mineralization event. This study also presents a rare example of xenotime compositional alterations and resetting of U–Pb ages induced by low to moderate salinity carbono-aqueous fluids at low temperatures. The textural relationships between gold minerals in contact with such composite xenotime crystals demonstrate that they could have precipitated before, coeval with, or after the dated domains. Since low to moderate salinity carbono-aqueous fluids are...
commonly involved in the formation of lode gold deposits, it’s crucial to examine xenotime textures and recognize potential alteration textures before carrying out isotopic dating of xenotime collected from these deposits. Without prior compositional and textural characterization, attempts to date such composite crystals could yield mixed dates and meaningless ages.

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

**INTRODUCTION**

The formation of lode gold deposits commonly involves multiple hydrothermal stages or events (e.g., Arne et al. 2001; Essarraj et al. 2001; Bateman and Hagemann, 2004; Meffre et al. 2016; Fougerouse et al. 2017). The episodic nature of hydrothermal systems may be identified by well-developed superimposed textures, such as breccias, ribbons, and a cross-cutting network of veinlets (e.g., Dowling and Morrison, 1989; Goldfarb et al. 2005; Voisey et al. 2020; Jian et al. 2021). However, it is challenging to determine whether vein systems result from the gradual cooling of a single hydrothermal fluid or multiple hydrothermal events that occur millions of years apart. It is especially difficult to accurately determine the timing of each individual hydrothermal event and the timing of gold deposition. The difficulties mainly arise from the scarcity of suitable dating minerals/mineral domains directly related to gold precipitation that remain closed to isotope re-equilibration during subsequent hydrothermal events.

Monazite and xenotime are robust geochronometers that have low rates of Pb diffusion and low susceptibility to Pb loss at high temperatures, with Pb closure temperatures of 890°C for xenotime and 940°C for monazite (for a 10 μm grain with a cooling rate of 10°C/Ma: Cherniak et al. 2004; Cherniak, 2006). However, the two minerals undergo coupled dissolution–reprecipitation reactions at
temperatures <400°C (Townsend et al. 2000; Rasmussen and Muhling, 2007; Budzyń et al. 2015a,b), leading to crystals that may have multiple, but discrete, age domains from which precise dates for multiple hydrothermal events may be obtained (e.g., Fielding et al. 2017; Budzyń et al. 2018). Although many lode gold deposits contain trace amounts of hydrothermal monazite or xenotime, the size of most hydrothermal xenotime grains is typically <10 μm, and combined with its low abundance make it difficult to find suitable crystals from which complex, multi-stage hydrothermal histories may be reconstructed (e.g., McNaughton and Rasmussen, 2018).

This study presents detailed in situ LA-ICP-MS U-Pb dating of xenotime and monazite in assemblages with native gold and Au (Ag) tellurides from the Xiaoqinling lode gold district, central China. Composite xenotime and monazite crystals formed through coupled dissolution–reprecipitation reactions reveal two discrete gold mineralization events, with an early Cretaceous gold mineralization event preceded by a previously overlooked middle Jurassic gold mineralization event.

GEOLOGICAL SETTING

Marginal parts of the North China Craton host hundreds of lode gold deposits of mainly Early Cretaceous age (Mao et al. 2005; Li et al. 2012a; Deng et al. 2016), with a total gold resource exceeding 3,600 tonnes Au (Li et al. 2012a; Deng et al. 2016). The Xiaoqinling gold district in the southern margin of the North China Craton represents the second-largest gold production area in China, with a proven gold reserve of more than 630 tonnes (Jian et al. 2015, 2022a).
Mesozoic tectonomagmatic evolution of the Qinling-Dabie orogen

The Xiaoqinling district is located at the southern margin of the North China craton and belongs to the Qinling-Dabie orogen (Fig. 1). The WNW-trending Qinling-Dabie orogen delineates the boundary between the North China craton and the Yangtze craton. This orogenic belt resulted from multistage collisional events between the North China craton and the Yangtze craton; the final collision between the two cratons occurred in the Triassic (Dong and Santosh, 2016). During the Late Triassic, the Qinling-Dabie orogen evolved into a post-collisional extensional domain, which is indicated by the emplacement of post-collisional intrusions, including alkaline intrusions (Wang et al. 2007; Li et al. 2012a; Cao et al. 2015), carbonatites (Xu et al. 2010; Du et al. 2020; Zheng et al. 2020; Tang et al. 2021), and rapakivi-textured granitoids (Wang et al. 2011).

Since the Jurassic, eastern China, including the eastern part of the Qinling-Dabie orogen, became a part of the circum-Pacific tectonic regime, with the subduction of the Izanagi plate (or paleo-Pacific plate) beneath the Eurasian continental margin (Mao et al. 2021a). The subduction began with a steep angle but changed to a flat angle in the Middle-Late Jurassic (Wu et al. 2019; Mao et al. 2021a). Since the Early Cretaceous, eastern China evolved into an extensional setting (Mao et al. 2021a) due to lithospheric thinning driven by the rollback of the paleo-Pacific plate (Wu et al. 2019; Ma et al. 2021). The flat subduction and subsequent rollback of the paleo-Pacific plate gave rise to widespread magmatism and ore formation, making the Late Mesozoic the most important magmatic and metallogenic period in eastern China.

Geology of the Xiaoqinling gold district

The strata exposed in the Xiaoqinling gold district are dominated by Archean amphibolite-facies
metamorphic rocks of the Taihua Group (Fig. 1), which consists of biotite plagiogneiss, amphibolite
gneiss, amphibolite, quartzite, and marble (Cai and Su, 1985). These rocks probably formed in the
Neoarchean and have been subjected to amphibolite-facies metamorphism in the Paleoproterozoic
(Zhou et al. 1998; Ni et al. 2003; Li et al. 2007). The Archean rocks were intruded by
Paleoproterozoic pegmatite/granite (Li et al. 1996; Li et al. 2007), Proterozoic and Mesozoic granitic
intrusions (Wang et al. 2010; Hu et al. 2012; Li et al. 2012), and Paleoproterozoic and Early
Cretaceous mafic dikes (Wang et al. 2008; Bi et al. 2011). Jurassic magmatism, although widespread
in eastern China, has rarely been reported in the Xiaoqinling gold district. The Huashan granite
complex has a zircon age of 146 ± 2 Ma (Mao et al. 2010). Several Jurassic porphyritic stocks,
however, have been reported from the Xiong’ershan gold district, about 100 km east of the
Xiaoqinling district, and in a similar geologic setting (e.g., Niutougou, Miaoling, and Qiyugou gold
deposits: Wang et al. 2012; Li et al. 2014; Wang et al. 2020). However, these Jurassic porphyries do
not appear to be directly related to gold mineralization since they all postdate gold mineralization
(Wang et al. 2020). At the Qiyugou Au deposit, for instance, the quartz porphyries were emplaced at
158.6 ± 1.1 to 157.3 ± 1.1 Ma (LA-ICP-MS zircon U–Pb age), while gold mineralization occurred at
132.9 ± 1.5 Ma (molybdenite Re-Os age of gold ore samples) and is genetically related to the 130.9
± 1.9 Ma hornblende monzogranite (LA-ICP-MS zircon U–Pb age).

Early Cretaceous plutons are widely exposed across the gold district. These are, from east to west,
the Niangniangshan biotite monzogranite (142 ± 3 to 129 ± 2 Ma: Wang et al. 2010; Li et al. 2012b),
the Wenyu biotite monzogranite (141 ± 2 to 136 ± 3 Ma: Wang et al. 2010; Li et al. 2012b), and the
outer phase of the Huashan granite complex (132 ± 1 Ma: Hu et al. 2012).

The nearly E-W–striking Taiyao and Xiaohe faults define the northern and southern boundaries of
the Xiaoqinling gold district. The two normal faults developed during the Cenozoic extension, resulting in the exposure of the basement rocks (Li et al. 2020). The more than 1,200 gold-bearing quartz veins concentrate along the axes of several EW-striking steep folds and are controlled by small- to medium-size EW-striking faults. The S16 gold-bearing quartz vein, from which the studied ore samples were collocated, is about 30 km southwest of Lingbao city, Henan province, central China. The S16 gold-bearing quartz vein, from which the studied ore samples were collocated, is a newly discovered concealed vein with an average gold grade of ~6 g/t. It is 0.1 to 2.5 m wide and extends about 1.5 km in a roughly east-west direction, dipping to the south (Fig. 1). The S16 gold-bearing quartz vein is about 30 km southwest of Lingbao city, Henan province, central China, and belongs to the south ore belt of the Xiaoqinling gold district. The south ore belt hosts most of the gold-bearing quartz veins, which concentrate along the Laoyacha anticline (Fig. 1).

**SAMPLE MATERIAL AND METHODS**

**Sample selection**

The studied ore samples were collected underground from the S16 gold-bearing quartz vein. The ore samples for geochronological study consist mainly of quartz and pyrite (Fig. 2). Other minerals present in small or trace amounts include xenotime, monazite, scheelite, celestine, gold, native tellurium, muscovite, as well as a variety of sulfides (e.g., chalcopyrite, bornite, sphalerite, and galena) and tellurides (e.g., sylvanite, petzite, calaverite, stützite, hessite, altaite, rucklidgeite, and 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.

RESULTS

Vein mineralogy and paragenesis

At least three hydrothermal stages, including two gold-mineralization stages, are recognized in the
studied ore samples (Figs. 2, 3, 4). The first hydrothermal stage (I) is characterized by the precipitation of milky white quartz, which makes up more than 90% of the vein volume. The second stage (II) is characterized by the growth of pyrite, scheelite, xenotime, monazite, and celestine on fracture planes in quartz (Fig. 2). Pyrite contains composite mineral inclusions (<1–50 μm in diameter) consisting mainly of lingbaoite (a recently named mineral with the chemical formula of AgTe₃, Jian et al. 2020), sylvanite [(Au,Ag)₂Te₄], stützite [Ag₅₋ₓTe₃], native tellurium, and chalcopyrite, with minor bornite, galena, and altaite (Figs. 3A–G). These inclusions outline the primary growth zones in pyrite and generally display a negative crystal shape. They were interpreted as primary melt inclusions, which were trapped as polymetallic melt droplets during the growth of the host pyrite (Jian et al. 2021, 2022b). The third stage (III) is the main gold deposition stage. This stage is characterized by native gold and tellurides (petzite [AuAg₃Te₂], calaverite [AuTe₂], tellurobismuthite [Bi₂Te₃], altaite [PbTe], and rucklidgeite [PbBi₂Te₄]) as inclusions or fracture fillings in early minerals (e.g., quartz, pyrite, and scheelite, Figs. 2–4). The stage III gold-bearing mineral assemblages (e.g., native gold-calaverite-petzite-tellurobismuthite) commonly coexist with low to moderate salinity H₂O-CO₂ fluid inclusions along healed fractures in quartz (Figs. 3I–K). The total homogenization temperatures of these fluid inclusions have been investigated from many gold-quartz veins in the Xiaoqinling gold district and cluster at 200 to 400°C (Fan et al. 2003; Li et al. 2012b; Xiong et al. 2013). The cross-cutting relation between stage II and stage III gold-bearing minerals is illustrated in Figures 3A–B, in which stage II tellurides occur as inclusions in pyrite while stage III gold and tellurobismuthite occur along quartz grain boundaries.
Characterization of xenotime and monazite

Xenotime and monazite crystals occur as inclusions in pyrite and scheelite, or along quartz fractures (Figs. 2D, 4). Individual xenotime and monazite crystals are typically 10–80 μm in diameter (Figs. 4–6), but large crystals (up to 350 μm in diameter, Figs. 4H, I) have also been observed. The two minerals most commonly occur in contact with each other, and monazite has also been observed as inclusions in xenotime. Cathodoluminescence (CL) imaging of xenotime reveals that xenotime crystals have a dark, pristine core surrounded by bright altered domains, which developed near grain rims or healed microfractures (Figs. 4I, 5). There is a sharp reaction front between altered and pristine xenotime domains (Figs. 4D–I, 5). The xenotime cores display distinct oscillatory zoning truncated at the boundary with the altered domains (Fig. 5). There is an epistatic relationship between altered and pristine xenotime domains. For example, examination of the xenotime crystals using polarized light shows that altered and pristine xenotime domains in each grain are optically continuous (Figs. 4D, F, H). Altered xenotime also preserves the external dimension of pristine xenotime. These textural features suggest that the altered xenotime domains in our sample set formed through coupled dissolution-reprecipitation reactions (e.g., Putnis, 2002, 2009). Native gold and stage III tellurides have been observed as inclusions in the altered domains of xenotime, or occur in contact with the altered domains (Figs. 4D–I).

Xenotime cores and rims show distinct major and trace element features (Tables A5, 6, Fig. A2). EPMA analysis shows cores contain higher and more consistent Y concentrations (0.91–0.92 apfu, atoms per formula unit on the basis of 4 oxygens) whereas Y concentrations in the altered rims vary from 0.81 to 0.92 apfu. LA-ICP-MS trace element analysis reveals xenotime cores contain 1.4–4.1 wt% LREE (La to Eu), 9.0–13.0 wt% HREE (Gd to Lu), 1000–2600 ppm Si, 730–4600 ppm Ca,
12–19 ppm Rb, 5–19 ppm Sr, 29–220 ppm Zr, 240–620 ppm Pb, 1000–5800 ppm Th, and 1900–
5900 ppm U, while xenotime rims have higher concentrations of HREE (12.4–19.5 wt%), Si (0.1–2.1
wt%), and Rb (25–37 ppm), and lower concentrations of LREE (0.7–1.2 wt%), Zr (10–106 ppm), Pb
(84–256 ppm), Th (500–1900 ppm), and U (800–2400 ppm). In the chondrite-normalized REE
pattern (Fig. 7), neither the cores nor rims have an Eu anomaly. This differs from igneous xenotime,
which is commonly characterized by a pronounced negative Eu anomaly (e.g., Rasmussen, 2005;
Aleinikoff et al. 2015).

While xenotime crystals may show well-formed crystal faces, monazite occurs as subhedral-
anhedral grains, which form larger aggregates with irregular outlines (Fig. 6). Occasionally, elongate
monazite grains grow as radial, flower-shaped assemblages (Figs. 6, A3). Monazite shows a faint
core-rim texture under high-contrast SEM-BSE imaging (Fig. 6). The core has a heterogeneous
texture with chaotic, patchy zoning, and contains a dense population of mineral inclusions (≤10 μm,
mainly iron oxides) and smaller fluid inclusions. The rim is relatively homogenous and inclusion-
free, with faint patchy zoning. Like xenotime, the monazite rim may preserve the external dimension
of pristine monazite (e.g., the top right monazite grain in Fig. 6), suggesting the altered rim formed
through coupled dissolution-reprecipitation reactions. The heterogeneous core represents a mixture
of pristine and secondary monazite.

EPMA WDS analysis (Table A5) and X-ray mapping reveal that monazite rims contain 0.01–0.08
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–
0.15 apfu Nd, while the partially altered cores have lower concentrations of Si (0.01–0.06 apfu), Th
(0.005–0.007 apfu), and La (0.21–0.23 apfu), and higher concentrations of Nd (0.15–0.16 apfu).
Other elements show little systematic variation between the core and rim. LA-ICP-MS trace element
data of monazite are available in Table A7. LA-ICP-MS analysis (a spot size of 10 μm) does not have
the spatial resolution to resolve the altered monazite rim and the partially altered monazite core.
Monazite shows an LREE-enriched smooth pattern in the chondrite-normalized REE diagram,
without a distinct Eu anomaly (Fig. 7).

U-Th-Pb isotope data

One hundred and thirteen U–Th–Pb isotopic analyses were carried out on ten xenotime crystals.
The locations of analyses, along with the analytical numbers and apparent $^{206}\text{Pb}/^{238}\text{U}$ ages, are
presented in Figure 5. U–Th–Pb isotope data are listed in Tables A8 and presented graphically in
Figure 9. Among them, 33 analyses are not considered geologically significant and are excluded
from the age analysis. The omitted analyses include 20 analyses with discordance values ($1 -
^{206}\text{Pb}/^{238}\text{U}/^{207}\text{Pb}/^{235}\text{U} \times 100 \) > 5% or <-5% and 13 analyses obtained from the incompletely altered
domains of xenotime. Explanations for the discordance and incompletely altered domains are
presented in the “Discussion” section.

After exclusion of the omitted analyses, the 46 analyses of pristine xenotime cores yield $^{206}\text{Pb}/^{238}\text{U}$
dates from 164.4 ± 6.1 to 153.2 ± 5.6 Ma, $^{207}\text{Pb}/^{235}\text{U}$ dates from 160.6 ± 6.9 to 152.2 ± 6.0 Ma, and
$^{208}\text{Pb}/^{232}\text{Th}$ dates from 168.2 ± 11 to 139.1 ± 7.6 Ma. These data define a weighted mean $^{206}\text{Pb}/^{238}\text{U}$
age of 157.11 ± 0.83 Ma (MSWD = 0.71), a weighted mean $^{207}\text{Pb}/^{235}\text{U}$ age of 155.93 ± 0.93 Ma
(MSWD = 0.60), and a Tera-Wasserburg lower intercept age of 156.49 ± 0.94 Ma (MSWD = 0.55).
The three ages overlap with each other within the margin of error. The remaining 41 analyses of
xenotime rims yield $^{206}\text{Pb}/^{238}\text{U}$ dates from 142.4 ± 5.8 to 128.5 ± 5.1 Ma, $^{207}\text{Pb}/^{235}\text{U}$ dates from 146.9
± 9.4 to 129.4 ± 7.2 Ma, and $^{208}\text{Pb}/^{232}\text{Th}$ dates from 150.0 ± 21 to 121.5 ± 9.1 Ma. These data define
a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 135.46 ± 0.93 Ma (MSWD = 1.07), a weighted mean $^{207}\text{Pb}/^{235}\text{U}$ age of 135.2 ± 1.4 Ma (MSWD = 1.05), a Tera-Wasserburg lower intercept age of 135.5 ± 1.1 Ma (MSWD = 1.05), and a Concordia age of 135.33 ± 0.91 Ma (MSWD = 0.41). The four ages overlap with each other within the margin of error.

Thirty-eight U–Th–Pb isotopic analyses were collected on 11 monazite crystals. The locations of analyses and analytical numbers, along with the apparent $^{206}\text{Pb}/^{238}\text{U}$ ages, $^{207}\text{Pb}/^{235}\text{U}$ ages, and $^{208}\text{Pb}/^{232}\text{Th}$ ages, are shown in Figure 6. Results are listed in Table A9 and presented graphically in the Tera-Wasserburg Concordia diagram in Figure 8. Monazite shows large variations in $^{207}\text{Pb}/^{235}\text{U}$ (3730 ± 36 to 208 ± 8 Ma), $^{206}\text{Pb}/^{238}\text{U}$ (1897 ± 61 to 161 ± 6 Ma), and $^{208}\text{Pb}/^{232}\text{Th}$ dates (463 ± 15 to 141 ± 5 Ma). The U–Pb ages are highly discordant, with discordance values ranging from 23 to 79. Nevertheless, the U-Pb isotope dataset forms a linear array in the Tera-Wasserburg Concordia diagram, yielding an upper intercept age of >4.5 Ga and a lower intercept age of 158.6 ± 3.3 Ma (MSWD = 3.7), which overlaps with the ages of xenotime cores within the margin of analytical error.

**DISCUSSION**

**Remarks on monazite and xenotime ages**

Although many monazite and xenotime dates are concordant or near concordant, the two minerals may be affected by low-temperature hydrothermal alteration and yield discordant ages (e.g., Rasmussen et al. 2011; Seydoux-Guillaume et al. 2012; Didier et al. 2013; Budzyń et al. 2018, 2021, 2022; Budzyń and Sláma, 2019). Factors causing age discordance during hydrothermal alteration include incomplete replacement of mineral domains (Grand'Homme et al. 2016; 2018) and...
incorporation of initial Pb in secondary monazite and xenotime (e.g., Seydoux-Guillaume et al. 2012; Didier et al. 2013; Budzyń et al. 2022). For instance, altered monazite domains with apparently homogeneous composition at a microscale may correspond to nanomixtures of primary and secondary monazite, yielding discordant ages (Grand'Homme et al. 2016; 2018). During hydrothermal alteration of monazite, initial Pb could accumulate in the monazite lattice along the microcracks (e.g., Budzyń et al. 2022) or be incorporated as nanosized Pb-rich inclusions (Seydoux-Guillaume et al. 2003; Fougerouse et al. 2018).

Twenty analyses of xenotime yield highly discordant dates with >5% or <-5% discordance, suggesting the incorporation of common Pb. Among them, thirteen analyses were obtained from the rims, two from the cores, and three from the incompletely altered domains. Eleven analyses with >5% discordance were placed on micro-fracture or porous places (e.g., analytical points 1 and 7 in section V16-101A, see the top left xenotime grain in Figs. 5, A1). Common Pb could present as nano-scale Pb-bearing minerals, such as altaite (Pb as an essential element) or tellurobismuthite (Pb as a minor component), along monazite microcracks and grain boundaries. Two minerals are commonly observed to occur in contact with xenotime and monazite (Fig. 4C). Accordingly, we propose the source of common Pb can be attributed to micro-cracks or porous spaces, which are more developed in xenotime rims. Quartz is another source of common Pb. Eight analyses designed to analyze the thin xenotime rims are contaminated by the quartz matrix; it is visible from the laser ablation pits that quartz was ablated (e.g., analytical points 19–21 in section V16-103A, see the central right xenotime grain in Figs. 5, A1). Common Pb could be present within quartz-hosted fluid inclusions or along the grain boundaries between quartz and xenotime. Thirteen analyses obtained from the incompletely altered domains (i.e., mixture of pristine and secondary xenotime) of xenotime
are also excluded from the age analysis. In Figure 5 (section V16-103A, the large grain in the top right) and Figure A2 (xenotime in the third row), for instance, the incompletely altered domain in the upper part of a xenotime grain partially preserves the oscillatory zoning of the pristine xenotime core. Ages and U-Th concentrations of this domain fall between the pristine core and the completely altered rim on the left.

Monazite shows highly discordant U–Pb ages (discordance values ranging from 23 to 79) and large variations in $^{207}\text{Pb}/^{235}\text{U}$ (3730–208 Ma), $^{206}\text{Pb}/^{238}\text{U}$ (1897–161 Ma), and $^{208}\text{Pb}/^{232}\text{Th}$ ages (463–141 Ma). Nevertheless, the U-Pb isotope dataset forms a linear array in the Tera-Wasserburg Concordia diagram, with an upper intercept age of >4.5 Ga and a lower intercept age of 158.6 ± 3.3 Ma (MSWD = 3.7), suggesting the discordance is caused by the incorporation of common Pb (e.g., Schoene, 2004), which affected the more sensitive $^{207}\text{Pb}/^{235}\text{U}$ ratio (e.g., Budzyń et al. 2022).

The source of common Pb may be attributed to the extensive micro-cracks and grain boundaries, which are not easily recognized under the optical microscope but become apparent under high-contrast SEM-BSE imaging. Analytical spots placed within individual monazite grains without visible micro-cracks (e.g., analytical spots 15–21 in section V16-103a, Fig. 6) show younger $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages than those placed in monazite aggregates with grain boundaries and micro-cracks (e.g., analytical spots 1–14 in section V16-103a, Fig. 6). Common Pb could accumulate in the monazite lattice along the microcracks (e.g., Budzyń et al. 2022). Similar to xenotime, common Pb could also present as nano-scale Pb-bearing minerals, such as altaite or tellurobismuthite, along monazite microcracks and grain boundaries. The abundant mineral inclusions in monazite are less likely to the sources for common Pb, because X-ray mapping shows that the inclusions contain lower Pb concentrations than the surrounding monazite (Fig. A3).
Due to the limited width (i.e., <10 μm) of the altered rim (i.e., secondary monazite) and the chaotic patchy zoning of the partially altered core (i.e., mixture of pristine and secondary monazite), the laser spot size (i.e., 10 μm) does not have the spatial resolution to resolve pristine and secondary monazite. Nevertheless, despite the mixture sampling of pristine and secondary monazite, monazite U–Pb data form a linear array and yield a lower intercept age of 158.6 ± 3.3 Ma (MSWD = 3.7). One possible explanation is that the alteration of monazite occurred shortly after the precipitation of pristine monazite, less than the error of the lower intercept age. Accordingly, these altered (or partially altered) monazite domains with high common Pb could yield geologically reasonable lower intercept ages, which overlap with the ages of pristine monazite within the margin of error. Similar results have been reported from the Sri Lanka monazite (Seydoux-Guillaume et al. 2012) and the Montasset monazite, France (Didier et al. 2013).

While monazite and xenotime do occur in contact with each other, monazite ages do not reflect the ca. 135 Ma hydrothermal event recorded by xenotime rims formed through coupled dissolution-reprecipitation reactions. One possible explanation is that this hydrothermal event only induced partial dissolution of monazite, but no compositional alteration. This is supported by the fact that monazite contains abundant unhealed micro-cracks with little to no evidence of compositional change along their edges, and shows a more anhedral shape than xenotime.

**Compositional alteration of monazite and xenotime**

One feature of the studied monazite is Th enrichment in the altered monazite rims. This contrasts with many natural monazite samples, which normally form secondary monazite with lower Th concentrations (e.g., Poitrasson et al. 2000; Rasmussen and Muhling, 2007; 2009; Seydoux-
Guillaume et al. 2012) via dissolution-reprecipitation reactions at low temperatures (i.e., ≤400°C).

For these natural samples, that decreasing Th content may be attributed to the high Th content in pristine monazite (i.e., >4 wt% ThO₂) and limited structural incorporation of Th in secondary monazite at lower temperatures. This is because the substitution of huttonite (ThSiO₄) into monazite lattice is temperature-dependent (Hetherington et al. 2010; Seydoux-Guillaume et al. 2012), with higher structural incorporation of Th at higher temperatures and vice versa. Accordingly, monazite alteration experiments conducted at high temperatures (i.e., ≥600°C) form secondary monazite with high Th contents (Seydoux-Guillaume et al. 2002; Hetherington et al. 2010; Harlov et al. 2011), while low-temperature alteration experiments (i.e., ≤600°C) result in secondary monazite with low Th contents (e.g., Williams et al. 2011; Budzyń et al. 2015a; Grand'Homme et al. 2018).

In our case, Th enrichment in the altered monazite is likely due to the relative low Th concentrations (<4.5 wt% ThO₂, Tables A5, A7, A9). A low concentration of Th is typical for hydrothermal monazite (Schandl and Gorton, 2004), which normally contains <4 wt% of ThO₂ (e.g., Schandl and Gorton, 2004, Catlos et al., 2013; Janots et al. 2012) and is frequently used to date hydrothermal gold deposits (e.g., Rasmussen et al. 2006; Fielding et al. 2017; Zhao et al. 2019; Deng et al. 2020; Liu et al. 2021). However, the mobility of Th during the alteration of hydrothermal monazite has rarely been addressed, partially due to previous studies focused on isotopic dating and a lack of careful examination to recognize potential alteration textures. This study demonstrates that ²⁰⁸Pb/²³²Th ages, commonly overlooked in geochronological studies on hydrothermal monazite, should be presented and discussed due to Th enrichment in the altered monazite.

In contrast to monazite, the mechanisms of xenotime alteration are less well-known and understood due to its lower abundance in nature. Several works documented fluid-mediated
alteration of xenotime in nature. These studies demonstrate that xenotime may break down into secondary phases such as apatite, epidote, and hingganite (Broska et al. 2005; Hetherington and Harlov, 2008; Majka et al, 2011; Ondrejka et al. 2022). Xenotime could also undergo coupled dissolution-reprecipitation reactions, resulting in compositional alterations that affected the age record (e.g., Hetherington et al. 2008; Rasmussen et al. 2011; Fielding et al. 2017; Budzyń et al. 2018), but the fluids inducing the dissolution-reprecipitation reactions are not well characterized, partially due to the lack of co-existing fluid inclusions. Experimental studies on xenotime alterations focused on alkali-rich aqueous fluid conditions (e.g., Hetherington et al. 2010; Harlov and Wirth, 2012; Budzyń et al. 2015b, 2017; Budzyń and Sláma, 2019). Hetherington et al. (2010) reported partial dissolution of xenotime in acid and brine fluids, but no compositional alteration. The recent experimental work of Budzyń and Sláma (2019) confirms that xenotime may be affected by re-equilibration induced by alkali-rich aqueous fluid via coupled dissolution-reprecipitation reactions under temperature conditions of 550–650 °C, resulting in U–Pb age disturbance.

While it’s widely accepted that CO₂ can promote the solubility of REE since CO₃²⁻ forms strong complexes with the REE (e.g., Wood, 1990; Williams-Jones et al. 2000; Hetherington et al. 2010; Zhou et al. 2016), the role of CO₂ in xenotime alterations has been rarely addressed. This study presents an example of xenotime compositional alteration and resetting of U–Pb ages caused by coupled dissolution-reprecipitation reactions, which are induced by low to moderate salinity carbono-aqueous fluids at low temperatures (i.e., <400°C). Since these fluids are commonly involved in the formation of lode gold deposits (e.g., Groves et al. 1998; Goldfarb et al. 2005), it’s crucial to examine xenotime textures and recognize potential alteration textures before carrying out isotopic 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 $^{206}\text{Pb}/^{238}\text{U}$ 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 $^{206}\text{Pb}/^{238}\text{U}$ 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]$_2$Te$_4$) 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...
primary melt inclusions trapped as polymetallic droplets that scavenged gold from aqueous fluids with high efficiency. During later hydrothermal events, polymetallic melt inclusions could be released from the host mineral and continue to scavenge gold from fluids, due to fracturing of the host mineral or migration of the melt inclusions to the crystal surface. Aside from S16 gold-bearing quartz vein, the characteristic lingbaoite-sylvanite-bearing mineral assemblage, and by analogy, the earlier gold mineralization event has also been observed in other parts of the Xiaoqinling gold district, such as the S60 gold-bearing quartz vein (Jian et al. 2020, 2021, 2022b) and the Jinqu gold deposit (Chang et al. 2020). Our study, therefore, reveals a previously overlooked yet important Late Jurassic gold mineralization event in the Xiaoqinling gold district.

Late Jurassic ages have been only reported from the Luzhougou gold deposit (two Re-Os molybdenite model ages of 149 ± 8.4 Ma and 154 ± 1.1 Ma: Li et al. 2012a) in the Xiaoqinling gold district. The lack of reported Late Jurassic ages likely results from the scarcity of geochronometers that are able to preserve the Late Jurassic age information after the Early Cretaceous hydrothermal overprint. Most of the Early Cretaceous ages in the Xiaoqinling gold district were obtained from $^{40}$Ar/$^{39}$Ar dating of micas, with a few Re-Os molybdenite and U-Pb monazite ages (Fig. 10 and Table A10). The low $^{40}$Ar/$^{39}$Ar closure temperatures of micas (e.g., ~300°C for biotite and ~400°C for muscovite: Harrison et al. 1985, 2009; Schaen et al. 2021), suggest their isotopic system could be easily reset during later hydrothermal events. For instance, our study reveals that the ca. 135 Ma gold mineralization event is characterized by the mineral assemblage of native gold-calaverite-petzite-tellurobismuthite, which coexists with low to moderate salinity H$_2$O-CO$_2$ fluid inclusions along healed fractures in quartz (Figs. 3I–K). The total homogenization temperatures of these fluid inclusions cluster at 200 to 400°C, a range that overlaps with the $^{40}$Ar/$^{39}$Ar closure temperatures of
biotite and muscovite.

To the east of the Xiaoqinling gold district, abundant Late Jurassic ages have been reported in the adjacent Xiong’ershan region. Examples include the Wuzhangshan monzogranite pluton (SHRIMP zircon U–Pb age of 157 ± 1 Ma: Mao et al. 2010), granitic porphyries in the Shangfanggou Mo deposit (SHRIMP zircon U–Pb age of 158 ± 3 Ma, Mao et al. 2010), Nannihu Mo deposit (SHRIMP zircon U–Pb age of 157 ± 3 Ma, Mao et al. 2010), Balipo Mo deposit (LA-ICP-MS zircon U–Pb age of 155.9 ± 2.3 Ma, Jiao et al. 2009), Qiyugou Au deposit (SIMS zircon U-Pb ages of 157.3 ± 1.1 and 158.7 ± 1.2 Ma, Wang et al. 2020), a Mo (Au?) mineralized vein in the Huaixiangwa Au deposit (Re-Os molybdenite mean age of 155.0 ± 2.2 Ma, Gao et al. 2018), and a Au mineralized vein in the Luanling Au deposit (Re-Os molybdenite isochron age of 163 ± 2 Ma, Chao et al. 2019).

Accordingly, the large-scale Jurassic magmatism and associated mineralization event in eastern China (e.g., Mao et al. 2021a, b; Goldfarb et al. 2021), in relation to the subduction of the paleo-Pacific plate beneath the eastern China continent (Mao et al. 2021a), might have also caused widespread gold mineralization in the Xiaoqinling gold district.

**Implications**

This study presents an example of xenotime compositional alteration and resetting of U–Pb ages caused by coupled dissolution-reprecipitation reactions, which are induced by low to moderate salinity carbono-aqueous fluids at low temperatures. Gold minerals in contact with such composite xenotime crystals could precipitate before, coeval with, or after the dated domains, depending on the relation between the gold minerals and the dated xenotime domains. Since low to moderate salinity carbono-aqueous fluids are commonly involved in the formation of lode gold deposits, it’s crucial to
examine xenotime textures and recognize potential alteration textures before carrying out isotopic
dating of xenotime collected from these deposits. Without prior compositional and textural
characterization, attempts to date such composite crystals could yield mixed age information and
meaningless ages.

This study also demonstrates that monazite and xenotime could be affected by low-temperature
hydrothermal alteration and yield discordant ages, resulting from incomplete replacement of mineral
domains or incorporation of common Pb. Common Pb could accumulate in the monazite and
xenotime along microcracks and grain boundaries. These features may be identified under high-
contrast SEM-BSE images but are not always visible in reflected-light photomicrographs or CL
images. During the alteration of hydrothermal monazite that typically contains low Th
concentrations, Th may be enriched in secondary monazite through coupled dissolution-
reprecipitation reactions. Accordingly, $^{208}\text{Pb}/^{232}\text{Th}$ ages, sometimes neglected in geochronological
studies on hydrothermal monazite from ore deposits, should be presented and discussed. This study
also highlights the potential of utilizing highly discordant U-Pb age data, which can be discarded in
geochronology studies but could potentially be used to constrain the age of metasomatic events as
the lower intercept in the Tera-Wasserburg Concordia diagrams.

**ACKNOWLEDGMENTS**

Bin Shi is thanked for his assistance with the SEM analysis. Lei Zhu and Huan Wang are thanked
for their assistance with the LA-ICP-MS analysis. Shuaiming Zhang and Guanguan Fang are thanked
for providing help and support during fieldwork. Constructive reviews by Sean Regan and an
anonymous reviewer considerably improved the paper and are greatly acknowledged. Callum
Hetherington is especially thanked for the editorial handling. This research was jointly funded by the National Natural Science Foundation of China (41972093, 41672092) and the Fundamental Research Funds for the Central Universities (2652020026).

REFERENCES CITED


Disturbance versus preservation of U–Th–Pb ages in monazite during fluid–rock interaction:
textural, chemical and isotopic in situ study in microgranites (Velay Dome, France):
Contributions to Mineralogy and Petrology, 165, 1051–1072.

Dong, Y. and Santosh, M. (2016) Tectonic architecture and multiple orogeny of the Qinling Orogenic

Dowling, K., and Morrison, G. (1989) Application of quartz textures to the classification of gold

Molybdenite Re-Os geochronology and isotope geochemical characteristics of Xigou
molybdenum deposit in Shaanxi Province and its geological significance: Mineral Deposits 39,

Engi, M. (2017) Petrochronology based on REE-minerals: Monazite, allanite, xenotime: Reviews in
Mineralogy and Geochemistry, 83, 365–418.

Essarraj, S., Boiron, M.C., Cathelineau, M., and Fourcade, S. (2001) Multistage deformation of Au-
quartz veins (Laurieras, French Massif Central): Evidence for late gold introduction from

Xiaoqinling lode gold metallogenesis in the Henan and Shanxi provinces, central China: Acta

Fielding, I.O.H., Johnson, S.P., Zi, J.W., Rasmussen, B., Muhling, J.R., Dunkley, D.J., Sheppard, S.,
geochronology to determine the age of orogenic gold mineralization: an example from the


alteration by anisotropic replacement. Chemical Geology, 484, 51–68.


Mao, J.W., Zheng, W., Xie, G.Q., Lehmann, B., and Goldfarb, R. (2021a) Recognition of a Middle–Late Jurassic arc-related porphyry copper belt along the southeast China coast: Geological characteristics and metallogenic implications: Geology, 49, 592–596.


Qiang, S.F., Bi, S.J., Deng, X.D., Guo, L.Q., and Li, J.W. (2013) Monazite U-Th-Pb ages of Qinnan gold deposit, Xiaoqinling district: Implications for regional metallogenesis and tectonic setting:


Chemical Geology, 88, 99–125


associated with carbonatites in the Qinling orogenic belt, central China: Lithos 118, 50–60.


**FIGURE CAPTIONS**

Fig. 1. Geologic map of the Xiaoqinling gold district and its position in China (compiled from Jian et al. 2015, 2021; Liu et al. 2021).
Fig. 2. Typical features of the S16 gold-bearing quartz vein shown by photographs. A. B. Underground exposure. C. Hand specimen. D. Polished thick section showing the occurrences of pyrite (euhedral large crystals), tellurides (black cloudy aggregates), and xenotime (very fine-grained red cloudy aggregates).

Fig. 3. Two stages of gold mineralization shown by photomicrographs (A–I: plane-polarized reflected light, J: reflected-transmitted light image created through focus stacking, K: reflected-transmitted light). A–H. Distribution of two stages (II, III) of minerals within and near two pyrite grains. I. Native gold and tellurides (stage III) occur as inclusions along a healed microfracture in quartz. J–K. Native gold and telluride (stage III) coexist with low to moderate salinity H₂O-CO₂ fluid inclusions along healed microfractures in quartz. Abbreviations: Alt = altaite, Au = gold, Bn = bornite, Clv = calaverite, Ccp = chalcopyrite, Gn = galena, Lb = lingbaoite, Ptz = petzite, Py = pyrite, Qz = quartz, Stz = stützite, Syv = sylvanite, Tbi = tellurobismuthite, Te = native tellurium.

Fig. 4. Occurrence of xenotime and monazite shown by photomicrographs (D, F, H: plane-polarized reflected light), BSE images (A–C, E, G), and CL image (I). A–C. Xenotime and monazite occur as inclusions in pyrite. D–G. Native gold and tellurides (stage III) occur in contact with xenotime. The two xenotime grains were dated by LA-ICP-MS. Their CL images with analyzed spots and ages labeled are shown in Fig. 5. G. Xenotime rims are brighter than core zones in BSE images. H–I. Native gold and tellurides (stage III) occur in contact with the rim of a xenotime grain or as inclusions in the altered domains of the xenotime. Note that altered domains of xenotime are brighter.
in CL image, while the unaltered domains are darker and show oscillatory zoning. Abbreviations: Alt = altaite, Au = gold, Clv = calaverite, Mnz = monazite, Ptz = petzite, Py = pyrite, Qz = quartz, Xtm = xenotime.

Fig. 5. Cathodoluminescence images of xenotime grains after LA-ICP-MS analysis. The 10 μm and 16 μm laser pits are for U-Th-Pb isotope and trace element analysis, respectively. SEM-BSE images of the 10 xenotime grains before LA-ICP-MS analysis are shown in Figure A1. WDS X-ray maps (Y, U, Th, Pb) of 6 xenotime grains before LA-ICP-MS analysis are shown in Figure A2.

Fig. 6. SEM-BSE images of monazite grains after LA-ICP-MS analysis. 206Pb/238U, 207Pb/235U and 208Pb/232Th ages of the analyzed spots are indicated.

Fig. 7. REE patterns of the xenotime and monazite. The data are normalized to C1 chondrite composition as compiled in Sun and McDonough (1989).

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

Fig. 9. Two episodes of gold mineralization and growth of monazite and xenotime illustrated by schematic drawing.
Fig. 10. Age distribution of gold deposits from the Xiaoqinling gold district. The age data, detailed in the Appendix (Table A10), were compiled from Xu et al. (1998), Wang et al. (2002), Li et al. (2012a, b), Qiang, 2012, Qiang et al. 2013, Zhao et al. (2019), and Liu et al. (2021).

APPENDIX

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

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

Fig. A3. Characterizations of the largest monazite grain before LA-ICP-MS analysis shown by BSE image (A), photomicrographs (B: plane-polarized reflected light; C: plane-polarized reflected light with gamma enhancement), and WDS X-ray maps (D–H).

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

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

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

Table A4. Analytical conditions of LA-ICP-MS trace element analysis of monazite
Table A5. Electron microprobe data of xenotime and monazite

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

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

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

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

Table A10. Age data of gold deposits from the Xiaoqinling gold district
Fig. 7

Monazite
Xenotime rim
Xenotime core

La Ce Pr Nd Sm Eu Gd Tb Dy Er Tm Yb Lu
Fig. 8

Xenotime core
Weighted mean age
157.11 ± 0.83 Ma, 2σ
MSWD = 0.71, n = 46

Xenotime rim
Weighted mean age
135.46 ± 0.93 Ma, 2σ
MSWD = 1.07, n = 46

Xenotime core
Weighted mean age
155.93 ± 0.93 Ma, 2σ
MSWD = 0.60, n = 46

Xenotime rim
Weighted mean age
135.2 ± 1.4 Ma, 2σ
MSWD = 1.05, n = 46

Xenotime core
Low intercepts age
156.49 ± 0.94 Ma, 2σ
MSWD = 0.55, n = 46

Xenotime rim
Lower intercepts age
135.5 ± 1.1 Ma, 2σ
MSWD = 1.05, n = 34

Monazite
Intercepts at
156.6 ± 3.3 & 5034 ± 37 Ma
MSWD = 3.7, n = 38
Fig. 9

Growth of pristine monazite

Dissolution–reprecipitation of monazite

Growth of pristine xenotime

Dissolution–reprecipitation of xenotime

ca. 157 Ma

Fluid

ca. 135 Ma

Dissolution of monazite

Fluid

Dissolution–reprecipitation of xenotime

Fluid

Stage III Au minerals

Stage II Au minerals

Py

Fluid inclusion

Qz

Xtm

Mnz

Micro-cracks

Inclusions

Monazite core

Monazite rim

Xenotime core

Xenotime rim