



Technical note: Pyrite (U,Th)-He geochronology using scanning fiber-laser He extraction: analytical workflow and case studies from two orogenic gold systems in the Russian Far East

Olga V Yakubovich^{1,2}, Nadezhda A. Vasilyeva^{1,2}, Ekaterina S. Pushkina^{1,2}, Lidia A. Sokolova^{1,2}, Boris M. Gorokhovskiy¹, Alexander B. Kotov¹, Elena V. Adamskaya¹, Maria O. Anosova³, Elena V. Vatrushkina⁴, Vyacheslav V. Akinin⁵

¹ Institute of Precambrian Geology and Geochronology (IPGG) RAS, Saint Petersburg, 199034, Russia

² Saint Petersburg State University (SPbU), Saint Petersburg, 199034, Russia

³ Vernadsky Institute of Geochemistry and Analytical Chemistry (GEOKHI) RAS, Moscow, 119991, Russia

10 ⁴ Geological Institute RAS, Moscow, 119017, Russia

⁵ North-East Interdisciplinary Scientific Research Institute n. a. N. A. Shilo (NEISRI) RAS, Magadan, 685000, Russia

Correspondence to: Olga V. Yakubovich (olya.v.yakubovich@gmail.com)

Abstract.

15 This study presents a new analytical approach to (U,Th)-He dating of individual pyrite grains. We demonstrate that a widely available commercial fiber-laser marking system operated in scanning mode can efficiently extract radiogenic He from pyrite encapsulated in quartz ampoules. The ampoules retain the thermal decomposition products and associated parent nuclides, allowing U and Th to be subsequently determined in the same material from which He was extracted. The proposed extraction technique was validated using pyrite from two gold-bearing sites in the Russian Far East: the Pavlik orogenic gold deposit in
20 the Magadan Region and the Upryamoe gold occurrence, Chukotka. The resulting pyrite (U,Th)-He ages are 139.3 ± 1.7 Ma (MSWD = 2.5; n = 7) and 125.4 ± 2.1 Ma (MSWD = 0.87; n = 5), respectively. Compared with the previously developed high-vacuum furnace procedure, the scanning fiber-laser approach increases the analytical throughput of pyrite (U,Th)-He dating by approximately an order of magnitude, allowing up to eight samples to be analysed per day. By making individual-grain age determinations faster and operationally simpler, the method enables larger datasets to be acquired and thereby improves the
25 statistical characterization of pyrite ages from a range of geological settings.

1 Introduction

Pyrite is a common mineral that forms in a wide range of geological settings. Its age is traditionally determined using Re-Os geochronology (Stein and Hannah, 2014), whereas the ⁴⁰Ar/³⁹Ar, Rb-Sr, and Sm-Nd isotope systems are applied less commonly (Christensen et al., 1995; Ivanov et al., 2015; Smith et al., 2001; Yang and Zhou, 2002). These methods provide
30 valuable constraints on the timing of pyrite formation and the associated geological processes and therefore remain essential tools in geochronological research. However, their application is analytically demanding and costly, commonly requires



relatively large amounts of material (typically tens of milligrams), and relies on access to high-resolution mass spectrometers. In the case of $^{40}\text{Ar}/^{39}\text{Ar}$ dating, the mandatory cooling period following sample irradiation substantially delays data acquisition. Moreover, these methods are not universally applicable. Pyrite may contain isotopically heterogeneous inherited Os or
35 insufficient concentrations of Re. In addition to the difficulties associated with low parent-nuclide concentrations, application of $^{40}\text{Ar}/^{39}\text{Ar}$, Rb-Sr, and Sm-Nd systems requires demonstrating that the measured age records pyrite formation rather than the age of entrained mineral inclusions. Alternative methods capable of dating individual pyrite grains are therefore of considerable interest.

Recent studies have shown that pyrite effectively retains radiogenic ^4He and can therefore be used as a (U,Th)-He
40 geochronometer (Yakubovich et al., 2019). The (U,Th)-He method has been successfully used to date pyrite from various types of ore deposits (Chernykh et al., 2024; Ivanova et al., 2024; Yakubovich et al., 2020, 2021), constrain the timing of epigenetic pyrite formation in oil-source rocks (Yakubovich et al., 2023b), and date tectono-hydrothermal activity (Yakubovich et al., 2025a). Compared with conventional isotope-geochronological techniques, this method is relatively simple, does not require high-resolution mass spectrometry or other costly analytical equipment, and can be applied to
45 individual pyrite grains or grain fragments.

The heterogeneous distribution of parent nuclides in pyrite requires He, U, and Th to be measured in the same sample (Yakubovich et al., 2020, 2019). However, He extraction from pyrite is accompanied by thermal decomposition, necessitating a specific analytical procedure that preserves the parent nuclides for subsequent analysis. A previously developed and successfully tested approach involves encapsulating pyrite in quartz ampoules sealed under vacuum (Yakubovich et al., 2020).
50 During heating in a high-vacuum furnace, the released He readily diffuses through the thin quartz walls, whereas U and Th remain in the ampoule together with the decomposition products (Shukolyukov et al., 2012). The ampoule can subsequently be recovered to determine the U and Th concentrations in the same grain from which He was extracted. Although this approach enables the sequential determination of He, U, and Th in individual grains, its analytical throughput is limited by the He-extraction step: each ampoule is heated separately in a high-vacuum furnace, where each sample loading requires several hours
55 of pumping to re-establish high-vacuum conditions.

Laser extraction of He is widely used in (U,Th)-He dating because it offers several advantages over furnace extraction, including lower He blanks and shorter extraction times. Excimer lasers are used for *in situ* analyses of He concentrations (Evans et al., 2015), whereas diode lasers are commonly used to heat samples (Foeken et al., 2006). In the latter case, the sample is typically wrapped in a refractory-metal foil, such as Nb or Pt. The foil absorbs the laser radiation, heats up, and
60 efficiently transfers heat to the enclosed sample. A similar approach could potentially be used to heat sealed quartz ampoules containing pyrite grains. If the temperature required for He extraction can be maintained long enough to ensure complete He release without compromising ampoule integrity, this approach could substantially increase analytical throughput. In this study, we developed and implemented such a procedure using pyrite from two gold-mineralization sites in the Russian Far East.



65 2 Fundamentals of (U,Th)-He dating of pyrite

The (U,Th)-He method is based on the accumulation of radiogenic ^4He produced by α decay in the ^{238}U , ^{235}U and ^{232}Th decay series. Uranium concentrations in pyrite range from several ppb to tens of ppm and may be strongly heterogeneous (Baranov and Vertepov, 1966; Large et al., 2014). Uranium is thought to be incorporated into the mineral through fixation of dissolved U at the pyrite surface during growth (Butler and Nesbitt, 1999; Descostes et al., 2010). Uranium and Th may also occur in
70 pyrite as micrometre-scale inclusions of accessory minerals including uraninite, monazite, apatite, zircon, titanite, and xenotime. Because the stopping distances of α particles commonly exceed the dimensions of these inclusions, a substantial proportion of the ^4He generated within them is implanted into and retained by the surrounding pyrite. Reliable (U,Th)-He age determination therefore requires quantification of U and Th occurring both as impurities incorporated into pyrite and in U- and Th-bearing accessory-mineral inclusions.

75 Experimental step-heating studies indicate that pyrite efficiently retains radiogenic ^4He : appreciable ^4He release begins at approximately 450 °C, coinciding with the temperature of pyrite decomposition under anoxic conditions (Yakubovich et al., 2019). This behaviour suggests that ^4He loss is limited while pyrite remains structurally stable, although alteration and recrystallisation may disturb the isotope system.

Pyrite can also preserve He trapped from the ore-forming fluid. However, its concentration in modern hydrothermal sulfides
80 ($\sim 10^{-10}$ – 10^{-8} cm³ STP g⁻¹; (Bortnikov et al., 2000; Luders and Niedermann, 2010; Stuart et al., 1994)) is generally several orders of magnitude lower than the amount of radiogenic ^4He accumulated in sufficiently old, U-bearing pyrite ($\sim 10^{-6}$ – 10^{-4} cm³ STP g⁻¹; (Yakubovich et al., 2019). For example, pyrite containing 1 ppm U would accumulate approximately 10^{-6} cm³ STP g⁻¹ of radiogenic ^4He over 10 Myr. A correction for trapped ^4He may become important for young samples, grains with low U contents, or pyrite formed in a He-rich environment.

85 3 Geological background and sample description

To test the new methodological approach to (U,Th)-He pyrite dating, we analysed pyrite from two gold-bearing sites in the Russian Far East: the Pavlik gold deposit in the Magadan Region and the Upryamoe gold occurrence in Chukotka.

3.1 The Pavlik deposit

The Pavlik orogenic gold deposit, together with the nearby Natalka deposit, ranks among the largest orogenic gold deposits in
90 northeastern Asia, with combined gold reserves exceeding 30 Moz (PAVLIK JSC, 2026; Polyus PJSC, 2024). Both deposits are located within the large Omchak ore cluster, Magadan Region, Russia. The cluster is underlain by Upper Permian diamictites of the Atkan Formation and carbonaceous shales and siltstones of the Pionerskaya and Omchak formations, with a total thickness of approximately 2 km. These rocks are intruded by relatively small bodies of post-ore Upper Cretaceous granitoids (ca. 87 Ma) and by a series of pre-ore dikes belonging to the Upper Jurassic Nera-Bokhapcha Complex, dated at
95 approximately 150 Ma (Akinin et al., 2023).



Structurally, the closely spaced Natalka and Pavlik deposits occupy narrow, wedge-shaped ore-bearing blocks bounded by northwest-striking faults oriented obliquely to the regional fold trend. The principal fault bounding the deposits to the east is the Omchak (Tenka) Fault, interpreted as a normal strike-slip fault. Secondary faults within the ore field, including reverse faults, reverse-slip faults, and strike-slip faults, are contractional structures with displacements ranging from a few metres to several hundred metres. Mineralization is controlled by a complex system of steeply dipping, longitudinal brittle structures. Mineralization at the Pavlik deposit belongs to the pyrite-arsenopyrite mineral type. The hydrothermal gangue assemblage is dominated by quartz and carbonate, with subordinate albite, ankerite, sericite, and chlorite. In addition to the dominant pyrite and arsenopyrite, the ore assemblage locally contains native gold, galena, sphalerite, chalcopyrite, pyrrhotite, and tetrahedrite-group minerals, which generally occur as inclusions in pyrite and arsenopyrite. The total sulfide content typically does not exceed 1-2 vol.%.

At the Natalka deposit, the age of mineralization is constrained as 133–136 Ma (136 ± 1 Ma – Re–Os isochron age obtained from ore-stage arsenopyrite and native gold; 133 ± 2 Ma – ^{40}Ar – ^{39}Ar plateau age of muscovite in ore-related quartz–feldspar metasomatites). Re–Os analyses of arsenopyrite, pyrite, and native gold from the Pavlik deposit failed to define a reliable isochron; nevertheless, the close geological and genetic relationship between Pavlik and Natalka suggests that mineralization at the two deposits was broadly coeval (Akinin et al., 2023).

The pyrite crystals selected for (U,Th)-He dating were obtained from the sulfide concentrate of the 200 kg NG-001 bulk sample collected at the 710 m level of Ore Zone 1 at the Pavlik deposit. The sampled ore consists of gray, silicified Upper Permian siltstone containing abundant disseminated pyrite and arsenopyrite and frequent, up to 5 mm thick arsenopyrite-quartz veinlets that host native gold. The ore is unoxidized and contains neither limonite nor scorodite. Backscattered-electron images of pyrite from this sample are shown in Fig. 1. The images were obtained using a Hitachi S-3400N scanning electron microscope equipped with an Oxford Instruments X-Max 20 energy-dispersive spectrometer, operated at an accelerating voltage of 20 kV and a probe current of 1.5 nA. The pyrite exhibits a blocky internal texture and contains numerous inclusions of chalcopyrite, sphalerite, quartz, calcite, feldspar, mica, ilmenite, apatite, and monazite. Some grains are compositionally zoned with respect to As.

Trace-element compositions of pyrite from sample NG-001 were determined by LA-ICP-MS at IGEM RAS using a Thermo XSeries 2 quadrupole ICP-MS coupled to a New Wave Research UP-213 laser-ablation system (fluence, 1.2 J cm^{-2} ; spot diameter, 50 μm ; line-scan mode). All analysed grains contained Au (0.15–240 ppm; mean, 37 ppm) and As (1200–28 350 ppm; mean, 10 186 ppm). The strong positive correlation between Au and As ($r = 0.90$; $n = 28$) indicates that Au occurs predominantly as chemically bound “invisible” gold. Uranium concentrations range from 0.01 to 3.8 ppm (mean, 0.7 ppm), and Th concentrations range from 0.01 to 10.3 ppm (mean, 2.2 ppm); both elements show significant positive correlations ($r = 0.7$ – 0.9 ; $n = 28$) with Zr, Er, Tm, Yb, Lu, and Hf.

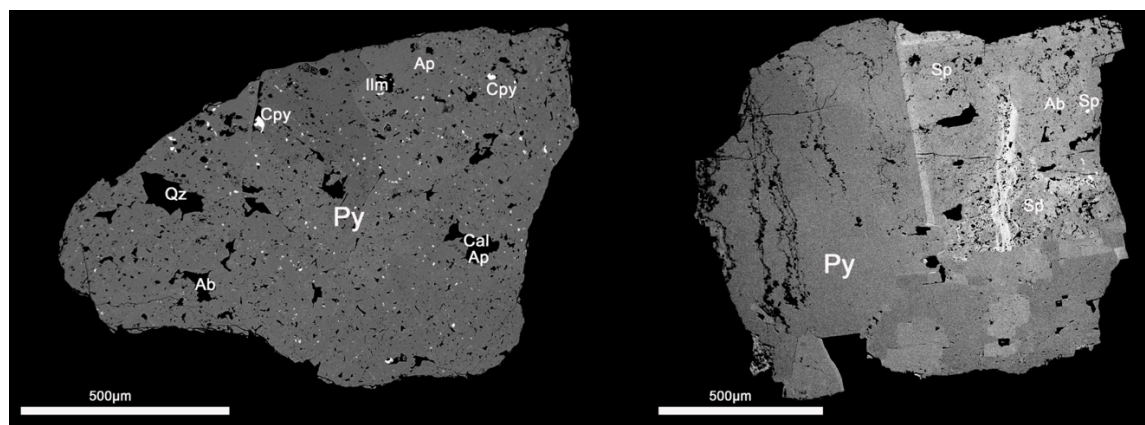


Fig. 1. Backscattered-electron (BSE) images of pyrite grains from the Pavlik deposit (sample NG-001). The grains exhibit blocky internal textures and compositional variations in As content. Mineral abbreviations: Py – pyrite; Cpy – chalcopyrite; Sp – sphalerite; Qz – quartz; Ilm – ilmenite; Ab – albite; Cal – calcite; Ap – apatite.

3.2 Upryamoe ore field

The Upryamoe ore field is located in western Chukotka, Russia, within the central part of the Gremuchinsky gold cluster of the Chukotka metallogenic belt. The ore field extends north-eastward for approximately 3.5 km, is up to 1.5 km wide, and covers an area of 12.1 km². It is underlain by Upper Jurassic–Lower Cretaceous terrigenous rocks of the Netpneyveem and Pogyniden formations, consisting mainly of altered sandstones, siltstones, and mudstones, with subordinate tuffaceous sedimentary rocks. These rocks were deformed and metamorphosed under greenschist-facies conditions and are locally affected by carbonatization, sericitization, kaolinitization, and sulfidation. Late Cretaceous microdiorite dikes of the Ichuveem Complex occur in the central part of the ore field, while geophysical data suggest the presence of an unexposed granitoid intrusion at depth (Canhimbue et al., 2025).

Structurally, the Upryamoe ore field is associated with a NW-trending anticlinal structure of the Rauchua fold-and-thrust zone. The orebodies are confined to saddle-reef carbonate-quartz veins and mineralized shatter zones; the total sulfide content typically ranges from 1 to 3 vol.%. The principal ore minerals are pyrite and arsenopyrite, accompanied by subordinate galena, sphalerite, chalcopyrite, tetrahedrite, and bournonite. Native gold is highly unevenly distributed and occurs predominantly as fine inclusions in pyrite and arsenopyrite. The mineralization is classified as an orogenic low-sulfide gold-quartz type.

The age of mineralization in the Upryamoe ore field is geologically constrained to postdate the Late Jurassic–Early Cretaceous host rocks (147–133 Ma). Re–Os analyses of arsenopyrite failed to define an isochron and therefore did not provide a more precise age constraint on mineralization; previous pyrite (U,Th)-He dating results date the mineralization as 123±4 Ma (n=3) (Canhimbue et al., 2025).

Cubic pyrite grains were manually separated from a quartz vein containing gold-sulfide veinlet-disseminated mineralization (sample C12-65.9). Pyrite from this sample contains visible gold inclusions; no other discernible mineral inclusions were



observed during optical-microscope examination of a polished-section. The pyrite selected for (U,Th)-He dating belongs to the productive gold-pyrite-arsenopyrite assemblage (pyrite III, (Canhimbue et al., 2025). Backscattered-electron images were obtained under the same operating conditions as those used for the Pavlik pyrite and are shown in Fig. 2. The grains exhibit compositional zoning defined by variations in As content. They contain inclusions of silicate minerals, apatite, and quartz, as well as relatively large inclusions of unidentified Pb-Cu-Sb sulfosalts, probably bournonite.

Trace-element compositions of pyrite III were determined by LA-ICP-MS using the same analytical procedure as that applied to sample NG-001 (Canhimbue et al., 2026). All analysed grains contained Au (1.6–55 ppm; mean, 6.5 ppm); in grains containing visible native-gold inclusions, Au concentrations reached 210 ppm. Arsenic concentrations ranged from 1855 to 87128 ppm (mean, 12 643 ppm). Au concentrations show a strong positive correlation with As ($r = 0.76$), consistent with the characteristics of auriferous pyrite in orogenic gold deposits. Pyrite III also contains elevated concentrations of Co (up to 2800 ppm), Ni (up to 3100 ppm), Cu (up to 2100 ppm), Pb (up to 2800 ppm), and Sb (up to 379 ppm).

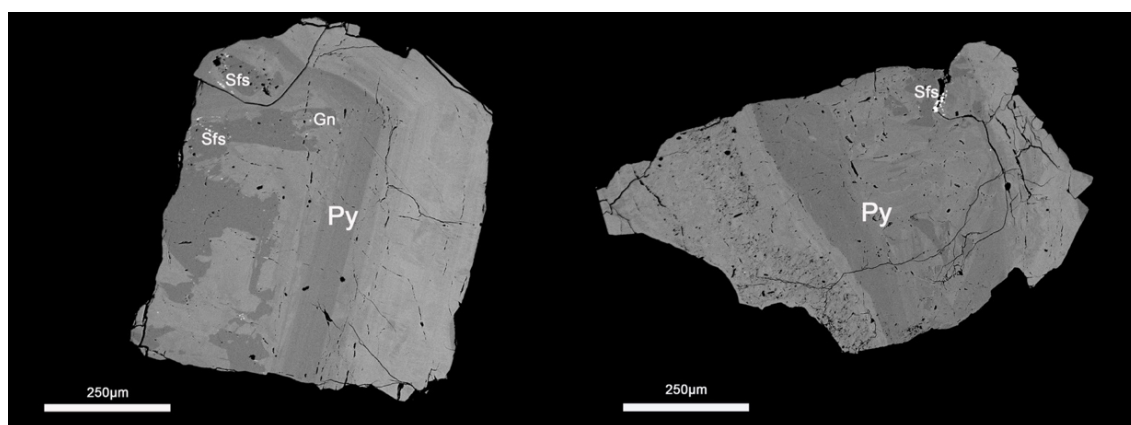


Fig. 2. Backscattered-electron (BSE) images of pyrite grains from the Upryamoe gold occurrence (sample C12-65.9).— The grains exhibit compositional zoning defined by variations in As content. Mineral abbreviations: Py —pyrite; Gn — galena; Sfs — unidentified Pb-Cu-Sb sulfosalt.

4 Methodology

4.1 Helium extraction

The ^4He concentration in pyrite was determined using a high-sensitivity MSU-G-01-M magnetic-sector mass spectrometer (IPGG RAS; (Shukolyukov et al., 2012) equipped with an in-house-built high-vacuum laser cell coupled to an ytterbium fiber-laser marking system (1064 nm; 50 W; (Yakubovich et al., 2025b). This widely available type of laser system is conventionally used to mark and engrave metal products. A photograph and schematic layout of the mass-spectrometric setup are shown in Fig. 3. The instrument was calibrated using the Knyahinya meteorite (Schultz and Franke, 2004) and the RS-Pt platinum



reference material (Yakubovich et al., 2023a) in a high-vacuum furnace (Extractor 2; Fig. 3b). The sensitivity of the mass-spectrometric system was monitored daily using a calibrated gas pipette connected to a He cylinder.

The quartz ampoules are approximately 1.2×12 mm in size. To heat this area efficiently and as uniformly as possible, the laser was operated in scanning mode. Because the laser marker was originally designed to engrave metal products, its control software allows the heating area to be defined. Here, the heating area was defined as a rectangle ($\sim 1.2 \times 12$ mm) that was repeatedly filled using a programmed raster-scan pattern. To achieve more uniform heating, the laser was positioned at approximately 1.5 focal lengths from the sample assembly, and the quartz ampoule was wrapped in refractory-metal foil.

To evaluate whether laser heating of quartz ampoules containing mineral grains provides effectively complete He extraction, we performed a series of experiments using Durango apatite, a widely used reference material for (U,Th)-He dating. A small fragment of Durango apatite was sealed in a quartz ampoule, wrapped in tantalum foil, and heated with the laser. Helium release was monitored continuously during heating with valves VM15, VM5, and VM6 open (Fig. 3). The initial laser settings were a scanning area of 2×12 mm, a laser power of 50%, and a frequency of 40 kHz. The laser power was gradually increased to 70%, and heating continued until no further He release was detected. This was achieved after approximately 2000 laser scans (30–40 min). The U and Th contents of the heated Durango apatite samples were subsequently determined to calculate their (U,Th)-He ages.

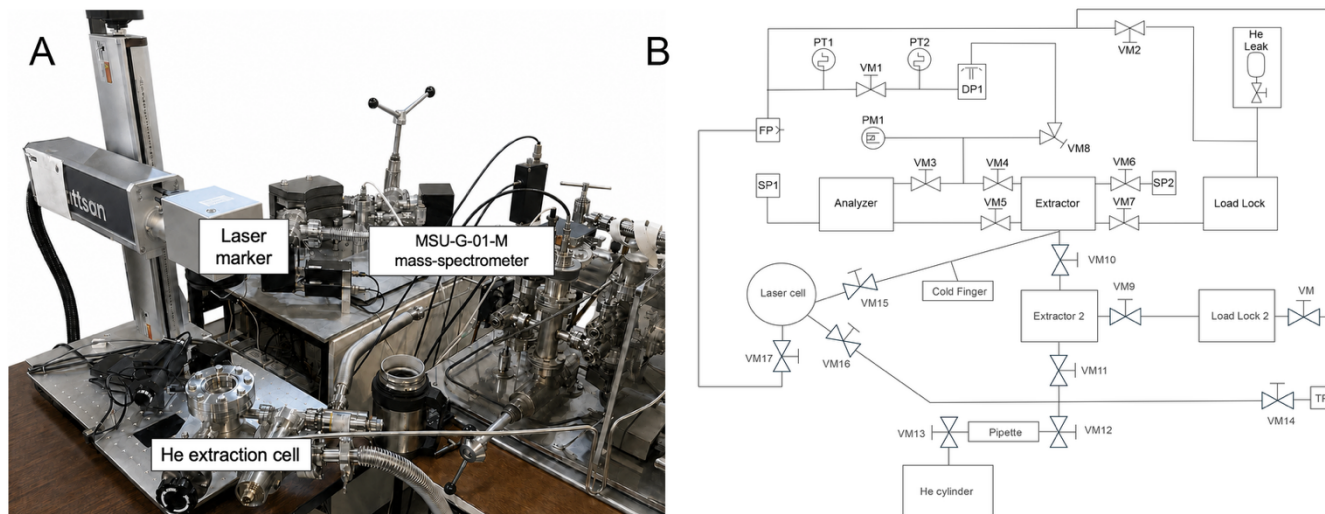


Fig. 3. MSU-G-01-M mass-spectrometric setup equipped with a high-vacuum laser-extraction cell. (a) Photograph of the instrument. (b) –Schematic layout. FP – forevacuum pump (Varian DS 202); TP – turbomolecular pump (Pfeiffer Hi Cube); DP – diffusion pump (Varian AX-65); SP – sorption pump (SAES NP10 getters); VM – manual valve; PT – Pirani gauge; PM – Penning gauge.

Individual pyrite grains were selected to test the performance of the scanning laser-extraction technique for pyrite (U,Th)-He geochronology. The complete sample-preparation and laser-heating He-extraction procedure is described below:



1. Individual pyrite grains approximately 300–500 μm in size and 1–2 mg in mass were hand-picked under a binocular microscope.
2. The selected grains were placed in a quartz ampoule, which was evacuated to 10^{-3} Torr and sealed under vacuum (Fig. 4a).
3. The sealed quartz ampoule was tightly wrapped in 12 μm thick tantalum foil (99.95%-purity; Fig. 4b).
4. The wrapped ampoule was placed in an elongated recess machined into a copper pan. The extraction cell can accommodate up to eight pyrite-containing ampoules in a single loading and pump-down cycle; the ampoules are subsequently heated and analysed sequentially. The assembly was covered with protective sapphire glass and loaded into the extraction cell (Fig. 4c).
5. The laser-extraction cell was first evacuated using a forevacuum pump (via VM17, with VM16 and VM15 closed; Fig. 3) and then using a turbomolecular pump (via VM16 and VM14, with VM17 and VM15 closed; Fig. 3). Pumping required approximately 12 h, after which the residual pressure in the cell did not exceed 10^{-8} Torr.
6. Heating was performed using a defocused laser beam operated in scanning mode (Fig. 4d). The area of the assembly to be heated was defined using the laser-control software (EzCad2, version 2.14.10). The He-extraction temperature was monitored using an optical pyrometer (Promin-M). The released He was purified from other gases using a cold finger cooled with liquid nitrogen and getter pumps (Fig. 3). Heating was performed in at least two extraction steps over a constant scanning area of $\sim 2 \times 12$ mm. The initial laser power was 50% for 2000 scans (~ 1050 °C), followed by a second step, typically at 80% laser power for ~ 1000 scans (~ 1300 °C). Heating continued until no further He release was detected for 10 min; He release was monitored continuously during heating with valves VM15, VM5, and VM6 open (Fig. 3b). The total measurement time was approximately 40–60 min.
7. The procedural blank was determined by heating an empty quartz ampoule wrapped in tantalum foil under the same conditions as the samples.
8. After He extraction, the quartz ampoules containing the pyrite decomposition products (pyrrhotite and sulfur; Fig. 4e) were removed from the extraction cell for subsequent determination of U and Th concentrations.

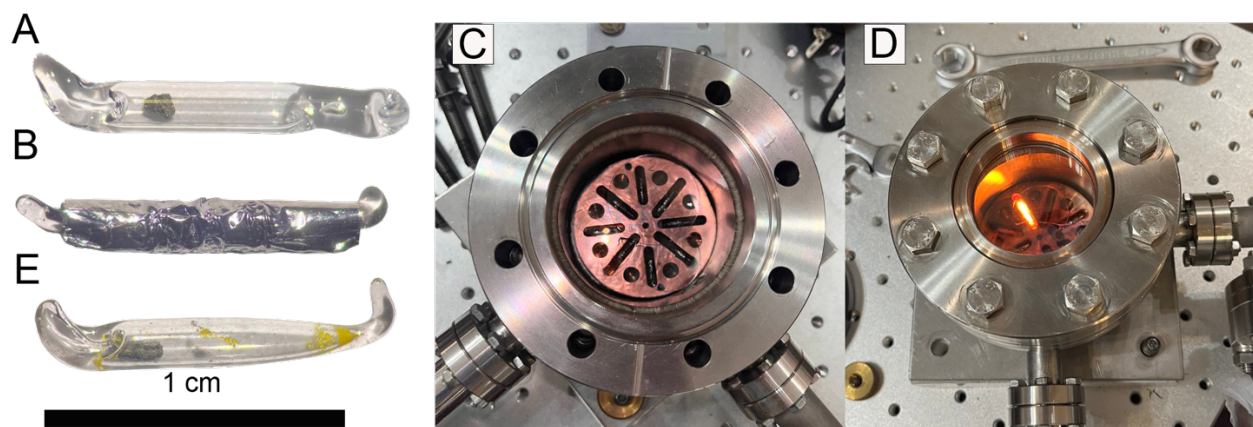


Fig. 4. Main sample-preparation and He-extraction steps. (a) – Sealed quartz ampoule containing a pyrite grain. (b) – Sealed quartz ampoule wrapped in tantalum foil. (c) – Samples loaded into the copper pan and covered with sapphire glass. (d) – Sample heating using the ytterbium fiber laser in a scanning mode. (e) – Quartz ampoule after degassing, containing the products of pyrite decomposition: yellow –sulfur and residual pyrrhotite.

4.2 Uranium and Th measurements

U and Th concentrations were determined by isotope-dilution inductively coupled plasma mass spectrometry (ICP-MS). Sample preparation was performed in the Laboratory of Isotope Geology at IPGG RAS as follows:

1. The entire quartz ampoule containing the pyrite decomposition products (Fig. 4e) was placed in a 3 mL Teflon vial and spiked with ^{235}U - ^{230}Th or ^{236}U - ^{230}Th tracer (Fig. 5a).
2. The sample was treated with 300 μL of HF and 200 μL of HNO_3 , followed by one drop of HClO_4 (Fig. 5b).
3. The closed Teflon vial was placed inside an outer Teflon vessel containing 1.5 mL of HF (Fig. 5c).
4. The complete assembly was sealed in a high-pressure digestion autoclave and heated at 220 $^\circ\text{C}$ for 48 h (Fig. 5d).
5. After digestion, the samples were evaporated to moist salts on a hot plate at 210 $^\circ\text{C}$ and then redissolved in 3 mL of 5% HNO_3 for subsequent determination of $^{235}\text{U}/^{238}\text{U}$ (or $^{236}\text{U}/^{238}\text{U}$) and $^{230}\text{Th}/^{232}\text{Th}$ ratios by ICP-MS. U and Th were measured using Thermo Scientific ELEMENT 2 (GEOKHI RAS) and ELEMENT XR (IPGG RAS) high-resolution ICP-MS, as well as an Agilent 7900 quadrupole ICP-MS (AES, SPbU). The instrument used for each analysis was selected according to availability at the time of measurement.
6. The procedural blank was determined using an empty quartz ampoule dissolved and measured under the same conditions.

The ability of the digestion protocol to dissolve refractory mineral inclusions in pyrite, such as zircon, was verified experimentally using a synthetic mixture. Relatively coarse zircon grains ($\sim 50 \mu\text{m}$) were added to pyrite in a quartz ampoule



prior to digestion. Complete dissolution of the added zircon grains confirmed that the protocol ensures quantitative recovery of U and Th hosted in such accessory-mineral phases (Ivanova, 2024).

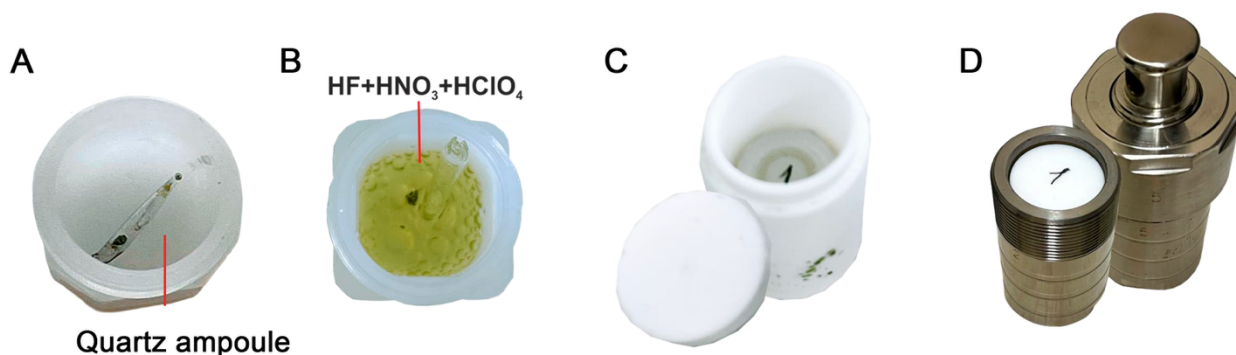


Fig. 5. Main dissolution steps for pyrite (U,Th)-He dating. (a) Quartz ampoule containing the degassed sample in a 3 mL Teflon vial. (b–d) – Preparation of the sample for autoclave digestion in a mixture of HF, HNO₃, and HClO₄.

U and Th contents in Durango apatite were determined by isotope-dilution ICP-MS following a similar chemical procedure, except that the quartz ampoules containing apatite were dissolved in a mixture of HF and HNO₃ without high-pressure autoclave digestion. (U,Th)-He ages were calculated using IsoplotR version 7.0 (Vermeesch, 2018). Given the relatively large size of the pyrite grains (>300 μm), no α-ejection correction was applied.

5. Results

The procedural hot blank obtained by laser heating an empty quartz ampoule wrapped in tantalum foil (1.1×10^{10} atoms) is indistinguishable from that previously measured using a high-vacuum furnace (1.1×10^{10} atoms; (Yakubovich et al., 2024). The (U,Th)-He ages obtained for Durango apatite (Table 1) range from 29.5 to 32.7 Ma and yield a weighted mean of 31.3 ± 1.0 Ma (MSWD = 3.2). Despite the moderate overdispersion of the individual analyses, the weighted-mean age agrees with the range of 31.04–31.44 Ma reported by other laboratories (Corona-Esquivel et al., 2018), supporting effectively complete He extraction from mineral grains encapsulated in quartz ampoules using the scanning fiber-laser procedure.

In total, 12 pyrite aliquots were analysed: seven from the Pavlik deposit and five from the Upryamoe ore field (three of the latter were previously analysed by (Canhimbue et al., 2025). The individual grains used for dating weighed 0.7–1.6 and 1.2–2.0 mg for Pavlik and Upryamoe, respectively. The Pavlik pyrite has U concentrations of 0.5–1.9 ppm and Th/U ratios of 2.6–7.4. Its ⁴He concentrations range from 1.4×10^{-5} to 8.3×10^{-5} cm³ STP g⁻¹. The weighted-mean age of the seven analyses is 139 ± 2.8 Ma. The Upryamoe pyrite contains markedly less U (0.14–0.31 ppm), whereas its Th/U ratios span a similarly broad range (2.4–6.4). Its measured ⁴He concentrations range from 0.32×10^{-5} to 0.97×10^{-5} cm³ STP g⁻¹. The weighted-mean age is 124.5 ± 1.8 Ma (n = 5).



Because the analysed pyrite grains show considerable variability in U and Th concentrations, He isochrons were constructed to obtain more robust age estimates. Both freely fitted isochrons yielded negative intercepts that are statistically indistinguishable from zero: $(-950 \pm 3250) \times 10^{10}$ and $(-565 \pm 786) \times 10^{10}$ atoms g^{-1} for Pavlik and Upryamoe, respectively.

275 The final regressions were therefore calculated with the intercept fixed at zero. The resulting pyrite (U,Th)-He isochron ages are 139.3 ± 1.7 Ma for the Pavlik deposit (Fig. 6a) and 125.4 ± 2.1 Ma for the Upryamoe gold occurrence (Fig. 6b).

Table 1. Results of (U,Th)-He dating of pyrite by the fiber-laser scanning He extraction technique.

Batch #	ID	weight, mg	Laser power, %	^4He , 10^{10} at	1σ , %	U, 10^{10} at	1σ , %	Th, 10^{10} at	1σ , %	Th/U	U, ppm	^4He , 10^{-5} cm^3 STP g^{-1}	Age, Ma	$\pm$, Ma
Pavlik Pyrite NG-001														
6	1661	1.6		130.3	1.7	333	2.6	1796.0	1.1	5.4	0.83	3.04	134	6
			50%	114.4										
			70%	15.0										
			80%	0.9										
6	1663	1.5		93.8	2.1	308	2	989.0	1.6	3.2	0.81	2.34	135	6
			50%	74.9										
			70%	16.5										
			80%	2.4										
6	1665	0.7		68.3	0.7	205	1.7	748.5	1.2	3.7	1.16	3.64	139	3
			50%	67.7										
			80%	0.6										
7	1780	0.8		29.2	1	105	2.4	268.8	1.4	2.6	0.52	1.36	135	5
			50%	28.8										
			80%	0.4										
7	1781	1.3		287.2	1	610	1.8	4521.3	1.2	7.4	1.86	8.25	134	3
			50%	287										
			80%	0.2										
8	2108	1.0		125.2	0.5	277	1.5	1740.1	1.5	6.3	1.10	4.67	142	2
			50%	121.6										
			80%	3.6										
8	2110	1.4		213.7	0.6	602	3	2488.3	3	4.1	1.71	5.70	140	5
			50%	207.6										
			80%	6.1										
Weighted mean: 139 ± 2.8 Ma; MSWD = 4.1														



Upryamoe Pyrite C12-65.9														
4	1495*	2.0		51.9	1.1	129.5	2.4	832.8	1.7	6.4	0.26	0.97	125	4
			50%	18.6										
			60%	18.2										
			70%	8.7										
			80%	4.5										
			90%	1.9										
4	1499*	1.7		28.3	0.5	116.1	3.0	273.4	2.5	2.4	0.27	0.62	122	5
			50%	18.6										
			60%	7.2										
			70%	2.0										
			80%	0.5										
5	1565*	1.8		38.8	0.9	139.1	1.5	432.5	2.5	3.1	0.31	0.80	125	3
			50%	21.6										
			60%	11.6										
			80%	4.4										
			90%	1.2										
6	1659	1.4		29.8	0.8	96.5	2.4	370.5	1.2	3.8	0.27	0.79	126	4
			50%	29.2										
			80%	0.6										
6	1667	1.2		10.2	2.0	41.6	2.4	102.2	1.9	2.5	0.14	0.32	121	6
			50%	7.4										
			70%	2.3										
			80%	0.4										
			85%	0.1										
Weighted mean: 124.5±1.8 Ma; MSWD = 1.1														
Durango apatite Dur-4														
1	1399	–		178.4	0.6	815.6	2.2	15895	2.5	19.5	–	–	30.9	0.5
2	1409	–		209.6	1.0	1007.9	2.3	17230	5.1	17.1	–	–	32.7	0.7
2	1411	–		178.7	1.2	920.3	1.9	16411	2.5	17.8	–	–	29.5	0.7
3	1430	–		260.3	0.9	1190.6	1.9	21958	2.2	18.4	–	–	32.3	0.7
3	1432	–		104.9	0.9	507.0	1.9	9091	2.1	17.9	–	–	31.3	0.6
Weighted mean: 31.3±1 Ma; MSWD = 3.2														
Empty Quartz ampoule in Tantalum foil														
	***	~ 40		1.1	47	1.3	74	6	97	4.6	–	–	–	–



* Samples-previously analysed by (Canhimbue et al., 2025).
** Samples with the same loading-batch number were loaded into the He-extraction cell simultaneously.
*** The He value is the mean of seven measurements from six separate batches; the U and Th values are the mean chemical blanks for empty quartz ampoules (Yakubovich et al., 2024).
**** The He, U, and Th contents of pyrite and apatite were blank-corrected; uncertainties in the He, U, and Th blanks were propagated into the uncertainties of the blank-corrected values and calculated ages.

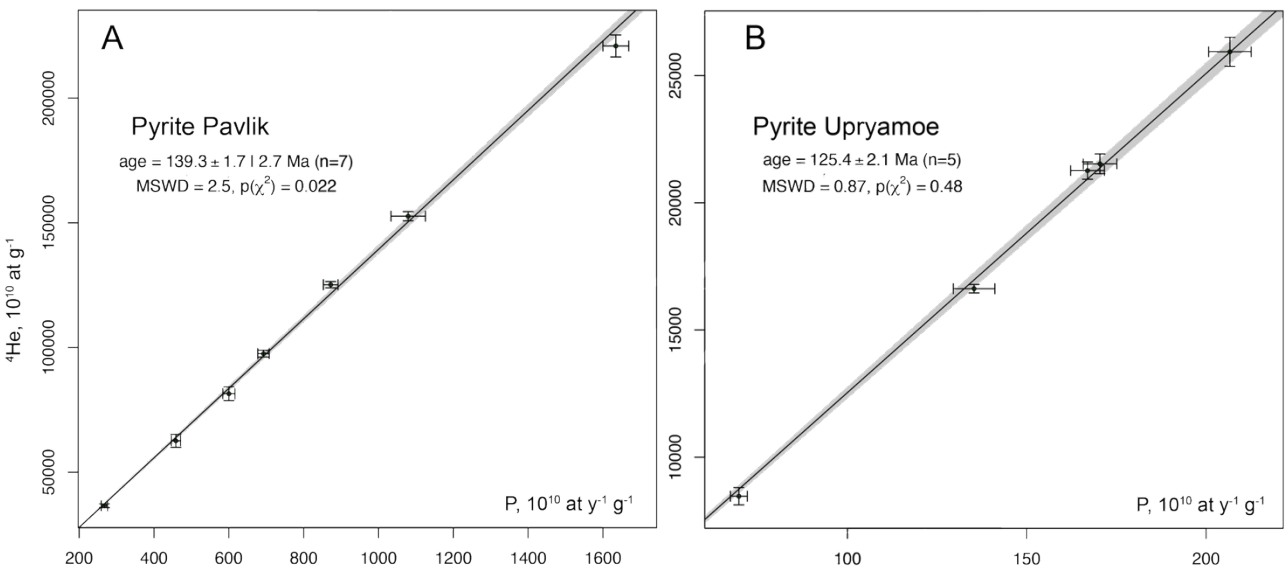


Fig. 6. Pyrite (U,Th)-He isochrons (a) the-Pavlik orogenic gold deposit, Magadan Region, and (b) – the Upryamoe gold occurrence, Chukotka. Error bars –represent 2σ uncertainties.

6 Discussion

6.1 Analytical performance of the scanning fiber-laser procedure

The proposed analytical procedure based on radiogenic He extraction from pyrite using a scanning fiber-laser system yields internally consistent and geologically meaningful pyrite (U,Th)-He ages. The zero-intercept regression ages obtained for the Pavlik deposit ($139.3 \pm 1.7 \text{ Ma}$; $n = 7$) and the Upryamoe ore field ($125.4 \pm 2.1 \text{ Ma}$; $n = 5$) are consistent with independent geological and geochronological constraints discussed below. The effectiveness of He extraction is independently supported by the Durango apatite analyses, which yielded a weighted-mean (U,Th)-He age of $31.3 \pm 1.0 \text{ Ma}$, consistent with published values. Together with the negligible He released during the final heating steps (Table 1), these results indicate that scanning the laser beam across the tantalum foil generates and maintains temperatures sufficient for effectively complete He extraction from the encapsulated mineral grains. No systematic relationship was observed between the measured ages and the heating sequence within a loading batch, suggesting that thermal effects on adjacent ampoules were negligible. The He blank obtained by heating empty quartz ampoules wrapped in tantalum foil in the laser-extraction cell (1.1×10^{10} atoms) is indistinguishable



from that previously obtained using a high-vacuum furnace (1.1×10^{10} atoms; (Yakubovich et al., 2024). This comparison indicates that laser extraction does not introduce a measurable additional He blank. The blank is therefore likely dominated by residual atmospheric He retained in the quartz ampoule after sealing under forevacuum conditions (10^{-3} Torr).

In its current configuration, the extraction cell accommodates up to eight ampoules in a single loading and pump-down cycle.

305 The samples are subsequently heated and analysed sequentially, increasing analytical throughput by approximately an order of magnitude relative to the previous high-vacuum furnace configuration, in which each ampoule required a separate pump-down cycle. Given the large working area of the laser marker (20×20 cm), the vacuum extraction cell could be further modified to accommodate even more samples per loading cycle.

6.2 Geological implications

310 The pyrite (U,Th)-He age obtained for the Pavlik deposit (139.3 ± 1.7 Ma) broadly agrees with the mineralization ages reported for the geologically and genetically related Natalka deposit: 136 ± 1 Ma (Re-Os) and 133 ± 2 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$; Akinin et al., 2023). This supports the previous interpretation that mineralization at Natalka and Pavlik, which together form a group of deposits with exceptionally large Au reserves (30 Moz), occurred broadly contemporaneously (Akinin et al., 2023). No evidence of magmatic activity between 139 and 133 Ma has been documented in the region. Thus, the gold-quartz
315 mineralization was likely related to metamorphic and metasomatic processes associated with regional-scale shear deformation rather than to magmatic activity, providing a potentially useful framework for regional gold exploration (Akinin et al., 2023). The Pavlik results confirm that pyrite (U,Th)-He dating can be successfully applied to orogenic gold deposits. The pyrite contains relatively high U and Th concentrations (up to 2 and 14 ppm, respectively), and the (U,Th)-He isochron intercept is statistically indistinguishable from zero ($-950 \pm 3250 \times 10^{10}$ atoms g^{-1}), indicating that the contribution of trapped He to the
320 calculated ages is likely negligible. The Pavlik results demonstrate that geologically meaningful (U,Th)-He ages can be obtained from inclusion-bearing pyrite (Fig. 1). The surrounding pyrite effectively retains a substantial proportion of the radiogenic He produced by these U- and Th-bearing phases. The moderate overdispersion of the (U,Th)-He ages (MSWD = 2.5) may be related to the complex internal structure of the pyrite, silicate inclusions and/or underestimation of α -recoil effects associated with the strongly heterogeneous distribution of parent nuclides.

325 The geological significance of the pyrite age obtained for the Upryamoe ore field was discussed in detail by Canhimbue et al., 2025. The additional analyses presented here provide a more precise estimate (125.4 ± 2.1 Ma) of the previously reported age (123 ± 4 Ma). From a geochronological perspective, the Upryamoe results demonstrate that As-zoned pyrite containing few mineral inclusions from low-sulfide orogenic gold-mineralization sites (Fig. 2) is suitable for (U,Th)-He dating. The pyrite contains sufficient U and Th (up to 0.3 and 1.2 ppm, respectively) and little trapped He, as indicated by an isochron intercept
330 statistically indistinguishable from zero ($-565 \pm 786 \times 10^{10}$ atoms g^{-1}).

The results from the Pavlik and Upryamoe gold-mineralization sites are particularly important because the (U,Th)-He system yielded reliable mineralization ages, whereas previous Re-Os analyses failed to provide robust age estimates. These results



demonstrate that single-grain pyrite (U,Th)-He geochronology can directly constrain the timing of gold mineralization if a robust paragenetic relationship is established.

335 7 Conclusion

This study presents a new analytical approach to (U,Th)-He dating of individual pyrite grains and grain fragments. We demonstrate that a widely available commercial fiber-laser marking system operated in scanning mode can efficiently extract radiogenic He from pyrite encapsulated in quartz ampoules. The ampoules retain the thermal decomposition products and associated parent nuclides, allowing U and Th to be subsequently determined in the same material from which He was
340 extracted. The approach was validated using pyrite from two Au-bearing sites in the Russian Far East: the Pavlik orogenic gold deposit in the Magadan Region and the Upryamoe gold occurrence in Chukotka. These samples yielded pyrite (U,Th)-He ages of 139.3 ± 1.7 Ma ($n = 7$) and 125.4 ± 2.1 Ma ($n = 5$), respectively. Compared with the previously developed high-vacuum furnace procedure, the scanning fiber-laser approach increases analytical throughput by approximately an order of magnitude by allowing up to eight ampoules to be loaded during a single pump-down cycle and subsequently analysed within
345 one working day. By making individual-grain age determinations faster and operationally simpler, the method enables larger datasets to be acquired and thereby improves the statistical characterization of pyrite ages from a range of geological settings.

Author contributions

OVY prepared the original manuscript draft. NAV performed the He, U, and Th measurements. LAS performed the mineralogical characterization and He measurements. ESP conducted the chemical preparation and He measurements. OVY,
350 ABK, NAV, LAS, BMG, and ESP developed the analytical methodology. MOA and EVA conducted the U and Th measurements. VVA and EVV provided the geological framework and samples.

Data availability

All data supporting the findings of this study are provided in the manuscript. A limited amount of pyrite material from the Pavlik deposit is available from the corresponding author upon reasonable request.

355 Competing interests

The authors declare that they have no conflict of interest.



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