Online Resource 1: Detailed analytical methods

The petrographic observations on the thin sections took place in the microscope laboratory of the Oulu Mining School in the University of Oulu and the Geological Survey of Finland (GTK) in Espoo. Petrographic observations were also aided with a high resolution JEOL TM JSM-7100F Field Emission SEM (FE-SEM) equipped with an energy dispersive detector for qualitative estimation of elemental composition at the Finnish Geoscience Research Laboratories (SGL), GTK, Espoo.

Sulfur isotopes were analyzed from pyrite, pyrrhotite and chalcopyrite by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). In total, 25 samples were analyzed, and 105 analytical spots were collected on pyrite, 44 on pyrrhotite and 12 on chalcopyrite. The analyses were performed using a Nu Plasma HR multicollector ICPMS equipped with a Photon Machine Analyte G2 laser ablation system at the Finnish Geosciences Research Laboratories located at the GTK in Espoo. Samples were ablated within a HelEx ablation cell (Müller et al., 2009) in He gas (gas flows = 0.4 and 0.1 l/min). Sulfur isotopes were analyzed at medium resolution ($\Delta M/M = 3000$) and data for ^{32}S and ^{34}S were collected in static mode. The diameter of the laser beam was 40 μm using a fluence of 3.5 J/cm3 at 3 Hz frequency. The total sulfur signal obtained was typically 1.5–5 V for pyrite whereas it was around 0.8–1.1 V for pyrrhotite and chalcopyrite. Under these conditions, after a 20 s baseline, 50–60 s of ablation was needed to obtain an internal precision of $^{34}S/^{32}S \leq \pm 5 \times 10^{-6}$ SE (Standard Error). The pyrite standard PPP-1 (Gilbert et al. 2014) and an in-house pyrite standard (Py2) have been used for external standard bracketing and quality control of analyses. The in-house pyrite standard Py2 has been previously measured by gas mass spectrometry. For in-house standard Py2, with $\delta^{34}S_{CDT}$ (‰) values of -0.4 ± 0.5‰ (1σ) we measured average values of -0.2 ± 0.33‰ (2σ, n = 17). For pyrrhotite, the in-house standard Polopo was used for quality control. The Polopo standard has also been previously measured by gas mass spectrometry. For a $\delta\ ^{34}S_{CDT}$ (‰) reference value of 5.6 ± 0.6 ‰ (1s) we have found an average value of 5.8 ± 0.4 ‰ (2s, n=6). Chalcopyrite samples were ablated using the same laser ablation parameters. Two in-house chalcopyrite standards have been used for external standard bracketing and quality control of analyses. Those standards have been measured by gas mass spectrometry. For a $\delta\ ^{34}S_{CDT}$ (‰) value of -0.7± 0.5 ‰, we have found an average value of -0.5 ± 0.7 ‰ (2s, n=5).

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) by means of an Analyte 193 ArF laser ablation system (Photon Machines, San Diego, USA) connected to a single collector Nu AttoM SC-ICP-MS instrument (Nu Instruments Ltd., Wrexham, UK) was applied to measure trace element contents of sulfide minerals. 18 samples were analyzed, and 81 analytical spots were collected on pyrite, 40 on pyrrhotite and 6 on chalcopyrite. All the analytical spots for the sulfide trace elements were placed next to already analyzed spots for sulfur isotope data. The laser was run at a pulse frequency of 10 Hz and a fluence of 2.5 J/cm^3 on the sample surface with a 50 μm spot size. Analyses were initiated with a 20 s baseline measurement, then the laser was automatically switched on for 40 s of signal acquisition. Analyses were conducted using time-resolved analysis (TRA) with continuous acquisition of data for each set of points. Mass-1 (Wilson et al. 2002) and UQAC were used as external standards for quality control of the analyses. The measurements were performed for 37 elements (Al, Si, S, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, Ga, Ge, As, Se, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, Ba, W, Pt, Au, Hg, Tl, Pb, Bi, Th, U) at low resolution (400 laser pulses) using the fast scanning mode. Data reduction

was carried out using the software GLITTER (van Achterbergh et al. 2000) which allows the baseline subtraction, the integration of the signal over a selected time resolve area, and the quantification using known concentrations of the external and internal standards. For our data, we used Fe as the internal standard, for the calculation of the trace element concentrations of the analyzed sulfides. By processing the data and eliminating individual spikes in the produced signals we ensured that the trace element data will not be affected by potential microinclusions of other minerals in the analyzed sulfide grains.

The compositional analyses of tourmaline took place at the GeoRessources department, Université de Lorraine, Nancy. Tourmaline crystals were observed and photographed with a scanning electron microscope (SEM) Hitachi S-4800 with an acceleration voltage of 15 kV. Chemical compositions of tourmaline crystals were obtained with a microprobe Cameca SX100 with an emission current of 20 nA and an acceleration voltage of 15 kV. Albite was used as a standard for Na and Si, olivine for Mg, an artificial standard of Al_2O_3 for Al, orthoclase for K, andradite for Ca, an artificial standard of $MnTiO_3$ for Ti and Mn, an artificial standard of Fe_2O_3 for Fe, vanadinite for Cl and an artificial standard of Cr_2O_3 for Cr.

For isotopic analysis of boron in tourmaline, an ion microprobe SIMS 1280-HR was used at the Centre de Recherches Pétrographiques et Géochimiques (CRPG), Nancy. Samples received a primary beam of O- of 13 kV with a diameter of about 20 μm. Secondary ions of ^{10}B and ^{11}B were analyzed with a mass resolution of 2000. 30 cycles were made for each of the analyses. Boron isotopes are reported as $\delta^{11}B‰$ relatively to the NIST SRM 951 standard using a value of 4.04362 for $^{11}B/^{10}B$ (Catanzaro, et al., 1970). Instrumental mass fractionation was determined using two tourmaline reference materials corresponding to dravite (Harvard #108796) and schorl (Harvard #112566), respectively described by Dyar et al. (2001) and Leeman and Tonarini (2001). Standards have been used depending on the tourmaline type which is analyzed to avoid matrix effect. The reproducibility (2σ) on standards is inferior to 1 for both standards.

A part of this study is based on the whole-rock geochemical data provided by Dragon Mining. The dataset comprises multi-element analyses including major and trace elements and REEs. The whole-rock chemical analyses were acquired by Als Global Ltd. at their laboratories in Rosia Montana, Romania and Vancouver, Canada during 2011. Gold assays were completed in Rosia Montana and the rest of the assays in Vancouver. Sample preparation was completed at the ALS Global facility in Outokumpu, Finland. Most of the elements (Ag, Ba, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Lu, Mo, Nb, Nd, Ni, Pb, Pr, Rb, Sm, Sn, Sr, Ta, Tb, Th, Tl, Tm, U, V, W, Y, Yb, Zn, Zr) were analyzed with the use of inductively coupled plasma mass spectroscopy (ICP-MS) using the analytical method ME-MS81 (Alsglobal 2019). The concentrations of selected metals (Ag, As, Cd, Co, Cu, Pb, Zn, Mo, Ni) were also measured with inductively coupled plasma atomic emission spectroscopy (ICP-AES) by using the four-acid digestion method ME-4ACD81 (Alsglobals 2019). Sulfur concentrations were measured with the S-IR08 method by using a Leco sulfur analyzer (Alsglobal 2019). Au concentrations were measured using the fire assay method AU-GRA22 and with atomic absorption spectrometry (AAS) method Au-AA25 (Alsglobal 2019). The concentration of major oxides (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, Cr_2O_3, TiO_2, MnO, P_2O_5, SrO, BaO) was measured by ICP-AES with the ME-ICP06 method (Alsglobal 2019). The whole-rock geochemical database was used as an aid in drill core logging and sample selection and it was also used to determine the protoliths of the altered Juomasuo rocks as well as to study the alteration associated with the mineralization.

Whole-rock chemical data was subjected to multivariate statistical analysis. More specifically, Principal

Component Analysis (PCA) was performed using the XLSTAT software package (Addinsoft 2020). Prior to this, the used data were subjected to a centred log-ratio transformation (clr-transformation; Aitchison 1986) in order to address the closure effect that geochemical data exhibits (Reimann et al. 2008). This was done using the GCDkit software (Janoušek et al. 2006) run in an R environment.

References

Addinsoft (2020). XLSTAT statistical and data analysis solution. Boston, USA. https://www.xlstat.com.

Aitchison J (1986) The Statistical Analysis of Compositional Data. Chapman and Hall, London, U.K., p. 416.

Alsglobal (2019) Schedule of Services and Fees, Geochemistry 2019. Available online at: https://alsglobal.azureedge.net/-/media/als/resources/services-and-products/geochemistry/fee-schedules/als-geochemistry-fee-schedule-cad.pdf

Catanzaro EJ, Champion CE, Garner EL, Marinenko G, Sappenfield KM, Shields WR (1970) Boric acid: isotopic and assay standard reference materials. NBS (US) Spec Publ 260-17: 1-71

Dyar M, Wiedenbeck M, Robertson D, Cross L, Delaney J, Ferguson K, Yates M (2001). Reference minerals for microanalysis of light elements. *Geostandards Newsletter: The J of Geostandards and Geoanalysis, 25*, pp. 441-463.

Gilbert SE, Danyushevsky LV, Rodermann T, Shimizu A, Gurenko A, Meffre S, Thomas H, Large RR, and Death D (2014). Optimisation of laser parameters for the analysis of sulphur isotopes in sulphide minerals by laser ablation ICP-MS. JAAS 29: 1042–1051

Janoušek V, Farrow CM, ERBAN V (2006) Interpretation of Whole-rock Geochemical Data in Igneous Geochemistry: Introducing Geochemical Data Toolkit (*GCDkit*), *J of Petrol*, Volume 47, Issue 6, p. 1255–1259.

Leeman WP, Tonarini S (2001) Boron isotopic analysis of proposed borosilicate mineral reference samples. Geostand Newslett 25:399-403.

Müller W, Shelley M, Miller P, Broude S (2009). "Initial performance metrics of a new custom-designed ArF excimer LA-ICPMS system coupled to a two-volume laser-ablation cell. Journal of Analytical Atomic Spectrometry, 24: 209-214.

Reimann C, Filzmoser P, Garrett RG and Dutter R (2008) Statistical Data Analysis Explained: Applied Environmental Statistics with R. John Wiley & Sons Ltd., Chichester, England, 362 pp

Van Achterbergh E, Ryan CG, Jackson SE ,Griffin WL (2001) Data reduction software for LA-ICP-MS, in Sylvester PJ (ed.), Laser ablation-ICP-mass spectrometry in the Earth Sciences: Principles and applications: Ottawa, Ontario, Miner Assoc of Canada, Short Course Series, 29, 239-243

Wilson SA, Ridley WI, Koenig AE (2002). Development of sulfide calibration standards for the laser ablation inductively-coupled plasma mass spectrometry. J. Anal. At. Spectrom, 17406-409.

Mineralium Deposita

Geochemical signatures of mineralizing events in the Juomasuo Au-Co deposit, Kuusamo belt, northeastern Finland

Mikael Vasilopoulos*, Ferenc Molnár, Hugh O´Brien, Yann Lahaye, Marie Lefèbvre, Antonin Richard, Anne-Sylvie André-Mayer, Jukka-Pekka Ranta, Matti Talikka

Affiliation of corresponding author: Oulu Mining School,University of Oulu, P.O. Box 3000, 90014 Oulu, Finland

**email of corresponding author: mikael.vasilopoulos@student.oulu.fi*