

Supplement 4. Methods

We spent three field seasons in the vicinity of the White Pine Mo-W deposit and in the East Traverse Mountains, mapping at a scale of 1:24,000. We collected a suite of 80 samples, representative of each intrusive igneous lithology, attempting to gather the freshest possible examples to establish igneous geochemistry as well as some heavily altered samples to understand the hydrothermal system.

We used a Rigaku ZSX Primus II X-ray fluorescence spectrometer at Brigham Young University to determine whole-rock major and certain trace element compositions of 59 of our 80 samples. See Supplement 4 for XRF methodology. Major element oxides (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , K_2O , and P_2O_5) were analyzed using fused glass disks. Uncertainties are less than 1% relative based on replicate analyses of standard reference materials (Dailey et al., 2018). Trace elements were analyzed using pressed powder pellets, and include Sc, V, Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Sm, Pb, Th, and U. XRF preparation included fine crushing in a tungsten-carbide shatterbox. Each sample was dried at 105°C, then calcined in a 1000°C muffle furnace for 4 hours to measure loss-on-ignition (LOI). Lithium metaborate fused glass disks were prepared using a Katanax K1 Prime fluxer. Glass disks were analyzed for major element concentrations. Separate pressed pellets were produced for each sample in a hydraulic press at 20 tons using a combination of sample powder and briquetting additive. Pressed pellets were analyzed for trace elements. All XRF analyses were performed at Brigham Young University using a Rigaku ZSX Primus II XRF spectrometer operating at 50 kV and 50 mA. Thirty international reference materials are used to construct the calibration curves using a fundamental parameters reduction method. Based on repeated analyses of international reference materials, estimates of uncertainty for XRF analysis are $\pm 1\%$ relative for concentrations above 0.2% for major elements. For trace elements, uncertainties are less than 7% relative for concentrations above 10 ppm; below that, uncertainties are about 10%. See the table below for comparison of accepted compositions with our analyses.

New U-Pb zircon ages were acquired for twelve samples from the Little Cottonwood stock and East Traverse Mountains. We characterized samples via CL imagery and selected spatial domains for analysis via LA-ICP-MS to mitigate potential complications caused by alteration and/or inheritance. Samples selected for geochronological work were crushed in a roller mill to 30 mesh size, then passed through a magnetic separator. The heavy minerals in the non-magnetic portion were then separated using tetrabromoethane and methylene iodide. Zircon grains were selected by hand, mounted in epoxy, polished, and carbon coated. Cathodoluminescence (CL) images of the zircon epoxy mounts were acquired at Brigham Young University using a Gatan miniCL detector, and a ThermoScientific Apreo C Low-Vacuum Scanning Electron Microscope or an ESEM XL30 FEI scanning electron microscope. Images were recorded using a spot size of 14 μm , a tilt of 0°, a scan acquisition time of 6 ms/pixel, and an accelerating voltage of 15 kV on the Apreo, and spot size of 6 μm , tilt of -10°, scan time of 66 ms/line, and voltage of 15 kV on the ESEM.

Uranium and lead isotopes in zircon were analyzed at the University of Utah using the methods of Couper (2016) and Stearns et al. (2020). The laser ablation system was a 193 nm Teledyne Photon Machines Analyte Excite, and the ICP-MS was either an Agilent 7500ce quadrupole or a Thermo Neptune Plus multicollector. The laser repetition rate was 6 Hz with a fluence of 9.5 J/cm² at 100% beam energy. Helium was used as a carrier gas at 1 L/min. Isotopic analyses were bracketed by analyses of the zircon standards Plesovice (Sláma et al., 2008) and 91500 (Wiedenbeck et al., 1995) which were also used to determine accuracy and propagate external uncertainties. Round robins included these standards as well as R33 and Temora II (Black et al., 2004), and SL2 (Gehrels et al., 2008). Approximately 35-50 spots analyzed in each sample. Supplement 5 contains ages of these reference materials. The accepted age for the Plesovice zircon is 1065 Ma; the weighted mean age of our 113 analyses is 1061.8 ± 5.7 Ma (2 s.e). This is 0.3% different than the accepted value. The weighted mean age of R33 was 414.7 ± 2.4 Ma (n=13) vs. the accepted age of 419 Ma—a 1.0% difference--and 554 ± 1.9 Ma—a 3.4% difference.

CL images of selected zircons are included in Supplement 6. As we desired to sample only the outermost, youngest rims of these small zircons, most spots were 20 microns in diameter, while others were sampled with a 15-micron spot because of the very small size and fine oscillatory zoning of the grains.

The isotopic data were reduced using Iolite 2.5 (Paton et al., 2011), including correction for laser-induced time dependent fractionation using the down hole correction procedure. Ages were extracted using IsoPlotR (Vermeesch, 2018). Data uncorrected for common Pb are plotted on Tera-Wasserburg diagrams (Fig. 4). The reported uncertainties include that based on counting statistics and the homogeneity and accuracy of the standards as propagated in quadrature (Supplementary Table 3), which were typically $\pm 2\%$ or about 600,000 y for these Oligocene rocks. Common Pb corrections for the ²³⁸U-²⁰⁶Pb ages were based on the Stacey-Kramer (1975) growth curves as incorporated in IsoPlotR. Only concordant ages were corrected for common Pb and used to construct rank order plots and KDE (Kernel Density Estimate) profiles (Figs. 4 and 5). These corrections were small and did not exceed analytical uncertainty. The concordia and even the weighted mean U-Pb ages of the concordant points had large MSWDs (mean square weighted deviates), showing that the range of ages exceeded that expected from analytical uncertainty alone. Moreover, KDE plots are commonly multimodal. We interpret these variations to represent real events—incorporation of zircon xenocrysts or antecrysts, and hydrothermal alteration--and used mixing models in Vermeesch's (2012) Density Plotter app to extract possible ages of peaks and shoulders on the complex age spectra.

BYU analyses of reference materials compared to accepted values from GeoRem.

	BHVO-2			JA-1			JA-2			JB-1a			JR-1			JR-2			RGM-1		
	BYU	Certified ^a	SD ^c	BYU	Certified ^a	SD ^c	BYU	Certified ^a	SD ^c	BYU	Certified ^a	SD ^c	BYU	Accepted ^b	SD ^c	BYU	Accepted ^b	SD ^c	BYU	Accepted ^b	SD ^c
Major oxides (wt. %)																					
SiO ₂	49.49	49.90	0.10	63.70	63.97	0.17	55.90	56.42	0.06	51.96	52.41	0.19	75.17	75.43	0.18	75.73	75.67	0.16	72.88	73.43	0.12
TiO ₂	2.70	2.73	0.01	0.84	0.85	0.01	0.68	0.66	0.00	1.29	1.28	0.01	0.12	0.11	0.01	0.07	0.08	0.00	0.29	0.27	0.00
Al ₂ O ₃	13.48	13.50	0.04	15.11	15.22	0.07	15.39	15.41	0.05	14.40	14.45	0.06	12.81	12.86	0.05	12.70	12.77	0.04	13.70	13.71	0.04
Fe ₂ O ₃	12.39	12.30	0.07	6.85	7.07	0.03	6.22	6.21	0.01	8.80	9.05	0.07	0.89	0.93	0.03	0.78	0.82	0.01	1.88	1.86	0.01
MnO	0.17	0.17	0.00	0.15	0.16	0.00	0.11	0.11	0.00	0.14	0.15	0.00	0.10	0.10	0.00	0.11	0.11	0.00	0.04	0.04	0.00
MgO	7.24	7.23	0.07	1.55	1.57	0.03	7.81	7.60	0.07	7.75	7.83	0.07	0.13	0.11	0.03	0.04	0.05	0.01	0.27	0.28	0.01
CaO	11.37	11.40	0.02	5.61	5.70	0.02	6.27	6.29	0.01	9.22	9.31	0.04	0.67	0.65	0.04	0.49	0.48	0.00	1.16	1.15	0.00
Na ₂ O	2.27	2.22	0.08	3.77	3.84	0.07	2.95	3.11	0.04	2.67	2.73	0.05	4.00	4.06	0.09	3.98	4.01	0.08	3.97	4.07	0.05
K ₂ O	0.51	0.52	0.00	0.76	0.76	0.00	1.74	1.81	0.00	1.39	1.40	0.01	4.43	4.41	0.02	4.48	4.45	0.01	4.33	4.30	0.01
P ₂ O ₅	0.28	0.27	0.00	0.16	0.17	0.00	0.15	0.15	0.00	0.25	0.26	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.05	0.05	0.00
Total	99.90	100.24	0.06	99.93	100.82	0.00	99.87	100.41	0.00	99.74	100.94	0.28	99.43	99.74	0.31	99.66	99.74	0.20	99.41	99.99	0.18
Trace elements (ppm)																					
Ba	88	131	2.3	292	303	3.8	313	315	2.4	525	489	3.5	60	45	2.6	43	31	0.5	796	809	3.8
Ce	34	38	2.7	12	14	5.4	29	34	1.6	65	66	6.8	50	47	4.5	41	38	1.1	44	47	6.6
Cr	315	280	1.5	4	6	1.0	461	450	3.1	387	392	2.6	4	3	1.0	6	2	0.5	3	4	1.0
Cu	121	127	0.7	41	41	0.3	30	28	0.4	56	57	2.9	3	2	0.6	3	1	0.1	12	12	0.6
Ga	21	22	0.2	17	17	0.2	17	17	0.1	18	18	0.2	17	17	0.3	17	18	0.1	16	15	0.3
La	13	15	1.6	4	5	1.6	16	16	1.5	41	38	1.8	22	20	1.4	17	15	0.6	23	26	1.8
Nb	18	18	0.1	2	1	0.2	9	9	0.2	27	28	0.3	16	15	0.3	19	18	0.1	9	9	0.2
Nd	15	25	1.1	14	11	3.0	17	14	0.5	28	26	3.3	23	13	2.6	19	20	1.1	20	19	2.0
Ni	123	119	0.7	2	2	0.6	151	134	0.8	135	140	0.6	4	1	1.2	3	1	1.0	3	4	0.7
Pb	2	2	0.4	5	6	0.7	19	19	0.5	7	6	0.7	20	19	0.4	22	22	0.5	24	24	0.4
Rb	12	9	0.1	12	11	0.8	71	71	0.5	40	39	0.4	257	257	0.8	301	310	2.2	148	150	0.7
Sc	33	32	0.6	29	28	0.5	21	18	0.4	28	29	0.6	5	5	0.5	5	5	0.1	5	4	0.4
Sm	4	6	0.2	4	3	0.7	4	3	0.3	5	5	1.1	5	6	0.9	5	5	0.2	5	4	1.0
Sr	381	396	1.8	250	264	1.3	244	250	1.4	444	444	2.5	29	30	0.3	8	8	0.1	103	109	1.0
Th	1	1	0.4	0	1	0.4	5	5	0.6	9	9	0.6	28	27	0.5	33	32	0.1	16	15	0.5
U	0	0	0.1	0	0	0.4	2	2	0.4	1	2	0.4	9	9	0.3	10	11	0.3	6	6	0.3
V	322	317	1.6	104	108	2.6	121	122	1.0	199	203	1.9	8	7	2.6	2	1	0.1	14	13	1.0
Y	26	26	0.2	28	29	1.0	18	18	0.2	23	24	0.6	48	45	0.9	53	50	0.2	25	25	0.5
Zn	101	103	0.6	87	91	0.5	65	65	0.3	81	85	1.4	31	30	0.4	30	29	0.3	35	32	0.4
Zr	169	172	0.8	81	84	0.4	112	112	0.4	141	142	1.2	104	101	0.2	100	91	0.6	226	220	4.0

^a GeoRem certified values.

^b Average Brigham Young University analysis using a Rigaku ZSX Primus II X-ray fluorescence spectrometer

^c SD = 1σ standard deviation of BYU analyses

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