Proceedings:
Montana Mining and Mineral Symposium 2025
September 17–18, 2025

Montana Bureau of Mines and Geology
Special Publication 125

Cover: Painting of the Pintler Mountains by Bulbul Majumder, MBMG.

PROCEEDINGS:
MONTANA MINING AND MINERAL SYMPOSIUM 2025
TECHNICAL PAPERS

Special Publication 125

Edited by Adrian Van Rythoven and Susan Barth

Montana Bureau of Mines and Geology, Butte, MT

https://doi.org/10.59691/WTEY8027

Technical Editor: Susan Barth

Scientific Editor: Adrian Van Rythoven

Cartographer/Graphic Designer: Susan Smith

Peer Reviewers: Kyle Eastman, John LaFave, and Adrian Van Rythoven

Symposium Committee: Daniel Brennan, Kyle Eastman, Christopher Gammons, Steven Quane, and Adrian Van Rythoven

Research Division Chief: John LaFave

MBMG Interim Director and State Geologist: John LaFave

Cite as:
Van Rythoven, A., and Barth, S., 2026, Proceedings: Montana Mining and Mineral Symposium 2025: Technical papers: Montana Bureau of Mines and Geology Special Publication 125, 94 p., https://doi.org/10.59691/WTEY8027

UUNO SAHINEN MEDALLION AWARD

The Silver Medallion is given annually by the Montana Bureau of Mines and Geology in memory of Dr. Uuno Sahinen (1906–1982), the first full-time Director and State Geologist of the MBMG (1969–1971).

The award is presented to those who made long-term and significant contributions to the understanding and development of the geologic and groundwater resources of Montana.

2024 Uuno Sahinen Medallion Awardee: Jerry Zieg

Jerry Zieg was born in Harlowton, Montana, in 1955 and raised on ranches in the White Sulphur Springs area. Much of his childhood was spent on the family ranch on the Smith River, and he became fascinated with the many outcrops that form the scenic cliffs along the Smith River canyon. In the 1960s, future State Geologist Henry McLernan mapped part of the Zieg ranch for his master's thesis, and took young Jerry along and taught him the rudiments of geologic mapping...and started him down a path of no return.

Jerry received his B.Sc. from the University of Montana and worked summers doing mineral exploration in Alaska with Placid Oil Co., where his first professional task as a geologist was, armed with a shovel and bar, digging a garbage pit to permafrost at Chandalar in the Brooks Range. He continued graduate work at U of M, and with the support of a pickup and gas money from Cominco American Inc. and the very loose oversight of Dr. Don Winston, he focused on the Newland Formation, host of the then-undiscovered Black Butte Copper deposits. He gained an M.Sc. degree in geology from U of M in spring 1981 and joined Cominco American Inc. to continue exploring for another Sullivan Zn-Pb-Ag discovery in the Belt Basin. His efforts led to discovery of the Black Butte copper deposits in 1985. Jerry spent 24 years with Cominco, exploring for base and precious metals not only in Montana but also throughout the western and upper mid-continent states and Alaska, as well as Peru and Brazil. His time with Cominco enabled him to visit mines and prospects throughout Canada, Australia, Latin America, and Ireland. He received the Cominco President's Award for his successful resource expansion at the Pend Oreille Zinc Mine in 2000.

Jerry left Teck Cominco in 2005 to join NovaGold in Alaska and became their Alaskan exploration manager, where in the Brooks Range he advanced the Arctic project in the Ambler district and helped initiate new work on the Bornite property with the owners, NANA Regional Corporation. He generated gold and base metal exploration projects throughout Alaska until 2008, when the ranch owners of the Black Butte copper deposits invited him to return home and begin a new round of work there. For this endeavor, he and former NovaGold executives in 2009 formed Tintina Resources Inc., now called Sandfire Resources America Inc. As Vice President of Tintina, Jerry and his team have successfully expanded and upgraded the copper resource, gained a mine operating permit, overcome the subsequent legal challenges, and continue to advance the project toward mine construction. Jerry is looking forward to completing this and carrying out further exploration efforts throughout Montana and beyond.

Aside from pursuing mineral discovery, Jerry's greatest professional enjoyments include mentoring young geologists into the realm of mineral exploration and development, bringing prosperity to the communities he works in, and communicating the positive benefit that responsible mineral development provides our society.

Jerry is a longtime member of the Society of Exploration Geologists, Society of Mining Engineers, Montana Mining Association, and American Exploration & Mining Association. He is an APG Certified Professional Geologist.

2025 Uuno Sahinen Medallion Awardee: Jack Horner

John R. "Jack" Horner was born (1946) and raised in Shelby, Montana, and graduated from Shelby High in 1964. Jack attended the University of Montana in Missoula for one year, majoring in Geology and minoring in Zoology. Failing classes, Jack was drafted into the U.S. Marine Corps, and spent 14 months with the 3rd Reconnaissance Battalion in Vietnam. Upon his return to Montana he went back to UM for another 6 years, never receiving a degree on account of severe dyslexia, but having learned a great deal of geology, paleontology, and zoology.

In 1972 Jack married Virginia Lee Cicotte, and together they raised their son Jason, who would spend nearly every summer with his dad in the field finding important dinosaur specimens. In 1975 Jack was hired as a fossil preparator in the Department of Geological Sciences at Princeton University, where he was soon promoted to Research Scientist after publishing a paper in *Nature Magazine* revealing the world's first nest of baby dinosaurs. In 1982 Jack was hired by the Museum of the Rockies, Montana State University in Bozeman as their first Curator of Paleontology. With funding from the National Science Foundation and numerous private donors, Jack began building one of the largest dinosaur paleontology programs in the world.

In 1986 Jack was awarded an Honorary Doctorate of Science from the University of Montana, and a MacArthur Fellowship. Jack has since received an Honorary doctorate of Science from Penn State, an Honorary Doctorate of Education from the Bridges Graduate School for Cognitive Diversity in Burbank, California, and an Honorary Doctorate of Humane Letters from Beacon College in Leesburg, Florida. In 2013, Jack was awarded the Romer Simpson Medal from the Society of Vertebrate Paleontology.

Jack worked at Montana State University for 34 years, as the Curator of Paleontology at the Museum of the Rockies, and Regent's Professor of Paleontology in the Departments of Earth Sciences, and Evolution and Ecology. He also taught courses in the Honors College. Jack chaired the dissertations of 12 doctoral students and the theses of 13 Masters students and 3 undergraduates.

Jack has 342 publications, including 12 books, and a plethora of popular articles. He was the technical advisor for the first five installments of the Jurassic Park and Jurassic World movies, and the TV series Terra Nova. He has given more than 1,000 invited lectures throughout the world, and has been featured in many documentaries, including 60 Minutes, the Discovery Channel, Nova, BBC, and many others.

In 2016 Jack retired from the Museum of the Rockies, Montana State University, and took a part-time teaching position as a Presidential Fellow at Chapman University in Orange, California, where he continues to teach, write papers, books, and mentor students. He happily returns to Montana each summer with Chapman students to collect dinosaur remains that they take back to their labs for preparation and research.

The Montana Bureau of Mines and Geology is proud to announce publication in December 2025 of Jack's latest work: *Dinosaurs of Montana*, co-authored with Ray Rogers.

TABLE OF CONTENTS

The Relationship of the Discovery and Development of the Philipsburg Mining District to Its Mineral Zonation..........*Antonioli and Beaucamp* 1

Fenitization Processes Associated with Emplacement of Carbonatites at Sheep Creek, Ravalli County, Montana..........*Gammons and Young* 2

A Metal Rhythm: Magmatic Evolution of the Santa Rita Porphyry Cu Deposit, New Mexico, U.S., from High-Precision Zircon Geochronology and Geochemistry..............*Gaynor and others* 3

Black Butte Copper Project Update 2025..........*Kyle Nacey* 4

Analysis of Rare Earth Element Enrichment in Phosphorite of the Phosphoria Formation, Southwest Montana..........*Nicholas Risedorf* 5

Uranium Mining on the Colorado Plateau: A Brief Overview of the Geology, History, Safeguarding, and Modern Status..........*John Stanfield* 6

New Investigation of the Ruby Graphite Deposit, Beaverhead County, Montana.....*Taylor and Gammons* 7

Systematic Characterization of Mine Waste in Montana for Critical Minerals.........*Adrian Van Rythoven* 8

Magnetotelluric Imaging of Alteration and Aquifers in Support of Testing the Thermochemical Model for Tier 1 Porphyry Copper Systems..........*Brimhall and others* 9

From Paper to Prospect: How Archives Power Geology and Mining Research.........*Chelsea Pincock* 17

Adit into carbonatite dike, Sheep Creek, Ravalli County, Montana. Photo by Adrian Van Rythoven.

The Relationship of the Discovery and Development of the Philipsburg Mining District to Its Mineral Zonation

Ted Antonioli[1] and Celine Beaucamp[2]

[1]*Contact Mining Company, Philipsburg, Montana*
[2]*Department of Geological Engineering, Montana Technological University, Butte, Montana*

The Philipsburg Mining District, located immediately east of the town of Philipsburg in southwest Montana, exhibits a pattern of mineral zonation similar to the much larger Butte District, ~72 km southeast (Beaucamp, 2025). In map view, the Philipsburg District zones from a Cu-Mo porphyry in the north (Stewart Gulch) to Cu-Ag mineralization in the Hope and related mines, to Ag-Pb-Zn high-sulfidation veins in the "Central Camp" (Two Percent to Algonquin mines) to high Ag-Au, low base metal mineralization in the Granite–Bimetallic Mine on the south end of the district.

An enigmatic aspect of this zonation pattern is the absence of a clear pathway for fluids to travel from north to south in the district. The principal veins strike east–west, perpendicular to the zonation pattern, not along it. North–south mineralization, such as at the Sharktown and Coyle Mines (Prinz, 1967), is sparse and discontinuous. This has spurred speculation since the early days of the District's development that a hidden "vein" or channel striking north–south is carrying the ore fluids north to south within the District (Antonioli, 2009).

Vertical zonation appears to be well expressed in the Central Camp veins. The upper part of the Pocahontas Vein, for example, has Ag-Pb-Zn mineralization with little Cu, similar to the peripheral zone in Butte. Historic reports indicate Cu increases in the deeper levels (800 and 1,000 feet below surface, as accessed from the Algonquin Mine), but the grade doesn't reach ore values. However, deeper drilling of the vein by the Hecla Mining Company encountered not only high-grade Ag and Zn, but also Cu grades in the mid-single digits (wt.%), indicating overlapping Cu and Zn ore grade mineralization, as seen in the intermediate zone in Butte. This vertical zonation might lead one to infer a buried mineralizing source deep beneath the Central Camp. This interpretation and the "hidden channel" hypothesis are not mutually exclusive, and resolving the merits of these hypotheses awaits further exploration.

Manganese ores have been extensively mined in the Central Camp portion of the Philipsburg District. Au is significantly elevated and correlates to the Mn mineralization in the southern part of the Central Camp, at and south of the Algonquin Mine. The operators of the Algonquin Mine in the 1950s recognized this pattern and installed a cyanide circuit to recover Au from the Mn ores.

The historical development of the district's Ag mines and mills was profoundly influenced by the mineral zonation. The first notable discoveries of ore were at the Cordova (ca. 1865) and Comanche (ca. 1866) Claims, which had "Hope-type" mineralization: Ag-rich quartz veins with notably low amounts of Pb and Zn sulfides. The first silver mill in Montana, built by the St. Louis and Montana Mining Company in 1867, used the Washoe Process: pan amalgamation that did not require roasting the ore prior to amalgamation. This mill successfully recovered Ag from "Hope-type" ores for nearly 50 years. However, after the company discharged the mining engineer in charge of building the mill, Philip Deidesheimer, they attempted to mill high-grade Ag ores with considerable Zn sulfides from the Poorman's Joy Mine (Two Percent Mine area within the Central Camp). Their recovery was so poor that the company was dissolved, with the mill superintendent forced into personal bankruptcy.

By the late 1870s and early 1880s, this lesson had been internalized by the District's miners, and several Reese River process (roasting) amalgamation mills were built (Emmons and Calkins, 1913). These operated until a combination of the 1893 Panic and the development of froth flotation led to the permanent end of Ag amalgamation by the early 1900s. Subsequent Ag mills at the Bimetallic and Trout Mines used superior froth flotation technology. This is still employed at the Contact Mining Company Mill today.

References

Antonioli, T., 2009, Road Log, Philipsburg Mining District: Northwest Geology, v. 38, p. 99–110, available at https://www.mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=31191 [Accessed July 2026].

Beaucamp, C.M., 2025, A geological and geochemical study of the Philipsburg Mining District, Granite County, Montana: Butte, Montana Technological University, Ph.D. Dissertation, available at https://digitalcommons.mtech.edu/grad_rsch/369 [Accessed July 2026].

Emmons, W.H., and Calkins, F.C., 1913, Geology and ore deposits of the Philipsburg quadrangle, Montana: U.S. Geological Survey Professional Paper 78, 271 p., https://doi.org/10.3133/pp78

Prinz, W.C., 1967, Geology and ore deposits of the Philipsburg district, Granite County, Montana: U.S. Geological Survey Bulletin 1237, 66 p., https://doi.org/10.3133/b1237

Fenitization Processes Associated with Emplacement of Carbonatites at Sheep Creek, Ravalli County, Montana

Chris Gammons and Tage Young

Department of Geological Engineering, Montana Technological University, Butte, Montana

The Sheep Creek area of southern Ravalli County, Montana, contains numerous small, carbonatite-related deposits rich in Nb and rare earth elements (REE; Heinrich and Levinson, 1961). The carbonatite bodies are typically <2 m wide, strike northwest or west, and dip moderately to steeply to the north. The carbonatite bodies are locally deformed, and are conformable to foliation in the host rocks (Risedorf, 2023). The host rocks belong to a 1.37 Ga bimodal, metaigneous complex consisting of granitic/augen gneiss and diabase/amphibolite.

When found in close proximity to a mineralized carbonatite body, the mafic wallrock is altered to a fenite assemblage that includes phlogopite, albite (or Na-rich plagioclase), calcite ± dolomite, magnetite, and sodic amphiboles (riebeckite, winchite). The mineral transformations are consistent with observed changes in the bulk chemistry of the mafic wall rocks, including consistent increases in K_2O, Na_2O, and H_2O/CO_2, and consistent decreases in SiO_2 and Al_2O_3. Fenite alteration is most strongly developed adjacent to carbonatite bodies that are strongly mineralized with Nb and REE minerals (Young, 2025). Unmineralized carbonatite occurrences have fenite zones that are weak or absent. Although the fenite is not strongly enriched in REE, transfer of SiO_2 and Al_2O_3 from the fenite back into the carbonatite bodies may have triggered deposition of REE-rich allanite and other silicate minerals (Ba-feldspar, actinolite, quartz) that are locally abundant in the carbonatite. An influx of SiO_2 may also have lowered the solubility of REE-phosphate in the carbonatite melts, resulting in deposition of monazite.

Most fenite occurrences described elsewhere formed by alteration of felsic country rock (granite, gneiss, siliciclastic metasediments). These fenite assemblages are rich in secondary alkali feldspar and aegirine, and form conspicuous, pink outcrops that surround the central carbonatite complex. Because the country rock in the Sheep Creek area has a mafic starting composition, the fenite occurrences at Sheep Creek have a completely different mineralogy, being rich in biotite, albite, and matrix calcite. These erode to a crumbly grus soil, and are easy to miss or ignore in the field. However, recognition of these rocks is important because they are vectors to a nearby mineralized carbonatite.

References

Heinrich, E.W., and Levinson, A.A., 1961, Carbonatic niobium–rare earth deposits, Ravalli County, Montana: American Mineralogist 46, p. 1424–1447.

Risedorf, Sarah, 2023, Investigation of the Sheep Creek carbonatites, Ravalli County, Montana: Butte, Montana Technological University, Masters Thesis 296, available at https://digitalcommons.mtech.edu/grad_rsch/296 [Accessed July 2026].

Young, Tage, 2025, Fenitization of mafic wallrock associated with emplacement of REE-rich carbonatites of Sheep Creek, southern Ravalli County, Montana: Butte, Montana Technological University, Masters Thesis 356, available at https://digitalcommons.mtech.edu/grad_rsch/356 [Accessed July 2026].

A Metal Rhythm: Magmatic Evolution of the Santa Rita Porphyry Cu Deposit, New Mexico, U.S., from High-Precision Zircon Geochronology and Geochemistry

Sean P. Gaynor,[1,2] Andreas Audétat,[3] Jia Chang,[3] Isabel Koran,[2] Andrew Kylander-Clark,[4] John M. Cottle,[4] and Blair Schoene[2]

[1]U.S. Geological Survey, Denver, Colorado
[2]Department of Geosciences, Princeton University, Princeton, New Jersey
[3]Bavarian Research Institute of Experimental Geochemistry and Geophysics, University of Bayreuth, Bayreuth, Germany
[4]Department of Earth Science, University of California, Santa Barbara

Models for porphyry Cu formation rely on factors such as crustal architecture, changes in magma genesis, and the degree and lifespan of magmatic fractionation to explain the formation of economic porphyry systems. Accurately constraining the magmatic lifespan and sources of mineralizing intrusions is crucial for assessing models for deposit formation. For example, the overall duration of magmatic processes has been interpreted to control the total metal endowment of individual deposits by enriching ore through overprinting of discrete hydrothermal–magmatic systems. The Paleocene Santa Rita porphyry Cu deposit, located in New Mexico, U.S., has been studied for decades, and serves as an archetype for porphyry Cu deposit models. Recent petrologic and geochemical research indicated that the hydrous nature of the mineralizing magmatism was inherited at depth. However, existing chronology for the emplacement and mineralization of the deposit lacks the precision necessary to deconvolve its complex magmatic history.

New high-precision zircon CA-ID-TIMS U-Pb geochronology and Hf isotope geochemistry from rocks associated with porphyry mineralization at Santa Rita indicate intrusive assembly, porphyry mineralization, and skarn formation were protracted and episodic. Mineralizing intrusions solidified diachronously over a period of 2.161 ± 0.045 Myr, within a total overall period of 3.769 ± 0.418 Myr of magmatism within the mineral district. However, there is no evidence in the crystal record indicative of a sustained upper crustal parental magma chamber, despite protracted magmatism and zircon age spectra from individual samples. Single crystal U-Pb zircon age distributions from temporally disparate mineralizing intrusions do not yield consistent or considerable overlap, despite overlapping Hf isotope compositions. Instead, these zircon data suggest that individual batches of mineralizing magma formed discretely from juvenile sources and emplaced separately between 59.905 ± 0.028 and 57.744 ± 0.035 Ma. Due to the tens to hundreds of kyr between emplacement and solidification of igneous pulses of the composite stocks, textural variability of the observed mineralizing intrusions is not a result of differential cooling histories due to geometry within a cooling stock. Instead, these variations must result from either crystallization prior to the emplacement level or late modification and annealing by hydrothermal fluids, as the individual pulses were emplaced too separate in time to have been comagmatic liquids. Pre- and post-mineralization magmas emplaced hundreds of kyr before and after the mineralizing intrusions host considerably more xenocrystic inheritances from Proterozoic basement, and therefore reflect different magma genesis or evolution relative to mineralizing intrusions.

Altogether, this dataset and ongoing work indicates that Laramide porphyry Cu formation in Arizona and New Mexico may be the result of shifting magma genesis over millions of years, and that protracted magmatic assembly may be significant for overall deposit endowment.

Black Butte Copper Project Update 2025

Kyle Nacey

Sandfire Resources America, Inc., White Sulphur Springs, Montana

The Black Butte Copper Project is located approximately 24 km north of White Sulphur Springs, Montana. The Project focuses on development of the Johnny Lee and Lowry sediment-hosted Cu sulfide deposits. The deposits are hosted within the Mesoproterozoic Newland Formation in the Helena Embayment (Lower Belt). The Newland Formation comprises dolomitic and calcareous turbidite debris flows and sub-wavebase carbonate beds. The two deposits formed from synsedimentary hydrothermal processes approximately 1.49 Ga along the northern margin of the Helena Embayment.

The Johnny Lee Deposit contains the Upper Copper Zone and the Lower Copper Zone. Combined, these zones comprise a measured and indicated resource of 10.9 Mt containing 2.9 wt.% Cu, and an inferred resource of 2.7 Mt containing 3.0 wt.% Cu. The Lowry Deposit contains the Middle Copper Zone and the Lower Copper Zone. These other two zones comprise an inferred resource of 8.3 Mt grading 2.4 wt.% Cu. Post-mineralization thrust faulting has carried the Johnny Lee Upper Copper Zone and Lowry Middle Copper Zone over the Johnny and Lowry Lower Sulfide Zones.

Analysis of Rare Earth Element Enrichment in Phosphorite of the Phosphoria Formation, Southwest Montana

Nicholas Risedorf

Department of Geological Engineering, Montana Technological University, Butte, Montana

The Phosphoria Formation is a world-class phosphate deposit in the Rocky Mountains that has produced over 230 Mt of commercial phosphate since the 1920s. Rare earth element (REE) mineralization in phosphorites was observed historically, but commercial recovery of REEs has not been reported. Increasing demand for domestic REE supply has made resource characterization a priority. This study investigates the distribution of REEs within the Phosphoria Formation across southwest Montana. Five stratigraphic sections of Retort Member subcrop were exposed to measure stratigraphy and collect samples for geochemical analysis. Thin sections and polished plugs of phosphorite samples were analyzed by petrographic microscopy, automated SEM-EDS, EMPA, and LA-ICP-MS. Assays indicate ∑REE + Y concentrations up to 3,480 ppm with an average of 1,362.6 ± 614.6 ppm ∑REE + Y and 25.46 ± 8.15 wt.% P_2O_5 across all phosphorite lithofacies (*n* = 133). Heavy REEs comprise 48 ± 5% of total REE content.

REEs are hosted in carbonate–fluorapatite (francolite), although correlations between phosphate and REE concentrations are variable. Lithologic interpretation of the stratigraphy indicates a cyclical pattern of enrichment at local scales, as well as regional variation in grade. Phosphoria strata in the Garrison and Philipsburg Districts along the northern paleobasin margin exhibit elevated grades averaging 1,667.77 ± 586.67 ppm ∑REE + Y and 26.37 ± 8.45 wt.% P_2O_5 (*n* = 60), compared to strata from Big Hole Canyon near the paleobasin center, which average 680.64 ± 258.31 ppm ∑REE + Y and 25.55 ± 5.56 wt.% P_2O_5 (*n* = 15). Locally, phosphorite beds at the top and base of the Retort Member exhibit elevated REE:P_2O_5 ratios, whereas middle beds are commonly depleted. Concavo-convex pressure solution textures on allochems in phosphorite are correlated with REE-enriched zones at lithologic facies transitions.

These textures are interpreted to enhance REE enrichment by remobilizing phosphate into porewaters, facilitating interaction with dissolved REEs, and promoting re-precipitation within phosphatic sediments. This interpretation can be further evaluated through detailed geologic mapping of phosphorite packstone facies, as well as core drilling and expanded stratigraphic sampling along the northern margins of the Phosphoria paleobasin.

Uranium Mining on the Colorado Plateau: A Brief Overview of the Geology, History, Safeguarding, and Modern Status

John Stanfield

Legacy Management Support Partner, U.S. Department of Energy

Anomalous U mineralization is a ubiquitous occurrence throughout various Mesozoic stratigraphic units across the Colorado Plateau. These mineral occurrences have been emplaced and concentrated via a complex culmination of geologic processes. Within contemporary human history, the Colorado Plateau has served as a principal source of scientific and defensive stocks of U. This spawned a rich mining history. However, it also left a legacy of physical and chemical hazards to be addressed by the federal government after its incentivization during the Manhattan Project and Cold War era. The Department of Energy Office of Legacy Management, in partnership with Legacy Management Strategic Partners, has taken the reins to protect human health and the environment through maintenance of historic U mill tailing disposal sites, spearheading safeguarding efforts of abandoned mine lands, rebuilding relations with afflicted indigenous populations, and maintaining active lease tracts of ore-bearing lands so future reserves of materials may be economically accessed.

New Investigation of the Ruby Graphite Deposit, Beaverhead County, Montana

Mikayla Taylor and Chris Gammons

Department of Geological Engineering, Montana Technological University, Butte, Montana

Abstract

The Ruby Graphite Deposit (aka Crystal Graphite Deposit) is located in the southern Ruby Mountains, Beaverhead County. The deposit contains unusually coarse-grained and highly crystalline graphite, a highly sought-after critical commodity in today's global economy. The graphite is hosted by high-grade metasedimentary and metaigneous rocks that reached peak metamorphism during the ~ 1.7 Ma Big Sky Orogeny. In this study, samples were collected from outcrops, mine dumps, and new (2023) drill core from the Ground Hog and Bird's Nest claims. The samples were examined by optical microscopy, SEM-EDS, and Raman spectroscopy. In addition, stable isotope analyses were conducted on graphite ($\delta^{13}C$), calcite from marble ($\delta^{13}C$ and $\delta^{18}O$), and pyrite ($\delta^{34}S$) that is locally intergrown with graphite.

Although this study is still in progress, it is evident that there are multiple generations of graphite mineralization. Much of the graphite is early, and has experienced peak metamorphic temperatures in the range of 790 ± 20°C (based on Raman geothermometry), consistent with the presence of sillimanite + biotite + garnet (+ graphite) in metasediment and metapegmatite. A second generation of graphite formed during retrograde metamorphism at an unknown date. This later graphite is intergrown with lower-temperature minerals, such as pyrite, calcite, prehnite, and pumpellyite, and therefore must have formed at temperatures <300°C, at shallower depths. Several mechanisms are proposed for deposition of the graphite:

1. Mixing of CO_2-rich and CH_4-rich metamorphic fluids;
2. Reduction of CO_2 by H_2(g) generated during metamorphism of nearby ultramafic intrusions; or
3. Redox reactions involving minerals rich in Fe^{2+} (garnet, biotite, diopside, pyrrhotite).

The possibility that some graphite could have formed by metamorphism of primary organic carbon in the host metasediments cannot be discounted. Any C-isotope evidence of an organic origin would have been lost by high-grade metamorphism and isotope exchange with calcite in the marble.

References

Taylor, Mikayla, 2025, Geologic and Geochemical Investigation of the Ruby Graphite Deposit: Butte, Montana Technological University, MS Thesis 365, available at https://digitalcommons.mtech.edu/grad_rsch/365 [Accessed July 2026].

Systematic Characterization of Mine Waste in Montana for Critical Minerals

Adrian Van Rythoven

Montana Bureau of Mines and Geology, Montana Technological University, Butte, Montana

Montana is a state with an abundance of legacy mines and mill sites. Many of these inactive sites have physical or chemical tailings left onsite in piles or drained ponds. Given the dynamic nature of commodity demand, many of these piles of mine waste can be considered as artificial mineral deposits: already at surface and pre-comminuted. Assessment of these sites as sources for future critical mineral production adds another facet to mine site remediation.

Under an Earth-MRI (USGS) grant, five such sites have been assessed in this fashion. Systematic mapping, sampling, and assaying these deposits will allow for the capture of any heterogeneities that a few grab samples would miss. This would also allow for a rough estimate of total contained critical mineral resource at each site. To expand upon this, mineralogical knowledge through powder X-ray diffractometry, optical petrography, and automated scanning electron microscopy (TIMA) would provide much more useful data to assess economic viability and/or environmental liability of any deposit.

One of these five sites is the inactive Calvert Mine in Beaverhead County, Montana. This W mine closed in the 1960s. Four mine dump domains were mapped as polygons at the mine with a total area of 29,547 m^2. Each polygon had a composite sample comprising 31 to 51 ~1 kg subsamples. The composite samples were sieved at 3.175 mm into coarse and fine size fractions.

Resulting assays showed a range of W grades from about 0.025 to 0.1 wt.%. The fine size fraction W grades were typically 50% higher than the coarse size fraction from the same domain of mine waste (fig. 1).

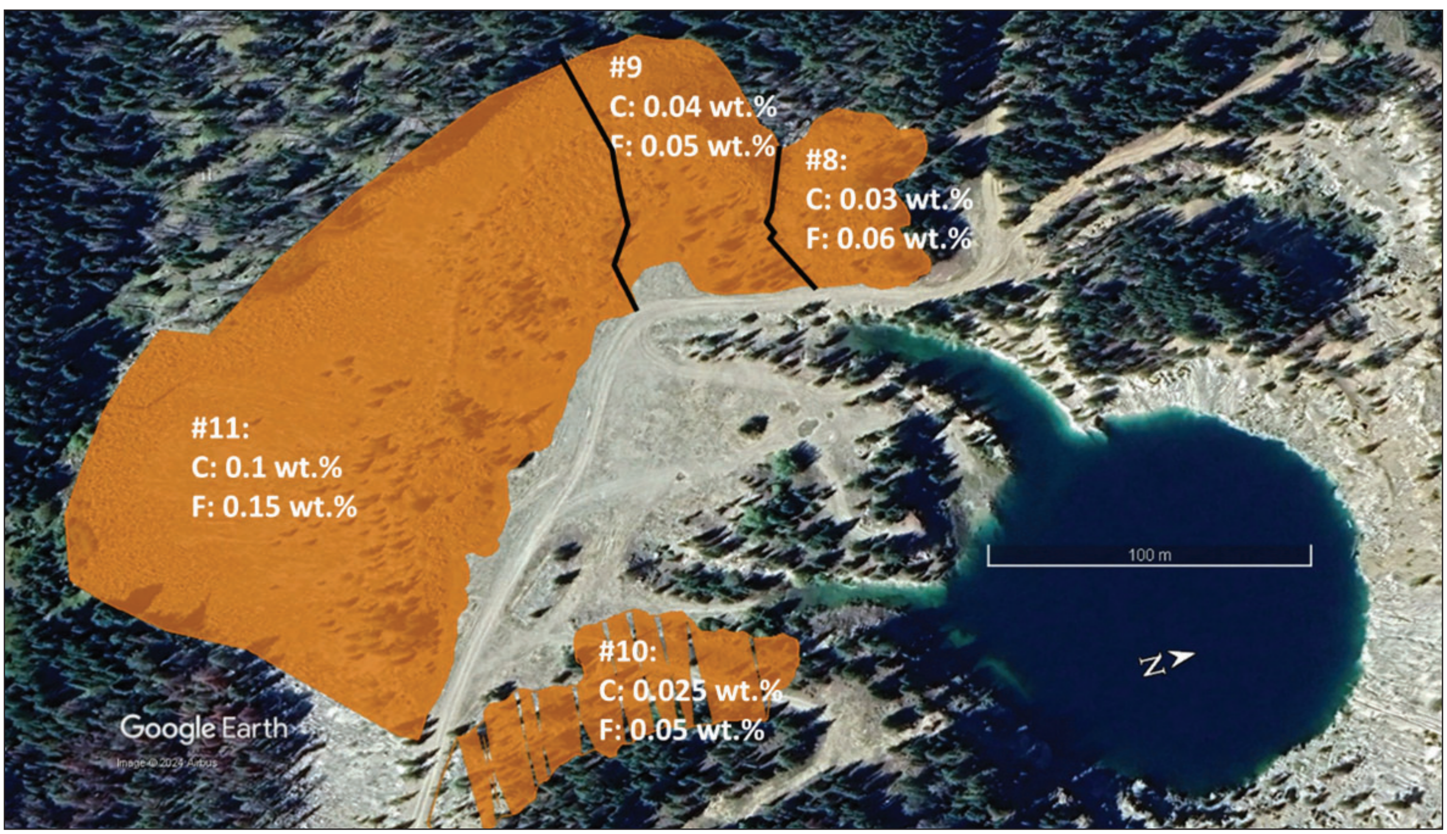

Figure 1. Tungsten (W) grades measured in the coarse (C) and fine (F) size fractions across four mine waste piles at the Calvert Mine, Beaverhead County, Montana.

Excavated cross trench in Retort Member, Madison County, Montana. Photo by Adrian Van Rythoven.

Mine dump, Edgar P Mine, Granite County, Montana. Photo by Adrian Van Rythoven.

Magnetotelluric Imaging of Alteration and Aquifers in Support of Testing the Thermochemical Model for Tier 1 Porphyry Copper Systems

George Brimhall, Ed Rogers, and Jim Freestone

Clementine Exploration, LLC

Abstract

Magnetotelluric (MT) geophysical survey methods in well-mapped project areas can have a decisive influence on the success of Cu exploration in Montana with minimal if any environmental disturbance. Pre-drilling phase projects on public land can operate under the casual use, leave-no-trace classification, with geological mapping and sampling using only hand tools. Use of distal orbicular actinolite alteration as a mineralogic guide for ranking potentially economic porphyry Cu deposits helps to filter out smaller uneconomic prospects early on. The operative thermochemical porphyry Cu model of Brimhall (2024) explains why actinolite orbs form at the outer edge of convective downward fluid flow only in large, long-lived porphyry hydrothermal systems by radial diffusion. Diffusion is slow compared to advection and requires great thermal stability and sufficient time for radial growth of orbs as a distal ring. Central to porphyry systems is the potassic alteration zone that constitutes the high resistivity targets in Cu exploration formed by upward advective flow where oxidation by molecular hydrogen outgassing from the parental magma occurred. Given the potential to erupt rather than convect, Tier 1 porphyry systems are of a Goldilocks size: not so large as to erupt nor so small that orbs don't form. Given a clear correlation of orbicular zones with sulfatic springs that reflect sulfide oxidation in the vadose zone at the Clementine prospect, spring mapping is essential to realistic interpretation of higher conductive zones appearing in MT sections and 3D models. These zones may also be conductive, as graphite is associated within the orb zones formed where H_2 gas concentrates under reducing conditions. The physical dimensions of ore shells in Tier 1, 2, 3, and 4 size systems are modeled here as a right circular cylinder, showing that a Tier 1 target has dimensions of 1 km diameter and 3 km depth. A MT survey with 87 grid points spaced at 100 or 200 m over 8 lines extending to a maximum length of 3 km reveals a cupola-shaped high-resistivity anomaly at depth at Clementine. This anomaly thins upwards to a diameter of 1 km and extends to the surface where it corresponds to an elliptical brecciated zone surrounding and co-axial with the central vein gossan system. Besides validating the accuracy of the geological cross-section and drill site selection, the MT survey also imaged aquifers in the orbicular zones that feed springs and probably identified their fountainhead as a water-filled paleo-karst cavity near the top of the Madison Formation.

Introduction

Porphyry copper deposits (PCDs) have often been described as giant geochemical anomalies in the Earth's crust (e.g. Heinrich, 2024), but they are also thermal anomalies of variable sizes. In order to integrate thermal considerations with chemical processes, a new thermochemical model of porphyry Cu genesis was developed (Brimhall, 2024) involving magmatic hydrogen outgassing, which controls early high-temperature oxidation. Thermodynamic modeling and phase equilibria were computed based on the potassic alteration mineral assemblage and biotite mineral chemistry and defines the oxidative cooling trend along the upwards flow trajectory. Central to this new porphyry Cu model is a key observation published by Bill Atkinson and Marco Einaudi, who, as Anaconda geologists, logged core at the Carr Fork area of the Bingham District, Utah. They first recognized and published a description of a new type of distal hydrothermal alteration with rounded orbicules containing actinolite (Atkinson and Einaudi, 1978) and noted it in diamond drill core at other major PCDs, including Escondida and El Hueso (Chile), Cajamarca (Peru), Morenci and Fortitude (USA), Cananea (Mexico), and Oyu Tolgoi (Mongolia; Einaudi, 2026). Brimhall (2018) recognized and mapped orbicular actinolite alteration over a 3 by 5 km zone at the Clementine prospect on Fleecer Ridge, Silver Bow County, Montana, and determined its radiometric age (Brimhall and Fanning, 2020) and thermochemical origin (Brimhall, 2021, 2024, 2025). Thermodynamic modeling revealed that propylitic alteration and the orb actinolite mineral assemblage represent the reduction accompanying a downwards flow trajectory approaching the parental pluton and source of heat. Given the presence of orbicular actinolite alteration at six major porphyry deposits, the presence of an orbicular actinolite ring may thus be a potential indicator of economic Tier 1 size PCDs (Brimhall, 2025), analogous in usage to the G-10 garnet indicator of diamondiferous diatremes by reflecting petrochemical processes at depth (Grütter and others, 2004, 2024). Orbicular actinolite forms at the outer edge of fracture-controlled advective fluid flow where diffusion predominates in thermal systems, lasting long enough for slow diffusional processes to develop orbs by radial diffusion at crack tips. Hence, a key objective here is to determine if an actinolite orb ring might only surround large, well-mineralized porphyries and hence provide a useful indicator of highly prospective systems in contrast to smaller, less economic occurrences. The geophysical imaging described below is designed to motivate pilot drill testing of the new thermochemical porphyry Cu model.

Geophysical Imaging

Exploration geophysics was conducted on the Clementine prospect of southwest Montana in August 2025 for two purposes. First, geophysical imaging helps guide initial deep pilot diamond drilling by discerning early high-temperature potassic alteration zones related to disseminated Cu-sulfide mineralization—the primary exploration target. Secondly, certain geophysical methods, including resistivity techniques, may image ground water aquifers as well. As diamond drilling requires large quantities of water, discovery of water locally can dramatically reduce the environmental impact of exploration as large tanker truck haulage becomes unnecessary. Hence, with locally available water, dust and degradation of the dirt access roads are avoided. Furthermore, as the Clementine prospect occurs within the Beaverhead–Deerlodge National Forest 28 km southwest of Butte, a geophysical technique was selected that avoids applying electrical current into the ground that might conceivably elevate the risk of wildfire, a major concern during the dry summer months. In contrast to active source geophysics, magnetotelluric (MT) imaging is a passive EM method utilizing weak natural variations in the earth's magnetic and electrical fields induced by solar wind and lightning storms to image resistivity in the subsurface. These natural sources induce telluric current flow in the ground that allows imaging of the earth's electrical resistivity structure from surface to great depths, depending upon the spacing of the points of measurements and length of the lines. Adopting certain assumptions to simplify the relationship, the ratio of the electric field to magnetic field provides simple information about subsurface conductivity or its reciprocal, resistivity.

Methods

The Spartan MT Technology of Quantec Geoscience was selected for subsurface imaging purposes. Informally, the MT system qualifies for "casual use" or "no trace left behind" with regards to permitting by the U.S. Forest Service as the environmental impact is minimal or absent (note that the U.S. Forest Service does not use this nomenclature). Only hand tools such as spades and hoes are used in its field implementation. The arrays of coils and electrode plates used at each site are temporarily buried overnight at shallow depths to avoid disturbance as the signal strength measured is very weak and the coils and plates are easily disturbed if not protected from the elements such as wind and temperature variations (fig. 1A). The three 1-meter-long coils and all equipment used for each site, including the data logger, GPS, electrode plates, and wiring coils, fit into a backpack weighing 38.6 kg. Spirit bubble levels and Silva compasses with declination adjustment were used for alignment of these coils to within 1° precision. Data processing by the Spartan system allows minor adjustments of the apparent coil orientation. After 24 hours of data collection at each site, all flagging and tags are removed, and dirt and soil are replaced using hand tools, tamped down, and smoothed over and inspected for environmental

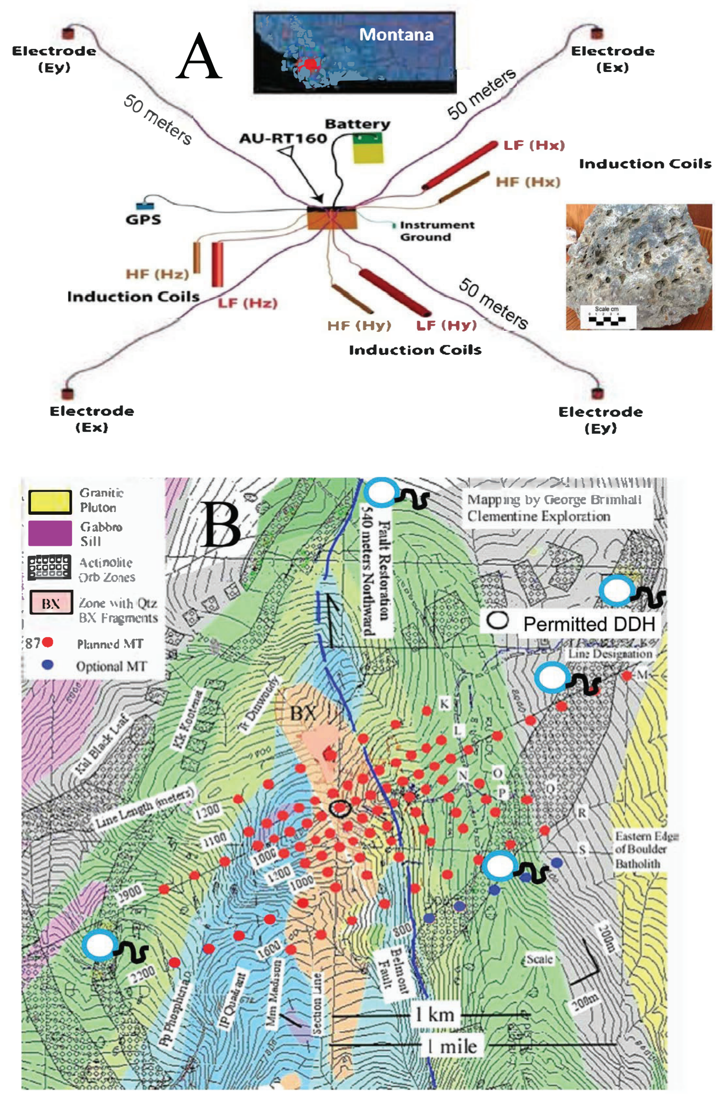

Figure 1. (A) The data collection array for each geophysical site is shown with a central data logger at the sites shown in (B). Extending outwards from the data logger are 50-m-long wires to flat plate electrodes in cardinal directions. Close to the data logger are three induction coils aligned north–south, east–west, and vertically. (B) Geological map of the Clementine prospect in southwest Montana. Springs are shown as white dots with squiggly black tails. A new montane forested wetland recognized here is shown on the top edge of B and is the only ecosystem of this type in central Silver Bow County.

compliance. Each site installation is equivalent to the annual natural soil disturbance of pocket gophers.

A remote reference MT station was selected 9 km to the north of Clementine near Flume Creek. This site was selected as it provided a noise-free environment with convenient access as part of the daily work travel routine while being sufficiently remote that disturbance by vandalism was not a problem. The functionality of each induction coil was checked by first setting up all the coils to be used in a parallel array and collecting data overnight.

Experimental Design

A total of 87 points positioned in nine traverse lines (labeled K through R) spaced 100 or 200 meters apart were designed using geological mapping by Brimhall (2018, 2021, 2024), as shown in figure 1B as red dots. Line S was deemed unnecessary. Along line M, circled in black, is our permitted deep pilot drill hole site in the center of the MT array, which expands outwards to provide necessary data for a 3D model around this pilot drill hole. Springs are shown as blue circles with a squiggly black tail and occur in and near actinolite orb zones, implying that the orb zones (fig. 2A) are highly permeable. Where orb zones are displaced by the Belmont Fault, a new montane forest wetland was recognized, shown with the green bar symbol.

Ranking Exploration Targets

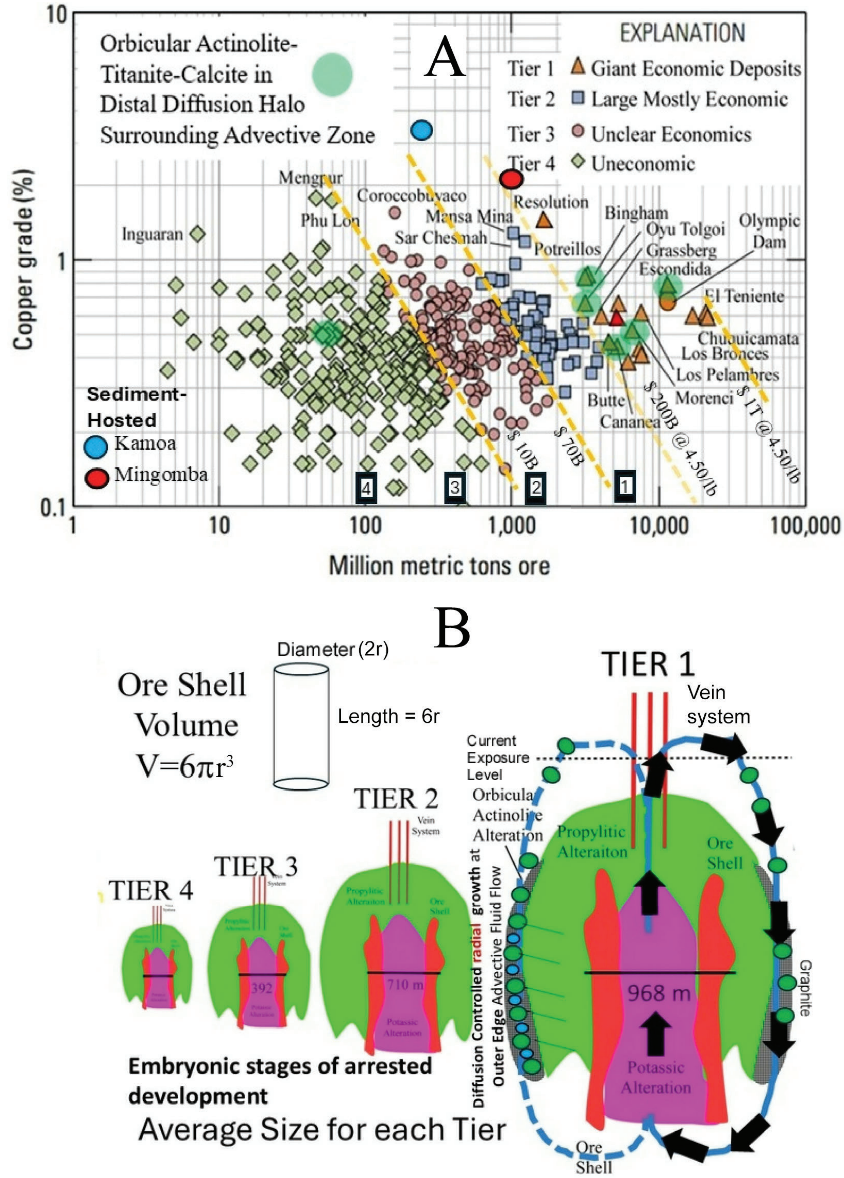

Figure 2. (A) Tonnage and copper grade for PCDs. The average for each tier is shown as a numbered black rectangle along the x-axis. The average values used are: Tier 1 (6,000 MT), Tier 2 (1,500 MT), Tier 3 (400 MT), and Tier 4 (100 MT). Tonnage and copper grade data are from Singer and others (2008) and Robinson and Menzie (2014). (B) The sizes of ore shells are shown for the average tonnages of Tiers 1 through 4.

Global porphyry Cu deposit (PCD) resources have been classified by the USGS into four economic tiers (Singer and others, 2008; Robinson and Menzie, 2014) as being Giant, Large, Moderate, or Small, with only the first two tiers being economic (fig. 2B). Hence the prime economic challenge in ranking drilling targets is recognizing geological factors presaging only Tier 1 or 2 size systems. In figure 2A, mines where actinolite orbs have been noted by Marco Einaudi in diamond drill core are circled in green. The *in situ* value of Cu computed at $4.50/lb is shown as a series of orange dashed lines drawn along the boundaries between the various tiers (fig. 2A). The high value of Tier 1 porphyry Cu resources relative to Tiers 3 and 4 is evident and illustrates the interest in discovering such PCDs to become reliable, stable Cu sources as global demand for Cu continues to surge. The rise of electric vehicles, the growth of AI infrastructure, and the ongoing transition to renewable and potentially sustainable energy are pushing Cu consumption higher than ever. Major new Cu discoveries have dropped by more than 80% since 2010, and 40% of current production comes from politically unstable regions. With the startup time being 15 years on average to develop a new Cu mine, it's clear the gap between supply and demand will only widen in the coming years. Most importantly for exploration strategy, outcropping ore bodies are a thing of the past, and far deeper deposits will become the norm. Resolution Cu in Arizona is an example of a Tier 1 PCD that occurs at depths exceeding 1,300 meters. For comparison, two major sediment-hosted Cu deposits (Komoa and Mingomba) are shown in figure 2A, illustrating their higher Cu grade but lower tonnage. While deeper PCDs will probably lack supergene enrichment blankets, hypogene processes may form Leadville–Gilman Colorado style mantos and Cu-Ag veins in deposits and carbonate replacement deposits within sedimentary wall rocks (Brimhall, 2021), as at the Hecla mining district west of Melrose.

Visualizing Porphyry Copper System Tier Size

In order to recognize a desired exploration target in geophysical imagery, the size of the target zones sought must be understood quantitatively. In figure 2B, the dimensions of each of the average tonnages of four USGS Tiers have been computed using a right circular cylinder of radius, r, length 6r, and density of 2.8 g/cc to model the volumes given as $6\pi r^3$ of the ore shell shown in red, as portrayed diagrammatically in the Lowell and Guilbert (1970) porphyry Cu model. We conclude that many but not all Tier 1 size systems develop a distal orbicular orb shell co-axial with the central vein sytem, as such systems are large enough to have had sufficient thermal mass to convect for a period of time long enough for the slow radial growth of orbs to form at the outer edge of maximum prograde convective fluid flow before retrograde collapse of the convective flow cell. Support for the accuracy of the thermo-chemical PCD model (Brimhall, 2024) came when graphite, predicted in the new thermo-chemical PCD model, was first recognized in the field by Neil Griffiths of the USGS in the type locality of distal orbicular actinolite alteration on the Parker Mine access road, where reducing conditions prevailed. The orb ring's zones are clearly highly permeable, as they correlate spatially with all the known springs on the Clementine pospect (fig. 1B).

There is a reason why PCDs clearly have a maximum size, as shown in figures 2A and 2B. PCDs have been described as "failed" large volcanic eruptions (Chiaradia and Caricchi, 2022). Strong petrological evidence supports this assertion, as one mineral in particular is critical to proving this. Anhydrite forms under highly oxidizing conditions in both the potassic assemblage in PCDs and in certain very large stratovolcanoes including El Chichon, Mexico, where their similarities to PCDs have been noted (Luhr and others, 1984; Luhr, 2008). These links include their occurrence with the tectonic metallogenic belt for PCDs known as the Ring of Fire, located along a convergent tectonic plate boundary subduction zone. It is possible then that mega-strata volcanic eruptions with primary igneous anhydrite represent the sudden interruption of the largest PCDs' development. Rather than develop a subsurface mineralized hydrothermal convective cell driven by the heat dissipation of the cooling porphyritic magma, the explosive exsolution of magmatic water caused the rigid carapace above the magma chamber to fail, explode, and erupt violently onto the earth's surface and into the stratosphere. Conversely, oxidized anhydrite-bearing mega-strata volcanic eruptions containing anhydrite can be considered as once-potential porphyry Cu magmas that, upon exsolution of magmatic water, breached the surface explosively rather than becoming a confined mineralized convective system at depth. The clear implication of this reasoning is that Tier 1 size PCDs are of a Goldilocks size: not big enough to erupt nor so small as to not develop orb zones that are aquifers today and control all springs at Clementine. Given the high correlation of actinolite alteration with Tier 1 size systems, we conclude that the potassic alteration zone we seek at depth at the Clementine prospect to have a size of about 1 km in diameter and vertical length of about 3 km (fig. 2B) for a Tier 1 system.

Geo-Spatial Data Management and Data Point Location in the Field

As the digital geological mapping was done using the NAD 1927 Western U.S. Zone 12 reference ellipsoid and Universal Transverse Mercator (UTM) metric coordinates, it was necessary to first convert the point (x,y) coordinates of each grid point into decimal latitude and longitude, then transform them into the WGS 84 reference ellipsoid using the App MyGeoData. CSV format files were converted into a GPX format for uploading into mobile mapping devices on smart phones using their internal GPS, for example on X Hunt or Google Earth. Obvious reference fiducial points at road intersections were used to verify the accuracy of the transformed (x,y) data. The workflow, with 8 to 10 people, including both Quantec and Childs Geoscience staff, reached a level of four two-person teams managing two sites per day.

Data Processing

Quantec proprietary QuickLay software (ver. 5.8.2.16) was used, coupled with Egbert MT processing code (Egbert, 1997). The data processing steps were: (1) coherent noise rejection using data acquired daily at the remote reference site at Flume Creek 9 km to the north; (2) proprietary digital filtering (scrubbing); (3) coherency sorting; and (4) impedance estimate stacking. Processing configuration was set to 12 frequencies per decade. Data were processed to output X at 0° True North Data Conventions: right-hand positive down coordinate system. Time dependence: $e + j\omega t$ auto- and cross-power spectral estimates for individual stations and sampling band were archived as spectral density matrix (SDM) files (Egbert output). Results were band-merged, edited, and saved as SEG-EDI4 (electronic data interchange) files.

Results of the Magnetotelluric Survey

The eight traverse lines (K through R) are perpendicular to the strike of the fold axis of the doubly plunging Clementine anticline and are centered on a vein gossan system thought to be the center of the district-scale ore-forming magmatic hydrothermal system. The longest line, M, is 2,900 m long, so as to image to a depth of about 3 km, and contains the deep drilling pilot hole site at 1,800 m from the east (0 meters) end of the line (fig. 3A). Line and point

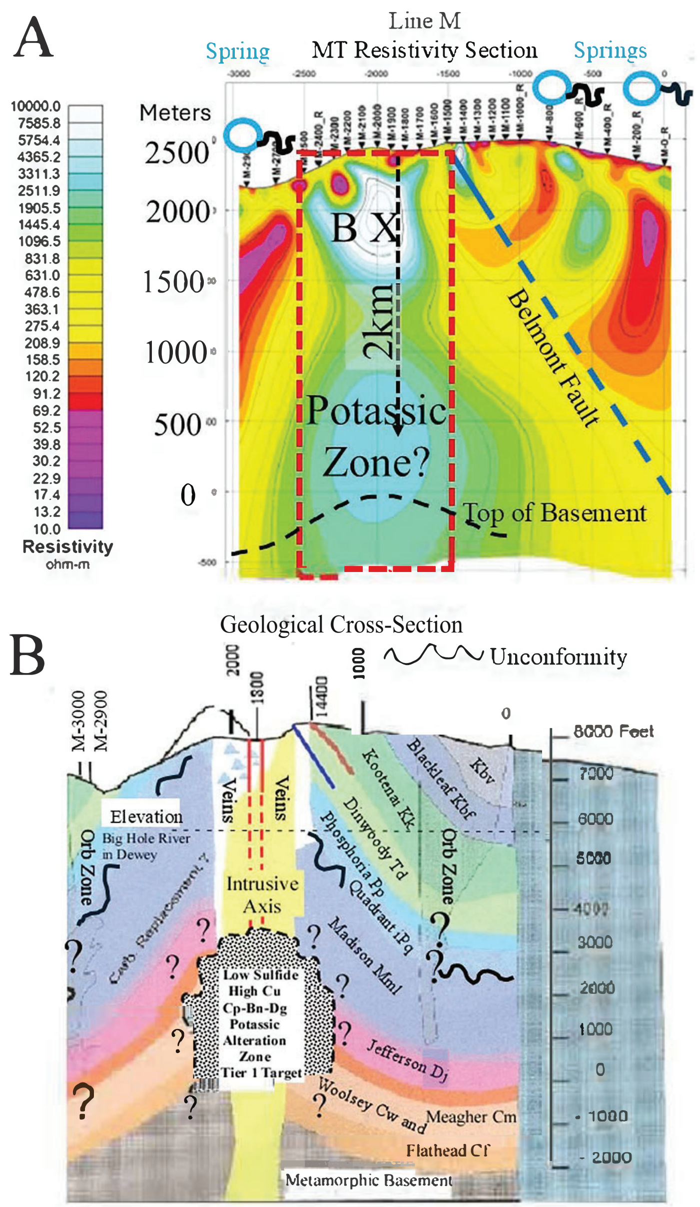

Figure 3. (A) MT results for line M. A breccia zone represents to the upper part of the resistivity high, with the cupola at depth thought to represent the Potassic alteration Zone with disseminated copper sulfides. The anticipated 2-km-deep drill hole is shown with a dashed black line. Symmetric highly conductive MT zones occur on both sides of the resistivity high and are interpreted to be the aquifers related to orbicular actinolite zones rimming the district, expressed as springs. The Belmont fault, shown as a dashed blue line, clearly truncates the conducting anomalies in its hanging wall, which are aquifers feeding the springs. (B) Geological cross-section along line M showing the central breccia zone and vein gossans.

spacing were designed so as to resolve at depth an expected potassic alteration zone with disseminated Cu-sulfides approximately 1 km in diameter, characteristic of a Tier 1 PCD and extending for about 3 km vertically. Given the rule of thumb that targets with a size at least one-quarter of the line spacing can be imaged, four resolvable targets exist. These targets (shown in fig. 3B) are: (1) the potassic alteration zone at depth, (2) an elliptical zone about 500 m wide containing breccia fragments (fig. 1B), and (3 and 4) symmetrical distal actinolite orbicular alteration bands surrounding the district on both sides that are groundwater aquifers controlling all of the known springs on Fleecer Ridge (fig. 2A). After data processing, two-dimensional sections and 3D models were generated by Quantec with resistivity anomalies that clearly reflect all four of the anticipated resolvable features in the geological cross-section.

A comparison of the geological cross-section and 2D MT interpretation is shown in figure 3, where a vertical high-resistivity zone about 1 km wide extends from the surface to a depth of 1 km, representing the large north–south-trending elliptical zone with brecciated rock fragments (at the center of fig. 3). Below a depth of 1 km, the top of a resistive cupola widens and extends to over a depth of 2.5 km, which we believe is a potassic alteration zone with disseminated Cu-sulfides, our prime drilling target. Notice that this cupola is below the elevation of the Big Hole River (fig. 3B). In addition, high conductivity zones clearly related to known surface springs within orbicular actinolite zones extend to depth, where they are truncated by the right-lateral Belmont fault.

3-D Resistivity Models

This section covers discovery of the likely spring fountainhead and interrelationships of hydrogeology, ancient ore-forming systems, and the landscape today. By eliminating resistivity less than 1500 Ω·m, the highly resistive zones are shown by peeling away the shell of more conductive rocks (fig. 4A). The permitted 2-km-deep pilot drill hole site is shown as a red circle, with a steep drill hole shown in black to test this potassic zone target. The high-resistivity anomaly clearly supports the location of our pilot deep drill hole test and supports the merits of the geological choice of this location, for which an operating permit from the U.S. Forest Service is in hand. An environmental restoration bond is also in place with the Montana Department of Environmental Quality. Figure 4A shows the effect of peeling away resistivities more than 200 Ω·m. Two low-resistivity (more conductive) anomalies are evident. Given a focus here on mineral exploration, these might appear to represent sulfide mineralization. However, the mapped occurrences of springs at the surface (fig. 1B) present a more likely interpretation. MT has long been established as an effective imaging tool for mapping aquifers (Aboud and others, 2014) and geothermal fields (Bennington and others, 2025), including silicate melts as at the Yellowstone hotspot underlying Montana. We interpret the axially symmetric MT conductive zones at Clementine to represent the aquifers occurring in and around the distal orbicular actinolite orb zones. The high conductivity of the water is best explained by dissolved sulfate and graphite in the orb zone rocks. The large tube-like conductive anomaly on the east side we interpret to be a water-filled paleo-karst cavity located below the unconformity at the top of the Madison

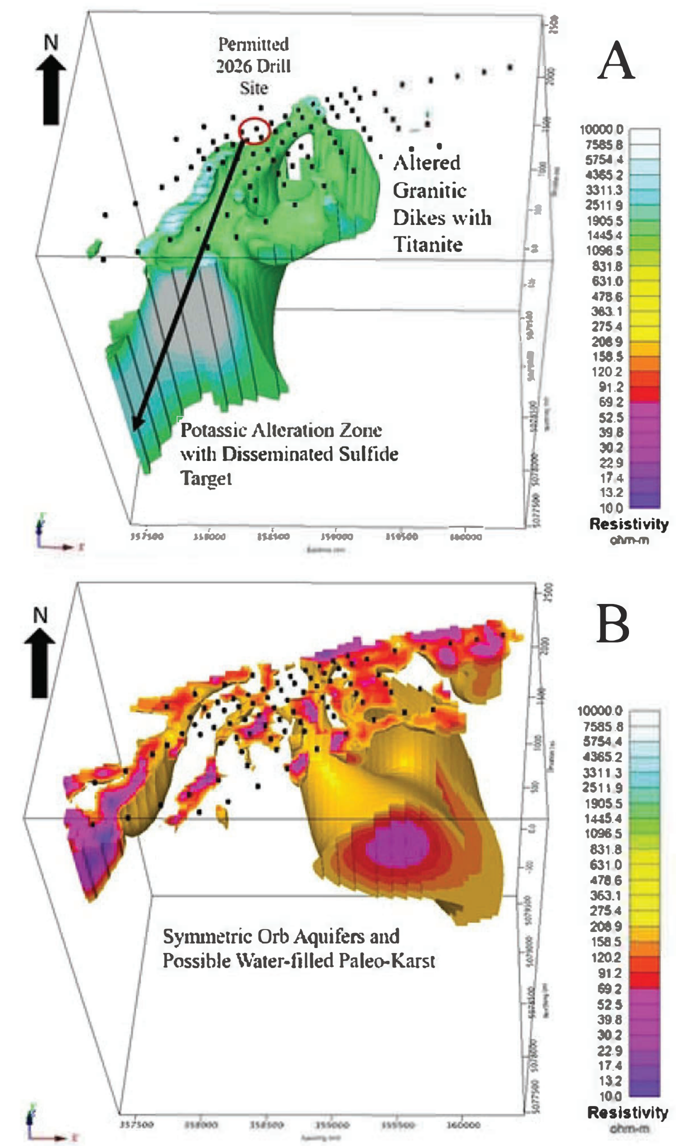

Figure 4. (A) Black dots are the grid points where the MT measurements were made. Resistivity model with resistivities more than 200 Ω·m. (B) Resistivity model with resistivities less than 200 Ω·m. Groundwater aquifers are interpreted to represent the axially symmetric conductive zones.

Formation, which is well known in Montana for its paleo-karst caverns, including the world-famous Lewis and Clark caverns. Locally such paleo-karst can be seen along the Big Hole River opposite Dewey. Should this potential fountainhead of the springs be confirmed by water well drilling, back-up water resources might well be provided for summer range cattle during inevitable extreme droughts as regional aridification intensifies. Sharing such rare water resource equity generated by independent holistic mineral exploration with the community contributes to earning a social license for mining. The kinship of the Fleecer Ridge landscape, water resource functionality, and local wetland ecosystem with the architecture of the ore-forming system proves its deep-rooted place in nature.

Fleecer Ridge Hydrogeology: Springs, Montane Swamp Forest Wetland, and Topography

Surface mapping of springs and subsurface MT imaging reveal a connected flow field beneath Fleecer Ridge (figs. 1B, 3, 4) aquifers of hydrothermal origin control subsurface water flow today. A clear surface manifestation of this flow field is the Montane swamp forest wetland in the far north edge of the Clementine prospect, where the Belmont fault and an actinolite orb aquifer intersect on the eastern flank of the Indian Creek saddle (fig. 1B). The water-logged soils and shallow-rooted trees are prone to wind heave, producing a dead fall moss-covered vegetation. This occurrence of montane swamp forest wetland appears to be the first such system recognized in central Silver Bow County. More broadly, the prominent Fleecer Ridge and the Indian Creek Saddle landforms may well reflect the permeability structure of the 71 Ma-old mineralization system and its long-term influence on differential erosion rates over geological time.

Conclusions

The exploration target being sought at Clementine using MT imaging is the top of early stage high-temperature fracture-controlled disseminated Cu-sulfide mineralization with potassic alteration and its continuity with depth. MT imaging confirms the integrity of the surface geological mapping and supports the geological cross-section used in selecting the pilot deep drill hole location. We believe that a steeply west-dipping tabular resistivity anomaly extending more than 2.5 km in depth represents the sought-after drilling target and is of sufficiently large size to reflect a Tier 1 size PCD system with its upper reaches being brecciated. The vein gossans mapped on the surface are themselves breccia veins where the matrix surrounding the silicate clasts were sulfide now replaced by limonite. Below 1 km, the highly resistive anomaly broadens into a cupola that extends to a depth of over 2.5 km.

Our exploration method, implemented by geological mapping of distal orbicular actinolite, could, if tested by drilling of the target imaged by MT described above, provide an innovation that alters established norms for target ranking, exploration on public lands, and access to funding by advancing understanding of key processes. Unlike existing descriptive porphyry Cu models that are pictorial geospatial representations of alteration and mineralization in cross-section (Lowell and Guilbert, 1970), the new thermochemical model of Brimhall (2024) is supported by field geology and mineral chemistry of well-known mineral assemblages of potassic alteration, and uses chemical thermodynamics to discern the convective flow field. Early high-temperature potassic alteration is central and represents an upflow path of fluids, with outgassed H_2 causing oxidation of the magma. Propylitic and distal orbicular actinolite, in contrast, representsthe descending flow path where reduction occurs as H_2 concentrates.

What is unique about the operative thermochemical model of PCDs (Brimhall, 2024) is that it, through outgassing of molecular hydrogen H_2, explains oxidation of the magma as well as the reducing character of the distal descending fluids forming the orbicular actinolite orbs surrounding giant systems stable long enough for diffusion to operate, especially in sedimentary wall-rock surroundings. Simply put: the region from where H_2 departs becomes oxidized, and where H_2 goes becomes reduced so that the upflow and downflow pathways control oxidation and reduction, respectively. In contrast, the same model explains why porphyries that intruded granitic batholiths like the Butte District of Montana do not form actinolite orbs. The granite (biotite–K–feldspar–magnetite) mineral system exerts a powerful chemical buffering control on fluid composition. This impedes both early oxidation up into the bornite–chalcocite field, as well as precluding reduction where actinolite would otherwise be stabilized. This redox buffering explains the absence of bornite in the early high-temperature assemblage of Butte. Instead, chalcopyrite and pyrite are the only early sulfides and they occur inside of a district-scale magnetite cupola (Brimhall, 1977; Reed and Dilles, 2020) that is nested within a dome of biotitized hornblende representing the upper and outer edge of the potassic alteration (Roberts, 1973; Brimhall and others, 1985). Conversely, our model predicts that PCDs in sedimentary wall rock like Clementine are not buffered by granite and are thus unlikely to form a magnetite cupola as at Butte, but can host copper-rich skarns.

MT survey methods in well-mapped projects could have an important influence on exploration in Montana, especially on public lands, as it requires minimal environmental disturbance while offering powerful geological insights useful in drill testing of large, Tier 1, potentially economic PCDs. However, besides mapping geology, springs must be mapped in order to accurately interpret the MT imagery. Should pilot diamond drilling optimized by geophysical imaging lead to the discovery of new Tier 1 Cu mineralization, then the place of orbicular actinolite alteration in the porphyry Cu technology would be established as a lodestone indicator of Tier 1 magmatic-hydrothermal convection cells and porphyry Cu deposits at depth. The impact could be transformative as a tangible capital asset as it elevates significantly the probability of discovery of a large economic deposit and thus lowers risk. What is not often realized is that the oxidized parental magmas carry their own energy source in the form of dissolved water, that if exsolved with explosive force rather than being confined as in miarolitic cavities or pegmatites, will cause intense hydrofracturing and long-term thermal convection, which causes alteration and mineralization on a scale proportional to the size of the crustal magmatic thermal anomaly.

Implications for Exploration

For MT imaging to have maximum benefit, it requires the existence of accurate surface geological mapping with structural attitudes and faults that produce unique geospatial information obtainable by no other means (Brimhall and others, 2006). Geological mapping remains the only viable means of capturing geology at an accuracy and level of detail useful in exploration and mining. Mapping springs as possible sources of water for drilling is vital. Some features, including springs, remain enigmatic as mapping continues and only when a discernible pattern emerges is their origin understood. Mapping the orbicular actinolite alteration and realizing that springs were spatially associated with them is a perfect example of stepwise progress advanced by rare epiphanies. The essential point is the necessity of dignifying our ignorance by at least recording peculiar features on our maps and following through until they are understood.

Acknowledgments

Enthusiastic conversations with both Marco Einaudi and Bill Atkinson by the senior author confirmed the identification of the orbs at Clementine and assisted greatly in advancing our knowledge of the origin of this alteration at Clementine and its potential significance globally. The abiding support and executive collaboration of Doug Fuerstenau, Ray Morley, and Bruce Marsh are gratefully acknowledged. MT imaging was suggested by Tim Stockhausen of BHP in a discussion with the author and Aric Cunningham arranged by Emerson Melinsi. Kyle Eastman and Steve Quane are thanked for organizing the Mining and Minerals Symposium in 2025. Quantec Geoscience staff are thanked, including Ryley Kilham, Sam Edwards, Robert Gordon, and especially the field crew overseen by AJ Erasmus and led by Michelle Durban, which included Rajan Naran, Eric Guier, Jason Martens, and Nathaniel Nimitz for conducting the survey, supported by Childs Geoscience staff Griffin Bouma, Jack Brown, Alex Greenfield, Riley Leigh, Barrett Nichols, Henry Stahl, and Ruger Whitmore. John Childs is thanked for outstanding management of work teams in high demand during a short Rocky Mountain field season. The regional airborne geophysical survey of the USGS provided an opportunity to collaborate, and we thank Mike Cosca, Eric Anderson, Ben Magnin, Theresa Schwartz, Julia McIntosh, April Allen-Langhans, Mario Guzman, Snir Attia, Jonathan Funk, and Neil Griffiths.

References

Aboud, E., Saud, R., Asch, T., Aldamegh, K., and Mogren, S., 2014, Water exploration using magnetotelluric and gravity data analysis; Wadi Nisah, Riyadh, Saudi Arabia: NRIAG Journal of Astronomy and Geophysics, v. 3, no. 2, p. 184–191, https://doi.org/10.1016/J.NRJAG.2014.09.002

Atkinson, W., and Einaudi, M.T., 1978, Skarn formation and mineralization in the contact aureole at Carr Fork, Bingham, Utah: Economic Geology, v. 75, p. 1326–1365, https://doi.org/10.2113/gsecongeo.73.7.1326

Bennington, N., Schultz, A., Bedrosian, P., Bowles-Martinez, E., Lynn, K., Stelten, M., Tu, X., and Thurber, C., 2025, The progression of basaltic–rhyolitic melt Storage at Yellowstone Caldera. Nature, v. 637, p, 97–102., https://doi.org/10.1038/s41586-024-08286-z

Brimhall, G.H., 1977, Early fracture-controlled disseminated mineralization at Butte, Montana: Economic Geology, v. 72, p. 37–59.

Brimhall, G.H, 2018, Orbicular alteration at the clementine porphyry copper prospect of southwest Montana: Defining the edges of advective flow in the porphyry copper paradigm: Montana Bureau of Mines and Geology Special Publication 120, p. 71–84.

Brimhall, G., 2021, Deep sediment-hosted porphyry copper deposits with critical mineral potential and the geochemical relationship of orbicular actinolite alteration to district zoning and oxidation by carbonate dissolution CO_2 release, *in* Scarberry, K.C., Gammons, C.H., and Barth, S., eds., Montana Bureau of Mines and Geology Special Publication 123, p. 27–58, https://doi.org/10.59691/YXKU1170

Brimhall, G.H, 2024, An operative porphyry copper model based on thermochemical evidence of convective gaseous hydrogen transport and mega-strato volcanic eruptions containing anhydrite, in Van Rythoven, A., and Barth, S., eds., Montana Bureau of Mines and Geology Special Publication 124, p. 11–32, https://doi.org/10.59691/TTSI4436

Brimhall, G.H, 2025, Mappable thermochemical indicators of economic porphyry copper deposits in mine design, production, and closure conference, available at https://www.youtube.com/@susieanderson-ml2mo [Accessed July 2026].

Brimhall, G., and Fanning, M., 2020, Supporting the transition to deep porphyry copper exploration: SHRIMP U/Pb radiometric dating of titanite ($CaTiSiO_5$) in the distal and superjacent orbicular alteration zone of the Clementine prospect, southwest Montana, *in* Scarberry, K.C., and Barth, S., eds., Montana Bureau of Mines and Geology Special Publication 121, p. 117–132.

Brimhall, G.H., Agee, C., and Stoffregen, R., 1985, Hydrothermal conversion of hornblende to biotite: Canadian Mineralogist, v. 23, p. 369–379.

Brimhall, G.H, Dilles, J., and Proffett, J., 2006, The role of geological mapping in mineral exploration in wealth creation in the minerals industry: Anniversary Publications of the Society of Economic Geologists Special Publication 12, p. 221–241.

Chiaradia, M., and Caricchi, L., 2022, Supergiant porphyry copper deposits are failed large eruptions: Communications Earth & Environment v. 3, no. 107.

Einaudi, M., 2026, Geology and discovery of porphyry copper deposits, 2nd ed.: New Haven, Conn., Society of Economic Geologists, 500 p.

Grütter, H.S., Gurney, J.J., Menzies, A.H., and Winter, F., 2004, An updated classification scheme for mantle-derived garnet, for use by diamond explorers: Lithos, v. 77, p. 841–857, https://doi.org/10.1016/j.lithos.2004.04.012

Grütter, H., Gurney, J., Menzies, A., and Winter, F., 2024, An updated classification scheme for mantle-derived garnet, for use by diamond: Lithos, v. 77, no. 1, p. 841–857, https://doi.org/10.1016/j.lithos.2004.04.012

Heinrich, C.A., 2024, The chain of processes forming porphyry copper deposits: Economic Geology, v. 119, p. 741–769, https://doi.org/10.5382/econgeo.5069

Lowell, J.D., and Guilbert, J., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p. 373–408, https://doi.org/10.2113/gsecongeo.65.4.373

Luhr, J., 2008, Primary igneous anhydrite: Progress since its recognition in the 1982 El Chichón trachyandesite: Journal of Volcanology and Geothermal Research, v. 175, p. 394–407, https://doi.org/10.1016/j.jvolgeores.2008.02.016

Luhr, J., Carmichael, I., and Varekamp, J., 1984, The 1982 eruptions of El Chichón Volcano, Chiapas, Mexico: Mineralogy and petrology of the anhydrite bearing pumices: Journal of Volcanology and Geothermal Research, v. 23, p. 69–108, https://doi.org/10.1016/0377-0273(84)90057-X

Reed, M., and Dilles, J., 2020, Ore deposits of Butte, Montana, *in* Metesh, J.J., and Gammons, C.H., eds., Geology of Montana—Special Topics: Montana Bureau of Mines and Geology Special Publication 122, v. 2, 41 p., available at https://mbmg.mtech.edu/pdf/geologyvolume/ReedDilles-ButteChapter_Final.pdf [Accessed July 2026].

Roberts, S.A., 1973, Pervasive early alteration in the Butte district, Montana, *in* Miller, R.N., ed., Guidebook for the Butte field meeting of the Society of Economic Geologists: Society of Economic Geologists Guidebook: Butte, Mont., Anaconda Company, p. HH1–HH8.

Robinson, G.R., and Menzie, W.D., 2014, Economic filters for evaluating porphyry copper deposit resource assessments using grade-tonnage deposit models, with examples from the U.S. Geological Survey Global Mineral Resource Assessment: Scientific Investigations Report 2010–5090–H.

Singer, D. A., Berger, V. I., and Moring, B. C., 2008, Porphyry copper deposits of the world: database and grade and tonnage models: U.S. Geological Survey Open-File Report 2008-1155.

From Paper to Prospect: How Archives Power Geology and Mining Research

Chelsea Pincock

Montana Bureau of Mines and Geology, Montana Technological University, Butte, Montana

1. Abstract

The Montana Bureau of Mines and Geology (MBMG) Data Preservation Program is undertaking a comprehensive project to preserve, scan, and provide public access to its extensive collection of historic mining and geology maps, field reports, assays, and other associated documents. Supported by a 3-year grant from the U.S. Geological Survey's (USGS) National Geological and Geophysical Data Preservation Program (NGGDPP), the project involves systematic rehousing of physical materials into archival-quality containers, large-format scanning, metadata creation, digital preservation workflows, and development of a web-based discovery and access system. Additionally, the program is creating an interactive geospatial web application using ArcGIS and CollectionBuilder that allows users to explore archival holdings by mining district boundaries. By bridging archival curation with modern digital infrastructure and GIS-based interfaces, the MBMG Data Preservation Program transforms legacy paper and map holdings into findable, accessible, and usable resources for geologists, mining professionals, historians, community stakeholders, and the public. The project emphasizes the critical role of archives in geological and mining research. It demonstrates how archival investment can significantly enhance resource discovery, prevent redundant work, and support responsible land use, heritage preservation, and scientific investigation.

2. Introduction

Historic geologic and mining records, including maps, field notes, reports, correspondence, and core and sample collections are foundational to understanding the geology, mineral potential, and mining history of a region. The MBMG Data Preservation program houses many of these resources for the state of Montana (fig. 1). However, without proper preservation and digital access, these materials risk deterioration, loss, or underutilization. It is the program's responsibility to advocate that its existence is far more than to store "old paper." Data Preservation strives to increase awareness that archived holdings provide critical context, support ongoing research and exploration, and enable public access to geological heritage. This paper describes the processes by which the program preserves and digitizes its historic map and document collections, and outlines how these efforts are being transformed into a publicly accessible digital resource utilizing findable, accessible, interoperable, and reusable (FAIR) data principles (Wilkinson and others, 2016).

Figure 1. Overview of map drawers and rolled maps housed in the MBMG Data Preservation archive.

3. Collection Overview

The historic maps housed by the MBMG (fig. 1) were acquired through donations from several sources, including mining companies, the USGS, and individual geologists. These maps are the focus of USGS grant funding. There are between 15,000 and 20,000 maps documenting mining claims, geologic formations, underground workings, mineral occurrences, and other features across Montana. Many are unique, hand-drafted, and represent decades of fieldwork and mining operations.

Critical mining and geologic context are found within the associated document files, which include reports, assay sheets, correspondence, photographs, production records, and other manuscript materials generated throughout the lifespan of mining operations. The documents are arranged by mining claims within their respective counties, forming a parallel paper record that complements the map holdings. Collectively, they number in the tens of thousands and represent a substantial body of primary-source data that enriches the spatial and geologic information depicted on the maps.

The document collections provide essential interpretive context that cannot be conveyed solely through cartography. Assay sheets contain analytical results such as ore grades, mineralogical characteristics, and sampling locations tied directly to mapped features. Technical reports expand upon mapped observations by describing stratigraphy, structural relationships, alteration patterns, and development plans. Correspondence between miners, company officials, landowners, and field geologists often explain decisions behind claim boundaries, exploration strategies, and the construction or abandonment of mine workings. Photographs and field notes preserve visual and narrative details about surface conditions, mining equipment, adits, shafts, or exposure quality at the time of mapping.

Additionally, Data Preservation curates collections including drill core, hand samples, thin sections, and other materials related to geologic investigations and mining operations. These papers and specimens are also available for research, subsampling, or inspection on appointment. Utilizing the diverse collections can provide comprehensive insight into past mining and geological research across the State. Given the breadth and volume of the archival holdings, systematic preservation, organization, and access, systems are required to ensure long-term usability.

4. Preservation and Rehousing

The maps were stored in suboptimal enclosures that were typically the wrong size to support their contents, and not sturdy enough to support the maps properly over time. Several maps were not housed within map drawer protection; instead, they were rolled and haphazardly placed on top of cabinets, where they risked dust, light damage, and tearing. They were vulnerable to folding stress and handling wear. Also problematic was the absence of any organization, making them nearly impossible to find upon request, especially if the maps had not been scanned. Without intervention, these maps risked loss of context and severe damage, undermining both their physical integrity and research value.

The documents also faced several preservation issues. These files were stored in acid-free folders, but were not enclosed in appropriate boxes that would protect them from light, dust, and water. Many documents exceeded the folder size and were folded to fit, incurring risk of folding stress and tearing. Upon deeper investigation, many of the papers had been misplaced: either placed under an incorrect claim, or included in claims that did not contain relevant information for the assigned item, but rather information about mining companies or mineral deposits. This led program members to reconsider the organization of the document collection to improve findability and better support research.

4.1. Procedures (Maps)

Large-format map drawers previously contained up to 200 to 300 maps, divided by flimsy partitions and often disordered. Under reorganization procedures, each drawer holds no more than 10 durable folders, and each folder contains 10 maps. These regulations were chosen due to the size of the objects. These maps and folders are inherently awkward to handle and therefore susceptible to damage due to their size and weight (Ritzenthaler, 2010).

The new, sturdier folders are appropriately sized to hold the maps. The front of the map folders includes the Montana county, drawer number, and folder number on the lower right corner. The lower left corner is labeled with an index of the contents, ordered by content. This system ensures rapid retrieval and reduces the risk of misplacement or damage. These physical preservation efforts alone significantly improve the longevity and usability of the archival holdings (see fig. 2).

4.2. Procedures (Documents)

The documents are organized alphabetically by Montana county, and the folders within each county represent a mining claim. Each folder's contents are transferred to acid-free folders and placed in archival-quality boxes that protect against light, dust, water, and environmental damage. Each document folder is labeled with a claim name, a county name, and a folder number, all ordered alphabetically by claim. The boxes are labeled with a county, a claim name range for their contents, and a box number (see fig. 3).

Any item exceeding safe handling dimensions is removed and rehoused in flat-file storage or oversized map drawers. Items are placed within protective oversized folders labeled with the county, the associated claim name,

Figure 2. A map drawer before rehousing versus the same map drawer after rehousing procedures.

Figure 3. Document shelf before rehousing versus the same shelf after rehousing procedures.

and a unique oversized identifier. The original claim folder retains a placeholder sheet indicating the relocation, along with a brief description of the oversized item to maintain intellectual continuity. To ensure that users can still discover and request these materials, metadata links the oversized physical storage location to the claim-level record. Information such as drawer number, oversize folder ID, physical dimensions, and a note on the item's relationship to the claim is included in the metadata database. This allows oversized documents to be stored in appropriate long-term environments while remaining intellectually integrated with the rest of the collection. This practice is essential for maintaining both preservation quality and user access, especially when oversized diagrams or maps contain critical explanatory information tied to the claim's geological features.

5. Digitization Workflow

Digitization serves multiple purposes, but the two main ones are preservation and access. Digitization helps preserve the original maps by reducing handling. It helps with access by enabling remote viewing and downloading. The digitization workflow consists of scanning, file management, metadata creation, digital preservation, and public access deployment.

5.1. Scanning

Maps are first pulled from their drawers and enclosures. They are assessed for quality and then scanned. If the quality is not conducive to scanning, they are repaired before scanning. Unsuitable conditions include torn edges, dirt buildup, the presence of staples or fasteners, and curling. Maps are scanned with a high-resolution, large-format scanner (up to 60 inches) at 600 DPI. This resolution is sufficient to capture all lines, annotations, labels, and geospatial detail. The resulting master image scans are stored as lossless TIFF files. After scanning, each image is reviewed for clarity, completeness, and accurate orientation. This includes checking for distortions, missing margins, and legibility of fine-scale details.

5.2. Digital Organization

The map files are then organized digitally, the same way they are physically. There is a digital folder for each drawer, with corresponding subfolders that mirror the physical folders. Each map scan within these folders is named according to its physical location and matches the index in the physical folder. For example, a scan that is physically located in drawer 1, folder 2, and is the first map in the folder will receive a file name with the code 001-02-01 followed by its index title (fig. 4). This makes both the digital and physical maps easy to locate.

5.3. Metadata

This is the heart of the digital archiving process. Metadata is essentially data about data. For each map, information such as geographical information, title, author, description, physical storage location, digital identifiers, usage notes, and keywords is recorded in our in-house metadata entry software and stored in a database. This step is crucial as it powers the search functions users will use to navigate the items uploaded to the MBMG Data Preservation website. While tedious, this is the most critical step in the digitization process, and it must be completed accurately and carefully. Errors can cause the web app to malfunction, preventing users from finding what they need. Additionally, the metadata aids accessibility for those who need extra accommodations to access our files.

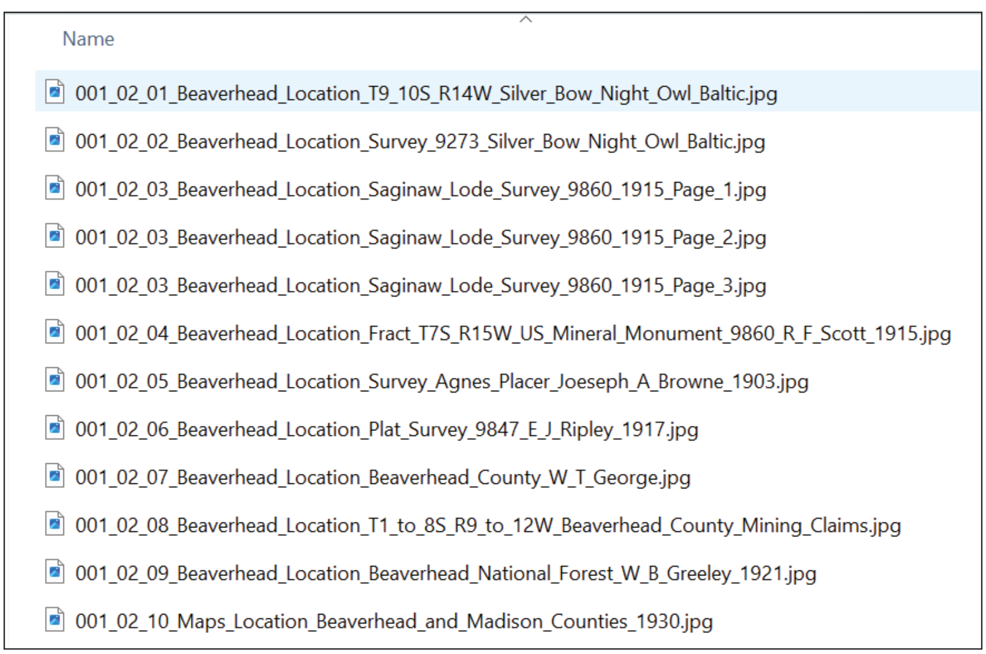

Figure 4. Example of digital file organization and naming conventions.

5.4. Accessibility Considerations

Ensuring accessibility for scanned maps and associated documents requires careful planning at each stage of the digitization and publication workflow. Optical Character Recognition (OCR) converts typed or clearly printed text into machine-readable form, enabling search functions, screen readers, and metadata extraction across the collection. For legacy materials, especially those containing annotations, variable typefaces, or degraded printing, OCR accuracy may vary. In these cases, a combination of automated OCR and human review improves reliability. When OCR is not feasible—such as with handwritten field notes, marginalia, or cartographic labels—descriptive metadata is strengthened to convey essential information that would otherwise be inaccessible to users relying on assistive technologies.

Providing text alternatives for visual elements is another critical accessibility component. Maps, diagrams, and photographs require alt text or long descriptions that summarize their purpose, geographic coverage, key features, and any significant geologic or mining information they convey. Because maps inherently present spatial and layered information, text descriptions focus on conveying relationships rather than reproducing the visual data verbatim. For complex materials, a hierarchy of descriptions may be used, offering both a brief alt-text summary and an extended narrative description accessible via linked metadata fields.

Compliance with WCAG 2.2 (Web Content Accessibility Guidelines 2.2) also involves providing users with tools that support perceptual and navigational needs. Map viewers should include zooming, panning, and rotation capabilities to ensure that small text, symbols, and detailed geologic features remain readable at high magnifications. Adjustable contrast modes or color-blind-friendly palettes can improve legibility, particularly for maps that use conventional geologic colors or hatch patterns that may be difficult for some users to distinguish. Keyboard navigation support, logical reading order within PDFs, and structured metadata all contribute to a more accessible user experience. Taken together, these considerations allow scanned maps and historical mining documents to meet contemporary accessibility expectations while preserving their scientific and archival integrity.

5.5. Digital Preservation

To ensure the longevity and integrity of digital objects, Data Preservation implements a multi-tier digital preservation strategy as suggested by O'Meara and Stratton (2016). Master files are retained as the "original" or authoritative copy. File derivatives of the master copy are created for access. These formats include PDF/A, JPEG2000, and compressed JPEGs for efficient web viewing and download. All master and access files are stored in multiple secure locations, both onsite and offsite. Regular backups and version control are maintained. Each file receives a SHA-512 checksum ("digital fingerprint"). Periodic fixity checks compare new checksums against the original. Any mismatch triggers a restore from backups to prevent data loss from silent bit rot or corruption.

5.6. Public Access Deployment

To make the digitized collection discoverable, Data Preservation uses CollectionBuilder (Center for Digital Inquiry and Learning), a digital collections platform. CollectionBuilder supports item-level records with metadata and descriptive content, embedded viewers for maps and documents, download options for files, and search and filter functionality. Existing collections, such as the Stope Book collection, demonstrate the power of this system. As the map digitization project progresses, all newly scanned maps and documents will be added, producing a comprehensive, searchable digital archive.

6. Interactive Geospatial Discovery Tool

Recognizing that many users (especially geologists, engineers, and land-use planners) think spatially, Data Preservation is developing an interactive GIS-based discovery tool for archival objects. The tool uses geodata files defining polygons, such as mining districts across Montana. When a user clicks on a district polygon, a pop-up or side panel lists all maps and documents associated with that district (fig. 5). Clicking one of those entries opens the item

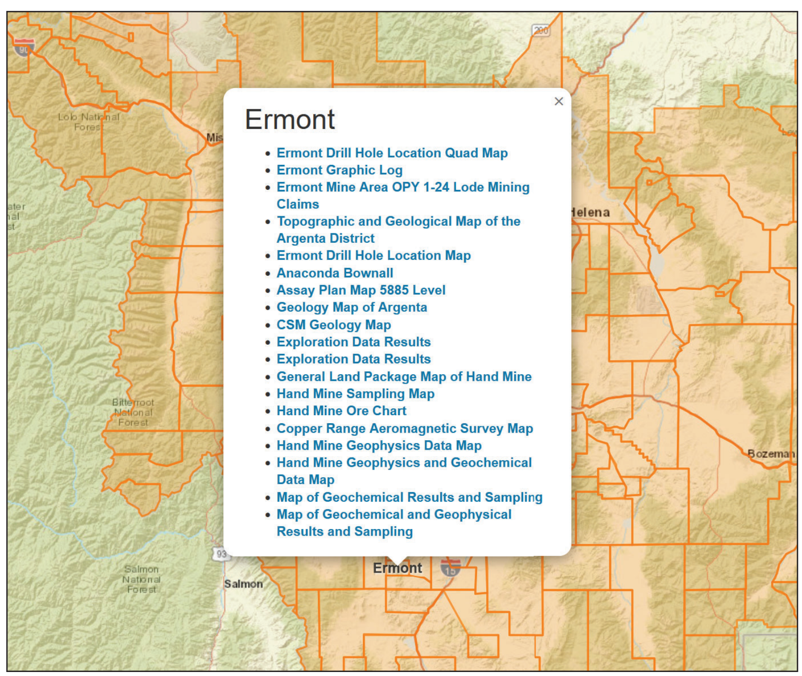

Figure 5. Screenshot illustrating the interactive map viewer with an example of a popup with a list of maps and documents applicable to the Ermont Mining District.

record. The record includes metadata, a preview image, and a download link. A prototype is functional as of this writing; however, development is ongoing for detailed map metadata display, performance optimization, and accessibility compliance. This spatial interface enables users to explore archival holdings by geography rather than solely through textual search.

7. Significance for Geology, Mining, and Public Stakeholders

The archival preservation and digital access process has multiple interrelated benefits, including efficiency and cost savings, support for mining and exploration, scientific research, heritage preservation, and data resilience. Researchers and industry professionals can reuse historic data rather than duplicate fieldwork or re-survey previously examined areas. This reduces redundant effort and saves time and money. Historic maps often contain detailed information on past claims, underground workings, mineral occurrences, and geologic features. These are all critical for exploration, due diligence, environmental assessment, and reclamation planning. Geologists and students can use archived data for regional studies, structural analyses, mineral resource assessments, and temporal comparisons. By making historic records available, the archive helps preserve that heritage and enables public access to information that might otherwise remain locked in storage. Finally, physical maps deteriorate over time. Digital preservation ensures that information remains intact and accessible for future generations.

8. Challenges and Lessons Learned

To date, Data Preservation has encountered challenges typical of archival and digitization efforts. Tens of thousands of maps and documents require systematic handling, and the scope of work often exceeds initial time or staffing estimates due to unforeseen labor involved. Although the USGS grant funds map scanning and preservation, rehousing and metadata creation are on the MBMG's own dime. Without institutional commitment and support, this part of the archive can lag. Data Preservation also involves recognizing that metadata errors can significantly impair discoverability. Strict quality control and standardized workflows are essential. The institutional technical infrastructure must maintain backup systems, storage redundancy, and data security. Finally, building a user-friendly web interface and GIS tool requires coordination and collaboration among archivists, developers, and user community stakeholders. Accessibility for persons with disabilities adds further technical and design requirements. These challenges underscore the need for institutional buy-in, long-term staffing, and sustainable funding if archival projects are to succeed.

9. Conclusion and Future Directions

The MBMG Data Preservation Program's ongoing efforts to preserve, digitize, and provide access to historic geology and mining records represent a model for how state geological surveys can safeguard their legacy collections and transform them into living resources. By combining traditional archival practices with modern digital preservation strategies and web- and GIS-based delivery, the Program is making Montana's geologic heritage available to scientists, industry professionals, community members, historians, and future generations.

Future work will focus on completing the scan and metadata backlog, finishing development of the interactive geospatial discovery tool, adding more records and physical objects into the metadata database, and advocating for continued funding and institutional support to maintain and expand the digital archive.

The success of this project demonstrates that archival preservation is far more than "storing old paper." It enables research, prevents redundancy, fosters public access, and preserves knowledge. In short, archives power geology.

10. References

Center for Digital Inquiry and Learning CollectionBuilder Home: CollectionBuilder, available at https://collectionbuilder.github.io/ [Accessed December 2, 2025].

O'Meara, E., and Stratton, K., 2016, Preserving digital objects, *in* Prom, C.J., ed., Digital Preservation Essentials: Society of American Archivists, 135 p.

Ritzenthaler, M.L., 2010, Preserving archives & manuscripts (2nd ed.): Society of American Archivists, 525 p.

Web Content Accessibility Guidelines (WCAG) 2.2, available at https://www.w3.org/TR/WCAG22/ [Accessed December 2, 2025].

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., and others, 2016, The FAIR Guiding Principles for scientific data management and stewardship: Scientific Data, v. 3, no. 1, p. 160018, https://doi.org/10.1038/sdata.2016.18

Derelict cabins, Ruby Graphite Project, Beaverhead County, Montana. Photo by Adrian Van Rythoven.

Open pit, Calvert W Mine, Beaverhead County, Montana. Photo by Adrian Van Rythoven.

Tailings pile, Nettie Mine, Silver Bow County, Montana. Photo by Adrian Van Rythoven.