University of Nevada, Reno student chapter of the Society of Economic Geologists Field trip report: Iron, Copper, and VHMS systems of Norrbotten and Västerbotten, Sweden, 2022

The field trip crew with geologists from Copperstone Resources outside of Kiruna, Norrbotten, Sweden. Back row, left to right: *Daniel Sandoval Moreno, *Maximilian Kroeckert, Ernest Brakohiapa, Alison Mertz, **Olcay Ayoğlu, Sarah Shapley, Alex Holmwood, Dominique Cottrell, Neal Mankins, Nick Brodeur, Elvis Nkioh Nsioh, and William X. Chávez, Jr. (*Copperstone Resources staff; **University of Oulu student). Front row, left to right: David Muller, Claudio Araya, Sarah Bennett, and Ethan Haft. Behind the camera: Koray Tasbicen.

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Introduction

The University of Nevada, Reno chapter of the Society of Economic Geologists entered a hiatus during the COVID-19 pandemic. A transition to online learning and social distancing during most of 2020 and 2021 removed many students from the field and discouraged face-to-face interaction critical to academic and professional success. Among the greatest disappointments was cancelling a summer 2020 trip to world-class epithermal deposits of New Zealand's North Island due to travel restrictions. The pandemic dashed hopes of postponing an excursion to New Zealand to 2021 or 2022 as well. A slow return to normalcy in late 2021 and renewed interest in domestic field trips helped pull the UNR back from its period of inactivity.

Our first field trip of the 2021-2022 academic year took us to the Original 16-to-1 Mine in Alleghany, California, where we toured the underground workings and collected samples from a well-renowned orogenic Au deposit. During the spring 2022 semester, we found ourselves touring open pits at SSR Mining's Marigold operation near Winnemucca, Nevada. Both of these day trips prepped us to step up and handle something a little bit bigger, such as a field trip to northern Sweden.

Dr. William X. Chávez, Jr. and the students of New Mexico Tech's SEG chapter kept us in the loop regarding a trip to northern Sweden after one of the UNR chapter members met Dr. Chávez, Nick Brodeur (NMT's chapter President at the time), and Dominique Cottrell (NMT's chapter Treasurer at the time) on the 2nd Michael J. Fitzgerald Student Mapping Course. After discussing the Sweden trip with fellow UNR students, three of us expressed interest in joining NMT in May 2022 to Norrbotten and Västerbotten Counties. Learning about deposits in northern Sweden, including those in the world-class Skellefte district, introduced us to significantly different perspectives regarding ore deposit genesis that we wouldn't be exposed to in Nevada. Please enjoy reading about UNR's experience with New Mexico Tech and UTEP in northern Sweden.

Industry contacts

Boliden AB

- Rodrigo Jr. Embile, Environmental Engineer - Geochemist
- Viktor Grundström, Exploration Geologist
- Mac Persson, Exploration Geologist
- Christian Stenvall, Exploration Geologist

Copperstone Resources

- Marcello Imaña, Chief Geologist
- Maximilian Kroeckert, Exploration Geologist
- Daniel Sandoval Moreno, Exploration Geologist
- Elvis Nkioh Nsioh, Exploration Geologist

LKAB

- Sergio Francisco Castro Reino, Geology Specialist
- Henrikki Rutanen, Specialist in Mine Geology

Faculty and student participants

Faculty

- William X. Chávez, Jr., Professor of Mineral Engineering, New Mexico Tech

Students

New Mexico Tech:
- Ernest Brakohiapa
- Sarah Bennett
- Nicholas Brodeur
- Dominique Cottrell
- Ethan Haft
- Alison Mertz
- Koray Tasbicen

University of Nevada, Reno:
- Alexander Holmwood
- Neal Mankins
- Sarah Shapley

University of Texas at El Paso:
- Claudio Araya
- David Muller

Itinerary

Day 1, 9/17/22: Underground tour of the Kiirunavaara deposit with LKAB, Kiruna, Norrbotten

Day 2, 9/18/22: Field tour and discussion of the Luossavaara deposit, Kiruna, Norrbotten

Day 3, 9/19/22: Discussion and tour of the Aitik open-pit operation with Boliden, Gällivare, Norrbotten

Day 4, 9/20/22: Overview, core shed visit, and field visit of the Viscaria copper deposit with Copperstone Resources, Kiruna, Norrbotten

Days 5-6, 9/21/22 – 9/22/22: Travel to Luleå, Norrbotten, and Skellefteå, Västerbotten

Day 7, 9/23/22: Visit to Boliden's Maurliden reclamation operation and field visits to VHMS system outcrops, near Boliden, Västerbotten

Day 8, 9/24/22: Core shed visit with Boliden, field visits to VHMS system outcrops, near Boliden, Västerbotten

Day 1, 9/17/22: Underground tour of the Kiirunavaara deposit with LKAB, Kiruna, Norrbotten

Our trip began with LKAB, which mines the Kiirunavaara orebody immediately adjacent to Kiruna, in northern Sweden. Sergio Francisco Castro Reino and Henrikki Rutanen, mine geologists at Kirunavaara, brought us to the underground theater for a presentation on Kirunavaara's history of exploration, discovery, mining, and shipping methods.

The Kiirunavaara deposit is a 4 km long and steeply dipping sheetlike formation characterized by iron oxide-apatite mineralization. It is oriented NNE-SSW and bounded by Paleoproterozoic volcanics in the hangingwall and footwall Westhues et al. (2016) dated two separate IOA orebodies in the deposit to 1877-1874 Ma, which immediately postdate the hangingwall and footwall units. Geologists have posited hydrothermal and magmatic origins for Kiirunavaara, but Westhues et al. (2016) rather suggest a magmatic-hydrothermal origin driven by syenitic and later granitic intrusions. Greenschist facies and amphibolite facies metamorphism affected both the rhyodacite and trachyandesite rocks post-emplacement.

Sergio and Henrikki additionally described LKAB's sublevel caving mining method. Upward drilling in fan-shaped patterns drops ore into horizontal tunnels. Later, the ore piles are mucked and dropped down a vertical ore pass into a production tunnel, where they are then transported by carts. While this process is highly efficient, land subsidence related to sublevel caving is beginning to encroach on the town of Kiruna. LKAB is funding and running a project to relocate portions of the town in advance of future land subsidence.

LKAB graciously allowed us to take plastic bags of iron ore pellets, which are the mine's final product, with us back to the United States. However, unlike the pellets in our pockets, these pellets do not normally hop on a commercial flight from Stockholm to Los Angeles. LKAB transports cars of iron ore pellets via rail to Narvik, Norway, where they are then distributed by cargo ships. Approximately 2 million tons of ore are shipped to Narvik each month.

Dr. William X Chávez, Jr. examines a reamer once used for upward raise boring while touring LKAB's underground museum.

View of the Kirunavaara operation and the town of Kiruna from the Luossabacken ski area. From front to back: Dr. William X. Chávez, Jr., Sarah Bennett, Ernest Brakohiapa, Ethan Haft, and Dominique Cottrell.

Day 2, 9/18/22: Field tour and discussion of the Luossavaara deposit, Kiruna, Norrbotten

Luossavaara, like Kiirunavaara, is a steeply dipping iron oxide-apatite deposit immediately adjacent to the town of Kiruna. The deposit, however, is cordoned off and is not currently being mined by LKAB. Luossavaara rather sits adjacent to the Luossabacken ski area and, while inaccessible, the deposit is easily viewable from the ski area's summit. We hiked the ski area in under an hour and discussed possible mechanisms of formation for the Kiirunavaara and Luossavaara deposits. Dr. Chávez encouraged us to consider a variety of parameters influenced possible hydrothermal fluid pulses at Kiirunavaara, including temperature, oxygen fugacity, and sulfur fugacity.

Day 3, 9/19/22: Discussion and tour of the Aitik open-pit operation with Boliden, Gällivare, Norrbotten

Boliden AB operates Sweden's largest open-pit copper mine just south of Gällivare. We had the privilege of touring the Aitik pit, collecting samples, and studying drill core from a recent near-mine exploration project during the third day of our trip to Sweden. Prior to touring the pit, however, Boliden AB's staff gave us a detailed overview of the mine's geology, outlined our plan to visit the pit and core shed, and how they run an efficient open pit mining operation.

Geology and core shed visit

Aitik is located along the Kiruna-Ladoga shear zone and his hosted in Paleoproterozoic biotite and sericite schists. Sheeted pegmatite dikes and a quartz monzodiorite are the only unmetamorphosed rocks exposed in the deposit (Wanhainen et al., 2012). While the quartz monzodiorite is mineralized (Wanhainen et al., 2012), the pegmatite dikes are barren and rather exhibit coarse-grained K-feldspar, muscovite, and tourmaline. The main ore zone, as both described by Wanhainen et al. (2012) and observed in drill core during later our visit, is a chalcopyrite-bearing biotite-garnet schist. Boliden AB drove our group to the bottom of the pit and allowed us to collect ore specimens, and many of these samples were so sulfide-rich that we could not find great examples of the host rock.

In-depth discussions of the deposit's genesis ensued when Dr. Chávez posed the question of whether Aitik is a deformed and metamorphosed porphyry deposit. We thought about this possibility while observing core samples from a near-mine exploration project. Much of the drill core included biotite-garnet schist crosscut by epidote- and albite-bearing veins. Our group eventually settled on Aitik being a strongly deformed and metamorphosed porphyry deposit, although its complex history makes it very different from any porphyry system we had seen in the western United States.

Operations

Aitik is notable for being northern Europe's largest open pit mining operation (Wanhainen et al., 2012). Boliden AB's efficiency in mining the Aitik deposit is also quite impressive. Boliden processes approximately 240,000 tons of material daily at a 1:1 ore to waste ratio. Transporting 120,000 tons of ore daily is a substantial task that Boliden AB facilitates with an electric pantograph system for its haul trucks. This system helps reduce haul trucks' diesel consumption for a portion of their journey from the pit bottom to the top. Increasing haul truck speed is an added bonus. Our group enjoyed learning about this particular aspect of the Aitik operation, as it demonstrates how a combination of high ore grades and innovative engineering are required to run an efficient and profitable open pit mine.

Here is a video of the pantograph at work: https://www.youtube.com/watch?v=hIuxpfDAkm0

Day 4, 9/20/22: Overview, core shed visit, and field visit of the Viscaria copper deposit with Copperstone Resources, Kiruna, Norrbotten

Koray Tasbicen, a graduate student under Dr. Chávez at New Mexico Tech, Olcay Ayoğlu, a graduate student at the University of Oulu, and Marcello Imaña, Chief Geologist at Copperstone Resources, introduced our group to the Viscaria project during our fourth day in Kiruna. Like the deposits we studied over the previous few days, Viscaria presented itself as enigmatic.

Viscaria is a copper deposit near Kiruna that had been mined before. However, it also exhibits significant iron mineralization in magnetite. Both copper and iron are hosted in greenstones metamorphosed from Paleoproterozoic volcaniclastics, which was unsurprising given what we learned from the geologic history in northern Norrbotten. We arrived at Copperstone's core shed under the assumption that Viscaria is a VHMS deposit, but interpreting the genesis of the deposit was difficult due to its complex multiphase history. The presence of lenticular and stratabound orebodies suggests that Viscaria could be a VHMS deposit, but we learned that looking for stockwork veining or brecciation in a feeder zone is critical to assessing this claim.

Koray Tasbicen described electron microprobe work on the Ni and Co contents of pyrite at Viscaria, and Olcay Ayoğlu discussed her research on occurrences lamellae in magnetite. Both projects are critical in addressing hydrothermal processes responsible for sulfide and oxide mineralization at Viscaria.

Days 5-6, 9/21/22 – 9/22/22: Travel to Luleå, Norrbotten, and Skellefteå, Västerbotten

Two days of respite followed an intense four days of learning and jet lag. We found the opportunity to be tourists in addition to geologists, as we stopped at the Arctic Circle sign along E10 between Kiruna and Luleå for a group photo.

Our group at the Arctic Circle. Left to right: Neal Mankins, Ernest Brakohiapa, Nick Brodeur, Alison Mertz, Sarah Bennett, Sarah Shapley, Ethan Haft, Dominique Cottrell, Alex Holmwood, David Muller, William X. Chavez, Jr., and Claudio Araya. Behind the camera: Koray Tasbicen.

Day 7, 9/23/22: Visit to Boliden's Maurliden East water treatement operation and field visits to VHMS system outcrops, near Boliden, Västerbotten

Maurliden East

Boliden AB hosted us during our first full day in the Skellefte district. Rodrigo Jr. Embile, an environmental engineer and geochemist with Boliden AB, kicked off our day by introducing us to

the Maurliden East water treatment project. Boliden AB treats wastewater from the former Maurliden East mining project with a geotube system. Each geotube, which resembles a massive waterbed, can hold between approximately 900-1000 m^3 of water and sludge. Contaminated water is treated with lime and drops out Al-hydroxides and gypsum in a sludge. The sludge is pumped into geotubes and is used as an adsorbing agent for toxic metals present in wastewater.

Maurliden West

Mac Persson, an exploration geologist with Boliden AB, introduced us to the Maurliden West VHMS system during the latter half of the day. Maurliden West is a VHMS deposit with a tight synform morphology related to post-emplacement deformation and metamorphism. The occurrences of stringer and massive sulfide mineralization were consequently compressed in a horizontal direction. Extrusion of submarine pyroclastic rocks on the seafloor was critical to ore mineralization during the early life of the deposit, as open spaces within these pyroclastics allowed space for sulfide precipitation.

Mac also described the relevant features of models describing VHMS deposit genesis during our visit to Maurliden West. Like with LKAB and the Kiirunavaara deposit, Boliden AB refers to hangingwalls and footwalls as lithologies above and below the orebody, respectively. The ore-forming zone in the VHMS model is horizontal and lenticular in character, and it is typically referred to as the “ore horizon.” VHMS deposits typically form in submarine environments within extensional tectonic settings. Pyroclastic volcanics utilize normal faults as pathways for upward migration and deposition on the seafloor. Hydrothermal fluids also utilize faults as pathways prior to ore deposition, and the resultant hydrothermal cell forms immediately above and proximal to these faults. Vesicular pyroclastics are the best hosts for hydrothermal sulfides, as they exhibit substantial space for mineral precipitation. Metal zonation in a typical VHMS deposit can exhibit gold in the core, copper and pyrite above gold, and Zn-Ag-Pb mineralization at shallower depths. Sulfate horizons, such as barite caps, are common as well. However, no barite cap exists at Maurliden West.

Exploration field stops

After discussing the genetic model for VHMS deposits, we ventured into the field and examined outcrops with submarine volcanic textures significant for exploration. We learned that distinguishing between vent-proximal and vent-distal volcanic features is critical to targeting VHMS orebodies. Examples of igneous features proximal to volcanic vents include spatter textures, elongate bombs ejected from the vent, hyaloclastites, and pillow basalts. Outcrops visited included porphyritic rhyolites, volcanic breccias with secondary quartz amygdules, dacitic volcanics with strong silicic alteration, and andesitic hyaloclastites crosscut by secondary quartz and affected by chloritic alteration.

The field trip group trekking between field stops during their first day in Västerbotten County.

Andesitic hyaloclastite outcrop interpreted to be a near-vent submarine volcanic feature. Adjacent clasts of hyaloclastite could fit together almost like jigsaw puzzle pieces. The green-gray color is a product of chlorite alteration.

Day 8, 9/24/22: Core shed visit with Boliden, field visits to VHMS system outcrops, near Boliden, Västerbotten

Boliden AB's team brought us to their core shed and field stops near their exploration project in Strömfors during the final day of our trip. Immediately prior to examining core, Viktor Grundström, an exploration geologist with Boliden, described the Strömfors project and exploration methods previously used for exploration in the Skellefte district. Boulder trailing, in which transport distances of ore-bearing boulders were estimated to determine the location of the parental orebody, used to be a very significant exploration method in the Skellefte district. Examining textures and volcanic features characteristic of submarine volcanic vents, however, seems to be a more commonly used technique now. Field reconnaissance, field sampling, and core drilling are among the most effective methods for finding and describing these textures and features. While RC drilling may be cheaper, RC chips do not preserve volcanic textures very well. We also noticed that core drilling preserves mineral textures extremely well, as we were able to observe examples of medium-grained actinolite overprinted by sulfides. These sulfides included chalcopyrite, arsenopyrite, and pyrite.

After the core shed visit, we toured multiple outcrops in the Strömfors area. A considerable amount of hiking was required, as finding outcrops in the densely vegetated Swedish backcountry proved to be difficult. We began the field tour by visiting outcrops exhibiting perlitic cooling textures and submarine volcanics with fiamme textures. Later, we discussed the incorporation of gold into arsenopyrite-bearing quartz veins as viewed in outcrop. During the last few stops, we examined near-vent volcaniclastic rocks and textures including altered scoria, monomictic volcanic breccias, and spatter textures resulting from volcanic bombs falling to the seafloor.

The crew examines quartz veins with arsenopyrite-bearing margins. Top left: Sarah Shapley. Top center: Koray Tasbicen.

Spatter texture related to ejection of volcanic material from a submarine vent.

Expenses from Stewart R. Wallace fund

Expenditure	Cost (USD)
Rental vehicle	996.60

Gasoline 5/16/22	69.11
Gasoline 5/18/22	40.07
Gasoline 5/20/22	45.94
Gasoline 5/22/22	25.52
Lodging	322.76
Total	1,500.00

Acknowledgements

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References

Company information

- LKAB: https://lkab.com/en/
- Boliden AB:
  - Aitik: https://www.boliden.com/operations/mines/boliden-aitik
  - Maurliden: https://www.boliden.com/globalassets/operations/exploration/mineral-resources-and-mineral-reserves-pdf/resources-and-reserves-maurliden-2018-12-31.pdf
  - Strömfors: https://www.boliden.com/globalassets/operations/exploration/mineral-resources-and-mineral-reserves-pdf/2021/bol_main-1846165-v1-resources-stromfors-2021-12-31.pdf
- Copperstone Resources:
  - Viscaria: https://copperstone.se/en_gb/viscaria-copper-project/

Papers

Wanhainen, C., Broman, C., Martinsson, O., and Magnor, B., 2012, Modification of a Palaeoproterozoic porphyry-like system: Integration of structural, geochemical, petrographic, and fluid inclusion data from the Aitik Cu-Au-Ag deposit, northern Sweden: Ore Geology Reviews, v. 48, pp. 306-331.

Westhues, A., Hanchar, J.M., Whitehouse, M.J., and Martinsson, O., 2016, New Constraints on the Timing of Host-Rock Emplacement, Hydrothermal Alteration, and Iron Oxide-Apatite Mineralization in the Kiruna District, Norrbotten, Sweden