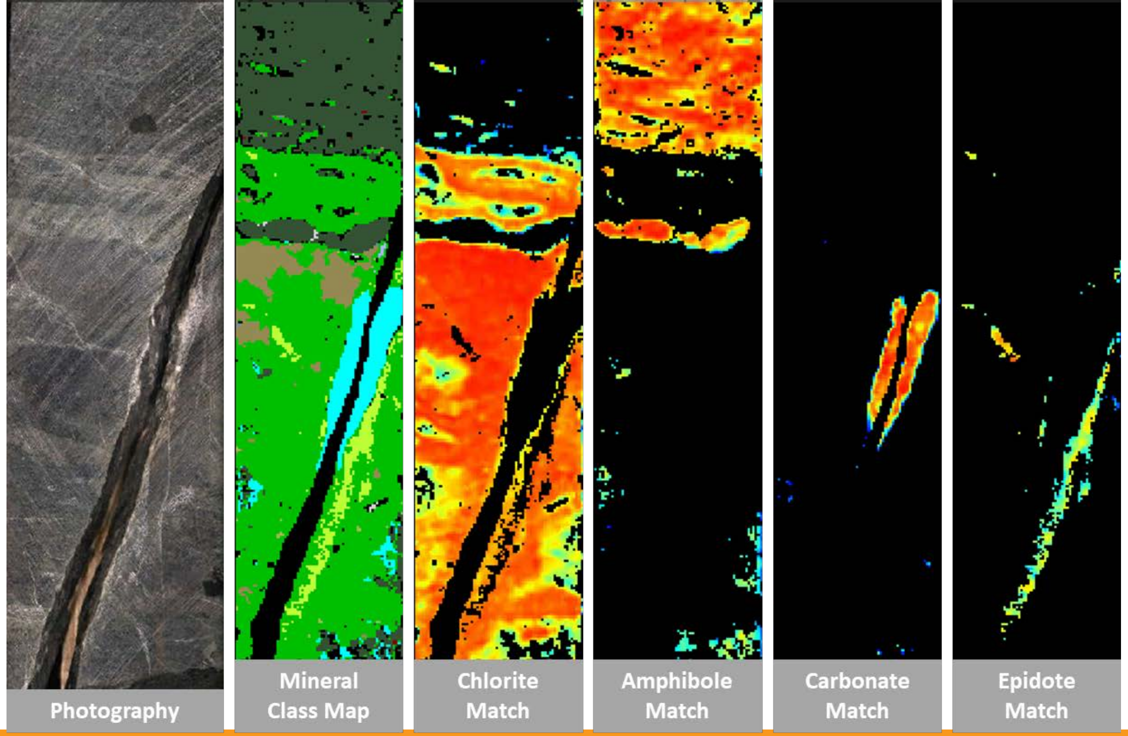


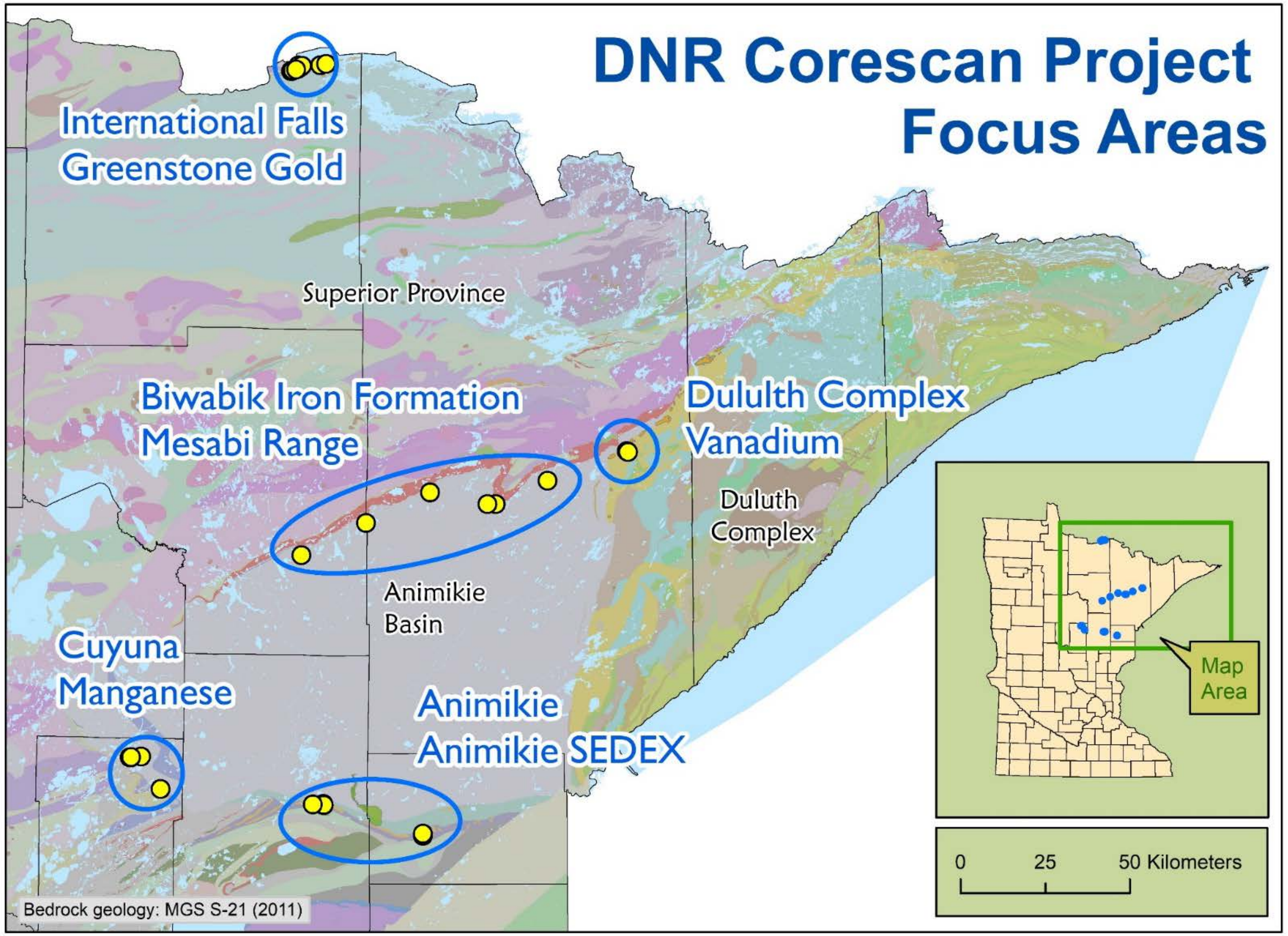
Corescan DCL Repository Results

Britt Bluemel, MSc | Principal Geochemist, Corescan
Cari Deyell-Wurst, PhD | Senior Spectral Geologist, Corescan
Lionel Fonteneau, MSc | Senior Spectral Geologist, Corescan

DEPARTMENT OF NATURAL RESOURCES

corescan

Focus Areas



Scanned Samples			
Job	**Projects**	**Total Amount**	**Depths**
JA0492	Animikie	810 ft.	LM-13-01 (203-454ft.); LM-13-02 (395-465ft.); LM-13-03 (346-506ft.); LM-13-04 (146-475ft.)
JA0465	Animikie SEDEX	217 ft.	K-1 (36-200ft.); KL-4 (119-500ft.)
JA0467	Biwabik Iron Formation	4,911 ft.	LWD-99-1 (347-1,344ft.); LWD-99-2 (580-1414ft.); MGS-2 (1574-2270ft.); MGS-5 (474-1252ft.); MGS-7 (741-1428ft.); MGS-8 (1125-2044ft.)
JA0464	Cuyuna Range Manganese	1,130 ft.	18423 (145-328ft.); 18709 (340-540ft.); 18713 (178-
JA0466	Duluth Complex Vanadium	2,099 ft.	LNG-001-2010 (54-794ft.); LNG-003-2010 (0-306ft.); LNG-011-2011(0-1053ft.)
JA0429	International Falls Greenstone Belt Gold	6,881 ft.	ND-1 (18-603ft.); ND-2 (29-653ft.); ND-3 (19-409ft.); RR-1 (6-1,602ft.); S-2 (4-452ft.); SS-1 (11-588ft.); SS-4 (39-412ft.); SS-7 (34-722ft.); SS-8 (31-502ft.); SS-9 (53-400ft.); TC35-1 (80-462ft.); TC36-1 (3-403ft.)

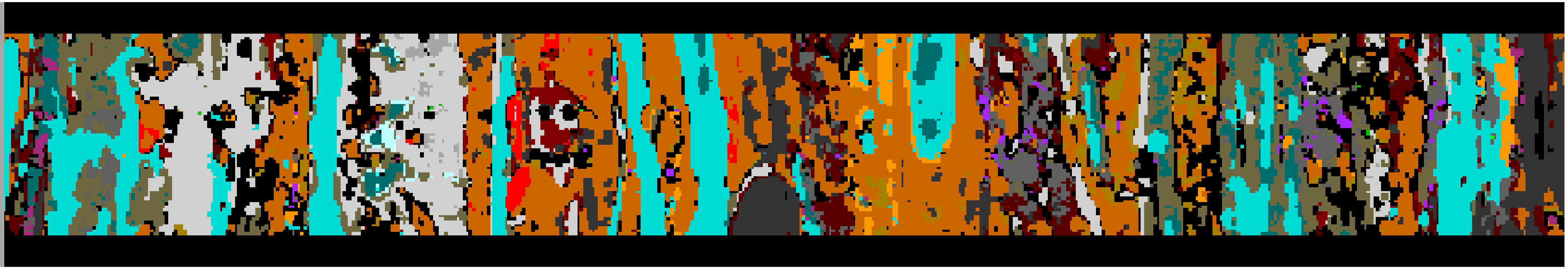
corescan

Drill Hole: LWD-99-1

477.90’ 477.40’

Photography

Mineral Class Map



Biwabik Iron Formation

Biwabik Iron Formation

- This iron formation is actively surface mined. Corescan mapping of ore grades and deleterious minerals within different stratigraphic intervals of the ore zone may highlight Corescan-3 system as a production tool for Minnesota's taconite industry.
- In 2009, the NRRI developed a stratigraphic system that linked all of the mined ore zones and waste submembers of the Biwabik Iron Formation. Corescan analysis may correlate this stratigraphy with distinct mineralogy or geochemistry, which may lead to a better understanding of how this vital mineral resource formed.
- This work may better define the contact between the iron formation and overlying Virginia Formation, and potentially identify hyperspectral markers for the Sudbury Impact event that has been petrographically identified in a few of these drill cores.

DDH	From	To	Total Feet	Total Meters	Comment
LWD-99-1	347	1344	997	265	Scan includes 200ft of overlying Virginia Formation (VF).
LWD-99-2	580	1414	834	252	LWD-99-1 and -2 are < 1mile apart
MGS-2	1574	2270	696	209	Proposed reference section for BIF
MGS-5	474	1252	778	235	Complete transect of BIF
MGS-7	741	1428	687	207	Complete transect of BIF
MGS-8	1125	2044	919	510	Scan of complete core, including 196ft of overlying Virginia Formation
		Total	4911	1497	

corescan

Biwabik – Mineral Key

Biwabik Fm

Mineral Name	Colour
Hematitic Quartz	
Goethite	
Nontronite	
Montmorillonite	
Kaolinite	
Chert + Illite/White Mica*	
NH4-Illite/White Mica	
Illite/White Mica	
Carbonate (Fe-rich)	
Hydrous Silica/Quartz	
Jasper + Carbonate (Fe-rich)	
Jasper	
Chert + Carbonate (Fe-rich)	
Microplaty Hematite	
Martite	
Fe-Oxide Mixture	
Talc (Fe-rich)	
Talc	
Minnesotaite	
Stilpnomelane	
Chlorite (Fe-rich)	
Chlorite	
Carbonate + Silicate	
Chert + Carbonate*	
Carbonate	
Magnetite Mixture	
Magnetite	
Chert Mixture	
Chert	
Chert + Slate	
Slate Mixture	
Slate	

First

Display Priority

Last

** Only displayed in the class map*

Virginia Fm

Mineral Name	Colour
Slate	
Slate Mixture	
Carbonate	
Carbonate (Fe-rich)	
Carbonate + Silicate	
Hydrous Silica/Quartz	
Illite/White Mica	
NH4-Illite/White Mica	
Chlorite (Fe-rich)	
Chlorite	
Chert Mixture	
Chert + Carbonate*	
Chert + Slate	
Chert	
Hematitic Quartz	
Goethite	
Nontronite	
Montmorillonite	
Kaolinite	
Chert + Illite/White Mica*	
Jasper + Carbonate (Fe-rich)	
Jasper	
Chert + Carbonate (Fe-rich)	
Microplaty Hematite	
Martite	
Fe-Oxide Mixture	
Talc (Fe-rich)	
Talc	
Minnesotaite	
Stilpnomelane	
Magnetite Mixture	
Magnetite	

First

Display Priority

Last

** Only displayed in the class map*

Pokegama Fm

Mineral Name	Colour
Quartz	
Hematitic Quartz	
Illite/White Mica	
NH4-Illite/White Mica	
Chert + Illite/White Mica	
Chlorite (Fe-rich)	
Chlorite	
Nontronite	
Montmorillonite	
Kaolinite	
Slate Mixture	
Slate	
Carbonate	
Carbonate (Fe-rich)	
Chert + Slate	
Chert + Carbonate	
Carbonate + Silicate	
Chert	
Chert Mixture	
Goethite	
Jasper + Carbonate (Fe-rich)	
Jasper	
Chert + Carbonate (Fe-rich)	
Microplaty Hematite	
Martite	
Fe-Oxide Mixture	
Talc (Fe-rich)	
Talc	
Minnesotaite	
Stilpnomelane	
Magnetite Mixture	
Magnetite	

First

Display Priority

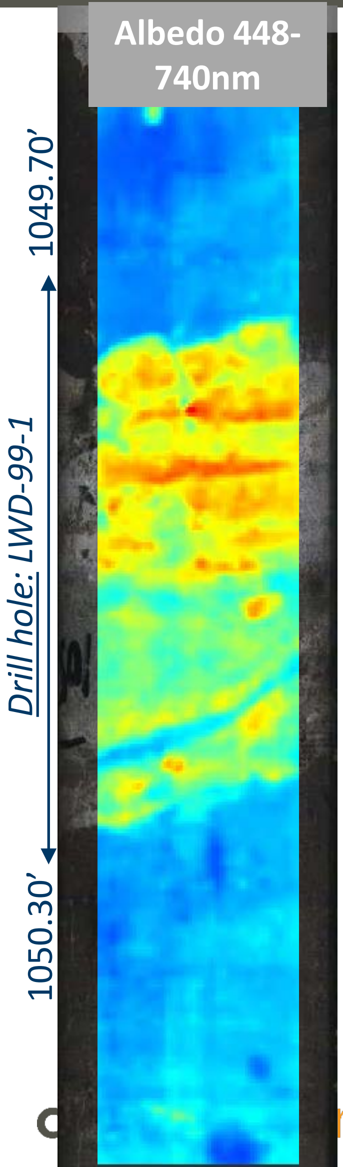
Last

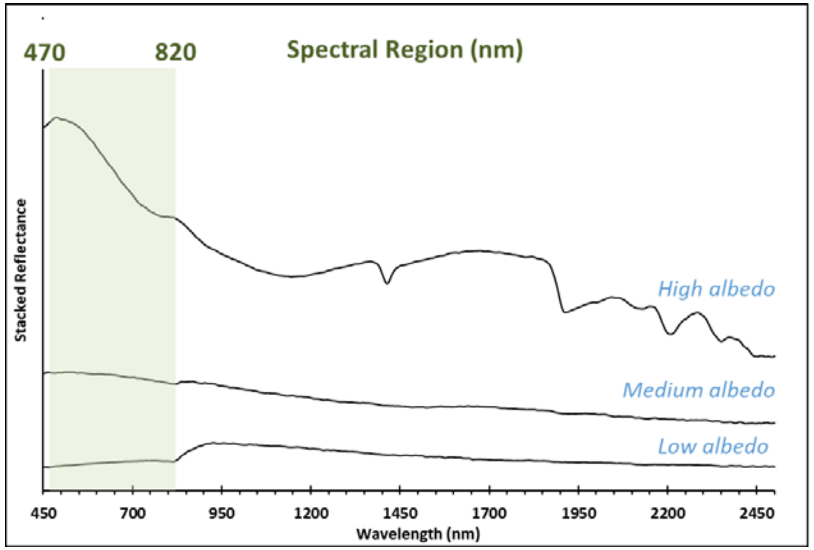
** Only displayed in the class map*

corescan

Biwabik Compositional Parameters

Albedo and carbonate grain size



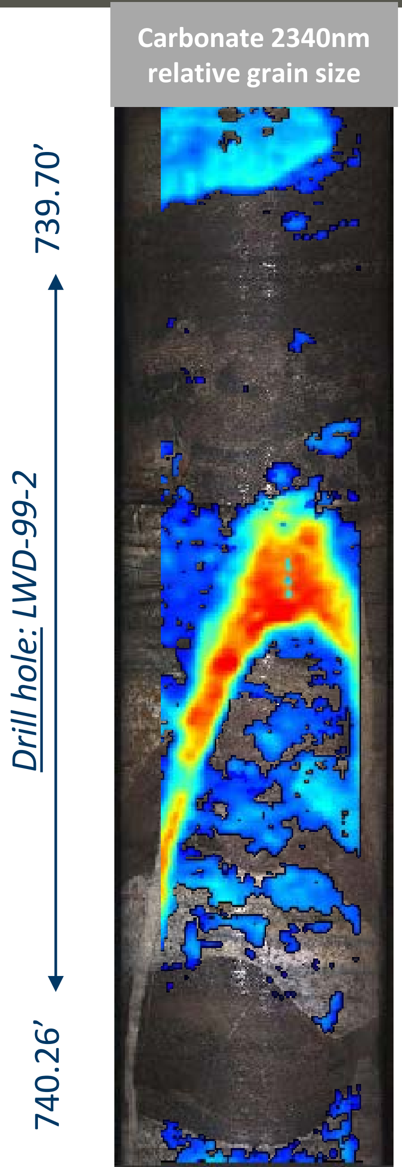


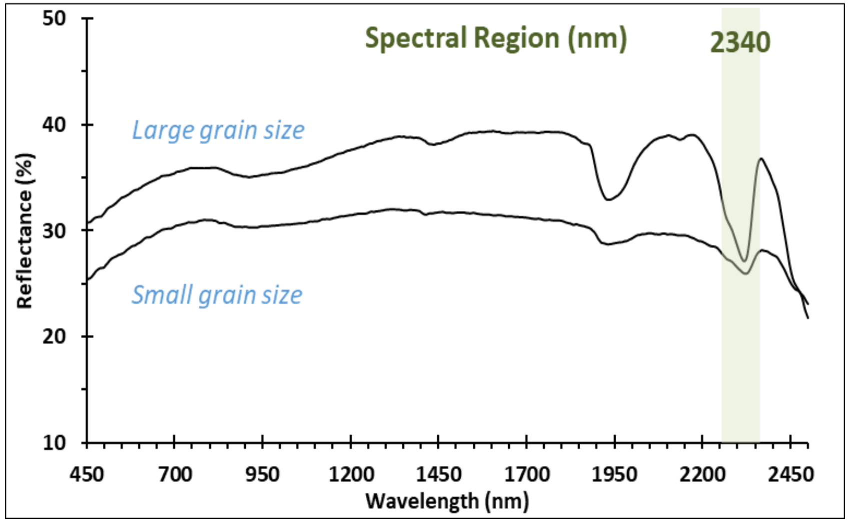
Albedo 448-740nm

Biwabik Iron Formation

- The Albedo 448-740 nm product represents the average reflectance or albedo calculated between 448 nm and 740 nm (VIS range)
- This product can aid in visualization of lithology; previous work has also shown correlation to Gamma Ray measurements
- Albedo can also be directly related to the grain size of the sediment

[Click here to view in Coreshed]





Carbonates 2340nm relative grain size

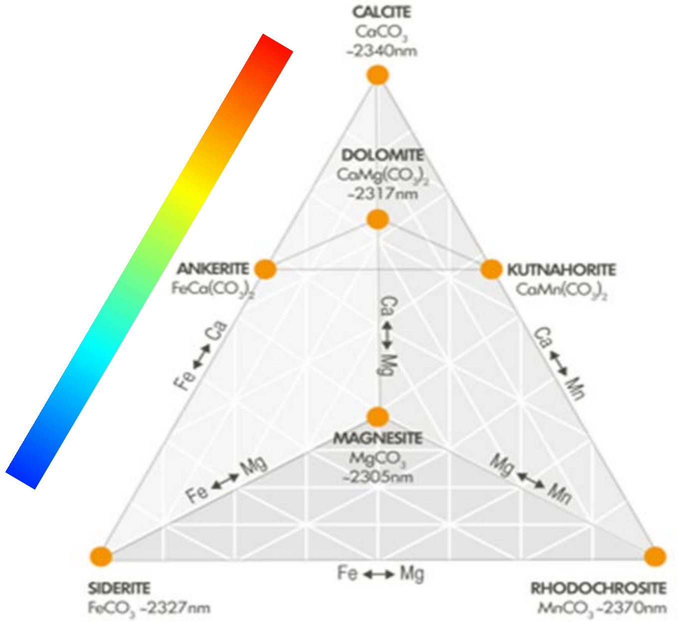
Biwabik Iron Formation

- According to Zaini et al. (2012) the depth of the 2330 nm absorption feature increases with the grain size up to 500 µm; in this project this depth is then normalised by the deepest feature

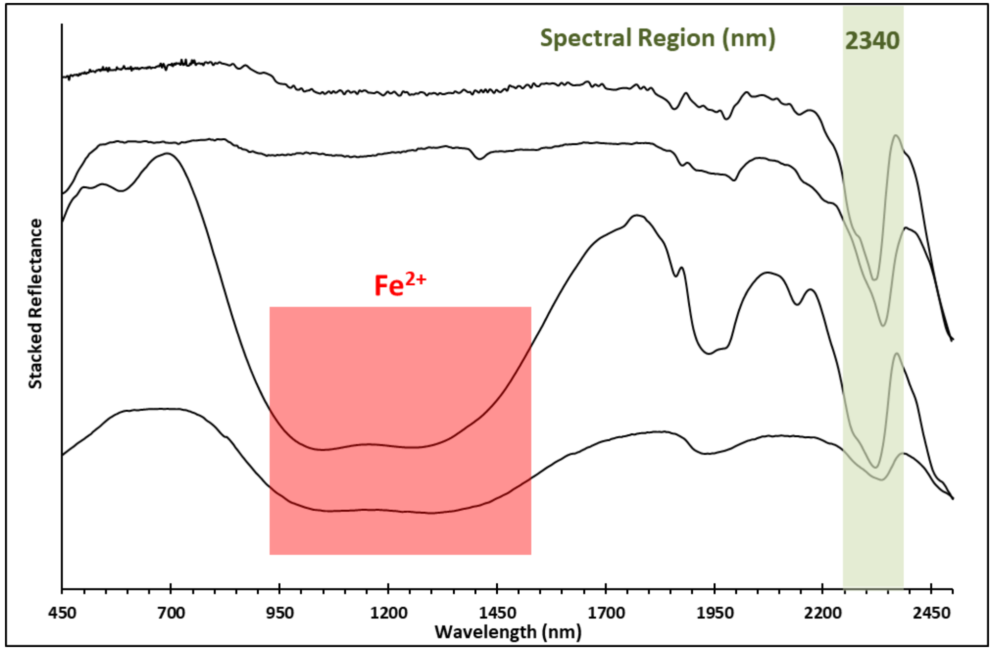
[Click here to view in Coreshed]

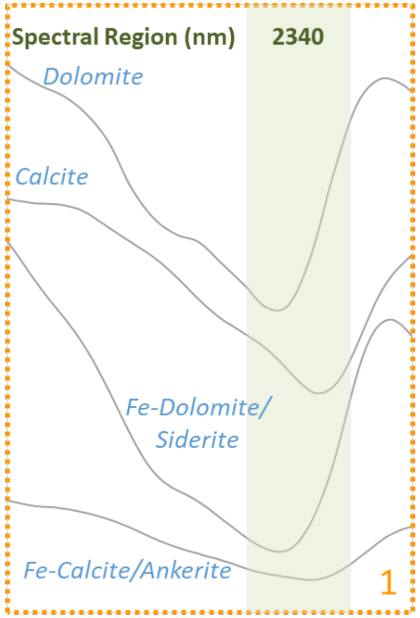
Biwabik Compositional Parameters

Carbonate speciation



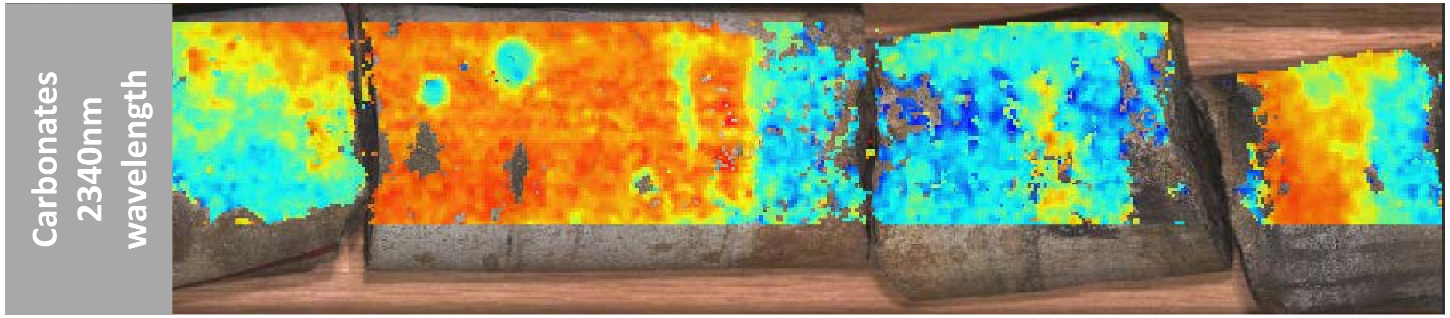
Source: Laukamp, 2011





Carbonates 2340nm wavelength

Biwabik Iron Formation



1076.00’ ←→ 1076.70’

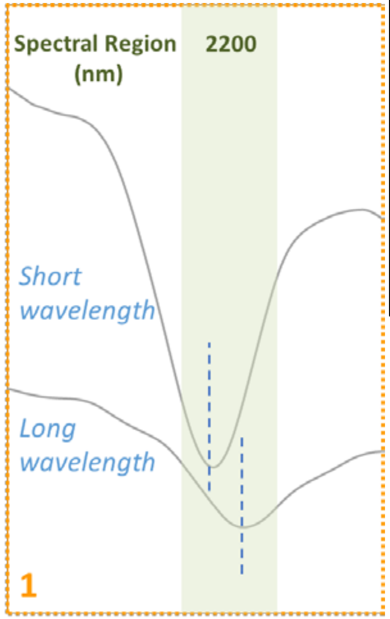
Drill hole: MGS-7

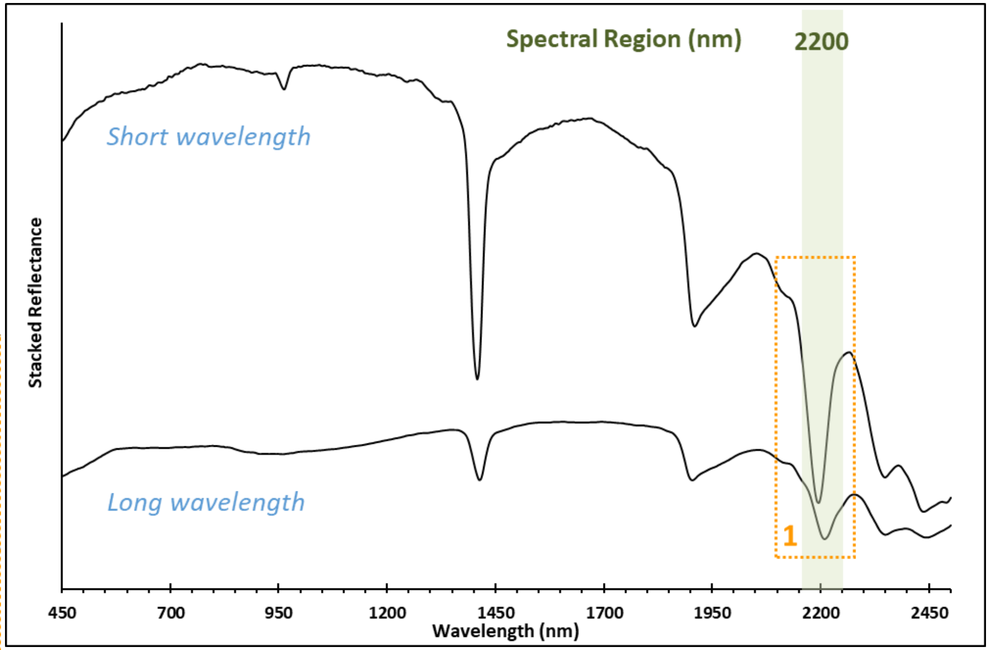
corescan

Click here to view in Coreshed

Biwabik Compositional Parameters

White Mica composition





White Mica 2200nm wavelength

$AB_{2-3}(X, Si)_4O_{10}(O, F, OH)_2$

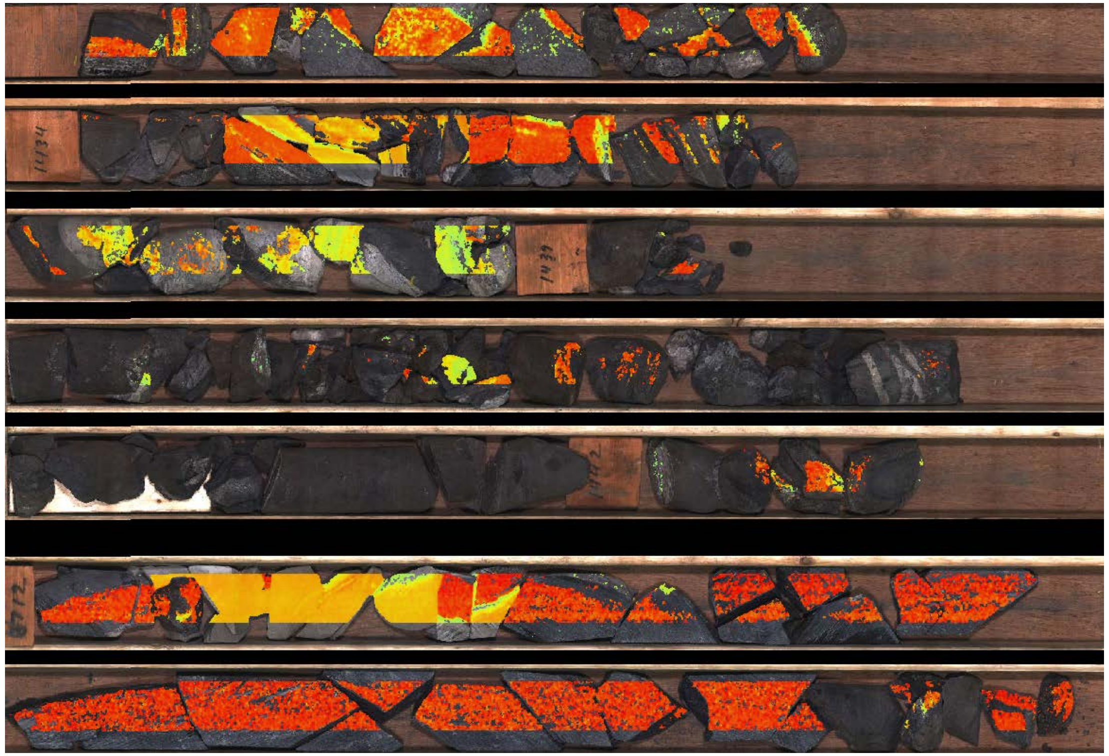
Biwabik Iron Formation

2185nm	2196nm	2212nm	2225nm

Paragonite	**Muscovite**	**Phengite, celadonite**
A: Na substitution	A: K substitution	B: Fe, Mg substitution
B, X: Al substitution		X: Si substitution

White Micas 2200nm wavelength

1425.00'



Drill hole: MGS-8

1446.00'

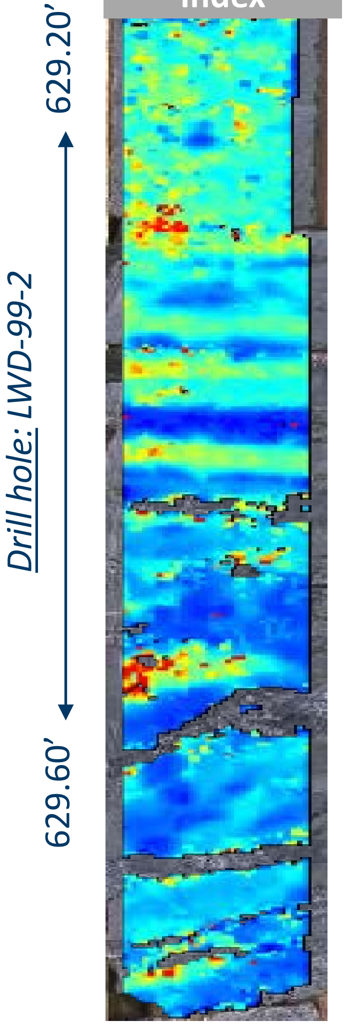
Click here to view in Coreshed

corescan

Biwabik Compositional Parameters

Illite Crystallinity Index

Illite Crystallinity Index

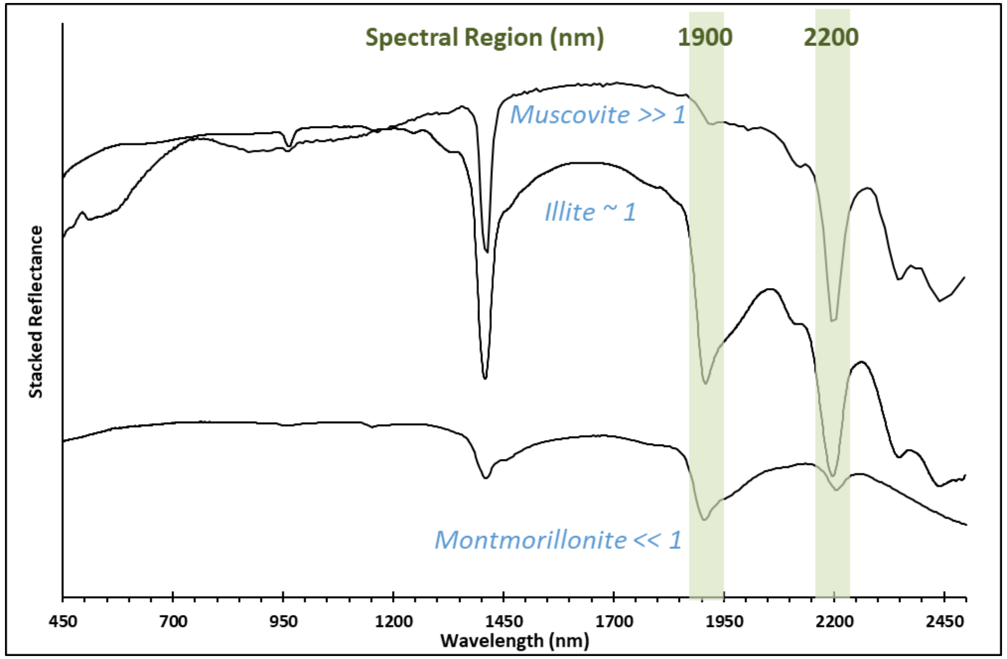


High temperature/
High crystallinity

$$ICI = \frac{2200D}{1900D}$$

D = depth

Low temperature/
Low crystallinity

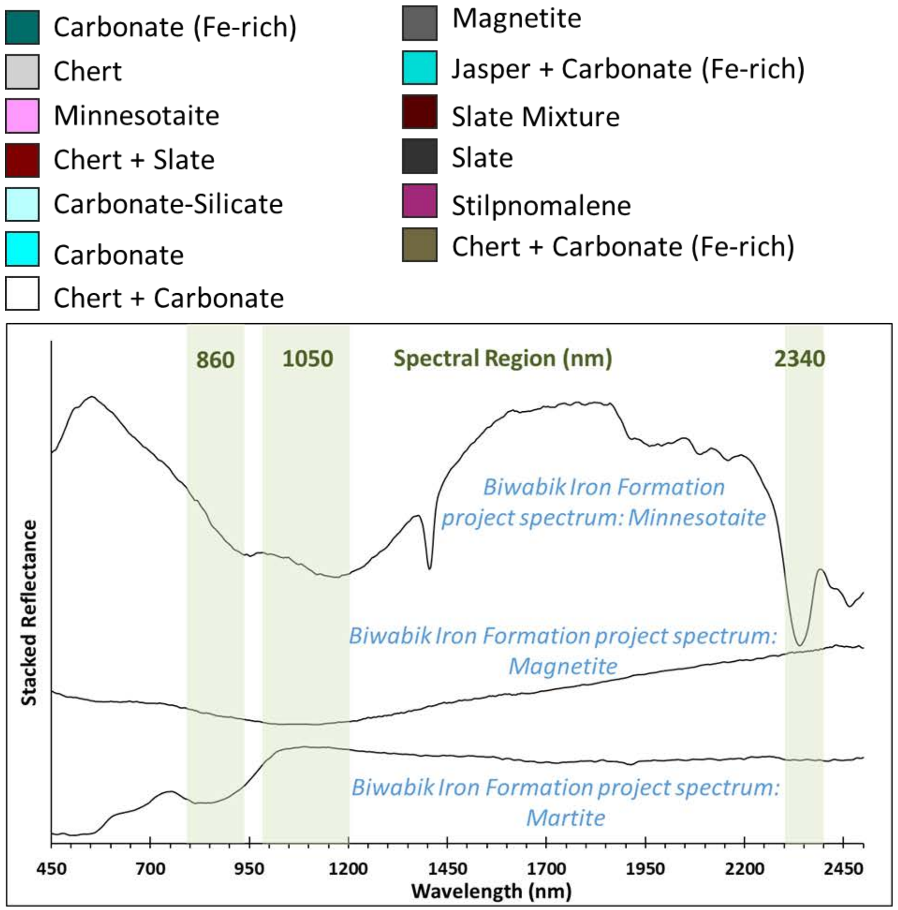


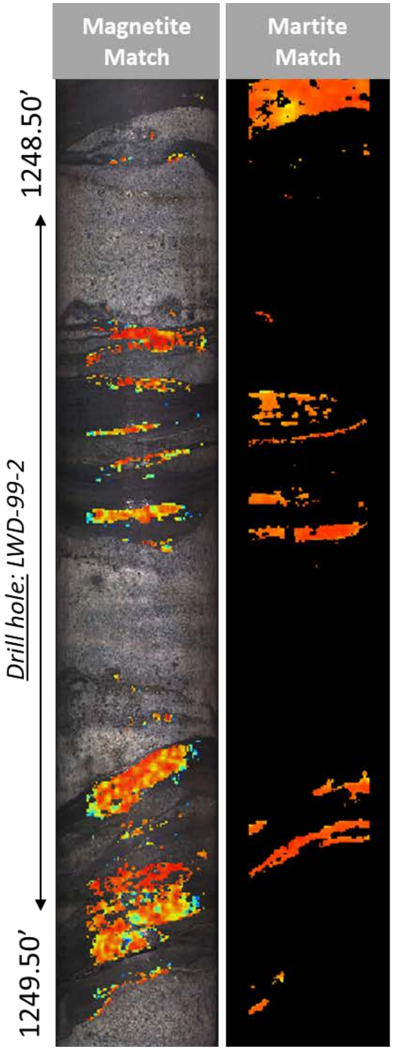
- The position of the ~2200nm Al-OH feature is indicative of the composition (paragonite, muscovite or phengite), while the ratio of the depth of the ~2200nm feature to that of the ~1900 feature is used as a ‘crystallinity index’

Illite Crystallinity Index
Biwabik Iron Formation

[Click here to view in Coreshed]

Biwabik Results





- Martite-rich bands can be differentiated from the more magnetic-rich bands using the VIS range which could help the taconite production
- Highlights the contact between the Biwabik Fm and overlying Virginia Fm… undocumented ammonium-bearing white mica is identified in the same location where Addison et al. (2005) identified an ~25 to ~58cm thick ejecta layer associated with the 1850Ma Sudbury impact event.

Click here to view in Coreshed

Click here to view in Coreshed

corescan

Cuyuna Range Manganese-Iron Formation

Cuyuna Range Manganese-Iron Formation

- **Goal**: Scan archived drill core from the Emily District, which hosts a cobalt-bearing manganese-rich iron formation and the one of the largest undeveloped manganese reserves in North America.

- **Scope**: Core from 5 locations in Crow Wing County.

- **Rationale**
  - Emily District's iron formation is similar to the Mesabi Range, but with much higher manganese content. Corescan may shed light on origin and mechanism of manganese enrichment.
  - Part of the Cuyuna Iron Range.
  - Emily District saw extensive exploration in 1950's, but no mines.
  - Active CMR manganese development project in West Ruth Lake Deposit.
  - Emily District iron formation may also have cobalt reserves (strategic mineral).

DDH	From	To	Total Feet	Total Meters*	Comment
18423	145	328	183	55	Low-Mn content (comparison core)
18709	340	540	200	61	West Ruth Lake Deposit; state minerals. Includes Mn-bearing silicate-carbonate iron formation.
18713	178	375	197	60	West Ruth Lake Deposit; state minerals. Mn ore zone 208-250'.
18715	254	599	345	105	West Ruth Lake Deposit; state minerals. Multiple ore zones (high Mn black ore, lean ore)
18961	284	489	205	63	East Ruth Lake Deposit, modern diamond drilling technique, nearly 100% recovery, no sludge analyses. Contains intervals of oxidized iron formation and Mn ore.
		Total	1130	344	Total does not include pending CMR core footage.

corescan

Cuyuna – Mineral Key

Mineral Name	Colour
Amphibole	
Chlorite	
Carbonate	
Goethite	
White Mica (NH4-rich)	
Carbonate (Fe-rich)	
Smectite (Fe-rich)	
Nontronite	
Montmorillonite	
White Mica	
Hydrous Silica/Quartz	
Kaolinite	
Chert	
Jasper	
Microplaty Hematite	
Hematite	
Magnetite	
Sediment	
Sediment Mn?	
Dark Sediment	

First

Display Priority

Last

**Only displayed in the class map*

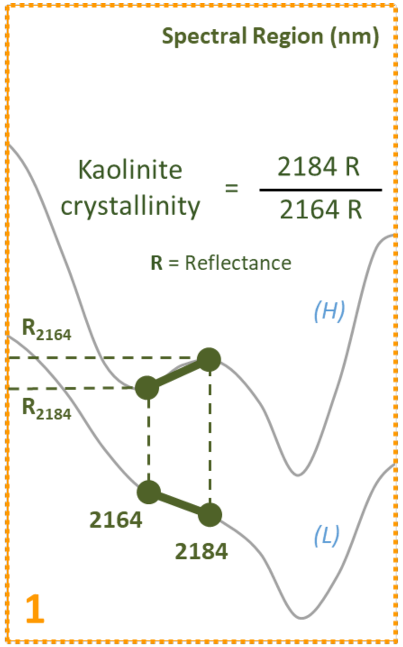
267.00’

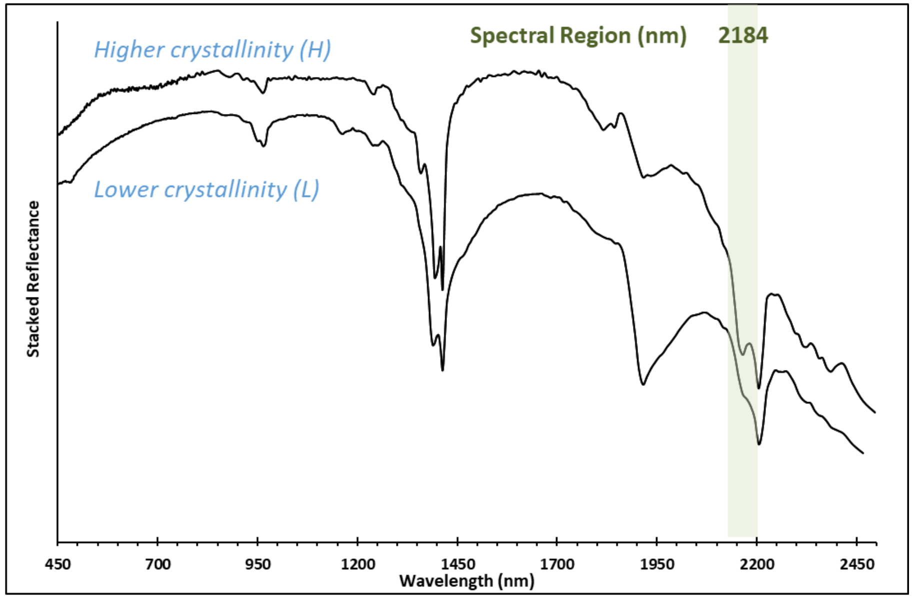
Drill Hole: 18713

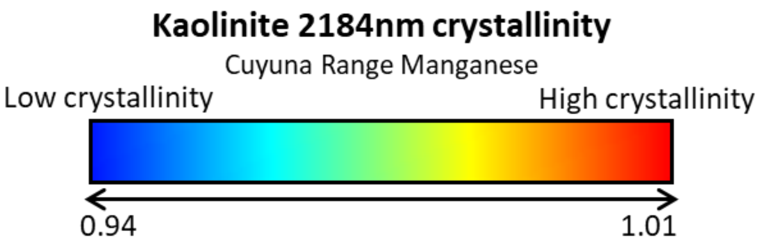
375.00’

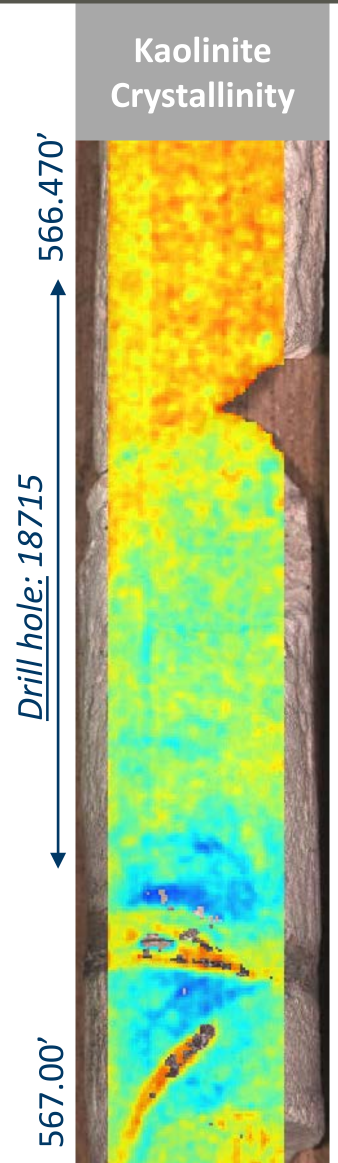
[Click here to view in Coreshed]

Cuyuna Compositional Parameters
Kaolinite Crystallinity









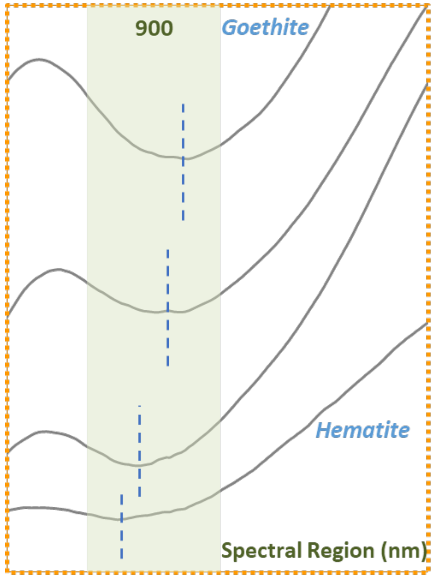
- 'Crystallinity' refers to the relative measure of structural order (e.g., dehydration) in layered silicates
- Major control over mineral crystallinity is temperature
  (i.e., higher formation temperatures produce more crystalline minerals)

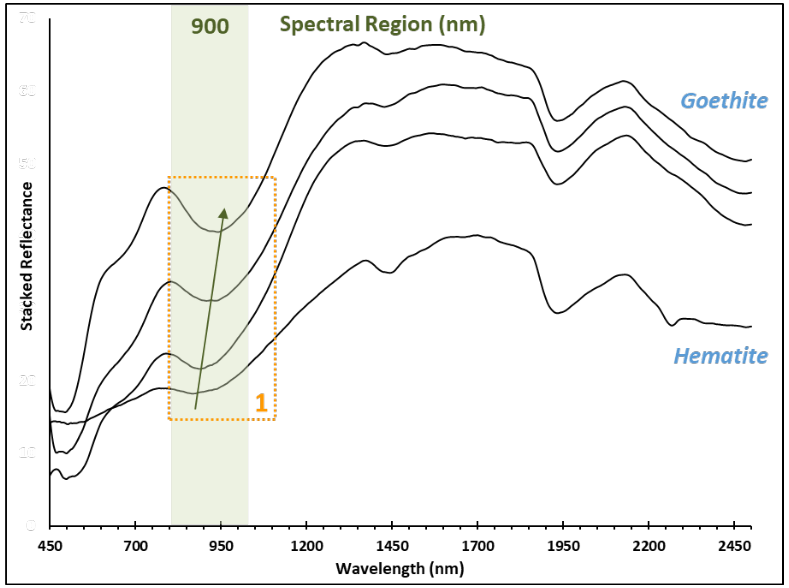
corescan

Click here to view in Coreshed

Cuyuna Compositional Parameters

Iron Oxide Composition





- In the VNIR, hematite ~ 860 nm and goethite ~ 940 nm; this feature shifts according to the relative abundance of goethite and hematite

Iron oxide 900nm wavelength

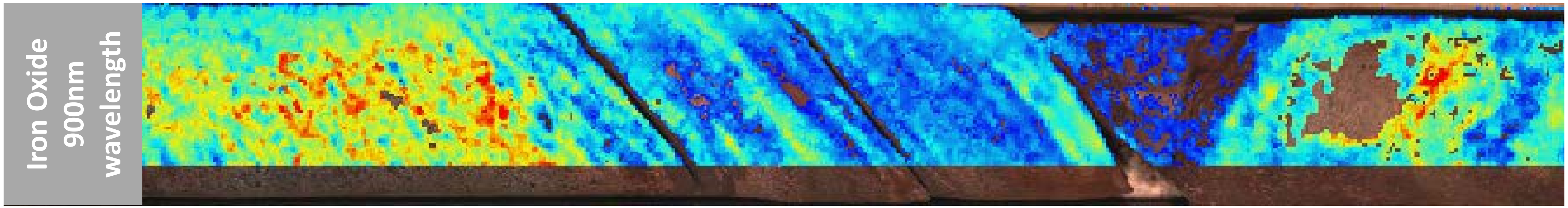
Cuyuna Range Manganese

Hematite (Fe_2O_3) Goethite (FeO(OH))

860nm 920nm

Drill Hole: 18961

447.78’ 448.60’

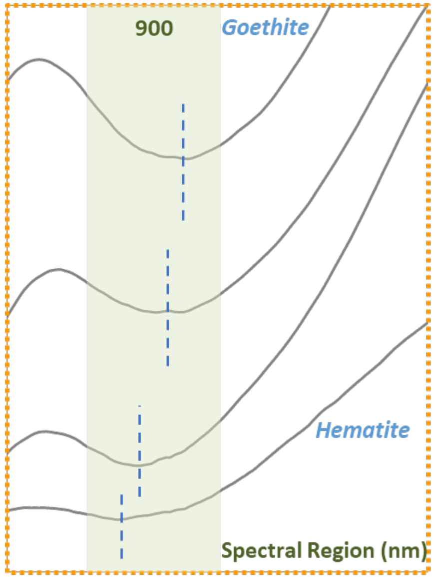


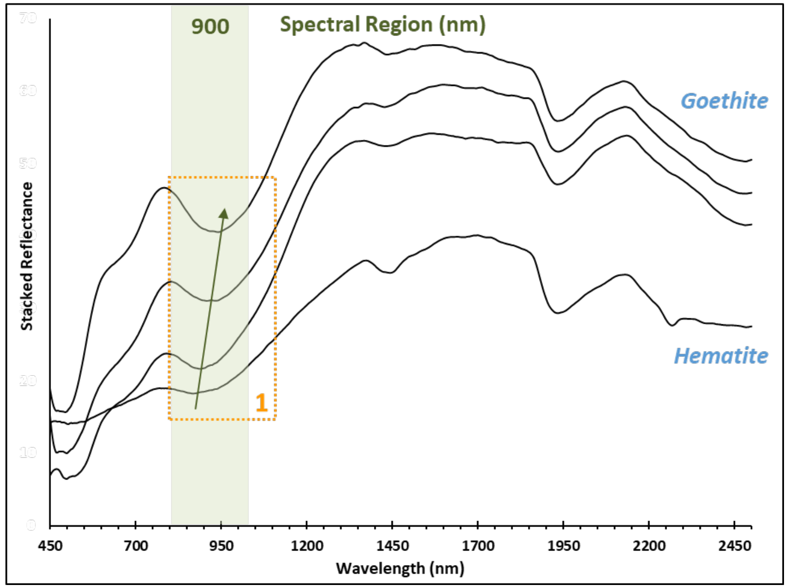
coreScan

Click here to view in Coreshed

Cuyuna Compositional Parameters

Iron Oxide Composition

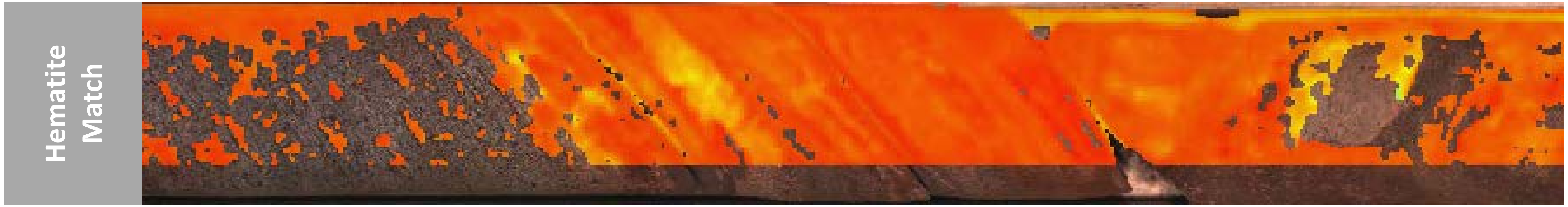




- The ability to quantify hematite vs goethite is vital information in these deposits for grade control and geomet properties

Drill Hole: 18961

447.78’ 448.60’

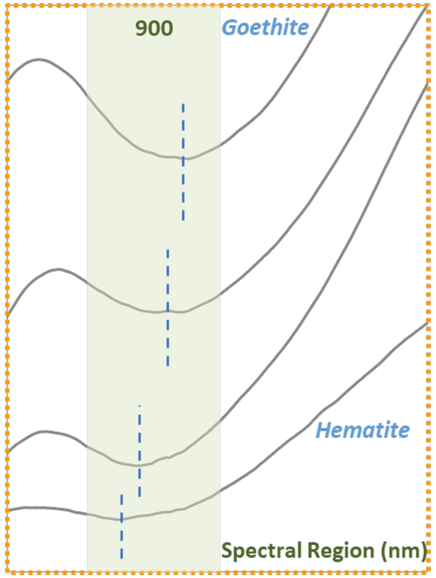


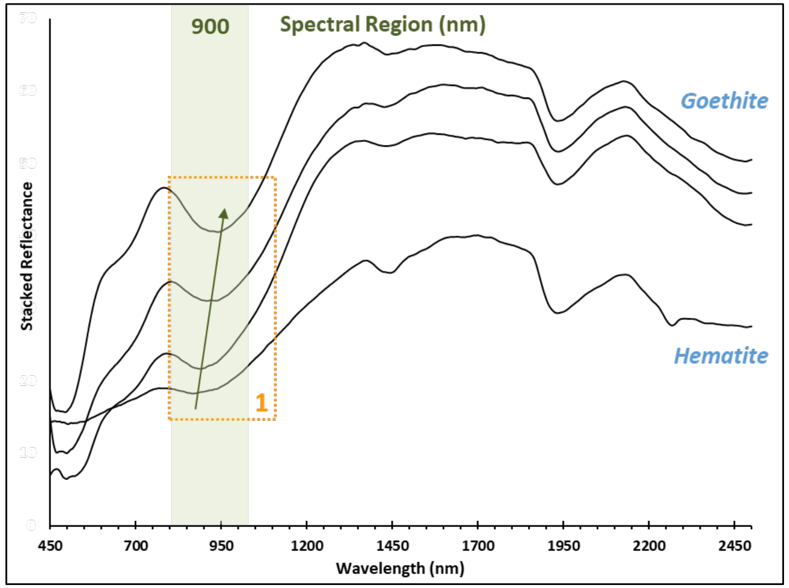
Click here to view in Coreshed

corescan

Cuyuna Compositional Parameters

Iron Oxide Composition





- The ability to quantify hematite vs goethite is vital information in these deposits for grade control and geomet properties

Drill Hole: 18961

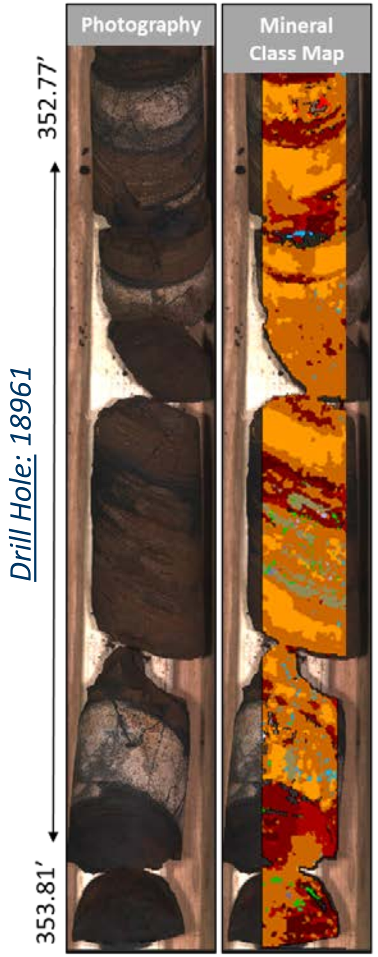
447.78’ 448.60’

Click here to view in Coreshed

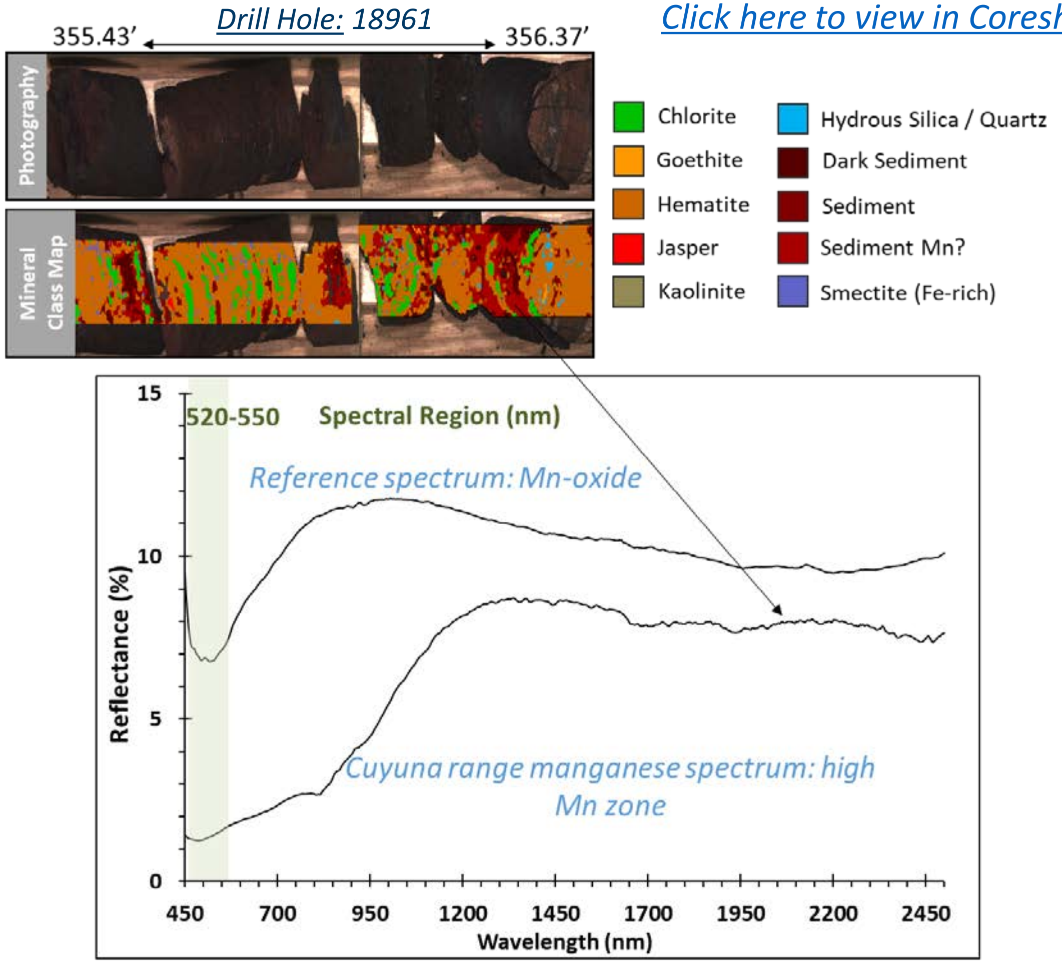
corescan

Cuyuna Results

- The core consists of Fe- and Mn-rich sedimentary layers with a range of VIS-SWIR active minerals including white micas (illite, muscovite), clays (kaolinite and several smectite varieties), and chlorite.
- Interbedded chert and jasper-rich layers are common.
- Carbonate (predominantly calcite, based on wavelength measurements; and Fe-rich carbonate) occur locally.
- Ammoniated white micas are concentrated in the argillite unit at the base of drill hole 18715.

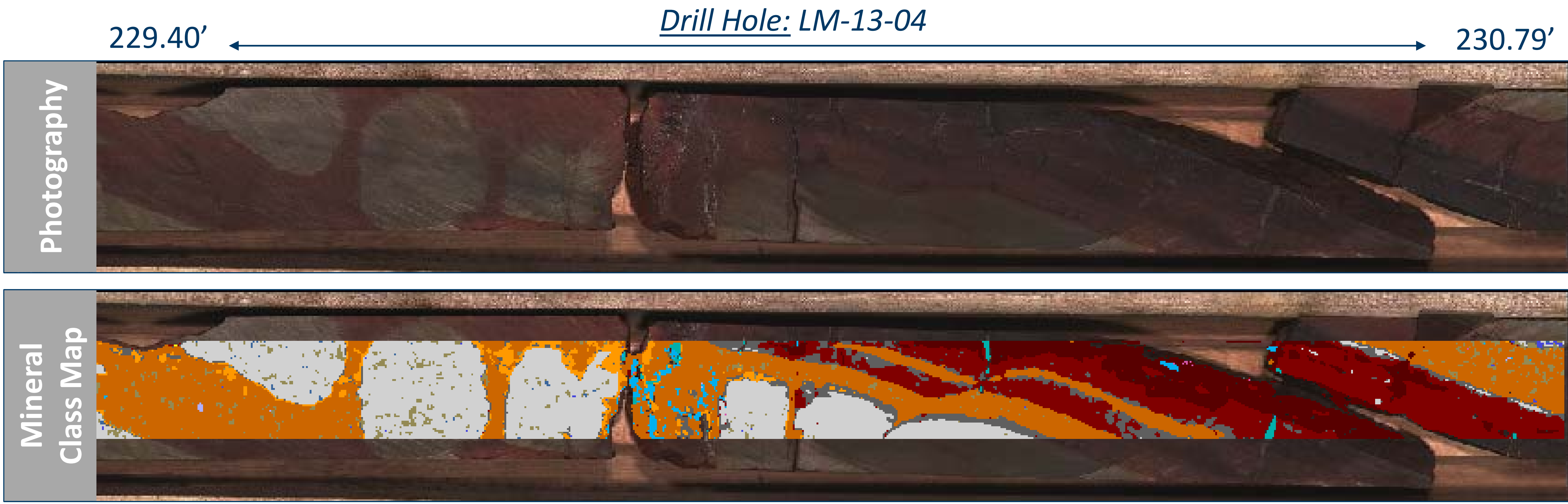


Click here to view in Coreshed



Click here to view in Coreshed

Hargrove, C.J., Lanza, N., Bell, J.F.III, Wiens, R.C., Johnson, J.R., Morris, R.V., 2014. Visible and near-infrared spectra of manganese oxides:
Detecting high manganese phases in Curiosity Mastcam multispectral images. American Geophysical Union, Fall Meeting 2014.



Animikie Basin and Animikie SEDEX

DEPARTMENT OF NATURAL RESOURCES

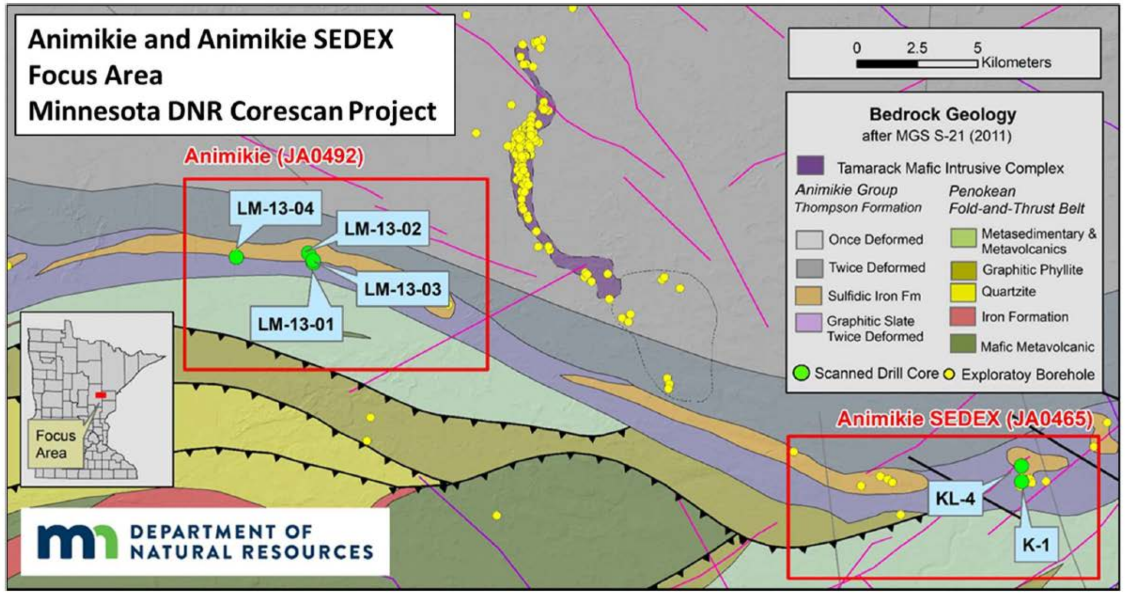
corescan

Animikie Basin & Animikie SEDEX

- **Goal**: Scan archived LawMan drill cores from the Carlton and Aitkin Counties, in the southern margin of the Animikie Basin.

- **Scope**: Core from four locations at the boundary of the Tamarack mafic intrusive complex and a sulfidic iron formation.

- **Rationale**
  - The LawMan drill core contains features (identified by the Minnesota Geological Survey in 2018) potentially related to the Sudbury Impact Event.
  - These are relatively recent cores to the Mn Drill Core Library (DCL), so were selected to help improve regional understanding of geology and mineral potential of the Animikie Basin.



DDH	From	To	Total Feet	Total Meters	Comment
LM-13-01	203	454	251	77	Qtz breccia with cpy/aspy at 262.5’
LM-13-02	395	465	70	21	Native Cu (?) logged at 203-213’
LM-13-03	346	506	160	49	Hematite-rich sediments
LM-13-04	146	475	329	100	Several logged zones of cherty BIF
		Total	810	247	

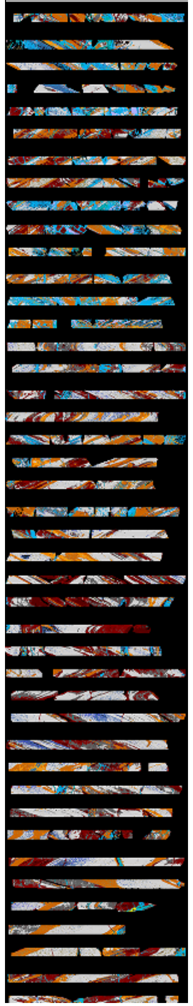
corescan

Animikie Basin & Animikie SEDEX – Mineral Key

Mineral Class Map

148.20’

Drill Hole: 18713



229.20’

Animikie Basin

Mineral Name	Colour	RGB Code
Sulphide		255, 255, 20
White Mica (NH4-rich)		70, 70, 220
Sulphate (Fe-rich)		163,41,122
Gypsum		213,87,171
Kaolinite		148,138,84
Carbonate (Fe-rich)		0,108,105
Carbonate		0,255,255
Chert + Carbonate (Fe-rich)		0,176,172
Epidote		188,255,55
Montmorillonite		175,175,255
Hydrous Silica/Quartz		0,176,240
Goethite		255,153,0
Hematite		204,102,0
Chlorite + White Mica*		196,215,155
White Mica		58,102,156
Chlorite		0,192,0
Chert		209,209,209
Sediment (Fe-rich)		112,104,64
Sediment 1		128,0,0
Sediment 2		88,0,0
Aspectral		95,95,95

First

Display Priority

Last

** Only displayed in the class map*

Click here to view in Coreshed

Animikie SEDEX

Mineral Name	Colour	RGB Code
Sulphide 1		255,0,255
Sulphide 2		255, 255, 20
Sulphide 3		255,151,151
White Mica (NH4-rich)		70, 70, 220
Carbonate (Fe-rich)		108,105
Carbonate		255,255
Kaolinite		191,183,143
Montmorillonite		151,151,255
Hydrous Silica/Quartz		83,141,213
Goethite		255,153,0
Hematite		204,102,0
Chlorite + White Mica*		196,215,155
White Mica		58,102,156
Chlorite		0,191,0
Chert (high albedo)*		166,166,166
Chert (low albedo)*		209,209,209
Sediment 1		128,0,0
Sediment 2		88, 0, 0
Sediment 3		151,071,0
Sediment 4		112, 104, 64
Aspectral		95,95,95

First

Display Priority

Last

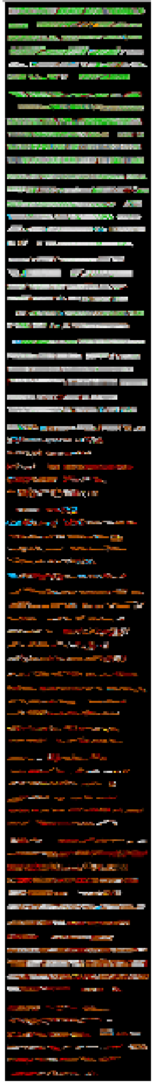
** Only displayed in the class map*

Click here to view in Coreshed

Mineral Class Map

36.00’

Drill Hole: K-1

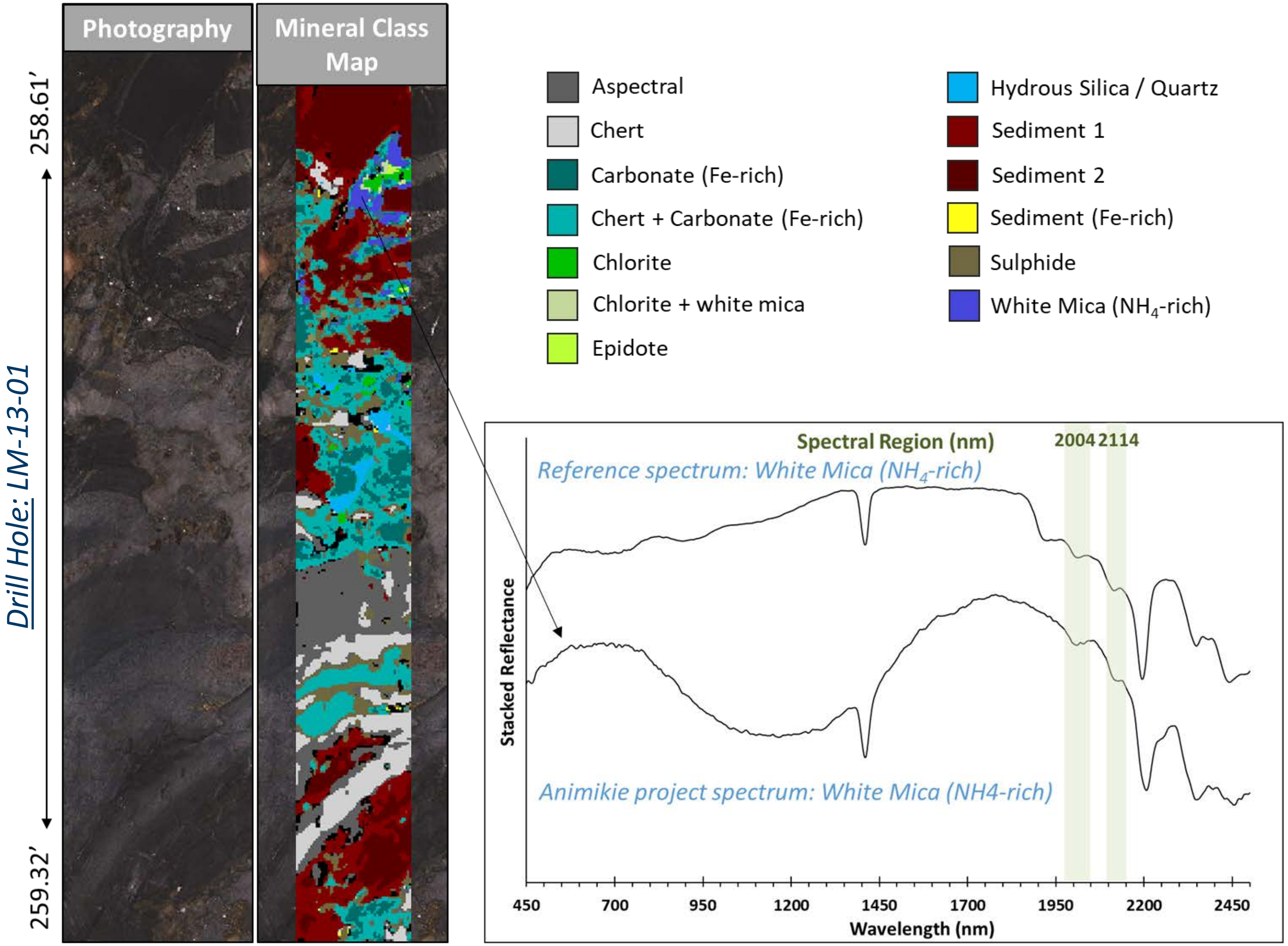


200.00’

corescan

Animikie Basin Results

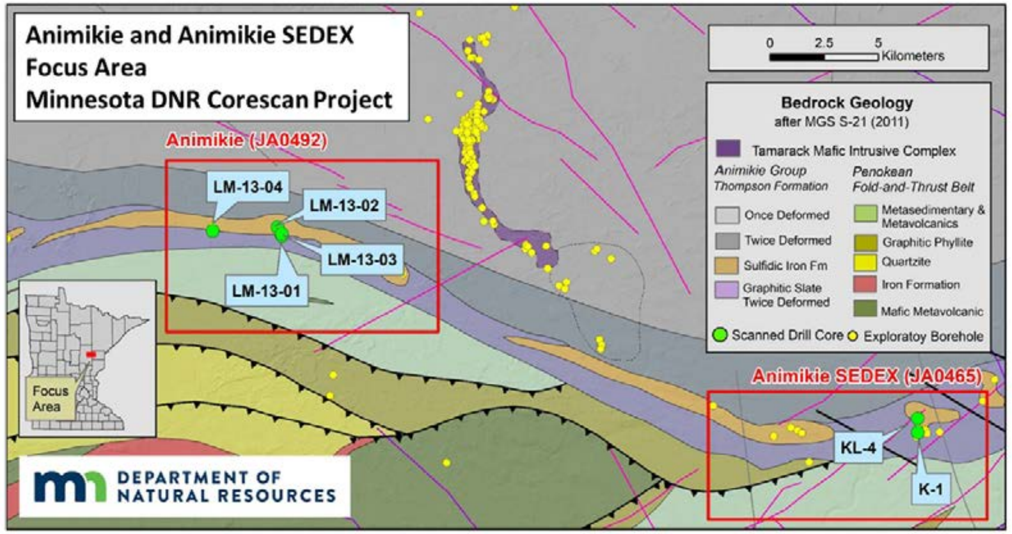
- The Animikie core is predominantly of banded intervals of ferruginous and cherty sediments.
- Ammonium-bearing (NH_4-rich) white micas are recognized locally in the Animikie drill core, but are not a major component
    - Distribution is irregular, and occurrences are noted in quartz-breccia zones, metasedimentary units, as well as Fe-rich banded sediments.
- Additional sampling could help clarify the relationship to Au occurrence and/or lithological domains
- White micas in general have a relatively narrow range of compositions (based on 2200nm wavelength positions) from Al-rich and Al-poor micas, but negligible Na- and/or Fe-components
- Chlorite compositions on average (based on 2250nm wavelength positions) are close to Fe end-member values.



Click here to view in Coreshed

Animikie SEDEX

- Goal: Scan archived drill cores with SEDEX potential.
- Scope: Core from two locations in the Kalavala Township, in Carlton County.
- Rationale
  - A company exploring for iron deposits intersected 'brown beds' of massive pyrrhotite, and one interval that graded 2% Zn.
  - The best SEDEX prospect currently recorded in Minnesota for copper and zinc mineralization.

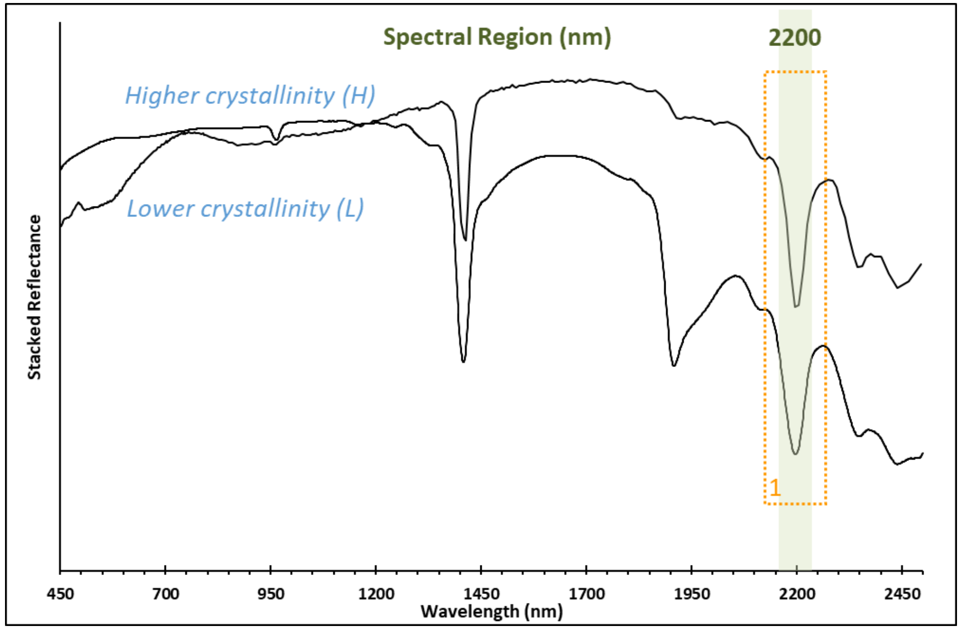


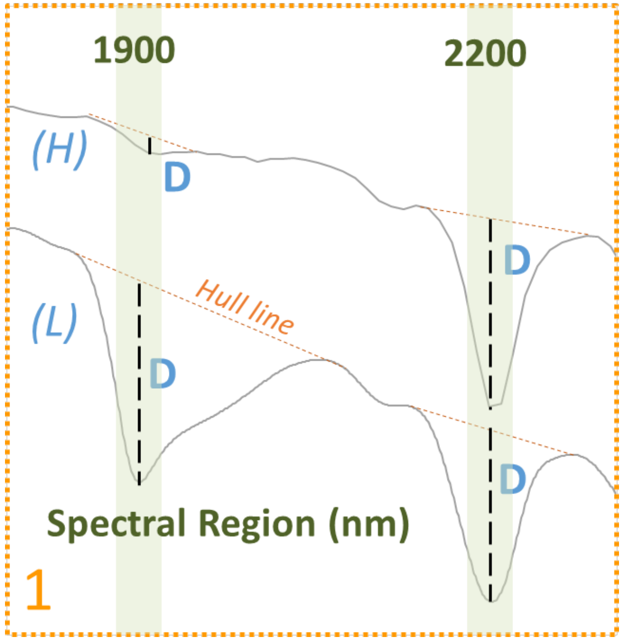
DDH	From	To	Total Feet	Total Meters	Comment
K-1	36	200	164	50	Trace Zn, Au, Ag
KL-4	119	500	381	116	Trace sphalerite logged at 435'
		Total	545	166	

corescan

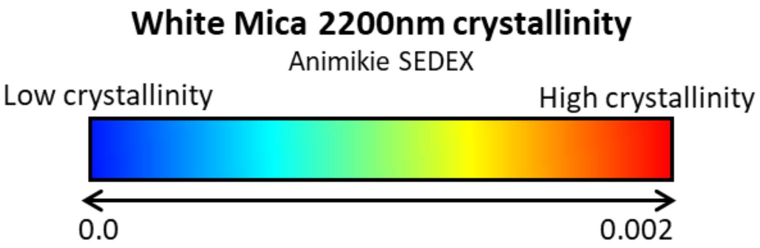
Animikie SEDEX Compositional Parameters

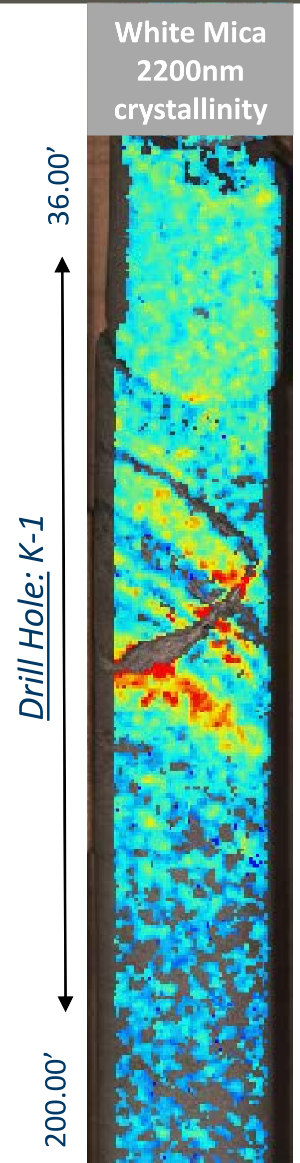
White Mica Crystallinity





- One measure of white mica crystallinity (2200x) is the relative 'sharpness' (Depth/Area) of the 2200nm feature.
- Crystallinity values are relative; *increases can typically be attributed to increasing temperature and/or dehydration of the muscovite/illite series.*





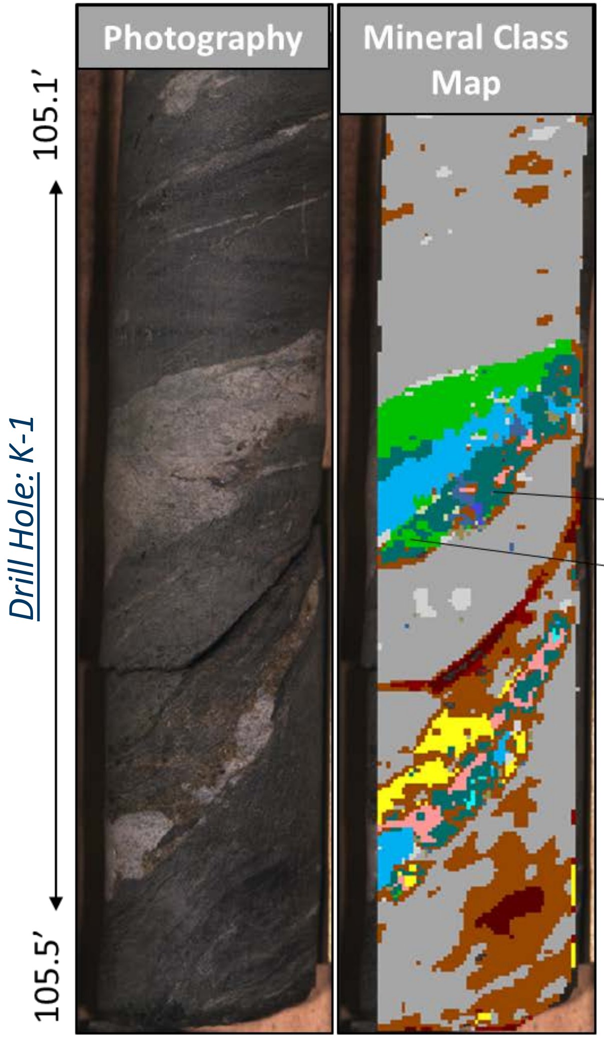
Click here to view in Coreshed

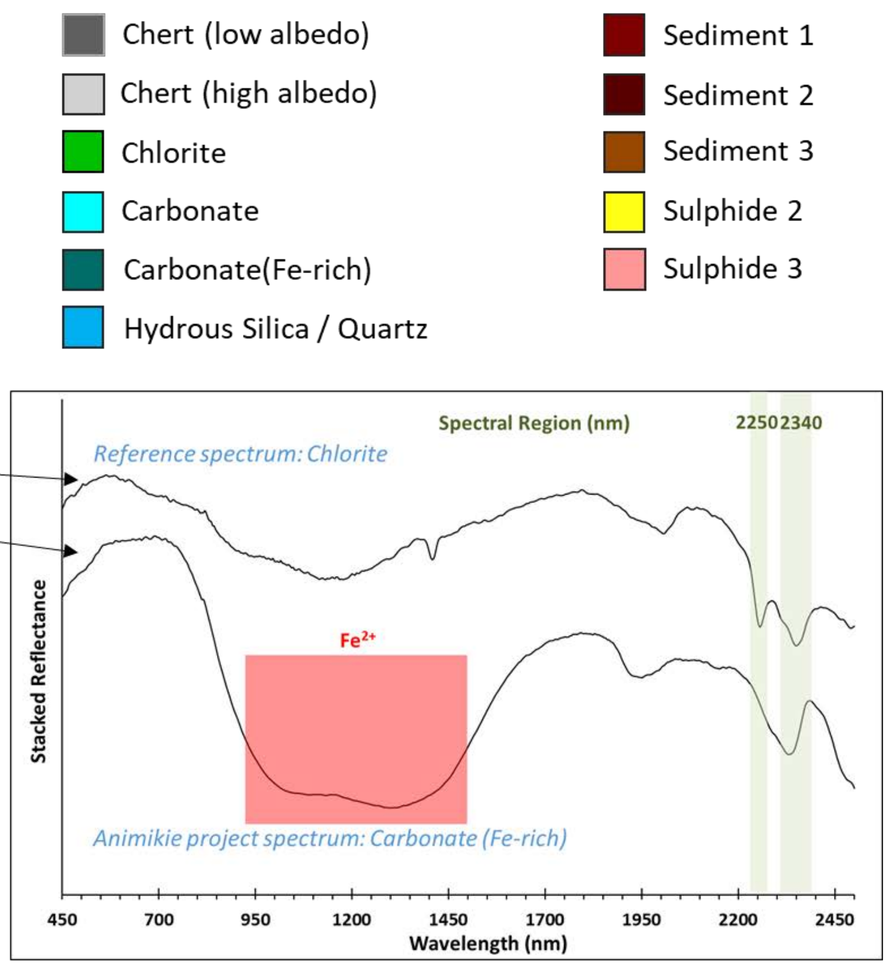
corescan

Animikie SEDEX Results

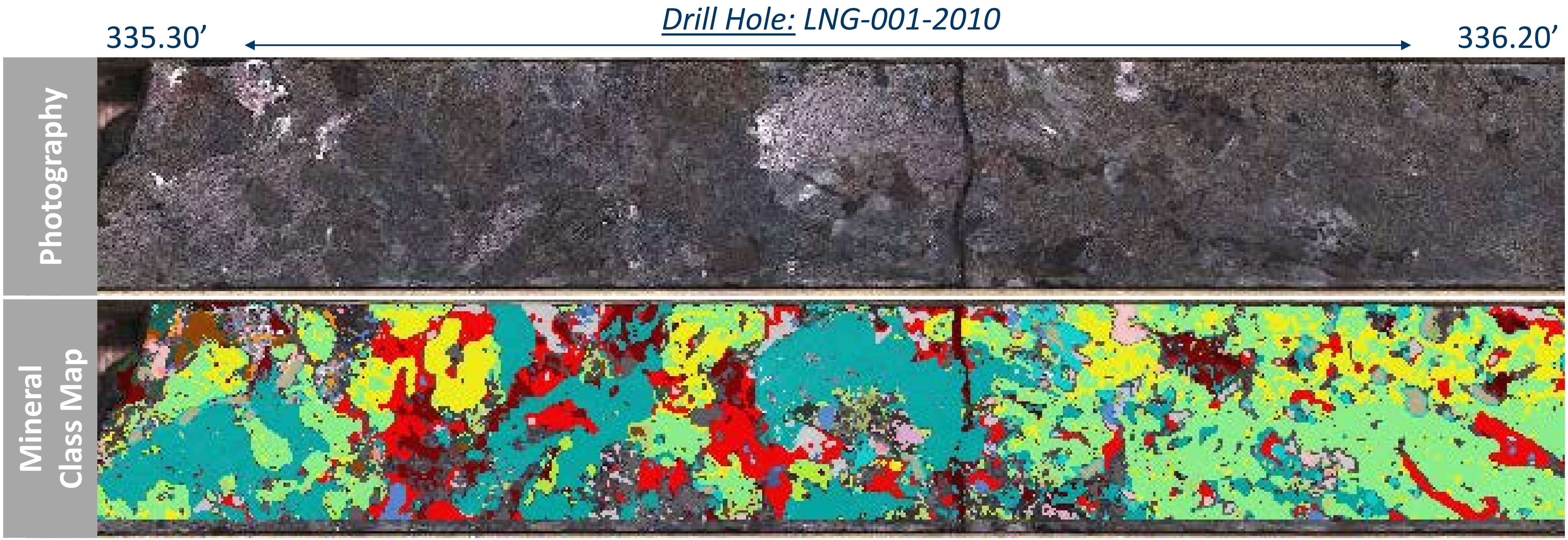
- The Animikie SEDEX core consist of interbedded graphitic slate, quartz-phyllite and argillite zones.
- Moderate pyrite and trace other sulfides (sphalerite) are noted in original drill logs
- Even though trace sphalerite was noted in original drill logs, a clear sphalerite spectrum was not detected in this study. Variations in the spectral features of iron-rich carbonates suggest Zn-substitution may occur, but further work would be required to confirm.
- White micas in general have a relatively narrow range of compositions (based on 2200nm wavelength positions) from Al-rich and Al-poor micas, but negligible Na- and/or Fe components – consistent with data from the Animikie basin drill core (see above).

[Click here to view in Coreshed]()





corescan



Duluth Complex Vanadium Project

DEPARTMENT OF NATURAL RESOURCES

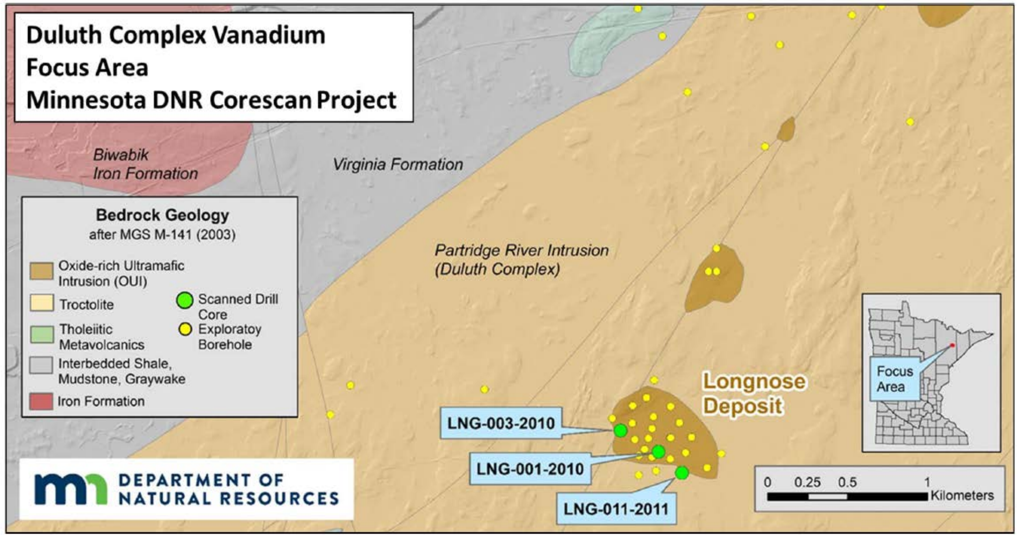
corescan

Duluth Complex Vanadium

- **Goal**: Scan core from an oxide-rich ultramafic intrusion (OUI) to determine whether hyperspectral core imaging can characterize vanadium-bearing titaniferous magnetite

- **Scope**: Three drill cores from the Longnose OUI in St. Louis County.

- **Rationale**
  - There are a series of small oxide-rich ultramafic intrusions along the western margin of the Duluth Complex that are titanium rich (ilmenite).
  - A new hydrometallurgical process has been developed that removes magnesium and isolates high-purity titanium dioxide. At a commercial scale, this process could lead to development of these titanium resources.
  - Some of the OUIs contain appreciable quantities of vanadium, in the form of vanadium-bearing titaniferous magnetite. Both titanium and vanadium are strategic minerals.
  - The Longnose OUI is the best-characterized OUI, with a 2011 NI43-101 technical report that assessed analytical results from 15 new drill holes. DNR has all of the logs and geochemistry from this drilling campaign.
  - A bulk sample from the Longnose OUI was also used in the pilot-scale development of the new hydrometallurgical process.
  - LNG-001-2010 and LNG-003-2010 both have complex layered geology and sampled intervals with >30% titanium and vanadium content >1500ppm. Range of vanadium from non-detect to 1500ppm should support evaluation of Corescan's ability to pick up variations in vanadium content at a spot scale.



DDH	From	To	Total Feet	Total Meters	Comment
LNG-001-2010	54	794	740	226	Complex layered geology and sampled intervals with >30% Ti & V >1500ppm. Extends into Partridge River Intrusion
LNG-003-2010	0	306	306	93	Contains intervals of Cu-Ni content on par with "typical" Duluth Complex ore grades
LNG-011-2011	0	1053	1053	321	Complex layered geology and sampled intervals with >30% Ti & V >1500ppm. Extends into Partridge River Intrusion
		Total	2099	640	

corescan

Duluth Complex – Mineral Key

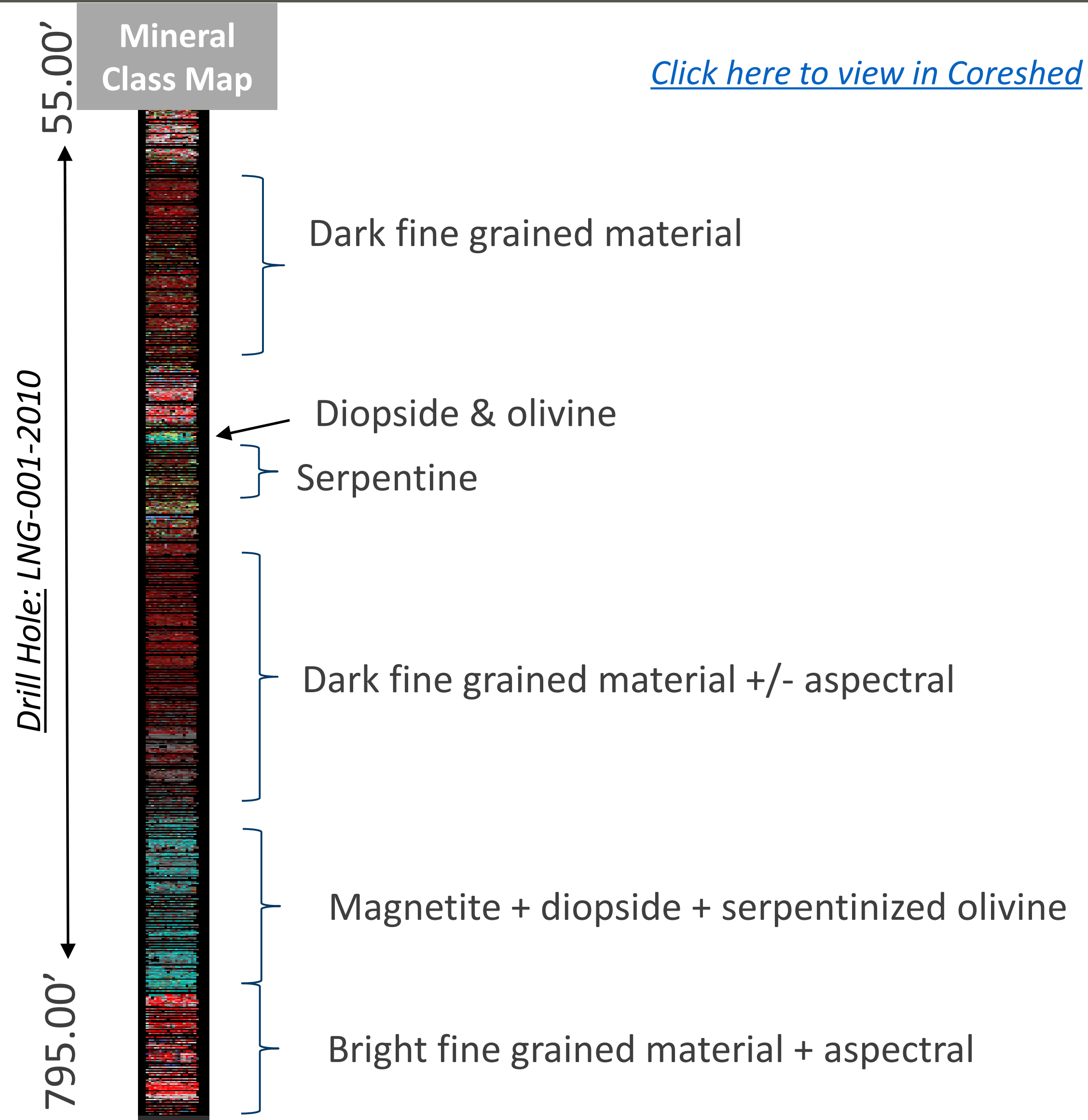
Mineral Name	Colour
Sulphide 1	
Sulphide 2	
Iddingsite*	
Goethite	
Hematite	
Natrolite	
Saponite	
Smectite (Mg-rich)	
Montmorillonite	
White Mica + Chlorite*	
White Mica	
Epidote	
Chlorite	
Calcite	
Prehnite	
Amphibole	
Talc (Fe-rich)	
Talc	
Phlogopite	
Antigorite	
Serpentine 2	
Serpentine 1	
Serpentinised Olivine	
Serpentinised Pyroxene	
Magnetite	
Orthopyroxene	
Clinopyroxene	
Diopside	
Olivine (Fe-rich)	
Olivine (MgFe-rich)	
Olivine (Mg-rich)	
Aspectral	
Bright Fine-grained Material	
Fine-grained Material	
Dark Fine-grained Material	

First

Display Priority

Last

**only displayed in the class map*

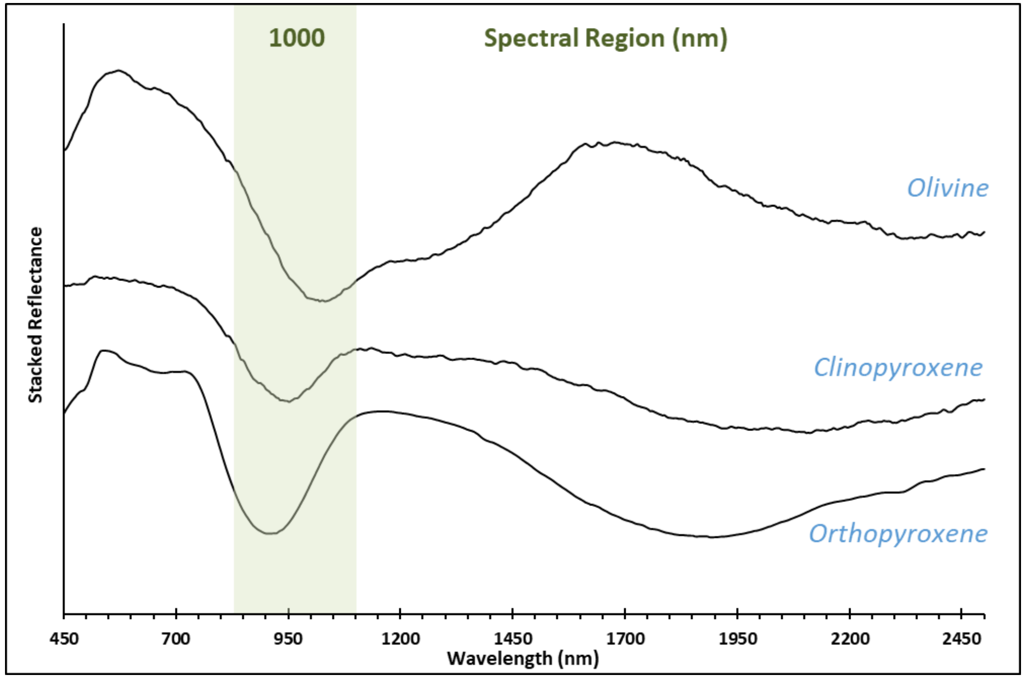


[Click here to view in Coreshed]()

corescan

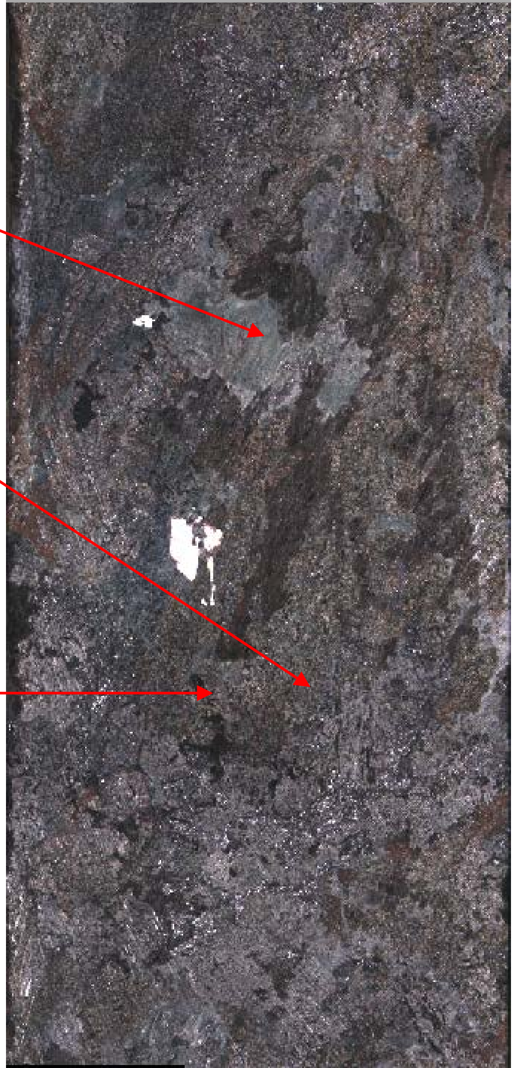
Duluth Complex Compositional Parameters

Pyroxene vs Olivine Speciation



- The tracking of the position and the shape of this crystal field absorption feature can distinguish orthopyroxene from clinopyroxene from olivine (Horgan et al., 2014)

Photography



Reference:

Horgan, B.H., *Cloutis, E.A., Mann, P. and Bell III, J.F., 2014. Near-infrared spectra of ferrous mineral mixtures and methods for their identification in planetary surface spectra. Icarus, 234, pp.132-154.*

Pyroxene - Olivine 1000nm wavelength

Duluth Complex Vanadium

900nm — 1050nm

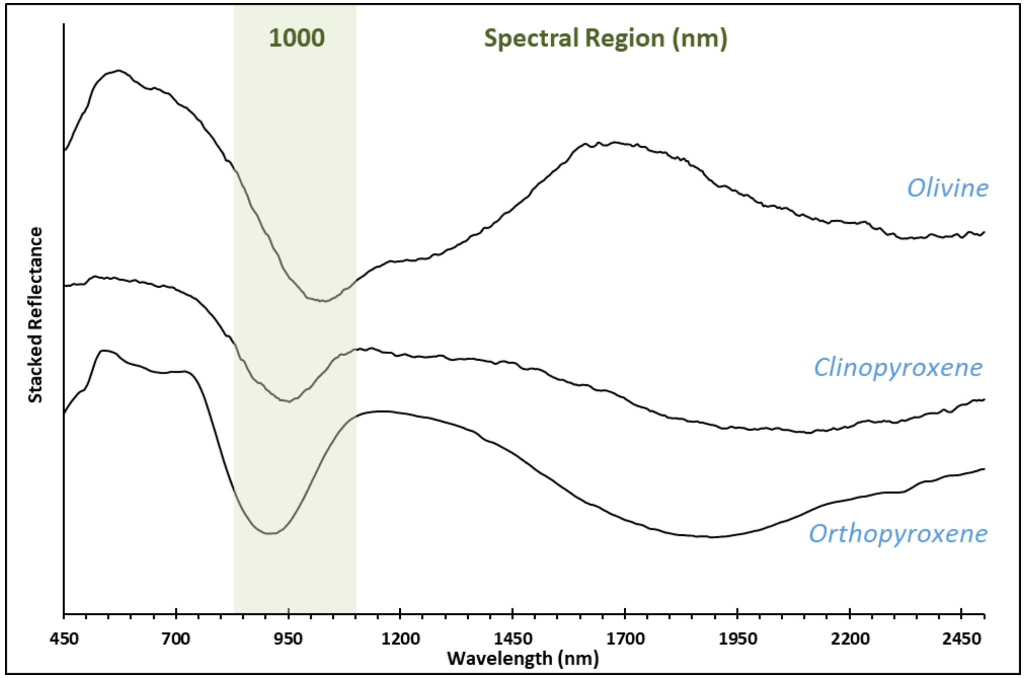
Orthopyroxene **Clinopyroxene** **Olivine**

Click here to view in Coreshed

corescan

Duluth Complex Compositional Parameters

Pyroxene vs Olivine Speciation

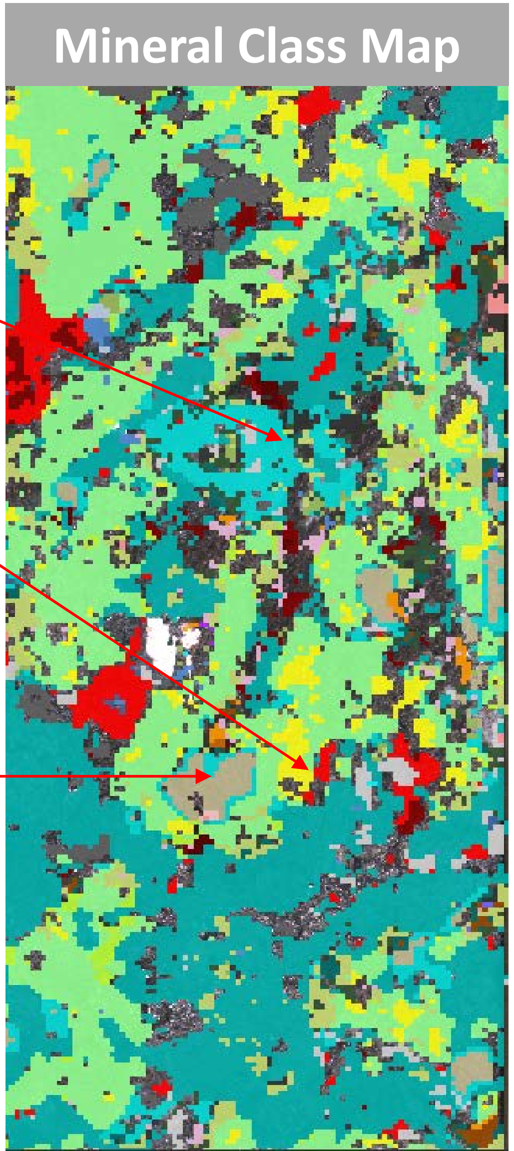


- The tracking of the position and the shape of this crystal field absorption feature can distinguish orthopyroxene from clinopyroxene from olivine (Horgan et al., 2014)

Clinopyroxene

Olivine

Orthopyroxene



337.86’

Drill Hole: LNG-001-2010

338.60’

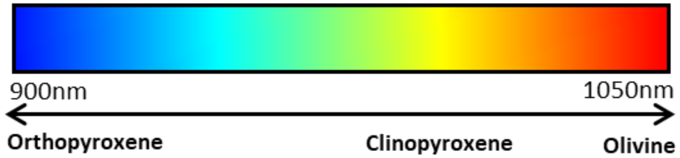
Reference:

Horgan, B.H., *Cloutis, E.A., Mann, P. and Bell III, J.F., 2014. Near-infrared spectra of ferrous mineral mixtures and methods for their identification in planetary surface spectra. Icarus, 234, pp.132-154.*

Click here to view in Coreshed

Pyroxene - Olivine 1000nm wavelength

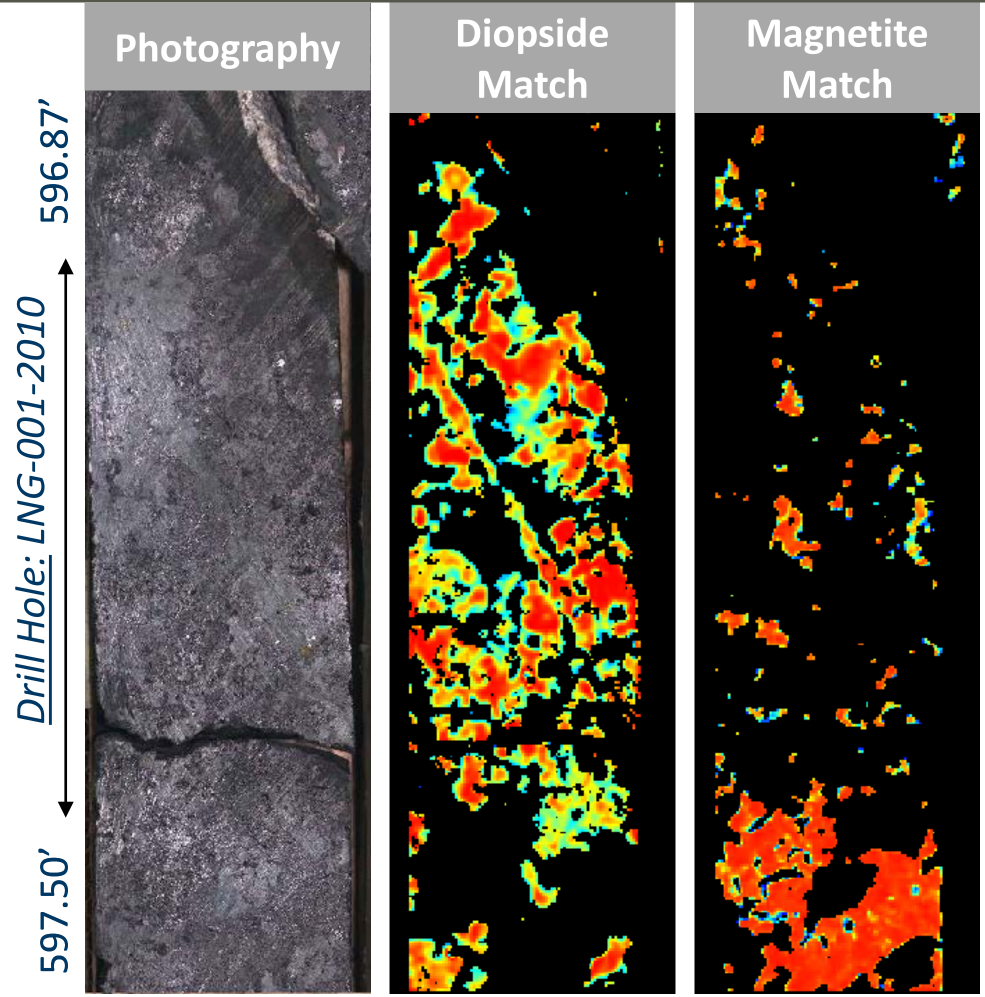
Duluth Complex Vanadium

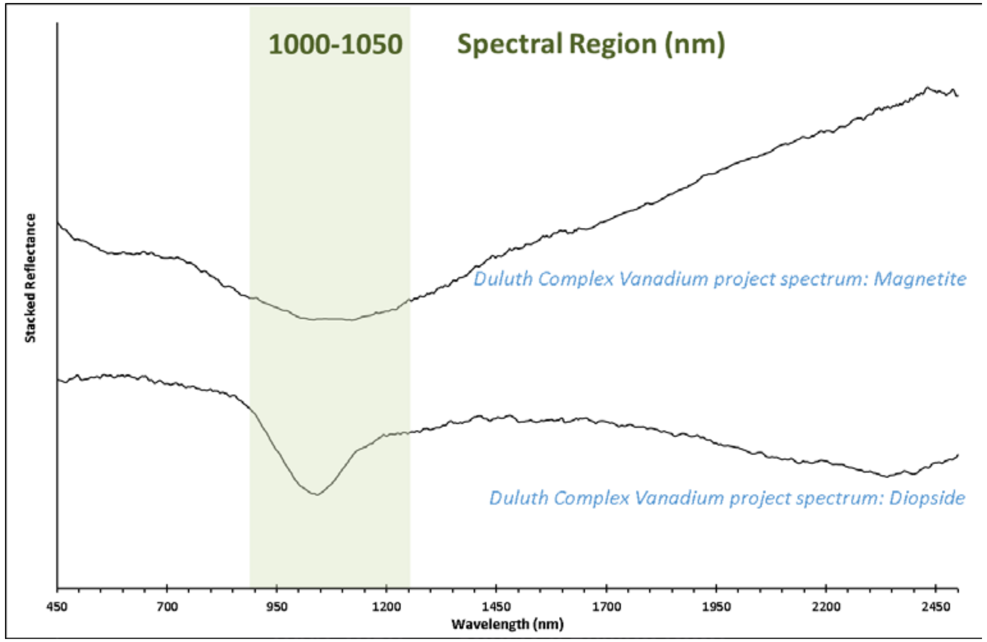


coreSCAN

Duluth Complex Compositional Parameters

Magnetite vs Diopside





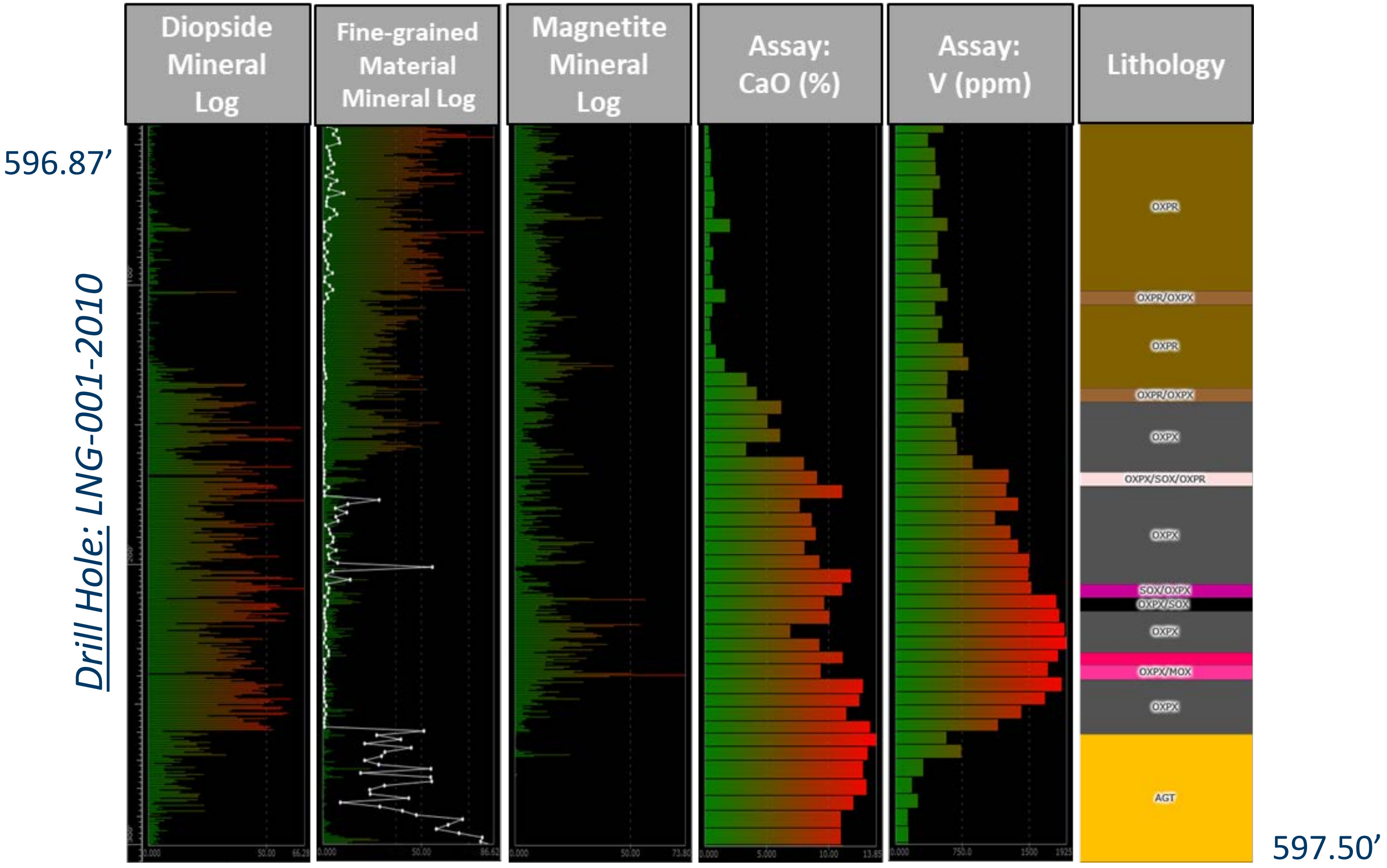
- Magnetite can be easily distinguished from diopside by tracking both the position and the shape of their crystal field absorption feature in the VNIR range around 1050nm

- Magnetite is the main mineral of the mineralized zones whereas diopside is the main constituent of the Oxide-bearing pyroxenolite zones

corescan

[Click here to view in Coreshed]()

Duluth Complex Vanadium Results



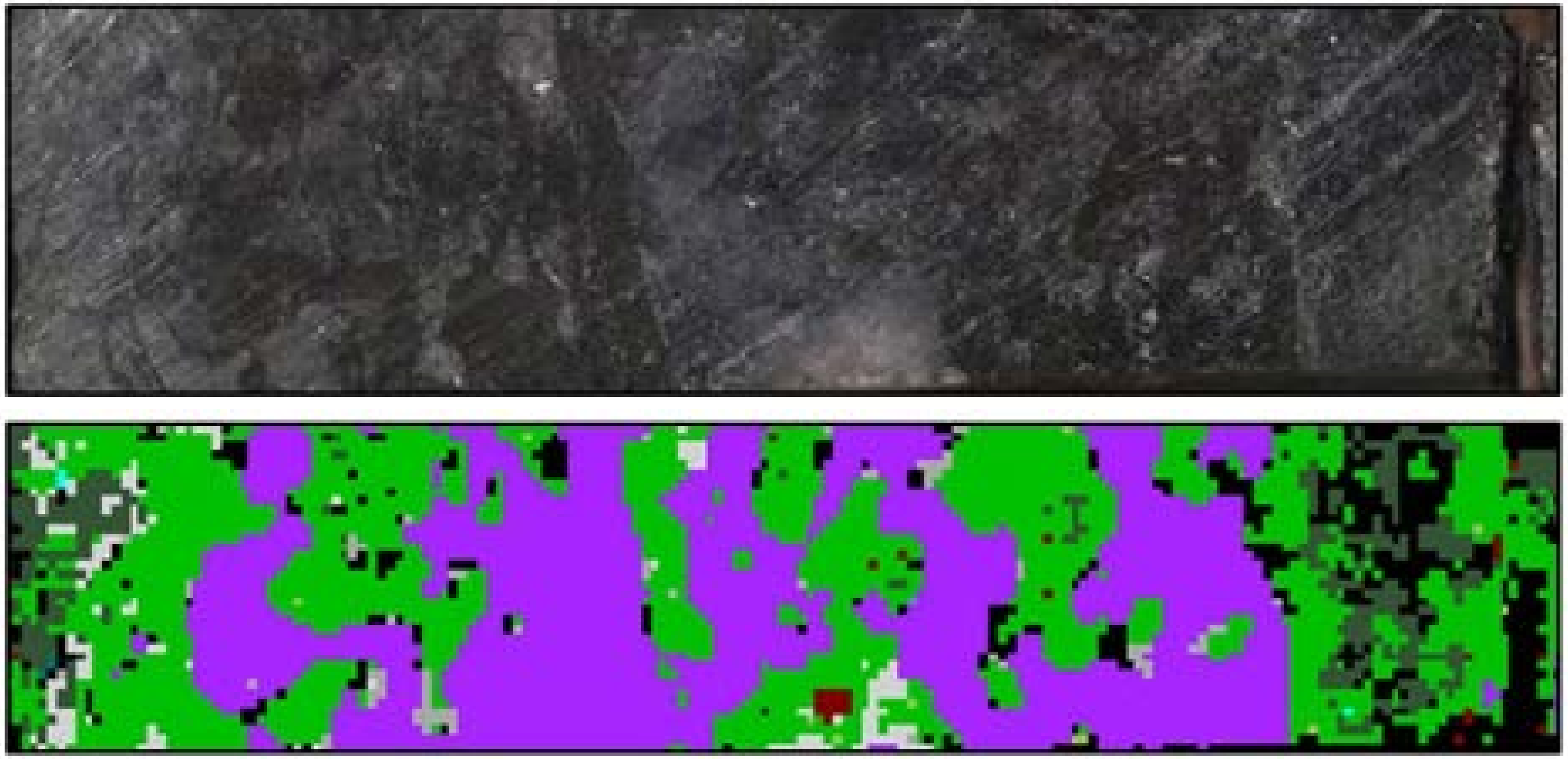
[Click here to view in Coreshed]()

Augite troctolite (AGT)

Oxide bearing peridotite (OXPR)

Oxide bearing pyroxene (OXPX)

- Mineralization is hosted by Oxide-bearing Ultramafic Intrusions that intruded into layered series intrusions of the Duluth Complex
- Correlations between the geochemistry, lithology, and the hyperspectral mineralogy
  - the *aspectral* unit can be interpreted as feldspar (plagioclase)
  - *bright fine-grained material* classes represent an olivine/feldspar mixture. Corroborated by the Ca (pct) and Al2O3 (pct) logs and corresponds with the troctolite unit
  - *fine-grained* and *dark fine-grained material* seem to correlate with the OXPR zones
  - *Diopside* is the main pyroxene type in the OXPX zones
- Ol-bearing peridotites are heavily serpentinized
- High V grades seem to correspond with the highest magnetite zones



International Falls Greenstone Gold Belt

DEPARTMENT OF NATURAL RESOURCES

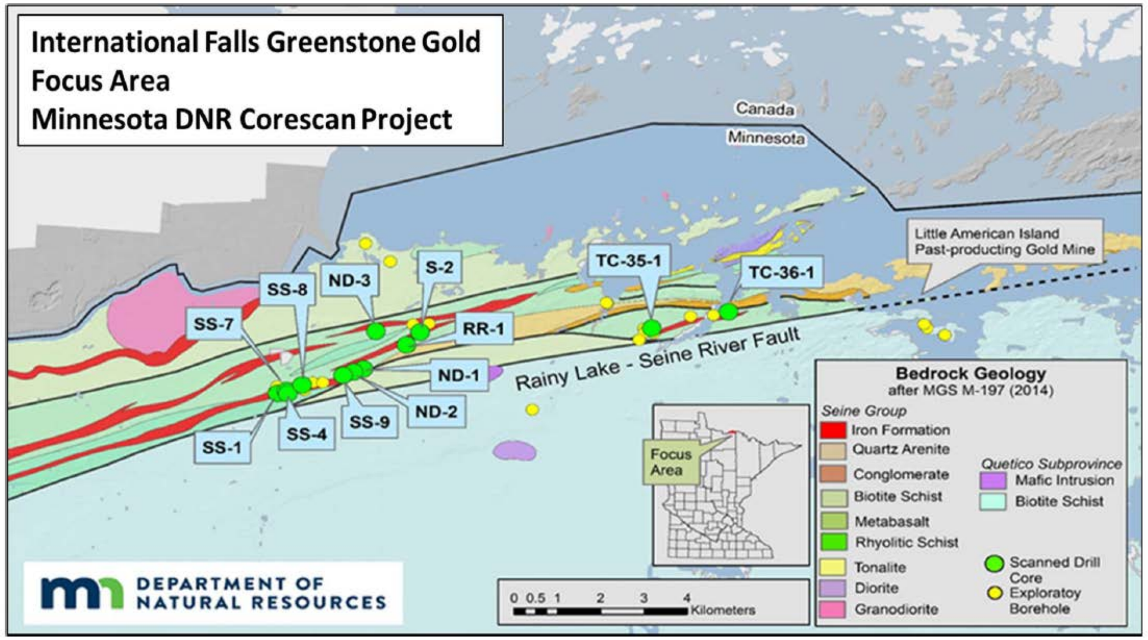
corescan

International Falls Greenstone Gold

Goal: Scan archived drill core from a gold-bearing Superior Province greenstone bedrock terrane near International Falls, just south of the Canadian border.
Scope: Core from thirteen locations in Koochiching County, just east of International Falls

- **Rationale**
  - Archean Superior Province greenstone terrane (Wabigoon Subprovince) that has many active and past-producing mines on Canadian side of the border.
  - New Gold Rainy River Mine located 50 miles northwest of this area.
  - Core locations are within the same major structure feature as Little American Island,
  - Minnesota's only historic gold mine (1890's).
  - More recent drilling campaigns produced several cores with gold mineralization.
  - MnDNR project work identified multiple gold mineral and geochemical associations, sometimes within same cores. Corescan may shed light on gold mineralization events, and provide information that supports new exploration campaigns on state-managed mineral rights in the region.

corescan



Core from thirteen locations in Koochiching County, just east of International Falls

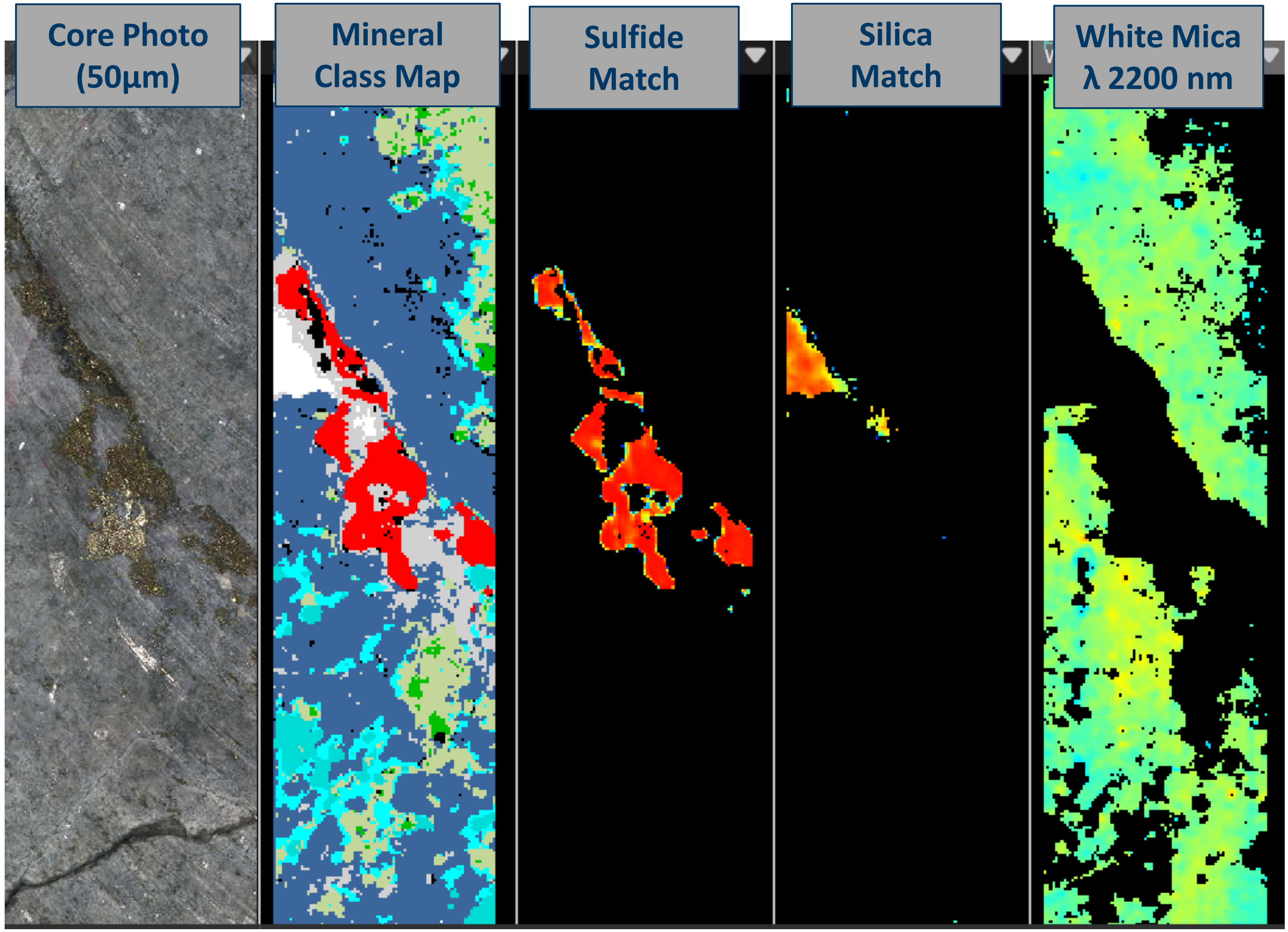
DDH	From	To	Total Feet	Total Meters	Comment
TC35-1	80	462	382	116	4,020ppb Au over 4ft interval
TC36-1	3	403	400	122	multiple gold associations
RR-1	6	1602	1596	486	Original DNR hole that got modern exploration programs going.
ND-1	18	603	585	178	multiple gold associations
ND-2	29	653	624	190	multiple gold associations
ND-3	19	409	390	119	multiple gold associations
S-2	4	452	448	137	multiple gold associations
SS-1	11	588	577	176	2,765ppb Au over 5ft interval
SS-4	39	412	373	114	8,016ppb Au over 5ft interval
SS-7	34	722	688	209	Same Au-bearing intervals as SS-4
SS-8	31	502	471	144	2,501ppb Au over 8.8ft interval
SS-9	53	400	347	106	hornblende and tourmaline
		Total	6881	2097	

Greenstone Gold Background

- Alteration style varies with the type and degree of deformation and with metamorphic grade.
- Includes a characteristic suite of minerals, including a regional and local association with carbonates, as well as potassic phyllosilicates, alkali feldspars, chlorite, Fe-sulfides, and quartz.
- Involves a progressive dilution of original bulk chemistry:
  - Alteration is accomplished by stripping of CaO and Na_2O, relative enrichment of Al_2O_3, and addition of K_2O, CO_2, H_2O, S, Au, and other incompatible elements.

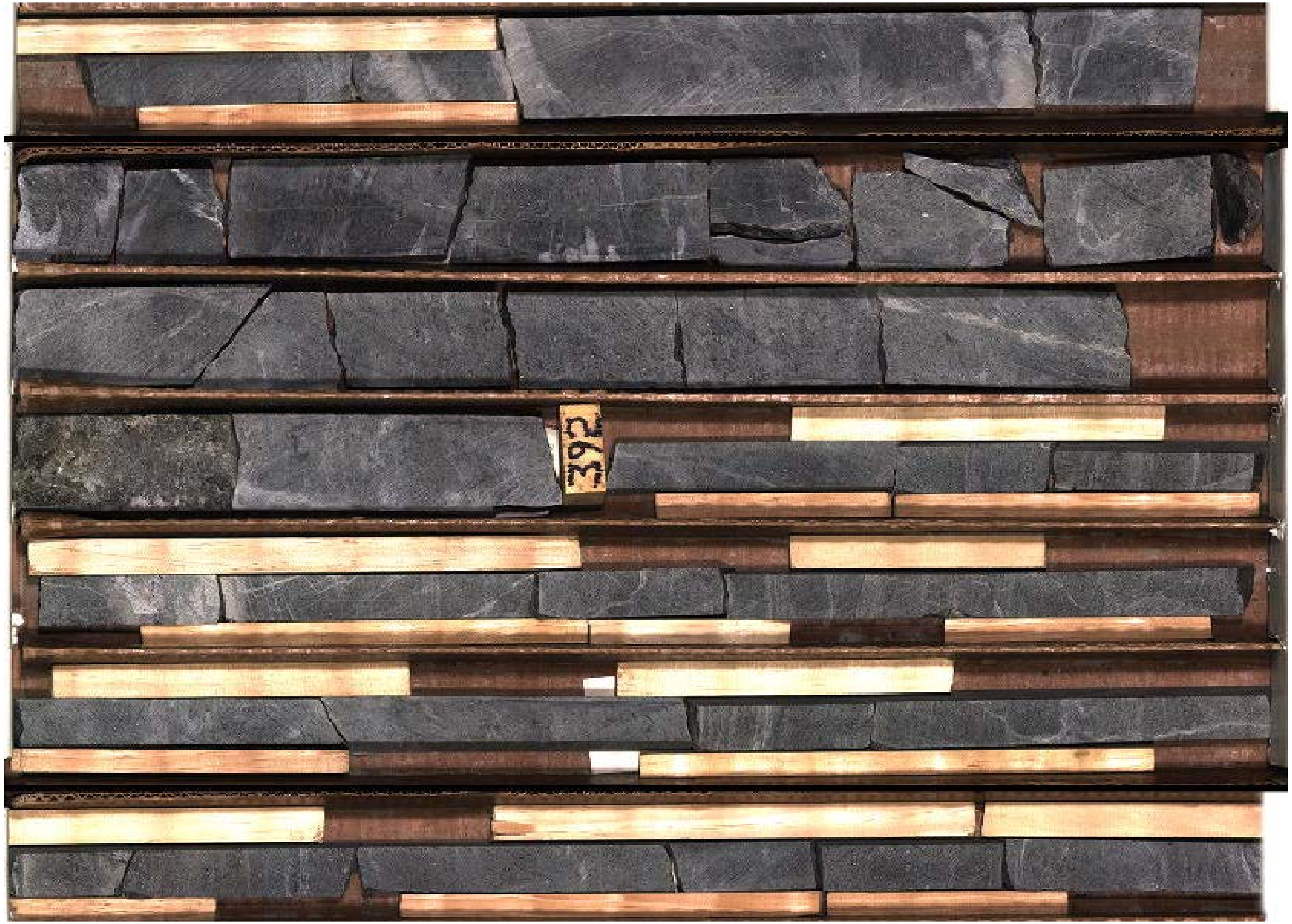
Common Gold Associations

- Hosted in quartz veins and/or disseminated in altered wall rock.
- Associated with B-W-Sb-Te-Mo-As bearing minerals.
- Observed to have white mica and “green mica” (contains Cr, V, Fe, or Ba) replace chlorite and talc as the dominant phyllosilicates with increasing gold-related alteration.
- Alteration related to gold mineralization reflects the introduction of K and CO_2 and the removal of Ca and Na.



link

Example International Falls Core Tray



corescan

International Falls – Mineral Key

Mineral Name	Colour	RGB Code
Tourmaline		167,37,255
Garnet		255,151,151
Green Mica		58,102,156
Talc		0,255,0
Epidote		188,255,55
Prehnite		155,187,89
Zeolite		255,237,105
Biotite		128,0,0
Amphibole		52,82,52
Carbonate (Fe-rich)		185,255,255
Carbonate		0,255,255
Sepiolite		196,215,155
Hydrous Silica/Quartz		250,250,250
Montmorillonite		175,175,175
White Mica + Chlorite*		148,138,84
White Mica + Aspectral*		188,207,230
Gypsum		213,87,171
White mica		83,141,213
Chlorite		0,191,0
Amphibole (Fe-rich)		45,95,45
Orthopyroxene		112,104,64
Clinopyroxene		168,128,0
Aspectral		209,209,209
Aspectral 2		166,166,166
Aspectral (Fe-rich)		0,108,105

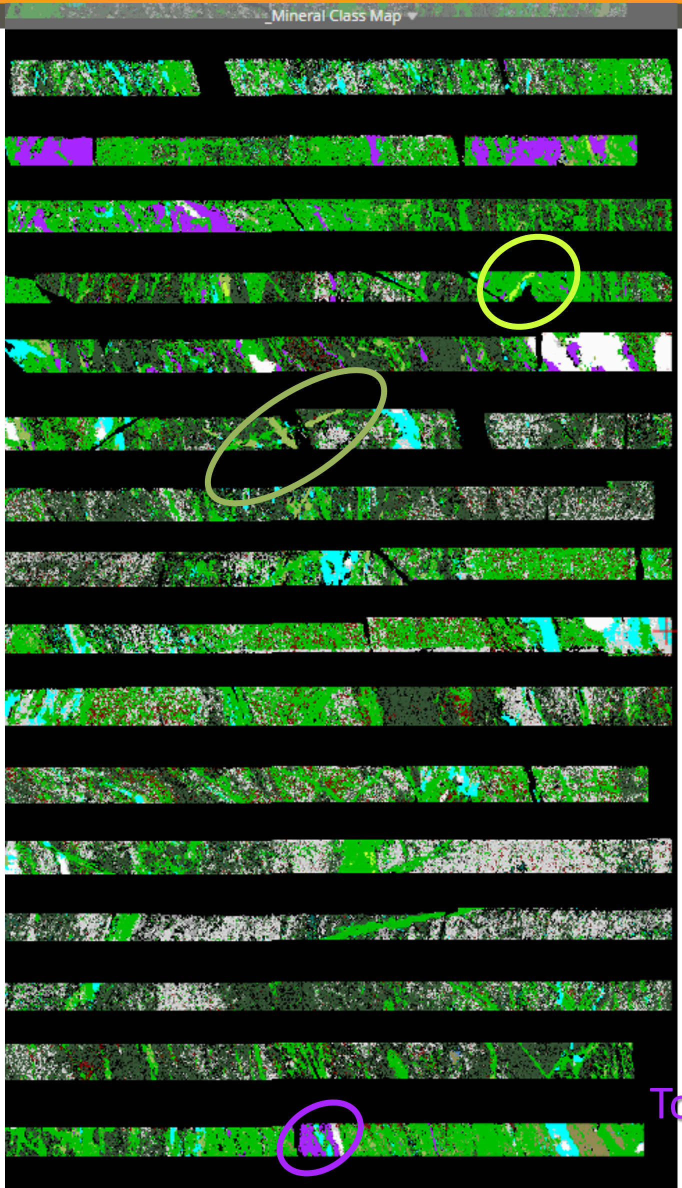
First

Display Priority

Last

**Only displayed in the class map*

TC35-1 @ ~100'



[Link]

Epidote veining

Prehnite veining

Tourmaline and carbonate

International Falls – Mineral Key

Phyllosilicates (micas, chlorites, biotites)

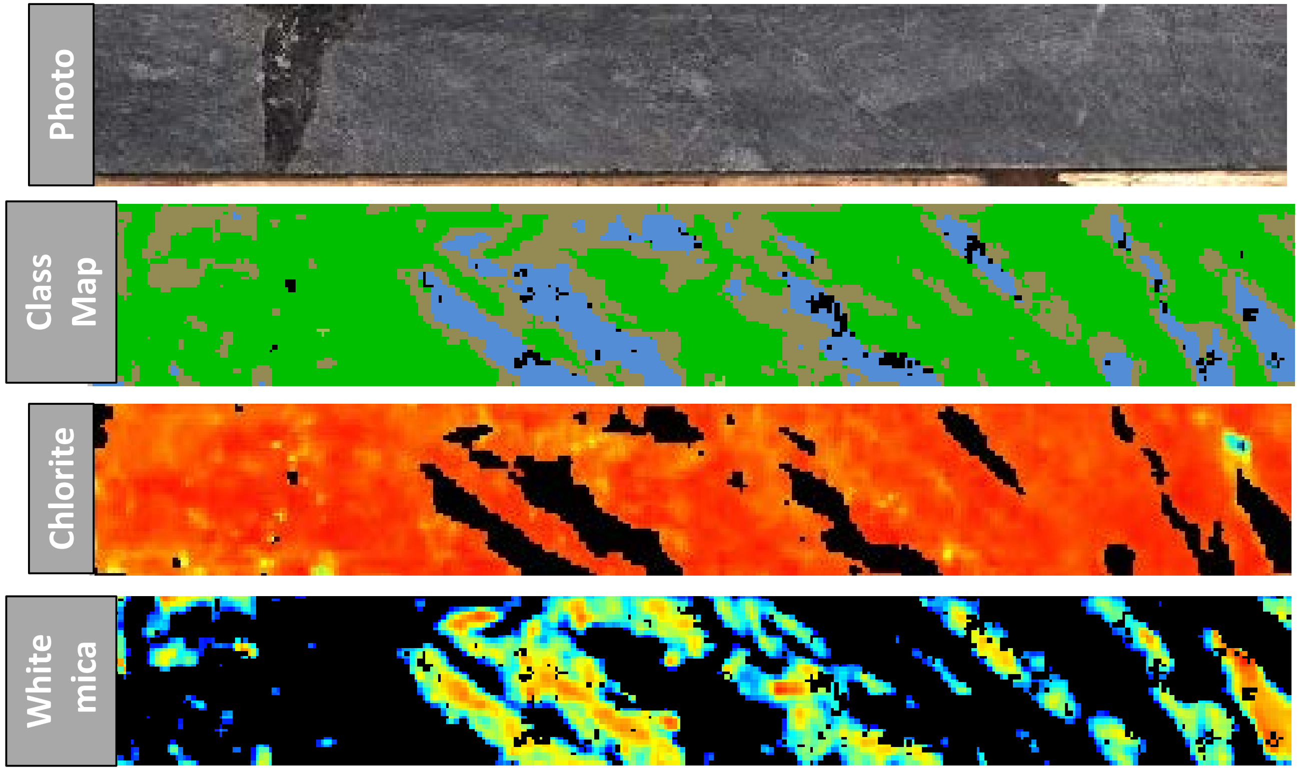
Mineral Name	Colour	RGB Code
Tourmaline		167,37,255
Garnet		255,151,151
Green Mica		58,102,156
Talc		0,255,0
Epidote		188,255,55
Prehnite		155,187,89
Zeolite		255,237,105
Biotite		128,0,0
Amphibole		52,82,52
Carbonate (Fe-rich)		185,255,255
Carbonate		0,255,255
Sepiolite		196,215,155
Hydrous Silica/Quartz		250,250,250
Montmorillonite		175,175,175
White Mica + Chlorite*		148,138,84
White Mica + Aspectral*		188,207,230
Gypsum		213,87,171
White mica		83,141,213
Chlorite		0,191,0
Amphibole (Fe-rich)		45,95,45
Orthopyroxene		112,104,64
Clinopyroxene		168,128,0
Aspectral		209,209,209
Aspectral 2		166,166,166
Aspectral (Fe-rich)		0,108,105

First

Display Priority

Last

**Only displayed in the class map*



TC36-1 @ 67'

Link

International Falls – Mineral Key

Pyroxenes & Amphiboles

Mineral Name	Colour	RGB Code
Tourmaline		167,37,255
Garnet		255,151,151
Green Mica		58,102,156
Talc		0,255,0
Epidote		188,255,55
Prehnite		155,187,89
Zeolite		255,237,105
Biotite		128,0,0
Amphibole		52,82,52
Carbonate (Fe-rich)		185,255,255
Carbonate		0,255,255
Sepiolite		196,215,155
Hydrous Silica/Quartz		250,250,250
Montmorillonite		175,175,175
White Mica + Chlorite*		148,138,84
White Mica + Aspectral*		188,207,230
Gypsum		213,87,171
White mica		83,141,213
Chlorite		0,191,0
Amphibole (Fe-rich)		45,95,45
Orthopyroxene		112,104,64
Clinopyroxene		168,128,0
Aspectral		209,209,209
Aspectral 2		166,166,166
Aspectral (Fe-rich)		0,108,105

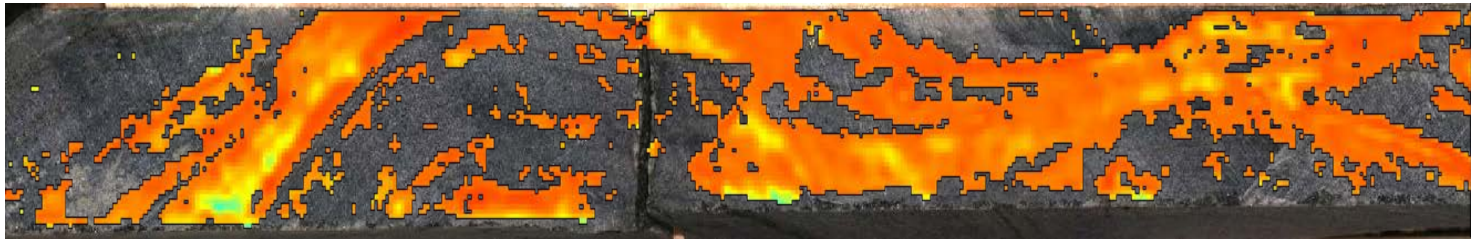
*Only displayed in the class map

First

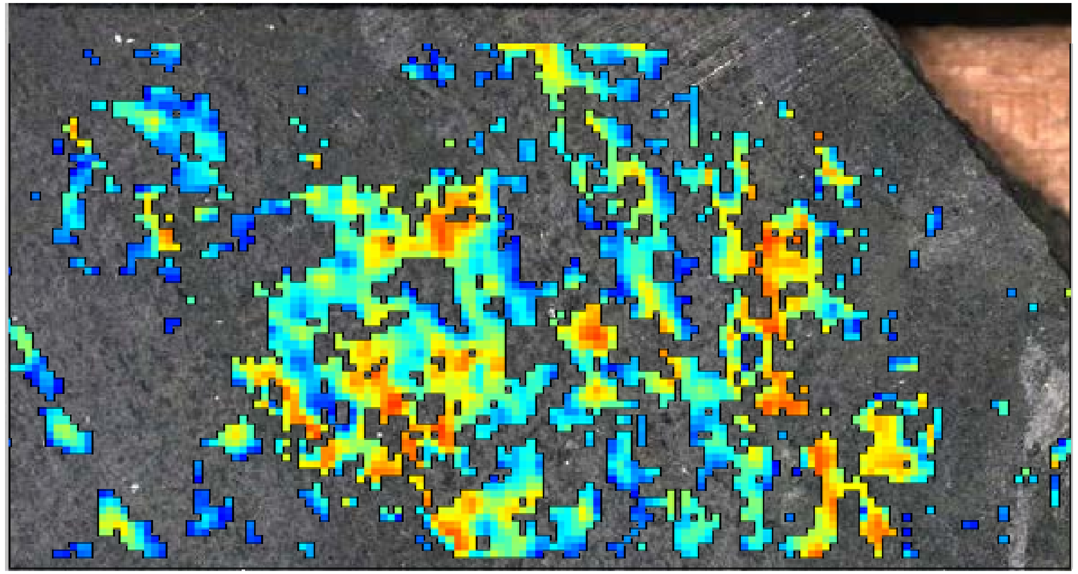
Display Priority

Last

Clinopyroxene from SS-9 @ 239'



Orthopyroxene from ND-3 @ 231'



International Falls – Mineral Key

Carbonates

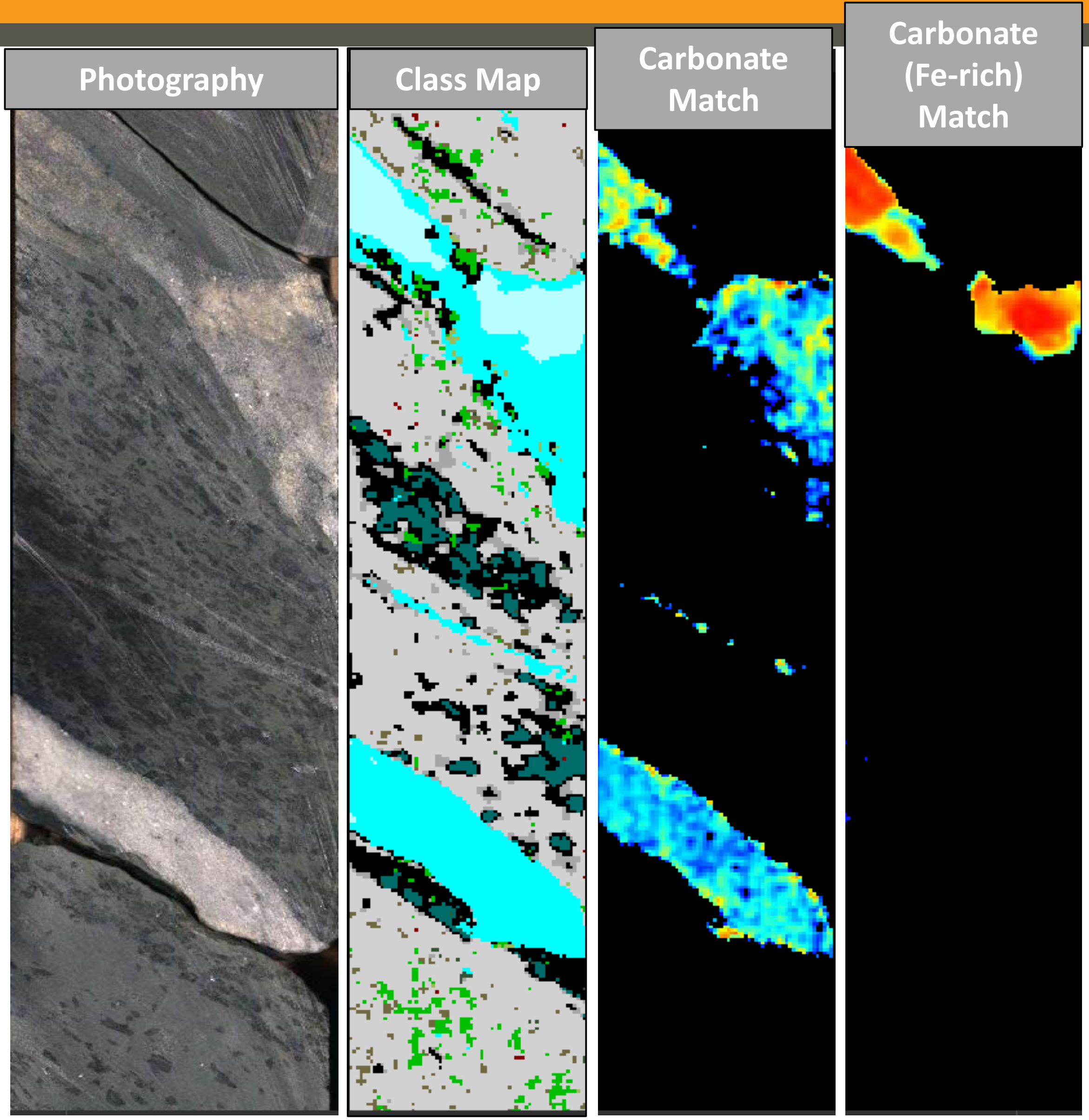
Mineral Name	Colour	RGB Code
Tourmaline		167,37,255
Garnet		255,151,151
Green Mica		58,102,156
Talc		0,255,0
Epidote		188,255,55
Prehnite		155,187,89
Zeolite		255,237,105
Biotite		128,0,0
Amphibole		52,82,52
Carbonate (Fe-rich)		185,255,255
Carbonate		0,255,255
Sepiolite		196,215,155
Hydrous Silica/Quartz		250,250,250
Montmorillonite		175,175,175
White Mica + Chlorite*		148,138,84
White Mica + Aspectral*		188,207,230
Gypsum		213,87,171
White mica		83,141,213
Chlorite		0,191,0
Amphibole (Fe-rich)		45,95,45
Orthopyroxene		112,104,64
Clinopyroxene		168,128,0
Aspectral		209,209,209
Aspectral 2		166,166,166
Aspectral (Fe-rich)		0,108,105

First

Display Priority

Last

**Only displayed in the class map*



International Falls – Mineral Key

Calcium-aluminium silicates (epidotes, prehnite, garnet)

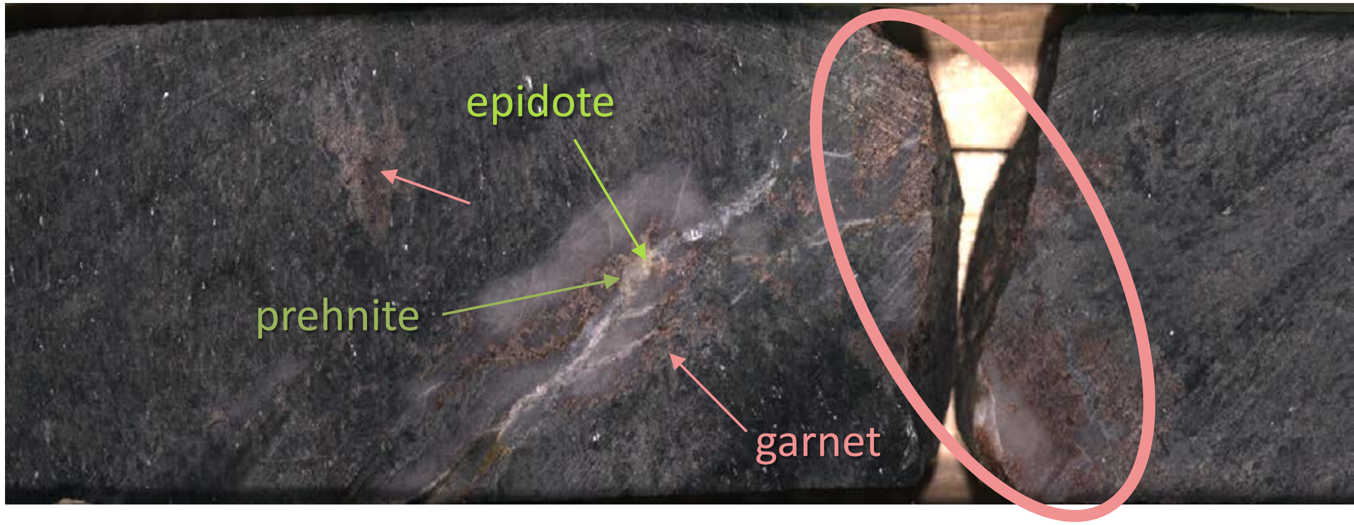
Mineral Name	Colour	RGB Code
Tourmaline		167,37,255
Garnet		255,151,151
Green Mica		58,102,156
Talc		0,255,0
Epidote		188,255,55
Prehnite		155,187,89
Zeolite		255,237,105
Biotite		128,0,0
Amphibole		52,82,52
Carbonate (Fe-rich)		185,255,255
Carbonate		0,255,255
Sepiolite		196,215,155
Hydrous Silica/Quartz		250,250,250
Montmorillonite		175,175,175
White Mica + Chlorite*		148,138,84
White Mica + Aspectral*		188,207,230
Gypsum		213,87,171
White mica		83,141,213
Chlorite		0,191,0
Amphibole (Fe-rich)		45,95,45
Orthopyroxene		112,104,64
Clinopyroxene		168,128,0
Aspectral		209,209,209
Aspectral 2		166,166,166
Aspectral (Fe-rich)		0,108,105

Only displayed in the class map

First

Display Priority

Last



DDH: SS-4 @ 115’

International Falls – Mineral Key

Tourmalines

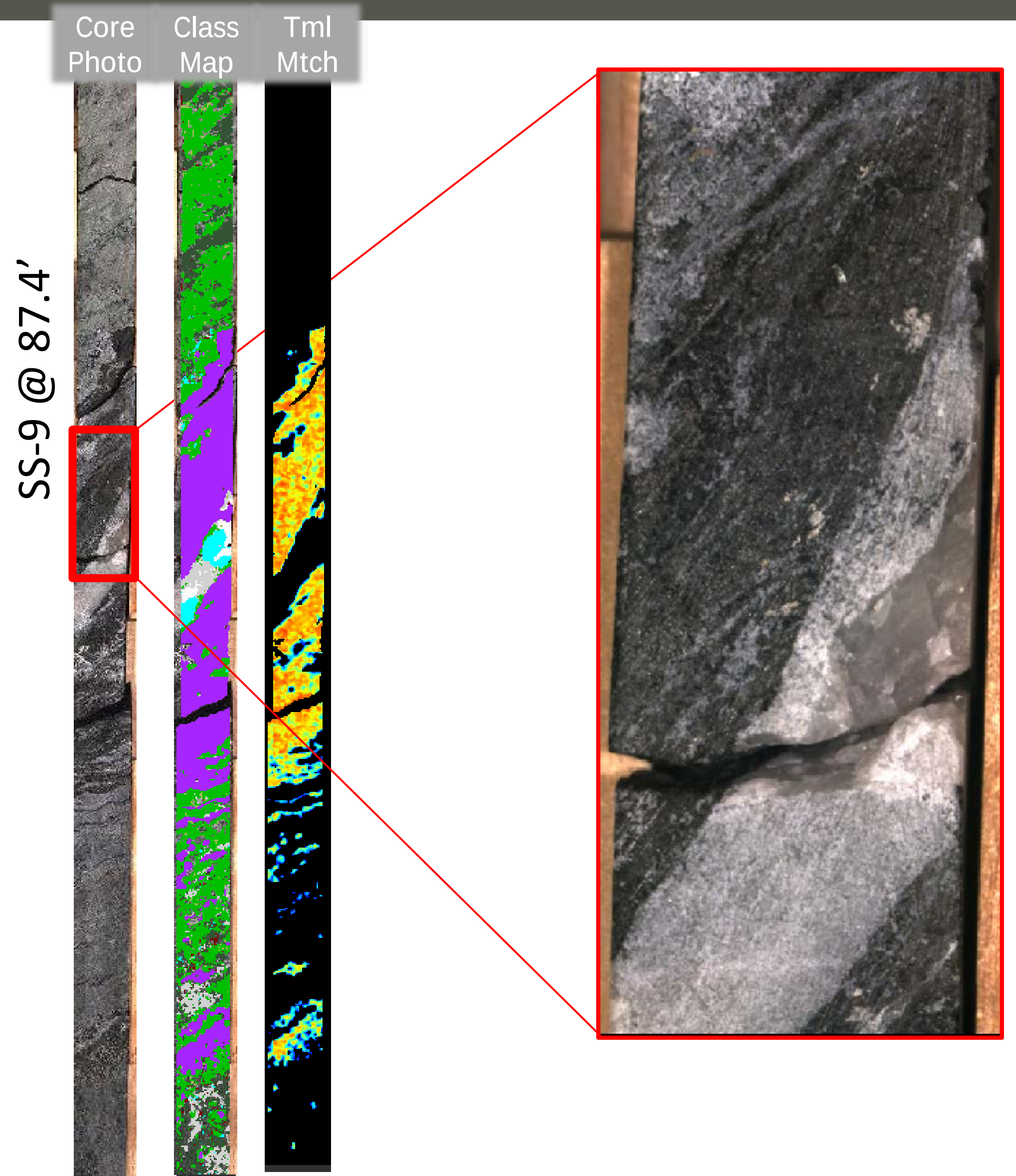
Mineral Name	Colour	RGB Code
Tourmaline		167,37,255
Garnet		255,151,151
Green Mica		58,102,156
Talc		0,255,0
Epidote		188,255,55
Prehnite		155,187,89
Zeolite		255,237,105
Biotite		128,0,0
Amphibole		52,82,52
Carbonate (Fe-rich)		185,255,255
Carbonate		0,255,255
Sepiolite		196,215,155
Hydrous Silica/Quartz		250,250,250
Montmorillonite		175,175,175
White Mica + Chlorite*		148,138,84
White Mica + Aspectral*		188,207,230
Gypsum		213,87,171
White mica		83,141,213
Chlorite		0,191,0
Amphibole (Fe-rich)		45,95,45
Orthopyroxene		112,104,64
Clinopyroxene		168,128,0
Aspectral		209,209,209
Aspectral 2		166,166,166
Aspectral (Fe-rich)		0,108,105

First

Display Priority

Last

**Only displayed in the class map*



International Falls - Tourmaline

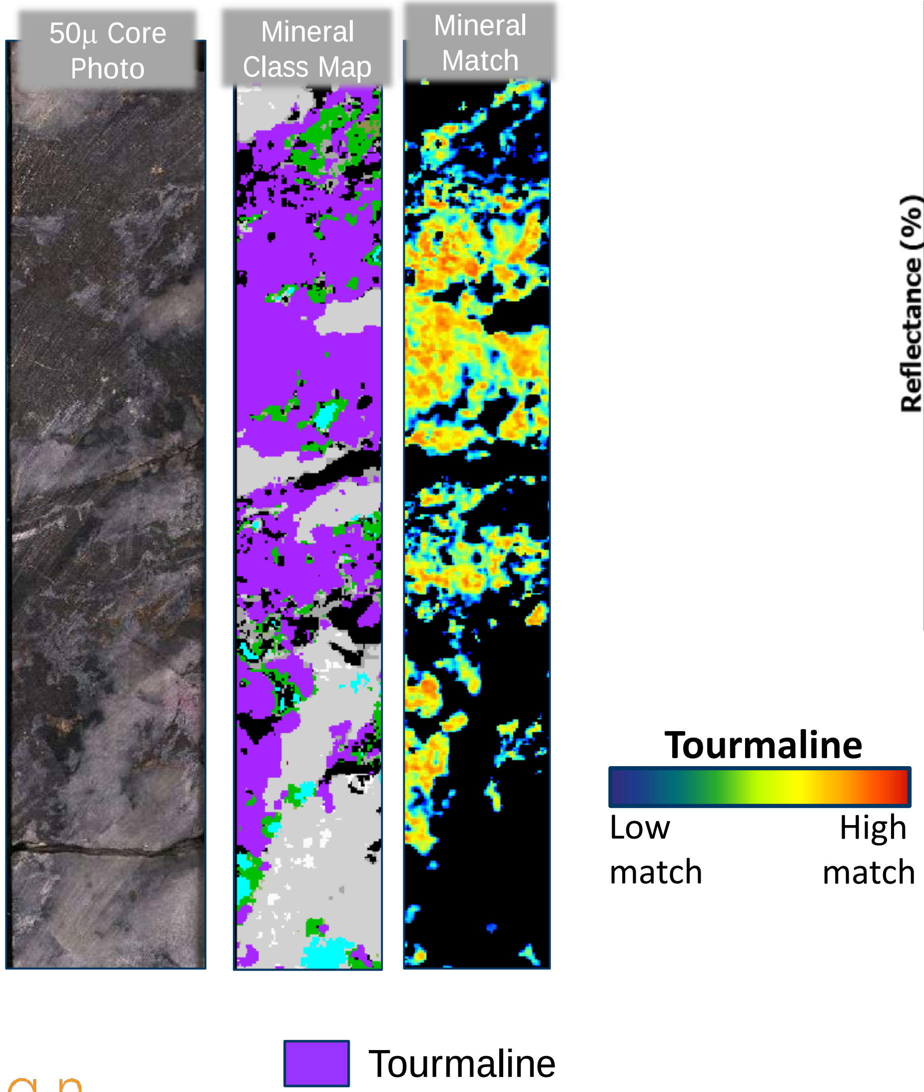
- *Tourmalines are of particular interest, given their association with Au mineralization.*

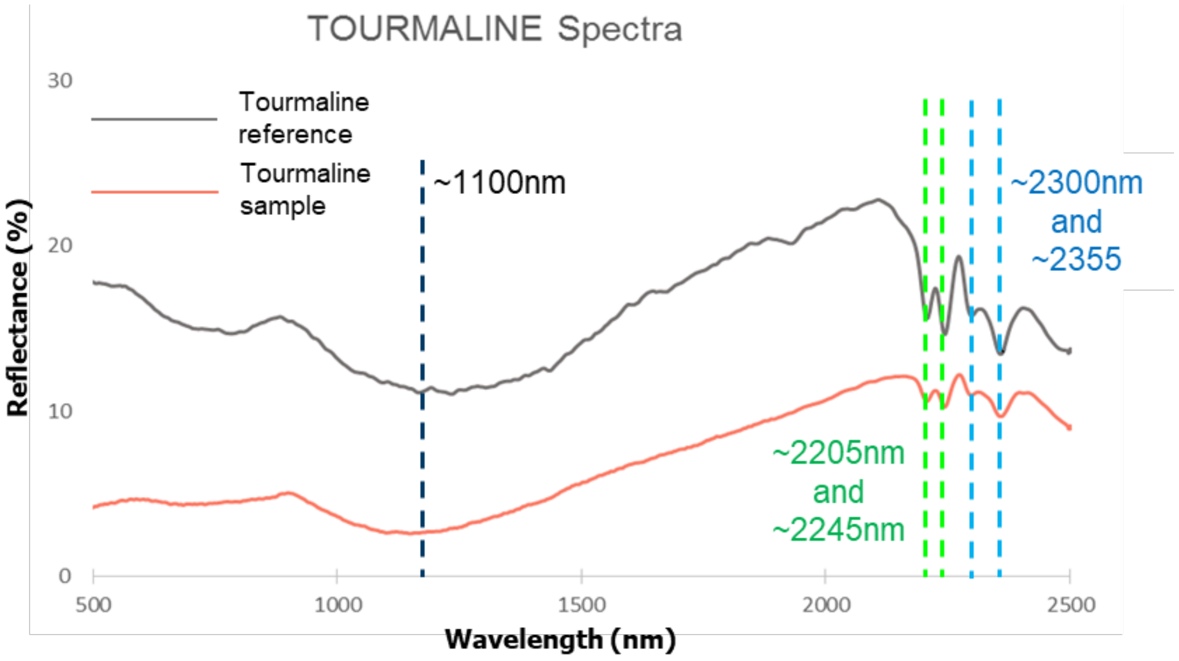
- Tourmalines at International Falls identified are dominated by schorl varieties (as determined by ~2350nm feature position; Bierwirth, 2008), although composition approaching dravite are also recognized.
  - Since the standard (2350nm) did not reveal significant variation in the tourmalines, several ‘test’ parameters were created, and the tourmaline chemistry was successfully tracked by measuring the 2200nm feature

- The 2350nm feature was also used to determine tourmaline crystallinity

International Falls Compositional Parameters

Tourmaline Spectral Characteristics





- The combination of absorption features at ~2210nm, ~2245nm, ~2305nm and ~2360nm are unique to tourmaline.
  - These features are due to X-O-H stretching vibrations, where X = Al, Mg, Fe or B.
- Broad features at ~1100nm – if present - are due to energy transitions in ferrous iron.

corescan

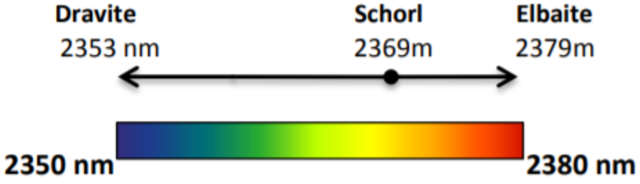
Tourmaline 2350nm wavelength variations

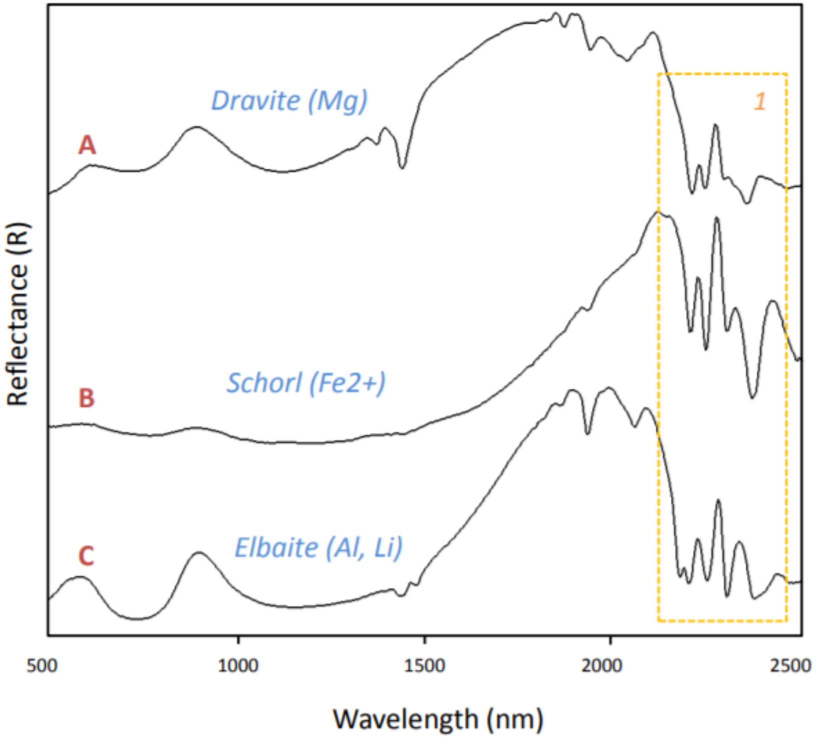
Tourmaline spectra are complex.

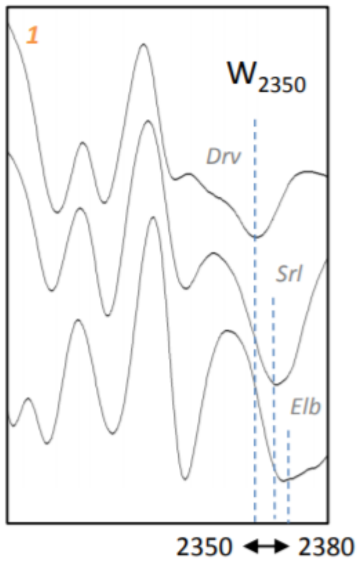
Less is known about the effects of chemical substitutions on SWIR features than most other porphyry-related alteration minerals.

However, variations in the 2350nm feature may be used to distinguish tourmaline species:

Tourmaline composition index 2350 nm position







(End-member tourmaline data courtesy of F. Bierwirth)

Dravite $NaMg_3Al_6Si_6O_{18}(BO_3)_3(OH)_3OH$

Elbaite $Na(Li_{1.5},Al_{1.5})Al_6Si_6O_{18}(BO_3)_3(OH)_3OH$

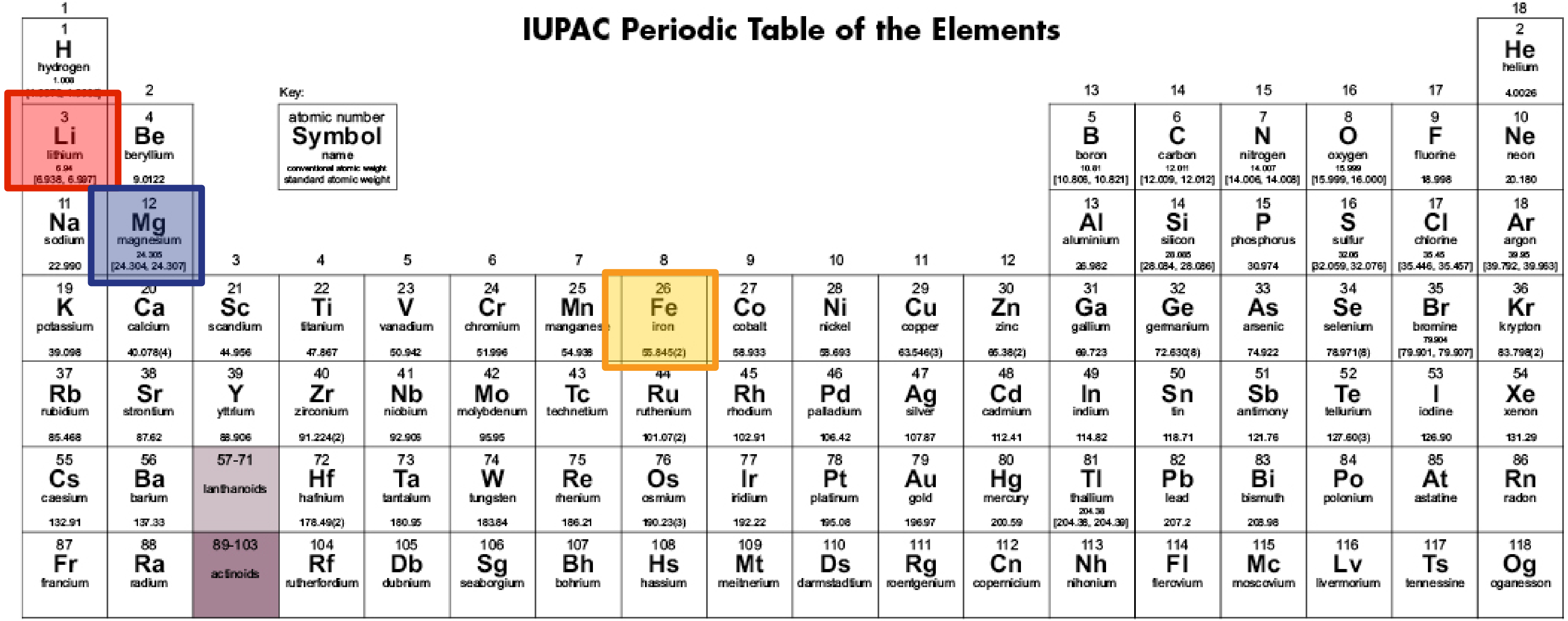
Schorl $NaFe^{2+}{}_3Al_6Si_6O_{18}(BO_3)_3(OH)_3OH$

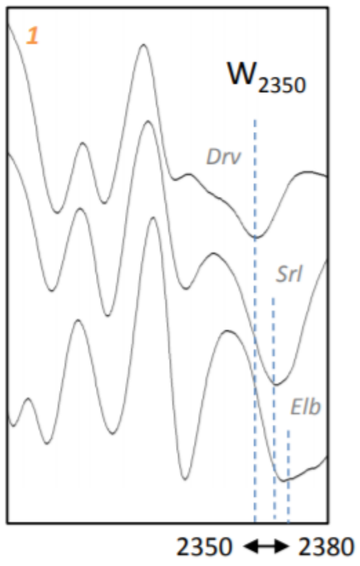
Compositional endmembers courtesy of Bierwirth, P.N., 2008.

Reference: Deyell et al., in prep.

corescan

Tourmaline 2350nm wavelength variations





Mg^{2+} = 0.65 Å

Fe^{2+} = 0.77 Å

Li^{1+} = 1.52 Å

Atomic Radii

Dravite 2353 nm | **Schorl** 2369m | **Elbaite** 2379m

Dravite $NaMg_3Al_6Si_6O_{18}(BO_3)_3(OH)_3OH$

Schorl $NaFe^{2+}{}_3Al_6Si_6O_{18}(BO_3)_3(OH)_3OH$

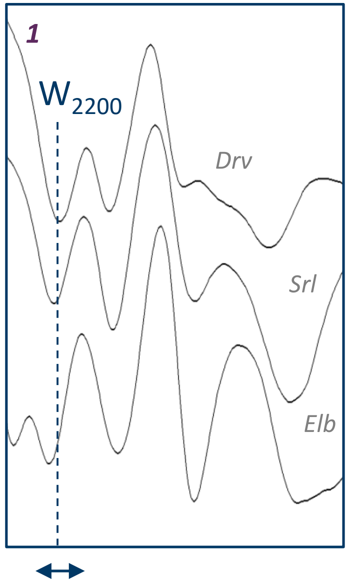
Elbaite $Na(Li_{1.5},Al_{1.5})Al_6Si_6O_{18}(BO_3)_3(OH)_3OH$

Reference: Deyell et al., in prep.

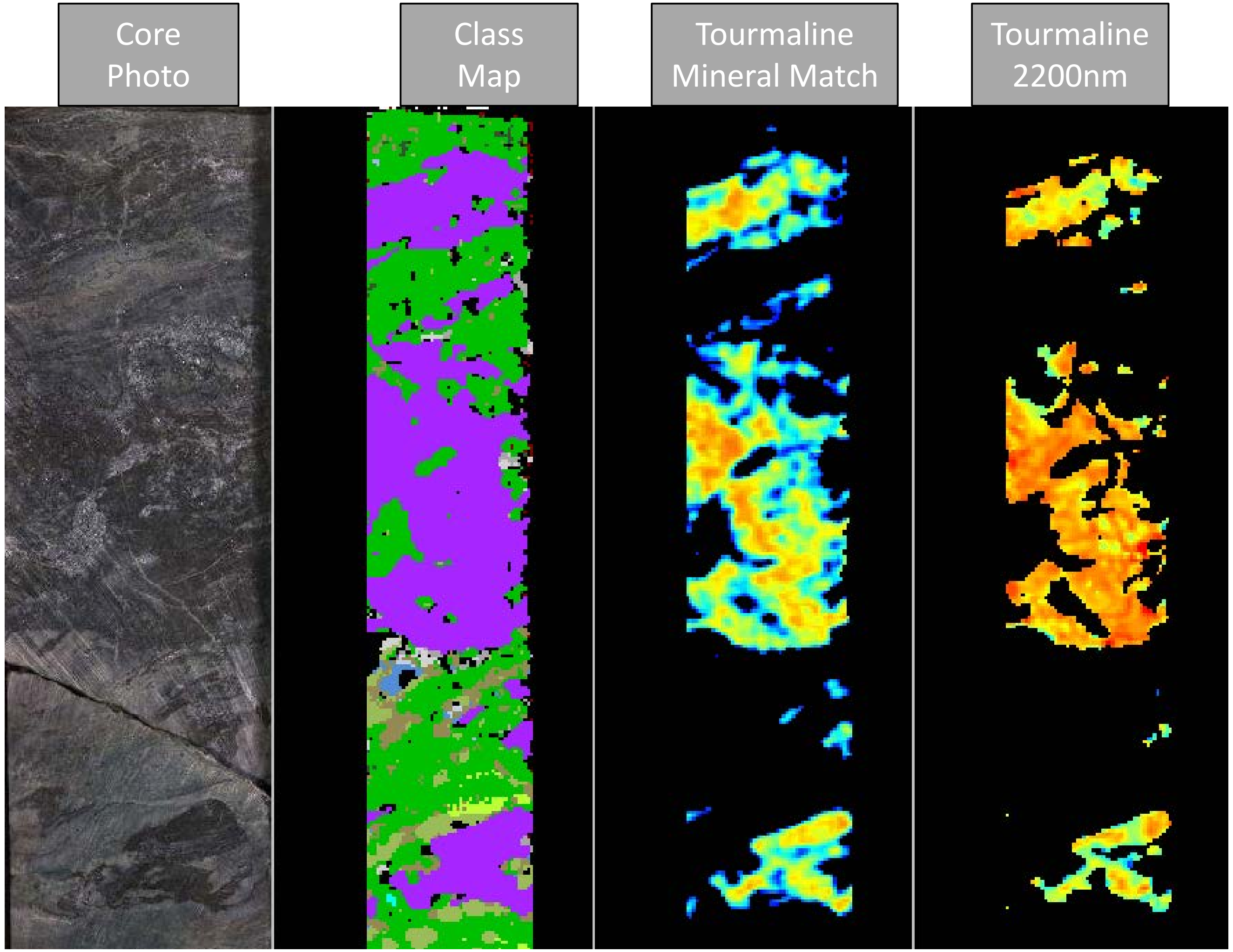
corescan

International Falls Compositional Parameters

Tourmaline 2200nm wavelength feature variations



Variations in the 2200nm feature position are attributed to variations in the Al content of tourmalines (negatively correlated with Mg and other Y-site cations) – similar to the white mica compositional variations (Duke, 1994)



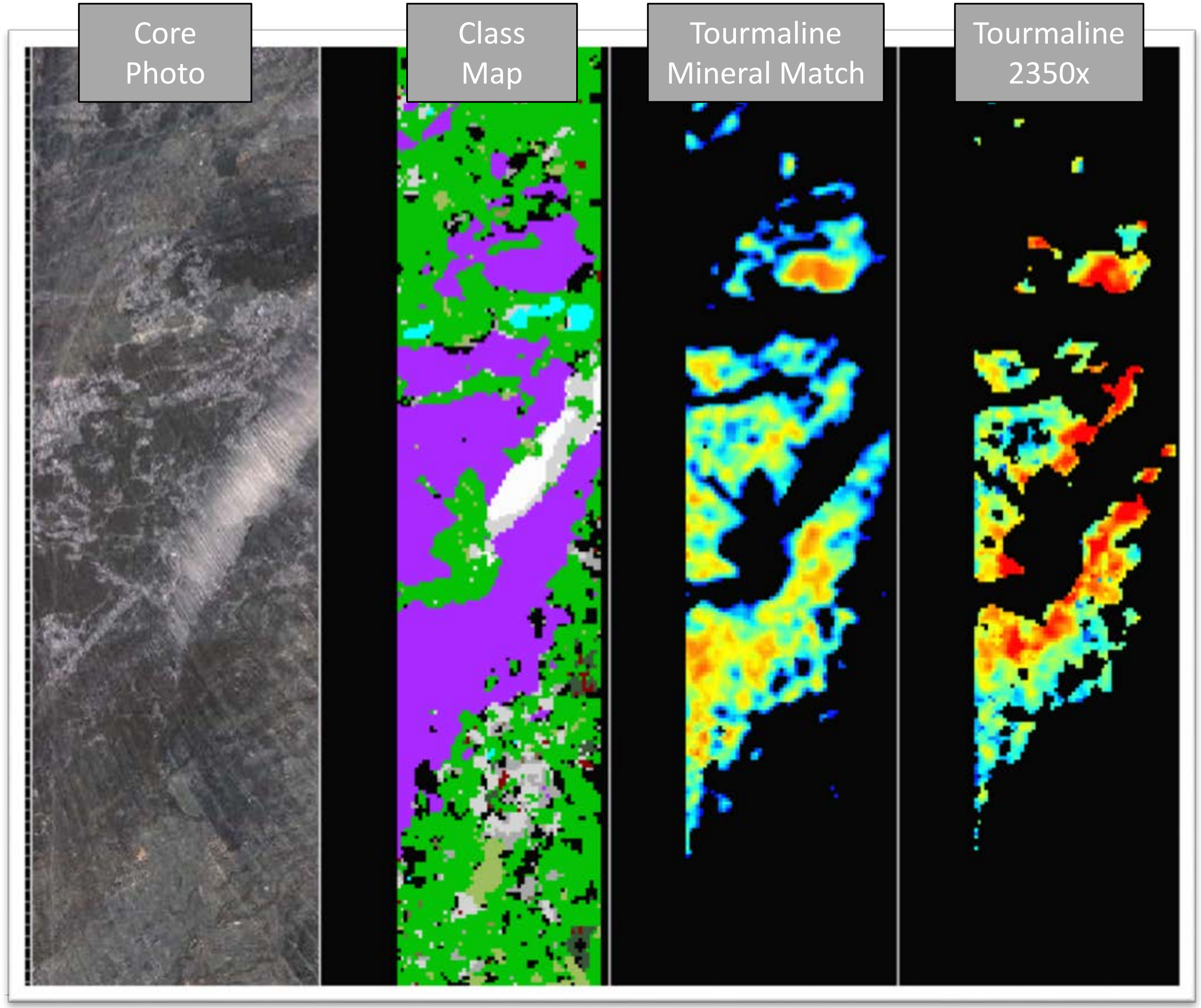
To our knowledge, no systematic study of these variations in tourmalines has been published.

It is not known what range or ‘end-members’ of these values to expect – but it could be worth tracking to see if any systematic variations are present in the dataset.

corescan

International Falls Compositional Parameters

Tourmaline 2350nm - Crystallinity



One other parameter we can explore is the relative ‘sharpness’ of the 2350nm feature (2350x).

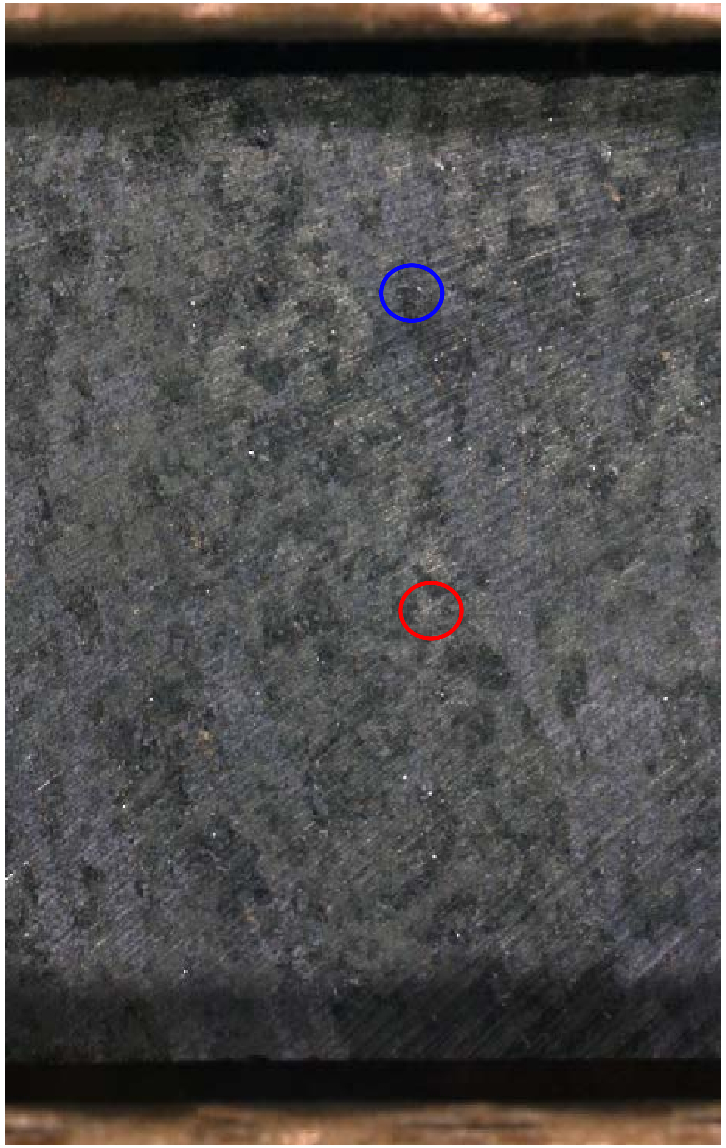
In other mineral groups such as white micas, we can use the Depth/Area of a specific feature as an indication of crystallinity (e.g., higher values = ‘sharper’ features = higher crystallinity). In the case of white micas in particular, crystallinity can be roughly correlated with temperature.

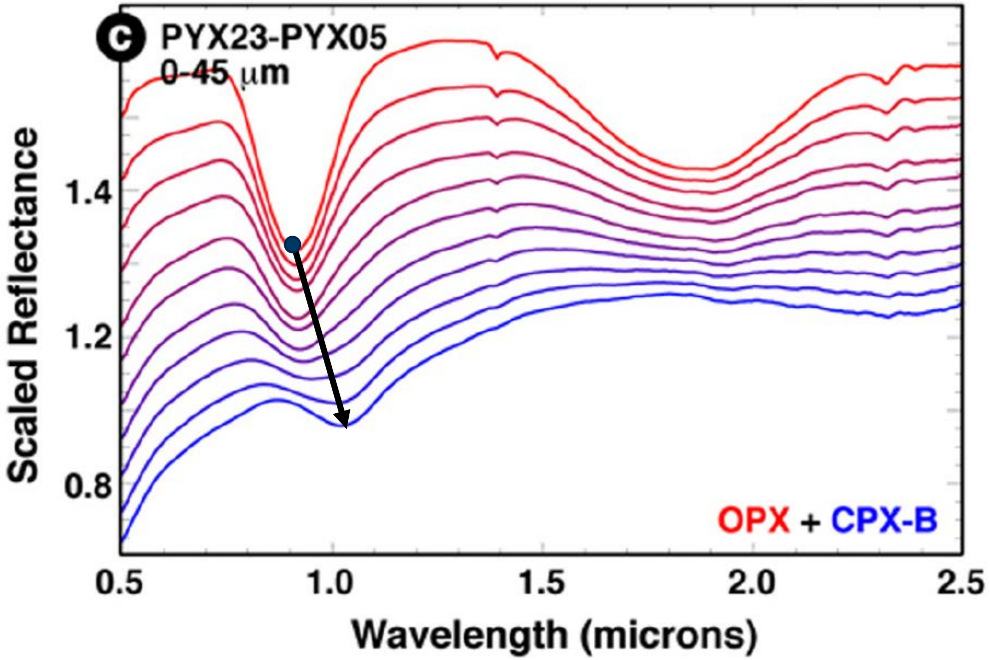
This may not be true of tourmalines – their chemistry is much more variable – but tracking systematic variations may be useful.

International Falls Compositional Parameters

Orthopyroxene vs Clinopyroxene

TC35-1 @ 296.6m





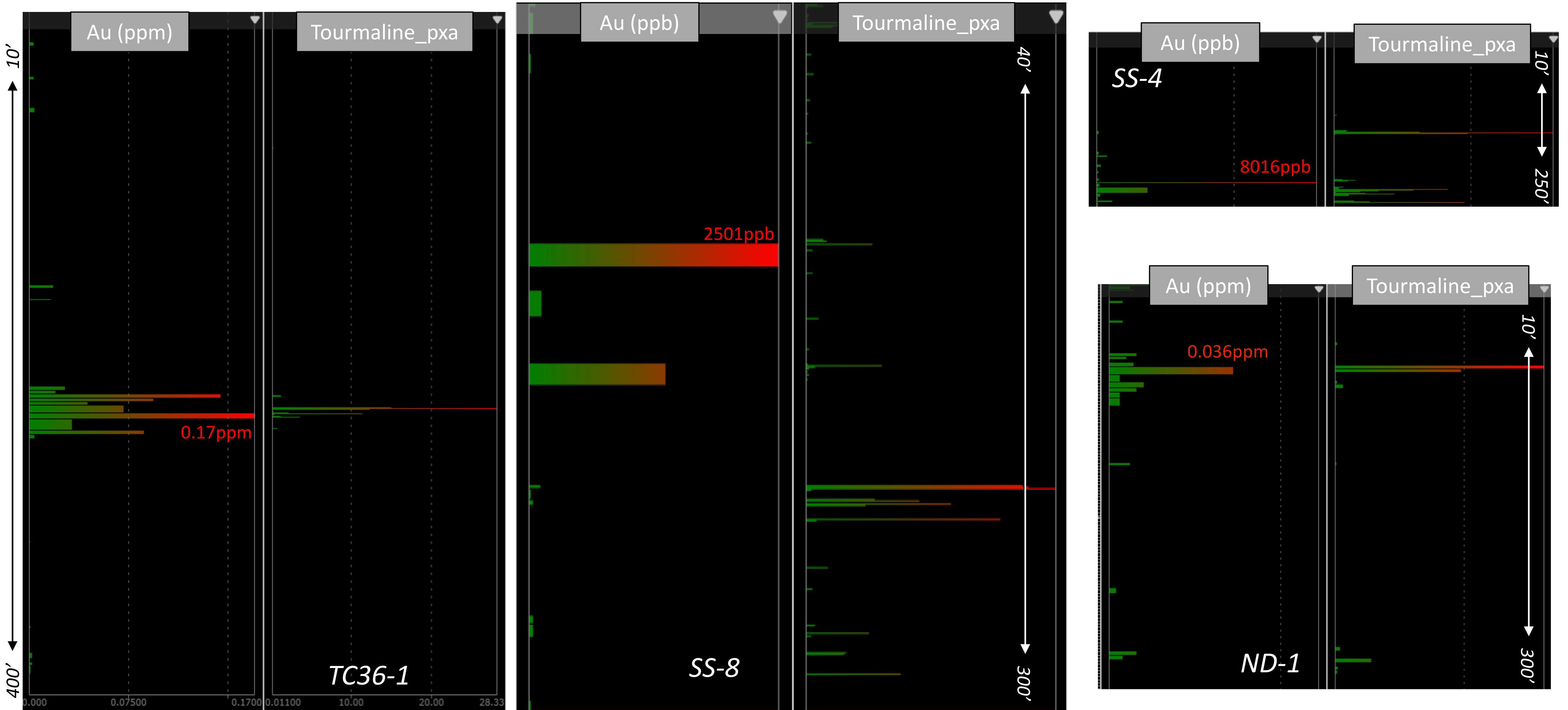
Enstatite (Opx) = 910 nm

Diopside (Cpx) = 1010 nm

corescan

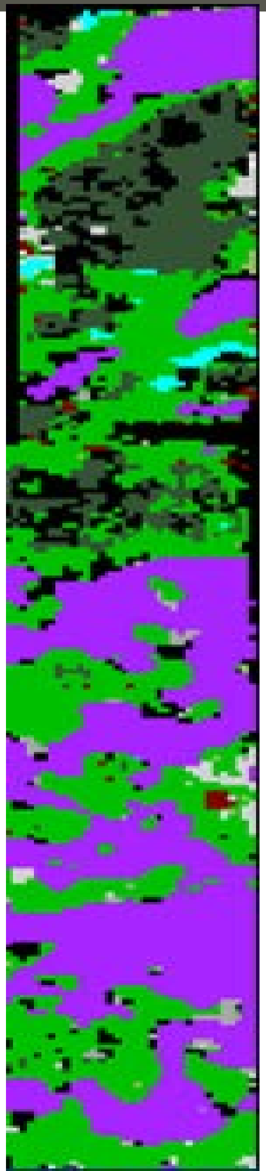
Ref: Horgan (2014)

Tourmaline spatial association with gold (downhole view)



International Falls Greenstone Gold – Summary

- The rocks of this gold-bearing granite greenstone terrane are very conducive to hyperspectral core imaging
  - Mineral groups identified: a range of phyllosilicates (micas, chlorites, biotites), clays, pyroxenes, amphiboles, sulphates, carbonates, calcium-aluminium silicates (epidotes, prehnite, garnet), and tourmalines.
  - Non-destructive technique so can still be readily utilized on archived quarter core
  - Mapped textures that might support a new mineralization model and ignite interest in the exploration community



<u>Recommendation for future work</u>

Confirmatory petrography/EMP analysis of scanned core, coupled with a systematic study of additional core from Focus Area, could reveal consistent trends in quartz-tourmaline-carbonate-sulfide veins and support additional mineral exploration/drilling working with this mineralization model.

corescan