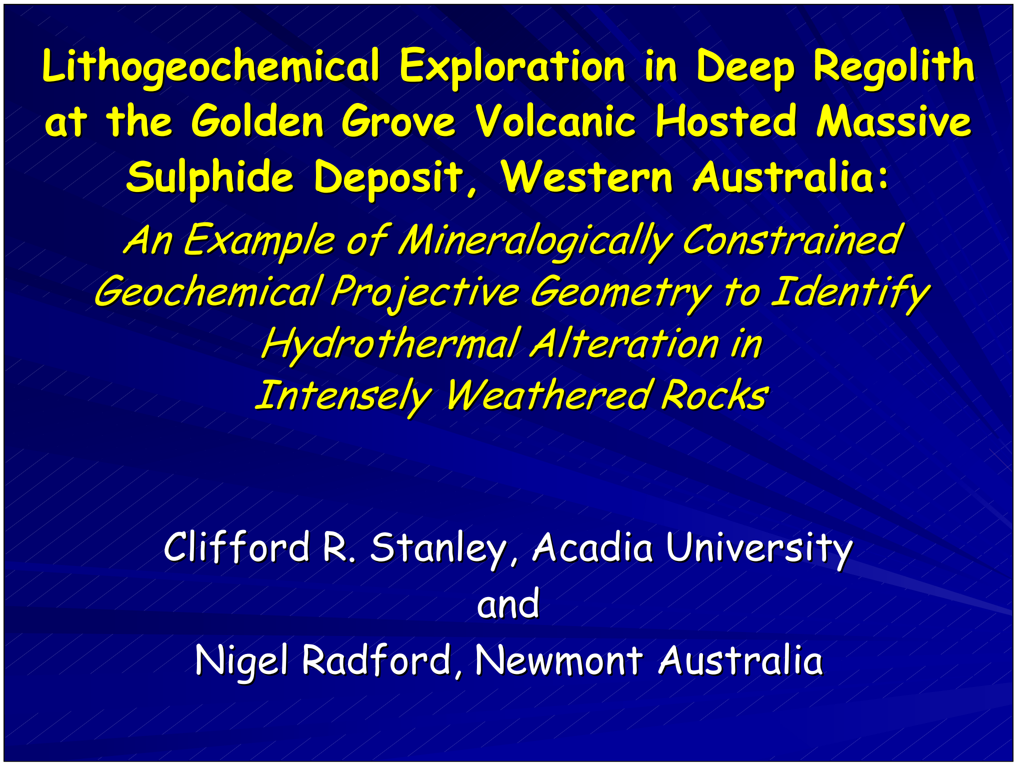

Lithogeochemical Exploration in Deep Regolith at the Golden Grove Volcanic Hosted Massive Sulphide Deposit, Western Australia:

An Example of Mineralogically Constrained Geochemical Projective Geometry to Identify Hydrothermal Alteration in Intensely Weathered Rocks

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and
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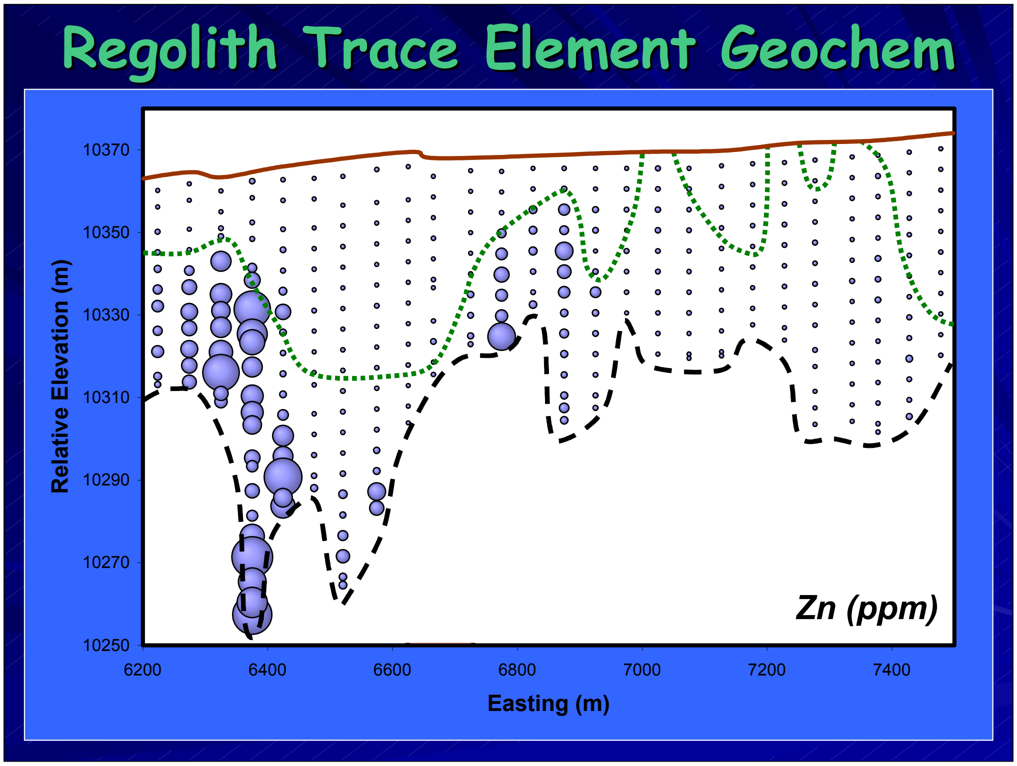
Good Afternoon,

I would like to present the preliminary results of a lithogeochemical study of regolith over the Golden Grove volcanic hosted massive sulphide deposit in Western Australia.

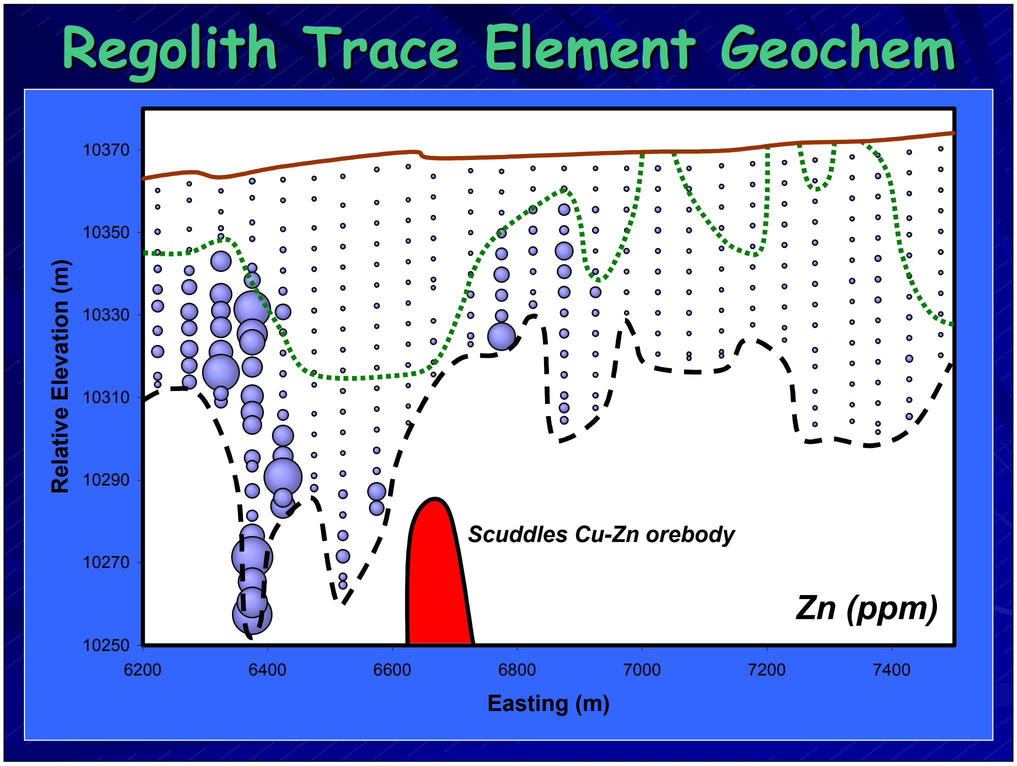
The purpose of this research was primarily to determine the extent to which hydrothermal alteration already defined in un-weathered rocks could be detected in intensely weathered regolith.



This study was initiated because soluble elements in many mineral deposits covered by regolith exhibit such mobility that they have little use in exploration for such deposits.

On this cross-section presenting rotary air blast hole results, the green line represents the base of oxidation; the black line represents the blade refusal depth.

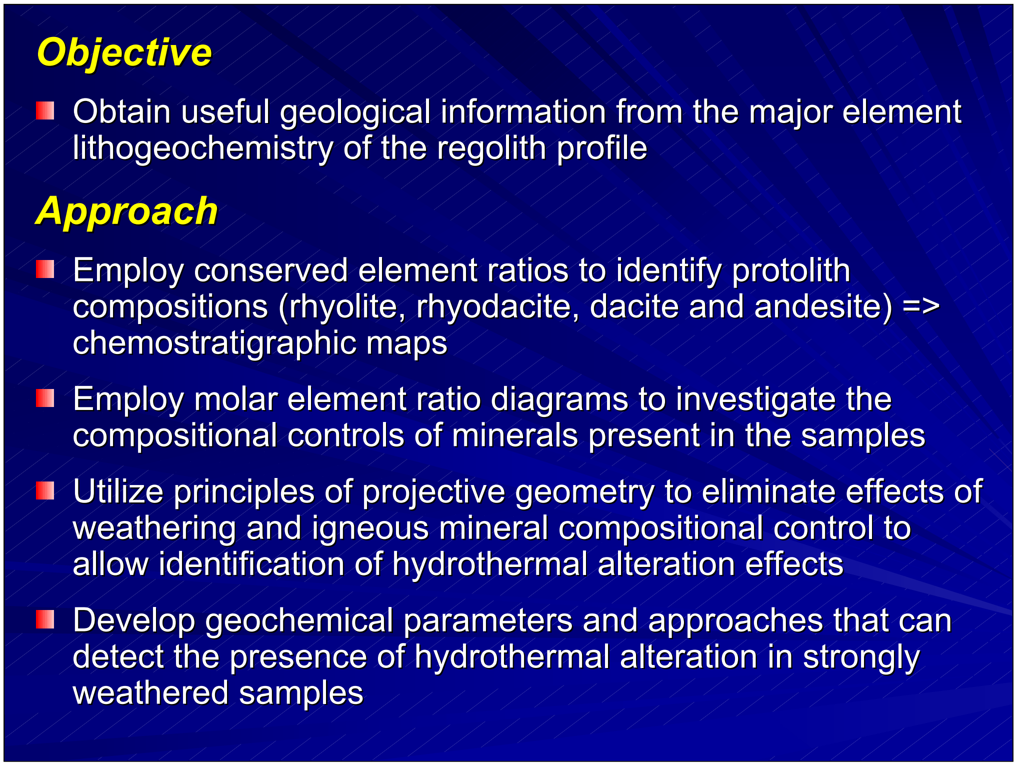
At Golden Grove, a large Zn anomaly exists within the regolith.



Regolith Trace Element Geochem

Unfortunately, this Zn anomaly is displaced up to 400 away from mineralization, making it difficult to confidently identify drilling targets using the principle metal in the deposit.

If hydrothermal alteration patterns can also be obtained from analysis of the RAB hole lithogeochemistry, more precise target definition is possible.



Objective

- Obtain useful geological information from the major element lithogeochemistry of the regolith profile

Approach

- Employ conserved element ratios to identify protolith compositions (rhyolite, rhyodacite, dacite and andesite) => chemostratigraphic maps
- Employ molar element ratio diagrams to investigate the compositional controls of minerals present in the samples
- Utilize principles of projective geometry to eliminate effects of weathering and igneous mineral compositional control to allow identification of hydrothermal alteration effects
- Develop geochemical parameters and approaches that can detect the presence of hydrothermal alteration in strongly weathered samples

As a result, the purpose of this research is determine how to obtain more information from the geochemistry of the regolith profile.

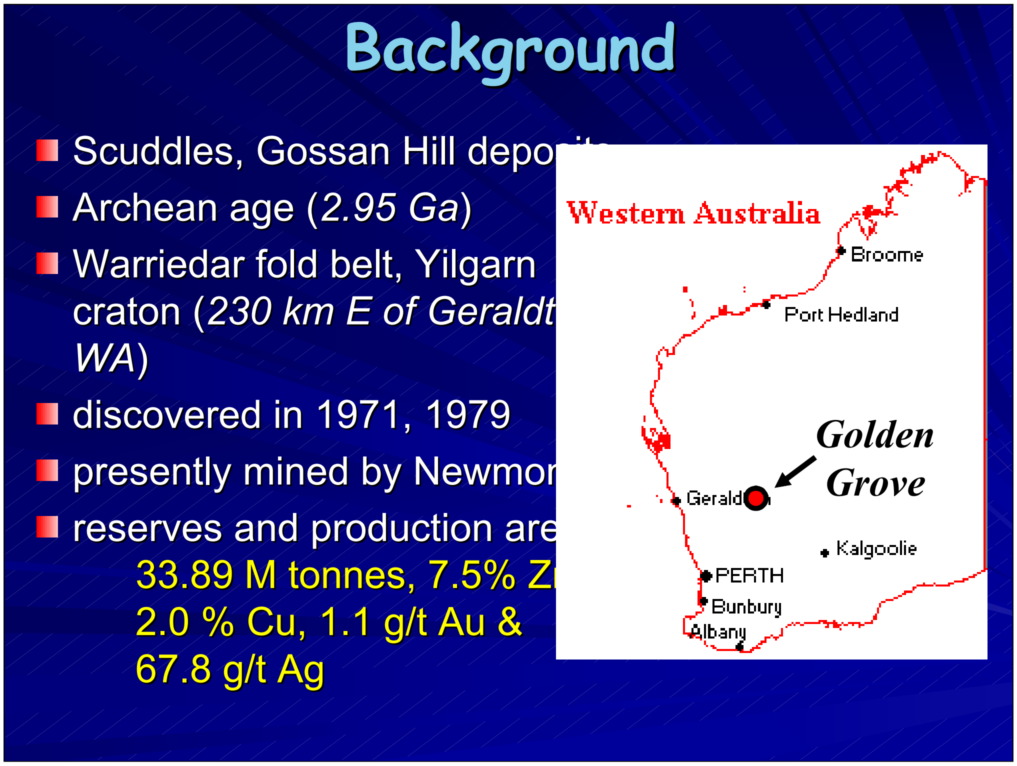
This involved:

1.) using conserved element ratios in the regolith to map the various volcanic compositions present,

2.) employing molar element ratio analysis to investigate the compositional controls on regolith geochemistry,

3.) utilize the principles of projective geometry to ‘see through’ the effects of igneous & sedimentary fractionation and supergene weathering, so as to isolate the effects of hydrothermal alteration, and

4.) to develop geochemical parameters that can be used to identify and quantify the intensity of hydrothermal alteration in regolith samples.



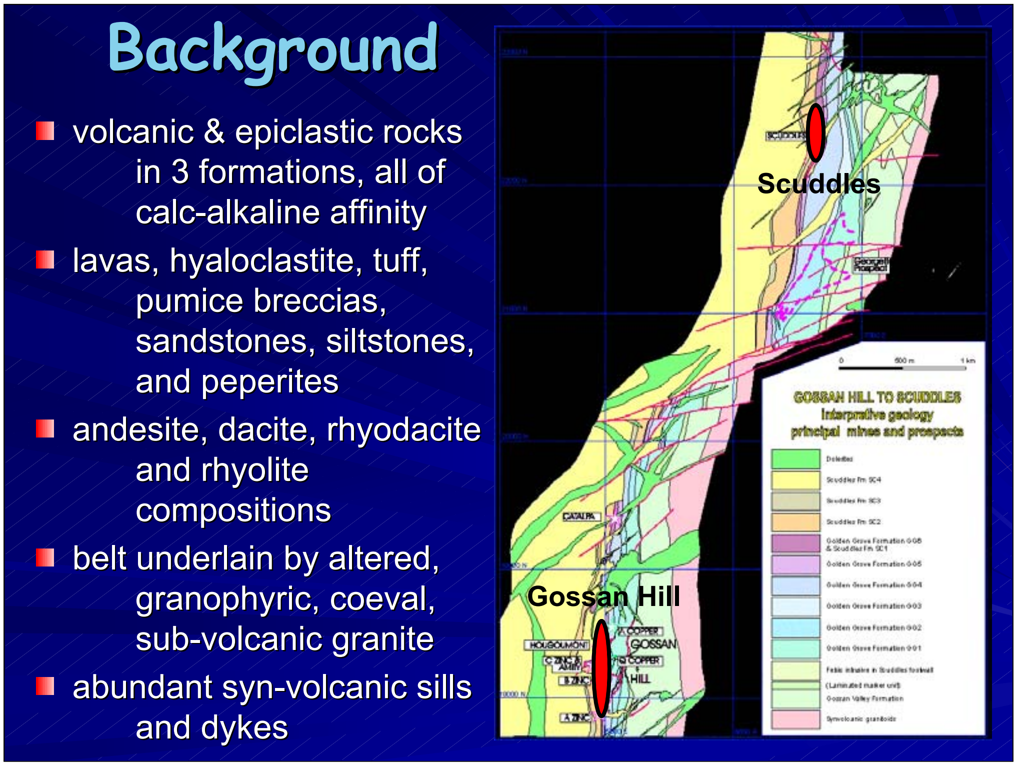
Background

- Scuddles, Gossan Hill depo
- Archean age (*2.95 Ga*)
- Warriedar fold belt, Yilgarn craton (*230 km E of Geraldt WA*)
- discovered in 1971, 1979
- presently mined by Newmo
- reserves and production are
  - 33.89 M tonnes, 7.5% Z
  - 2.0 % Cu, 1.1 g/t Au &
  - 67.8 g/t Ag

The Golden Grove massive sulphide camp is composed of two major deposits, Scuddles and Gossan Hill, which are themselves each made up of several zones.

These are hosted by the Archean Warriedar greenstone belt in the Yilgarn craton, approximately 450 km NE of Perth.

Discovered originally in 1971, the deposits are presently mined by Newmont, and production and reserves approach 34 M tonnes of high grade polymetallic Cu-Zn mineralization.



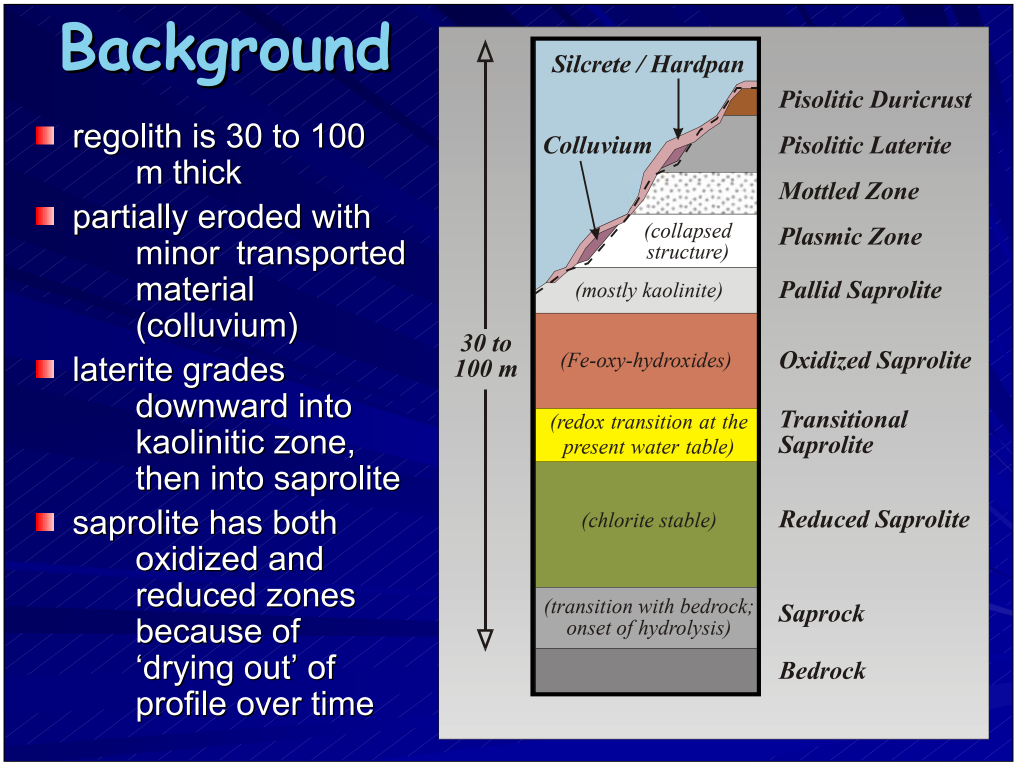
Background

- volcanic & epiclastic rocks in 3 formations, all of calc-alkaline affinity
- lavas, hyaloclastite, tuff, pumice breccias, sandstones, siltstones, and peperites
- andesite, dacite, rhyodacite and rhyolite compositions
- belt underlain by altered, granophyric, coeval, sub-volcanic granite
- abundant syn-volcanic sills and dykes

Host rocks consist of a variety of calc-alkaline volcanic and epiclastic rocks of andesite, dacite, rhyodacite and rhyolite composition.

These are underlain by a shallow level syn-volcanic granitic intrusive, and are cut by later dolerite dykes.

Mineralization occurs near the top of the Golden Grove formation.

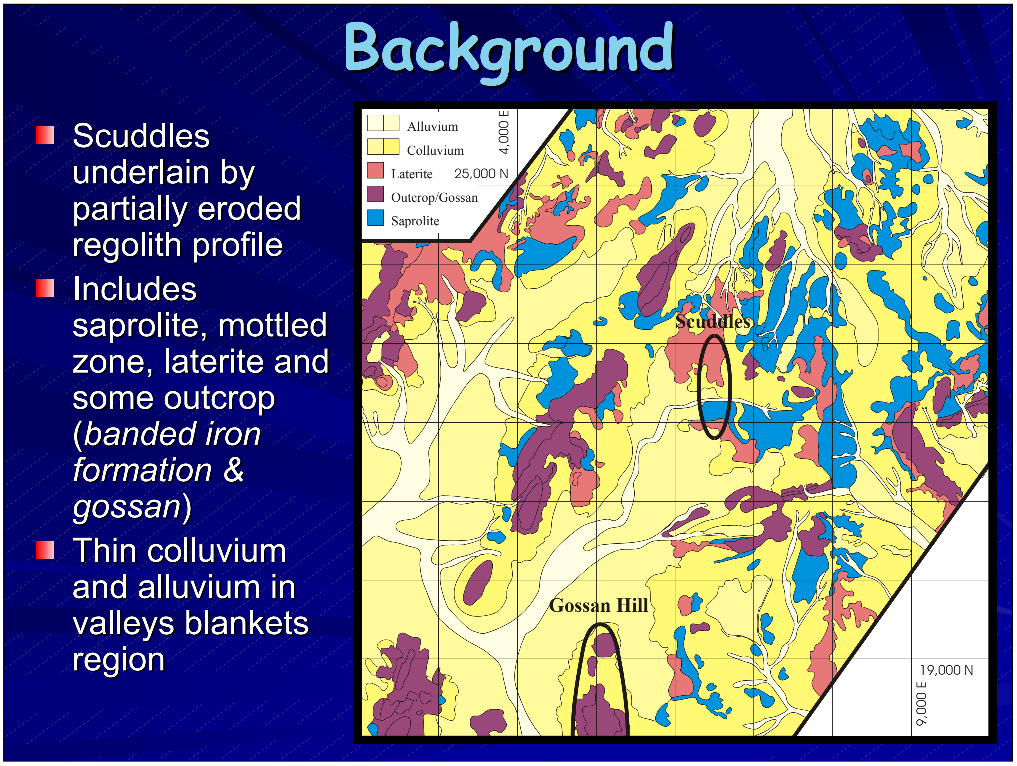


Background

- regolith is 30 to 100 m thick
- partially eroded with minor transported material (colluvium)
- laterite grades downward into kaolinitic zone, then into saprolite
- saprolite has both oxidized and reduced zones because of ‘drying out’ of profile over time

Regolith covers the mining camp, and ranges from 30 to 100 m thick.

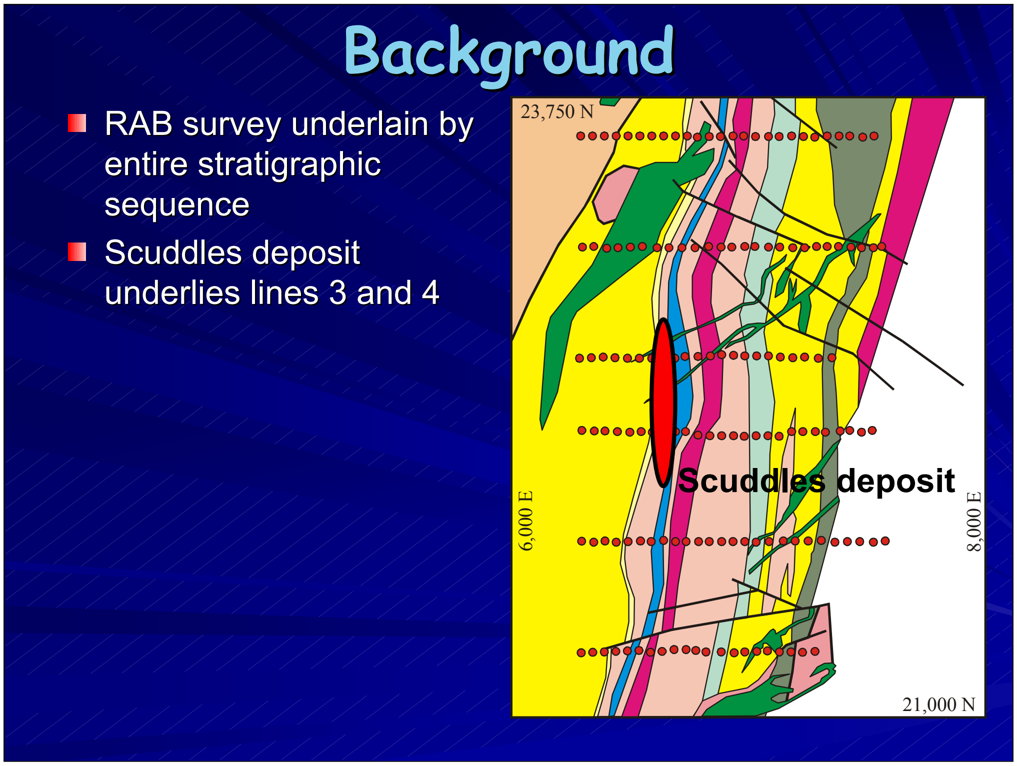
The regolith is partially eroded, and can exhibit laterite at the top, mottled and pallid saprolite zones, with oxidized and reduced saprolite zones at depth.



Background

- Scuddles underlain by partially eroded regolith profile
- Includes saprolite, mottled zone, laterite and some outcrop (*banded iron formation & gossan*)
- Thin colluvium and alluvium in valleys blankets region

Both Scuddles and Golden Grove deposits occur in areas with partially eroded regolith profiles. As a result, most regolith samples are from mottled zone or underlying saprolite and are not from the overlying laterite.



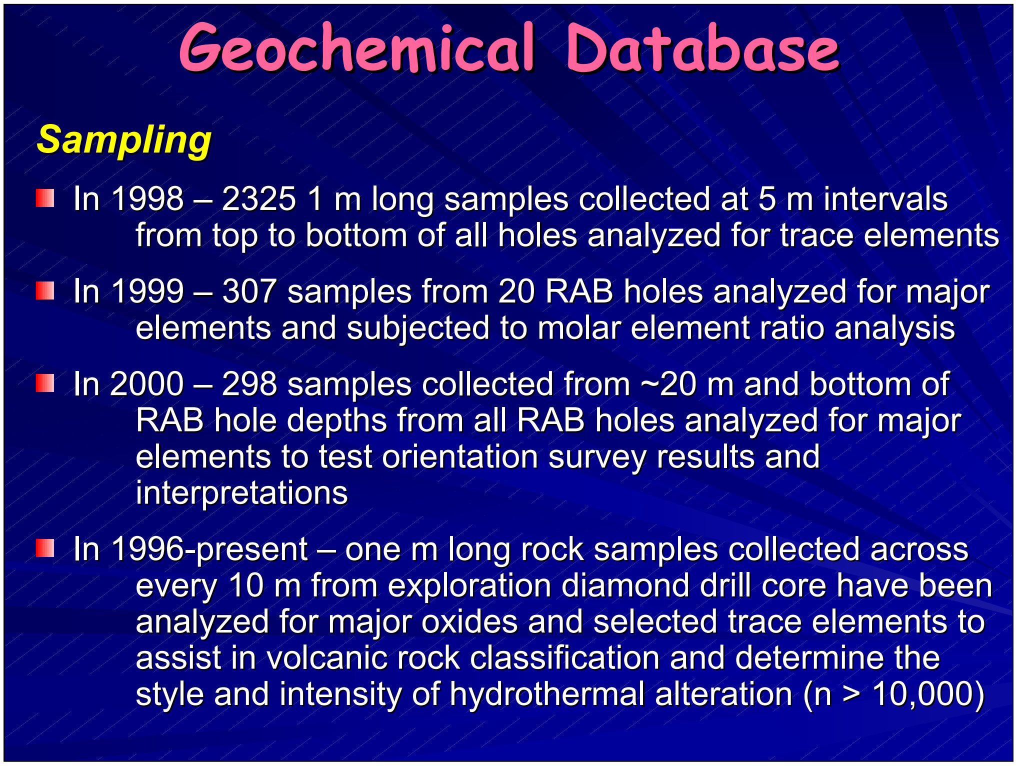
Background

- RAB survey underlain by entire stratigraphic sequence
- Scuddles deposit underlies lines 3 and 4

In 1998, a rotary air blast hole orientation survey was undertaken over the Scuddles deposit to determine the geochemical expression of the deposit in the regolith.

The survey consisted of 147 RAB holes on 6 lines that crossed the bulk of the camp’s volcano-sedimentary stratigraphy. These holes averaged 67 m deep.

The Scuddles deposit underlies lines 3 and 4.



Geochemical Database

Sampling

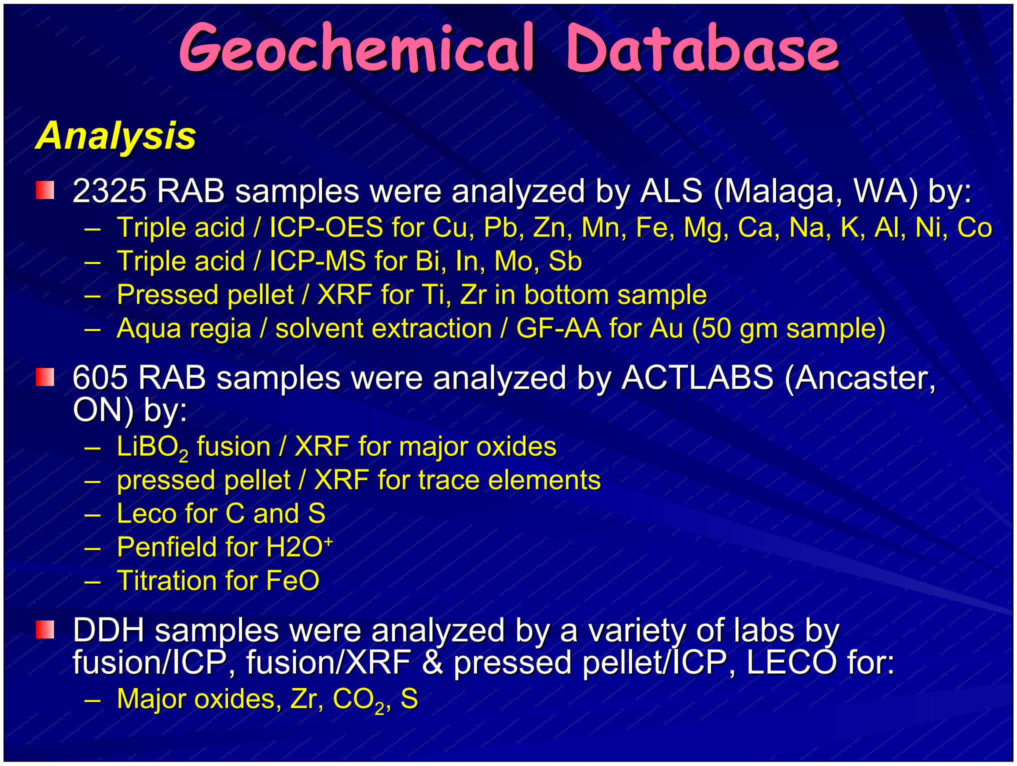
- In 1998 – 2325 1 m long samples collected at 5 m intervals from top to bottom of all holes analyzed for trace elements
- In 1999 – 307 samples from 20 RAB holes analyzed for major elements and subjected to molar element ratio analysis
- In 2000 – 298 samples collected from ~20 m and bottom of RAB hole depths from all RAB holes analyzed for major elements to test orientation survey results and interpretations
- In 1996-present – one m long rock samples collected across every 10 m from exploration diamond drill core have been analyzed for major oxides and selected trace elements to assist in volcanic rock classification and determine the style and intensity of hydrothermal alteration (n > 10,000)

2325 one meter long samples were collected every 5 meters in each hole and analyzed for trace elements.

In the following year, 307 samples were collected from 20 holes, analyzed for major oxides and evaluated using molar element ratio analysis.

After this major element orientation survey was completed, an additional 298 samples were analyzed for major elements to test its results.

Finally, over the past 7 years, an ongoing lithogeochemistry program has resulted in over 10,000 major and selected trace element analyses that have assisted in volcanic rock classification and determination of the style and intensity of hydrothermal alteration in un-weathered rocks.



Geochemical Database

Analysis

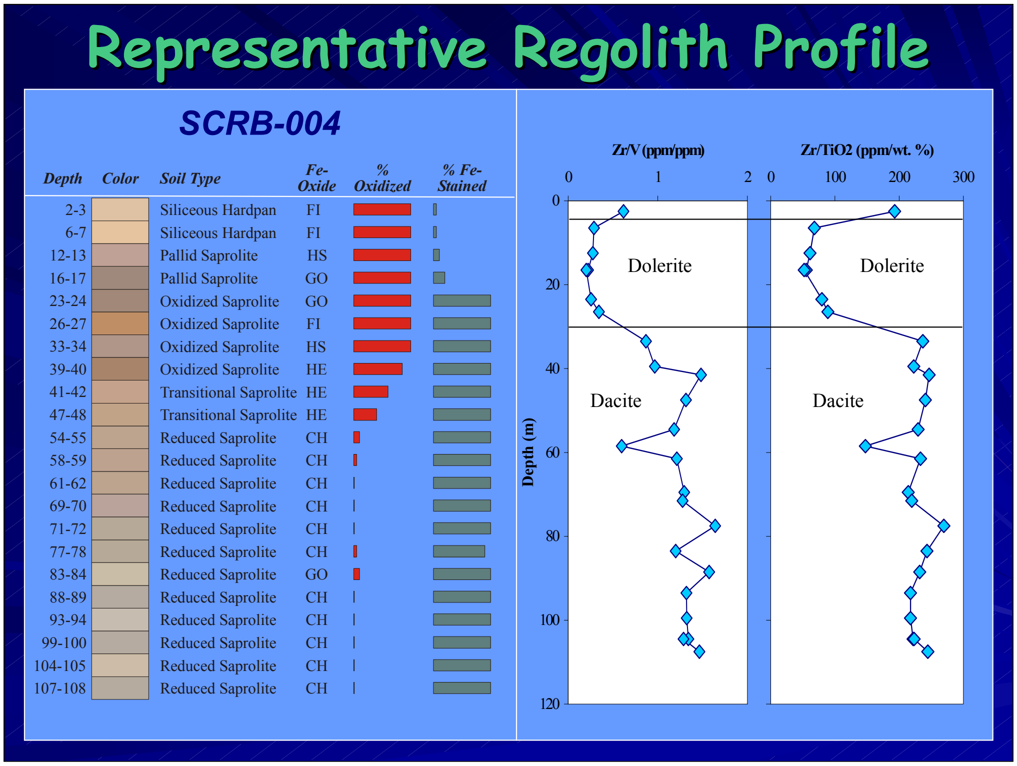
- 2325 RAB samples were analyzed by ALS (Malaga, WA) by:
  - Triple acid / ICP-OES for Cu, Pb, Zn, Mn, Fe, Mg, Ca, Na, K, Al, Ni, Co
  - Triple acid / ICP-MS for Bi, In, Mo, Sb
  - Pressed pellet / XRF for Ti, Zr in bottom sample
  - Aqua regia / solvent extraction / GF-AA for Au (50 gm sample)
- 605 RAB samples were analyzed by ACTLABS (Ancaster, ON) by:
  - $LiBO_2$ fusion / XRF for major oxides
  - pressed pellet / XRF for trace elements
  - Leco for C and S
  - Penfield for $H2O^+$
  - Titration for FeO
- DDH samples were analyzed by a variety of labs by fusion/ICP, fusion/XRF & pressed pellet/ICP, LECO for:
  - Major oxides, Zr, CO_2, S

For regolith samples, trace elements were analyzed using a triple acid / ICP-OES and ICP-MS regimen, plus gold by aqua regia and Ti and Zr by pressed pellet XRF.

For regolith samples, the major elements were analyzes by a lithium metaborate fusion and pressed pellet / XRF procedure, C and S were analyzed by Leco, H_2O^+ by Penfield and FeO by titration.

Rock samples were analyzed by total methods for major oxides, selected trace elements, C and S.

Quality controls results indicate good sampling and analytical quality.



Representative Regolith Profile

SCRB-004

Depth	Color	Soil Type	Fe-Oxide	% Oxidized	% Fe-Stained
2-3	■	Siliceous Hardpan	FI	🟥	▮
6-7	■	Siliceous Hardpan	FI	🟥	▮
12-13	■	Pallid Saprolite	HS	🟥	▮
16-17	■	Pallid Saprolite	GO	🟥	▮
23-24	■	Oxidized Saprolite	GO	🟥	▮
26-27	■	Oxidized Saprolite	FI	🟥	▮
33-34	■	Oxidized Saprolite	HS	🟥	▮
39-40	■	Oxidized Saprolite	HE	🟥	▮
41-42	■	Transitional Saprolite	HE	🟥	▮
47-48	■	Transitional Saprolite	HE	🟥	▮
54-55	■	Reduced Saprolite	CH	🟥	▮
58-59	■	Reduced Saprolite	CH	🟥	▮
61-62	■	Reduced Saprolite	CH	▮	▮
69-70	■	Reduced Saprolite	CH	▮	▮
71-72	■	Reduced Saprolite	CH	▮	▮
77-78	■	Reduced Saprolite	CH	🟥	▮
83-84	■	Reduced Saprolite	GO	🟥	▮
88-89	■	Reduced Saprolite	CH	▮	▮
93-94	■	Reduced Saprolite	CH	▮	▮
99-100	■	Reduced Saprolite	CH	▮	▮
104-105	■	Reduced Saprolite	CH	▮	▮
107-108	■	Reduced Saprolite	CH	▮	▮

Chip logging of the 20 RAB hole samples analyzed for major oxides was undertaken to identify the zone from which each sample was derived.

This relatively complete and representative hole illustrates the diversity of regolith material within the RAB holes.

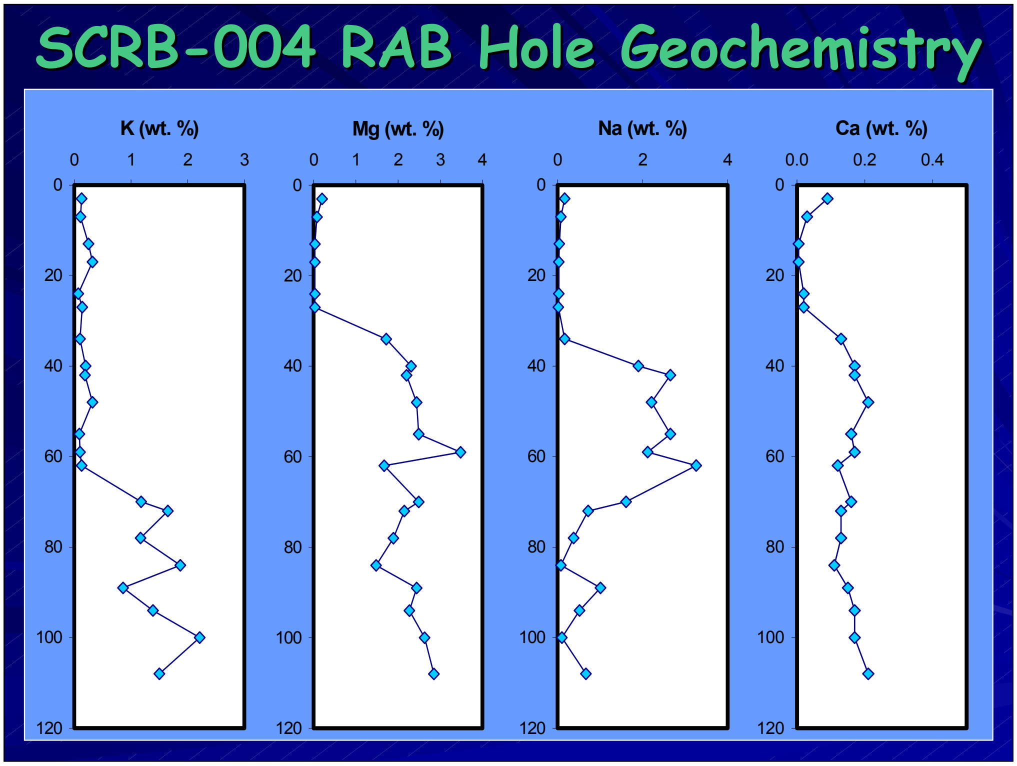
Sample powder colors were logged using a Munsell color chart, converted to CMYK colors on the computer, and are presented here in their true colors.

Based on these colors, the type of Fe-oxy-hydroxide mineral predominantly responsible for the observed color (including ferrihydroxide, goethite, specular and earthy hematite, jarosite and chlorite) was determined using the Kennecott Copper Company supergene Cu porphyry color scheme.

Percentage estimation of chip Fe-oxidation extent and Fe-mineral coloration were also made.

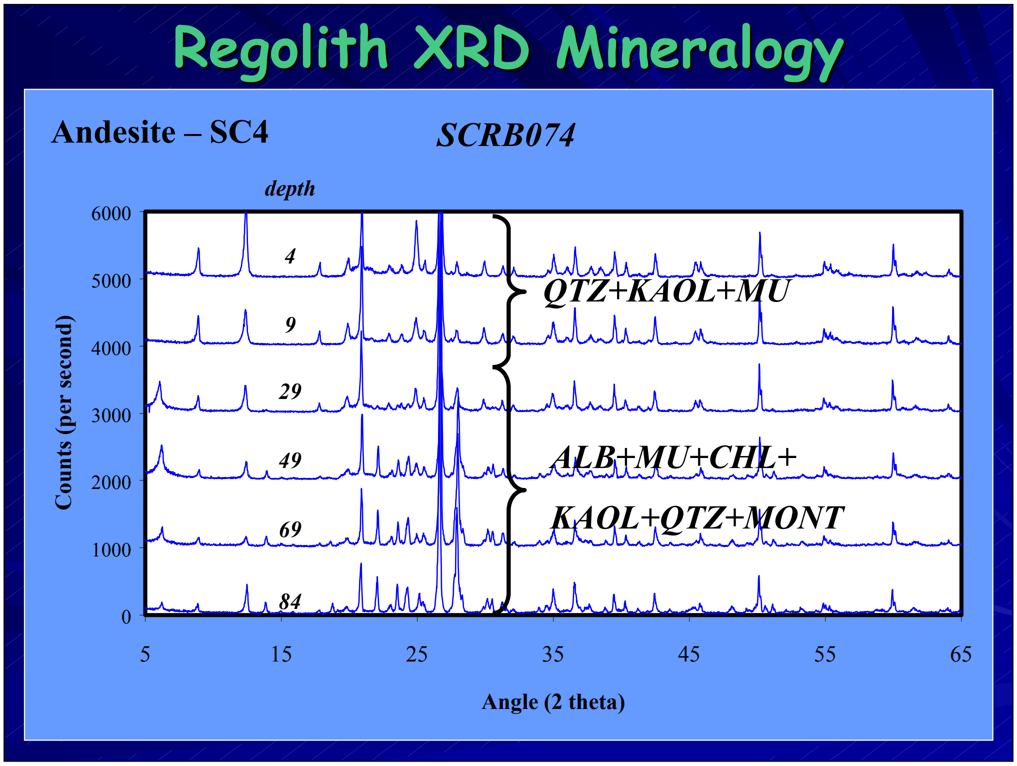
Downhole trace element geochemistry was plotted to assist in lithology identification.

The conserved element ratios of regolith samples indicate that two igneous rock compositions exist in this hole (dolerite and dacite).



SCRB-004 RAB Hole Geochemistry

Initial results also indicate that many major elements are retained in the regolith profile, indicating that many primary igneous, sedimentary and hydrothermal minerals may be meta-stable in at least the lower parts of the soil.

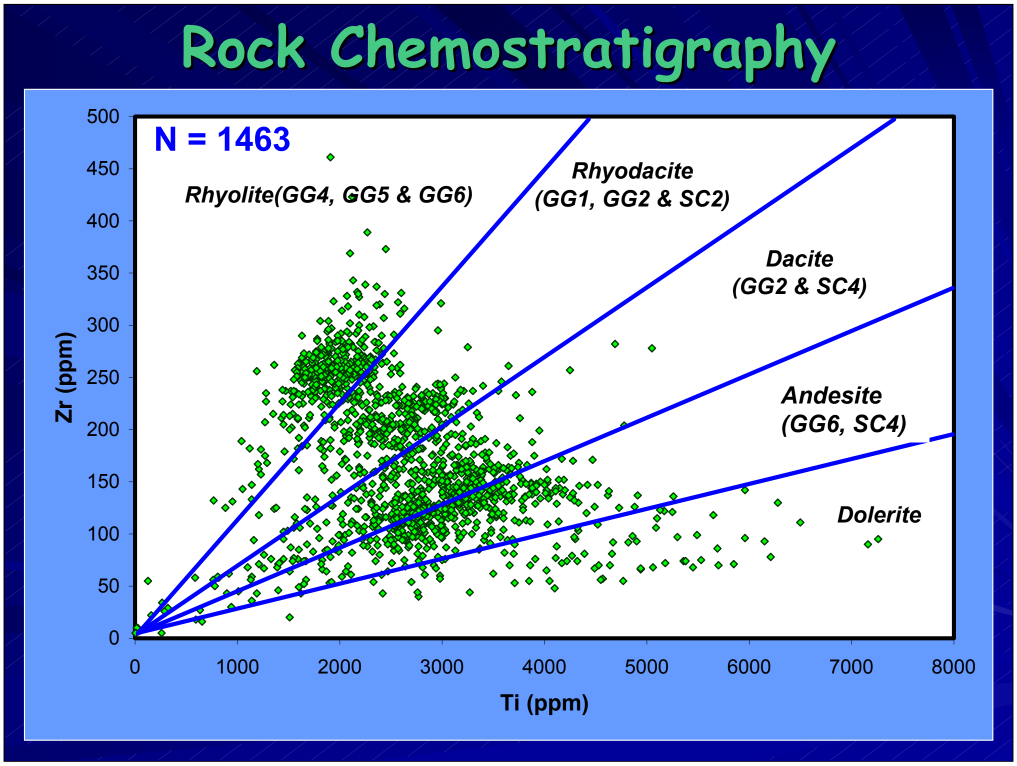


Regolith XRD Mineralogy

X-ray diffraction was undertaken on samples from RAB holes containing only one volcanic composition (based on constant conserved element ratios).

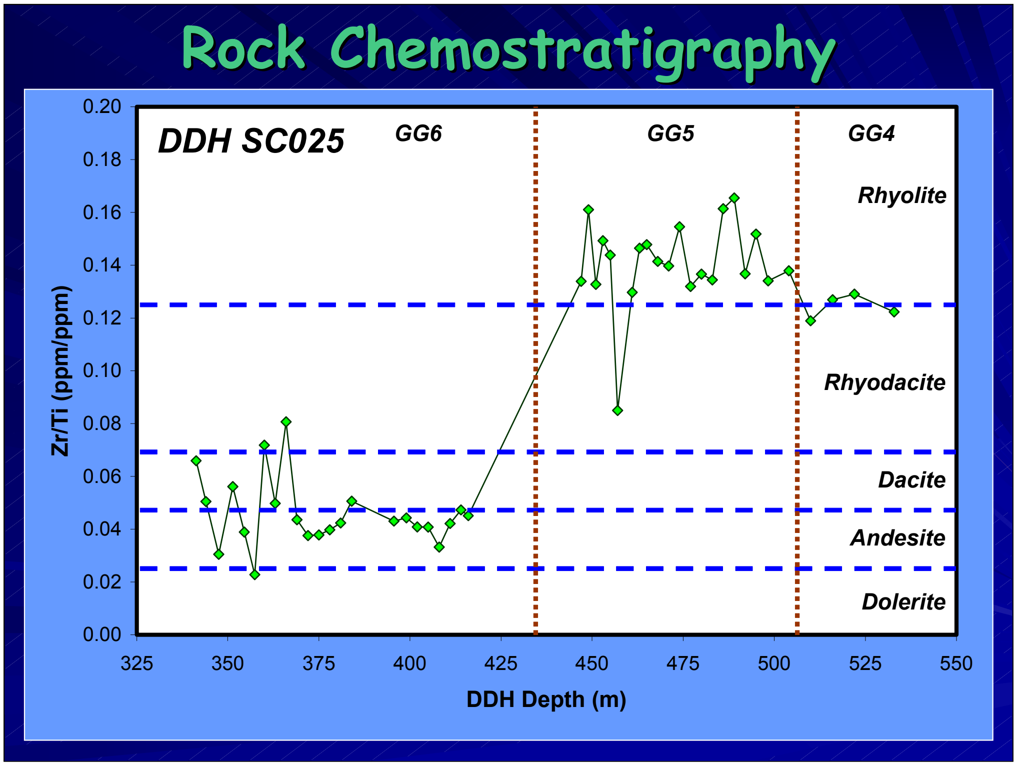
These results indicate that feldspar, muscovite, chlorite and quartz are present in the reduced and oxidized saprolite, but that only muscovite survives in the laterite, mottled zone and pallid saprolite.

The principle phyllosilicate mineral formed in the regolith is kaolinite, and montmorillonite is highly subordinate, probably because of the largely felsic composition of the rocks and the metastability of chlorite in the lower part of the regolith.



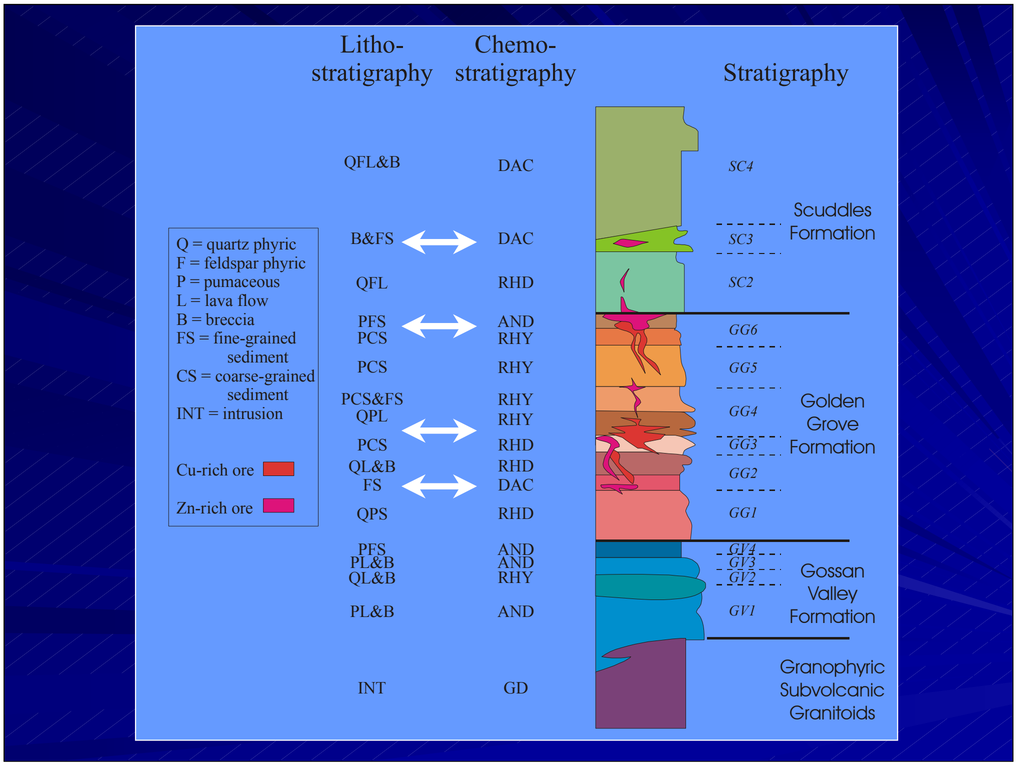
Rock Chemostratigraphy

In the underlying bedrock, conserved element ratios, such as Zr/Ti, can be used to identify the volcanic composition.



Rock Chemostratigraphy

These conserved element ratios assist in logging of drill core, and are particularly valuable when syn-volcanic dykes and faults disrupt the stratigraphy.



Litho-stratigraphy	Chemo-stratigraphy
QFL&B	DAC
B&FS	DAC
QFL	RHD
PFS	AND
PCS	RHY
PCS	RHY
PCS&FS	RHY
QPL	RHY
PCS	RHD
QL&B	RHD
FS	DAC
QPS	RHD
PFS	AND
PL&B	AND
QL&B	RHY
PL&B	AND
INT	GD

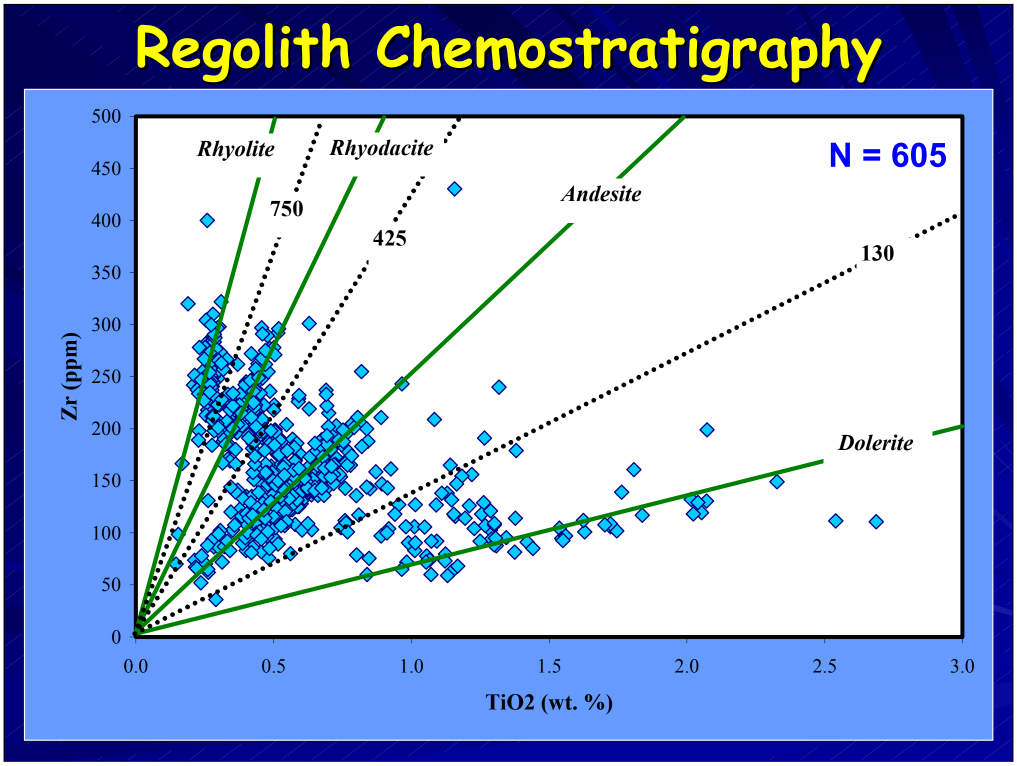
Q = quartz phyric
F = feldspar phyric
P = pumaceous
L = lava flow
B = breccia
FS = fine-grained sediment
CS = coarse-grained sediment
INT = intrusion

Cu-rich ore 🟥
Zn-rich ore 🟥

The chemostratigraphy developed at Golden Grove did not exactly correlate with earlier understandings of the stratigraphy; these inconsistencies have since been resolved, leading to a new understanding of the lithostratigraphy of the camp.

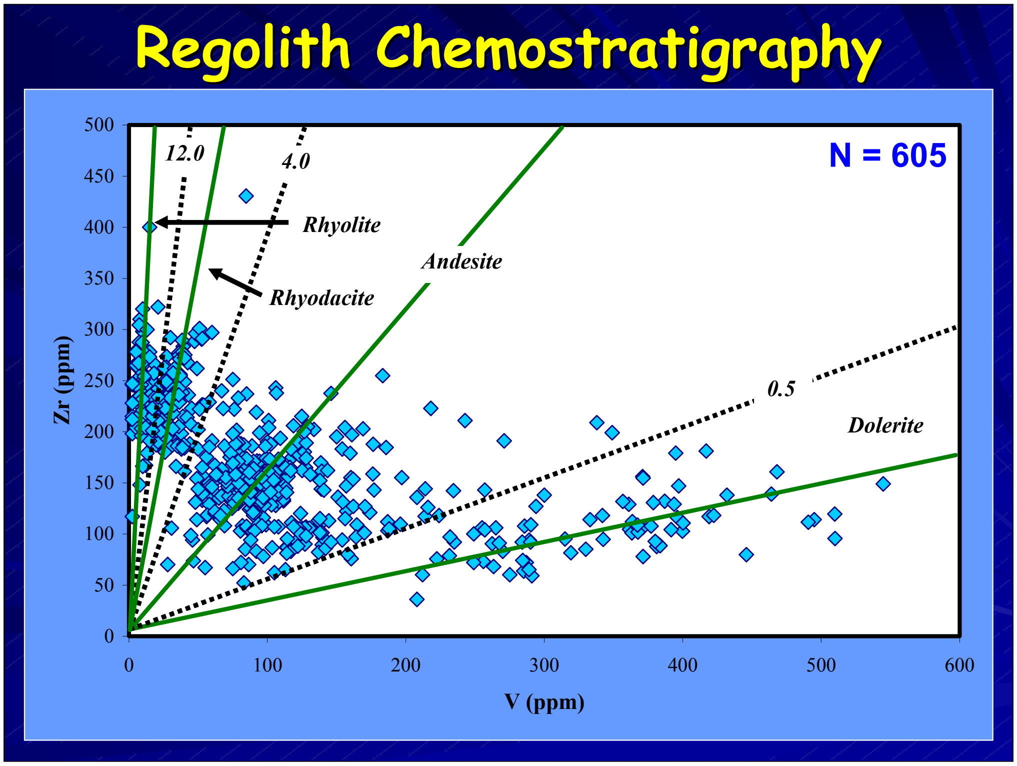
This new understanding has led to the recognition of four productive stratigraphic levels, instead of one, and is significantly assisting exploration for additional deposits within the camp.

If similar chemostratigraphic information can be derived from the regolith, additional exploration advantage can be achieved.



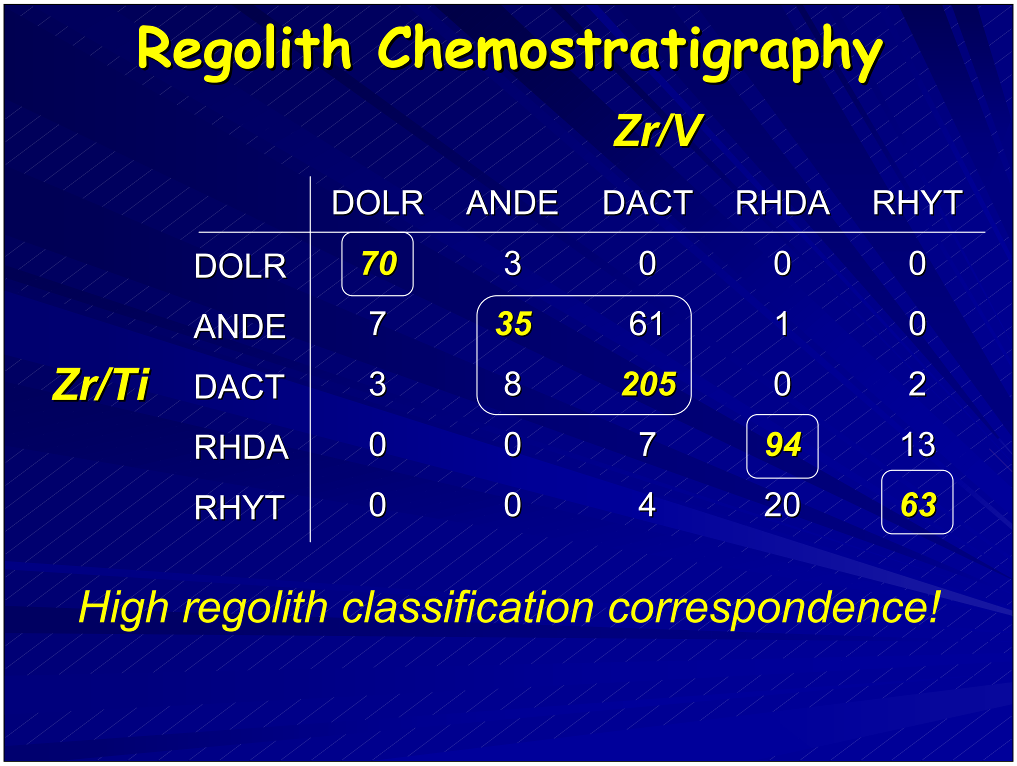
Conserved elements from regolith samples do allow a similar volcanic composition classification.

Zr/Ti ratios are very effective classifiers of the rock, even in the upper levels of the regolith.



Regolith Chemostratigraphy

In addition, Zr/V ratios also provide insight into the volcanic compositions.



Regolith Chemostratigraphy

Zr/V

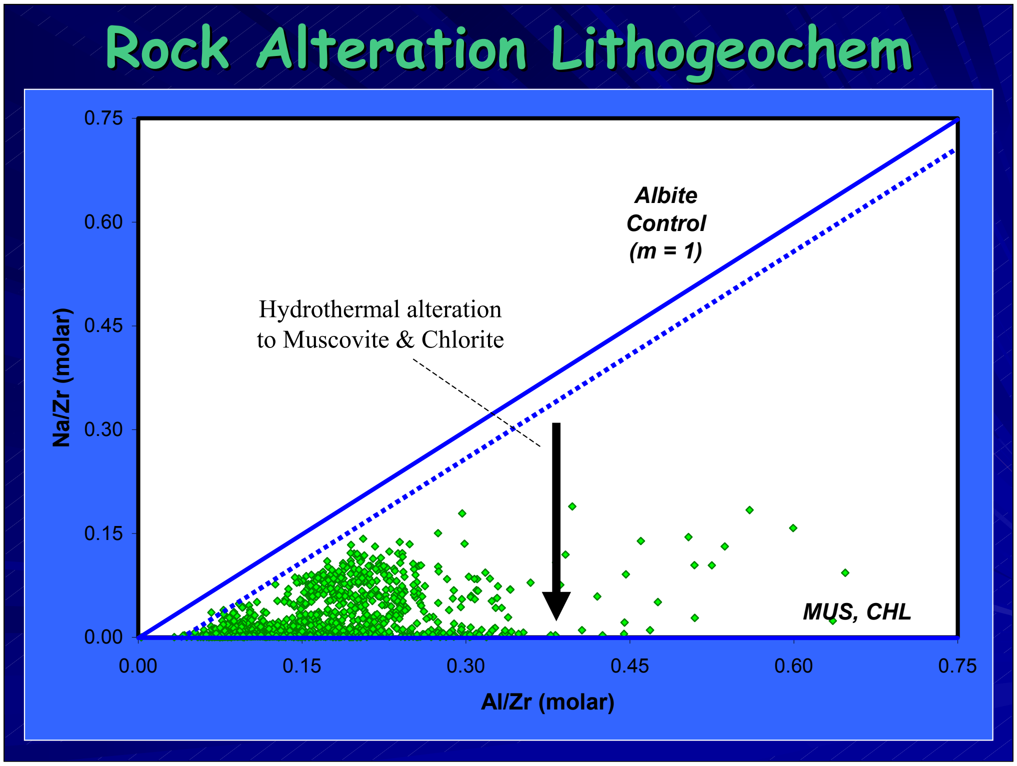
		DOLR	ANDE	DACT	RHDA	RHYT
	DOLR	***70***	3	0	0	0
	ANDE	7	***35***	61	1	0
Zr/Ti	DACT	3	8	***205***	0	2
	RHDA	0	0	7	***94***	13
	RHYT	0	0	4	20	***63***

High regolith classification correspondence!

In fact, these two conserved element ratios produce volcanic rock classifications that are highly consistent, with few samples classified differently by the two ratios.

With the recognition of conserved elements in the regolith dataset, Pearce element ratio analysis can be undertaken.

This analysis was directed toward recognizing the controls on the compositional variations observed in the regolith.



Possible processes responsible for these variations include:

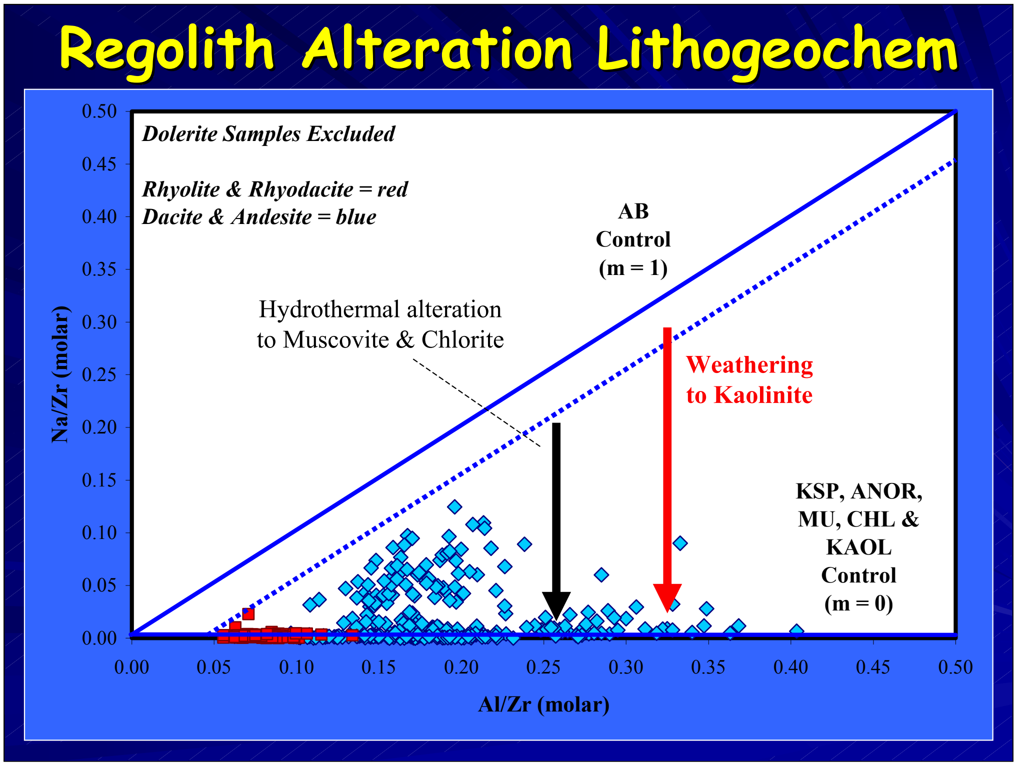
1.) igneous fractionation (of quartz and feldspar phenocrysts),
2.) hydrothermal alteration (of feldspar to muscovite and chlorite), and
3.) weathering (to kaolinite).

On the following PER diagrams, we compare the geochemical patterns observed in the host rocks, with the patterns observed in the regolith.

This PER diagram models the effects of albite fractionation along a line with unit slope in rocks from the Scuddles area.

The upper edge of these data plot along a line with unit slope, confirming at least partial control of the rock compositions by albite sorting.

This indicates that albite is the predominant feldspar composition in the volcano-sedimentary host rocks.



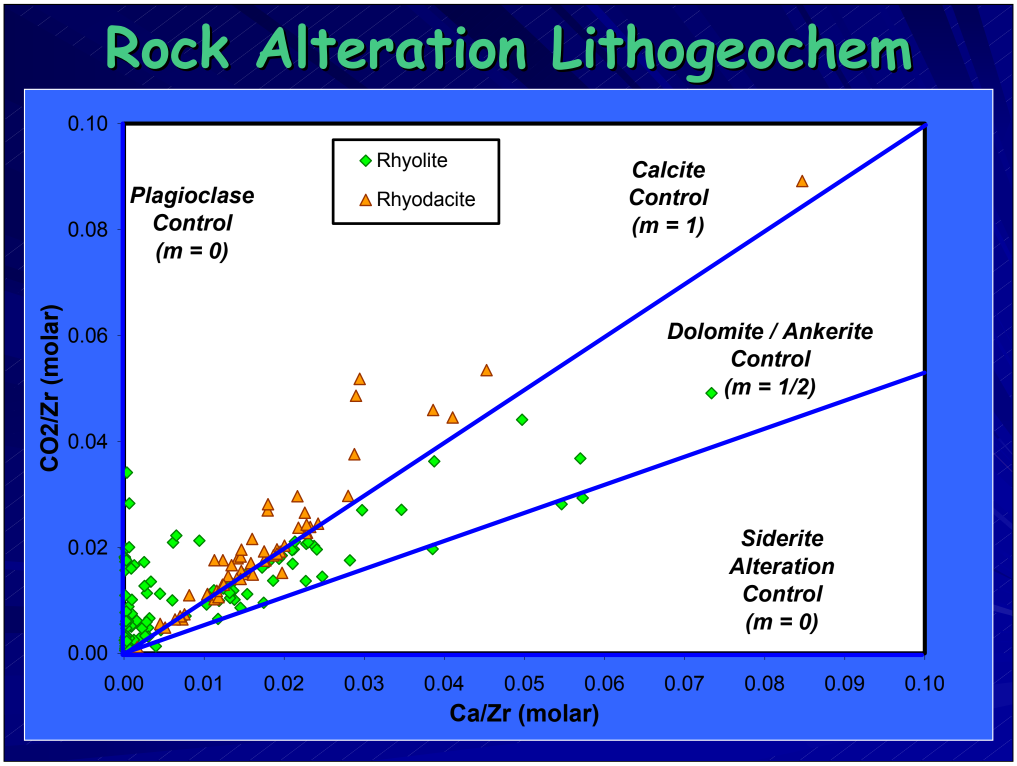
Regolith Alteration Lithogeochem

Regolith samples do not exhibit quite the same behaviour on this PER diagram, as they do not quite plot up to a line with unit slope; however, this is likely due to the effect of hydrolysis that occurred during weathering.

This hydrolysis involves alkali loss, forming kaolinite, and thus displaces rock compositions in the same direction as hydrothermal alteration on this PER diagram.

As a result, it is likely that weathering is responsible for the absence of regolith compositions plotting along a line with unit slope.

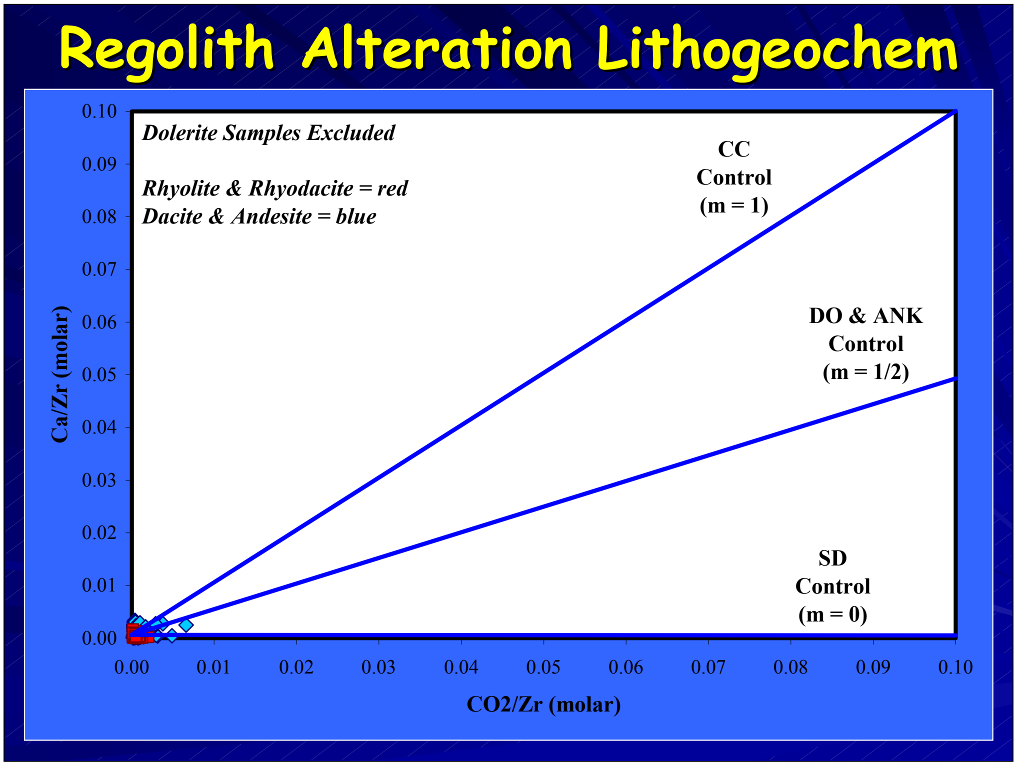
Nevertheless, the similarity between the regolith and underlying bedrock indicates that albite is relatively meta-stable in regolith, a conclusion that is consistent with X-ray diffraction results.



Rock Alteration Lithogeochem

In the underlying host rocks, ankerite is a predominant alteration mineral in rhyolite, whereas calcite is a predominant alteration mineral in the rhyodacites.

The majority of samples plot up to but not right of these corresponding control lines on this PER diagram, confirming these controls.

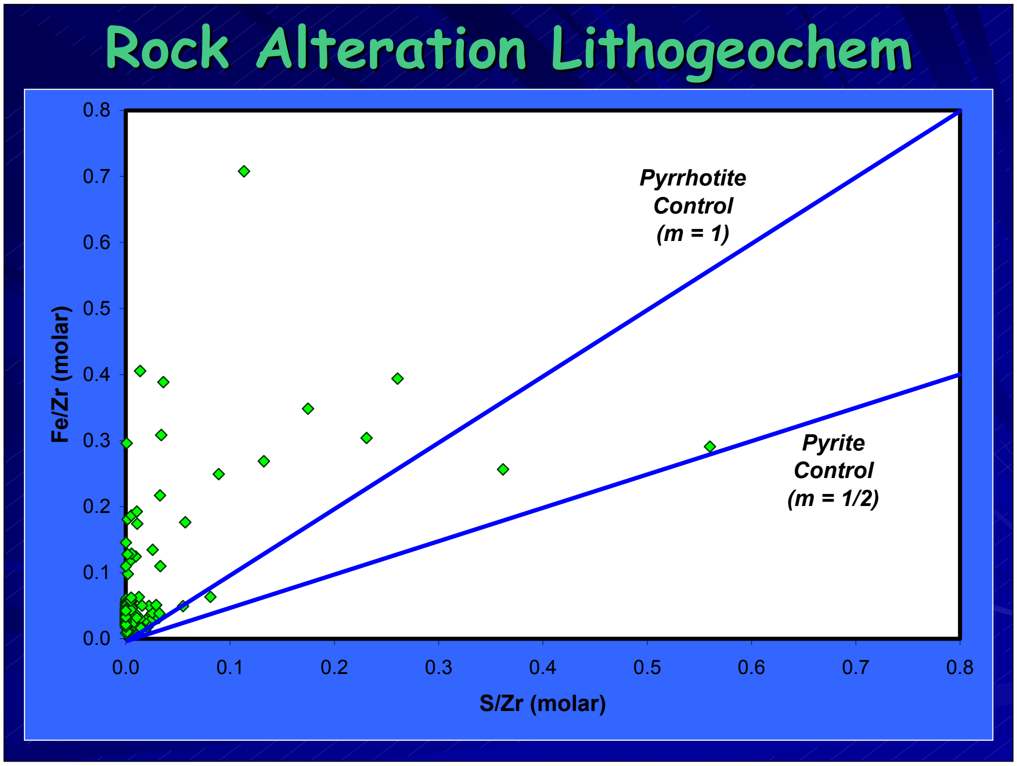


Regolith Alteration Lithogeochem

However, on this identical PER diagram, no evidence of carbonate control is apparent in these regolith samples.

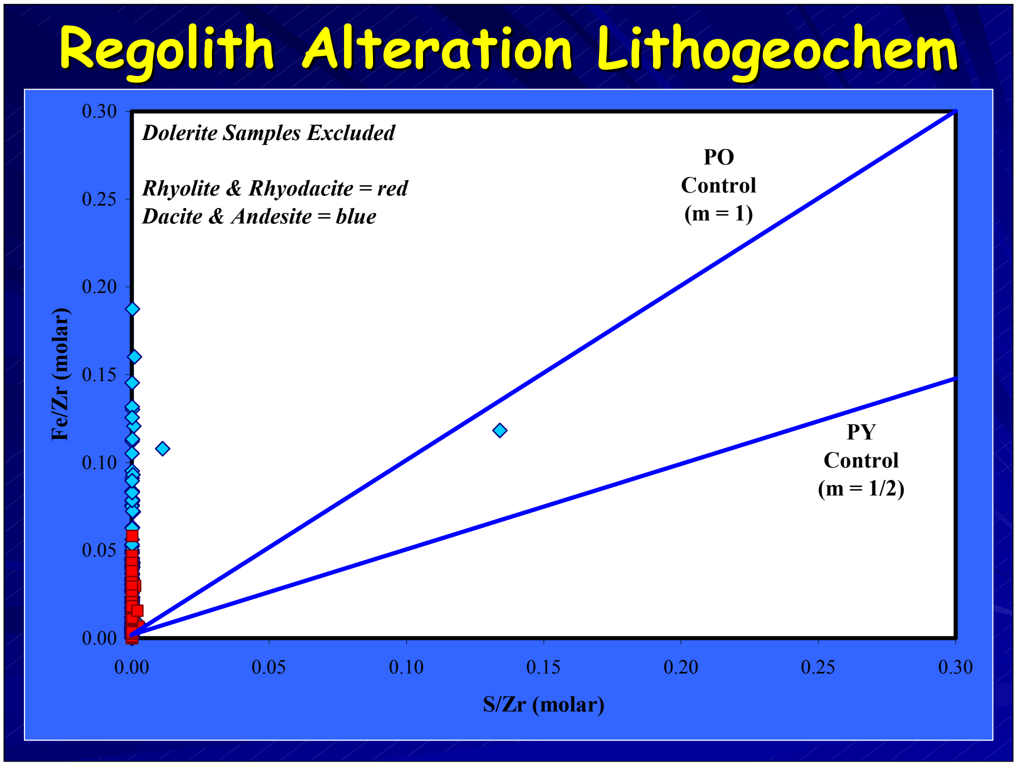
In fact, the regolith contains no Ca or CO_2, because these have been destroyed by weathering processes.

This observation is consistent with the X-ray diffraction results, which did not report the presence of carbonate minerals in the regolith.



Similarly, sulphide minerals occur in the host rocks to the Golden Grove deposits.

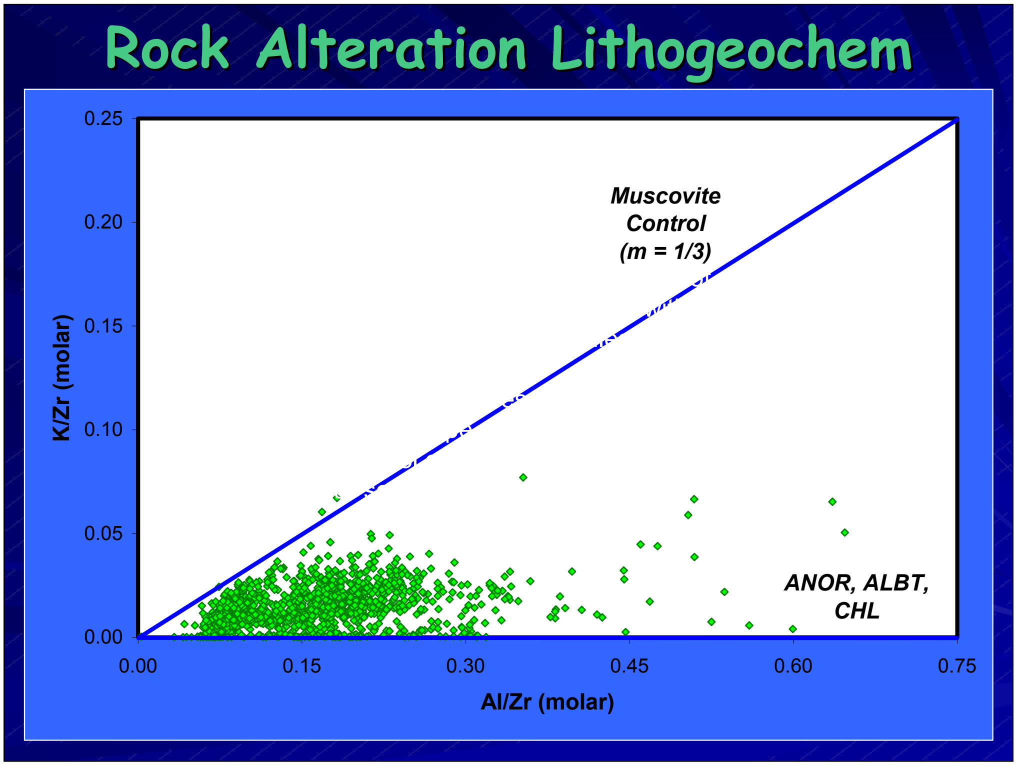
On this PER diagram, samples plot to the left of the pyrite control line, indicating that most rocks contain pyrite plus some other Fe-bearing mineral, in this case chlorite.



The analogous PER diagram exhibits no such pattern, as no regolith samples contain appreciable amounts of S.

This result is also consistent with X-ray diffraction observations, as no sulphide minerals were identified in the regolith, as they were likely destroyed during weathering.

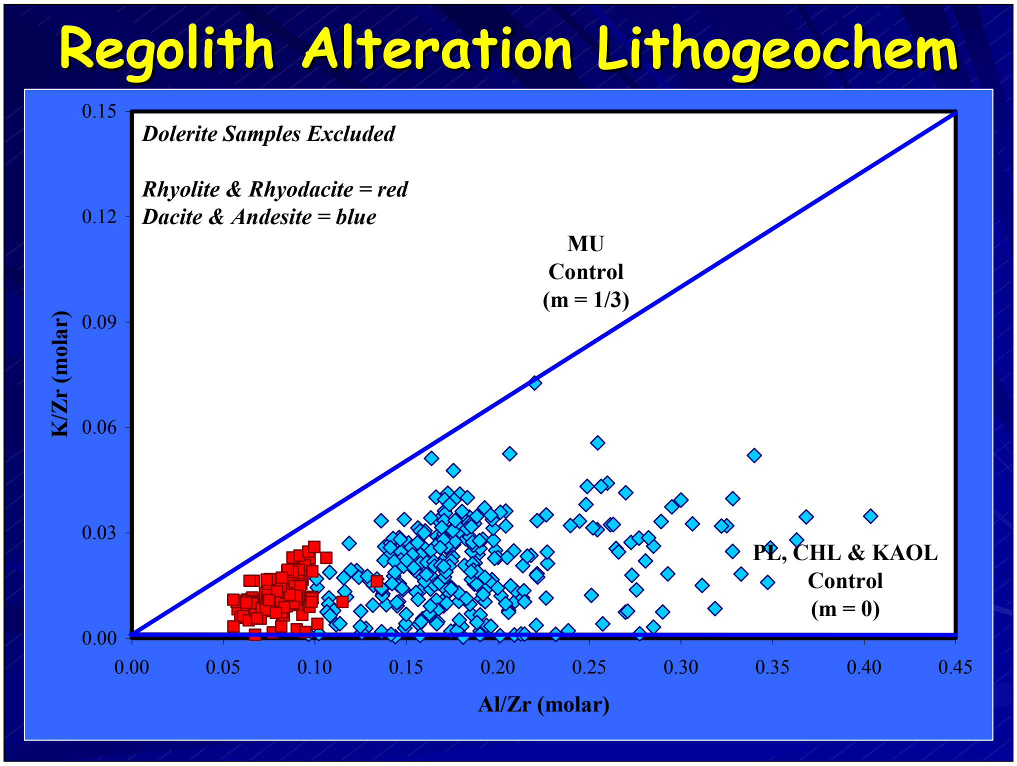
Note that significant Fe/Zr values remain in the regolith, indicating that overall, Fe was not removed by weathering.



Rock Alteration Lithogeochem

This PER diagram investigates and quantifies the extent of muscovite alteration in the underlying rocks from the Scuddles area.

The upper edge of these data plot along a line with slope of 1/3 corresponding to the K/Al ratio of muscovite, and confirming the presence of muscovite as an important alteration mineral near the VHMS deposits.



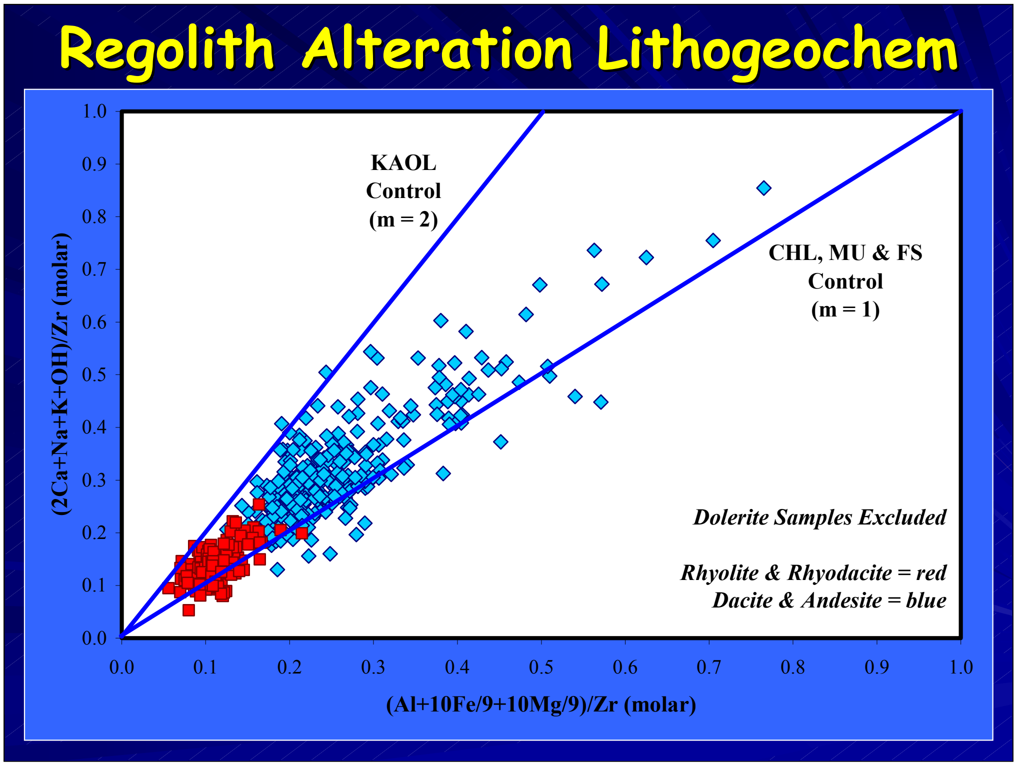
Regolith Alteration Lithogeochem

Dolerite Samples Excluded

Rhyolite & Rhyodacite = red
Dacite & Andesite = blue

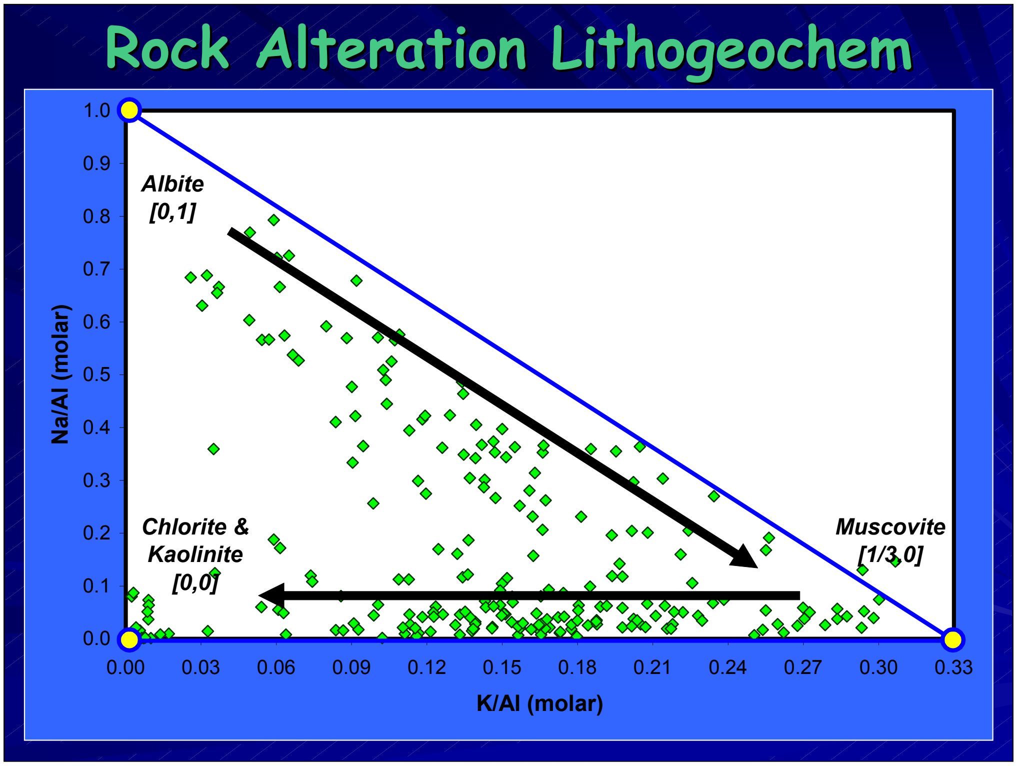
The analogous PER diagram plotting the regolith samples exhibits the same limiting line with slope of 1/3, indicating compositional control by muscovite.

This indicates that muscovite must be relatively meta-stable in the regolith, making the use of K/Al ratios to estimate the intensity of muscovite alteration possible in regolith samples.



Regolith Alteration Lithogeochem

On this PER diagram, weathered kaolinite-bearing samples plot on a line with slope of two, whereas fresh and hydrothermally altered samples plot along a line with unit slope.

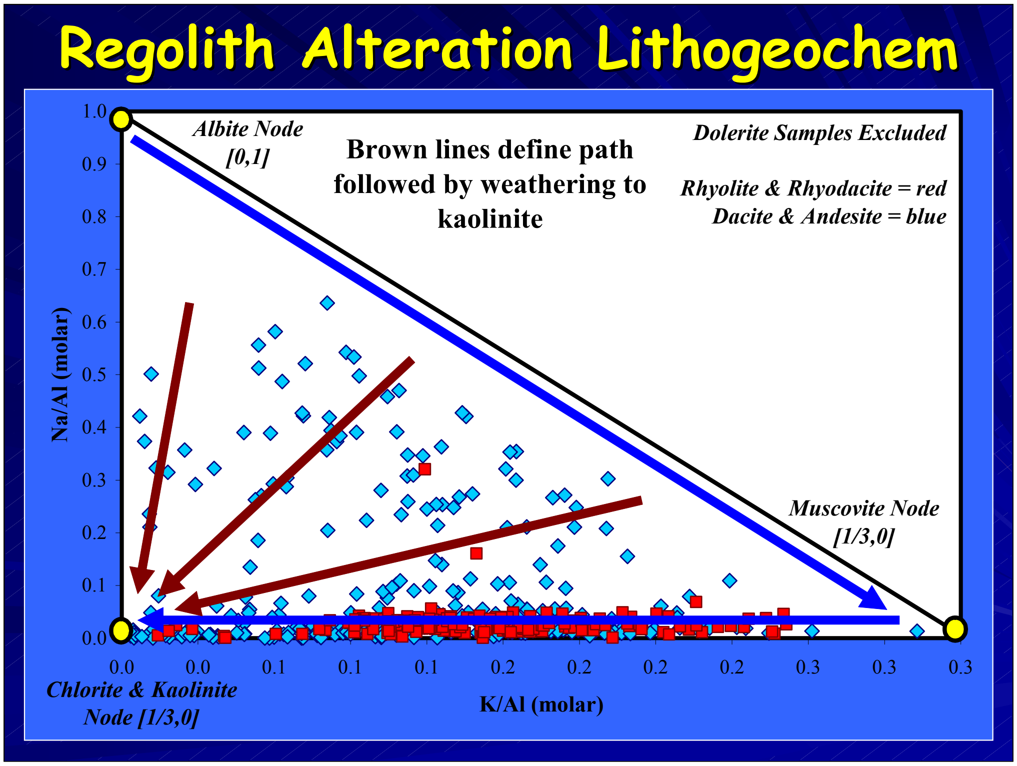


Rock Alteration Lithogeochem

Molar element ratio diagrams that contain a non-conserved element in the denominator can also be designed to illustrate the effects of alteration and weathering.

Al has been used as the denominator of these ratios to create a diagram on which the compositions of albite, muscovite, chlorite and kaolinite plot.

Rock samples plot on two trends, one corresponding to muscovite alteration of albite, and one corresponding to chlorite alteration of muscovite.



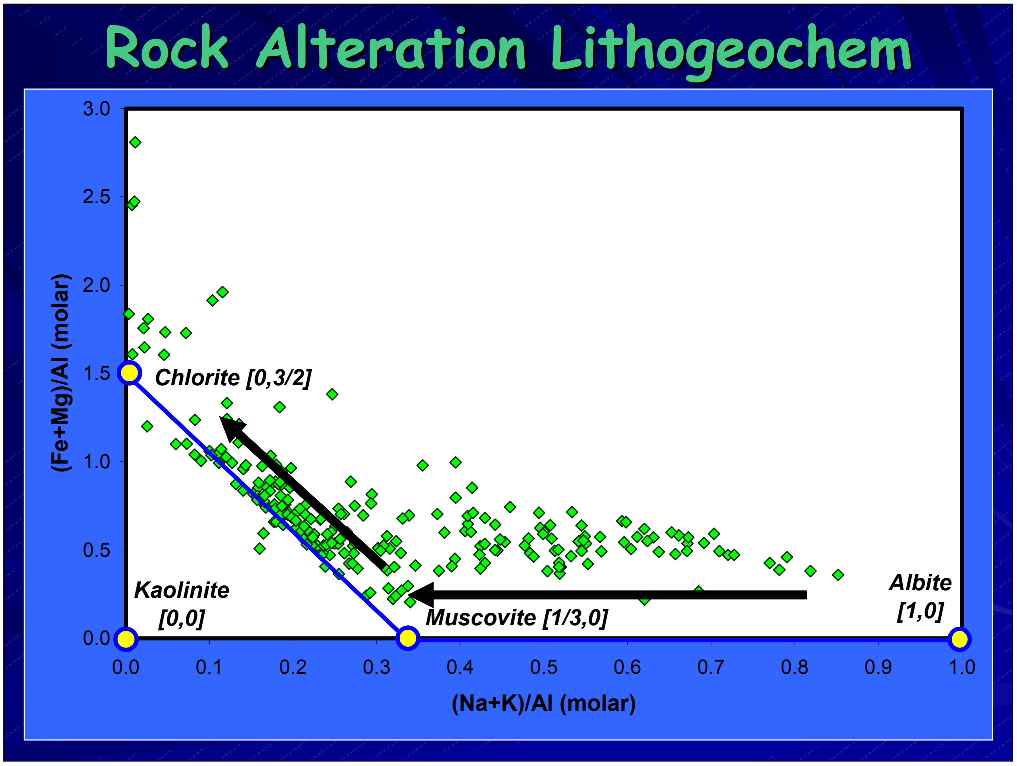
Regolith Alteration Lithogeochem

Brown lines define path followed by weathering to kaolinite

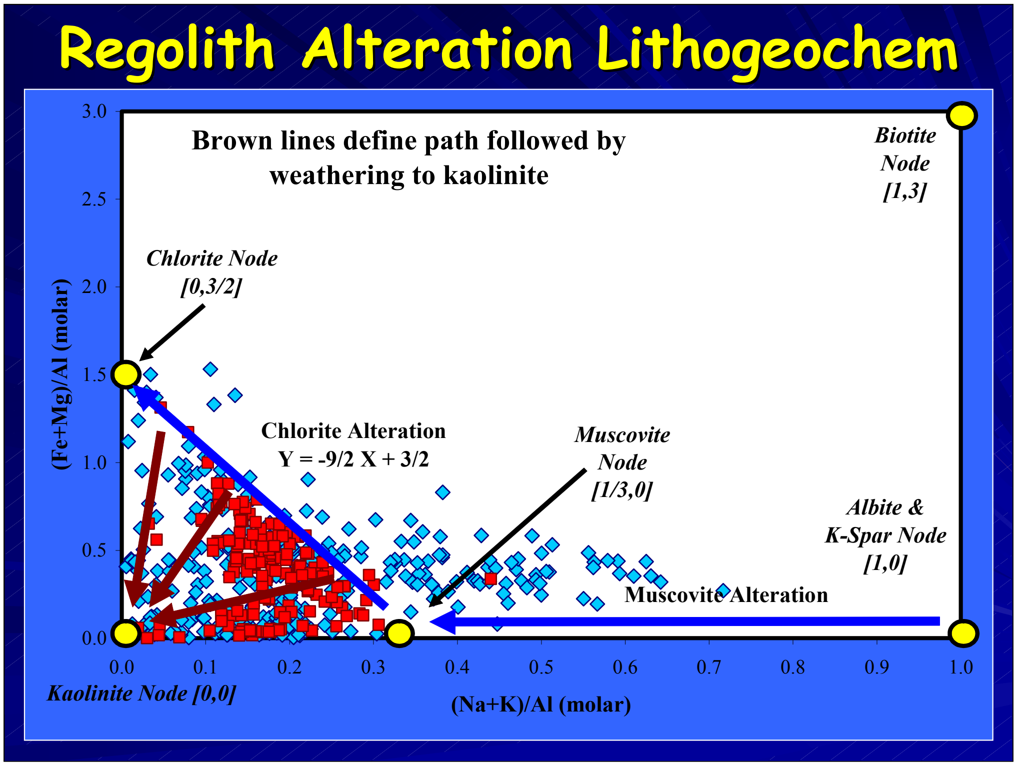
Dolerite Samples Excluded

Rhyolite & Rhyodacite = red
Dacite & Andesite = blue

In the regolith, these two trends are not evident. This is likely because weathering of albite and, to a lesser extent, muscovite have displaced the rocks compositions on this diagram toward the origin as kaolinite was created during weathering.



This MER diagram also exhibits two trends corresponding to muscovite and chlorite alteration in the underlying host rocks.

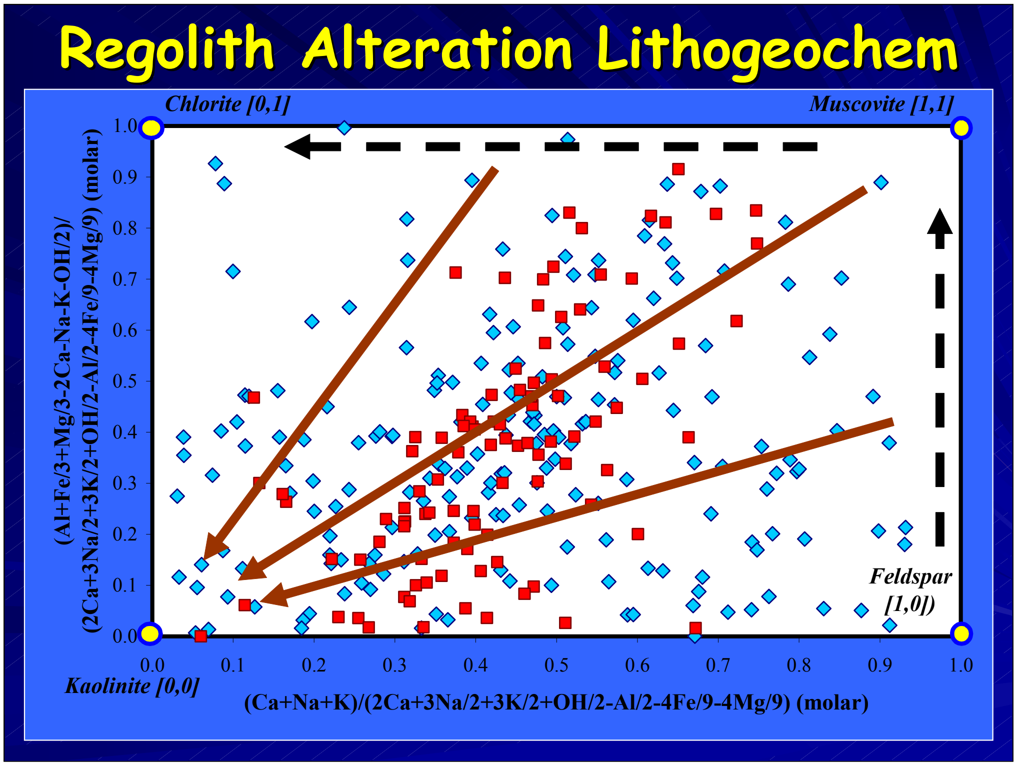


Regolith Alteration Lithogeochem

Brown lines define path followed by weathering to kaolinite

A similar pattern exits on this MER diagram, however, many of the samples are displaced toward the origin.

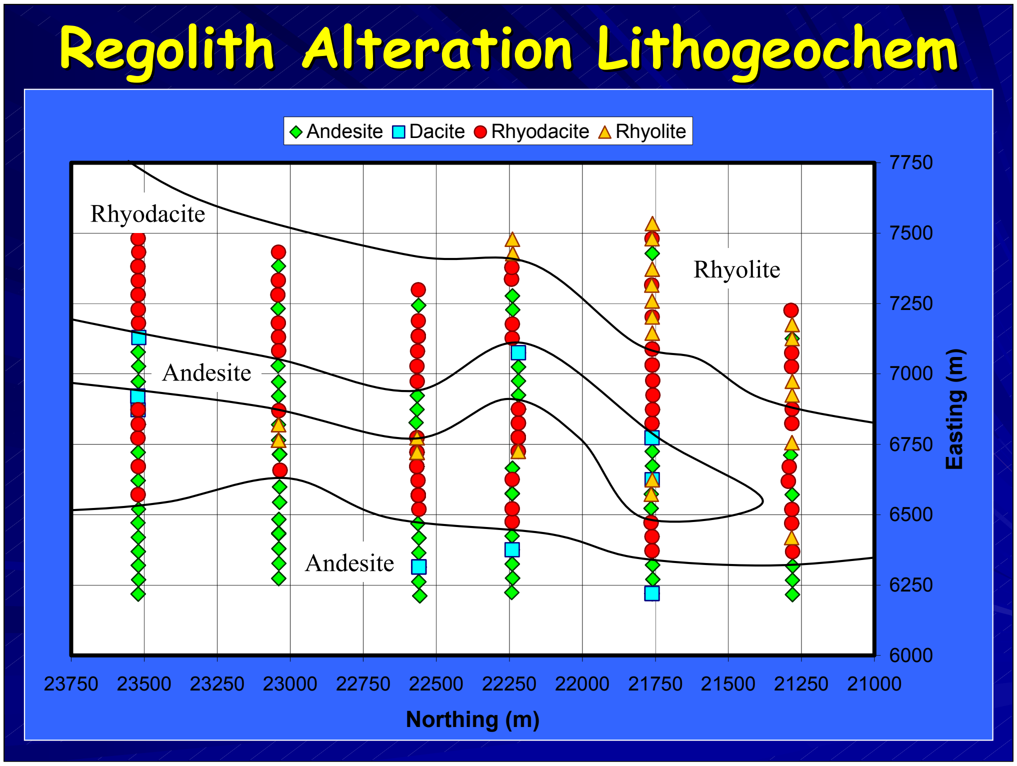
This is also due to the weathering of the primary igneous and secondary alteration minerals into tertiary kaolinite.



Lastly, an MER diagram has been designed that allows identification and quantification of chlorite and muscovite alteration in the host rocks to the Golden Grove deposits. This diagram has complicated numerator and denominator linear combinations of elements, but causes feldspar, muscovite, chlorite and kaolinite compositions to plot at the nodes indicated.

As a result, fresh rocks will plot at the feldspar node. As these fresh rocks become hydrothermally altered to muscovite, their compositions are displaced upward to the muscovite node. As further alteration takes place, their compositions are displaced toward the chlorite node. Finally, as weathering takes place, the rocks compositions are displaced toward the origin.

To determine the style and intensity of hydrothermal alteration in weathered rocks, one must merely project the rock compositions back to the lines joining feldspar, muscovite and chlorite. Mathematically, this may be done by dividing the ordinate numerator by the abscissa numerator.

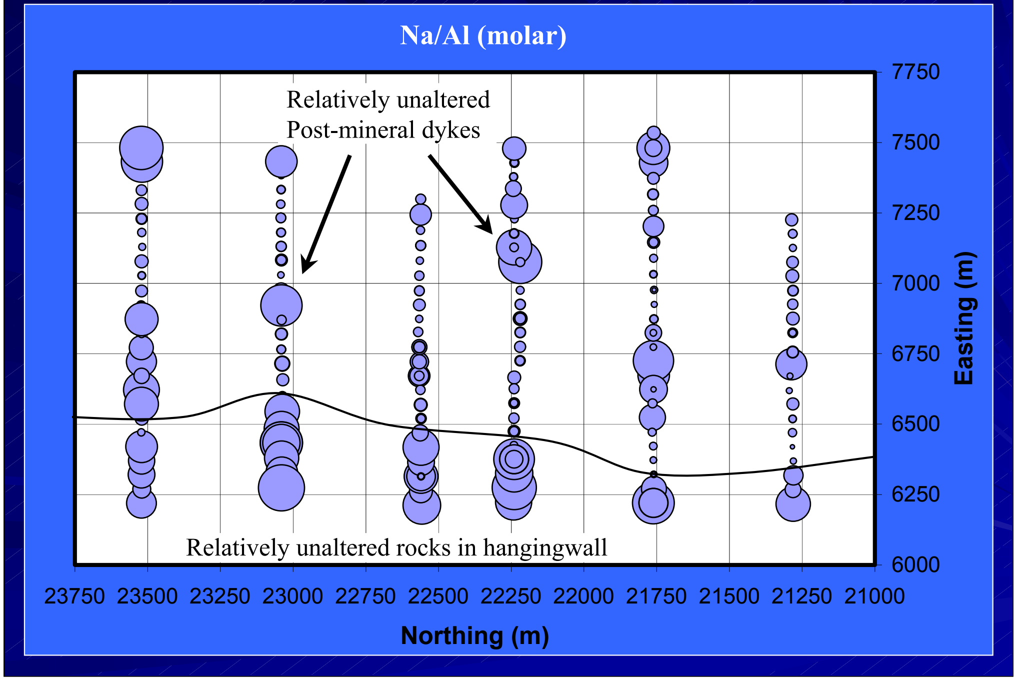


Regolith Alteration Lithogeochem

Classification of regolith samples based on Zr/TiO2 ratios (dolerite excluded) provides insight into the chemostratigraphy of the volcano-sedimentary pile.

Compositional variations allow recognition of individual stratigraphic units.

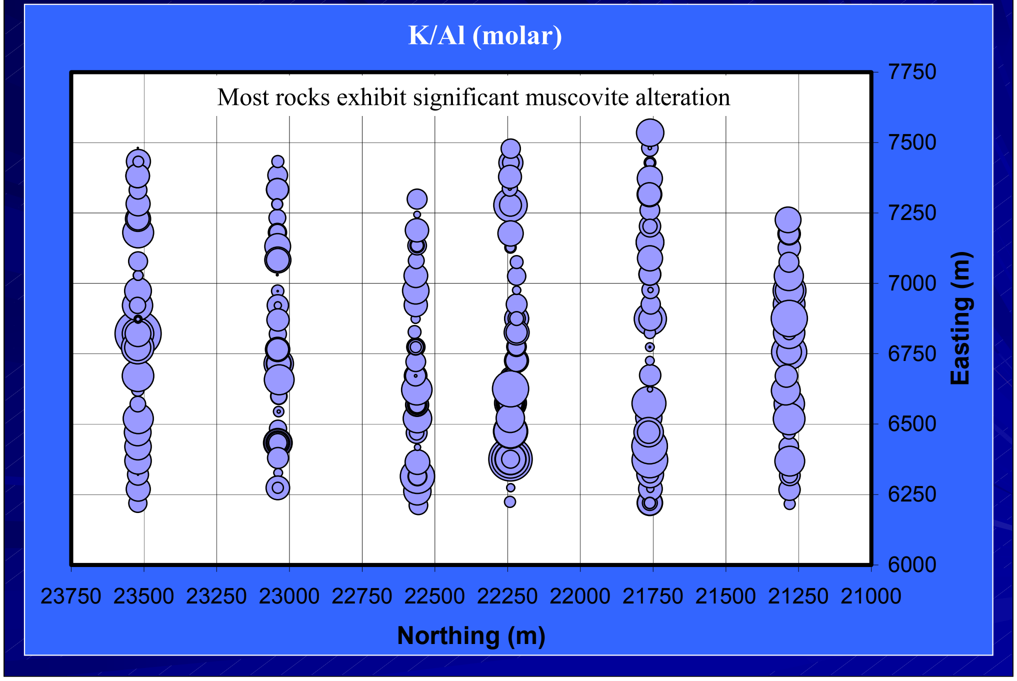
Regolith Alteration Lithogeochem


Na/Al (molar)

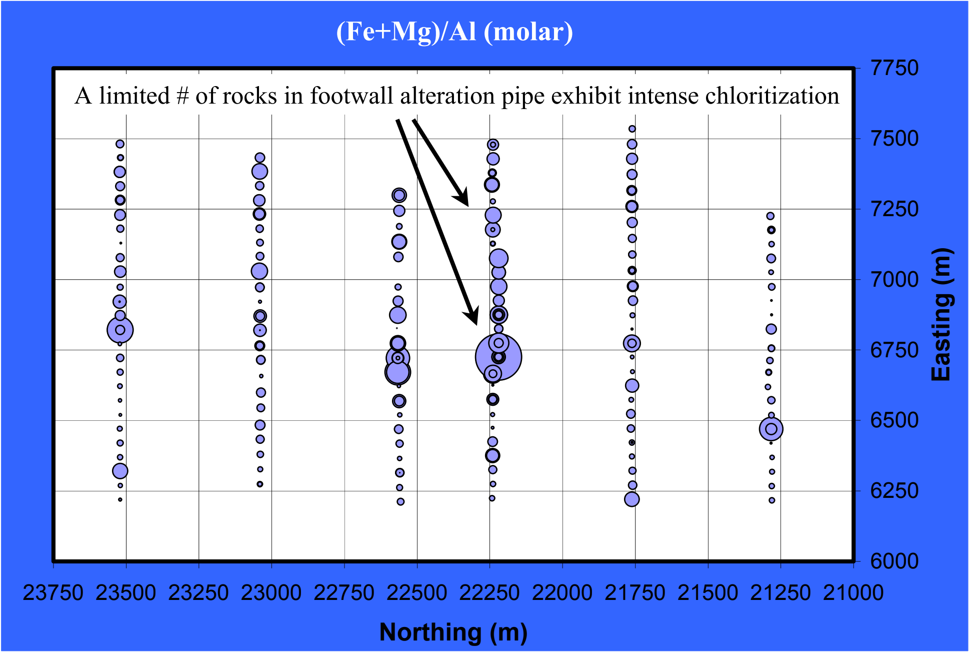
Relatively unaltered
Post-mineral dykes

Relatively unaltered rocks in hangingwall

Regolith Alteration Lithogeochem

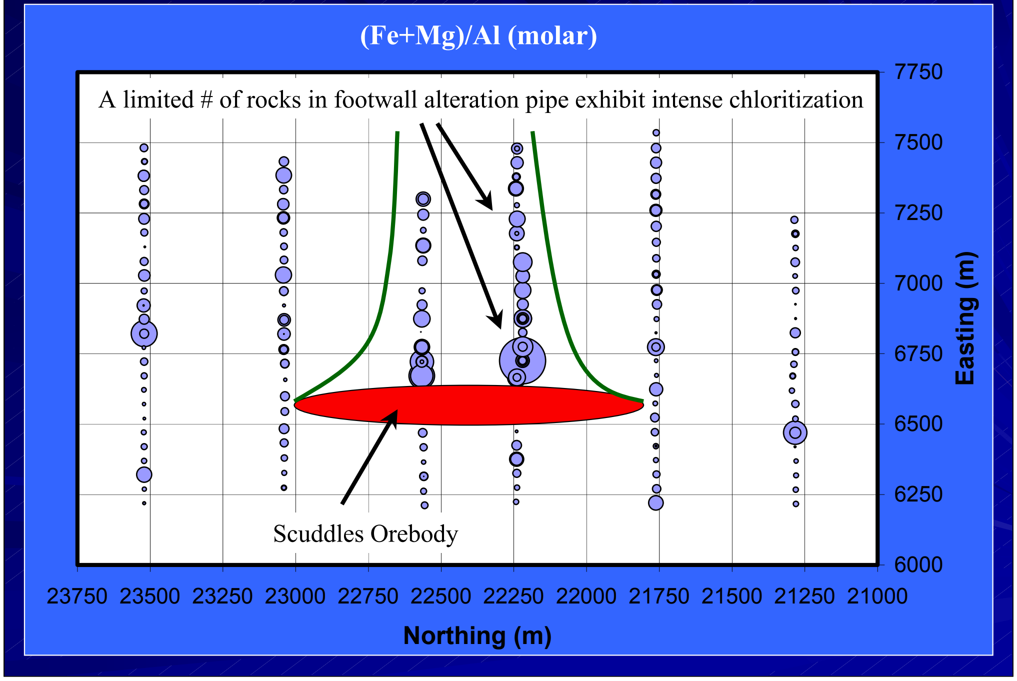


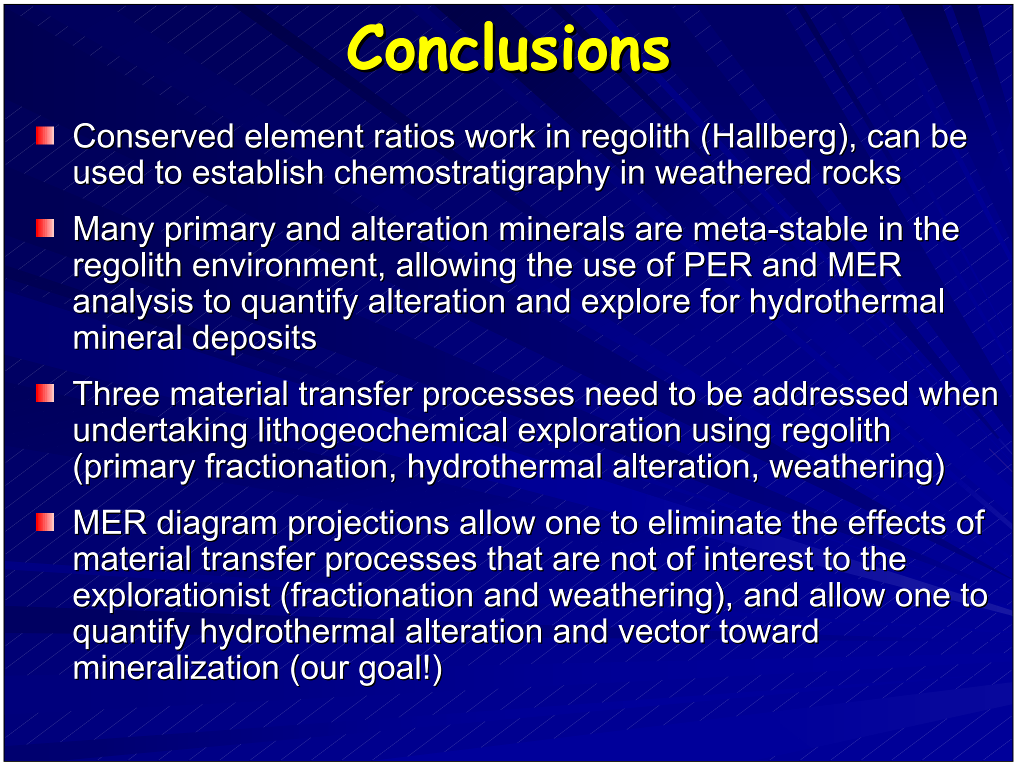
Regolith Alteration Lithogeochem



A limited # of rocks in footwall alteration pipe exhibit intense chloritization

Regolith Alteration Lithogeochem





Conclusions

- Conserved element ratios work in regolith (Hallberg), can be used to establish chemostratigraphy in weathered rocks
- Many primary and alteration minerals are meta-stable in the regolith environment, allowing the use of PER and MER analysis to quantify alteration and explore for hydrothermal mineral deposits
- Three material transfer processes need to be addressed when undertaking lithogeochemical exploration using regolith (primary fractionation, hydrothermal alteration, weathering)
- MER diagram projections allow one to eliminate the effects of material transfer processes that are not of interest to the explorationist (fractionation and weathering), and allow one to quantify hydrothermal alteration and vector toward mineralization (our goal!)

In summary, conserved element ratios work in regolith (Hallberg), can be used to establish chemostratigraphy in weathered rocks.

Many primary and alteration minerals are meta-stable in the regolith environment, allowing the use of PER and MER analysis to quantify alteration and explore for hydrothermal mineral deposits.

Three material transfer processes need to be addressed when undertaking lithogeochemical exploration using regolith (primary fractionation, hydrothermal alteration, weathering).

MER diagram projections allow one to eliminate the effects of material transfer processes that are not of interest to the explorationist (fractionation and weathering), and allow one to quantify hydrothermal alteration and vector toward mineralization (our goal!).