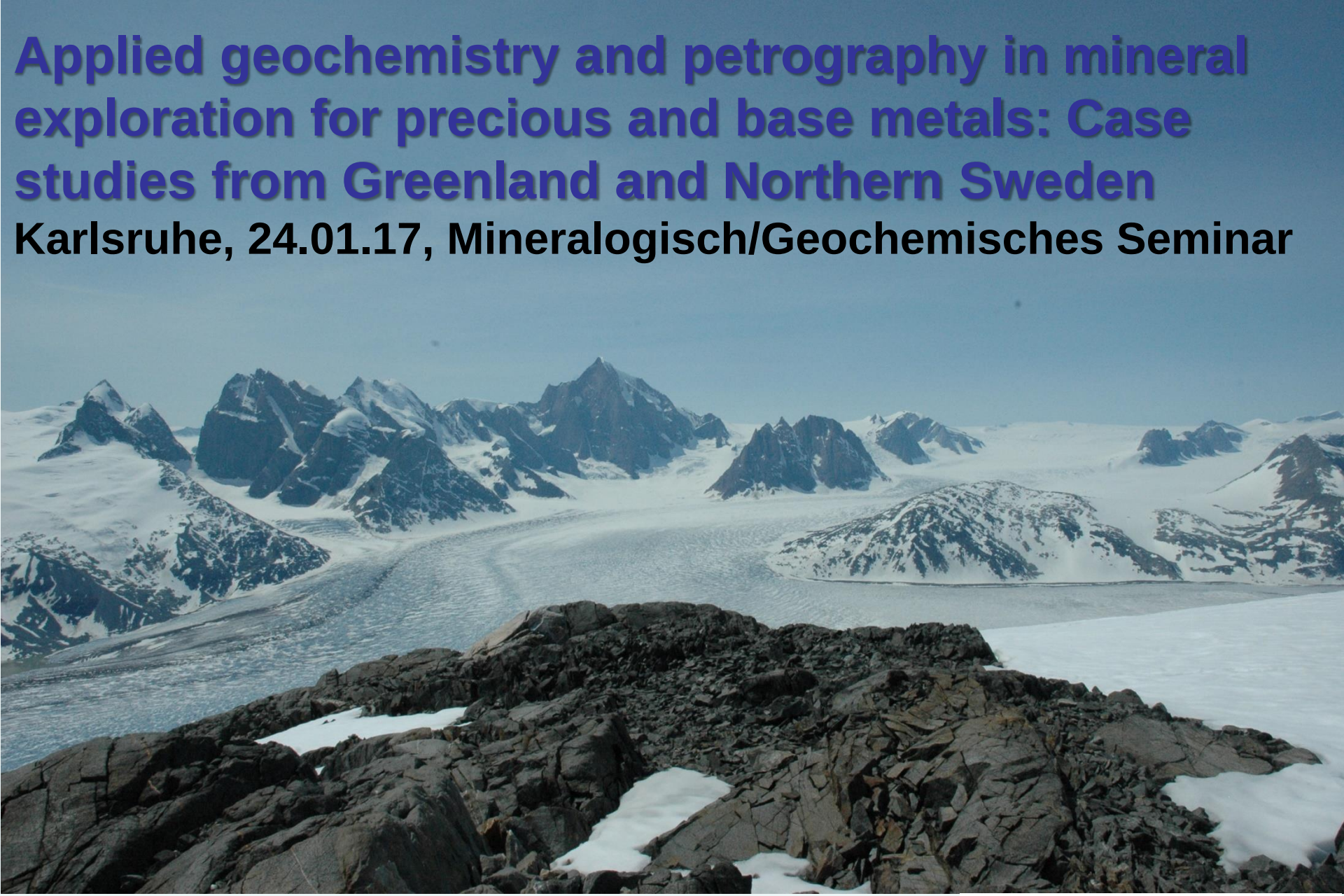
# Applied geochemistry and petrography in mineral exploration for precious and base metals: Case studies from Greenland and Northern Sweden

**Karlsruhe, 24.01.17, Mineralogisch/Geochemisches Seminar**




KIT Karlsruhe Institute of Technology

**Denis Martin Schlatter**

HELVETICA EXPLORATION SERVICES GmbH

# Outline of presentation

- Mineral potential of Greenland
- Geology, geochemistry, petrography and hydrothermal alteration of gold deposits/occurrences in Archean West Greenland and Paleoproterozoic South Greenland
- Paleoproterozoic VMS massive sulfide deposits of the Skellefteå district and gold deposits of the Gold Line in Northern Sweden
- Geochemical Comparison of the Nalunaq gold mine (South Greenland) and the Svartliden gold mine (Northern Sweden)
- Conclusions and how applied geochemistry and petrography in mineral exploration for precious and base metals has helped to focus gold exploration and to prioritize targets

# Metal markets and commodities

Chart of the Week

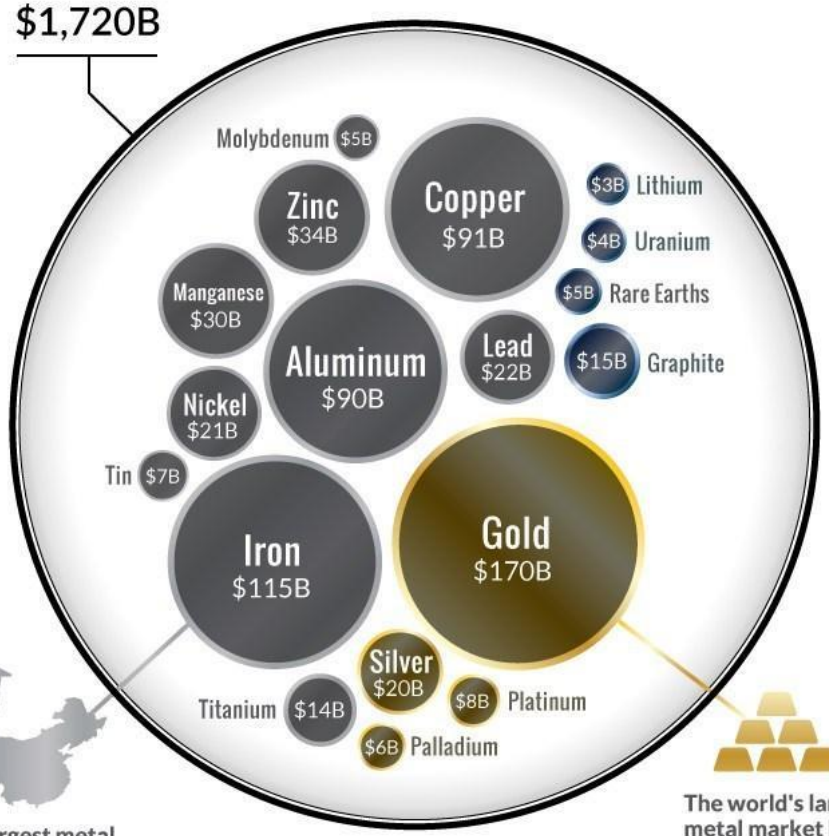
## BIG OIL

The oil market is bigger than all raw metal markets combined

Oil
$1,720B

The global market for oil was 94 million barrels per day in 2015.

This puts the oil market at $1.7 trillion per year with today's prices - **far more than all raw metals combined!**




**The largest metal market by tonnage is iron ore.**

China alone consumes 1 billion tonnes per year mostly to produce steel.

**The world's largest metal market by dollar value is gold.**

The physical market is worth $170 billion per year at today's spot price.

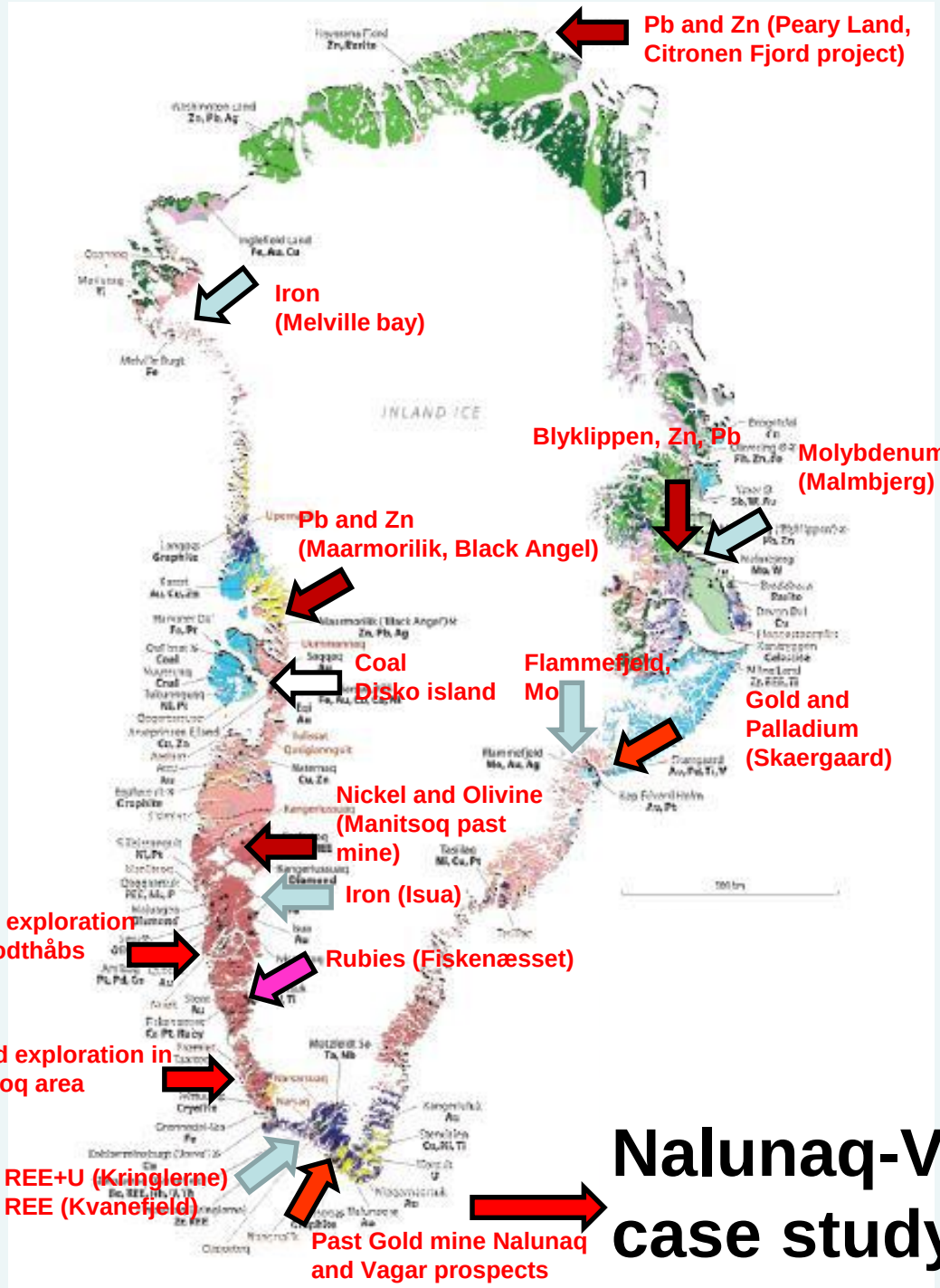
SOURCES: Infomine, EIA, World Gold Council, Johnson Matthey, Cameco, Benchmark Minerals

visualcapitalist.com

**NZZ, 19.01.2017**

**Venus Statue from 1597 by Giambologna in bronze and produced by G. Meyer from Stockholm. Bought and saved from a French Scrap dealer in the 1980ies**

# Greenland: Mineral occurrences, past mines and potential of future new mining projects



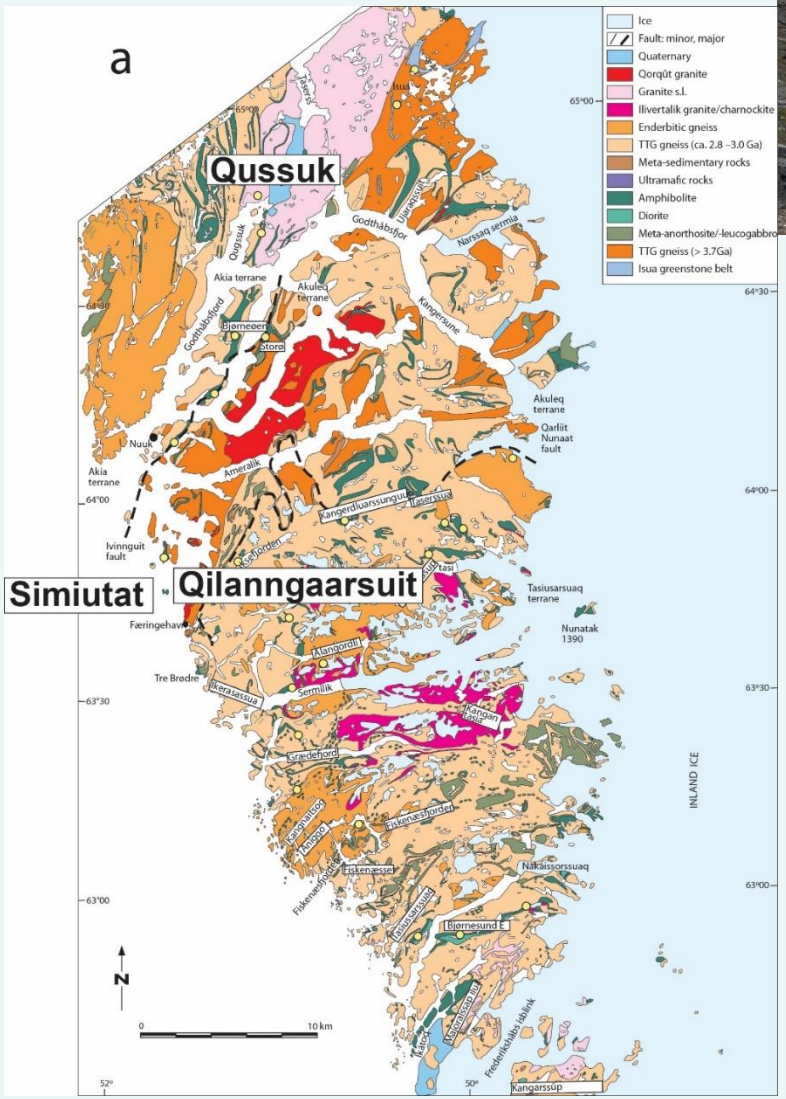

Map from GEUS.dk

**Godthåbs Fjord gold and Nuuluk gold case studies**

**Nalunaq-Vagar case study**

# Location of gold occurrences in the Godthåbs Fjord

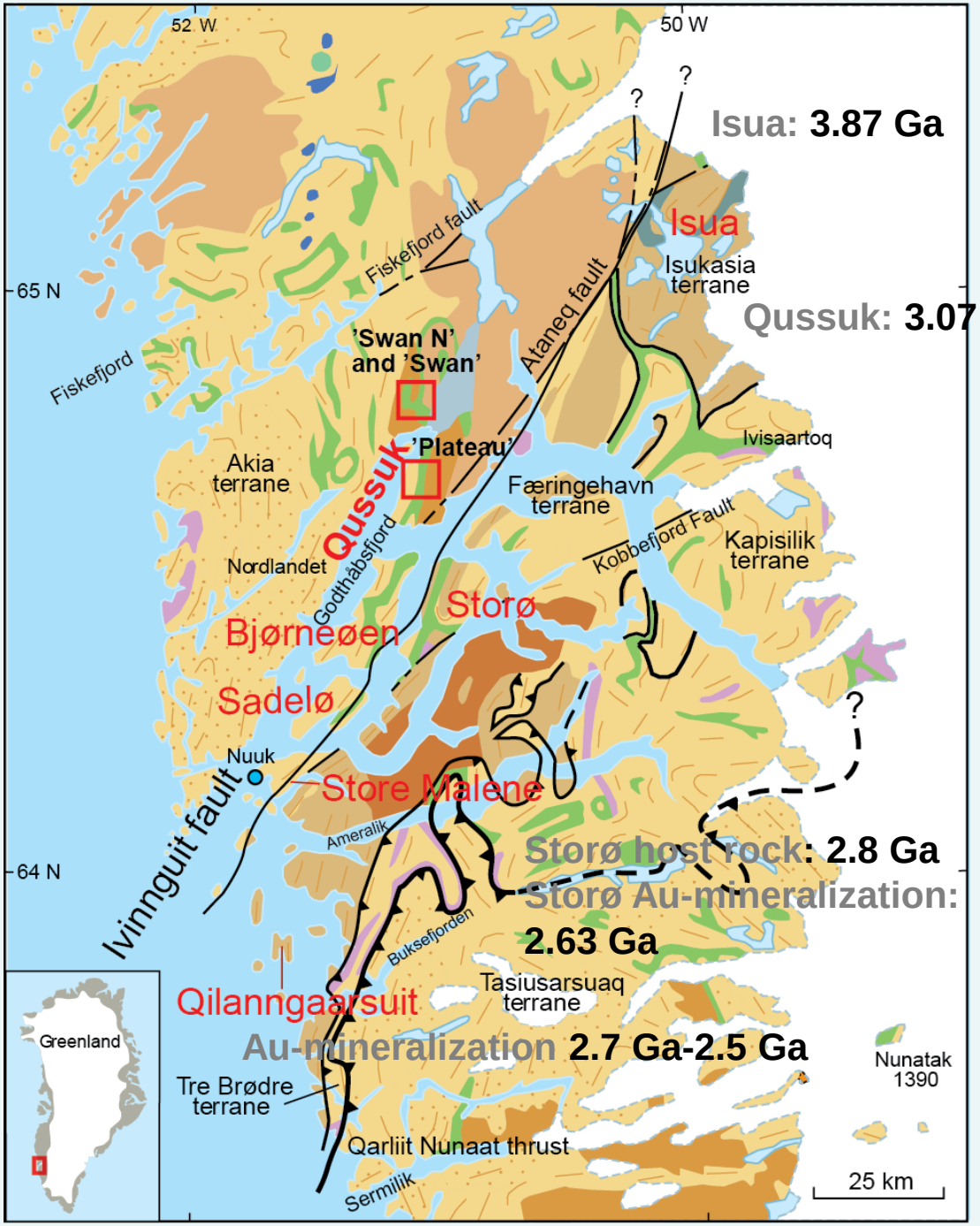
Qussuk looking towards the Godthåbs Fjord system





Kolb, Dziggel, Schlatter (2013)

# Geology of the Godthåbs Fjord area

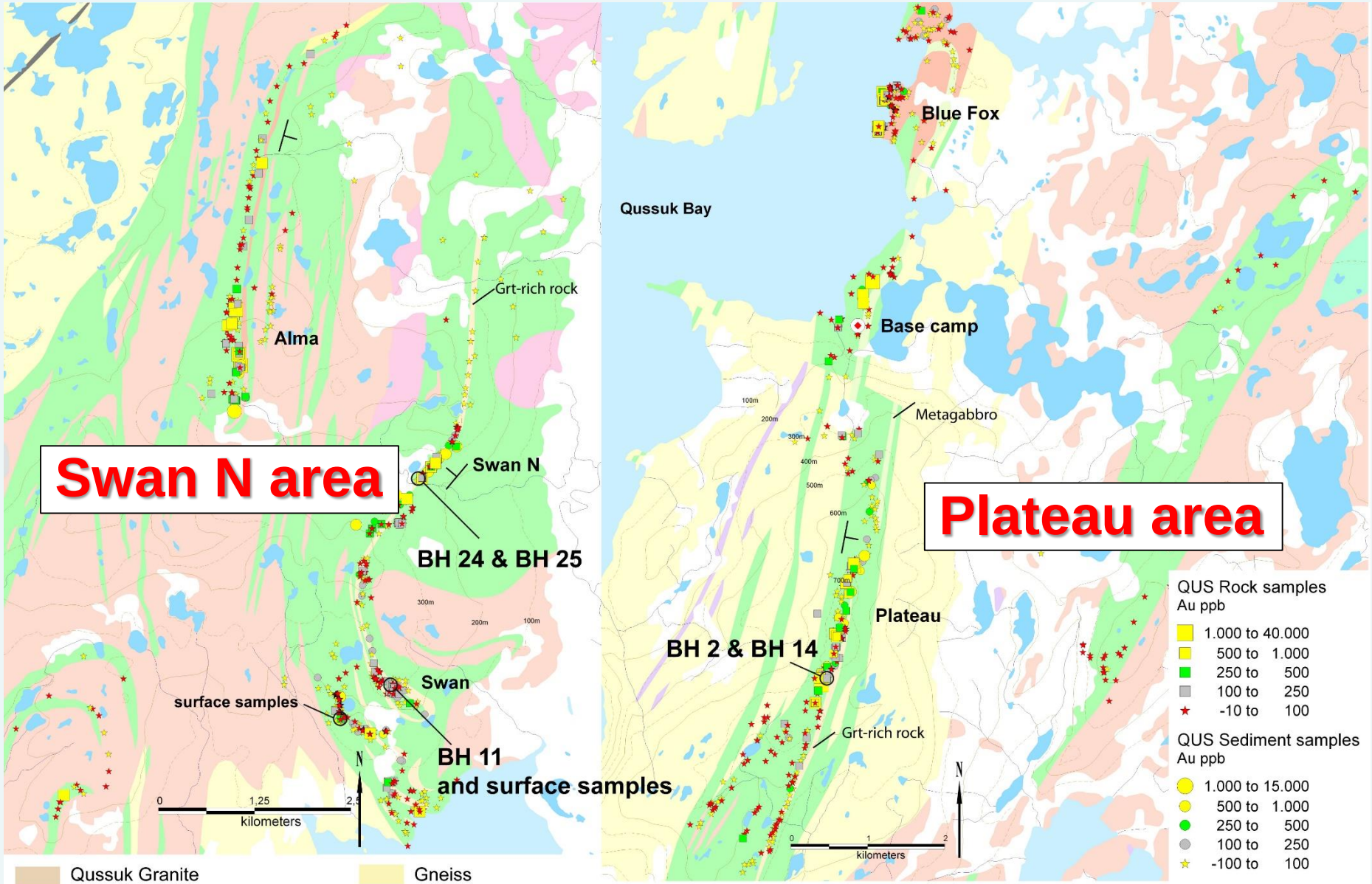



**Ivinnguit fault 2.6 to 2.66 Ga old, dividing Akia and Faeringhavn terrane**

- Terrane boundary
- Internal terrane boundary
- Palaeoproterozoic fault
- Structural trend line
- Granulite facies
- Quaternary cover
- Qôrqut granite complex
- Meso- to Neoarchaean granites
- Meso- to Neoarchaean late-kinematic tonalitic-granodioritic plutons
- Meso- to Neoarchaean grey orthogneiss and granitic rocks
- Eoarchaean gneiss
- Noritic intrusions (Akia terrane)
- Supracrustal belts (undifferentiated)
- Anorthosite-metagabbro complexes
- Isua Greenstone Belt

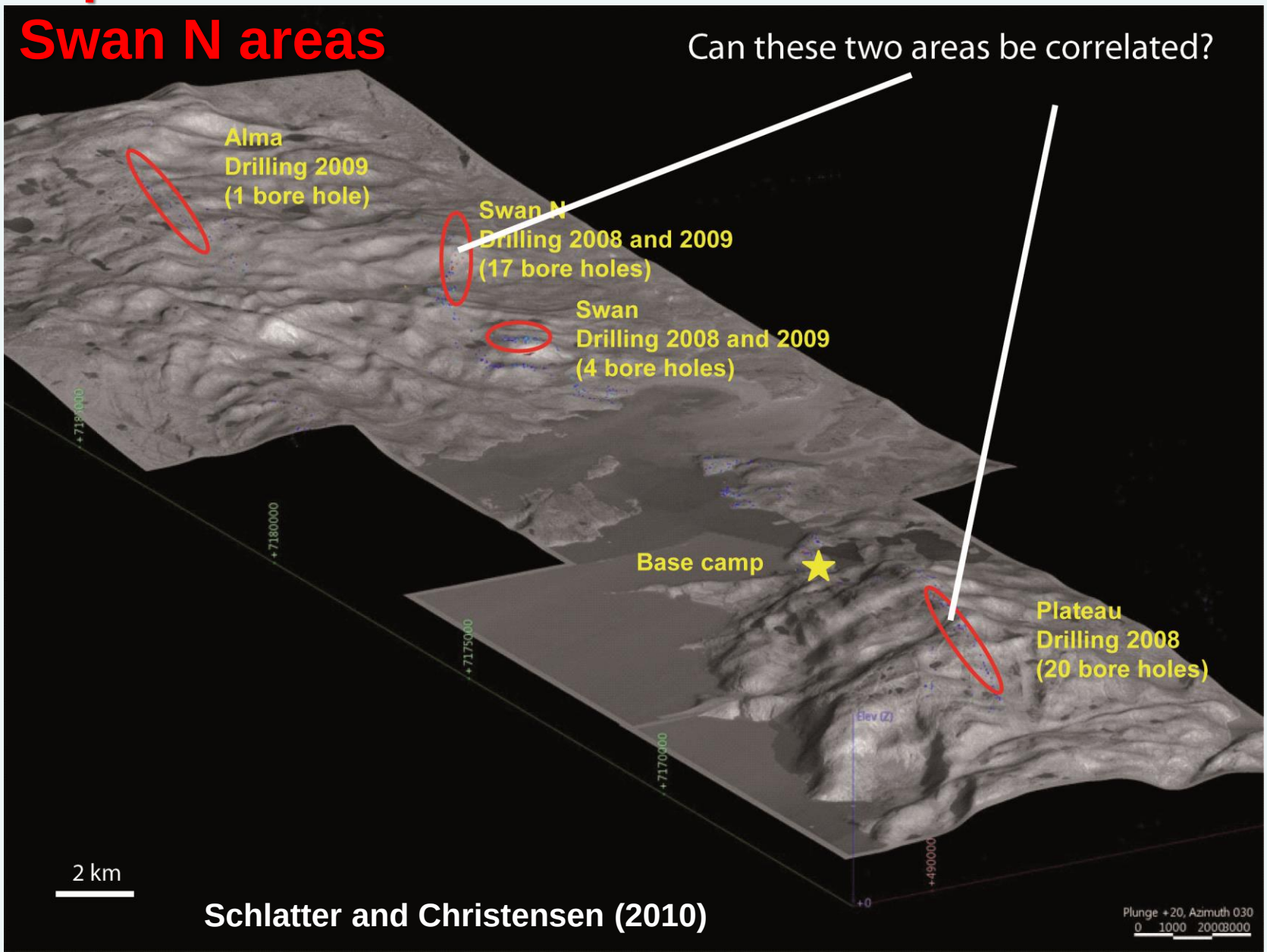
Schlatter and Christensen (2010)

# Geology of the Qussuk area and exploration results from rock and sediment sampling



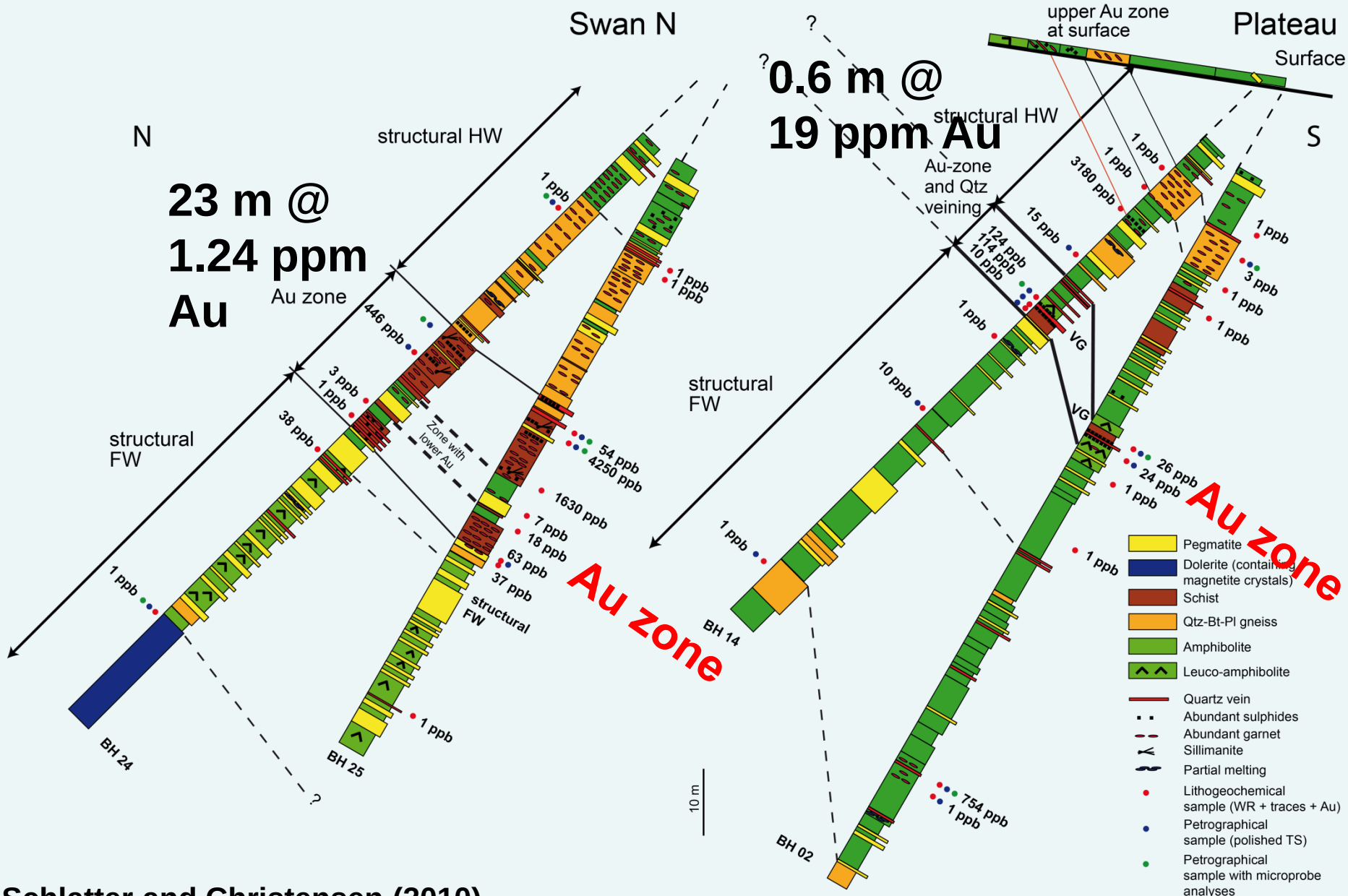

Schlatter and Christensen (2010)

# Location of the Qussuk Au targets and exploration drill locations in the Plateau and Swan N areas




Schlatter and Christensen (2010)

# Geology defined from logging of drill hole profiles




Schlatter and Christensen (2010)

# Rocks from the Plateau Au-zone and from wall rocks


BH-02-13.8m; hanging wall

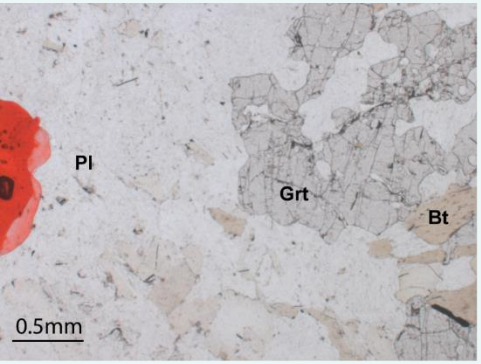

BH-14-37m; Au-zone, gold grain is encircled


BH-02-@~46m; Au-zone

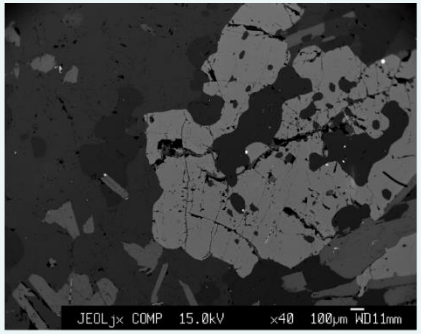

BH-14-@~59m; footwall

**Schlatter and Christensen (2010)**

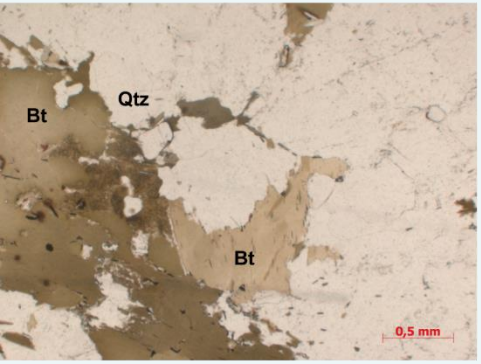
# Petrography of the hanging wall and the gold zone of the Platea area



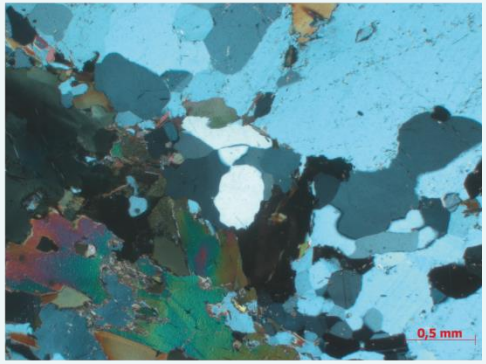
BH-02-13.95m; hanging wall



BH-02-13.95m (BSE image)



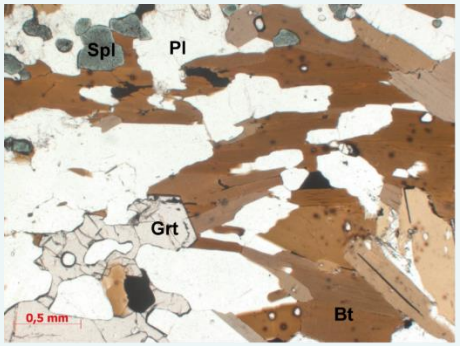
BH-14-36.7m; Au-Zone



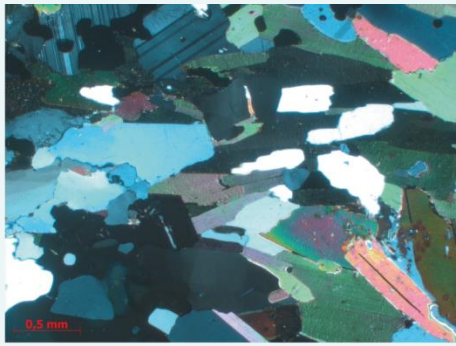
BH-14-36.7m; Au-Zone

**Biotite and quartz in Au zone**

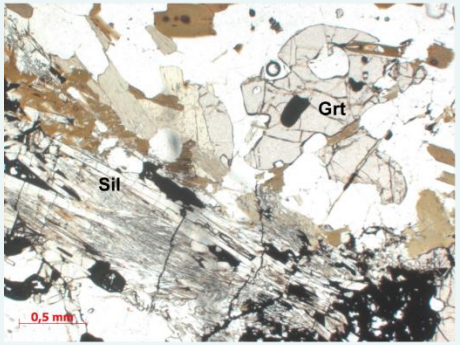
# Petrography of the hanging wall and the gold zone of Swan N



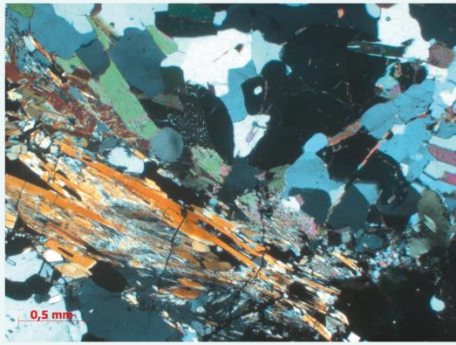
BH-24-19m; hanging wall



BH-24-19m; hanging wall



BH-25-43.3m; Au-Zone

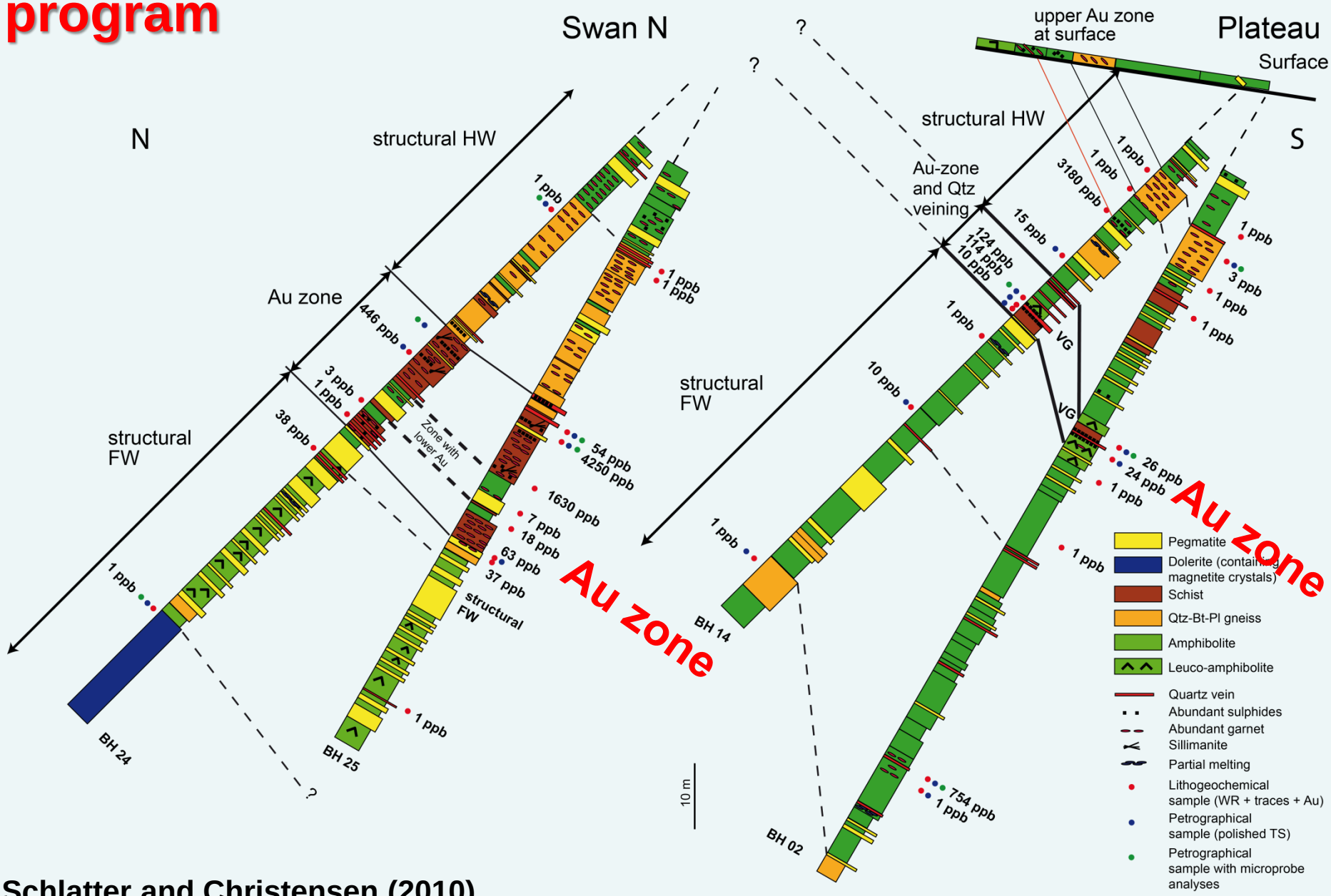


BH-25-43.3m; Au-Zone

**Garnet and sillimanite in Au zone**

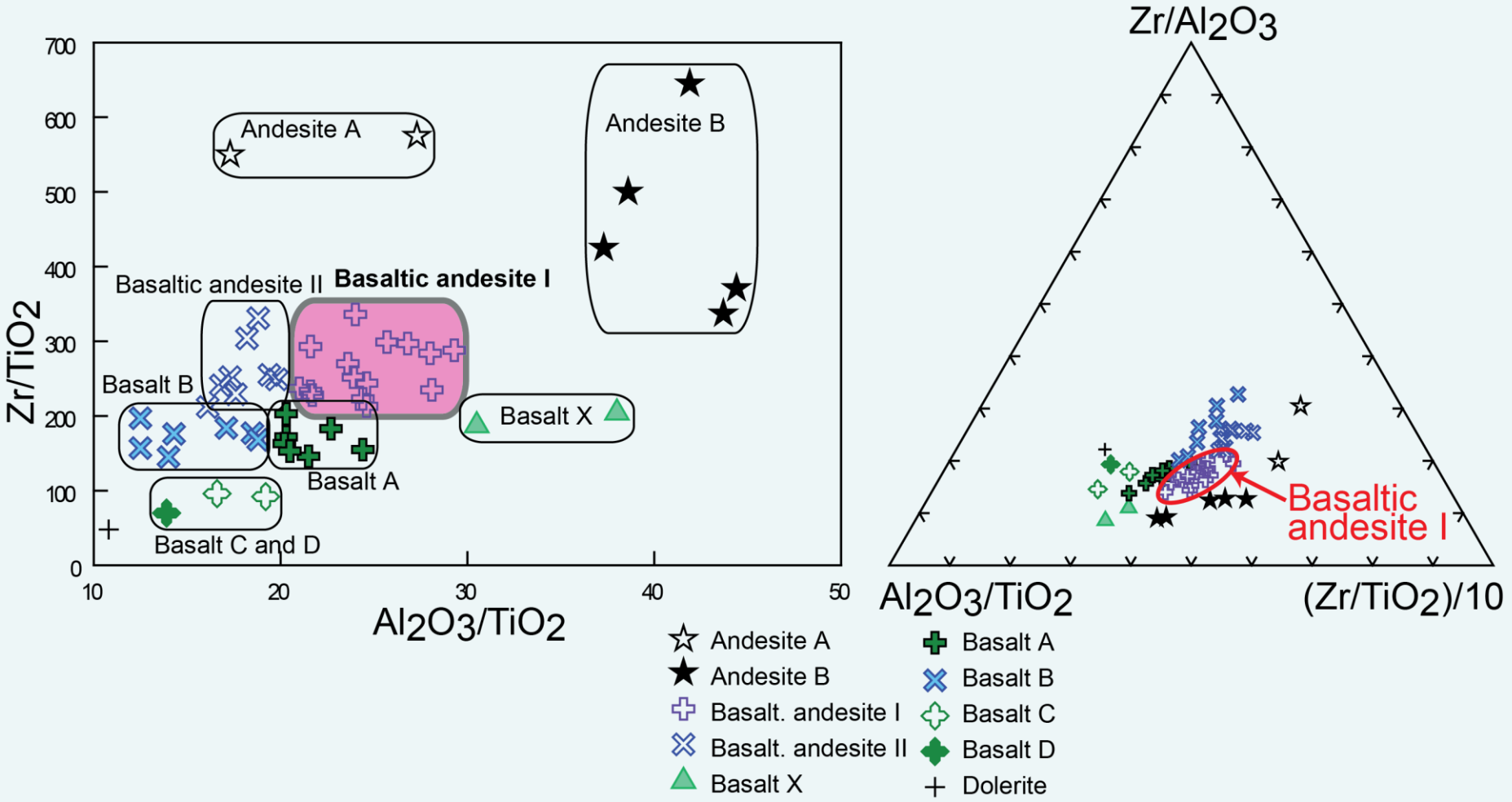
**Schlatter and Christensen (2010)**

# Lithogeochemical and petrographic sampling program



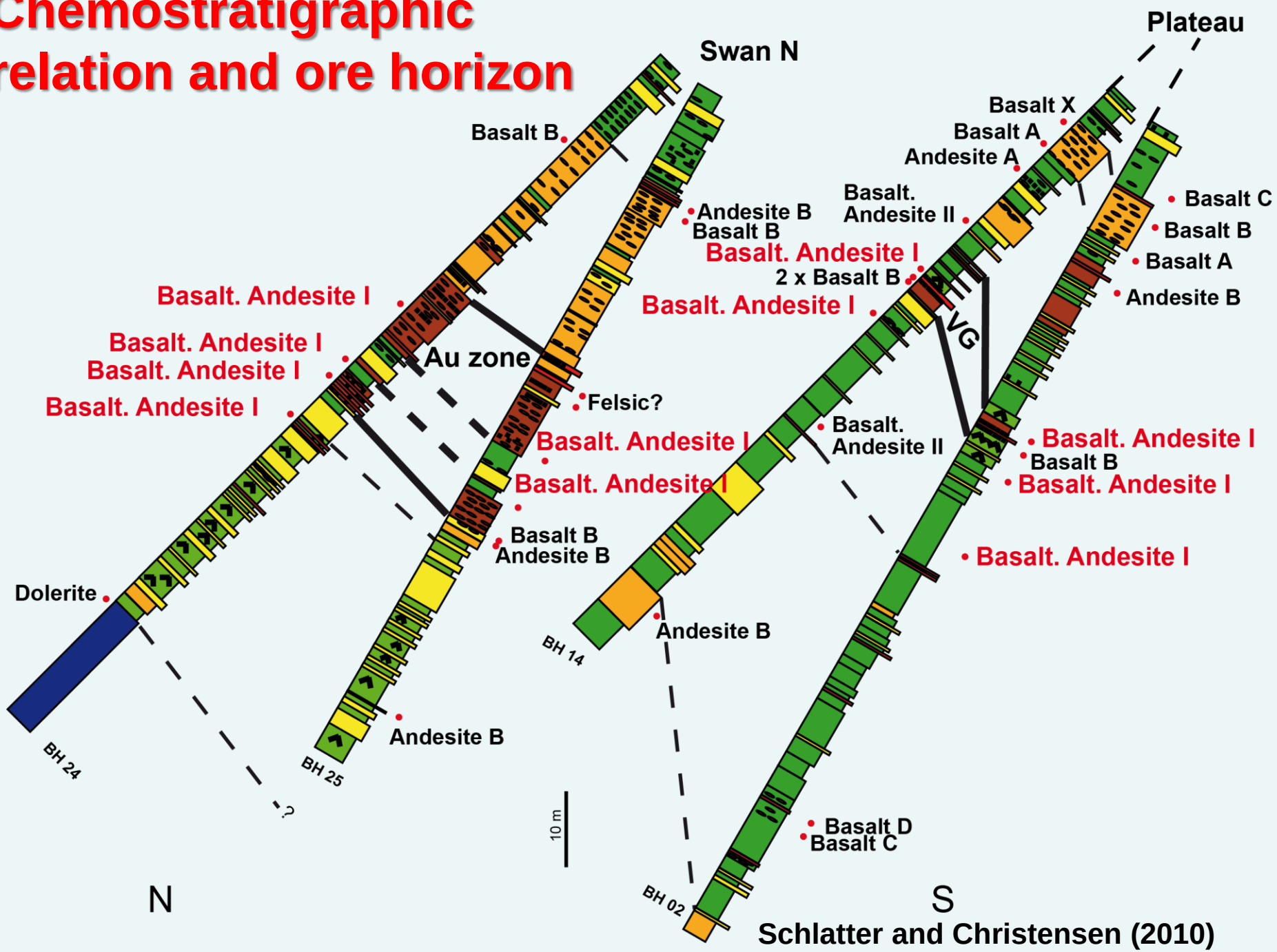

**Schlatter and Christensen (2010)**

# Refined rock classification of the amphibolitic rocks based on immobile element ratios



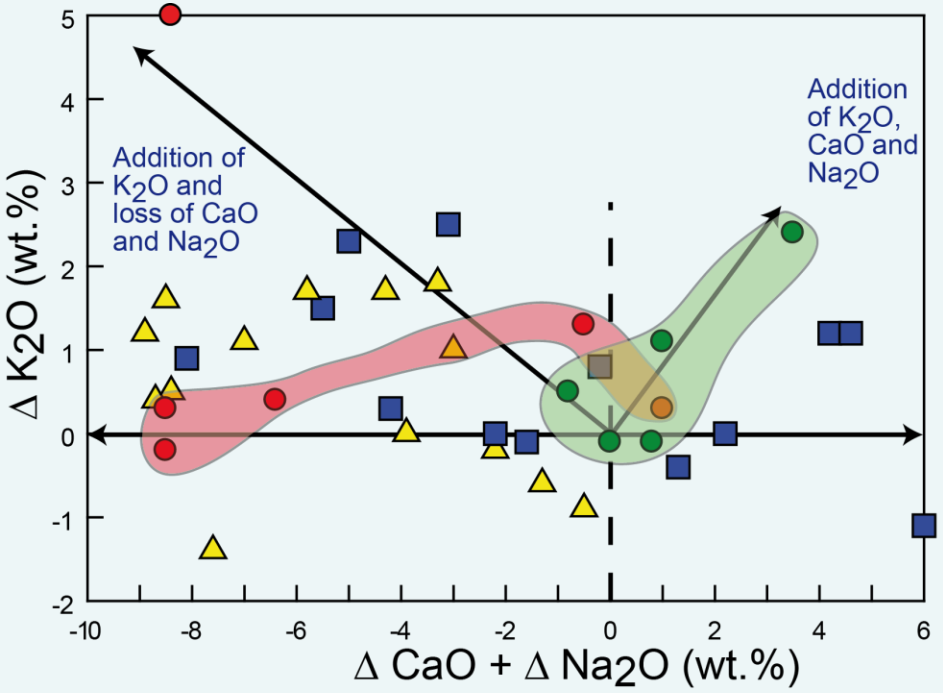

**Schlatter and Christensen (2010), inspired by Kolb (2010)**

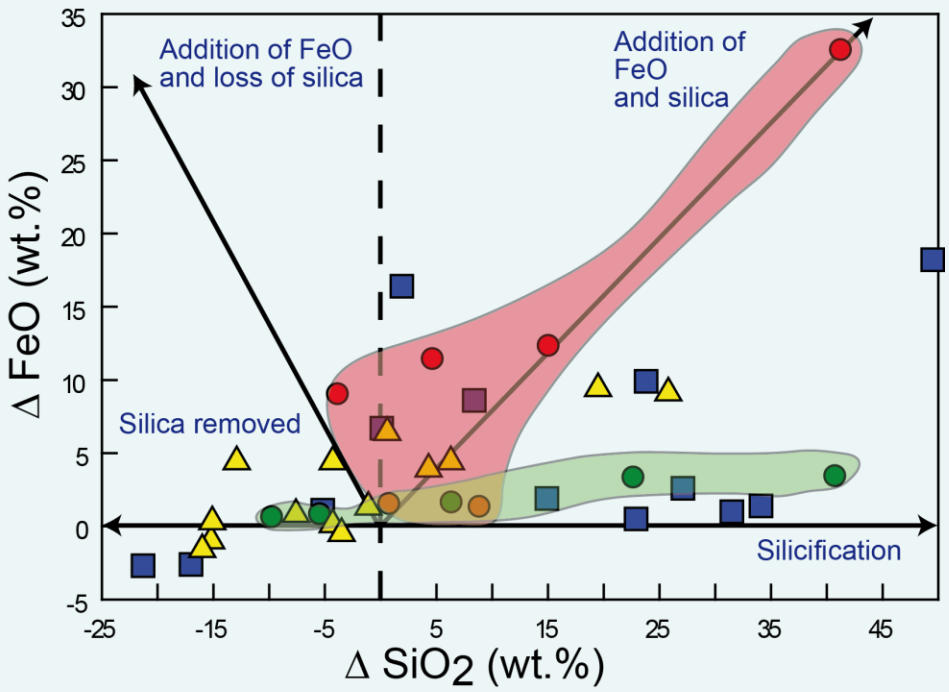
# Chemostratigraphic relation and ore horizon




Schlatter and Christensen (2010)

# Classification of hydrothermal alteration based on results of mass change calcultions




**Samples from the gold zones:**

- Swan N samples from the Au-zone
- Plateau samples from the Au-zone
- Swan N and Plateau samples outside the Au-zone
- Samples from the Swan area

**Schlatter and Christensen (2010)**

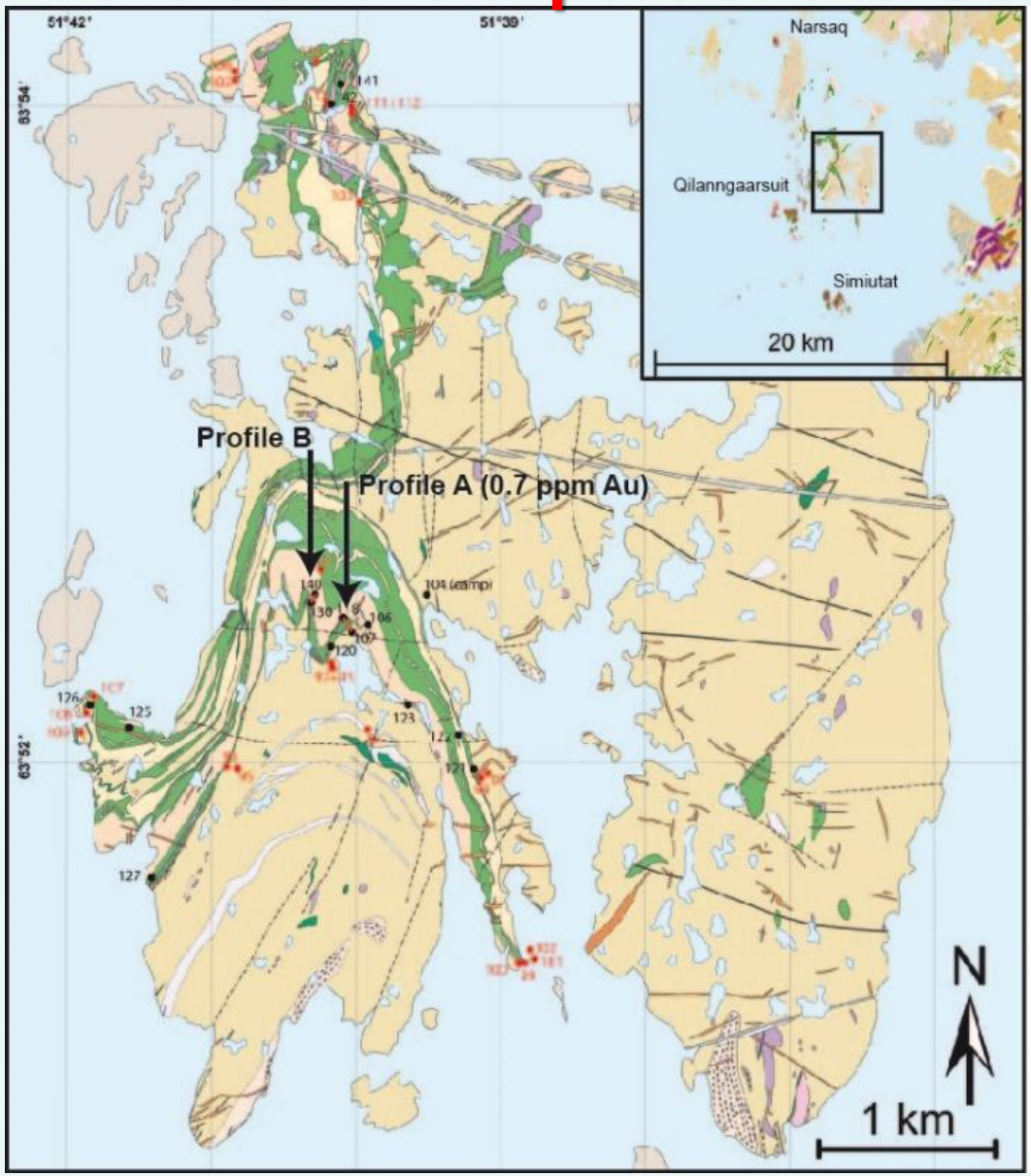
## Short summary Qussuk:

**Au is associated with pyrrhotite, chalcopyrite, biotite, muscovite and quartz**

**Favorable host rock is of basaltic Andesite I type**

**Hydrothermal alteration is characterized by gains of $K_2O$+FeO+$SiO_2$ and gains and losses of $Na_2O$+CaO**

# Geology of Qilanngaarsuit-Simiutat located in the southern part of the Godthåbs Fjord





- Water
- Not digitized
- Stations (e.g. '120' refers to station 08dms120 '110' refers to station 08bms110)
- Fault
- Dolerite dyke
- Pegmatite

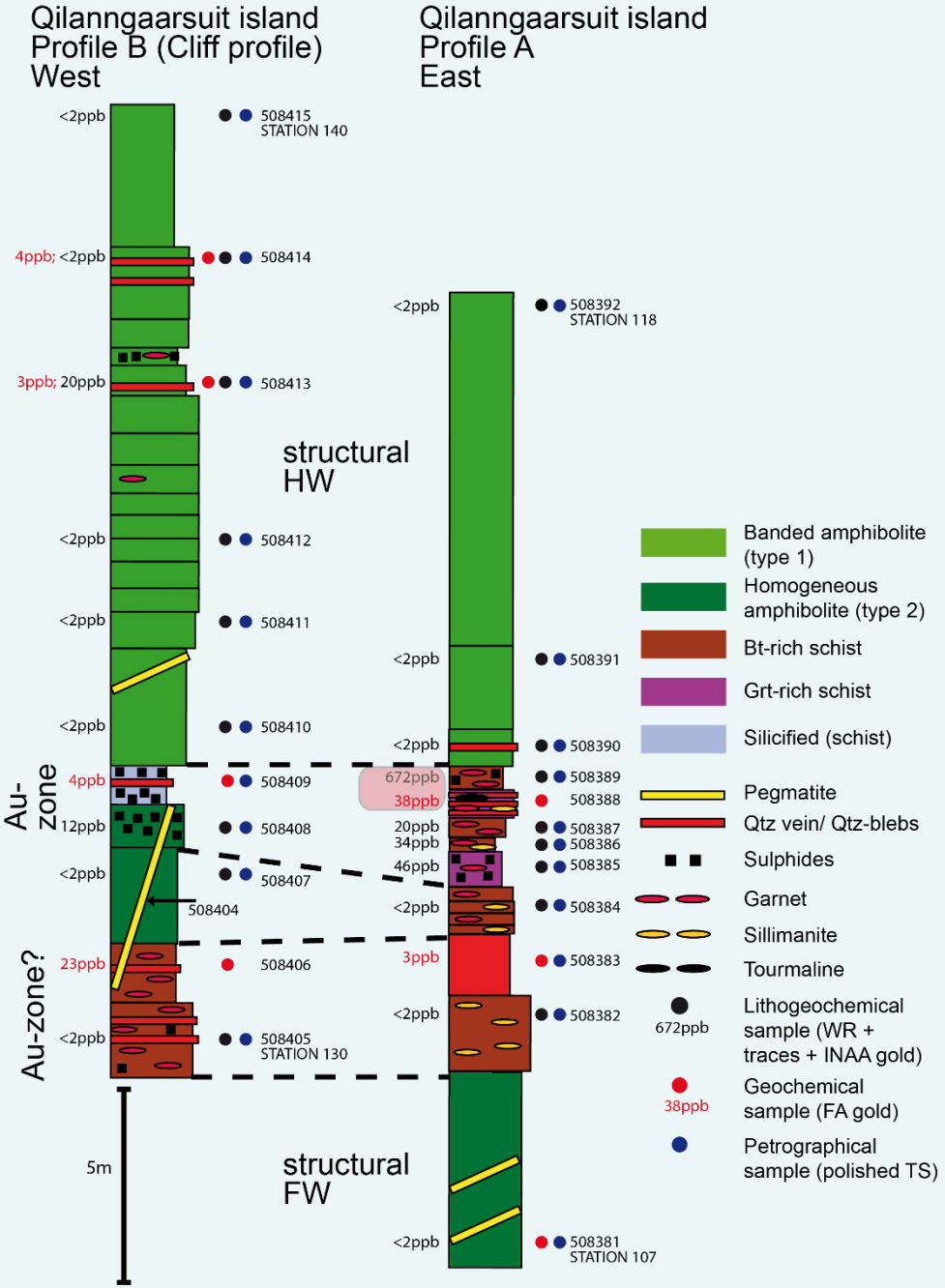
- Qtz vein with fuchsitic Ms
- Microgranite
- Garnet-rich biotite-sillimanite gneiss
- Marble
- Meta-ultramafic rocks
- Banded Amphibolite
- Homogeneous dark green Amphibolite
- Ameralik dyke (metamorphosed)
- Amphibolite (Akilia)
- Meta-diorite
- Augen gneiss
- TTG-gneiss (>3.7 Ga)

Kolb, Stensgaard, Schlatter, Dziggel (2009)

# It is an island in the Southern part of the Godthåbs Fjord (not the South China Sea)

# Qilanngaarsuit, Profile B, looking South

Kolb, Stensgaard, Schlatter, Dziggel (2009)



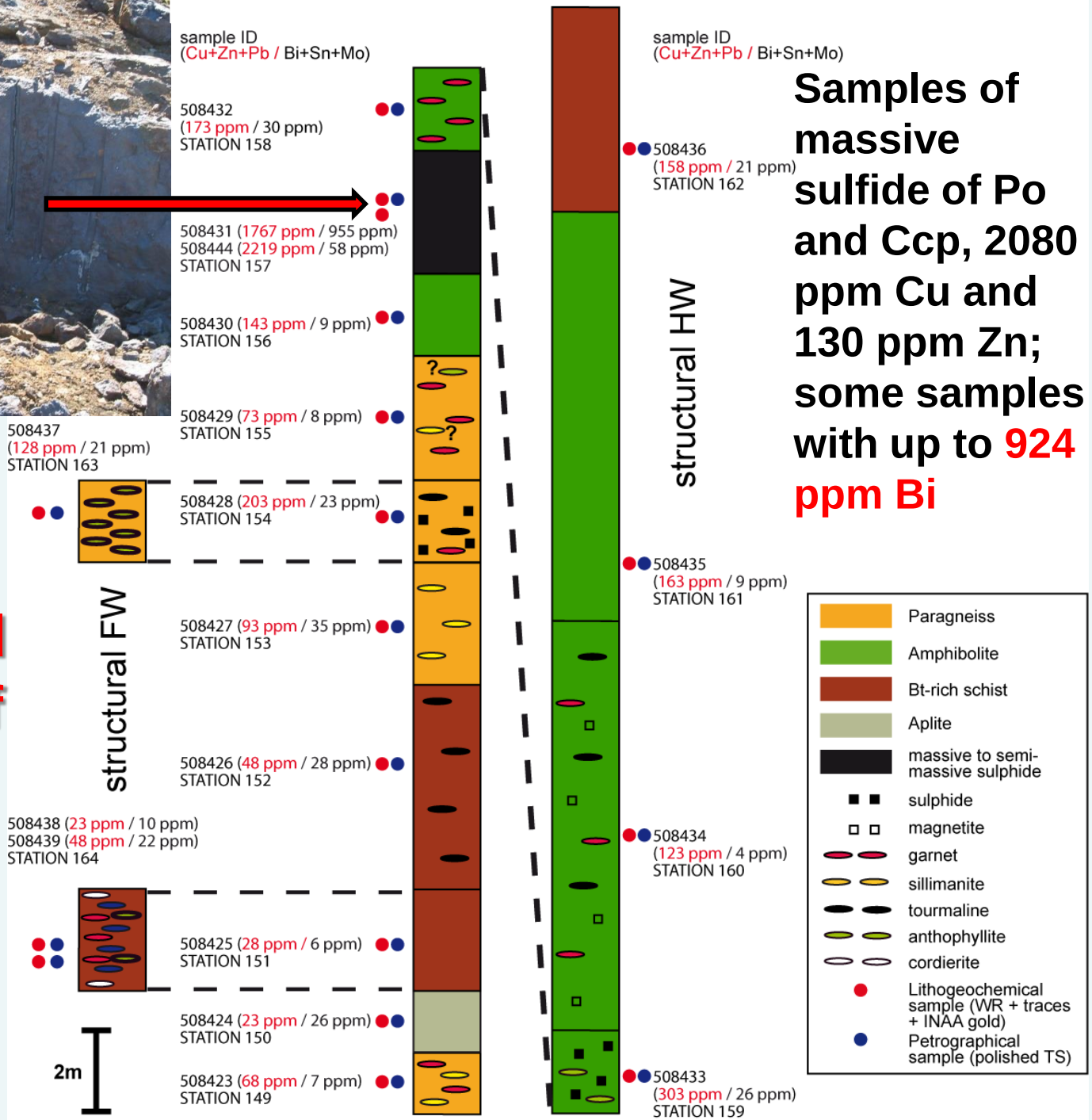
# Au mineralization in fold structures in numerous quartz veins and sulphides in Bt-Grt-Sil-rich schist

**Hydrothermal alteration zone (2m wide)**

**Foliation parallel quartz veins (a few cm wide)**

Kolb, Dziggel, Schlatter (2013)

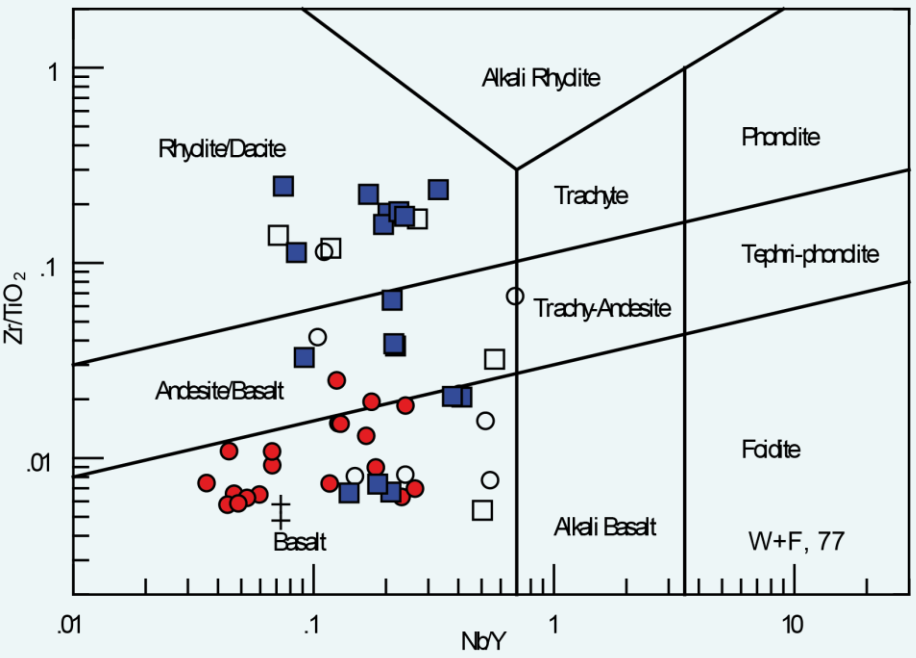
# Simiutat island: rock sequence and occurrence of massive sulfides

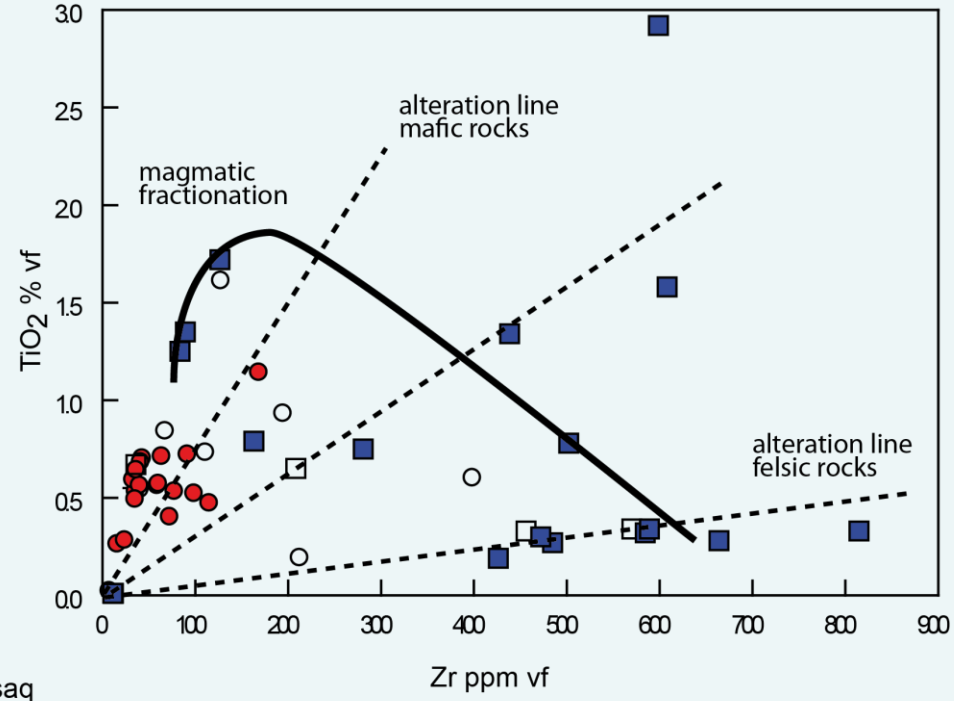



**Samples of massive sulfide of Po and Ccp, 2080 ppm Cu and 130 ppm Zn; some samples with up to 924 ppm Bi**

**Kolb, Stensgaard, Schlatter, Dziggel (2009)**

# Qilanngaarsuit-Simiutat: Lithogeochemical results




Qilanngaarsuit profiles
Qilanngaarsuit other rocks
Simiutat profiles
Simiutat other rocks
Narsaq

Schlatter (2009)

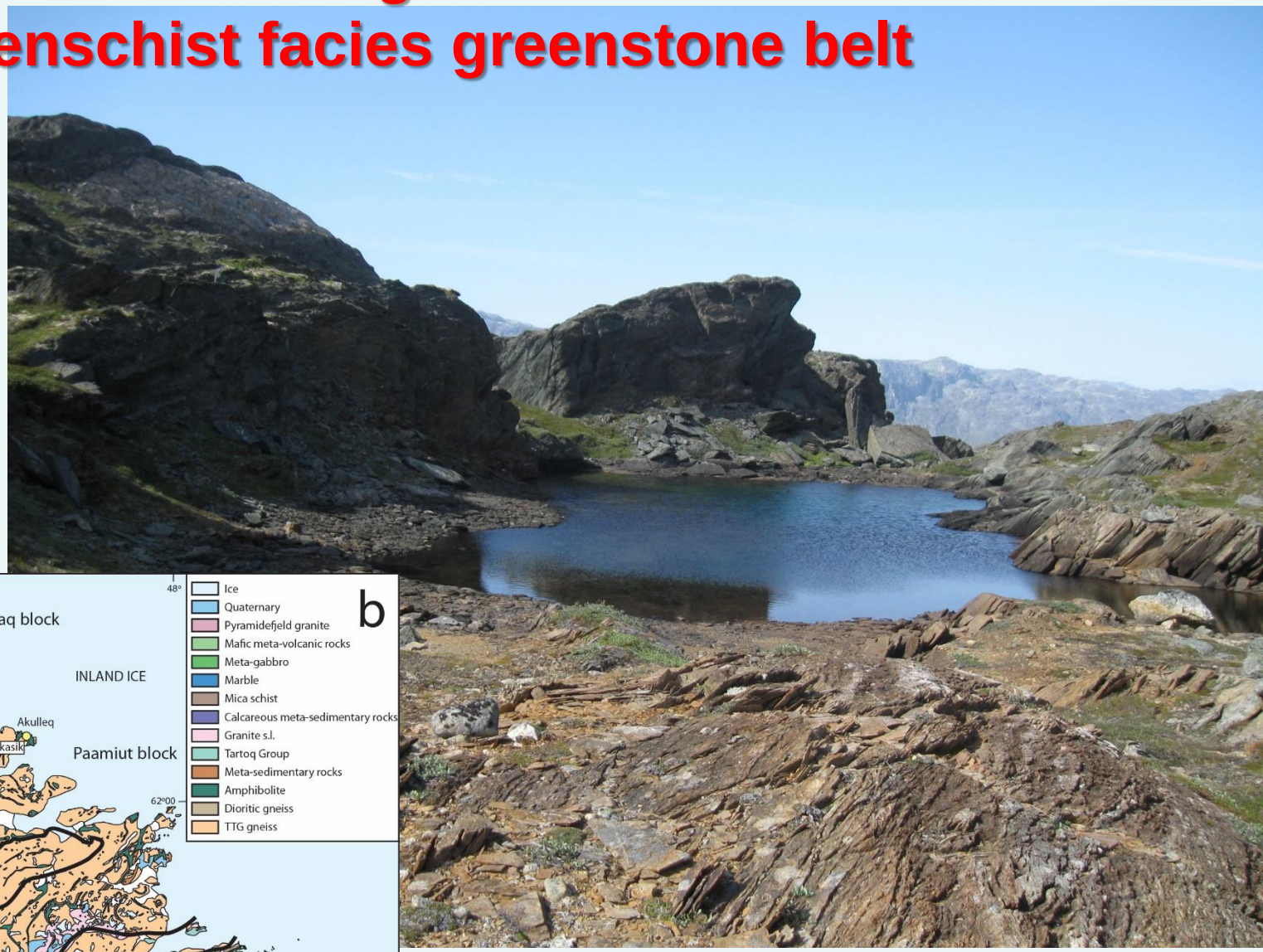
## Short Summary: Qillangaarsuit-Simiutat

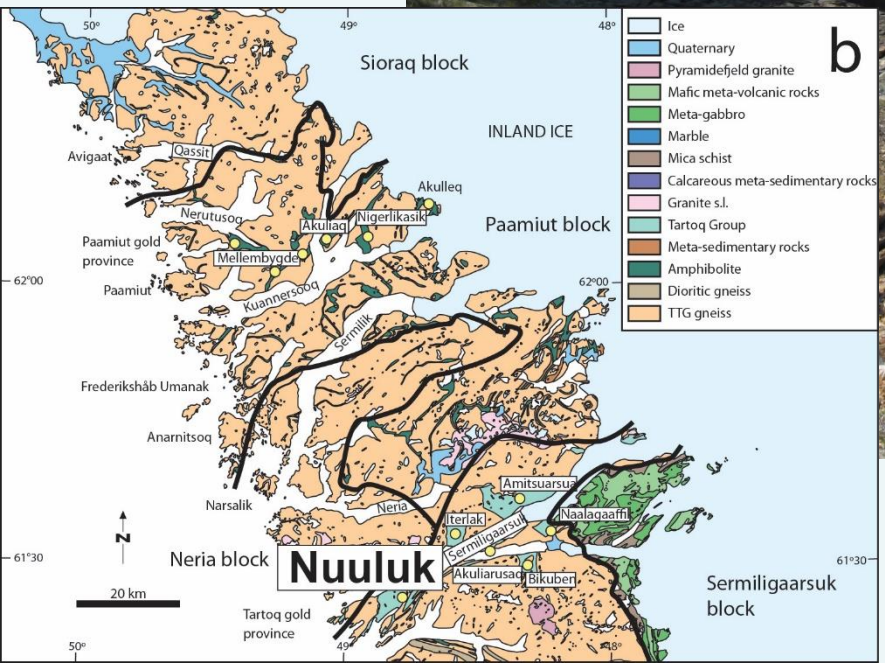
**Qillangaarsuit host rocks are basalts**

**Narrow Au zones associated with garnet, plagioclase, quartz, biotite, sillimanite and sulphides, in narrow Qtz veins and of epigenetic origin. Ore fluids were enriched in $SiO_2$, $K_2O$, LREE, Au, Cu, Zn, Mo and As (see Koppelberg et al., 2011)**

**Simiutat host rocks are altered basalts AND altered rhyolite-dacite**

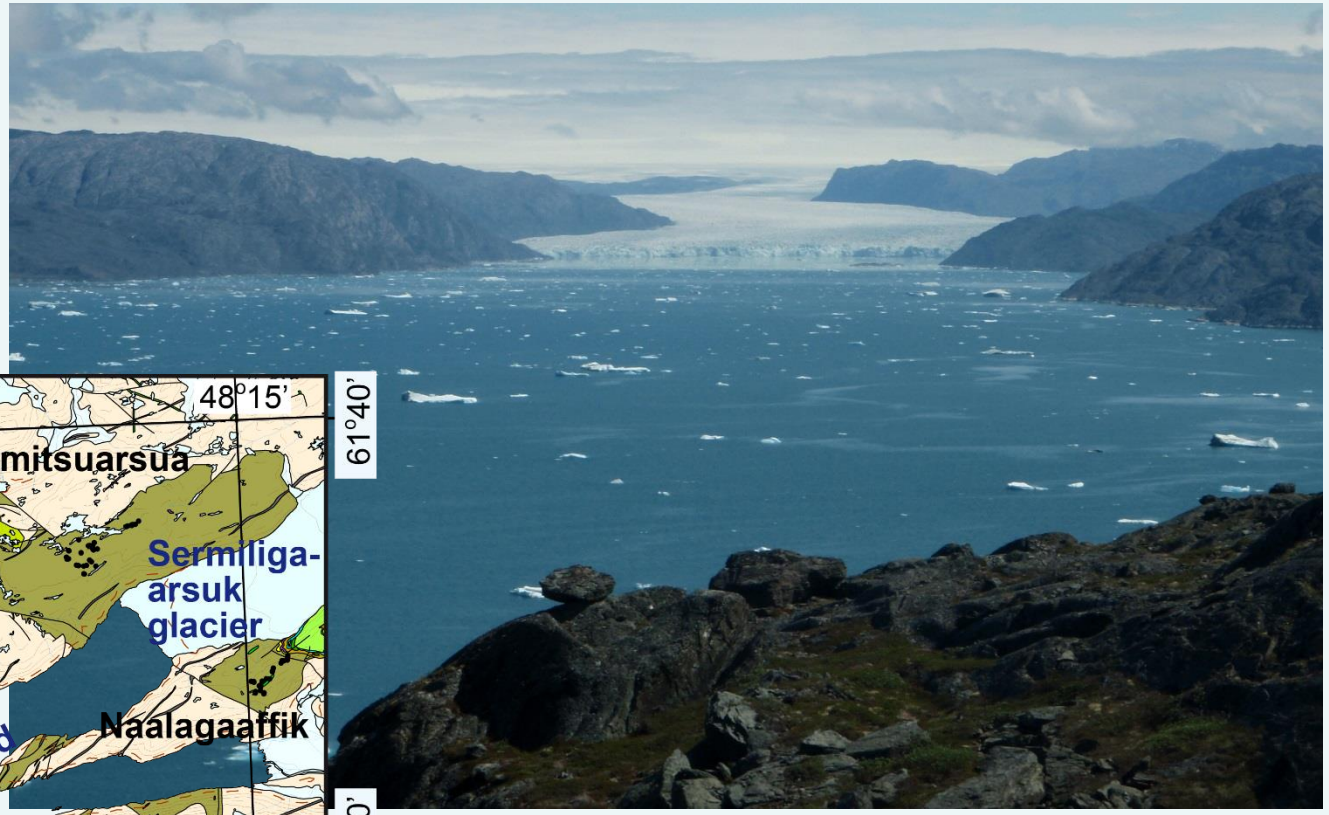
# Location of mesozonal gold occurrences in the Tartoq greenschist facies greenstone belt

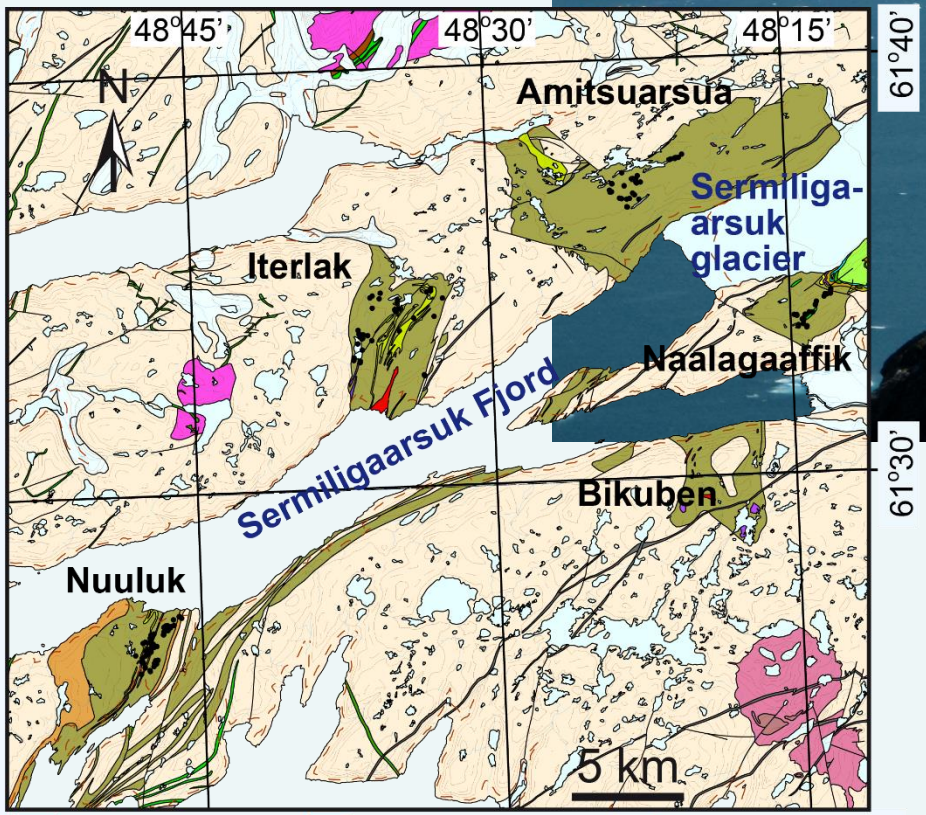






Kolb, Dziggel, Schlatter (2013)

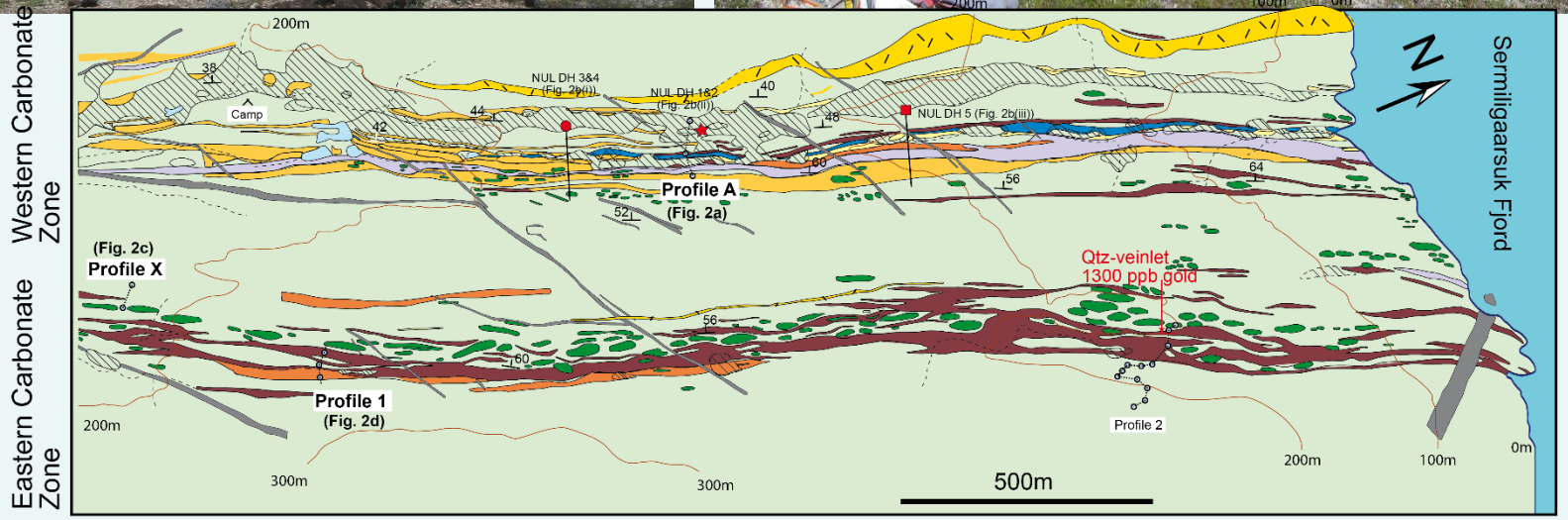
# Location of Nuuluk gold






Kolb et al. (2011)






**Primary lithology**

- Dolerite dyke
- Dark-green greenstone (knobbly)
- Light green greenstone (zoisite-epidote-carbonate-rich)
- Massive metavolcanic rock (Qtz-Fsp-carbonate rich)
- Graphite schist
- Magnetite (Mag) schist
- Qtz-Fsp-sericite-schist

**Hydrothermal alteration**

- Strong carbonate alteration (ankerite-dolomite)
- Moderate carbonate alteration (ankerite-dolomite, ± Mag)
- Sericite alteration
- Weak sericite alteration
- Weak chlorite alteration

- Magnetite
- Abundant chlorite
- Malachite
- Tennantite
- Sericite altered (in bands)
- Cr-mica (Fuchsite)
- Qtz vein
- Calcite vein
- Sulphide
- Iron oxide -hydroxide
- Tourmaline

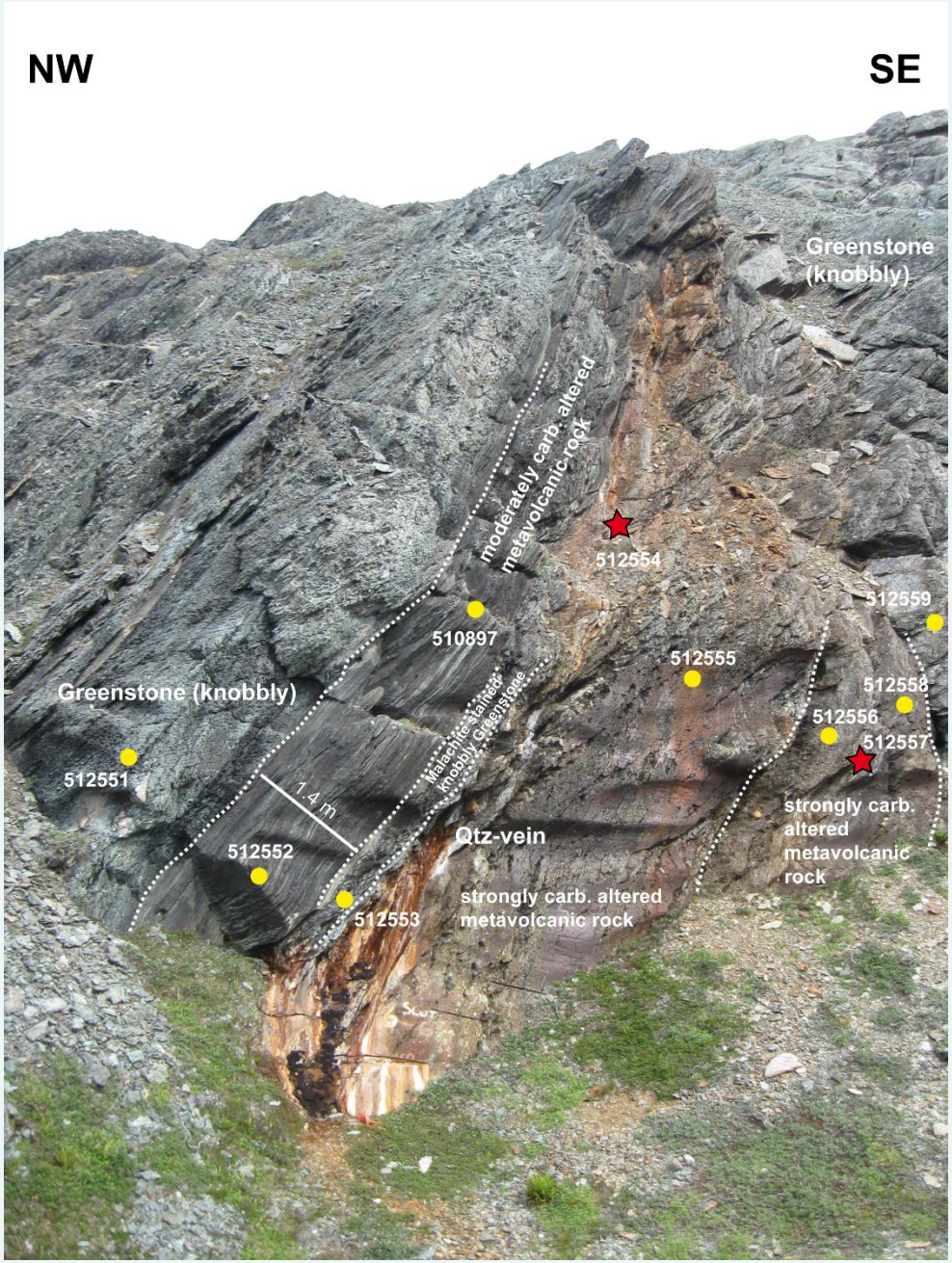
**Various**

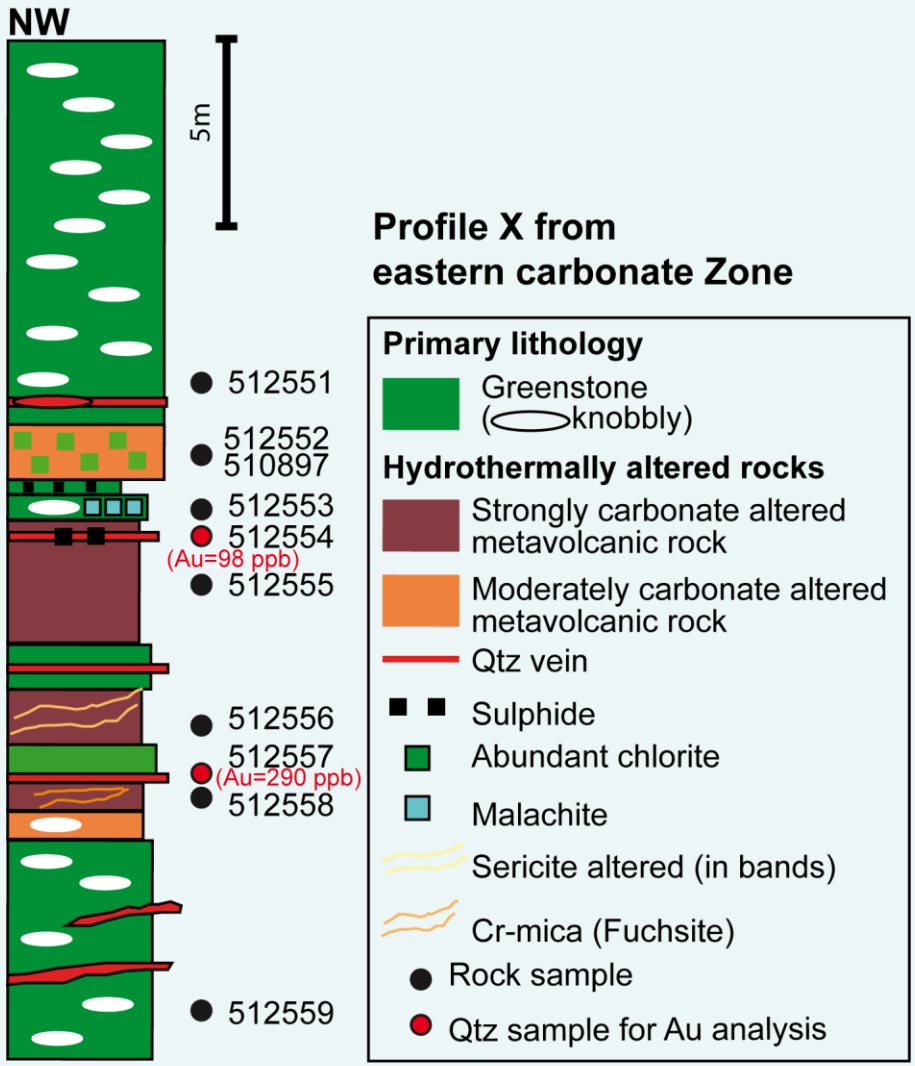
- Rock sample for major and trace element analyses (gold in ppb)
- Qtz sample for Au analysis (by fire assay, gold content in ppb)
- No outcrop
- Loose blocks in cliff face

**Kolb et al. (2011)**

**Au up to 50 ppm in lateral/frontal ramp systems, Au in Qtz-ankerite veins and in alteration zones**

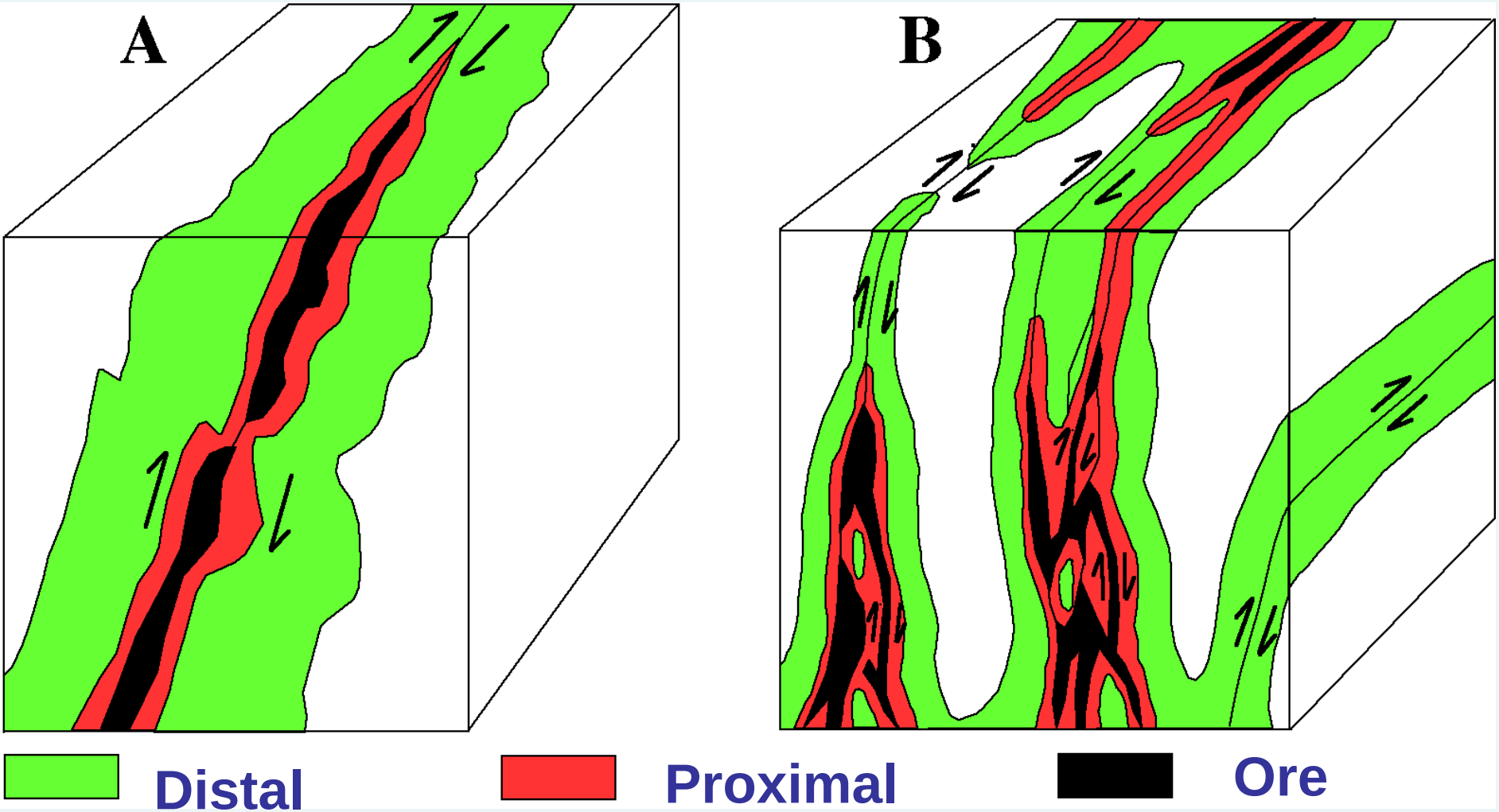
# Nuuluk profile at Edge of Eastern Carbonate Zone



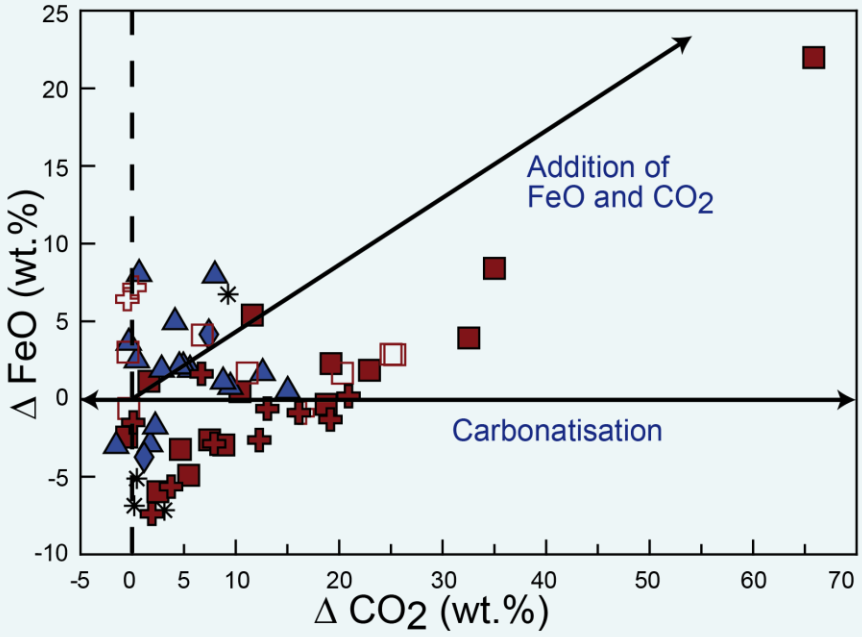

Schlatter and Kolb (2011)

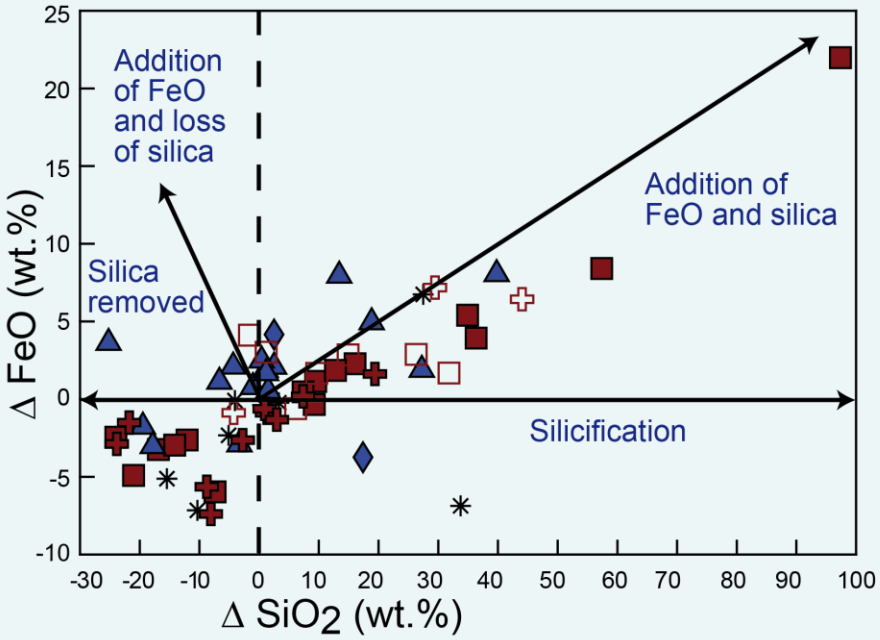
# Alteration envelope around orogenic gold mineralisation

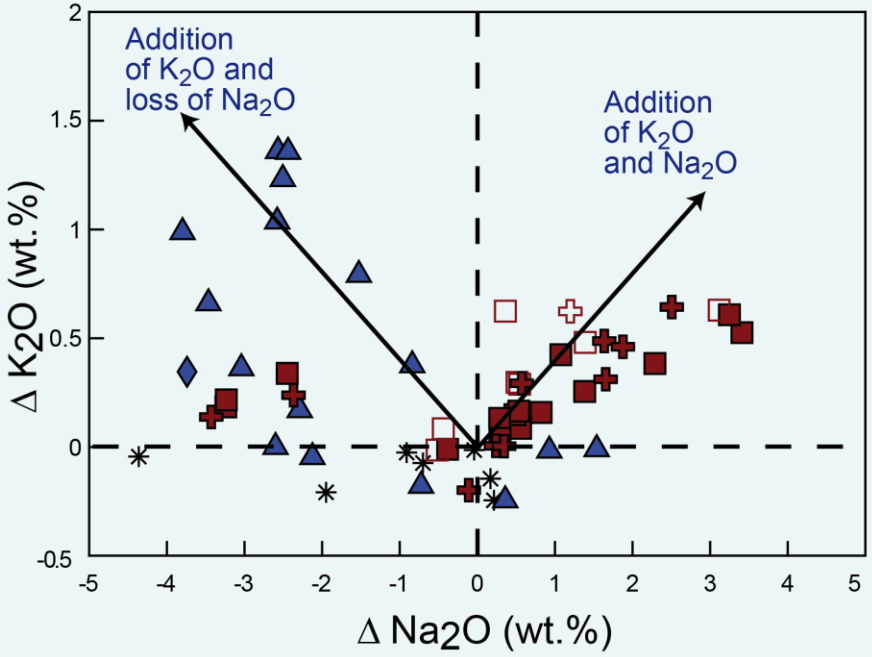



Pasi Eilu, 2014, revised after Colvine et al. 1988

# Hydrothermal alteration trends seen at Nuuluk




**Samples from the Western Carbonate Zone**

- Profile A
- Grab samples from magnetite schist and carbonate altered metavolcanic rocks

**Samples from the Eastern Carbonate Zone**

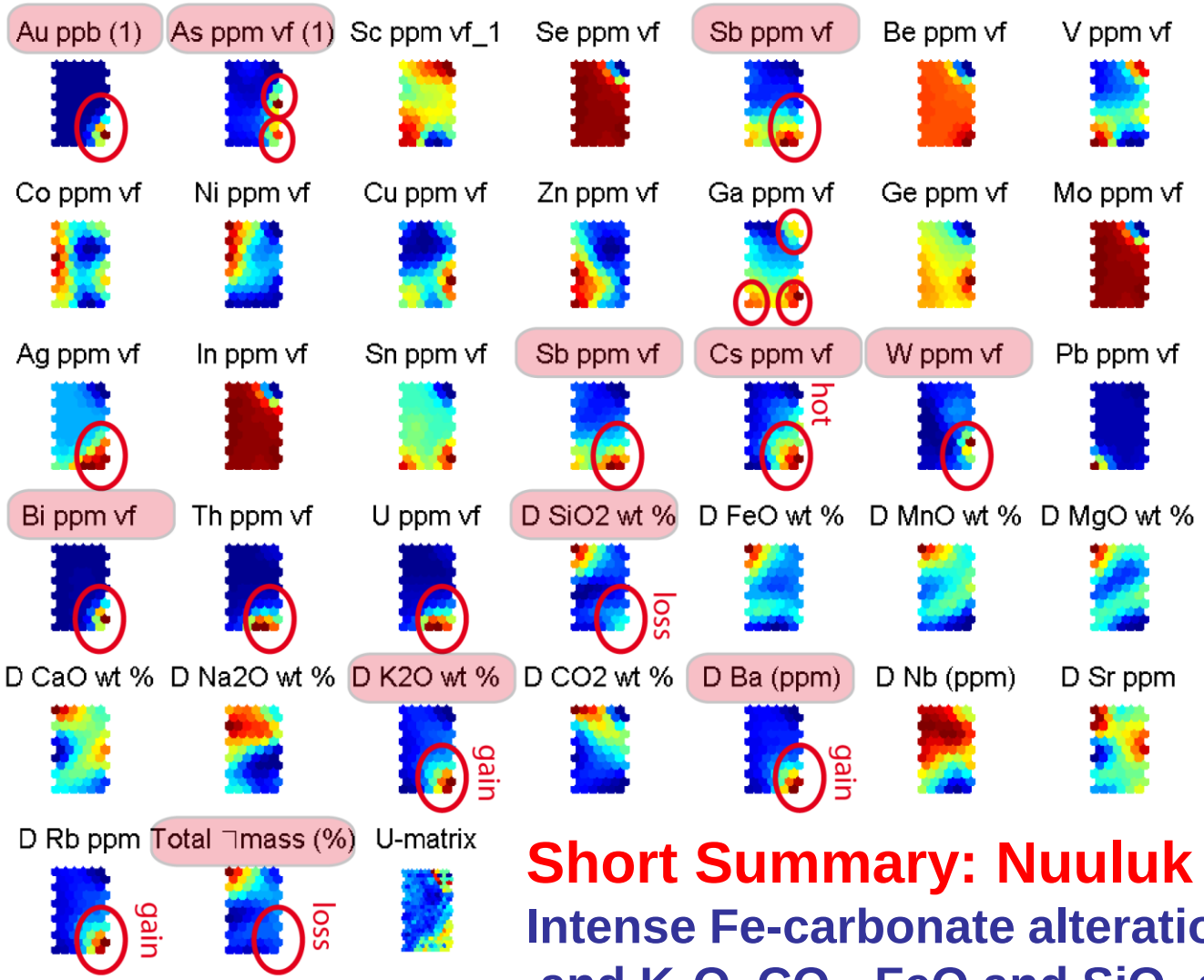
- Profile 1, Profile X, Profile 2
- Grab samples from altered metavolcanic rocks

**Samples from outside the carbonate zones**

- Grab samples from moderately altered metavolcanic rocks

**Schlatter and Kolb (2011)**

# Hydrothermal alteration trends seen at Nuuluk applying SOM methods



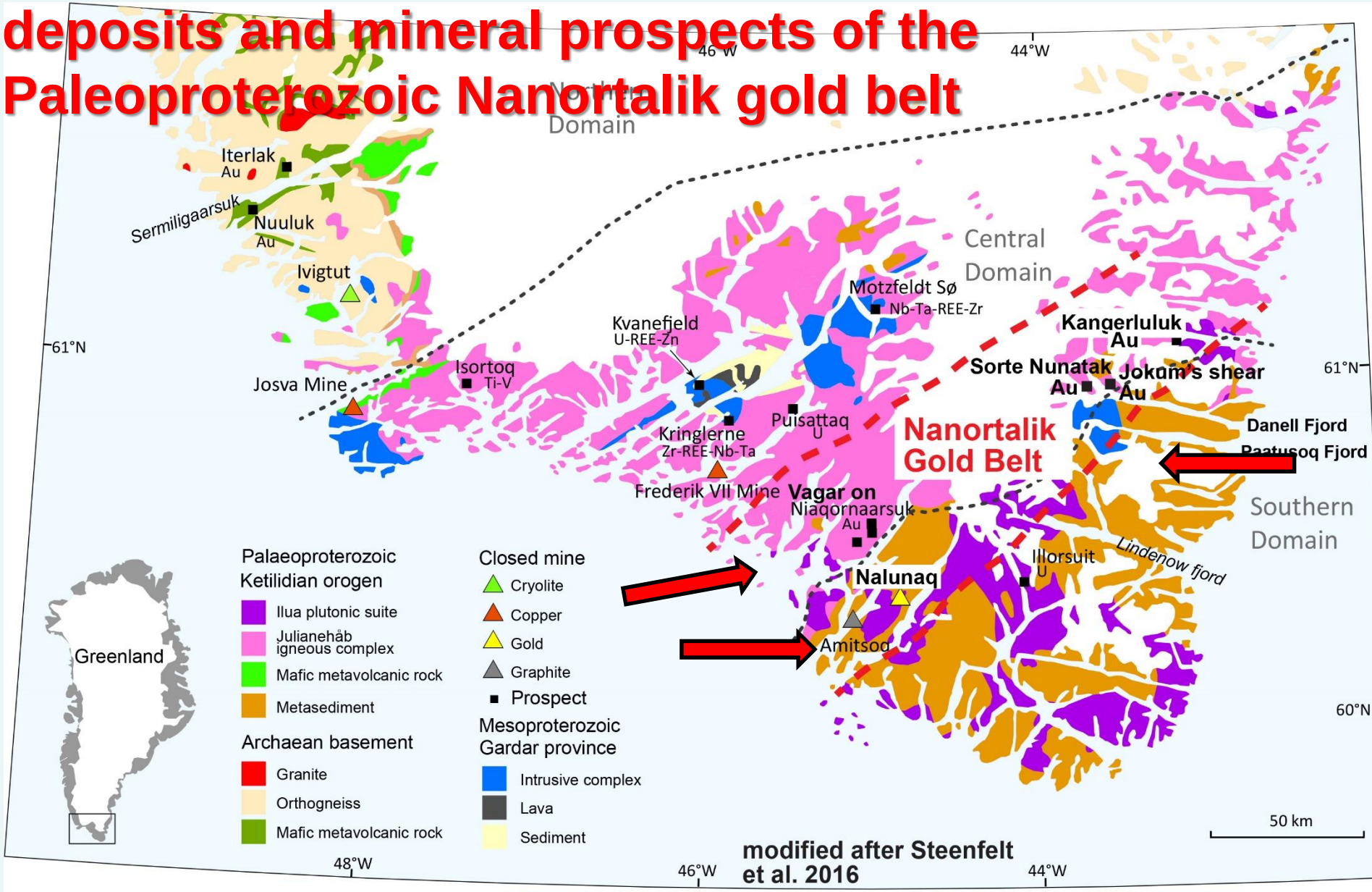

Schlatter and Kolb (2011)
SOM analysis by
Thorkild Rasmussen

## Short Summary: Nuuluk

**Intense Fe-carbonate alteration and $K_2O$, $CO_2$, FeO and $SiO_2$ added together with losses and gains of $Na_2O$**

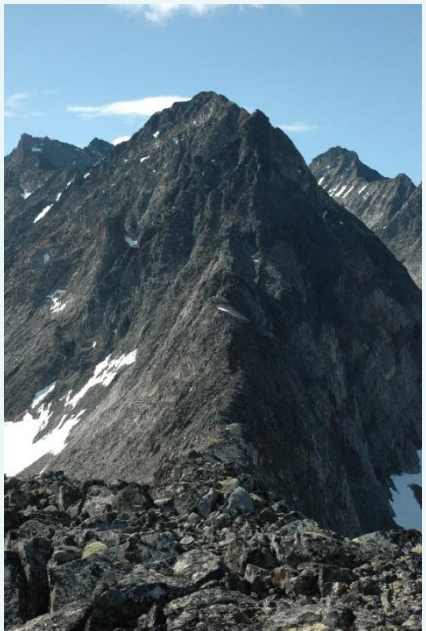
**Au associated with As, Sb, Cu, Ag, Cs, W, Bi**

# Geology of South Greenland and location of Au deposits and mineral prospects of the Paleoproterozoic Nanortalik gold belt



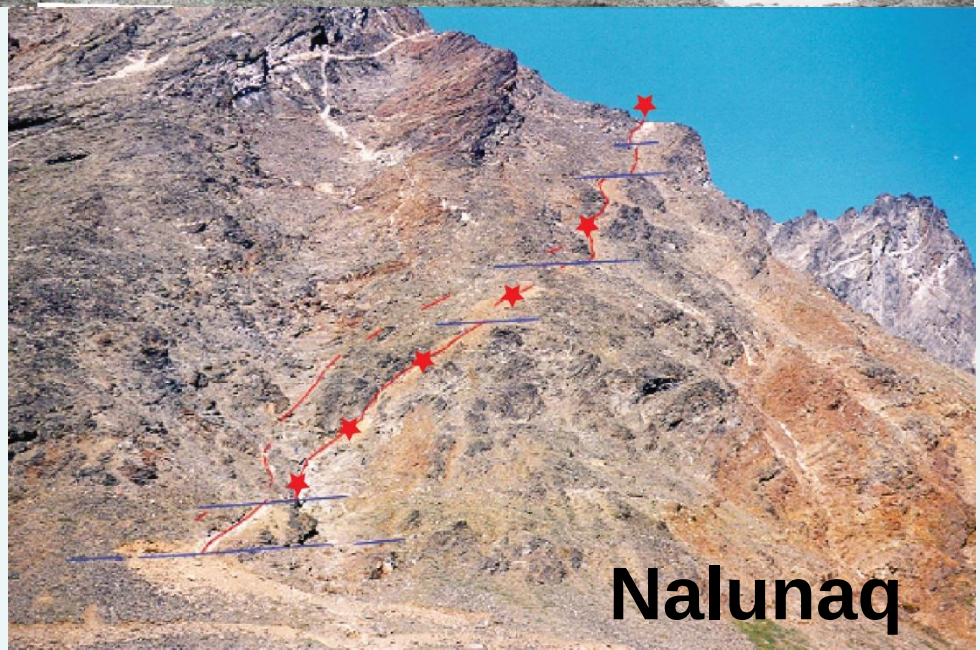

**Gold Belt is near the contact of granitic rocks and metasedimentary and metavolcanic rocks**

# Gold occurrences of the Nanortalik gold belt from shear zone hosted Nalunaq and Vagar

Vagar

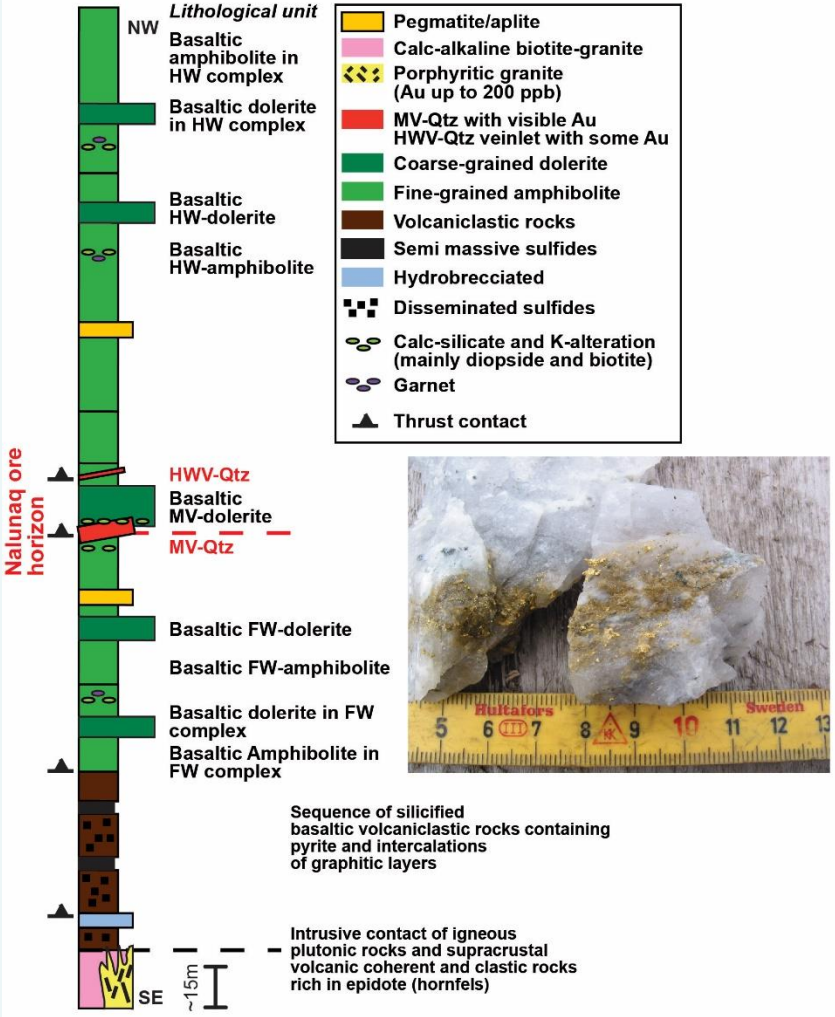
Schlatter and Hughes (2014)



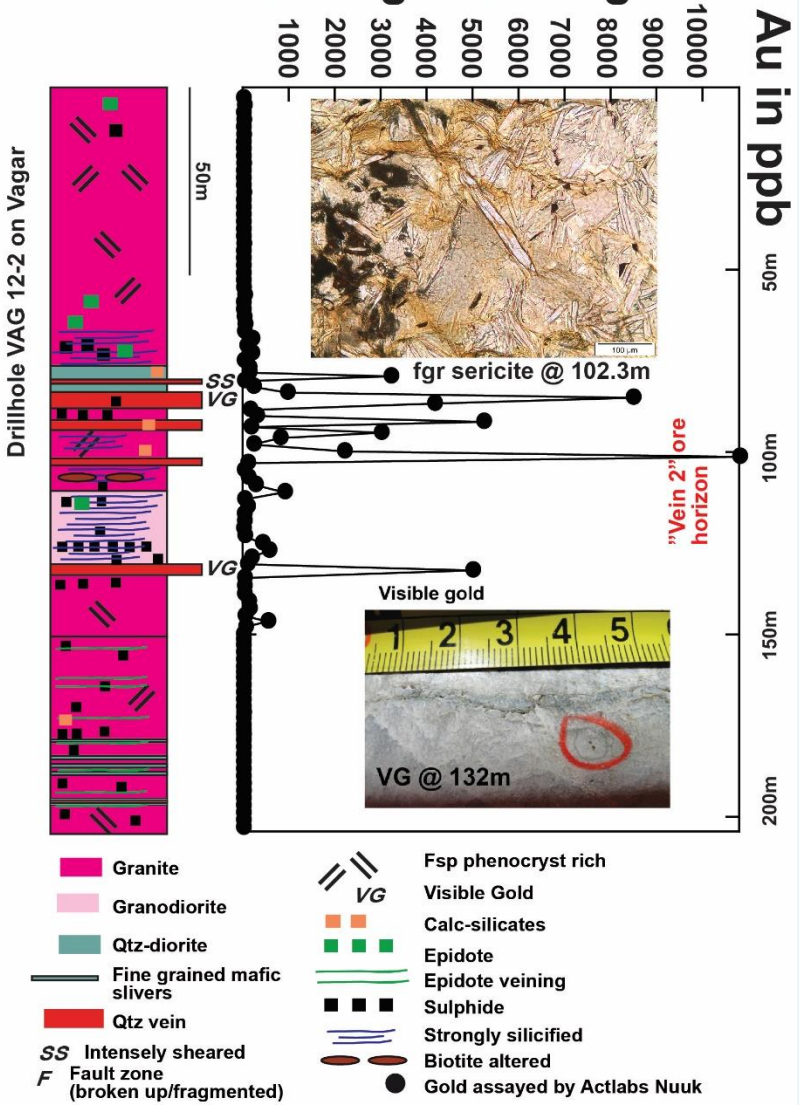
Nalunaq

# Comparison of Au settings from Nalunaq and Vagar

## Tectonostratigraphic sequence across the Nalunaq Au ore horizon



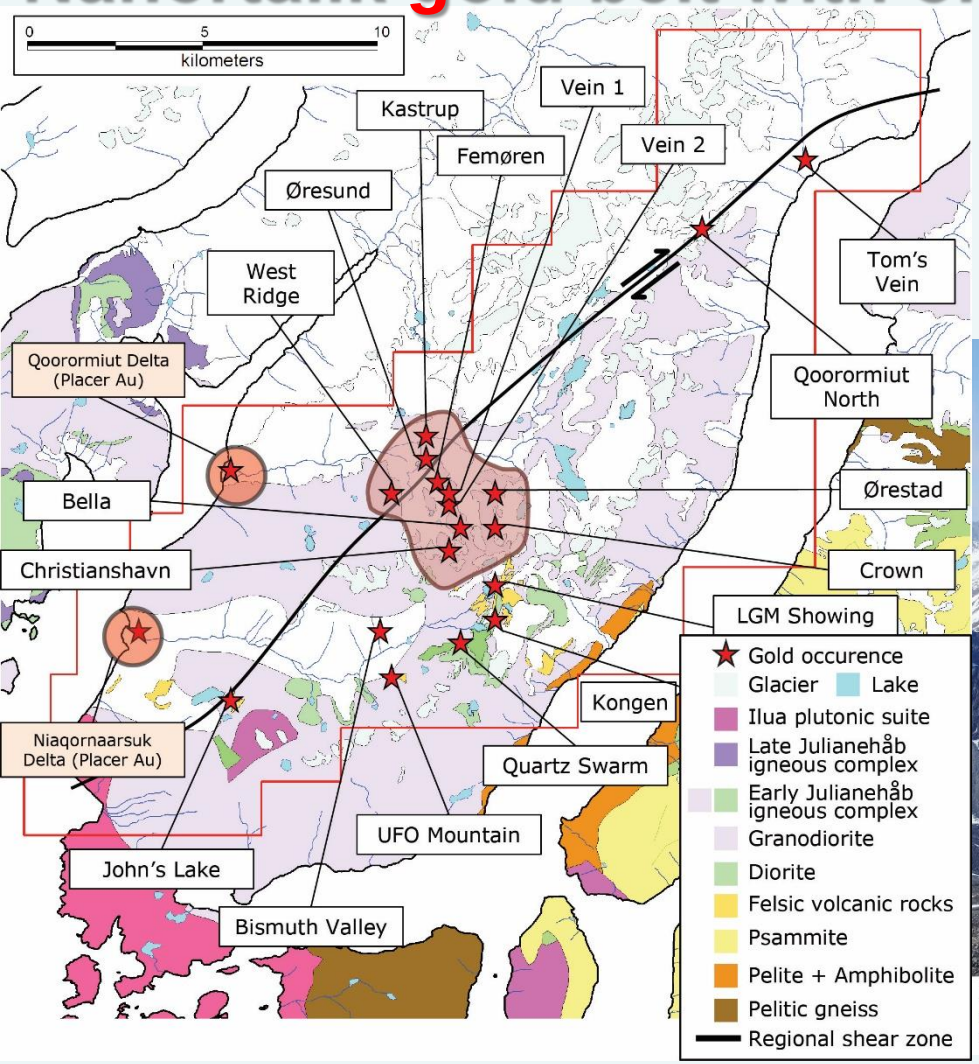

## Drill core log across the ore horizon of the "Vein 2" target on Vagar



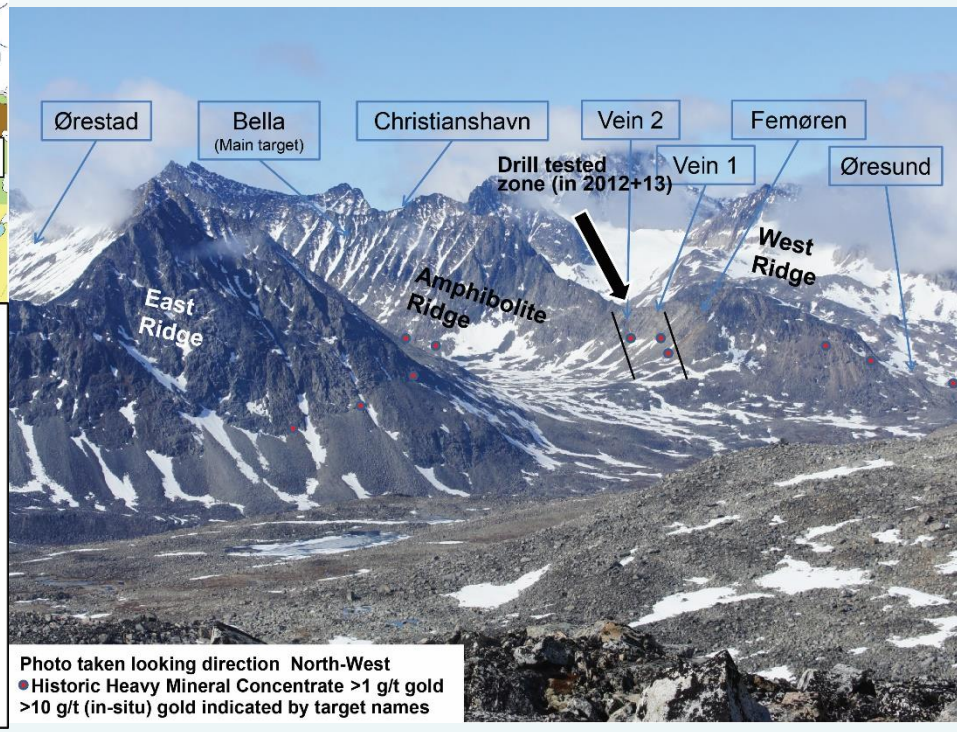

Schlatter and Kolb (2011); Schlatter et al. (2013)

**Both deposits are hosted mainly in Qtz veins but in different host rocks; Nalunaq: 10.7 t of gold, 15g/t, 713'000t ore, Vagar: 79m with 0.9 g/t Au**

# The Vagar license and the gold occurrences on the Niaqornaarsuk peninsula with 18 targets of the Nanortalik gold belt with only one target drilled



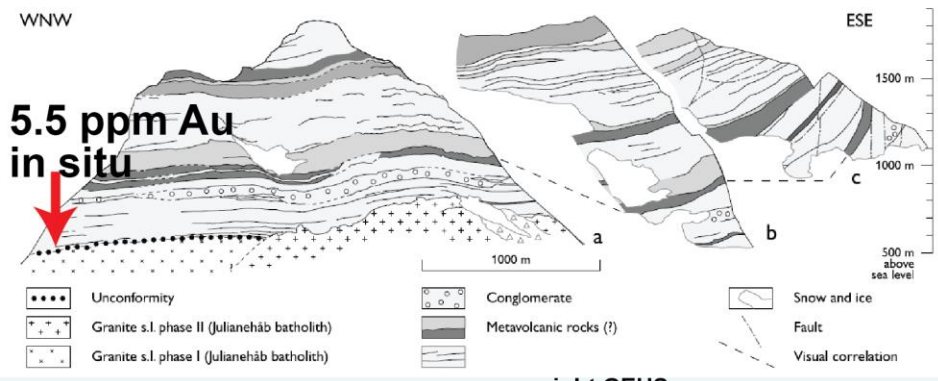

**Schlatter and Hughes (2014)**




**The geology of Vagar is dominated by granitoid rocks and a regional shear zone. Each target shows Au in situ > 10 ppm**

# Gold occurrences of the Nanortalik gold belt in South East Greenland

## Sorte Nunatak


copyright GEUS

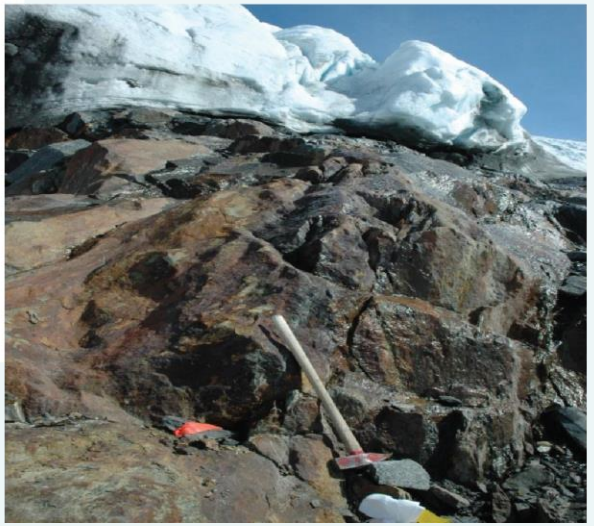
Auriferous quartz with 5.5 ppm gold and GEUS sample with 9 ppm Au and 4% Cu

## Kangerluluk

Schlatter and Hughes (2014)

Auriferous shear-hosted quartz veins up to 20 m wide; grab samples up to 17.5 ppm Au

## Jokum's shear

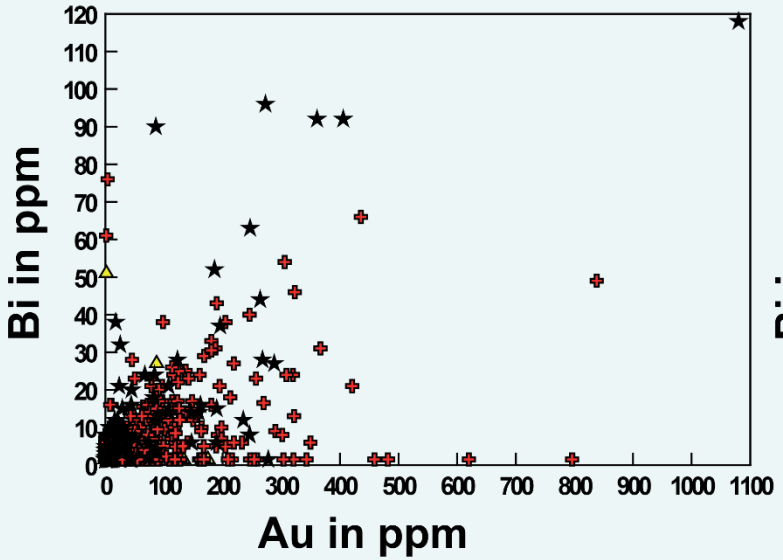


3.1 m @ 9.3 ppm Au in silicified and sulphidised rocks

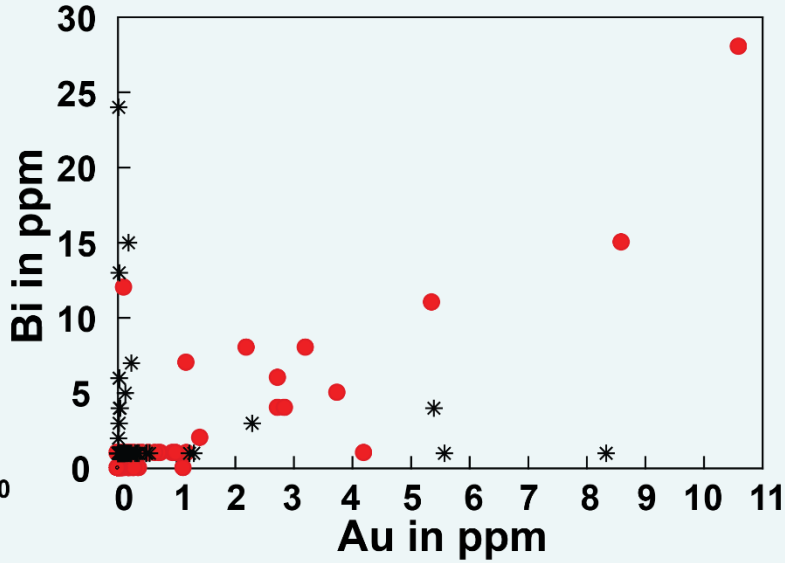
**Gold mineralization occur in a variety of different host rocks**

# Au-Bi relation from Nalunaq, Vagar and Jokum shear

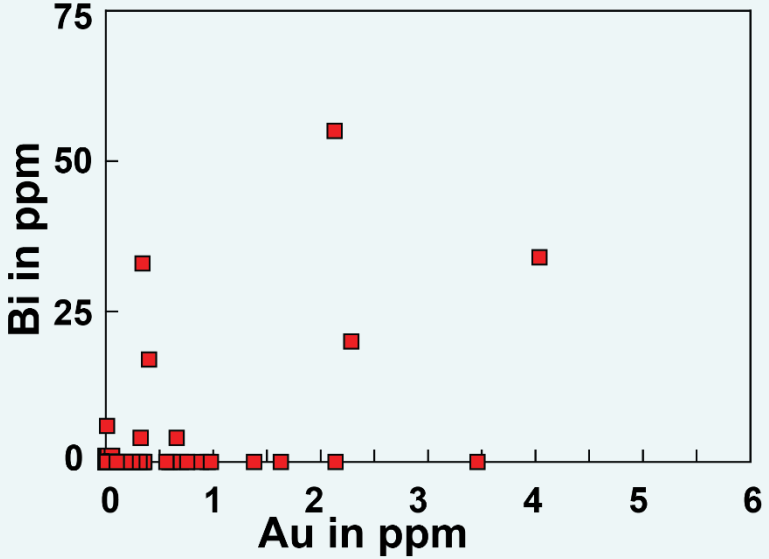
## Nalunaq (past gold mine)




## Vagar (drilled project)

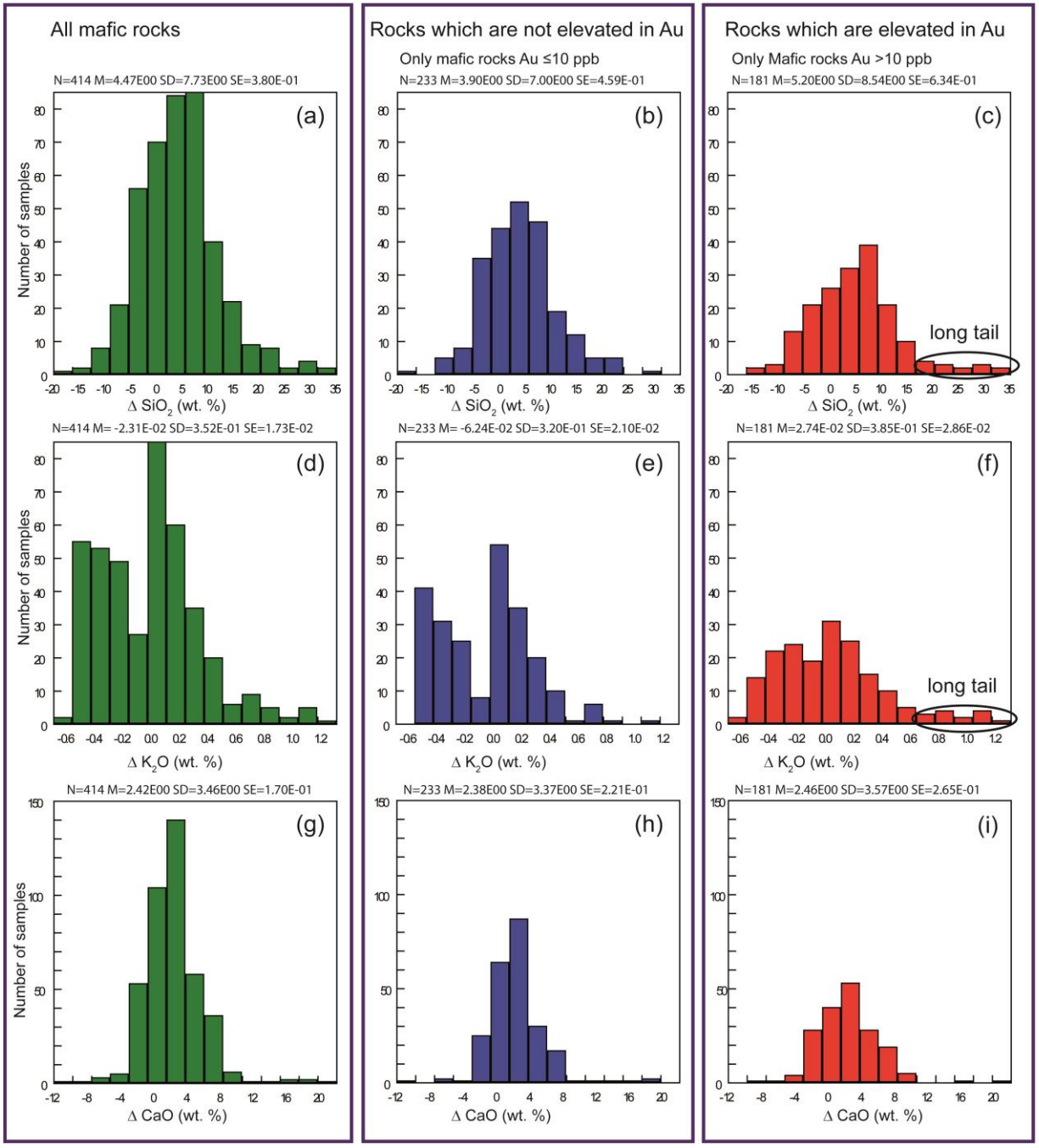



## Jokum's shear (exploration project)




**Other pathfinder elements for gold are Ag, As, Sb and W**

Schlatter and Hughes (2014)

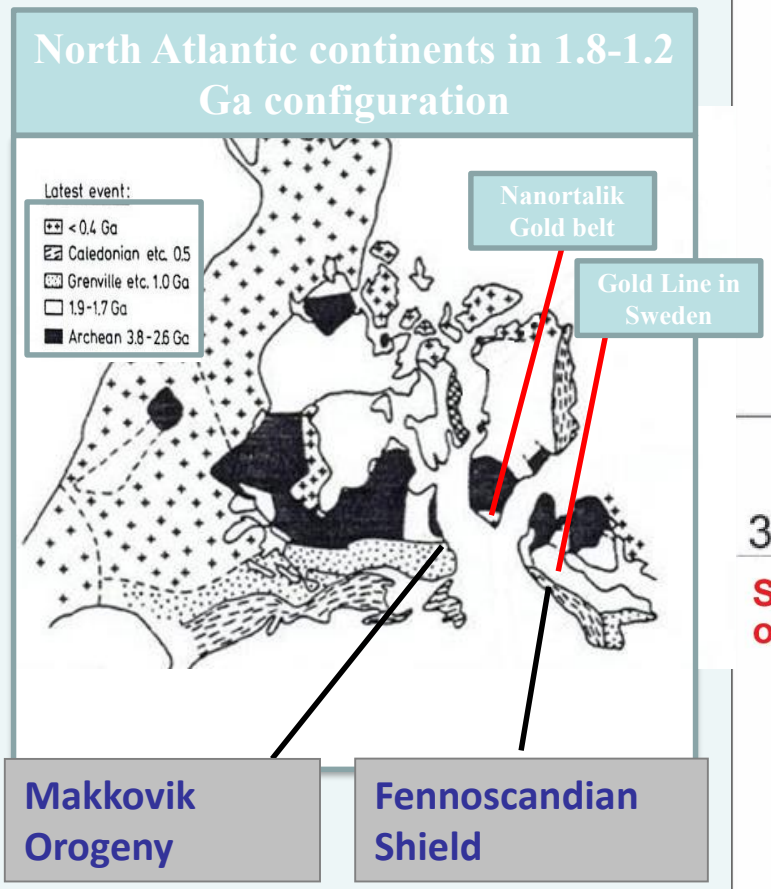



# Short Summary South Greenland gold:

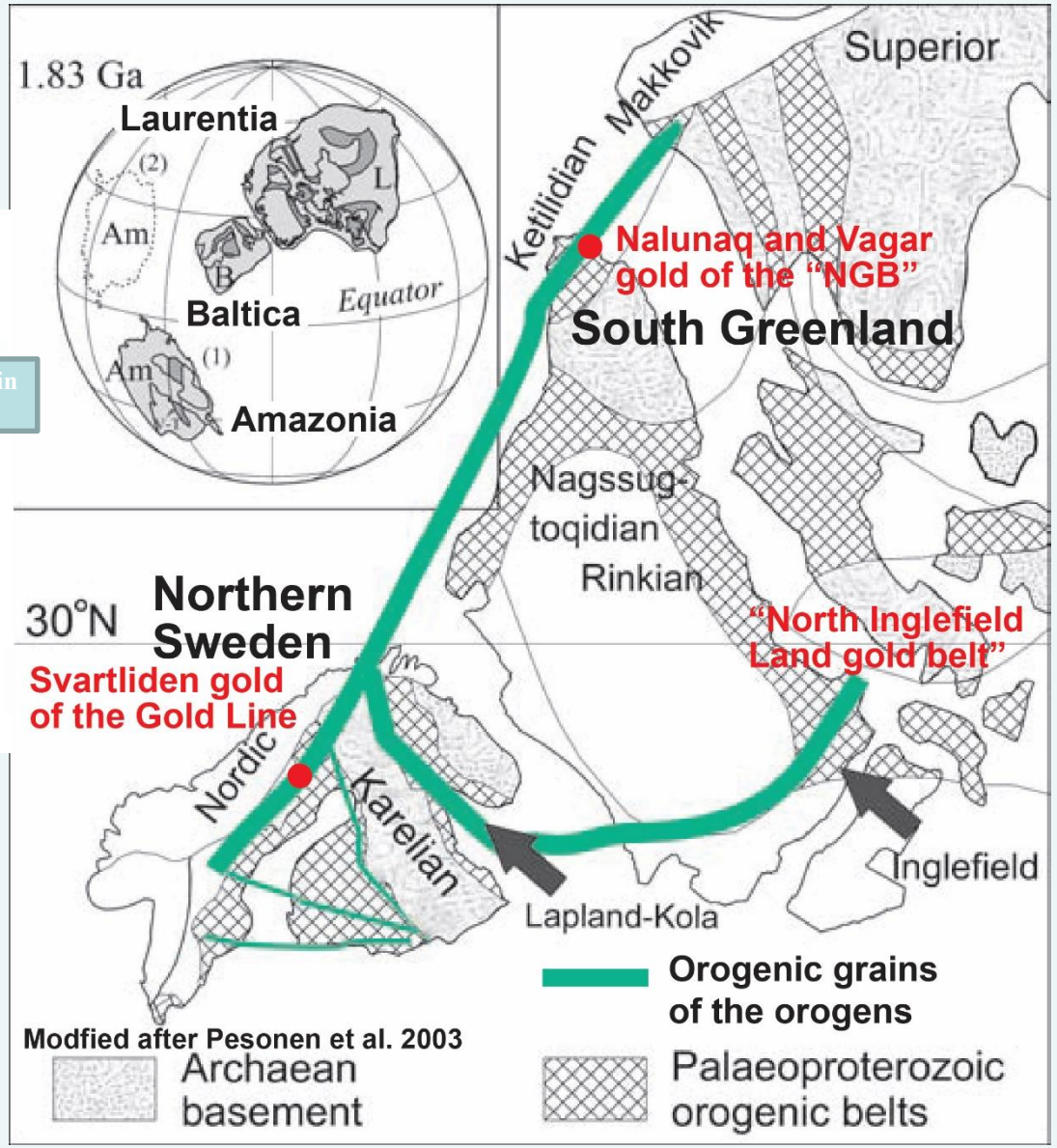
## Mass change calculations from samples from Nalunaq show that silicificaiton and addition of K represents favorable alteration and related to gold introduction

**Schlatter and Kolb (2011)**

# Reconstruction of the c. 1.8 supercontinent and location of Vagar gold on Laurentia and Svartliden gold on Baltica



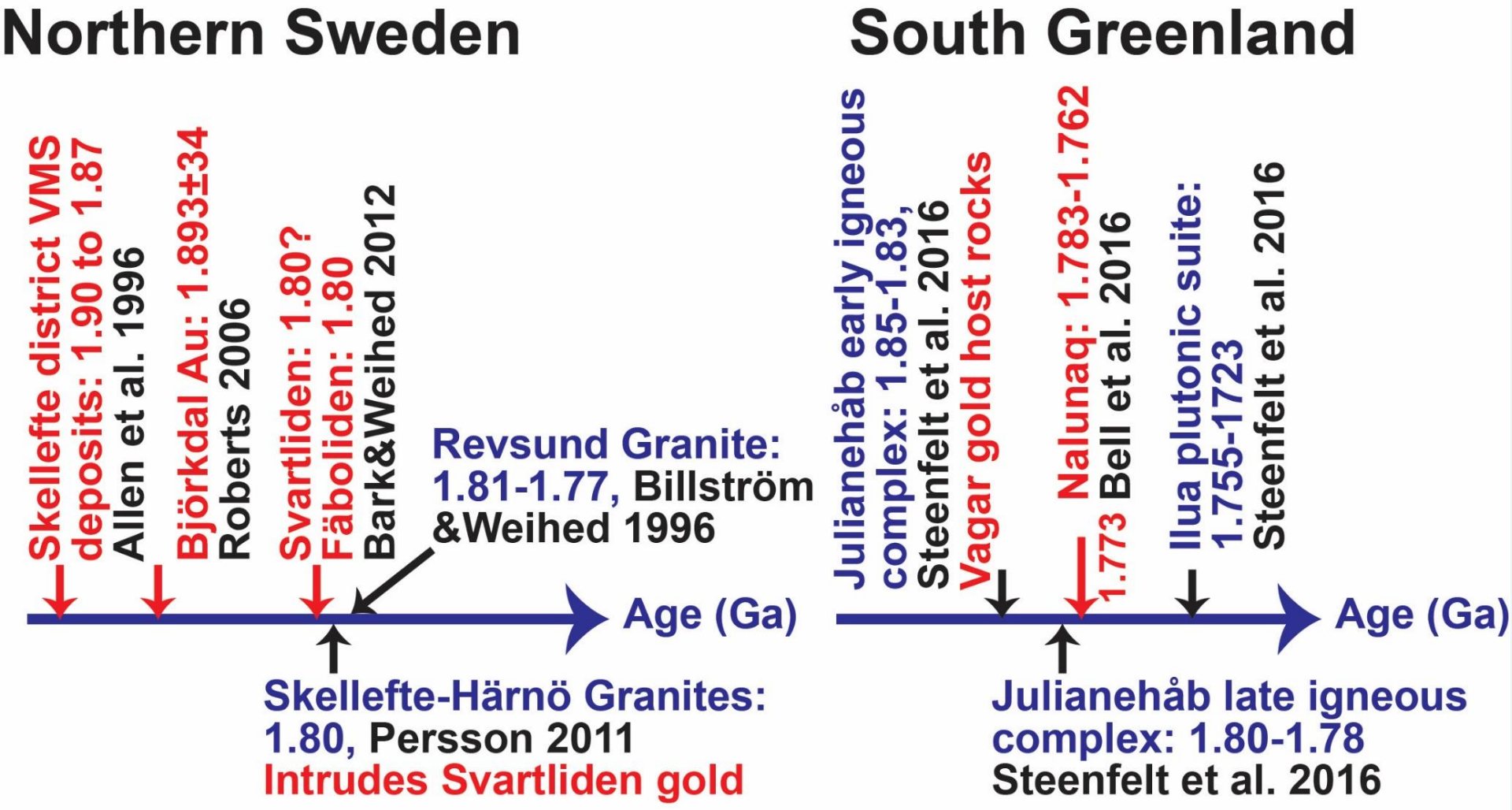

Patchett and Bridgwater, 1984




Lahtinen et al. (2008)

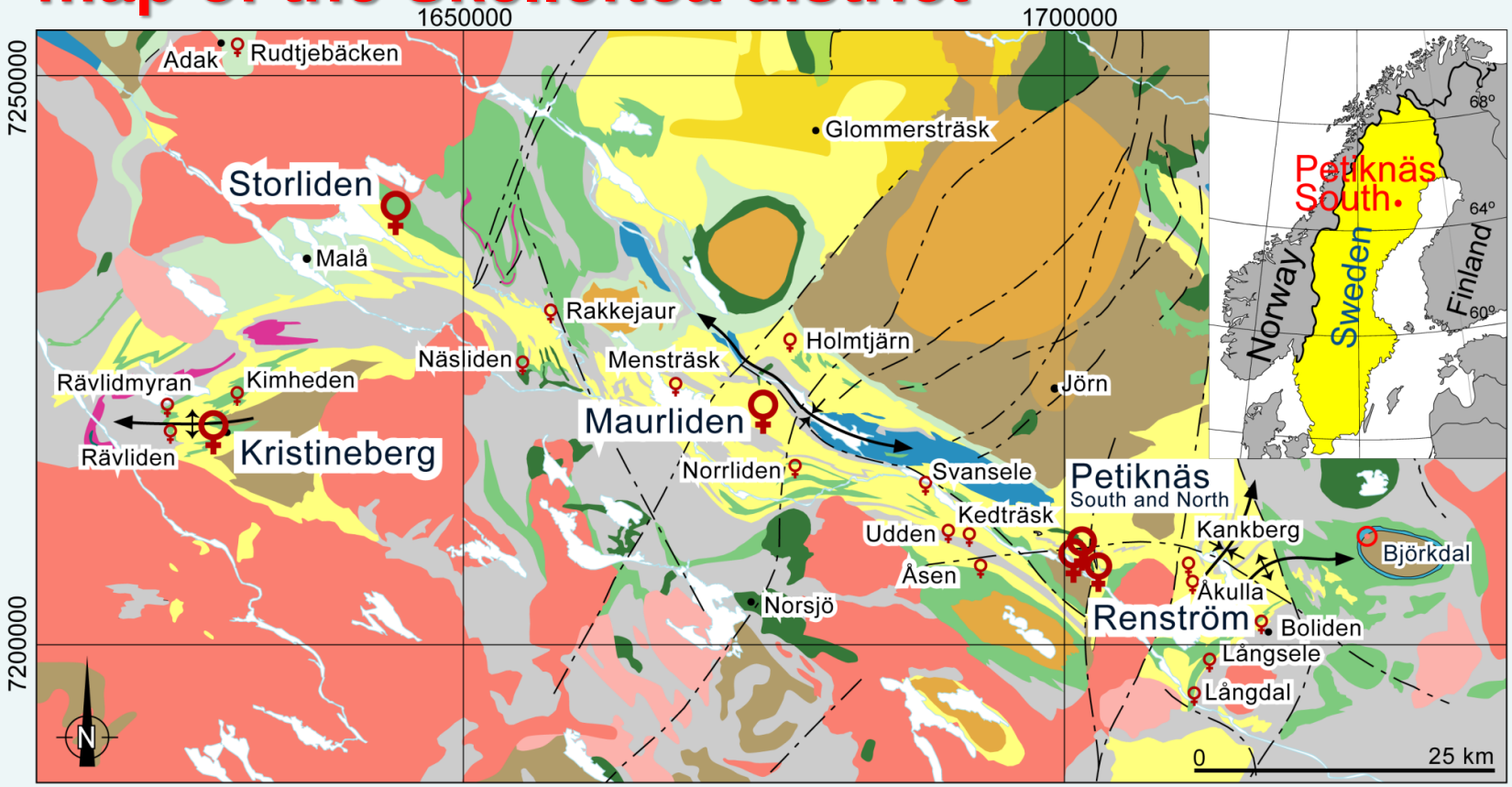
Location of Svecofennian orogeny (Nordic on map) and Ketilidian orogeny

# Comparison of granitoid ages of the Svartliden and Nalunaq mining areas




Schlatter et al. (2016)

# Case study from Sweden: Simplified geological map of the Skellefteå district




Post-volcanic granitoids of A- and I-type (Revsund type), c. 1.82-1.78 Ga

Post-volcanic granitoids of S-type (Skellefte type), c. 1.82-1.80 Ga

Gabbro and diorite

Ultramafic intrusions

Synvolcanic granitoids of I-type (Jörn III granit, Gallejaur monzonite) c. 1.87- 1.85 Ga

Synvolcanic granitoids of I-type (Jörn II granodiorite), c. 1.87 Ga

Synvolcanic granitoids of I-type (Jörn I tonalite and undivided) c. 1.89 Ga

Conglomerates and sandstones, polymict (Vargfors and Ledfat Groups) c. 1.87-1.85 Ga

Basalt-andesite and minor dacite lavas and sills (Vargfors Group), c. 1.88 - 1.86 Ga

Mudstone, black shales, sandstones and turbidites (Bothnian Group, Vargfors Group, Skellefte Group) c. >1.95 - 1.85 Ga

Subaerial to shallow water basalt-andesite (Arvidsjaur Group) c. 1.88 -1.87 Ga

Subaerial to shallow water rhyolite, dacite and minor andesite (Arvidsjaur Group), c. 1.88 - 1.87 Ga

Basalt-andesite and minor dacite lavas and sills, mainly submarine (Skellefte Group), c. 1.89 - 1.87 Ga

Rhyolite, dacite and minor andesite, mainly submarine (Skellefte Group), c. 1.90 - 1.87 Ga

Major VMS deposits

Major gold deposits

Antiform with plunge

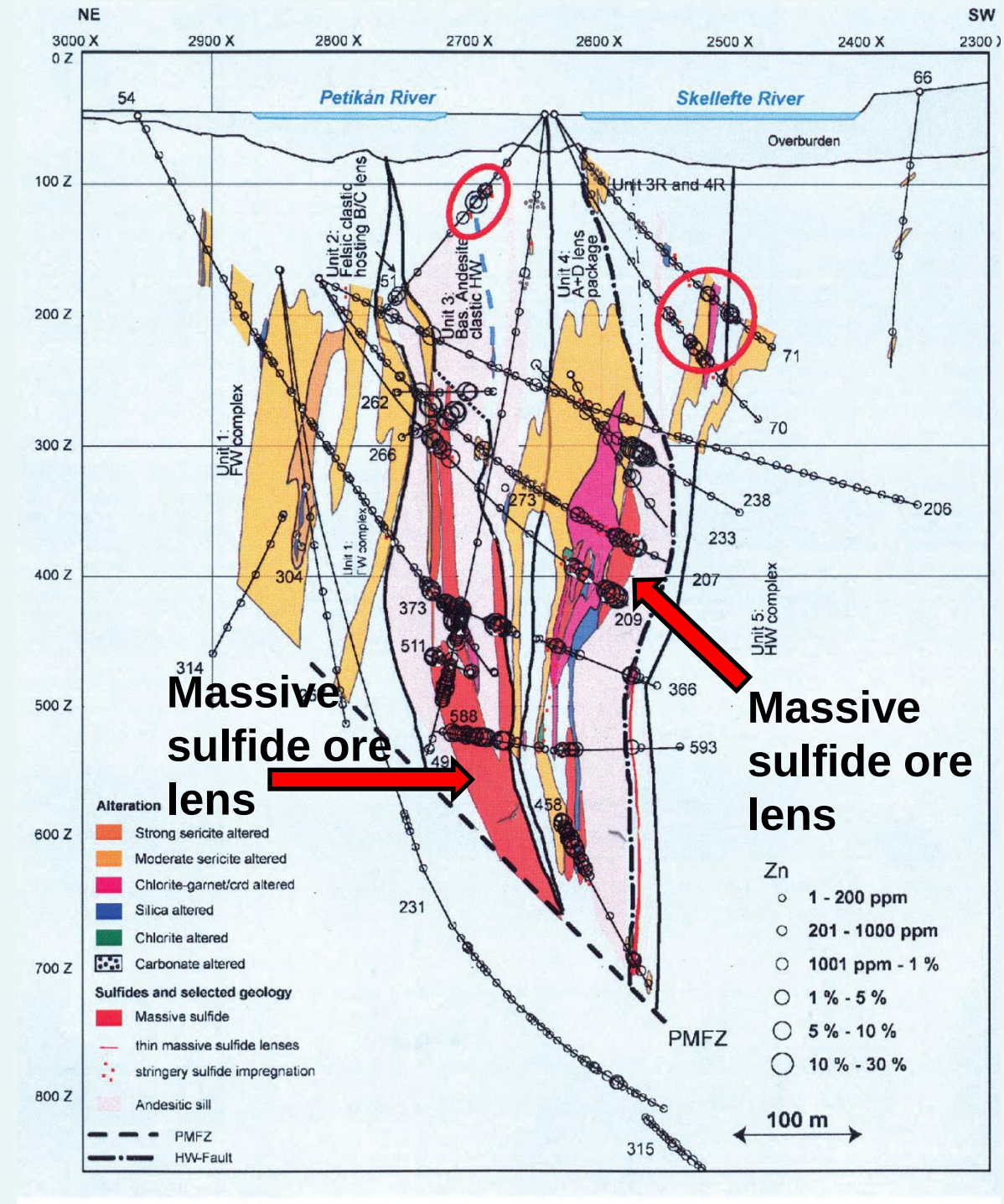
Synform with plunge

Major faults and shear zones

**Petiknäs South: mined between 1992 and 2006:**

**5.3 Mt at**
**4.9% Zn**
**0.9% Cu**
**0.9% Pb**
**31% S**
**2.4 g/t Au**
**102 g/t Ag**

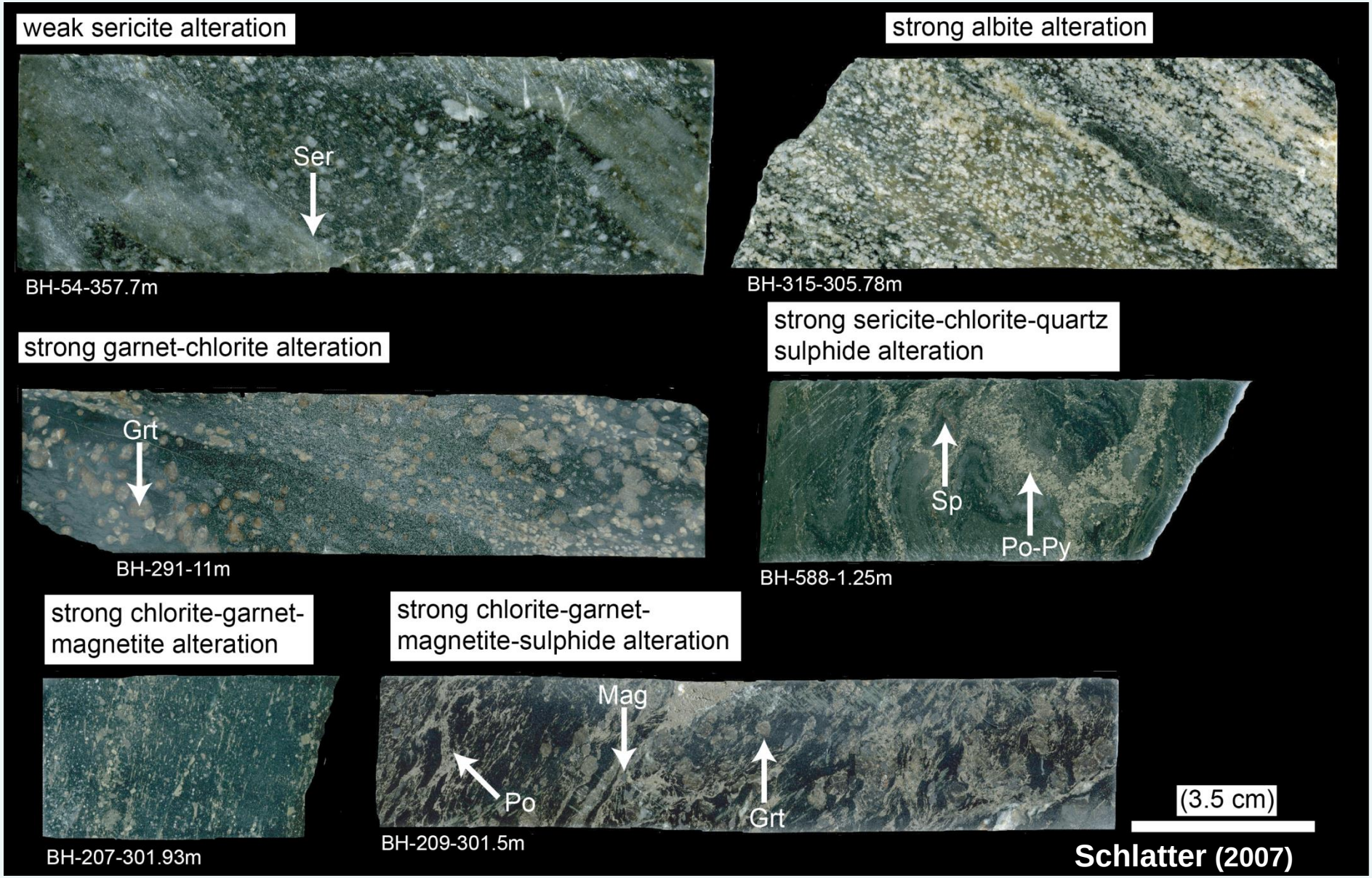
**Allen et al. (1996)**




# Petiknäs South: Alteration systems, and geochemistry as seen from the Zn dispersion

Schlatter (2007)

# Alteration minerals typically seen from alteration zones of VMS deposits, rock samples

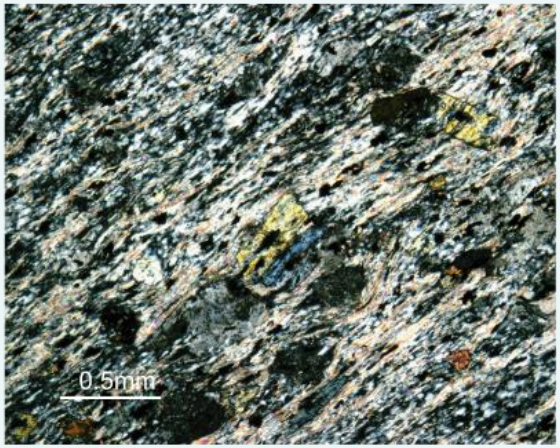


# Alteration minerals typically seen from alteration zones of VMS deposits, petrographic thin sections

Plagio which likely is completely replaced by quarz


PETS-BH291-23.6m (U1)

Zoisite porphyroblasts

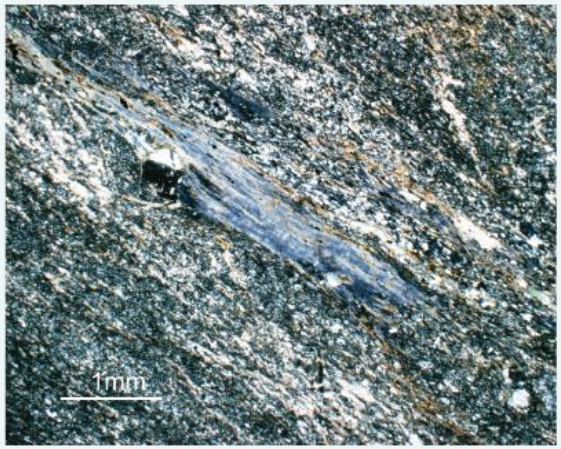



PETS-BH54-488.85m (U3)

Porphyroblast consisting of Plagioclase, K-Fps and Qz

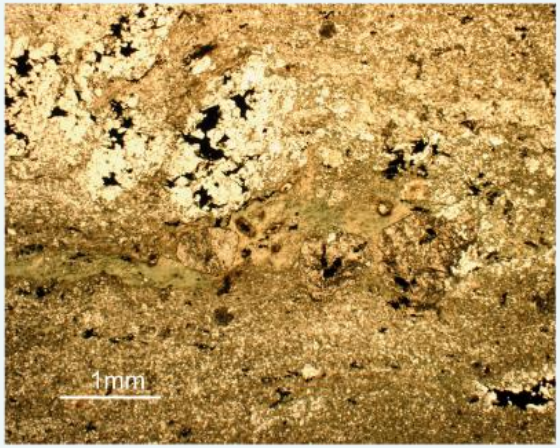

PETS-BH207-271.8m (U4)

Chlorite altered pumice clast



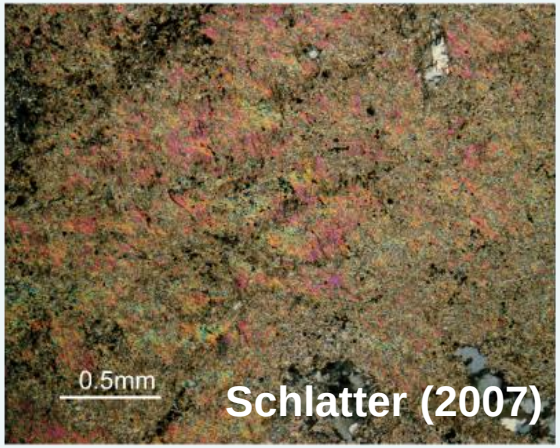

PETS-BH72-43.75m (U3)

Garnet porphyroblasts




PETS-BH207-281.35m (U4)

Pervasive sericite altered

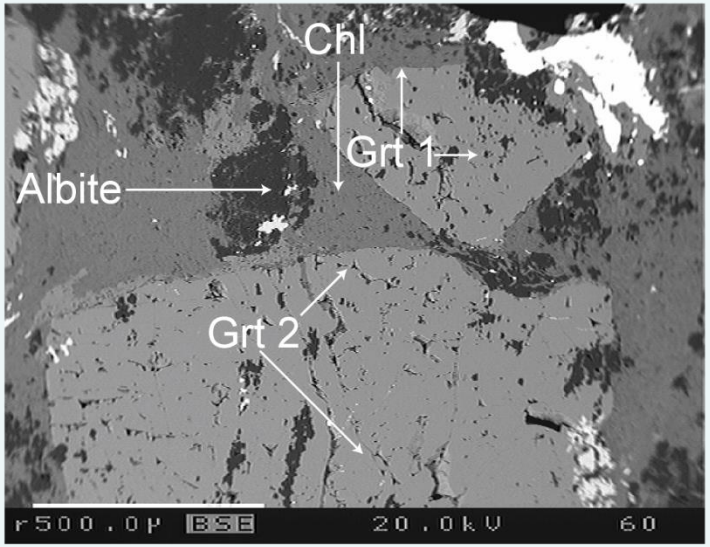



PETS-BH511-27.45m (U2)

# Alteration minerals seen proximal to Petiknäs South

Garnet porphyro-blast


Unit 4 Photo-micrograph (PPL)




Backscattered electron image

**MnO; FeO atomic wt%**

Grt 1: center 17.3; 17.7

Grt 1: rim 14.5; 20.2

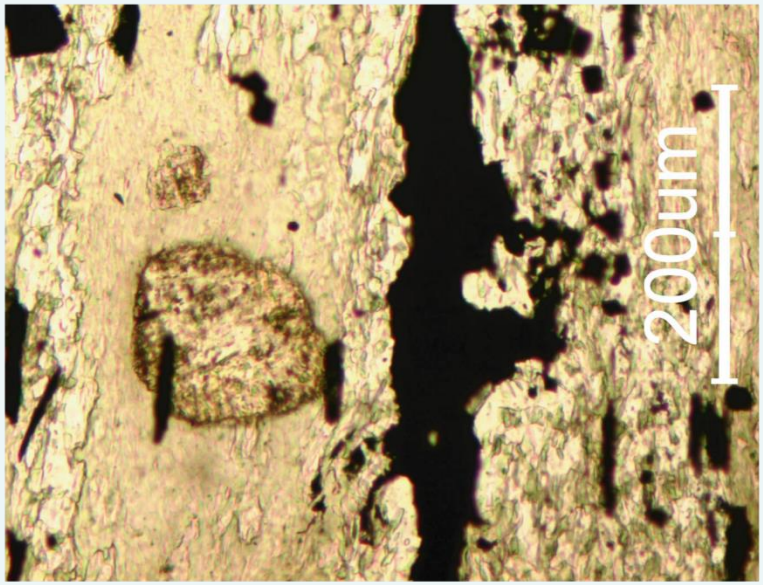
Grt 2: center 20.5; 13.6

Grt 2: rim 15.4; 19.5

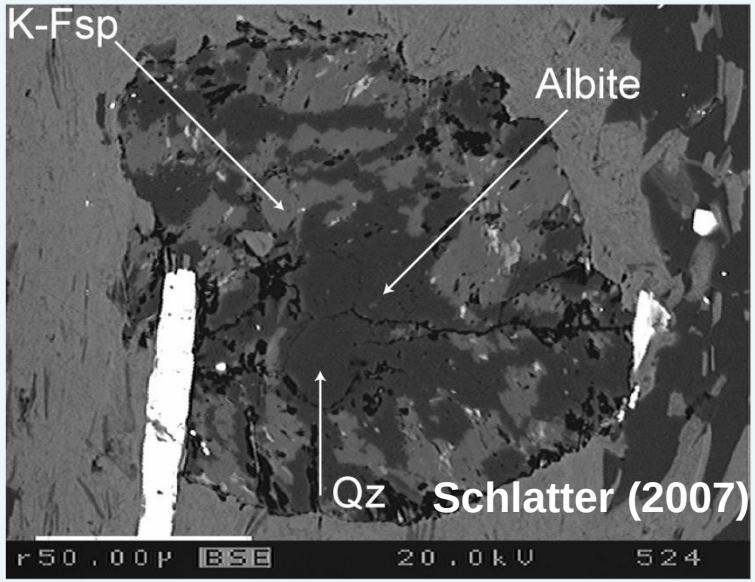
**$Al_2O_3$; CaO; MgO average atomic wt%**

20.0; 6.4; 0.4

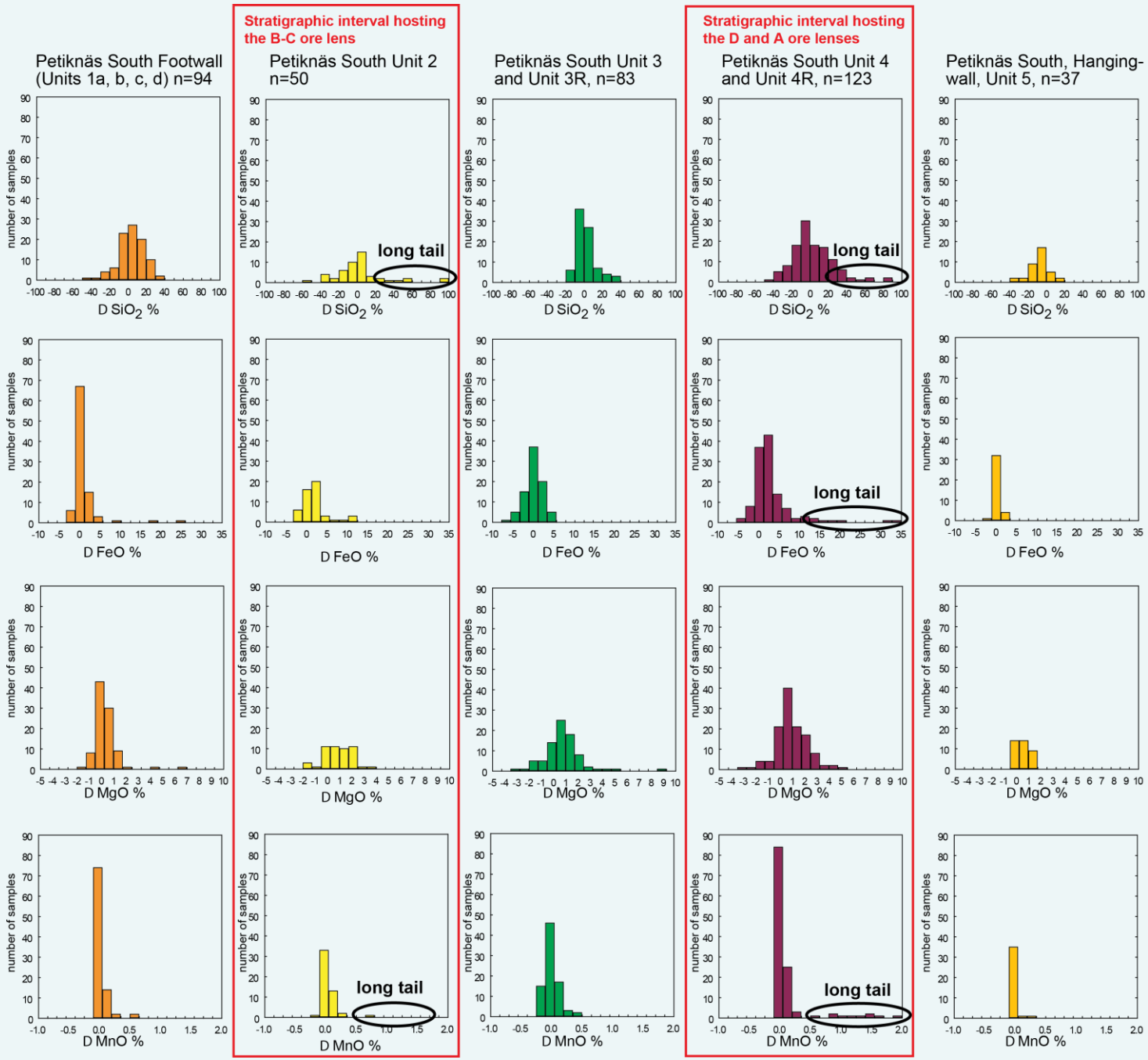
Feldspar porphyro-blast




Unit 4R Photomicrograph (PPL)




Backscattered electron image

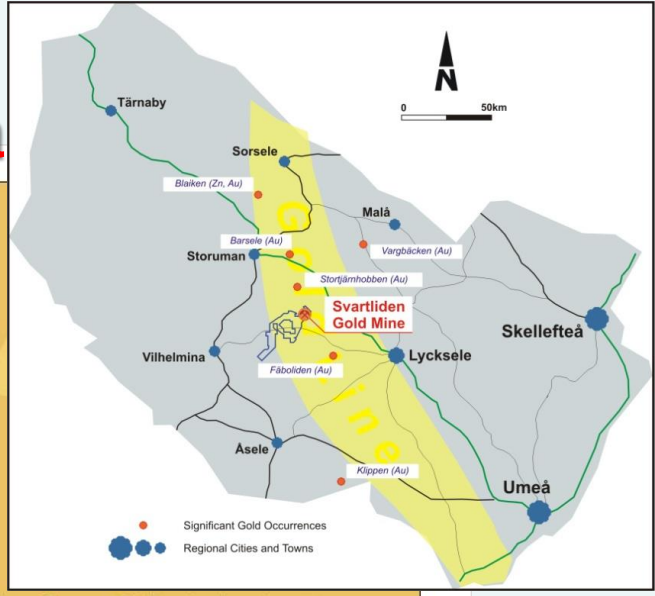


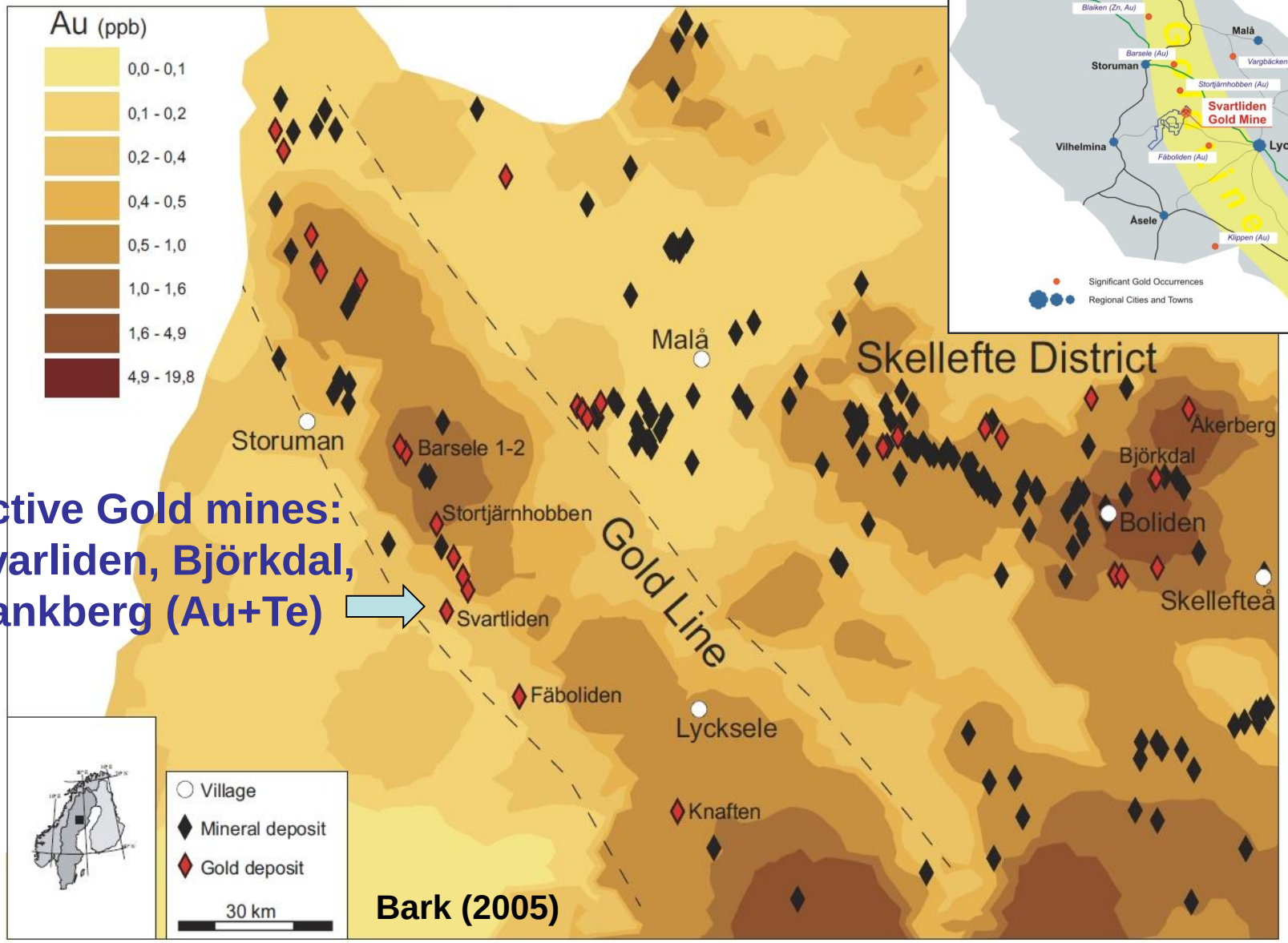

# Short Summary: Petiknäs S.

**Largest mass changes occur in the units that host the ore lenses, largest mass changes in $\Delta SiO_2$, $\Delta FeO$ and $\Delta MnO$ reflecting silicification addition of Mn-rich garnet and Fe rich chlorite**

Schlatter (2007)

# Gold anomalies of till overburden in the Gold Line and Svarliden area



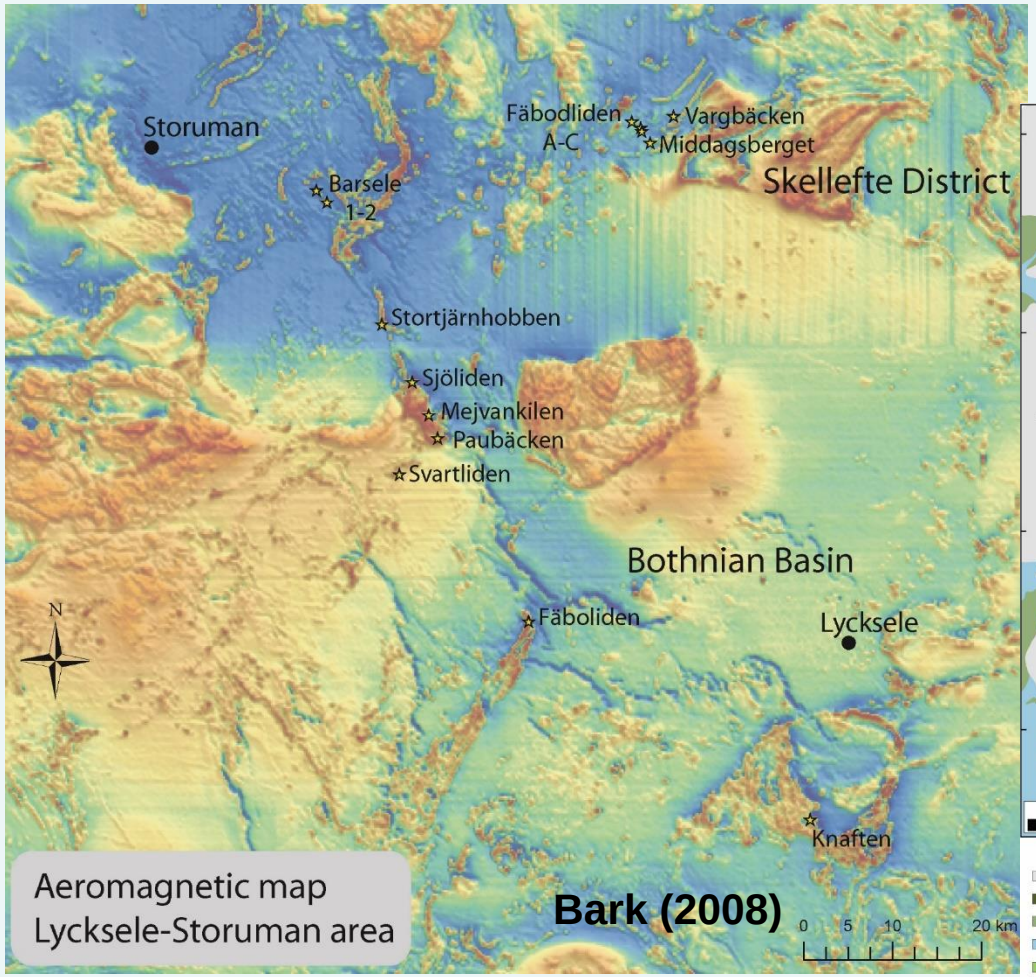



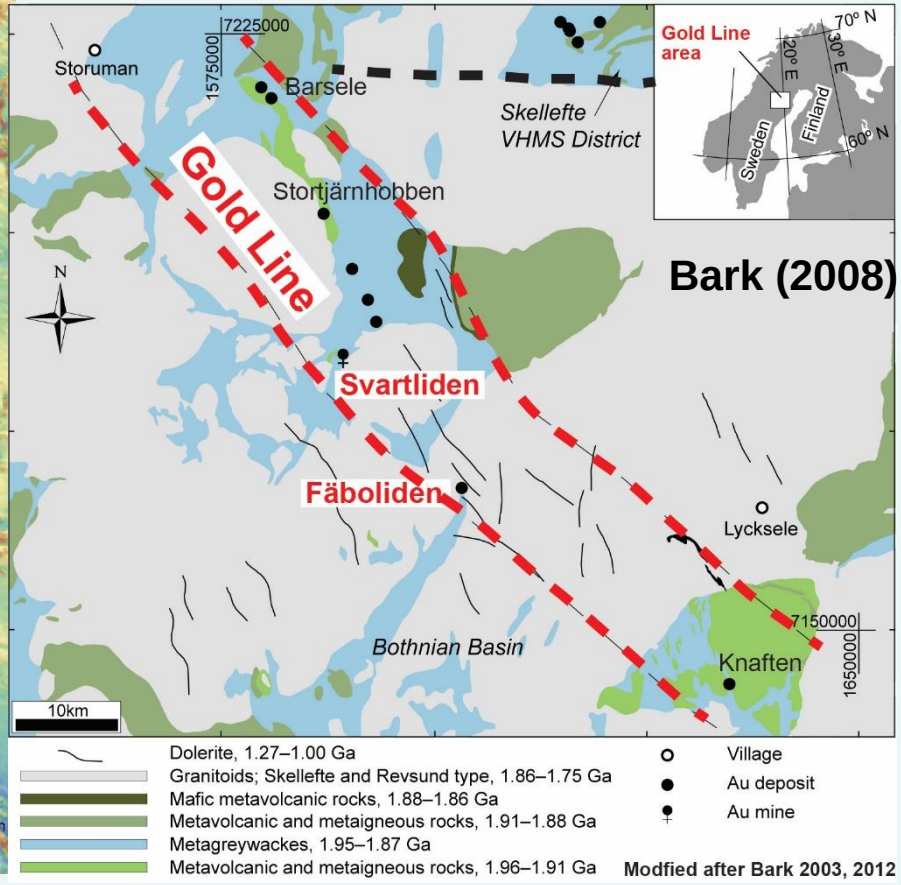

**Active Gold mines: Svarliden, Björkdal, Kankberg (Au+Te)**

**Bark (2005)**

**The Gold Line is > 170 km long and about 50 km wide**

# Aeromagnetic survey covering the Bothnian group and the Skellefteå district and geological map of the Svartliden area that is dominated by granitoids



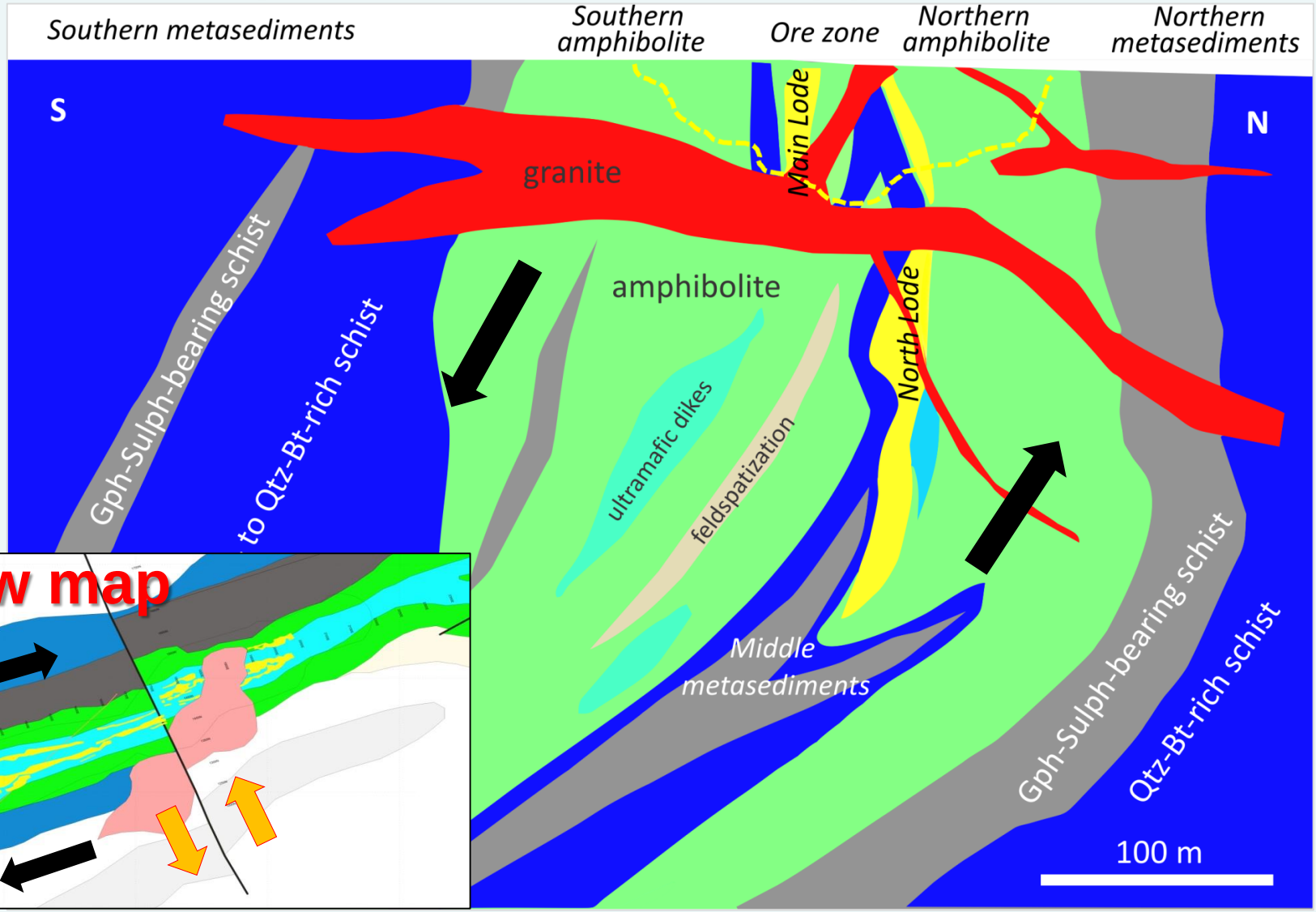




**Svartliden is located in metavolcanic-sedimentary sequences and is spatially associated with calc-alkaline granites**

# Svartliden Au deposit: 2.97 Mt, 4.26 ppm, >300’000 oz

## Cross section

Schlöglova et al. (2013)

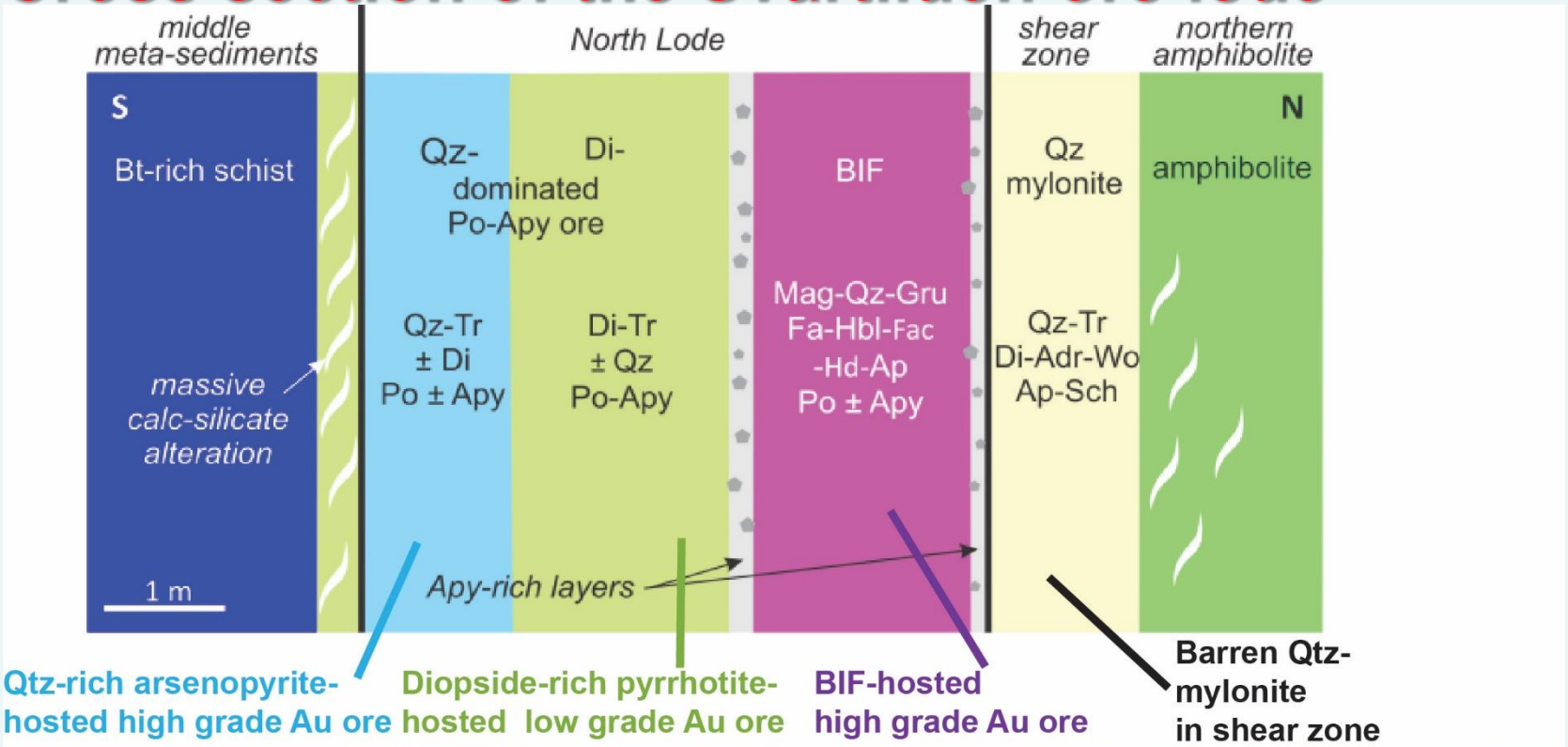


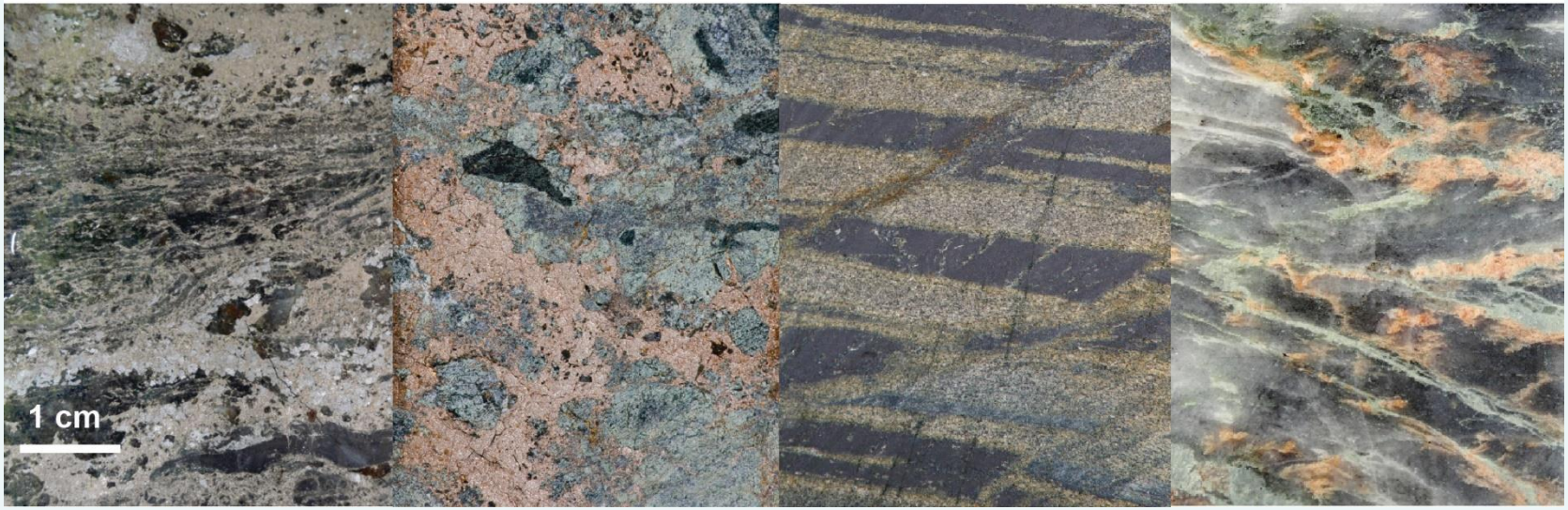

## Top view map




**Volcano-sedimentary sequence metamorph. and deformed under ductile amphibolite facies conditions, cross-cut by granite. Hypozonal orogenic Au mineralization at contact of amphibolite and metasediments, and BIF**

# Cross section of the Svartliden ore lode




Schlöglova et al. (2013)

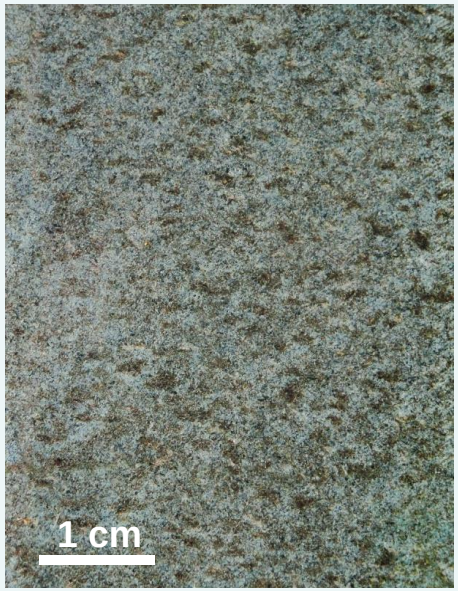
Ore is hosted by K-, Si- and Ca-altered amhibolite + schist, and BIF, accompanied by barren Qtz-mylonite (fill of the shear zone)

# Short Summary Svartliden host rocks and hydrothermal alteration

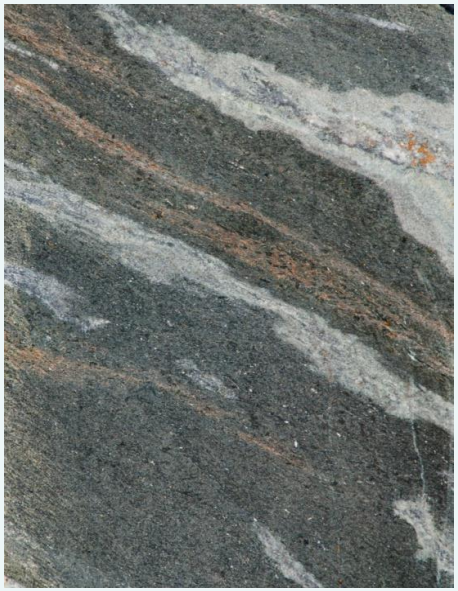
**Potassic alteration: biotite. Selective (fluid channels, distal) and pervasive (proximal to the ore zone)**
**Hosted in amphibolites, metasediments**
**Calc-silicate alteration: Cpx-Grt-Qtz-Cc bands or patches, selective (distal) and pervasive (proximal to the ore zone) hosted in amphibolites, metasediments, and the ore zone**
**Silicification: ore zone (pervasive) and the cross-cutting granite**
**Sulfidation: Apy-Po-Löll in the ore zone, BIF**

**Schlöglova et al. (2013)**

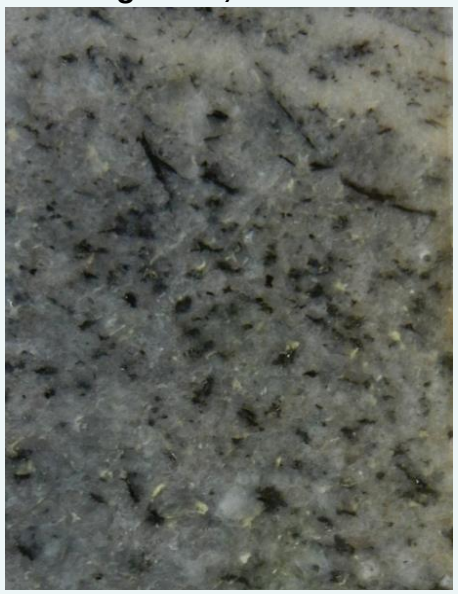
**K-alteration in amphibolite**




**Calc-silicate alteration in amphibolite**



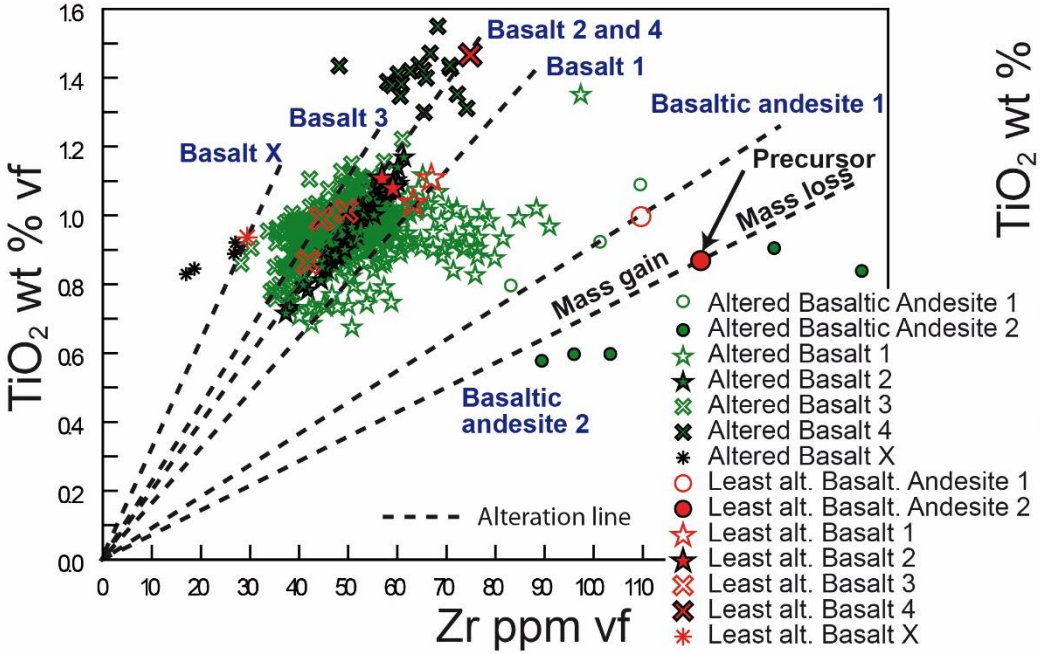
**Harnö granite, silicified**



**Photos: Dragon Mining AB ©**

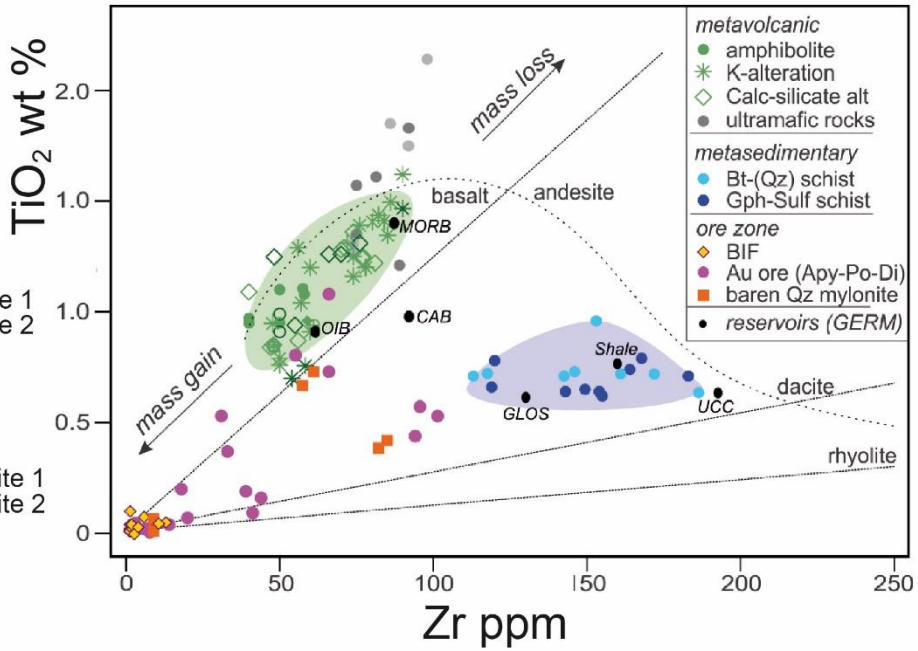
# Comparison of host rock geochemistry and hydrothermal alteration of the Svartliden and Nalunaq mines

## Nalunaq




Schlatter and Kolb (2011)

## Svartliden




Schlöglova et al. (2013)

# Overall Conclusions:

- Lithogeochemistry is a powerful tool to define rock types, including hydrothermally altered rocks, and to define favorable alteration trends for mineral exploration
- Petrography can supplement the geochemical study, and definition of the favorable suites of alteration minerals helps in defining the vector towards ore
- Geochemistry and petrography are used in combination with the geological data, and should be integrated together with the other geo-data in mineral exploration

# Thank you for your attention!

# Contact Info:


**Denis Martin Schlatter**

- Helvetica Exploration Services GmbH
- CEO, EurGeol, M. Sc., PhD
- Phone: +41 76 523 19 03
- denis.schlatter@helvetica-exploration.ch
- www.helvetica-exploration.ch


# Contact for Svartliden Info:


**Katerina Schlöglova**

- Institute of Geochemistry and Petrology, ETH Zurich
- Research assistant / PhD candidate
- Phone: +41 78 679 78 33
- katerina.schloglova@erdw.ethz.ch
- www.orefluids.ethz.ch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