Mineral geochemistry for precious and base metal exploration

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University of Michigan

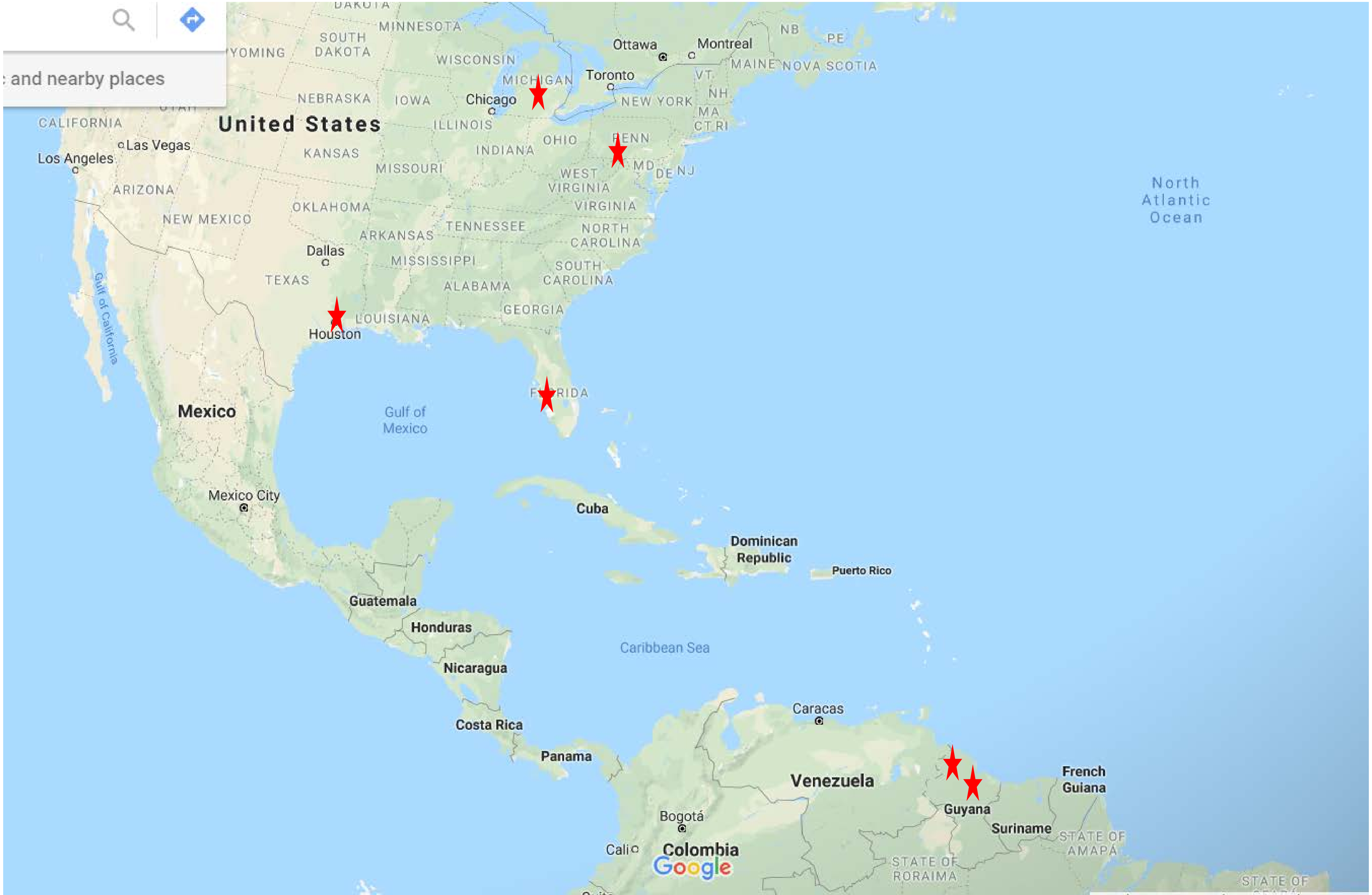
COESSING 2018
University of Ghana

Who am I?/ Where I’ve lived?

- Matthew’s Ridge, Guyana (home)
- Georgetown, Guyana
- Gettysburg, PA
- Tampa, FL
- Ann Arbor, MI
- Houston, TX

ALICANTO
MINERALS LIMITED

ExxonMobil
Energy lives here


and nearby places
DAKOTA
MINNESOTA
SOUTH DAKOTA
WYOMING
WISCONSIN
MICHIGAN
Ottawa
Montreal
Toronto
NB
PE
MAINE
NOVA SCOTIA
VT
NH
NEW YORK
MA
CT RI
NEBRASKA
IOWA
Chicago
UTAH
CALIFORNIA
United States
ILLINOIS
OHIO
PENN
Las Vegas
Los Angeles
KANSAS
INDIANA
MD
DE NJ
MISSOURI
WEST VIRGINIA
VIRGINIA
ARIZONA
OKLAHOMA
NEW MEXICO
ARKANSAS
TENNESSEE
NORTH CAROLINA
North Atlantic Ocean
Dallas
MISSISSIPPI
SOUTH CAROLINA
TEXAS
ALABAMA
GEORGIA
Gulf of California
LOUISIANA
Houston
FLORIDA
Mexico
Gulf of Mexico
Mexico City
Cuba
Dominican Republic
Puerto Rico
Guatemala
Honduras
Caribbean Sea
Nicaragua
Caracas
Costa Rica
Panama
Venezuela
French Guiana
Guyana
Bogotá
Suriname
STATE OF AMAPÁ
Cali
Colombia
STATE OF RORAIMA
STATE OF
Google

How do we feel about mining?

- Why do we mine?
- What do we mine?

ELEMENTS OF A SMARTPHONE

ELEMENTS COLOUR KEY: ALKALI METAL · ALKALINE EARTH METAL · TRANSITION METAL · GROUP 13 · GROUP 14 · GROUP 15 · GROUP 16 · HALOGEN · LANTHANIDE

SCREEN

49 In Indium · 50 Sn Tin · 8 O Oxygen

Indium tin oxide is a mixture of indium oxide and tin oxide, used in a transparent film in the screen that conducts electricity. This allows the screen to function as a touch screen.

13 Al Aluminium · 14 Si Silicon · 8 O Oxygen · 19 K Potassium

The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina (Al_2O_3) and silica (SiO_2). This glass also contains potassium ions, which help to strengthen it.

39 Y Yttrium · 57 La Lanthanum · 65 Tb Terbium · 59 Pr Praseodymium · 63 Eu Europium · 66 Dy Dysprosium · 64 Gd Gadolinium

A variety of Rare Earth Element compounds are used in small quantities to produce the colours in the smartphone's screen. Some compounds are also used to reduce UV light penetration into the phone.

ELECTRONICS

29 Cu Copper · 47 Ag Silver · 79 Au Gold · 73 Ta Tantalum

Copper is used for wiring in the phone, whilst copper, gold and silver are the major metals from which microelectrical components are fashioned. Tantalum is the major component of micro-capacitors.

28 Ni Nickel · 66 Dy Dysprosium · 59 Pr Praseodymium · 65 Tb Terbium · 60 Nd Neodymium · 64 Gd Gadolinium

Nickel is used in the microphone as well as for other electrical connections. Alloys including the elements praseodymium, gadolinium and neodymium are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium are used in the vibration unit.

14 Si Silicon · 8 O Oxygen · 51 Sb Antimony · 33 As Arsenic · 15 P Phosphorus · 31 Ga Gallium

Pure silicon is used to manufacture the chip in the phone. It is oxidised to produce non-conducting regions, then other elements are added in order to allow the chip to conduct electricity.

50 Sn Tin · 82 Pb Lead

Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.

BATTERY

3 Li Lithium · 27 Co Cobalt · 8 O Oxygen · 6 C Carbon · 13 Al Aluminium

The majority of phones use lithium ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery's casing is made of aluminium.

CASING

6 C Carbon · 12 Mg Magnesium · 35 Br Bromine · 28 Ni Nickel

Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.

Objectives

- To provide an introduction to economic geology and natural resources
- Introduction to using geochemistry for exploration
- To (hopefully) change the way you think about (geo)chemistry and natural resources

Geology 101

- Rocks are our friends.
- Atoms – elements – minerals – rocks

What is Economic Geology?

WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events
Random article
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Interaction

Help
About Wikipedia
Community portal
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Tools

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Economic geology

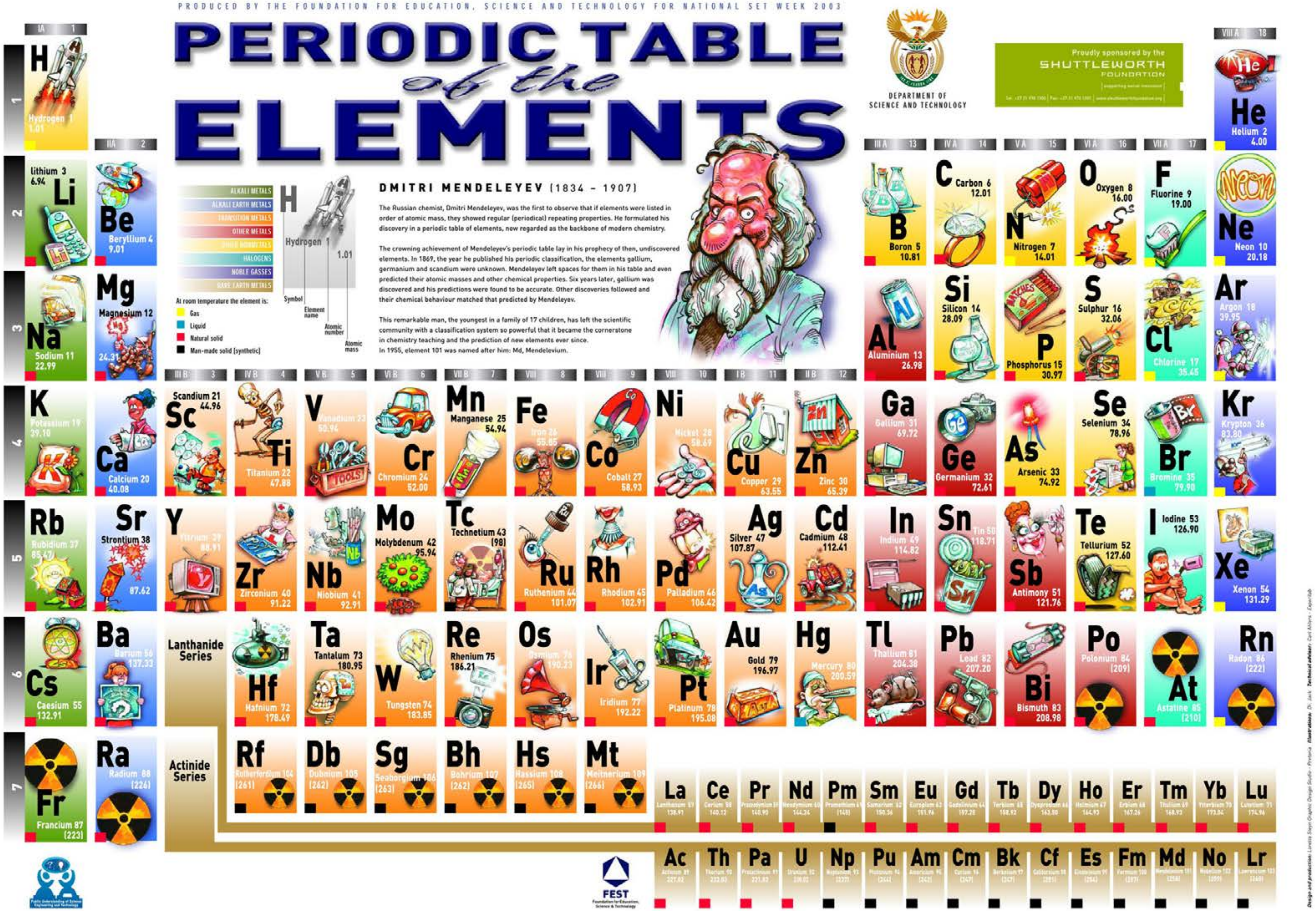
From Wikipedia, the free encyclopedia

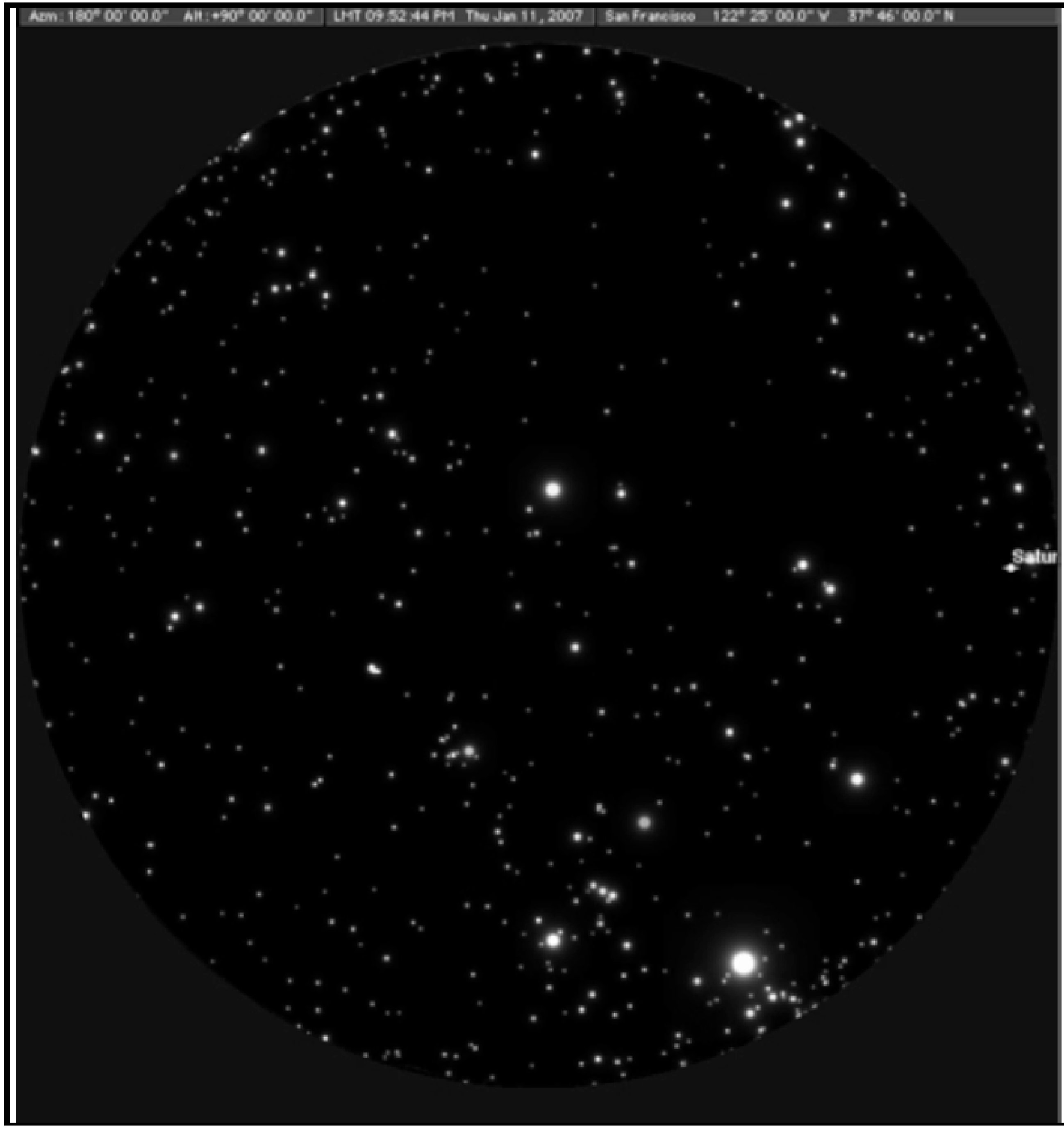
"Economic Geology" redirects here. For the journal, see Economic Geology (journal).

Economic geology is concerned with earth materials that can be used for economic and/or industrial purposes. These materials include precious and base metals, nonmetallic minerals, construction-grade stone, petroleum minerals, coal, and water. Economic geology is a subdiscipline of the geosciences; according to Lindgren (1933) it is “the application of geology”. Today, we might call it the scientific study of the Earth’s sources of mineral raw materials and the practical application of the acquired knowledge.[1] The term commonly refers to metallic mineral deposits and mineral resources. The techniques employed by other earth science disciplines (such as geochemistry, mineralogy, geophysics, petrology and structural geology) might all be used to understand, describe, and exploit an ore deposit.

Economic geology is studied and practiced by geologists. Economic geology may be of interest to other professions such as engineers, environmental scientists, and conservationists because of the far-reaching impact that extractive industries have on society, the economy, and the environment.

Contents [hide]


PRODUCED BY THE FOUNDATION FOR EDUCATION, SCIENCE AND TECHNOLOGY FOR NATIONAL SET WEEK 2003
PERIODIC TABLE of the ELEMENTS
DEPARTMENT OF SCIENCE AND TECHNOLOGY
Proudly sponsored by the SHUTTLEWORTH FOUNDATION
ALKALI METALS
ALKALI EARTH METALS
TRANSITION METALS
OTHER METALS
HALOGENS
NOBLE GASSES
RARE EARTH METALS
At room temperature the element is:
Gas
Liquid
Natural solid
Man-made solid [synthetic]
H
Hydrogen 1
1.01
Symbol
Element name
Atomic number
Atomic mass
DMITRI MENDELEYEV (1834 - 1907)
The Russian chemist, Dmitri Mendeleyev, was the first to observe that if elements were listed in order of atomic mass, they showed regular (periodical) repeating properties. He formulated his discovery in a periodic table of elements, now regarded as the backbone of modern chemistry.
The crowning achievement of Mendeleyev's periodic table lay in his prophecy of then, undiscovered elements. In 1869, the year he published his periodic classification, the elements gallium, germanium and scandium were unknown. Mendeleyev left spaces for them in his table and even predicted their atomic masses and other chemical properties. Six years later, gallium was discovered and his predictions were found to be accurate. Other discoveries followed and their chemical behaviour matched that predicted by Mendeleyev.
This remarkable man, the youngest in a family of 17 children, has left the scientific community with a classification system so powerful that it became the cornerstone in chemistry teaching and the prediction of new elements ever since.
In 1955, element 101 was named after him: Md, Mendelevium.
Lanthanide Series
Actinide Series
FEST



When you look at stars in a clear night sky, what differences can you see?

Periodic Groups and Natural Systems

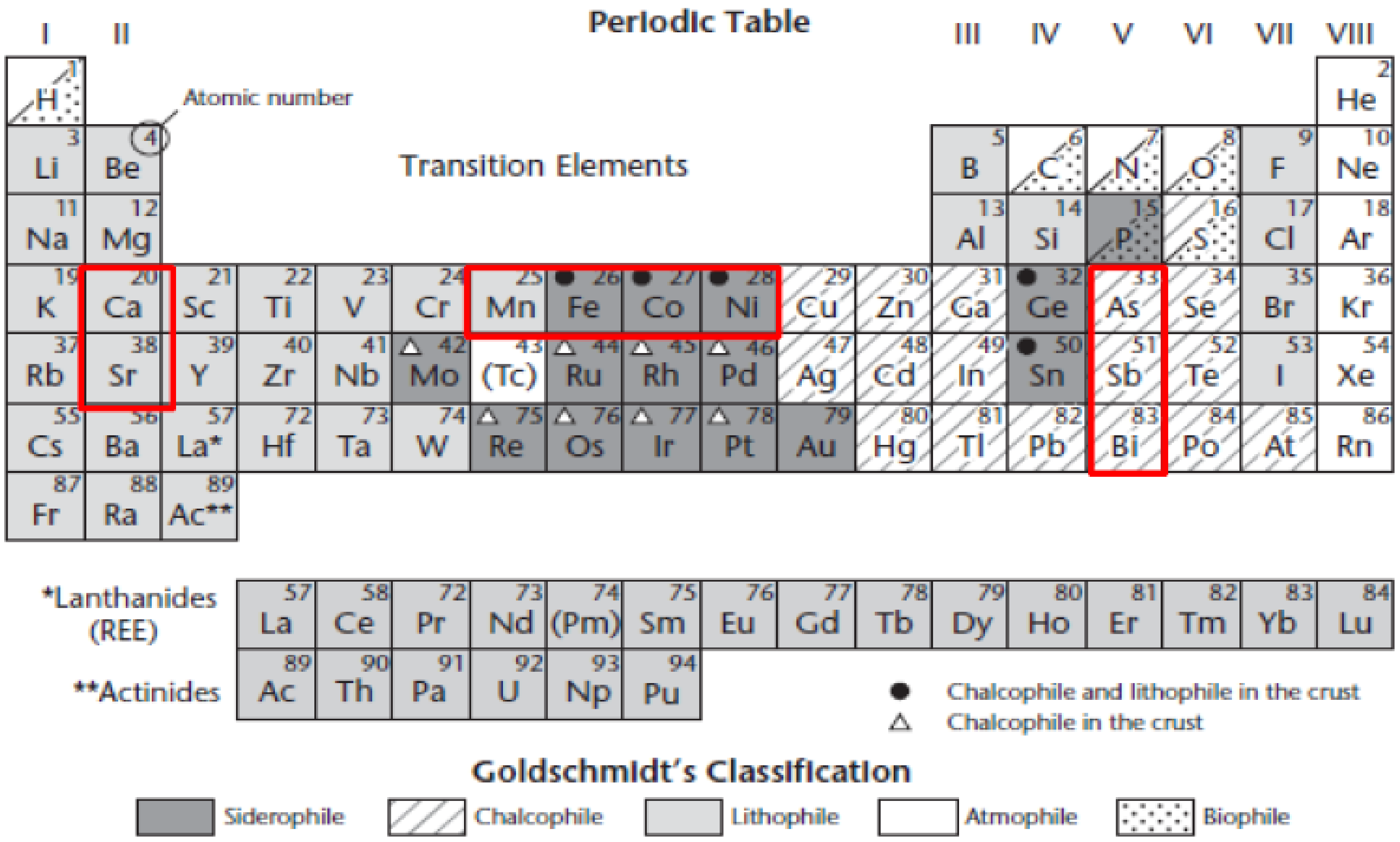


Figure 5.1: Periodic Table with superimposed Goldschmidt Classification.

from McQueen (2009)

Copper (Cu)

- Porphyry copper deposits
- Stratiform Cu deposits
- Iron oxide copper gold deposits

Chile, Peru, DRC, Zambia, USA

chalcopyrite

$CuFeS_2$

Iron (Fe): magnetite (Fe_3O_4) & hematite (Fe_2O_3)

- Manufacture of steel

- Banded iron formations
- Iron oxide copper gold deposits
- Iron oxide apatite deposits

- China, Australia, Brasil

Gold (Au)

- Jewelry
- Finances
- Electronics
- Dentistry and medicine

- Orogenic gold deposits
- Porphyry deposits
- Placer deposits

- China, South Africa, Ghana, Russia, USA, Canada, Australia

Aluminium (Al) [Al_2O_3]

- Bauxite
- Australia, China, Brasil

Phosphorus (P) – $Ca_5(PO_4)_3(F,Cl,OH)$

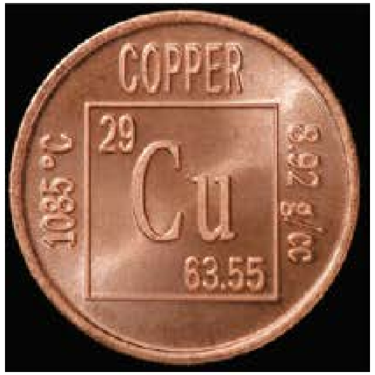
- Agriculture: Fertilizers and supplements for animals
- Construction
- Pharmaceuticals
- Water treatment

- Phosphorite
- Apatite

- USA, China, Morocco

Economic Geology: From Background to Ore

Element	*Oxidation state*	*Deposit type*	*Grade*[a] (median)	*Crustal abundance*[b]	*Clarke value*
Cu		Porphyry (volcano)	0.54%	27 ppm	200



[a] All percentages are in weight percent. [b] Continental crust; see Chapter 3.01. [c] Highly variable. [d] In concentrate.

The Clarke value is the ratio of the concentration of an element in an ore, relative to its average crustal concentration.

Simon, 2015

Economic Geology: From Background to Ore

Element	*Oxidation state*	*Deposit type*	*Grade*[a] (median)	*Crustal abundance*[b]	*Clarke value*
Cu		Porphyry	0.54%	27 ppm	200
Na		Halite	40%	2.3%	17
Zn		Sedimentary exhalative	5.6%	72 ppm	780
As		Sulfide deposits[c]	~0.1%	2.5 ppm	~400
Rb		Lepidolite[d]	Up to 3%	49 ppm	~610
Mo		Climax	0.19%	0.8 ppm	2,400
W		Skarn	0.66% WO_3	1 ppm	6,600
Pb		Sedimentary exhalative	2.8%	11 ppm	2,500
V		Layered mafic intrusions	~0.6%	138 ppm	~43
Au		Veins/Homestake	~10 ppm	1.3 ppb	~7,700
Ag		Creed vein	125 ppm	56 ppb	2,200
Ni		Komatiite	1.5%	59 ppm	250

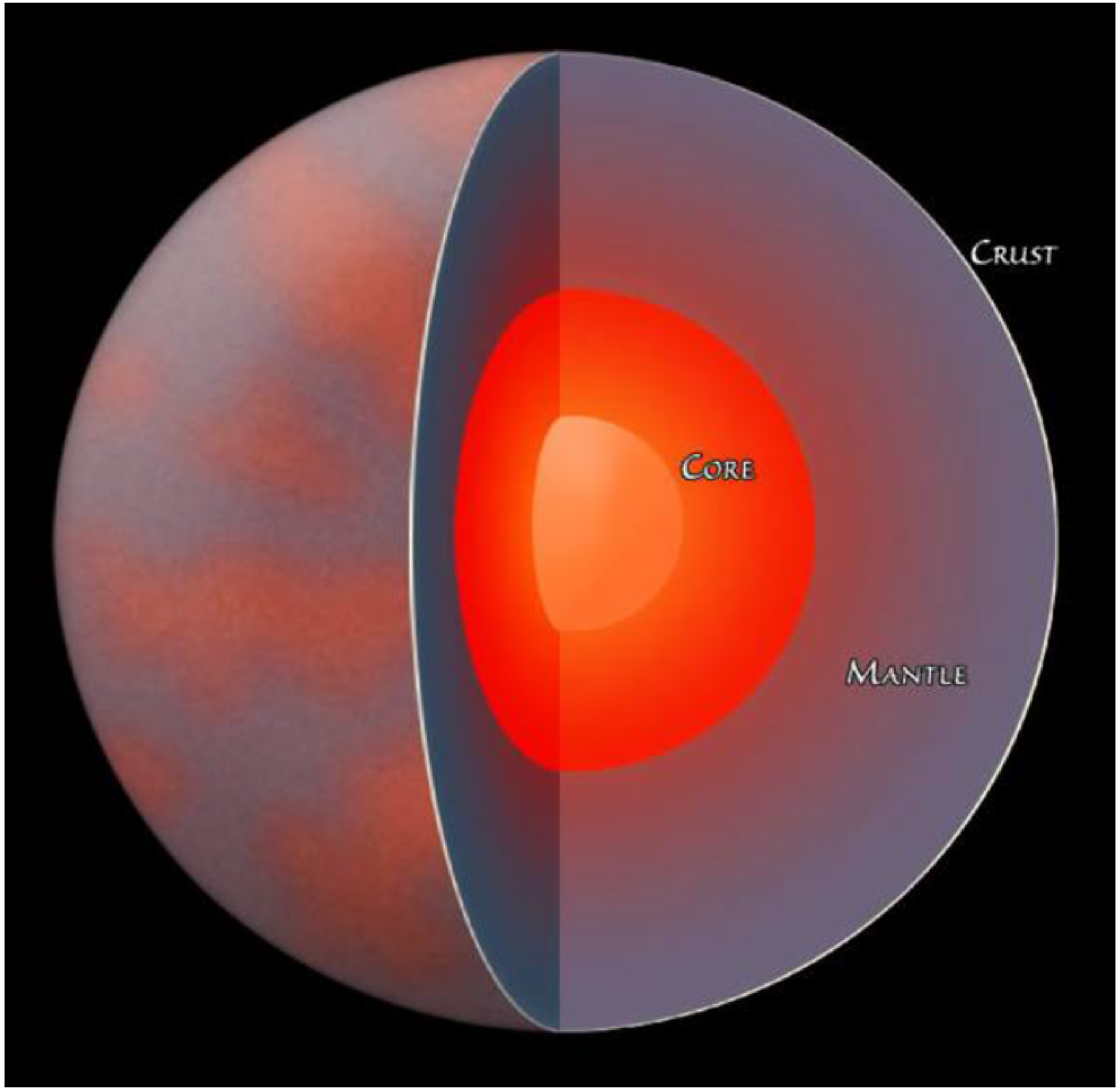
[a] All percentages are in weight percent. [b] Continental crust; see Chapter 3.01. [c] Highly variable. [d] In concentrate.

The Clarke value is the ratio of the concentration of an element in an ore, relative to its average crustal concentration.

Simon, 2015

ORIGIN OF MINERAL DEPOSITS - DIFFERENTIATION

Composition of Earth



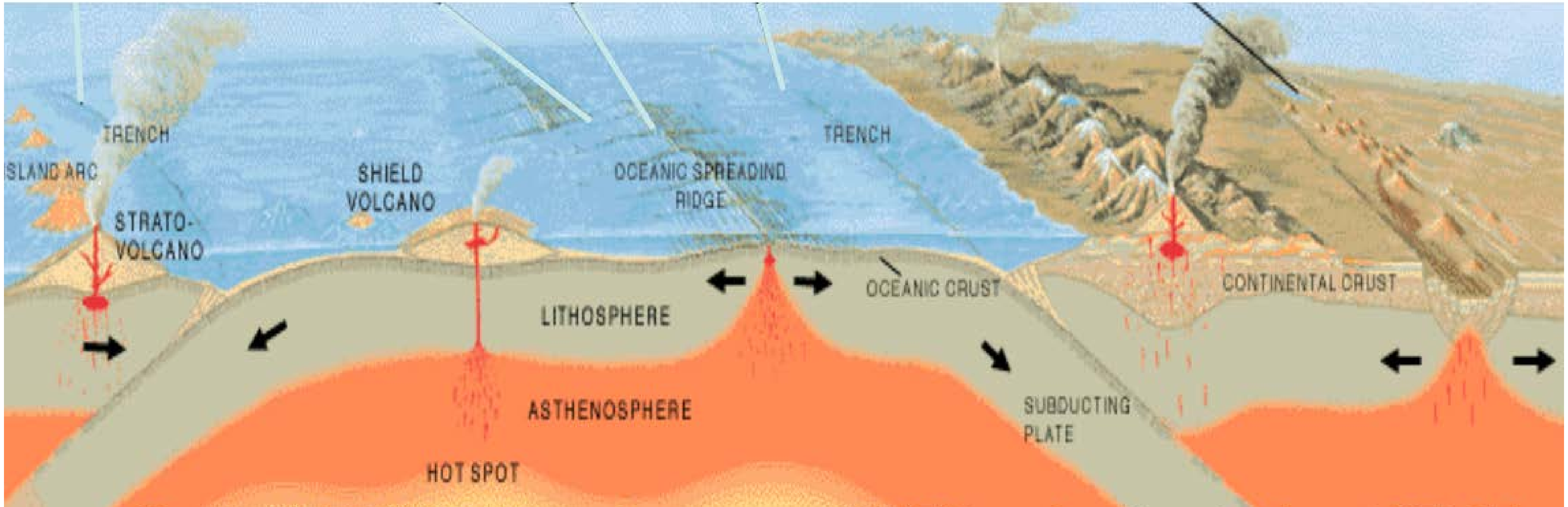
	Crust	Earth
Major Elements		
O	46.6	36.0
Si	27.7	15.0
Al	8.1	1.1
Fe	5.0	35.0
Ca	3.6	1.1
Na	2.8	0.6
K	2.6	0.1
Mg	2.1	13.0
Ti	0.4	0.1
H	0.1	-------
Trace Elements		
Mn	0.009	0.022
as ppm (parts per million)		
Sn	2	0.25
Cu	28	60
Ni	58	24000
Nb	20	1

Note how elements concentrate in different reservoirs

Simon, 2015

ORIGIN OF MINERAL DEPOSITS - DIFFERENTIATION

Composition of Mantle, Ocean Crust and Continental Crust



	Mantle-ULTRAMAFIC	Ocean crust-MAFIC	Continental Crust-FELSIC
Si	19.8 %	23.5	34.7
Al	1.2 %	8.3	7.2
Mg	23.2 %	4.6	0.2
Fe	9.6 %	8.6	1.4
Cu	15 ppm	94	55
Pb	0.5 ppm	7	15
Sn	0.5 ppm	1.5	3
Ni	2000 ppm	145	4.5

Simon, 2015

ORIGIN OF MINERAL DEPOSITS

Geologic processes that form mineral deposits (by forming ore minerals) along with deposits and elements that form by each process.

Surface Processes			
	Physical Sedimentation		
		Flowing water	Placer deposits - gold, platinum, diamond, (stream or beach) ilmenite, rutile, zircon, sand, gravel
		Wind	Dune deposits - sand
	Chemical Sedimentation		
		Precipitation from or in seawater	Evaporite deposits - halite, sylvite, borax, trona Chemical deposits - iron, volcanogenic massive
	Organic Sedimentation		
		Organic activity or accumulation	Hydrocarbon deposits - oil, natural gas, coal Other deposits - sulfur, phosphate
Subsurface Processes			
	Involving Water	Groundwater and related deposits - uranium, sulfur	
			Basinal brines - Mississippi Valley-type, sedex Seawater - volcanogenic massive sulfide, sedex Magmatic Water - porphyry copper-molybdenum, skarn Metamorphic water - gold, copper
	Involving Magmas	Crystal segregation - chromium, vanadium	
			Immiscible magma separation - nickel, copper, cobalt, platinum-group elements

Simon, 2015

Exploration

Exploration 101

- Decide on a commodity/ metal(s) of interest
  - What deposit type?
  - How does it form?
- What data will be most useful for finding the deposit?
  - Geochemistry?
  - Geophysics?
- Are there data available that lead you to a specific geographic area?
  - Where (country, region) do you want to be?

Geochemistry

- What elements will be most useful for finding the deposit?
- What samples can you collect?
  - Soil (stream/ lake sediments)
  - Rocks
  - Minerals
  - Stream water
  - Plant material

Geochem Targeting Tool Box

- Deposit models predict mineralogy, zonation and alteration
- Pathfinder elements or alteration zones can provide a larger target than the mineralization
- Element associations also depend on magma fractionation, weathering profile, sample type and analytical method

Bloom, 2018

Style Of Deposit	Element Association*
Ni (Cu, PGM) Sulphides	Ni-Cu-PGM-(Cr-Se-Bi-Co-Au)
Porphyry CuAu, CuMo, Mo	Cu-Au-Mo-(Zn-Pb-Ag-Sb-Ag)
Epithermal AuAg	Au-Ag-As-(Cu-Pb-Zn-Sb-Hg-W)
Skarns	Cu-Au-Zn-Pb-W-Mo-Sn-Bi-As-Sb
Proterozoic Fe-CuAu	Cu-Au-U-Co-(REE-Ba-F-Sn-W-Mo-Bi-As)
VHMS	Cu-Pb-Zn-Ag-Au-(As-Sb-Sn-Bi-Mo-Ba-W)
SHMS	Cu-Pb-Zn-Ag-(As-Sb-Mo-Mn-Bi-Au)
MVT	Pb-Zn-(Cd-Ag-Ba-F-Cu-Ni)
Red Bed Cu	Cu-Ag-Co-(Pb-Zn-U-Se-Mo)
Sedimentary UV(Cu)	U-V-Au-Mo-Se-(Ni-As-Co-Cu-Pb-Zn)
Mesothermal Au	Au-As-(Sb-W-Cu-Pb-Zn-Hg)

*In the weathering environment, some of these elements will be present in resistate minerals e.g. cassiterite and chromite.

Bloom, 2018

Bloom, 2018

Primary Geochemistry

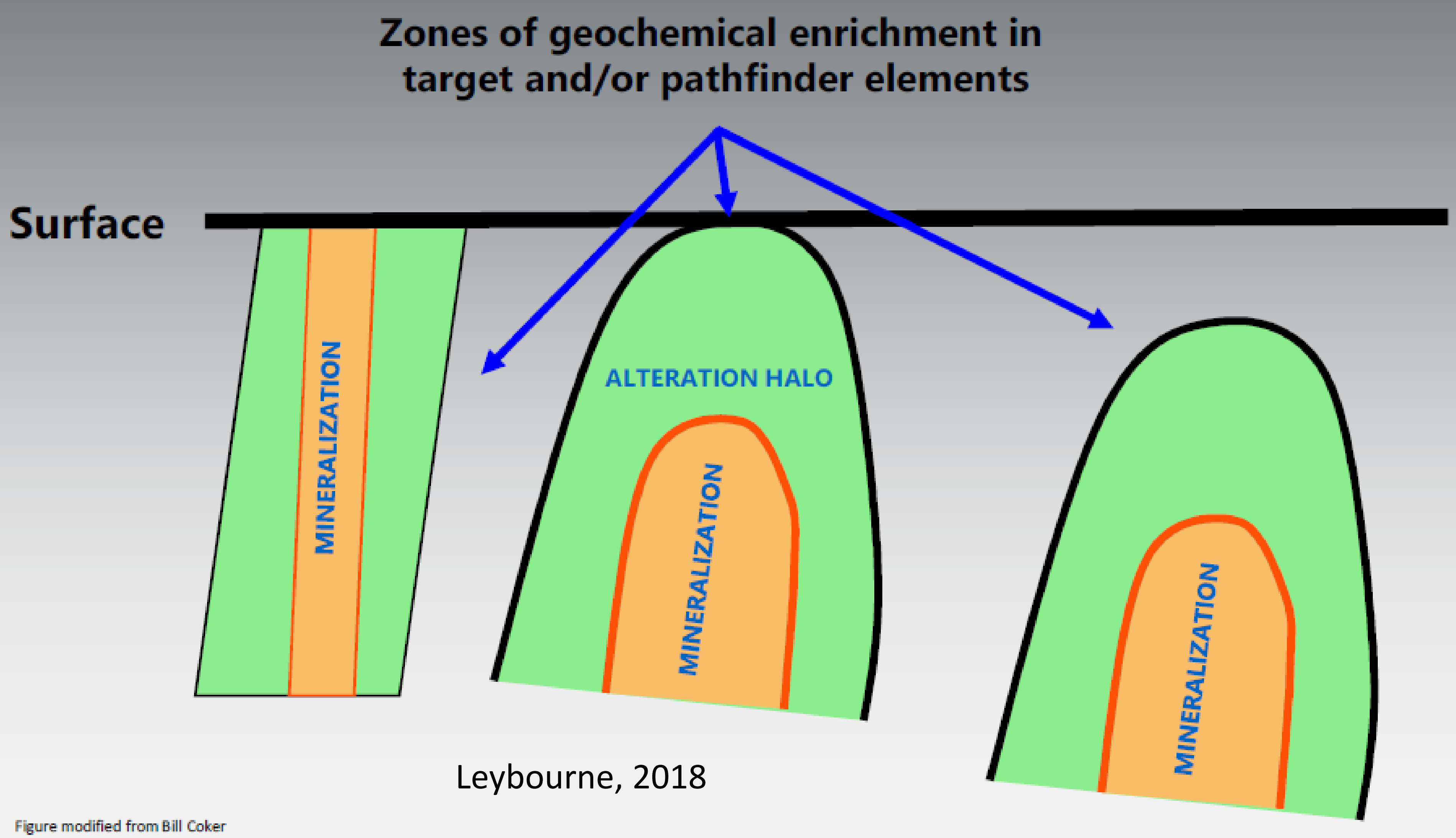
Element distribution in rocks associated with deposit formation

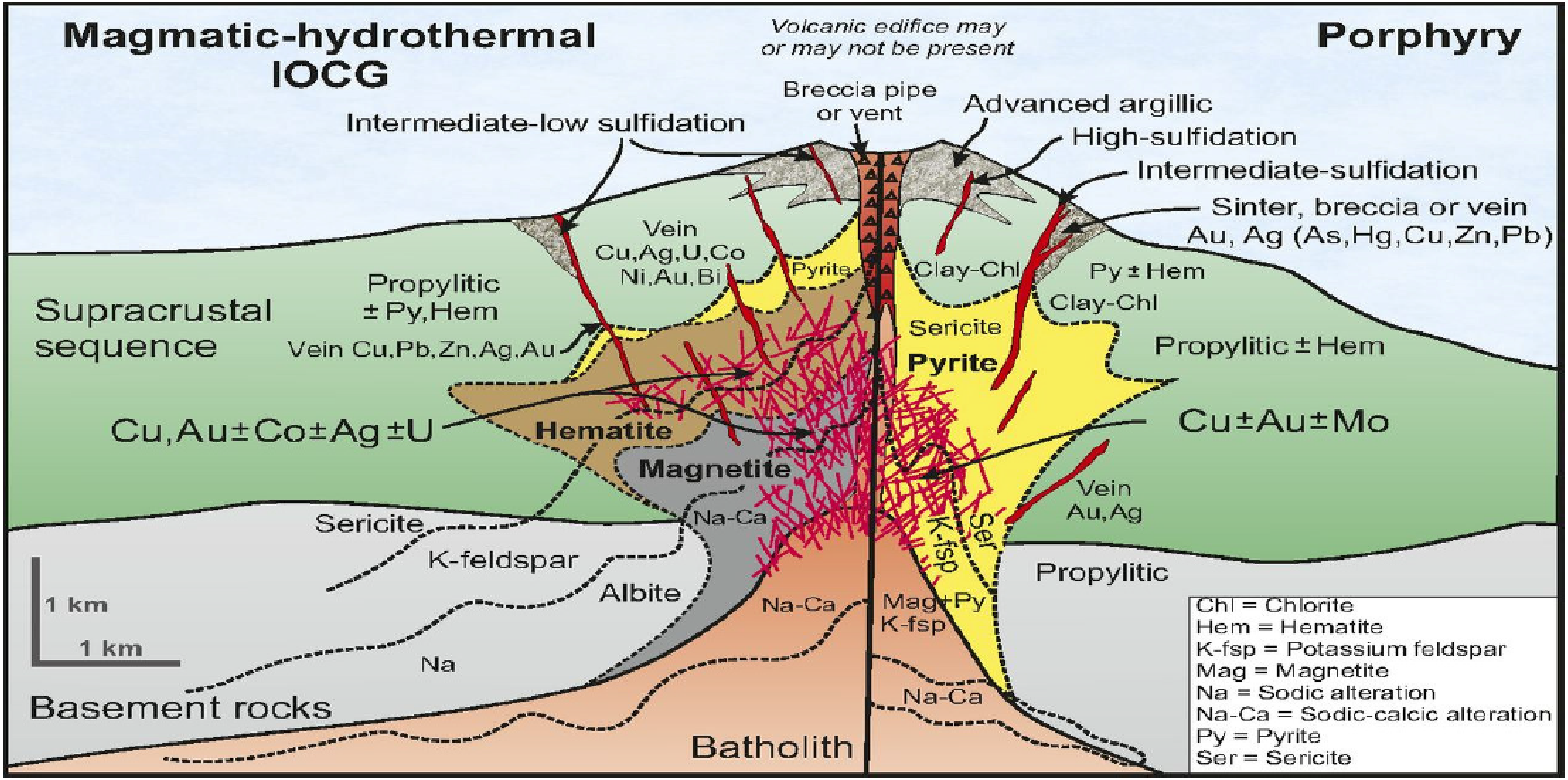
Secondary Geochemistry

Element distribution in the geochemical cycle (water, vegetation, soils, streams, glacial sediments)

Dispersion mechanically or by chemical mobility

Background


Zones of geochemical enrichment in target and/or pathfinder elements
Surface
MINERALIZATION
ALTERATION HALO
MINERALIZATION
MINERALIZATION
Leybourne, 2018
Figure modified from Bill Coker



J. Richards, A. Hamid Mumin (2012)

Bloom, 2018

Analytical methods

Choice of analytes to focus on for data analysis and interpretation – depends on the style of mineralization and the relative mobility by mechanical or hydromorphic dispersion

Type of deposit	Major components	Minor components	Labile components[A]	Relatively immobile components[B]
VMS	Fe, S, Cu, Zn, Pb	Cd, Hg, Au, As, Sb, Ba, Bi, In	Fe, S, Zn, Cu, As, Cd, Hg, Sb	Pb, Bi, In, Au, Ag, Ba
Porphyry Cu ± Mo	Cu, Mo, S	Fe, Ag, Au, Se, Re, As	Cu, Mo, S, Fe, Se, As, Re	Ag, Au
SEDEX	Fe, S, Cu, Zn, Pb	Ag, Au, Ba, Cd	Fe, S, Zn, Cu, Cd	Pb, Ba, Au, Ag
Gold (vein)	Au, Ag	As, Sb, Se, Te, S, Hg	S, Se, As, Hg, Te, Sb	Au, Ag
Ni-Ci-PGE	Ni, Cu, PGE	Cr, Co, S	Cu, S, PGE	Co, Ni, Cr
Kimberlite (diamond)	Sr, Nb, Ba, Cr, Ni	LILE, HFSE, REE	Sr, LILE	Ba, HFSE, Nb, Ba, Cr, Ni, REE
Unconformity uranium	U	Se, Mo, V, Cu, Pb	U, Se, Cu, Mo	U, Pb, V

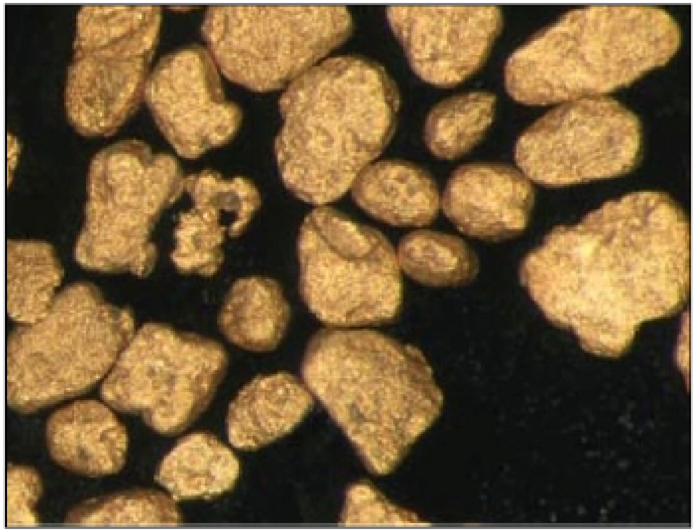
Leybourne, 2018

Gold!!!!!

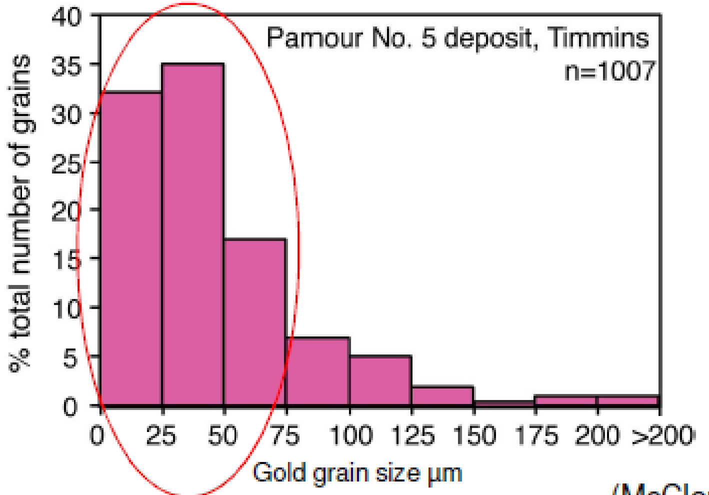
Gold deposits

- Greenstone hosted/ orogenic deposits
- Reduced intrusion related gold deposits
- Porphyry, epithermal and skarn deposits
- Iron oxide copper gold deposits
- Gold rich volcanogenic massive sulphide deposits
- Placer gold deposits

Gold Indicator Minerals



- Recovered from stream sediments since Roman times
- Most well known and widely used indicator mineral
- Others indicator minerals include sulphides, arsenides, tellurides, scheelite, tourmaline, rutile, barite, secondary minerals (jarosite, limonite, goethite, pyrolusite)
- Gold grains easily recovered from 10 µm to 2 mm size fraction of sediments
- Most gold grains recovered from till, 10 to 75 µm
- Gold within sulphides or in solid solution with sulphides will be detected with automated mineralogy methods and matrix till geochemistry



(McClenaghan, 1999, 2001)

McClenaghan, 2018

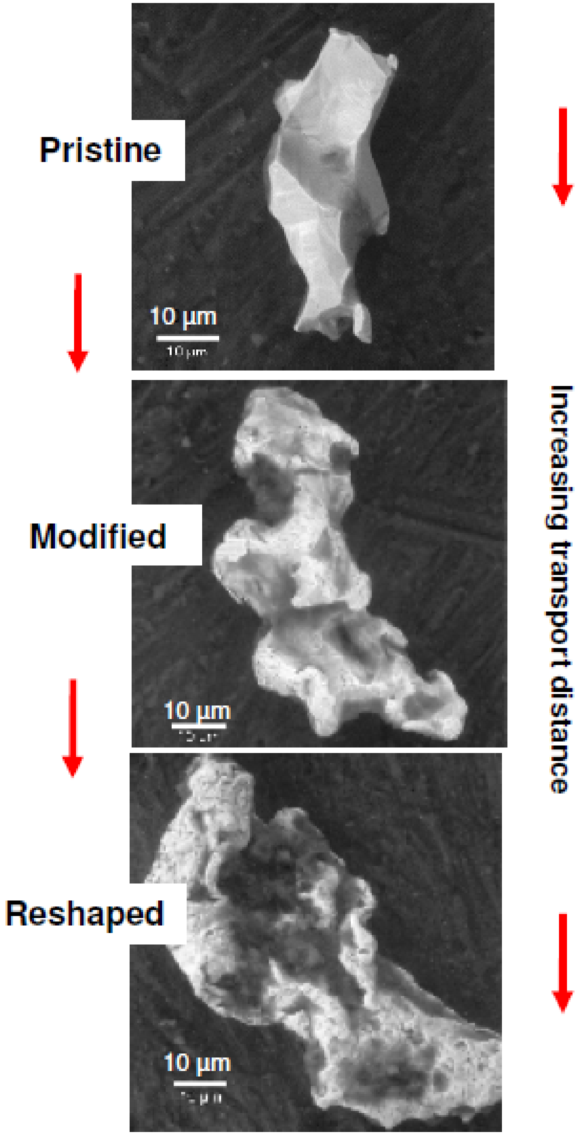
Gold Grain Morphology

• DiLabio (1990) classification scheme describes conditions and surface textures of gold grains related to glacial transport distance

• **Pristine gold grains:**
- Primary shapes and surface textures
- Appear not to have been damaged in transport
- Angular wires, rods and delicate leaves that once filled in fractures, occurred as crystals with grain molds, and as inclusions in sulphides

• **Modified gold grains:**
- Some primary surface textures
- Edges and protrusions have been damaged during transport
- Commonly striated
- Irregular edges and protrusions are crumpled, folded and curled
- Grain molds and primary surface textures preserved on protected faces of grains

• **Reshaped gold grains:**
- Primary surface textures destroyed
- Original grain shape no longer discernible
- Flattened to rounded resulting from folding of leaves, wires, rods
- Surfaces may be pitted from impact marks from other grains
- Surfaces are not leached of silver in most cases in glaciated terrain



(McClenaghan, 2001)

McClenaghan, 2018

Gold geochemistry

Economic Geology
Vol. 94, 1999, pp. 649–664

Lode and Placer Gold Composition in the Klondike District, Yukon Territory, Canada: Implications for the Nature and Genesis of Klondike Placer and Lode Gold Deposits

J. B. KNIGHT,[†]
Micro Science, RR #1, Site 29, Comp 10, Smithers, British Columbia, Canada V0J 2N0

J. K. MORTENSEN,
Department of Ocean and Earth Sciences, 6339 Stores Rd., University of British Columbia, Vancouver, British Columbia, Canada V6T 2B4

AND S. R. MORISON
Gartner Lee Ltd., Unit 212, 212 Main St., Whitehorse, Yukon Territory, Canada Y1A 2A9

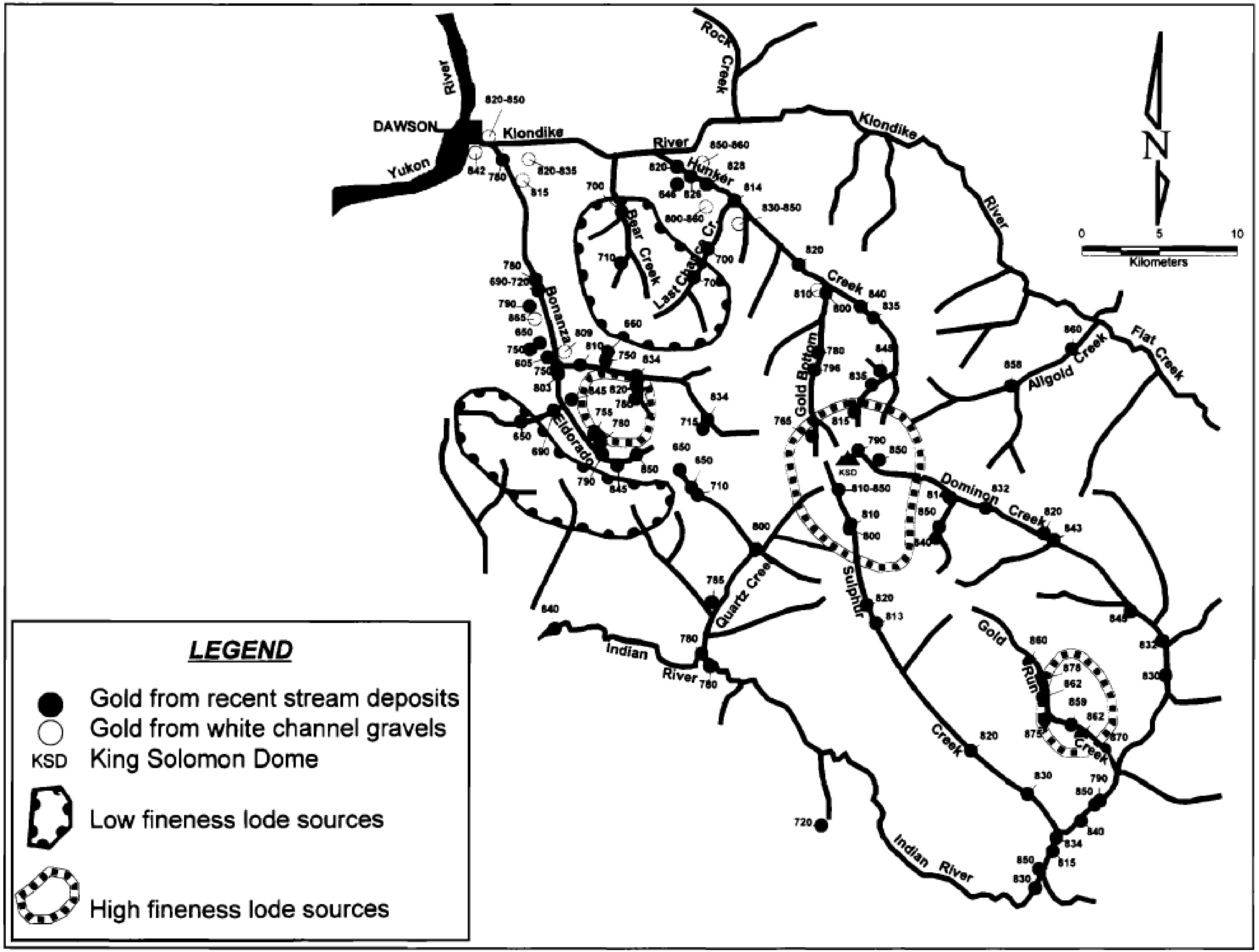
Microchemical Characterization of Alluvial Gold Grains as an Exploration Tool

Robert Chapman, Bob Leake and Mike Styles*
School of Earth Sciences, University of Leeds, Leeds LS2 9JT, United Kingdom
*British Geological Survey, Keyworth, Notts NG12 5GG, United Kingdom
E-mail: aedrjc@LUCS-03.NOVELL.LEEDS.AC.UK

Received: 15 October 2001

Application of microchemical characterization of placer gold grains to exploration for epithermal gold mineralization in regions of poor exposure

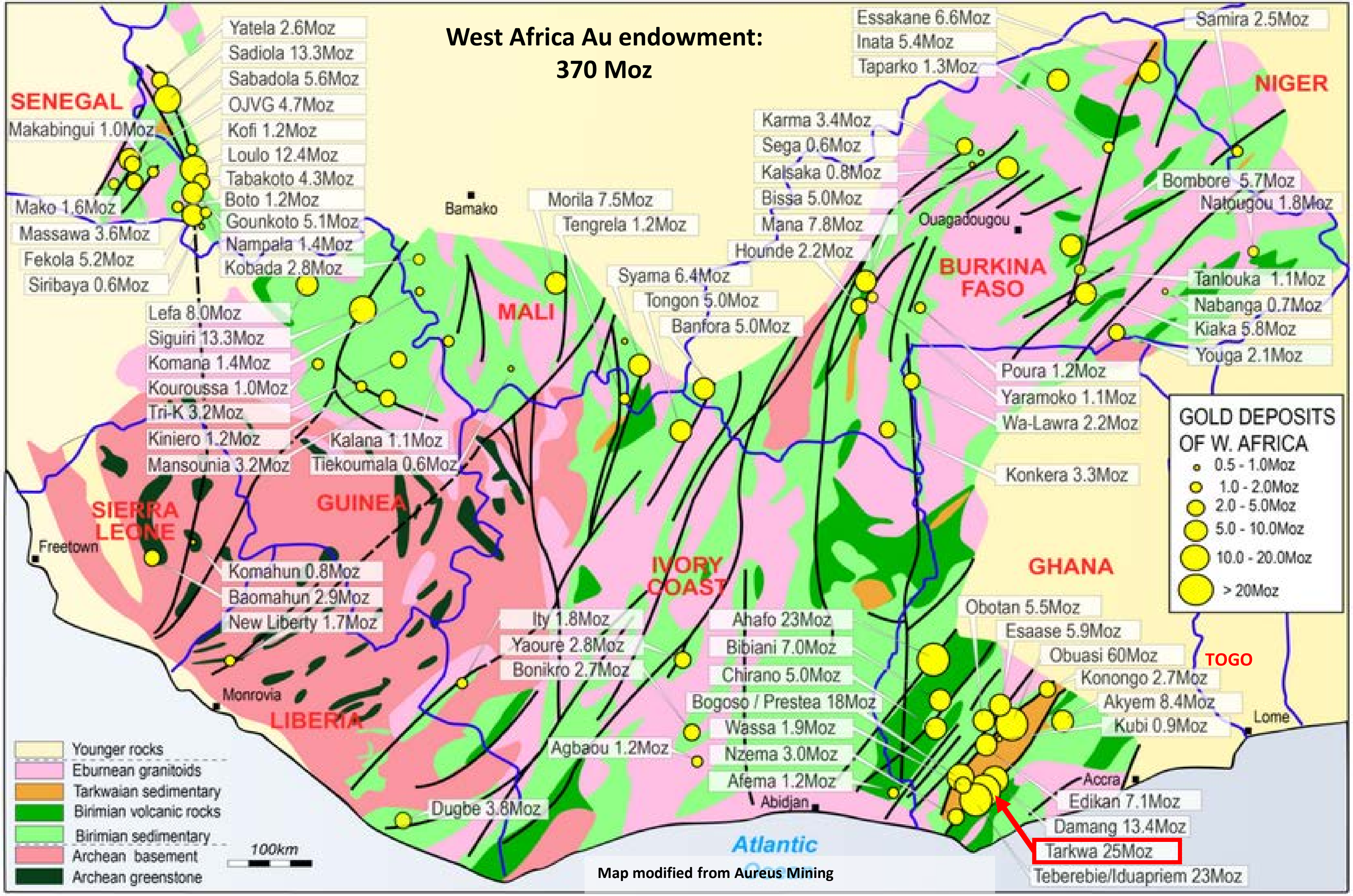
R.J. Chapman [a,*], J.K. Mortensen [b]



Knight et al., 1999

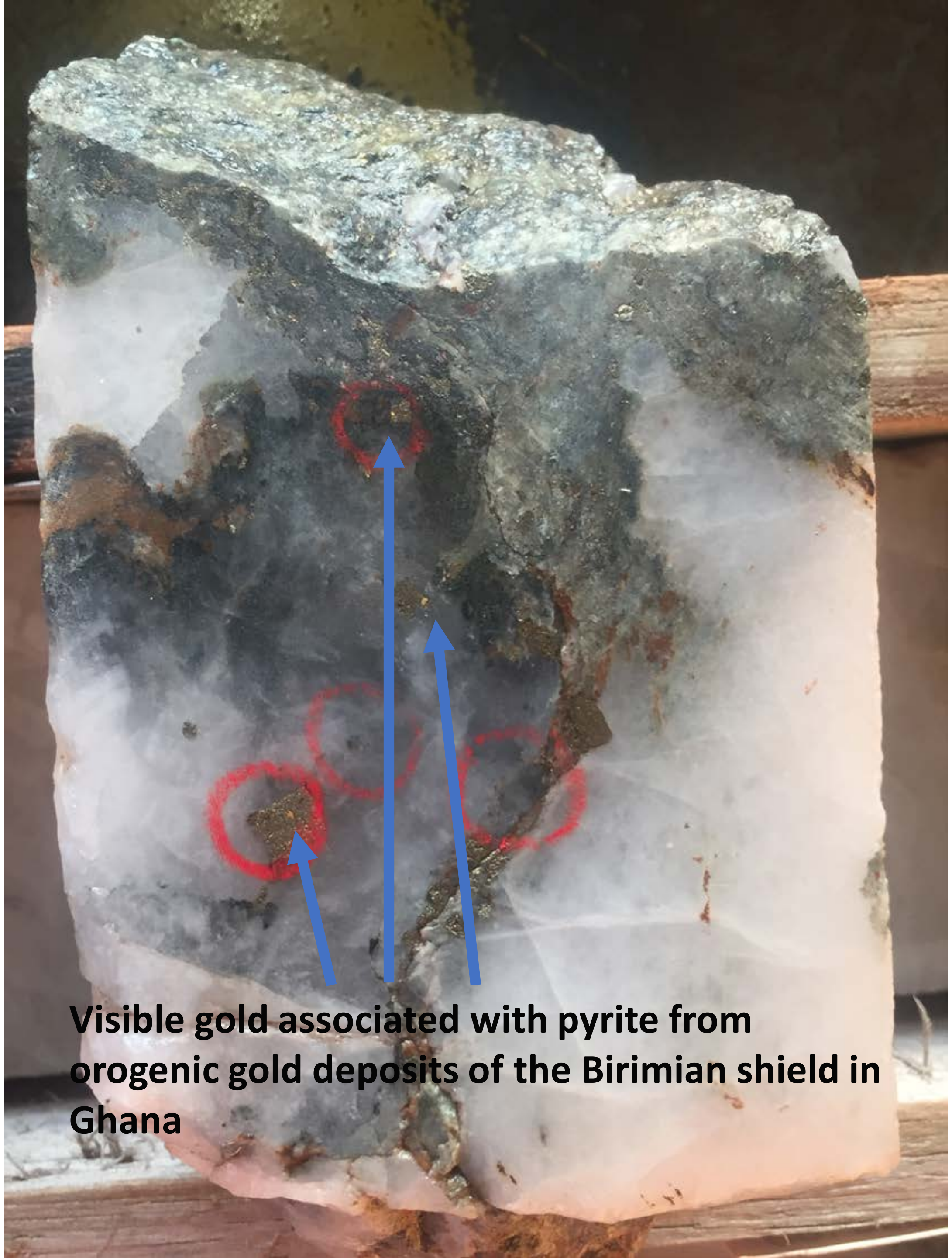
Gold in Ghana….

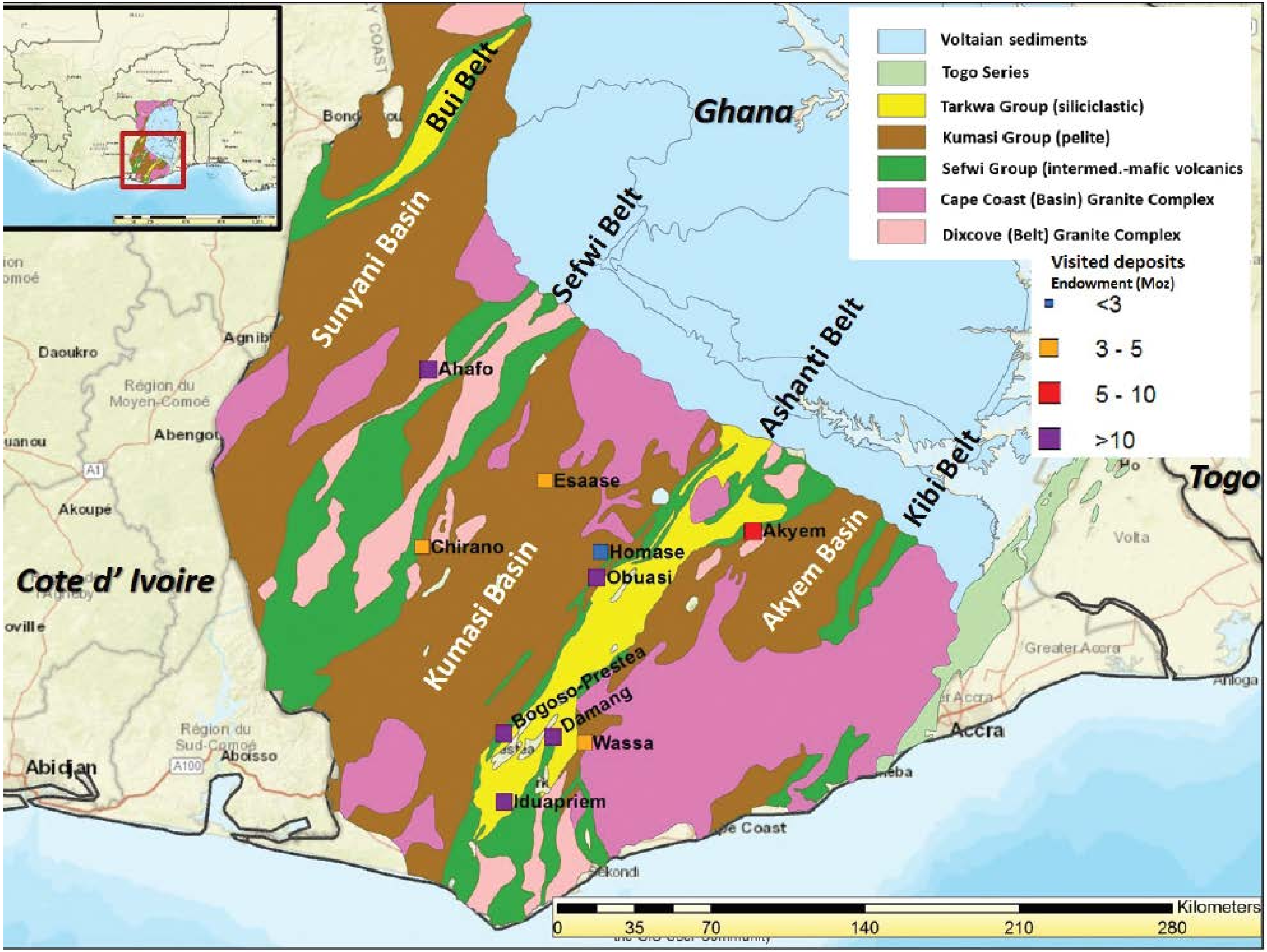
Regional geology and gold deposits



Map modified from Aureus Mining


Gold Ore from the Tarkwa basin


Visible gold associated with pyrite from orogenic gold deposits of the Birimian shield in Ghana


Voltaian sediments
Togo Series
Tarkwa Group (siliciclastic)
Kumasi Group (pelite)
Sefwi Group (intermed.-mafic volcanics
Cape Coast (Basin) Granite Complex
Dixcove (Belt) Granite Complex
Visited deposits
Endowment (Moz)
<3
3 - 5
5 - 10
>10
Ghana
Togo
Cote d' Ivoire
Bui Belt
Sunyani Basin
Sefwi Belt
Ashanti Belt
Kibi Belt
Kumasi Basin
Akyem Basin
Ahafo
Esaase
Chirano
Homase
Obuasi
Akyem
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Damang
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Iduapriem
Accra
Abidjan
Kilometers
0
35
70
140
210
280

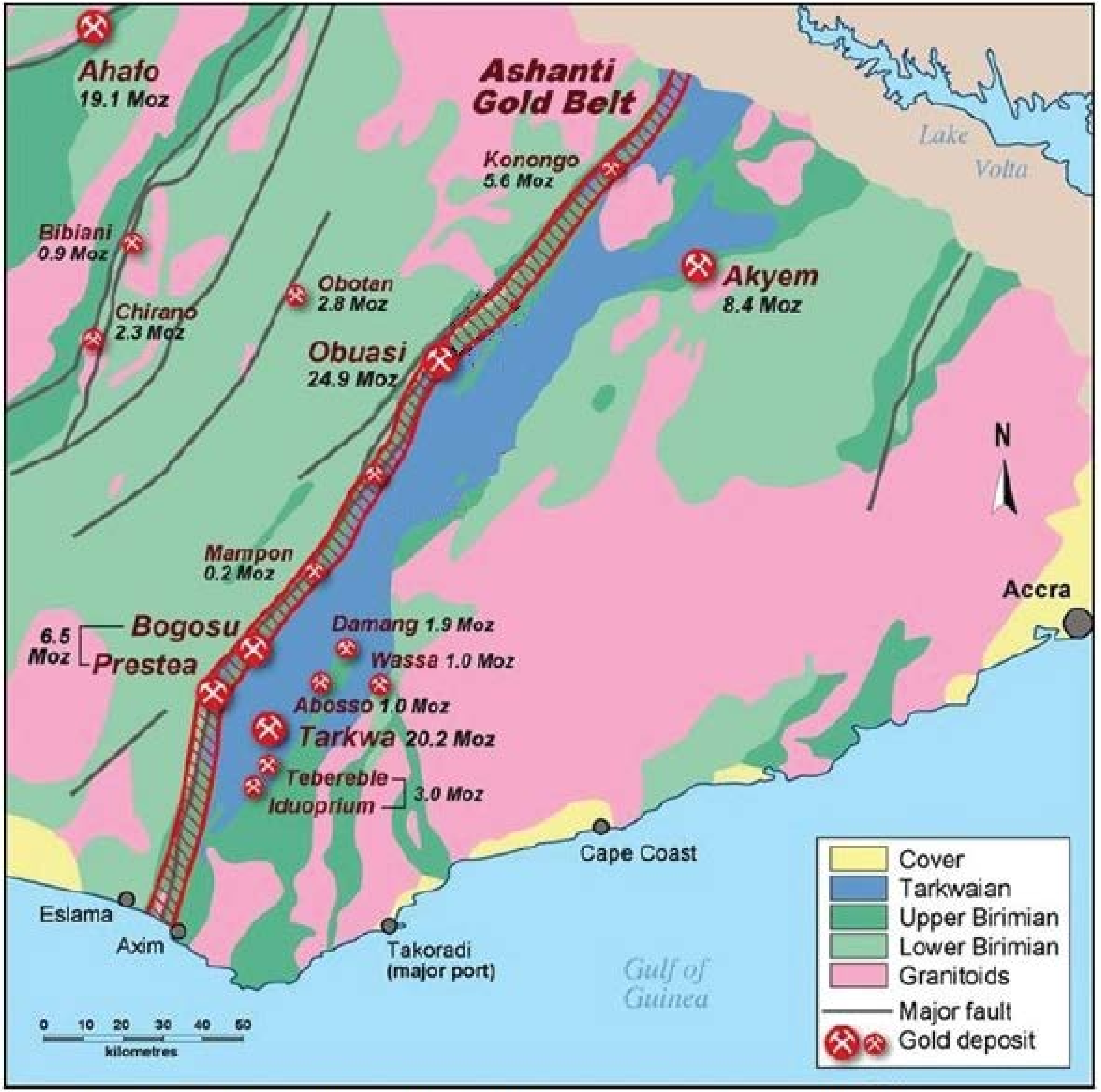


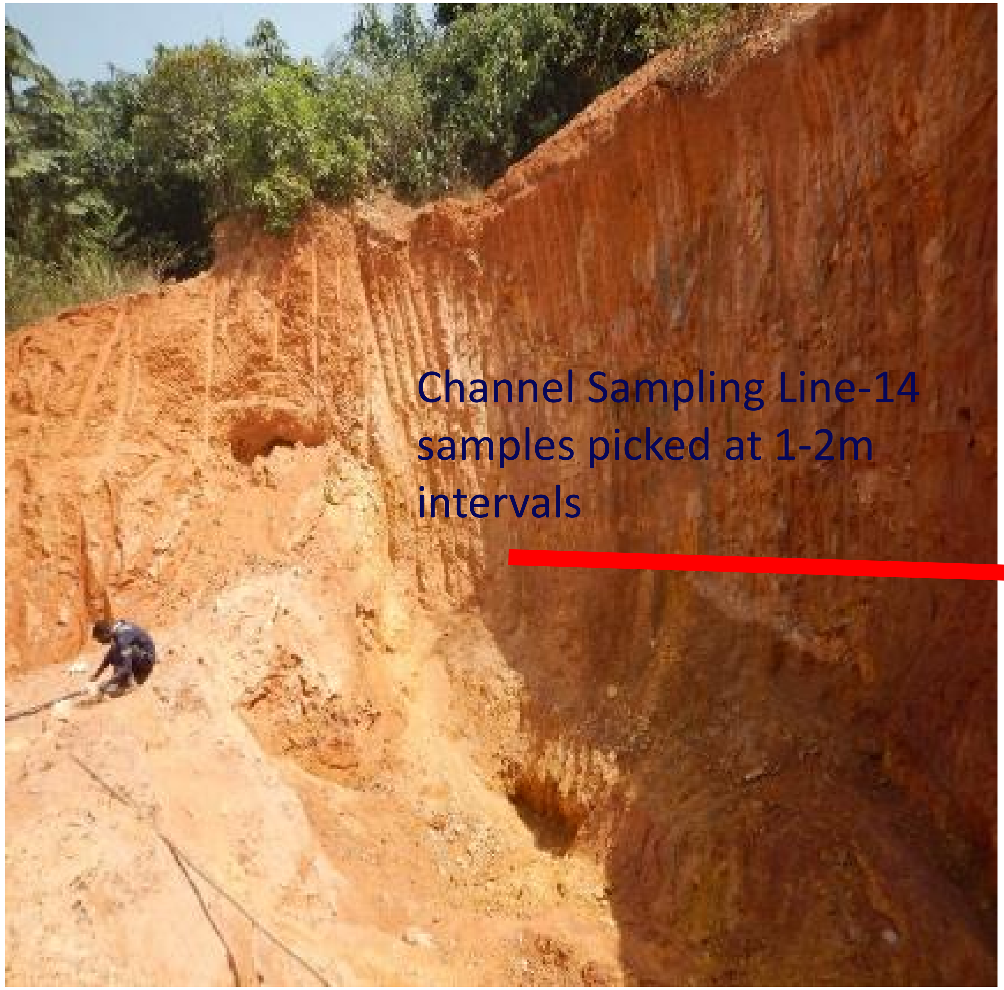
Figure 6-7. Location of Obuasi gold mine along the Axim-Konongo shear zone along the northwestern margin of the Ashanti greenstone belt. Other significant mines are also shown (Metals News, 2008).

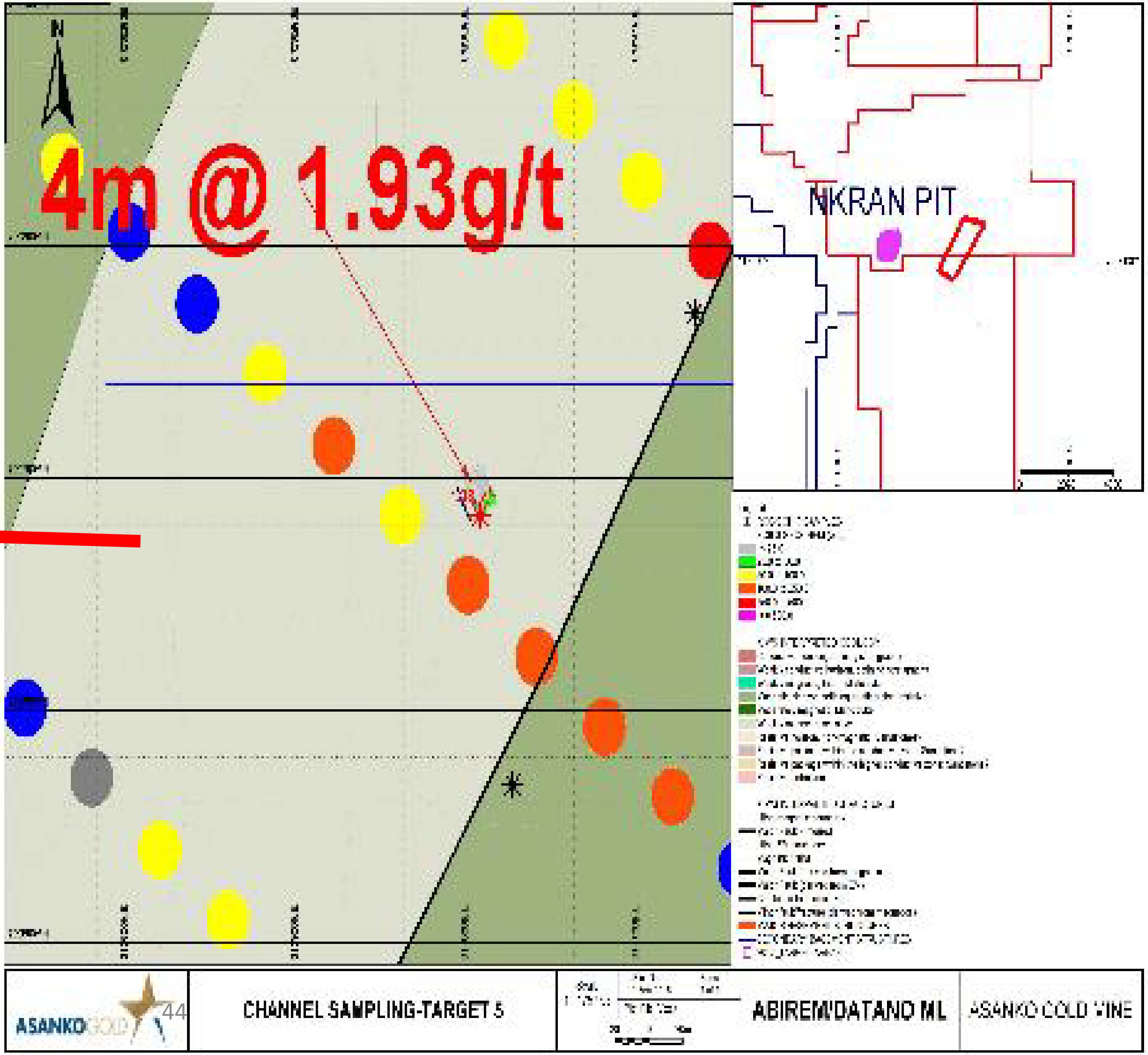

Ashanti belt main structure


Mined out pit on the Ashanti main structure

Using geochem for exploration in Ghana

CHANNEL SAMPLING





AsankoGold, 2018

Structure and Mineralization Characteristics

- **Structure**
  - Conforms with the general regional strike NNE – SSW structure, with folds plunging to NE
  - Multiplicity of deformational episode

- **Mineralisation**
  - Complex arrangement of deformed rocks
  - Mineralisation is hosted in deformation zones and proximal to contacts

    ✓ Styles of mineralization
    - Disseminated Arsenopyrite domains (Refractory)
    - Contact-related Vein Quartz
    - Granitoid/Stockworks (primary non- refractory)
    - Supergene oxide and transition ore

    ✓ Types of mineralization

  - Quartz vein type (quartz with free Gold, in association with lesser amount of various metal sulphides containing iron, zinc, lead and copper), non refractory

  - Sulphide ore (inclusion of gold in the crystal structure of arsenopyrite minerals. Higher gold grades tend to be associated with finer grain arsenopyrite crystals. Sulphide ore is generally refractory

AngloGoldAshanti, 2018

Two types of Mineralization

Sulphide Mineralisation with ASP

Quartz with Spec of Gold

Vary from 1-40m wide and 1-1,000g/t Au.

<u>Associated Attributes:</u>
Strong shearing, potentially faulted, fractured and friable domains

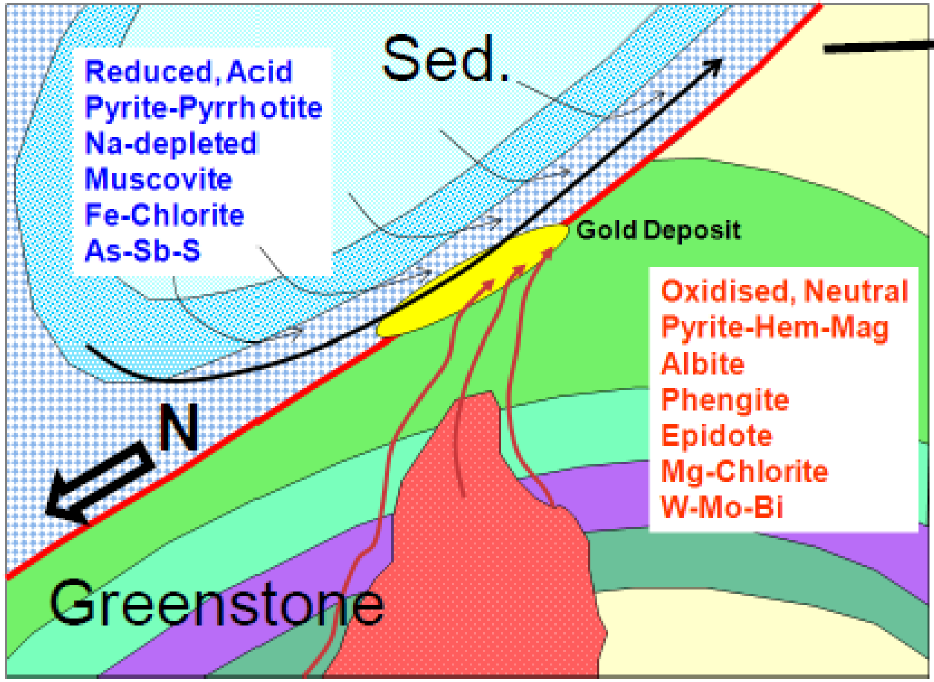
AngloGoldAshanti, 2018

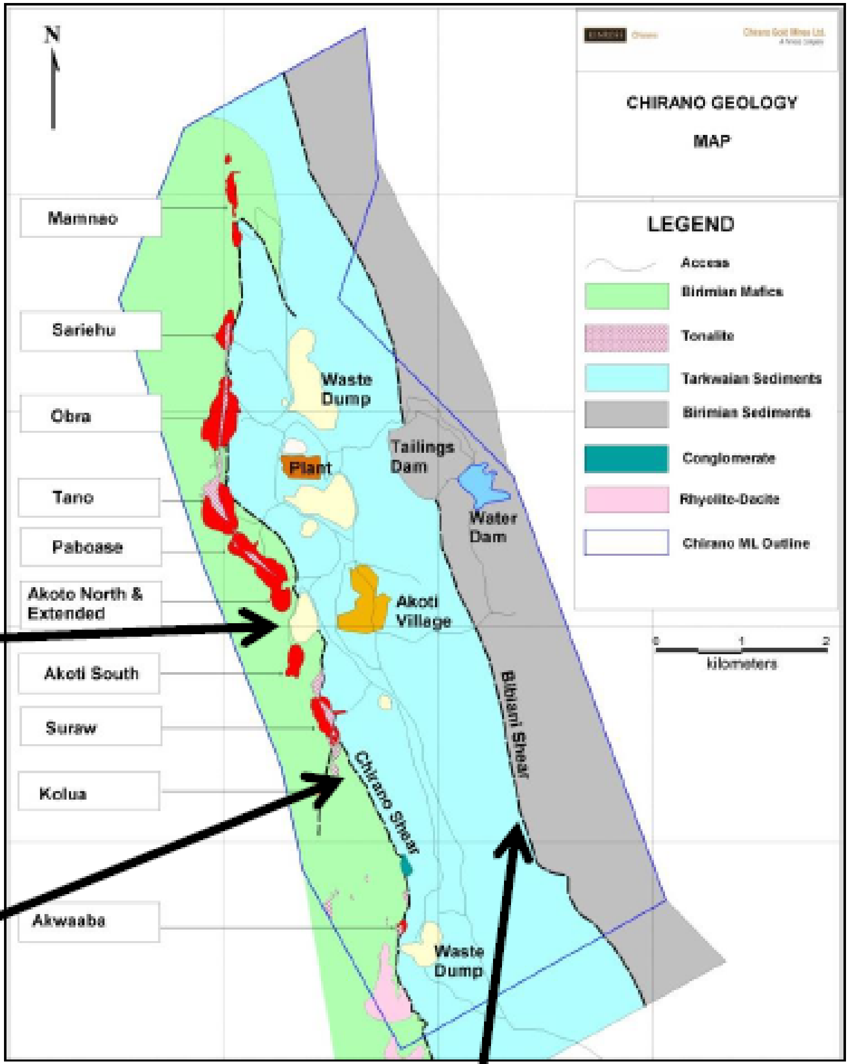
Deposition mechanism:

Chirano gold system comprises two types of shear hosted :

1. Chirano: *Porphyry intrusion-mafic volcanic-hosted deposit*
2. Bibiani: *Sediment-hosted deposit*

• Different mineralogy and chemistry
• Fluid mixing (evidence pyrite deposition of graphite selvages in black breccia - Akwaaba)





Chirano:
• Hematite-magnetite-pyrite
• Intense albite-ferroan dolomite alteration
• W-Mo-Bi pathfinder signature.
• Phengitic sericite and Mg-rich chlorite
• Arsenic depletion
• Gold is strongly related to pyrite

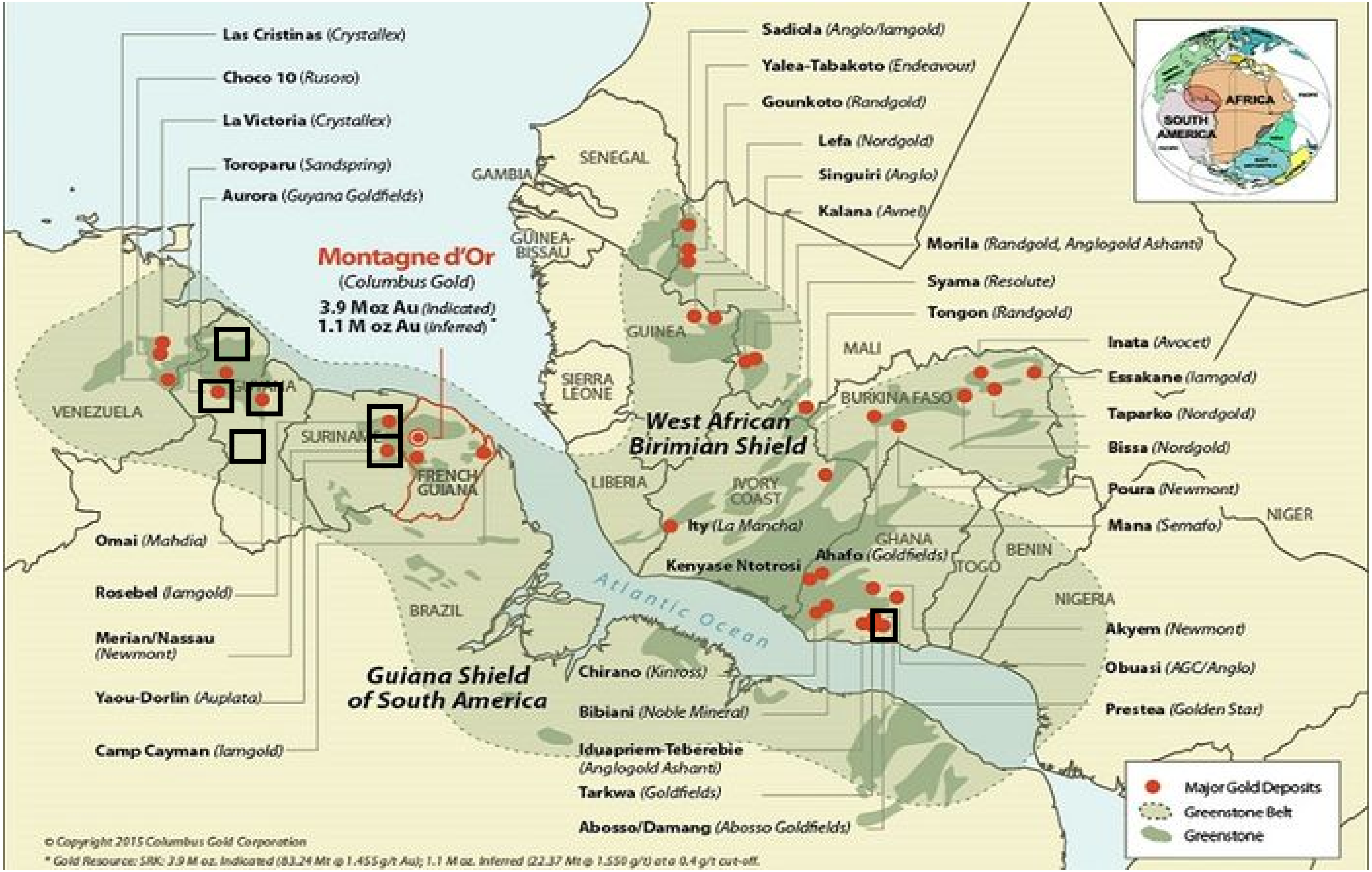
Bibiani
•Style graphitic shear
• Pyrite-arsenopyrite-graphite
• Intense sericite (paragonite)
• As-Sb pathfinder signature

Kinross, 2018

- Prestea Underground is hosted within Birimian Phyllites
- Gold mineralization is associated with the prolific fault zone referred to as the Ashanti Trend
- West Reef mineralization is hosted in a fault structure parallel to the Main Reef located ~250m in the hanging wall
- Gold occurs as free gold along carbonaceous partings within the quart veins or with pyrite and arsenopyrite

Golden Star Resources, 2018

Au geochem for exploration?


Las Cristinas (Crystallex)
Choco 10 (Rusoro)
La Victoria (Crystallex)
Toroparu (Sandspring)
Aurora (Guyana Goldfields)
Montagne d'Or
(Columbus Gold)
3.9 Moz Au (indicated)
1.1 M oz Au (inferred) *
VENEZUELA
SURINAM
FRENCH GUIANA
BRAZIL
Omai (Mahdia)
Rosebel (Iamgold)
Merian/Nassau (Newmont)
Yaou-Dorlin (Auplata)
Camp Cayman (Iamgold)
Guiana Shield of South America
Atlantic Ocean
SENEGAL
GAMBIA
GUINEA-BISSAU
GUINEA
SIERRA LEONE
LIBERIA
IVORY COAST
MALI
BURKINA FASO
GHANA
TOGO
BENIN
NIGERIA
NIGER
West African Birimian Shield
Sadiola (Anglo/Iamgold)
Yalea-Tabakoto (Endeavour)
Gounkoto (Randgold)
Lefa (Nordgold)
Singuiri (Anglo)
Kalana (Avnel)
Morila (Randgold, Anglogold Ashanti)
Syama (Resolute)
Tongon (Randgold)
Inata (Avocet)
Essakane (Iamgold)
Taparko (Nordgold)
Bissa (Nordgold)
Poura (Newmont)
Mana (Semafo)
Ity (La Mancha)
Kenyase Ntotrosi
Ahafo (Goldfields)
Akyem (Newmont)
Obuasi (AGC/Anglo)
Prestea (Golden Star)
Chirano (Kinross)
Bibiani (Noble Mineral)
Iduapriem-Teberebie (Anglogold Ashanti)
Tarkwa (Goldfields)
Abosso/Damang (Abosso Goldfields)
AFRICA
SOUTH AMERICA
Major Gold Deposits
Greenstone Belt
Greenstone
© Copyright 2015 Columbus Gold Corporation
* Gold Resource: SRK: 3.9 M oz. Indicated (83.24 Mt @ 1.455 g/t Au); 1.1 M oz. Inferred (22.37 Mt @ 1.550 g/t) at a 0.4 g/t cut-off.

Common Indicator Mineral Suites

- Gold grains (Au)
- Native copper (Cu)
- Kimberlite indicator minerals
- Platinum Group minerals (PGM)
- Sulphide minerals
- Metamorphosed VMS (e.g. gahnite, staurolite)
- Magmatic Ni-Cu-PGE minerals
- Porphyry Cu-Mo-Au minerals
- Scheelite, wolframite (W)
- Cassiterite (Sn)
- Cinnabar (Hg)
- Fluorite, topaz (F)
- Uranium minerals
- Rare earth element (REE) minerals

• May be recovered from <u>same</u> heavy mineral concentrate
• Archived concentrates can be re-examined

McClenaghan 2018

Trace Element Compositions Minerals

Sulphides	Present in % Amounts	Present in Trace Amounts
Pyrite	Cu, Co, Ni, Zn, **As,** Pb	Pb, V, Sb, Se, Mn, Ag, Au, Bi, Mo Cd
Pyrrhotite	Ni	Co, Cu, Mn, V, Zn, Sn
Arsenopyrite	Co	Mn, Ni
Chalcopyrite	Mn, Zn	Ni, Co, Sb, Ag, Se, As, Sn, V, Mo
Sphalerite	Fe, Mn, Cu, Cd, **Sb**, Sn, Ag, **As**	Co, Ni, Bi, In, Ga, Tl
Galena	Bi, Ag, **Sb**, Se, **As**	Cu, Mn, Sn, Zn, Cd
Silicates	**Present in Major Amounts**	**Present in Minor Amounts**
Plagioclase	K, Sr, Ba, Rb, Ti, Mn	P, Ga, V, Zn, Ni
K-feldspar	Na, Ca, Ba, Sr, Rb, Ti	P, Pb, Li, Ga, Mn, Al, Ti, Fe, Mg, Ca
Amphibole	Ti, F, K, Mn, Cl, Rb, Zn, Cr, V, Sr, Ni	Ba, P, Cu, Co, Ga, Pb
Pyroxene	Al, Ti, Na, Mn, K, Cr, V, Ni, Cl, Sr	P, Cu, Co, Zn, Li, Rb
Muscovite	Al, K, Fe, Ti, Mg, Ca, Na, Rb, Li	Mn
Biotite	Ti, F, Ca, Na, Ba, Mn, Rb, Cl, Zn, V, Cr, Li, Ni	Cu, Sr, Co, P, Pb, Ga
Olivine	Ni, Mn, Ca, Al, Cr, Ti, P, Co	Zn, V, Cu, Sc

Chalcophile

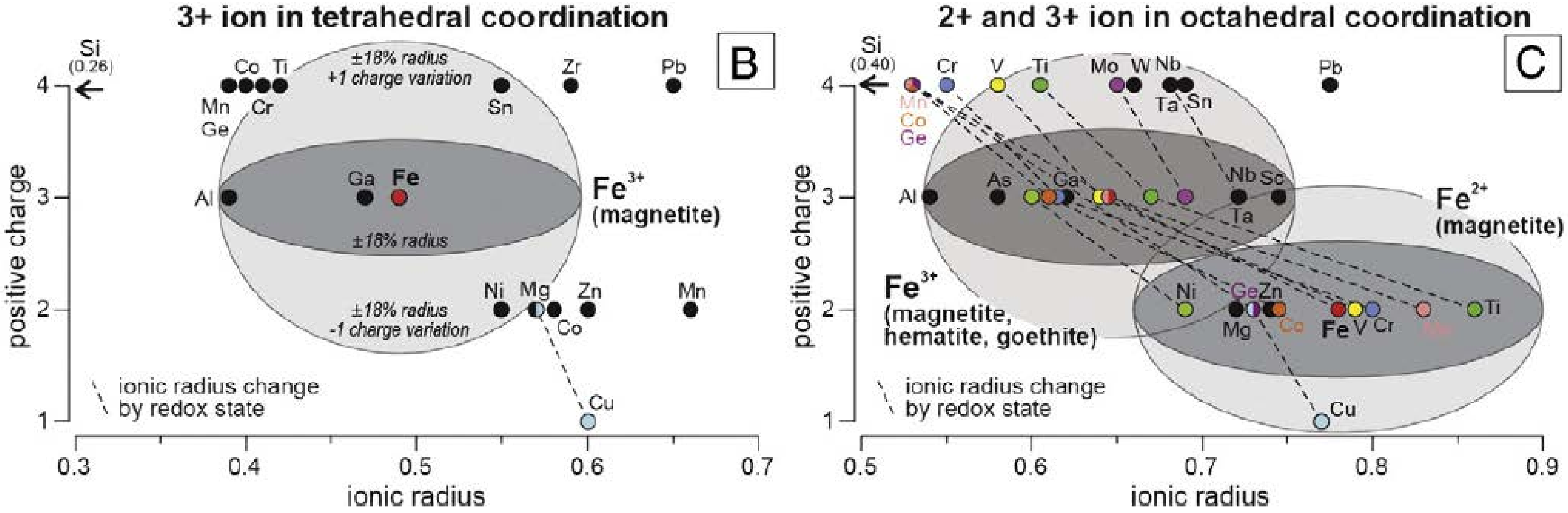
*Data from Lelong et al (1976), Joyce (1984) and Vaughan and Craig (1978).

Bloom 2018

Mineral geochem as a tool for exploration

Why Magnetite?

- Iron oxide (Fe_3O_4)
  - Can incorporate other elements into it's structure.



Nadoll et al. 2014

Why magnetite geochemistry?

DETRITAL MAGNETITE AS A PROVENANCE INDICATOR[1]

JEFFRY D. GRIGSBY[2]
Department of Geology
University of Cincinnati
Cincinnati, Ohio 45221

Miner Deposita (2011) 46:319–335
DOI 10.1007/s00126-011-0334-y

ARTICLE

Discriminant diagrams for iron oxide trace element fingerprinting of mineral deposit types

Céline Dupuis · Georges Beaudoin

Ore Geology Reviews 61 (2014) 1–32

Contents lists available at ScienceDirect

Ore Geology Reviews

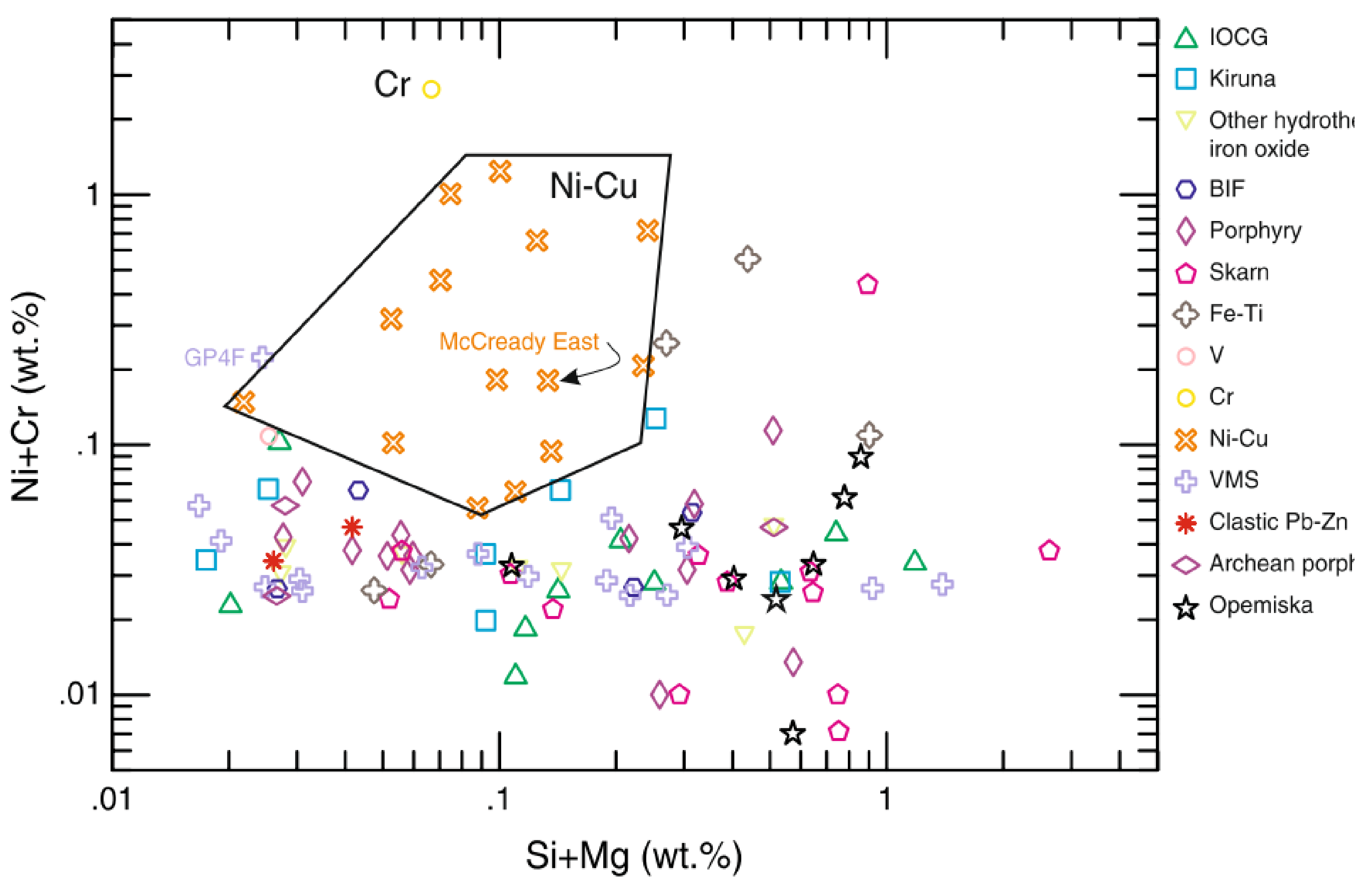
journal homepage: www.elsevier.com/locate/oregeorev

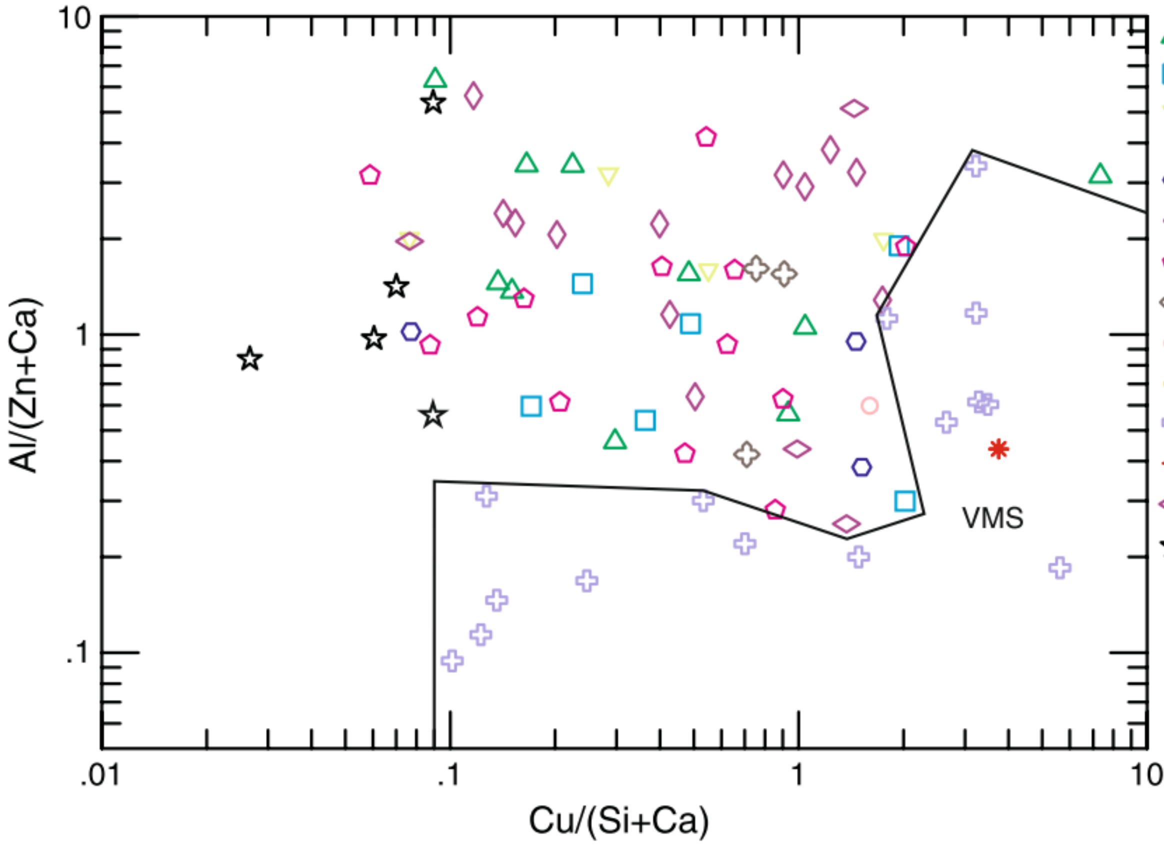
Review

The chemistry of hydrothermal magnetite: A review

Patrick Nadoll [a,*], Thomas Angerer [b], Jeffrey L. Mauk [c], David French [d], John Walshe [a]

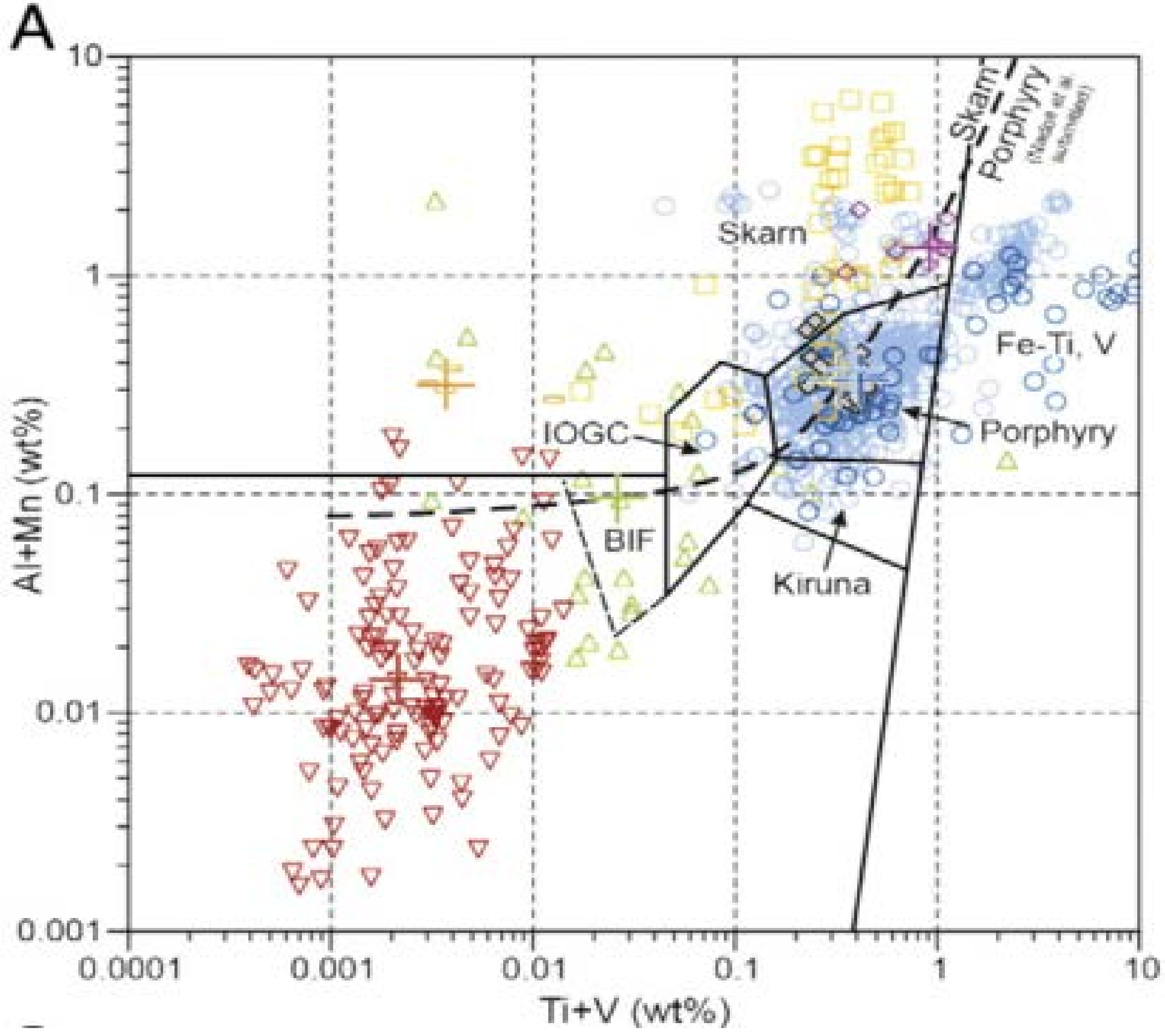
Variations in magnetite chemistry

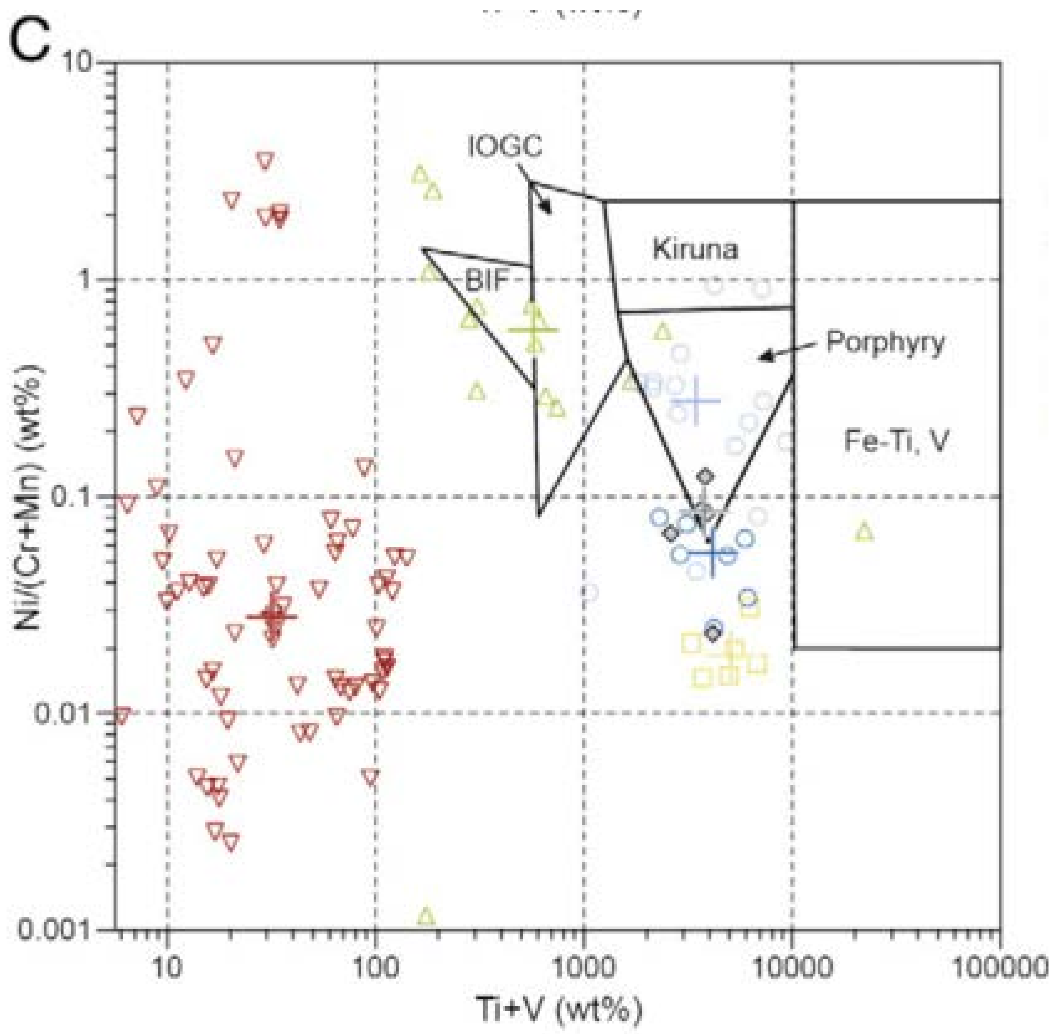




Dupuis and Beaudoin, 2011

Variations in magnetite chemistry





Dupuis and Beaudoin, 2011

Guyana Magnetite project

- Collect magnetite grains
- Analyze magnetite grains
- Use magnetite discriminant plots to determine ore deposit potential

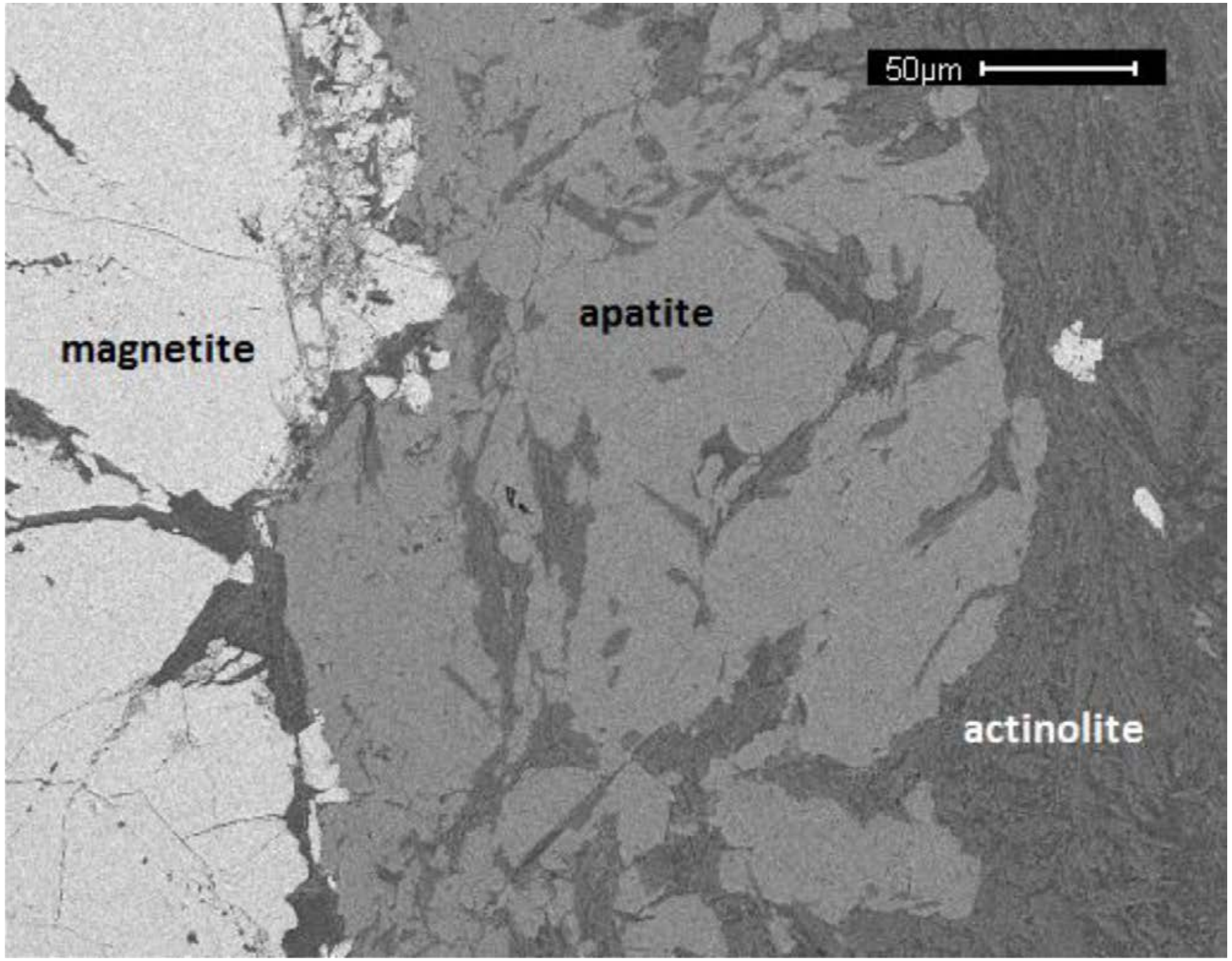
Mineral geochemistry for understanding how ore deposits form

Los Colorados apatite chemistry?

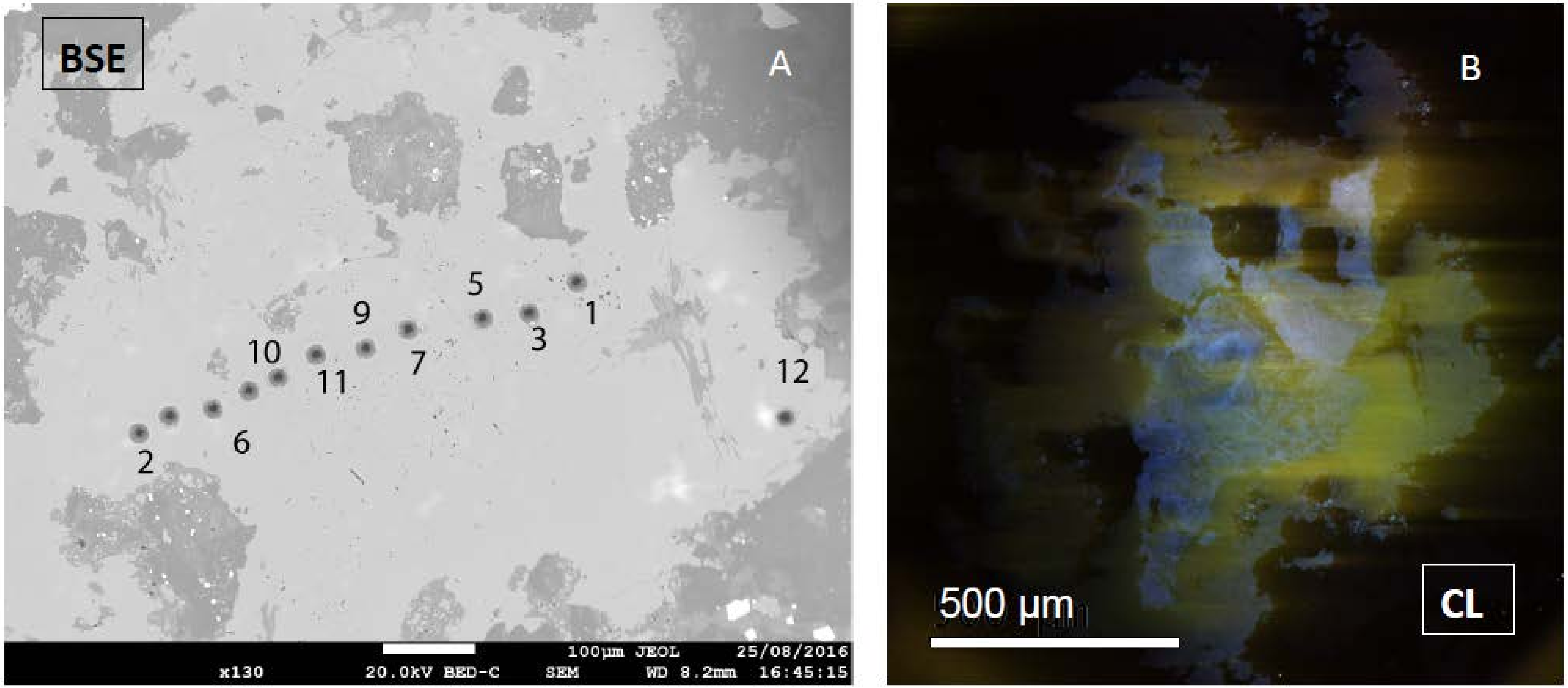
$Ca_5(PO_4)_3(F,Cl,OH)$ $[A_5(XO_4)_3(Z)]$

- A = Ca^{2+}, Sr^{2+}, Pb^{2+}, Ba^{2+}, Mg^{2+}, Fe^{2+}, REE^{3+}, Eu^{2+}, Cd^{2+}, Na^{+}, Al^{3+}, Y^{3+}, K^{+}, Mn^{2+}, Cu^{2+}
- X= P^{5+}, Si^{4+}, $S^{4/6+}$, As^{5+}, V^{5+}, C^{4+}
- Z= F^{-}, Cl^{-}, $S^{2-/1-}$, OH^{-}

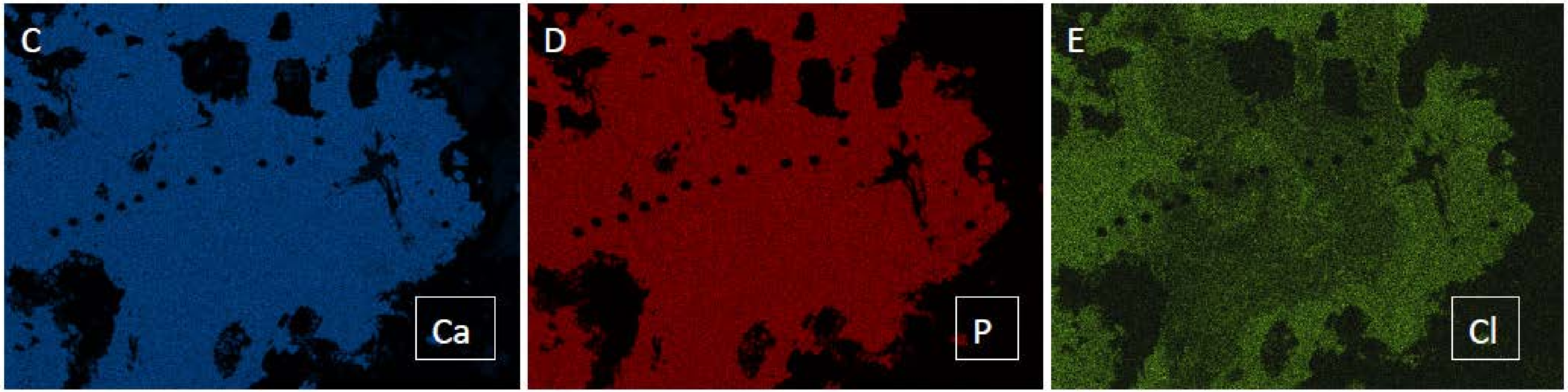
- Major (F, Cl, OH) and trace element chemistry can provide insights into fluid history.



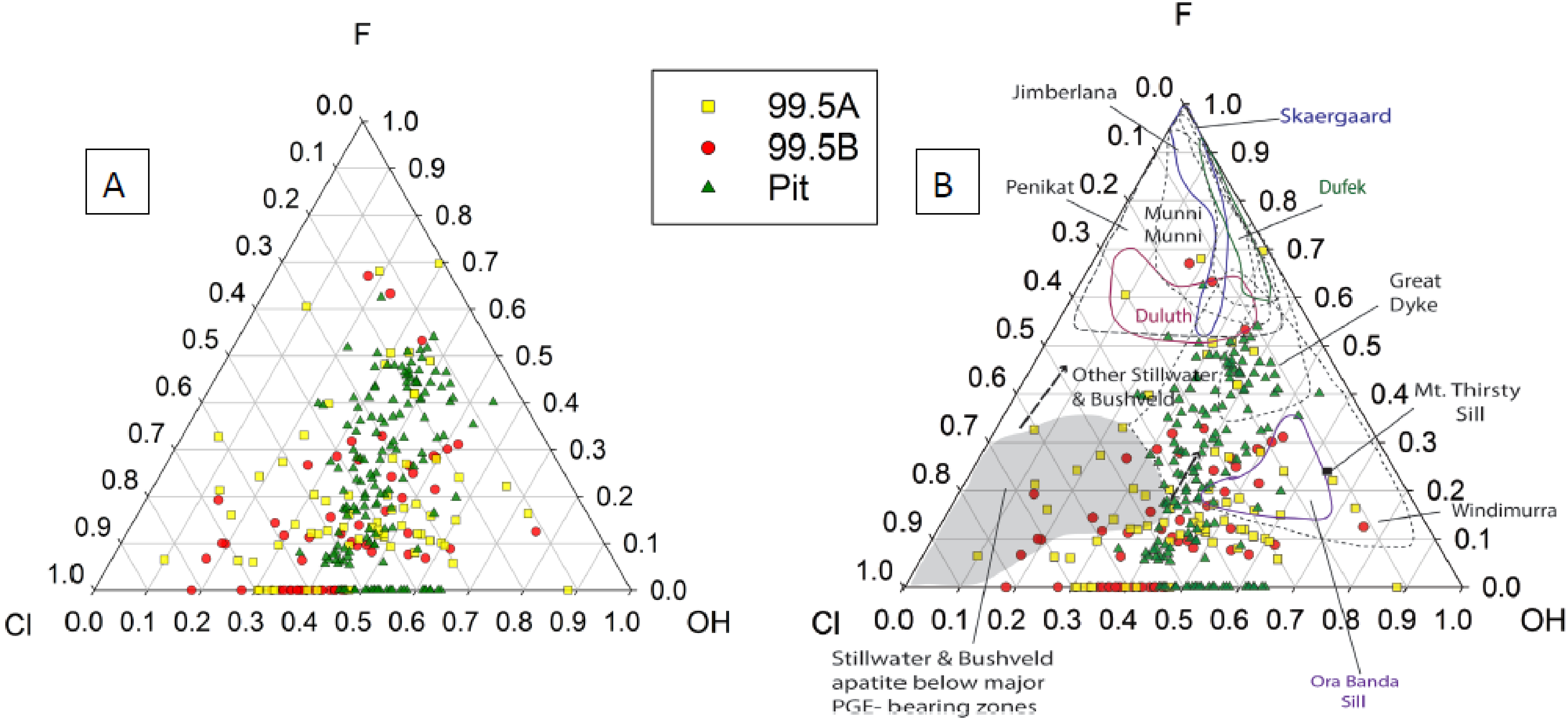
Pit sample



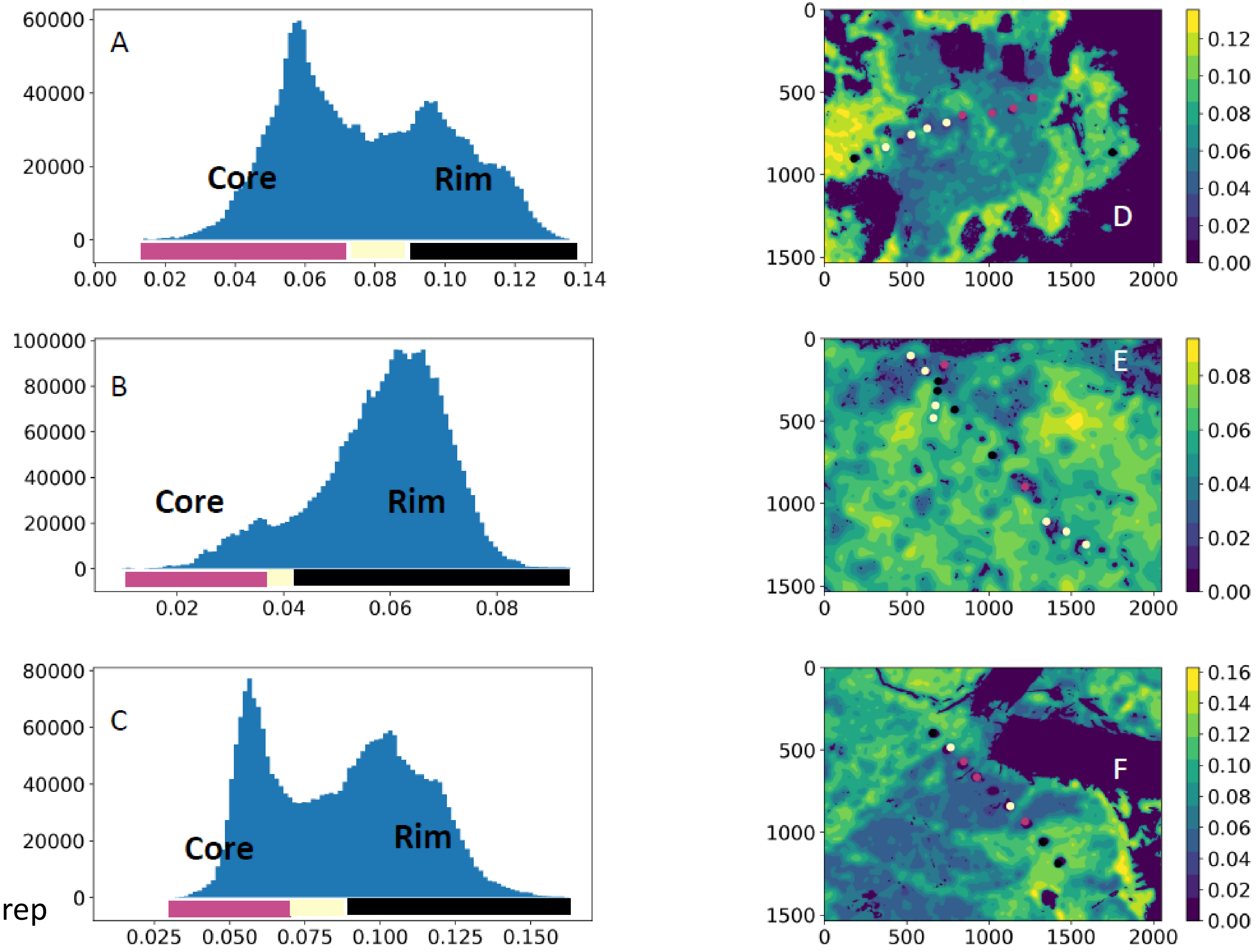
EDS Element Maps



La Cruz et al. in prep

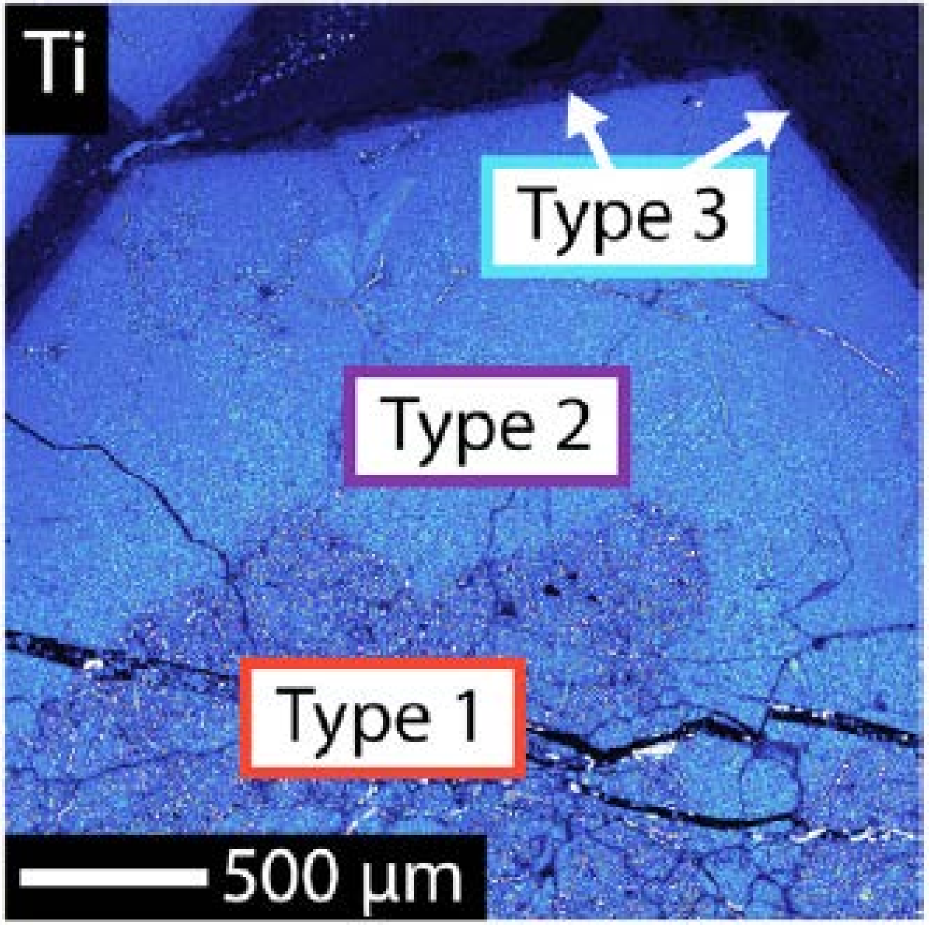


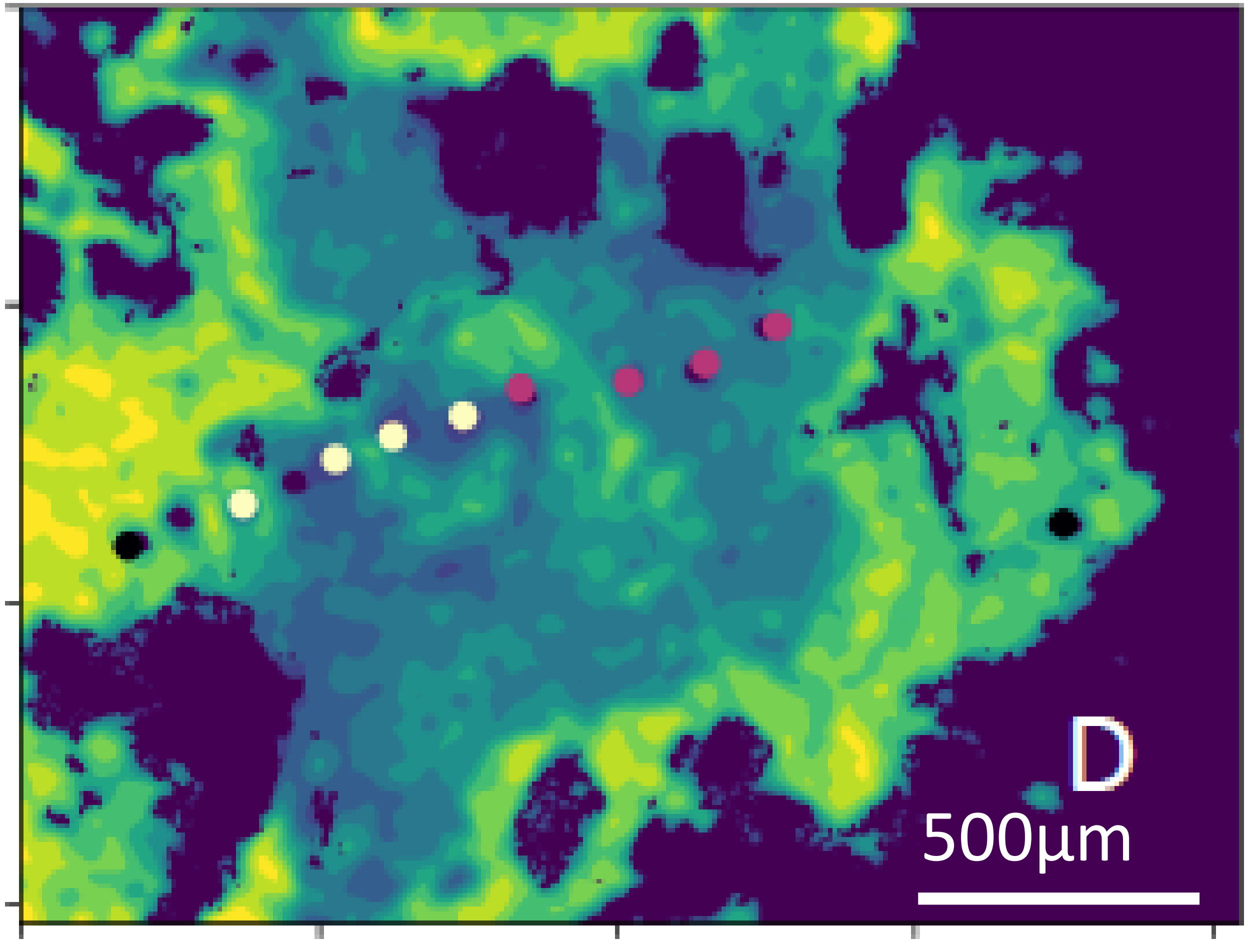
La Cruz et al. in prep



La Cruz et al. in prep

Similarities with magnetite and apatite chem





Knipping et al., 2015 a,b

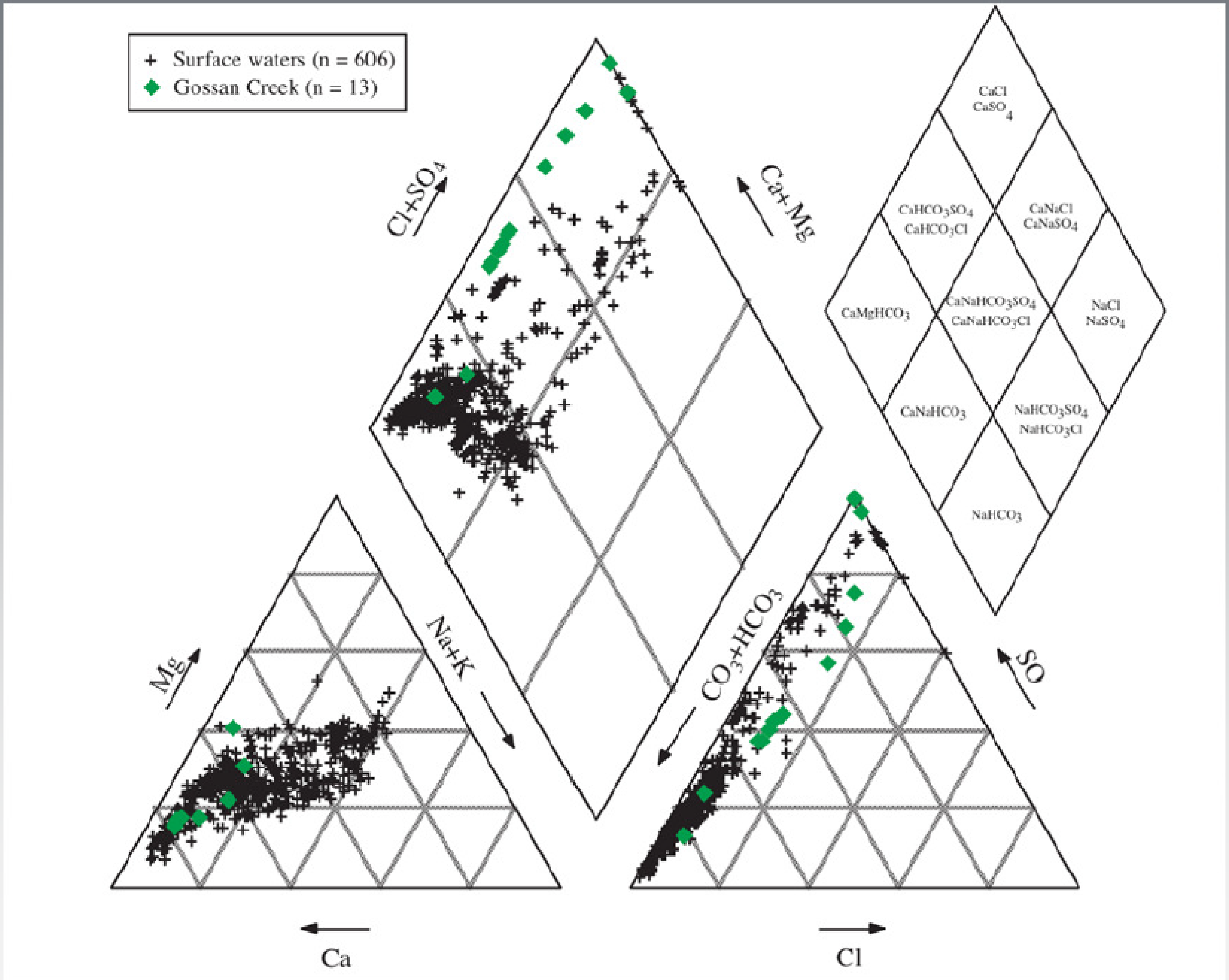
Aqueous geochem for exploration

Water chemistry

Major ions in water – typically not useful for direct exploration, but can help identify changes in water sources, water-rock reactions.

Here > 600 surface water samples – a subset has anomalously elevated SO_4 – and elevated Au

Leybourne 2018

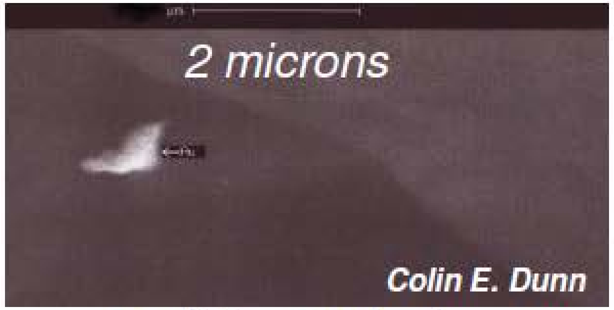


Biogeochemistry as a tool for exploration

Base Metals Southern British Columbia

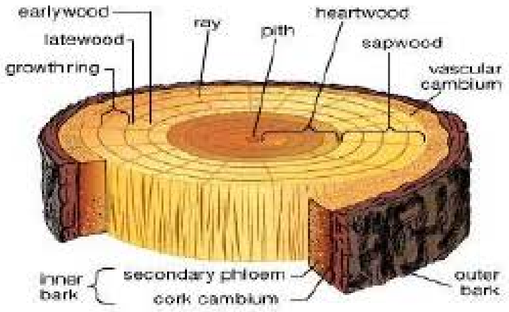
Dunn 2018

Metal Uptake and Transport in Trees



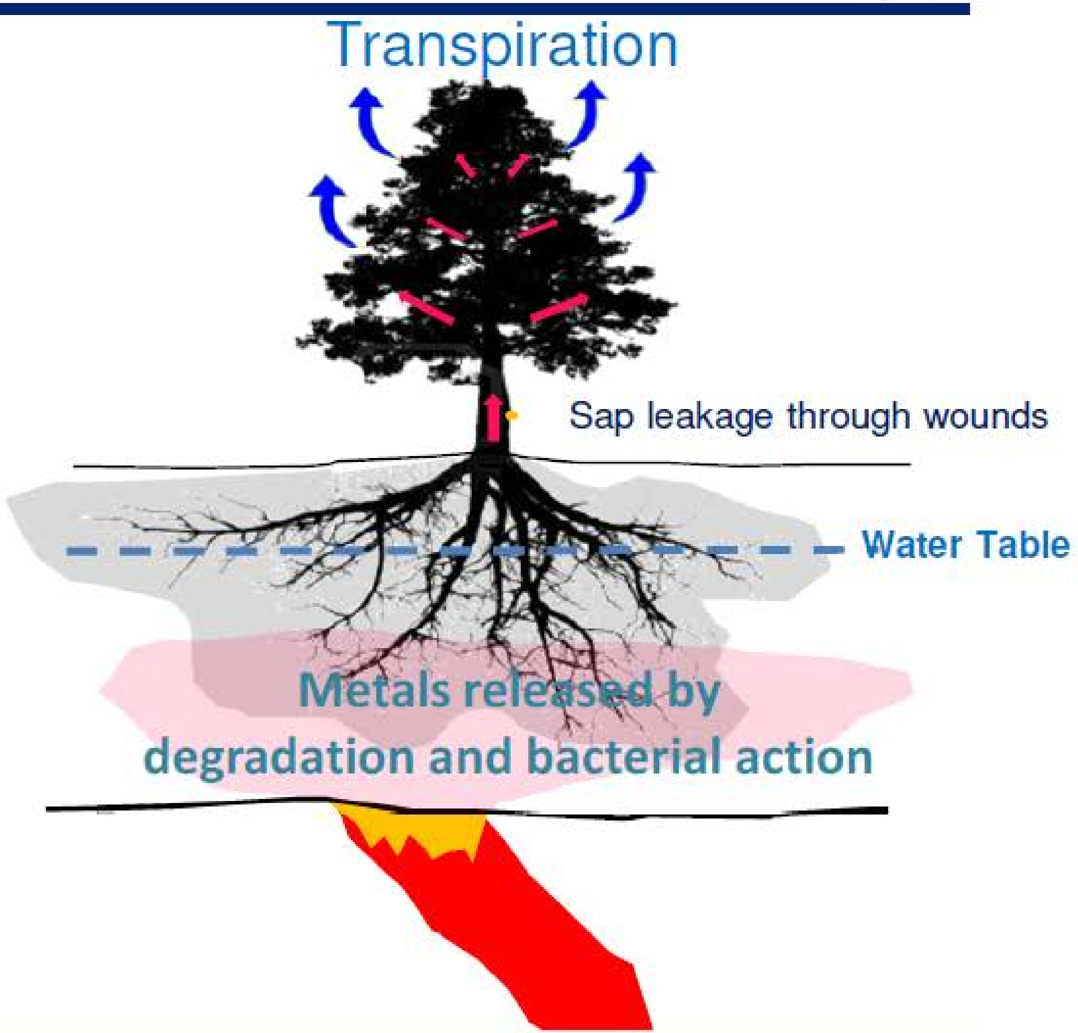
Gold in outer bark

Incorporation into Tissues



Transport in vascular system

Metal uptake facilitated by mycorrhizae



Douglas-fir Treetop Sampling

Dunn 2018

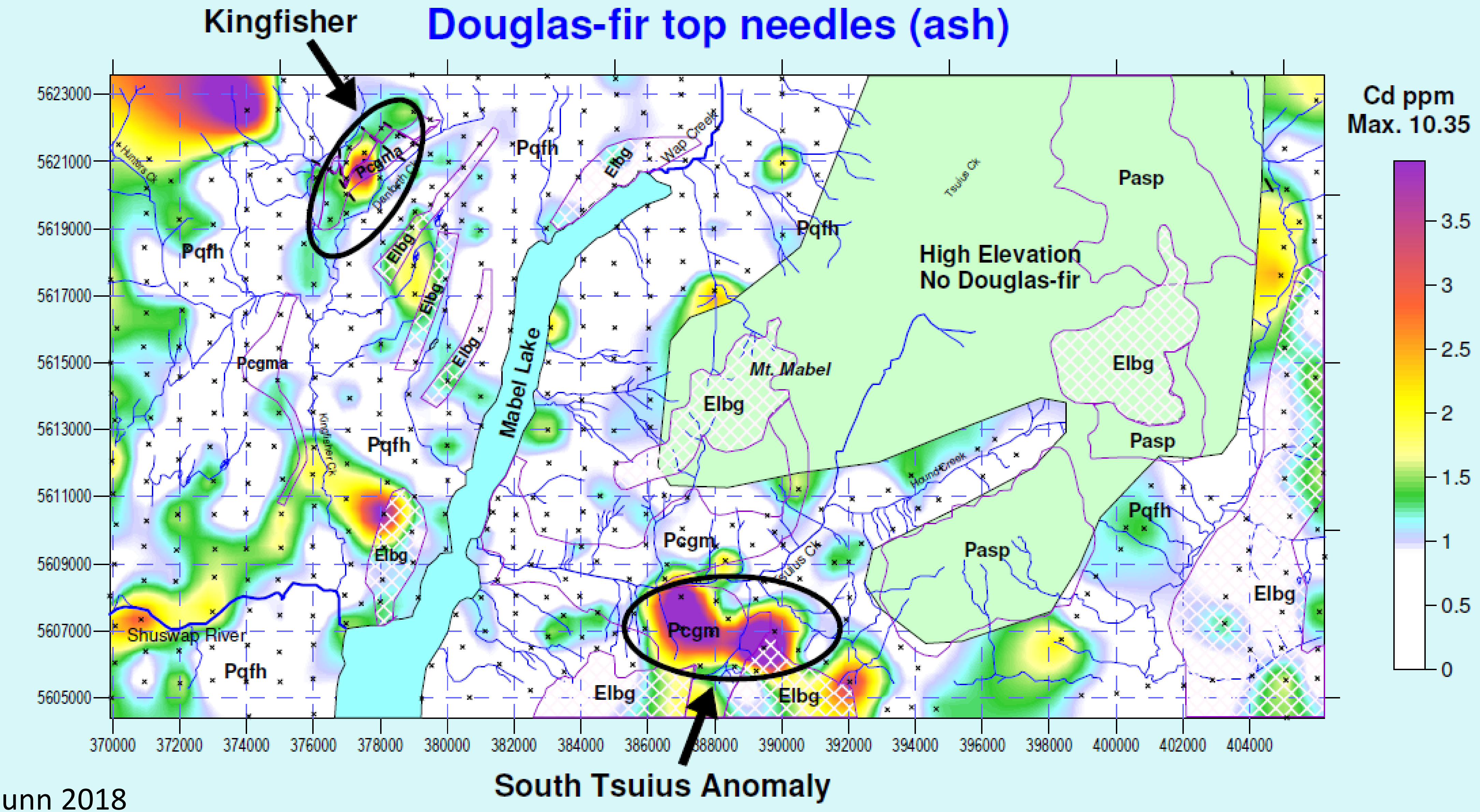
Sample Collection

Dunn 2018

Separation of Needles from Twigs

Dunn 2018

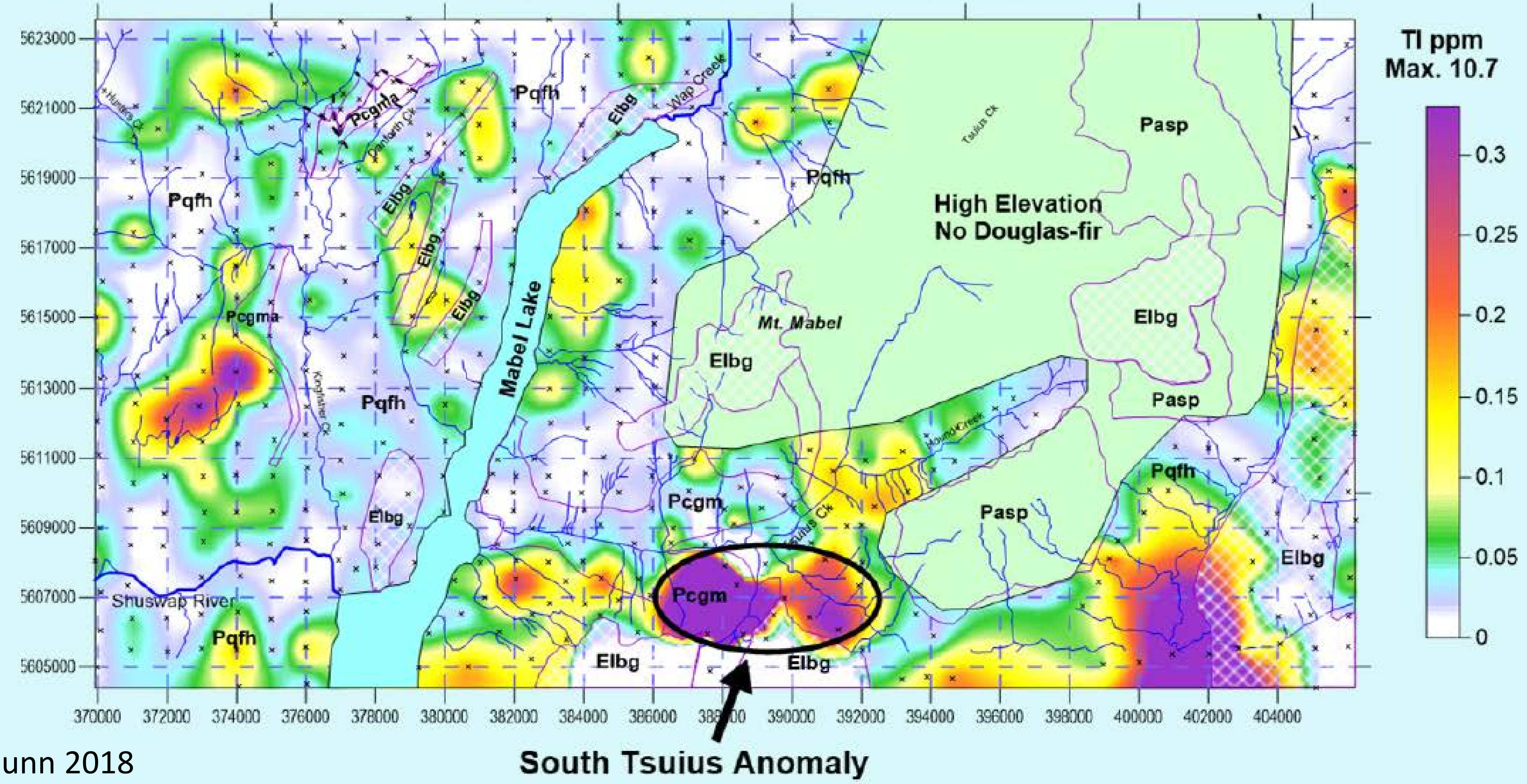
CADMIUM
Douglas-fir top needles (ash)



Dunn 2018

Colin E. Dunn

THALLIUM
Douglas-fir top needles (ash)



Dunn 2018

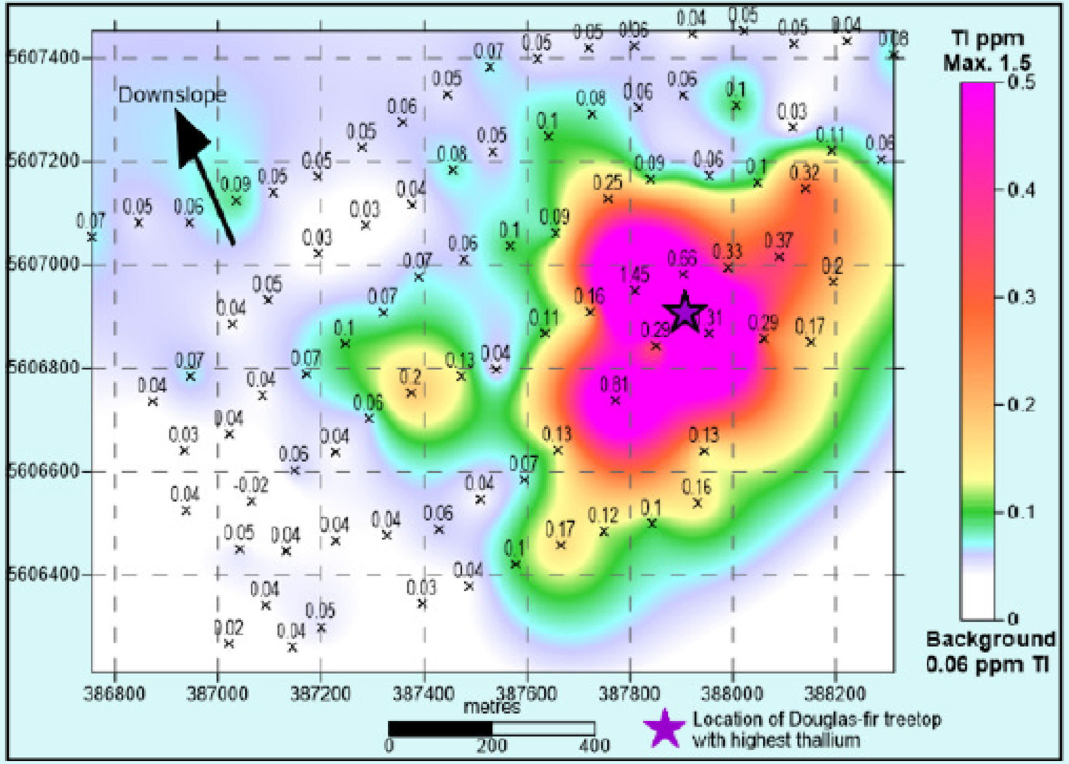
Colin E. Dunn

Bark Sampling

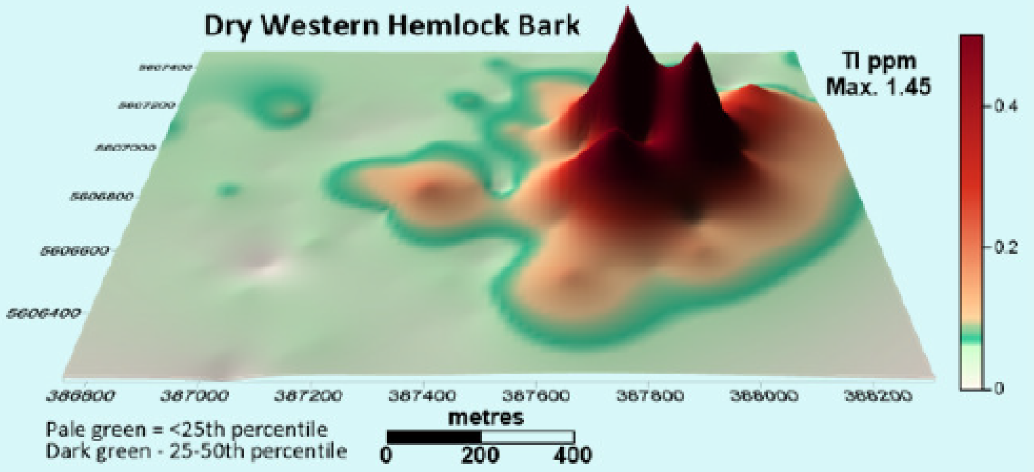
Dunn 2018

THALLIUM – Dry Western Hemlock Bark
South of Tsuius Ck

Contoured percentiles



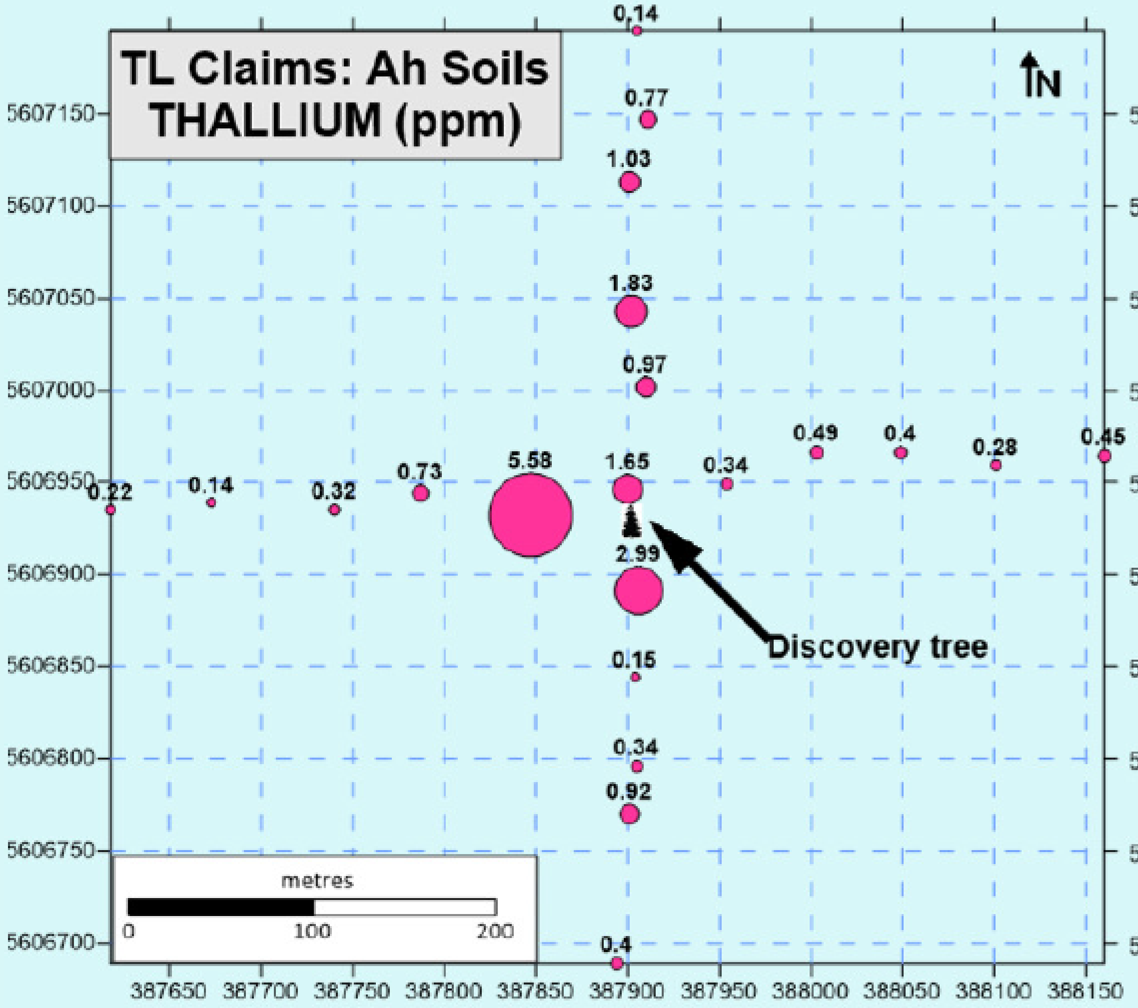
3D Surface Image

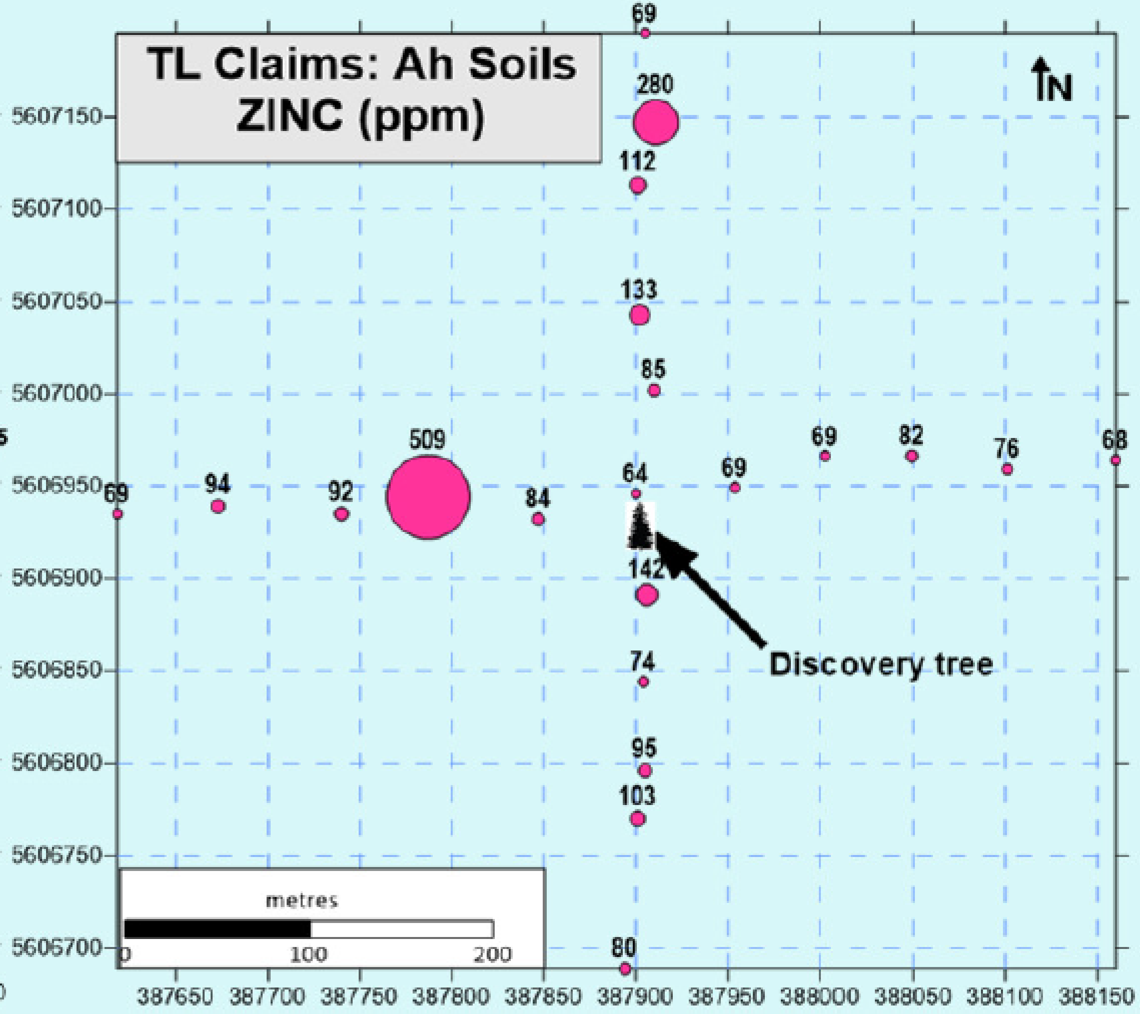


Dunn 2018

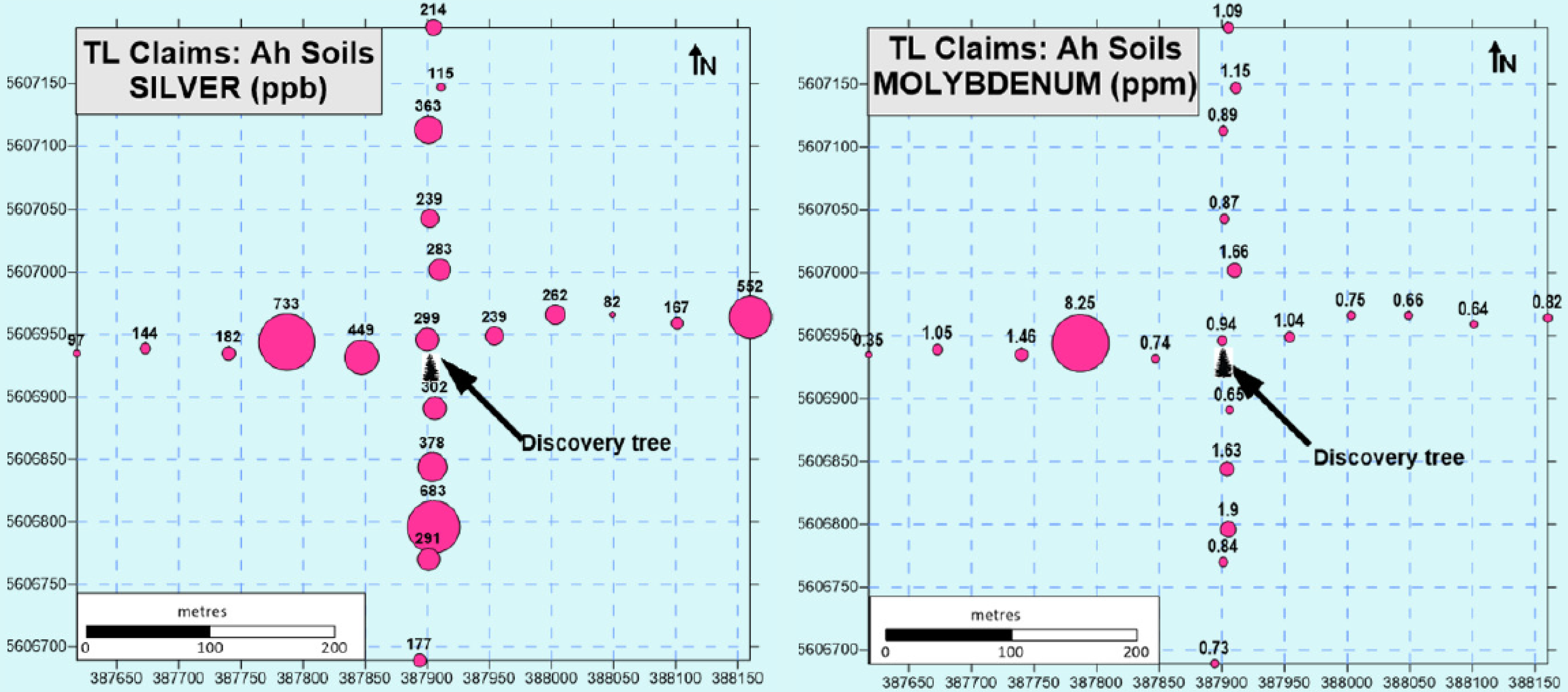
Continuous rock trench – 3 trenches

Dunn 2018

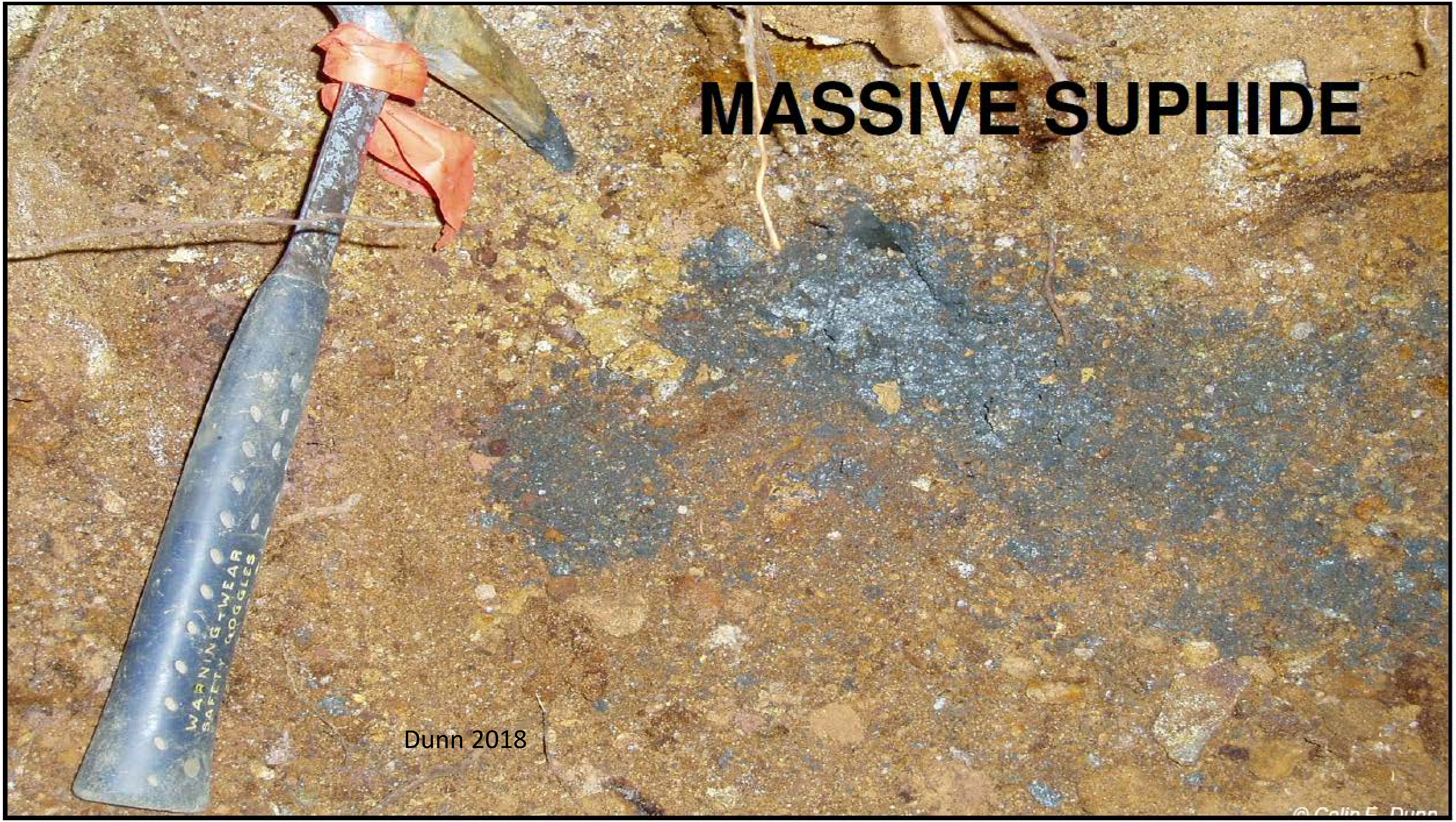

TL Claims: Ah Soils
THALLIUM (ppm)
N
Discovery tree
metres
0
100
200


TL Claims: Ah Soils
ZINC (ppm)
N
Discovery tree
metres
0
100
200

Dunn 2018

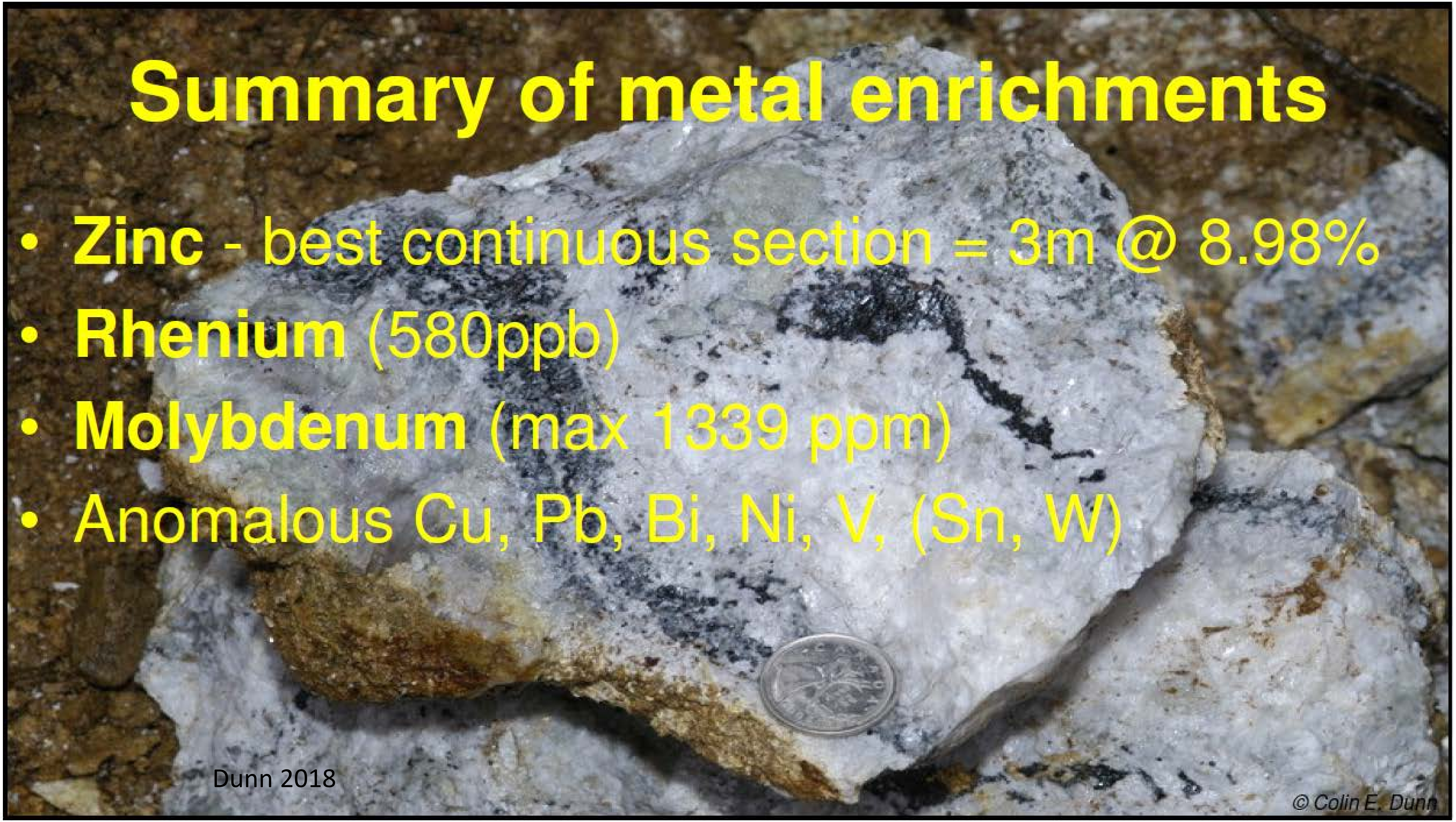

TL Claims: Ah Soils
SILVER (ppb)
N
214
115
363
239
283
733
449
299
239
262
82
167
552
97
144
182
302
378
683
291
177
Discovery tree
metres
0
100
200
5607150
5607100
5607050
5607000
5606950
5606900
5606850
5606800
5606750
5606700
387650
387700
387750
387800
387850
387900
387950
388000
388050
388100
388150
TL Claims: Ah Soils
MOLYBDENUM (ppm)
1.09
1.15
0.89
0.87
1.66
0.35
1.05
1.46
8.25
0.74
0.94
1.04
0.75
0.66
0.64
0.82
0.65
1.63
1.9
0.84
0.73

Dunn 2018


MASSIVE SUPHIDE
WARNING - WEAR SAFETY GOGGLES
Dunn 2018

Summary of metal enrichments

- **Zinc** - best continuous section = 3m @ 8.98%
- **Rhenium** (580ppb)
- **Molybdenum** (max 1339 ppm)
- Anomalous Cu, Pb, Bi, Ni, V, (Sn, W)



Dunn 2018

A Diamond Mine Udachnaya Pipe, an open-pit diamond mine in Russia, is more than 600 meters (1,970 ft) deep.

Simon, 2015


Arakaka trend, northwestern Guyana


Medium scale mining in northwestern Guyana


Medium scale mining in northwestern Guyana

Summary

- Ore deposits and mining are important for society to exist.
- If we don’t grow it, we must mine it. (We also mine to be able to grow things.)
- Can we figure out better ways to mine and regulate mining in order to mitigate harmful effects?
- The resources we need come from different types of deposits that exist globally.
- Geochemistry is a useful tool for finding these deposits.