Recent developments in komatiite Ni-Co sulfide deposits

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Running theme: how and why are komatiite-hosted different from mafic hosted

Length and timescale story – incl. Yao and Mungall

Updated volcanology model, genetic model overview

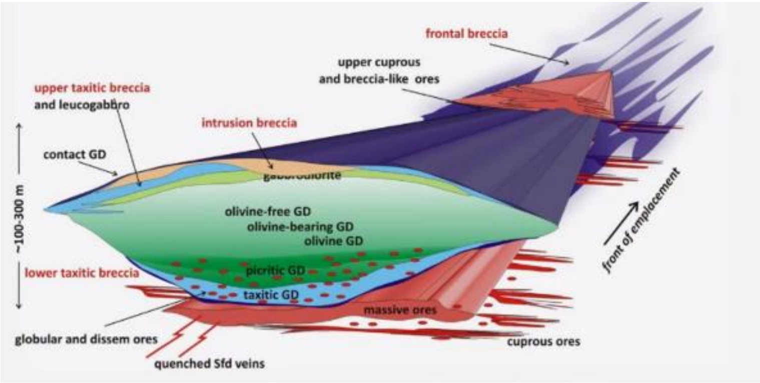
Disseminated sulfide ores – deposition mechanisms

Moran, sulfide emplacement, infiltration-melting zones and preservation

Lithochem tips and resources

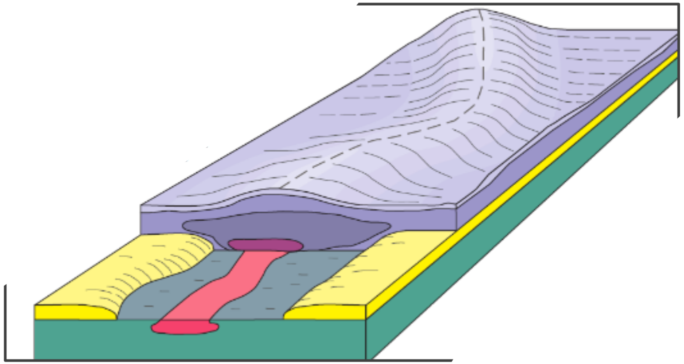
Komatiite hosted and mafic intrusion hosted ores: similarities, differences

Mafic intrusion-hosted



- Tube- or funnel-shaped conduits
- Thermal/mechanical erosion of floor and roof rocks
- Cross cutting massive ores
- Abundant "taxites" – contaminated, vari-textured to pegmatoidal volatile-rich gabbros
- Breccia ores common

Komatiite-hosted



- Lava tubes or channels
- Thermal/mechanical erosion of floor and roof rocks
- Mainly conformable ores at basal contacts
- No "taxites" – contaminated pyroxenites sometimes
- Breccia ores rare, restricted to passive intrusion breccias

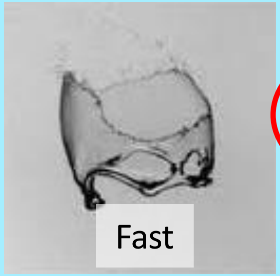
Dynamic physical systems

- 1000s of km scale
- Focus mass, momentum and heat into one place
- Transient, highly localised in space and time
- Multi-scale processes feeding into one another

Timescales and lengthscales

HARES

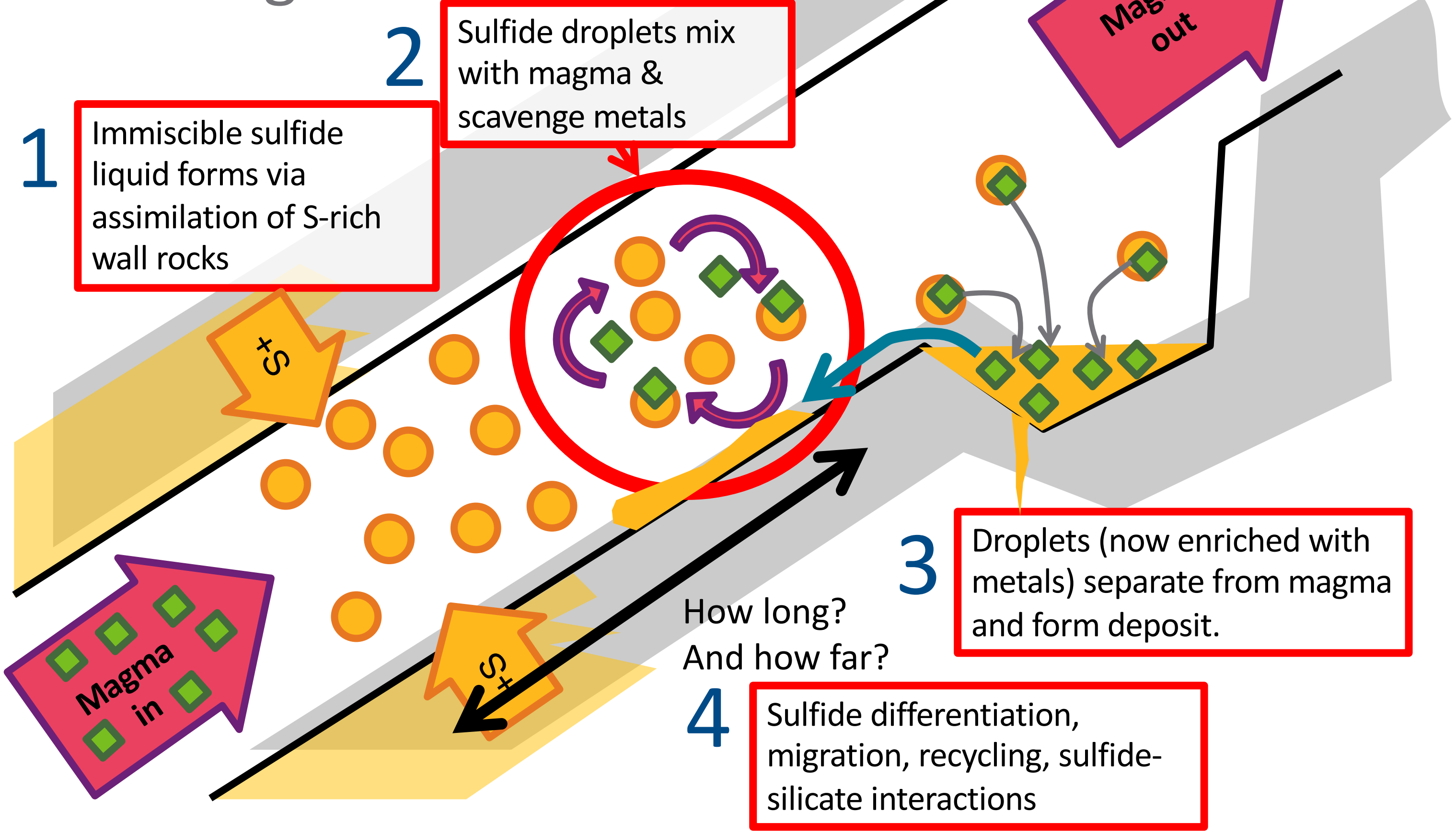
TORTOISES



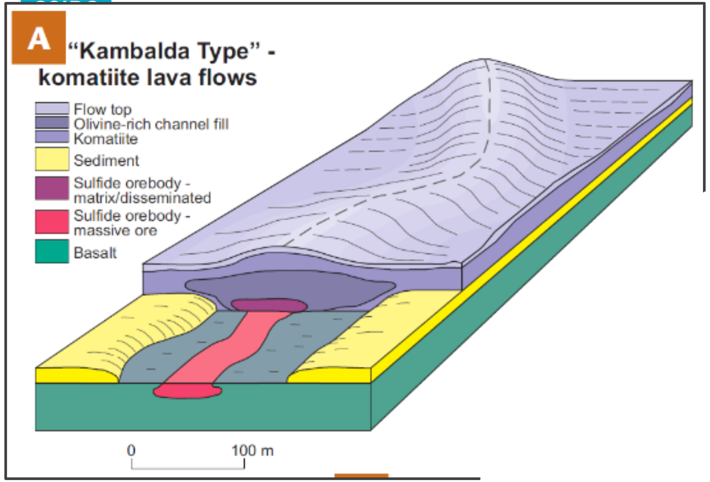
Fast intermittent processes operating at small scales

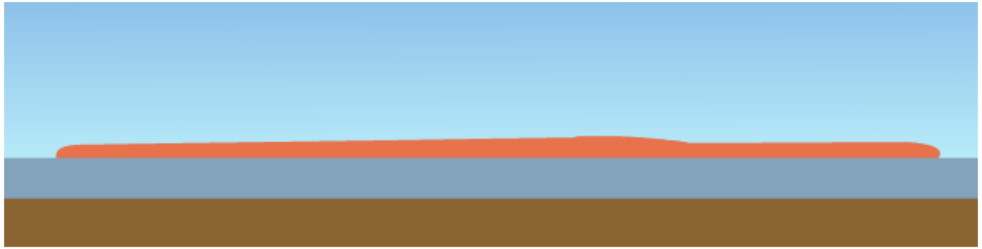
Slow continuous processes operating at large scales

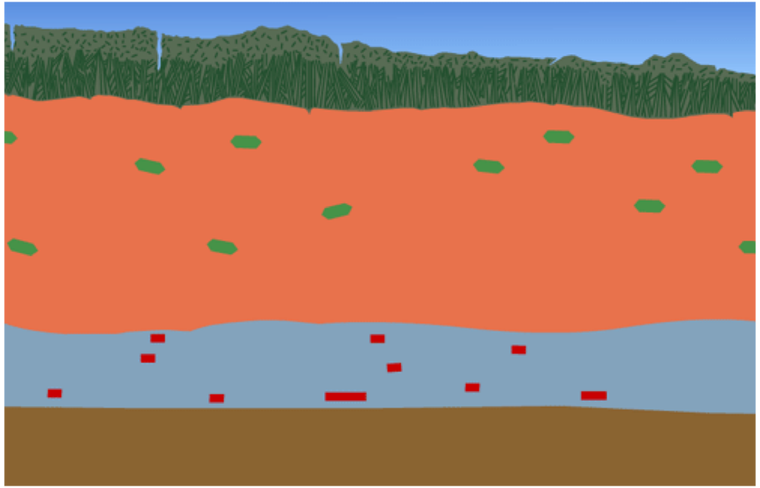
Forming a deposit



Origin of komatiite-hosted ores – the substrate erosion model

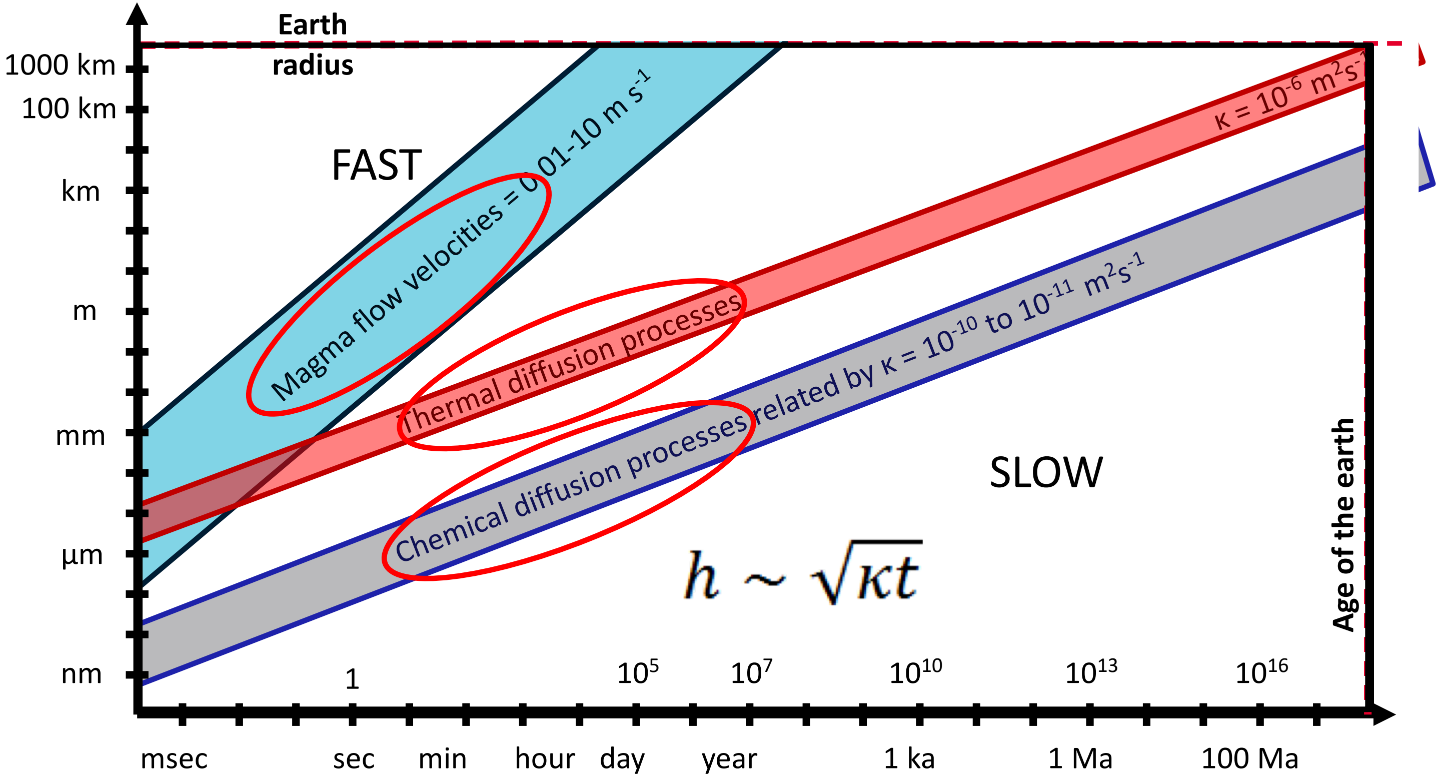


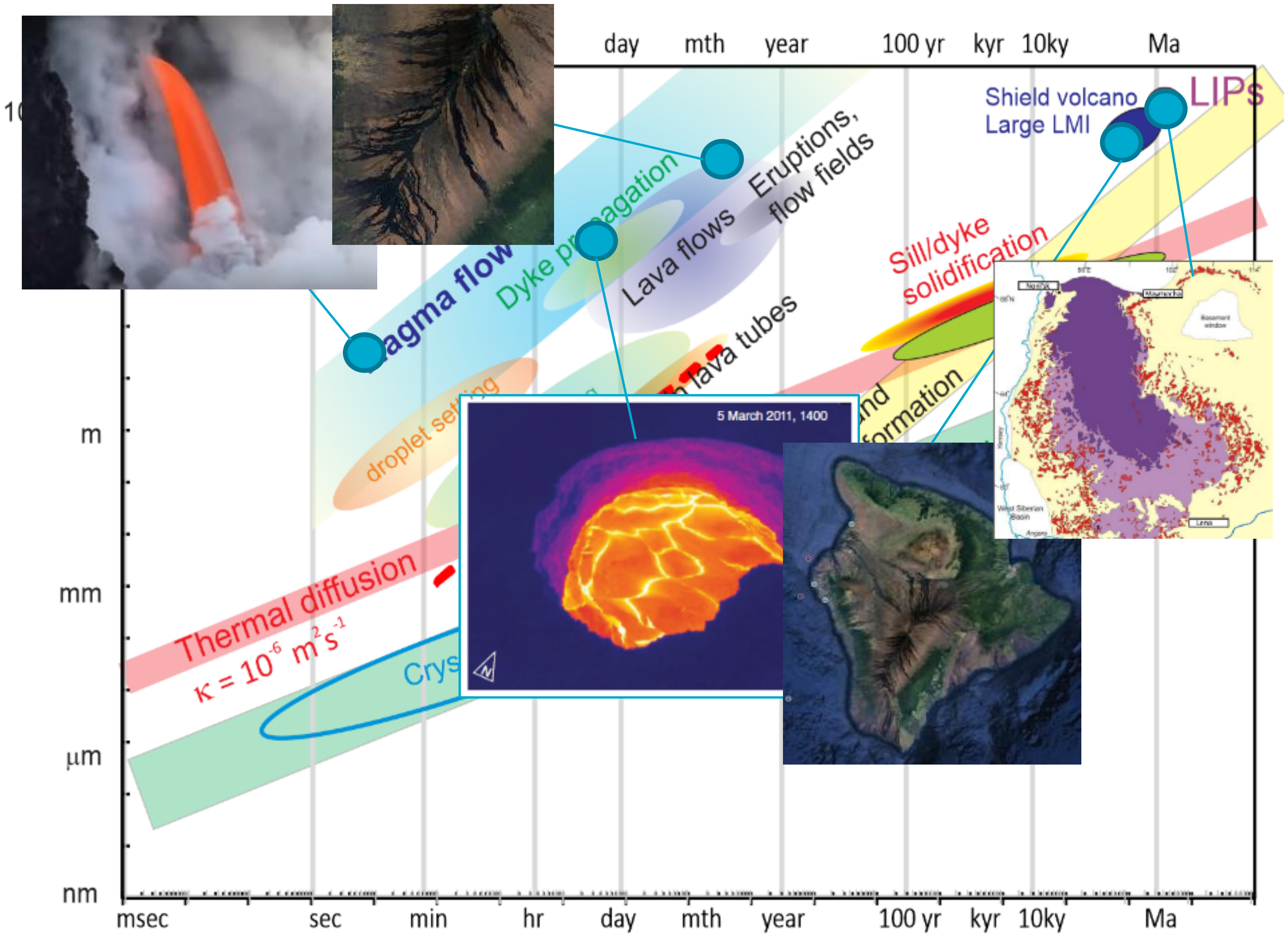




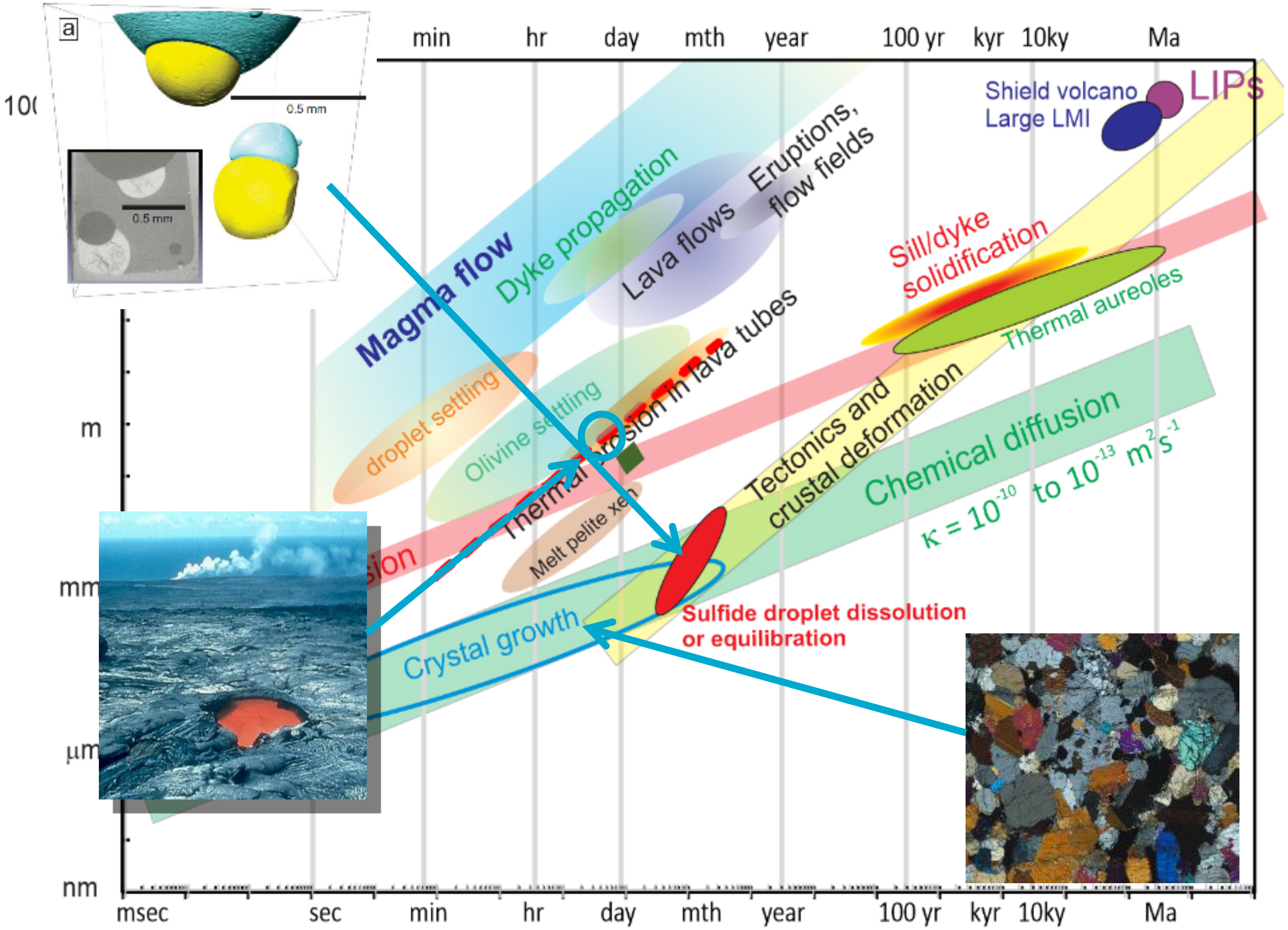
Prolonged flow heats country rocks
Incorporation/assimilation into magma
Melting of external sulfide component to mag-sul liquid

Meet the Jess-o-Gram…

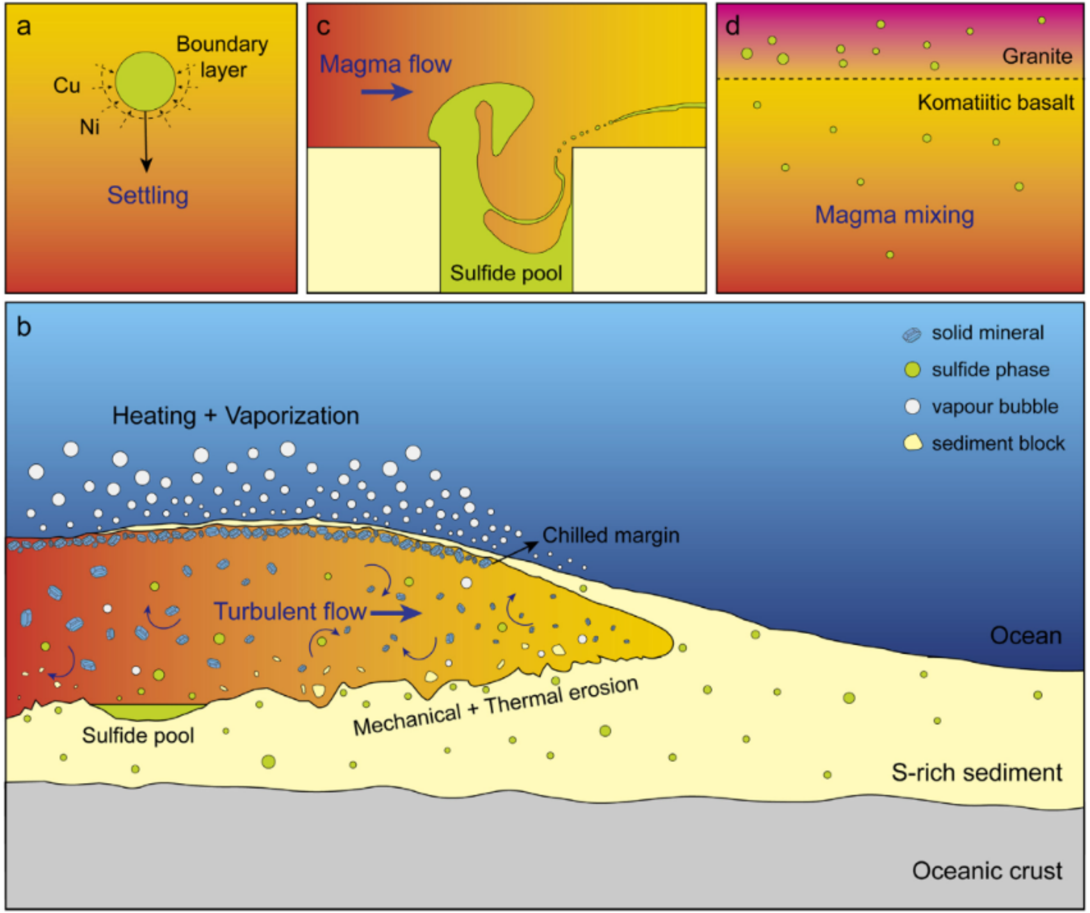




day
mth
year
100 yr
kyr
10ky
Ma
Shield volcano
Large LMI
LIPs
Eruptions,
flow fields
Lava flows
Dyke propagation
Magma flow
lava tubes
droplet settling
Sill/dyke
solidification
formation
Thermal diffusion
κ = 10^-6 m^2 s^-1
Crys
5 March 2011, 1400
m
mm
µm
nm
msec
sec
min
hr
day
mth
year
100 yr
kyr
10ky
Ma



a
0.5 mm
0.5 mm
min hr day mth year 100 yr kyr 10ky Ma
Shield volcano
Large LMI
LIPs
Magma flow
Dyke propagation
Lava flows
Eruptions, flow fields
Sill/dyke solidification
Thermal aureoles
droplet settling
Olivine settling
erosion in lava tubes
Thermal
Melt pelite xen
Tectonics and crustal deformation
Chemical diffusion
κ = 10^{-10} to 10^{-13} $m^2 s^{-1}$
Crystal growth
Sulfide droplet dissolution or equilibration
m
mm
µm
nm
msec sec min hr day mth year 100 yr kyr 10ky Ma



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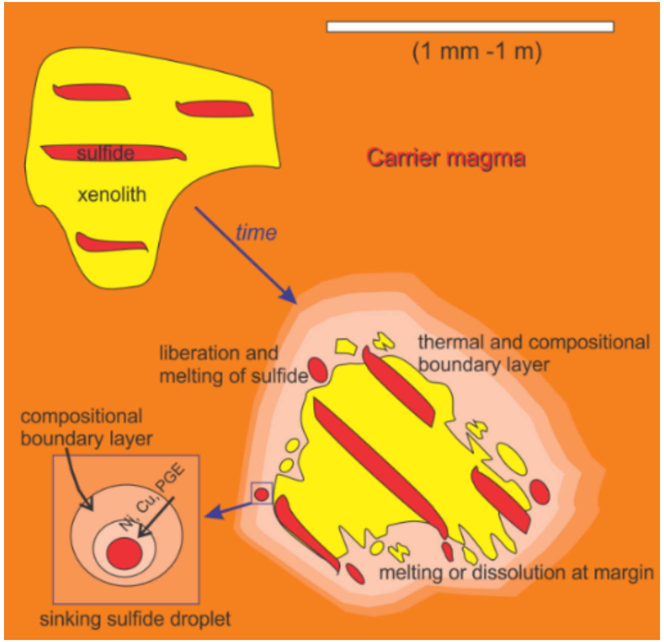
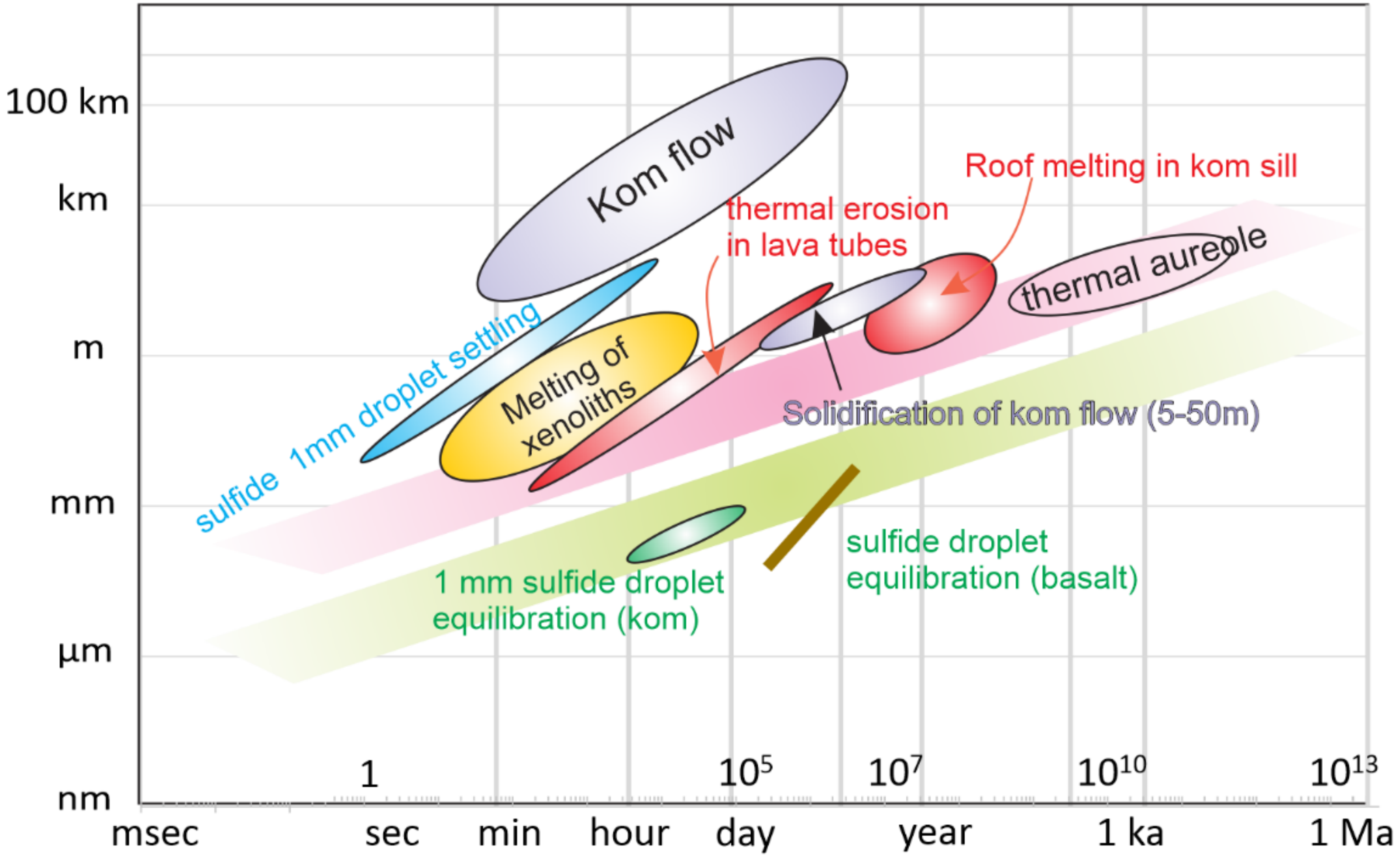
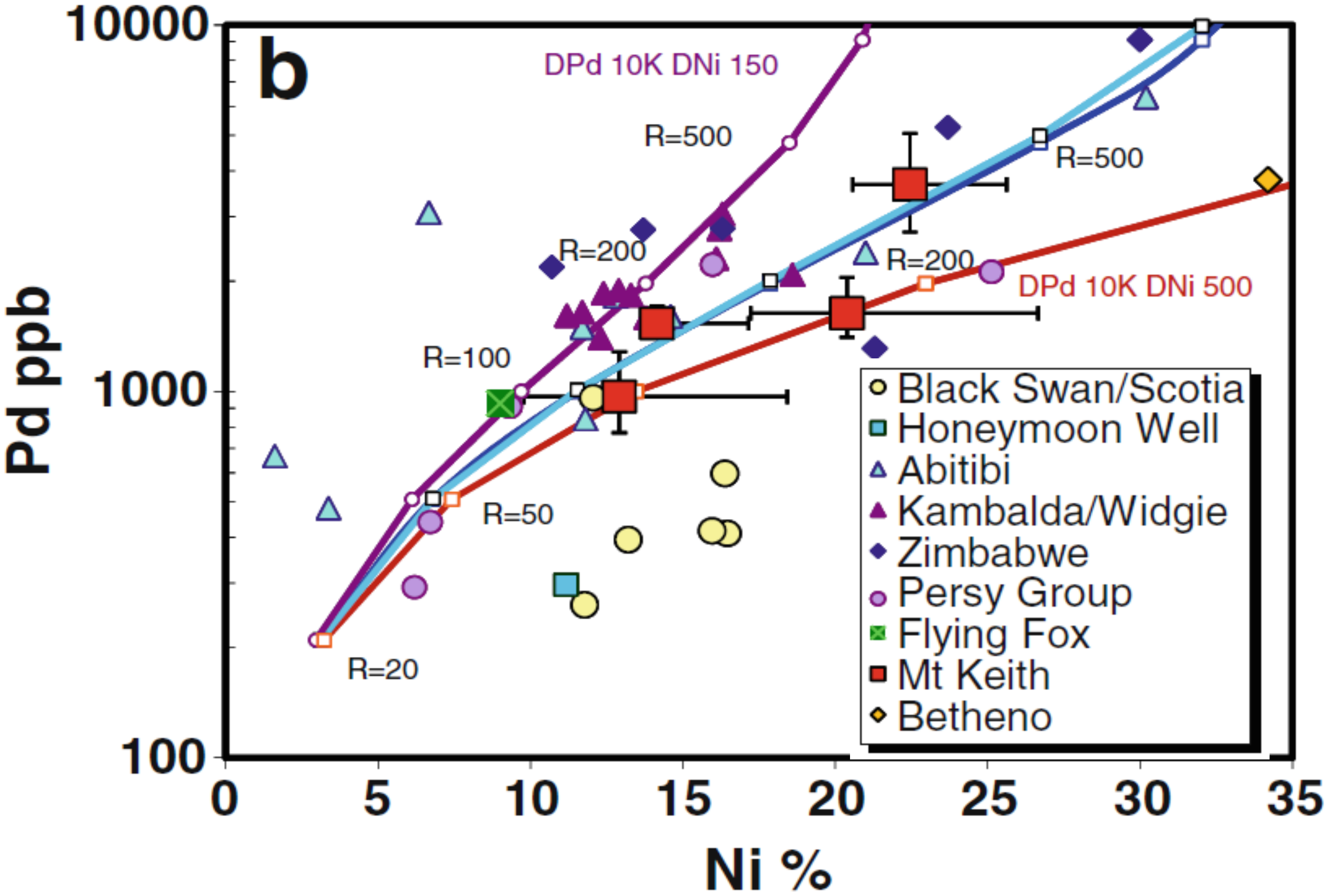
Kinetic controls on the sulfide mineralization of komatiite-associated Ni-Cu-(PGE) deposits

Zhuo-sen Yao, James E. Mungall

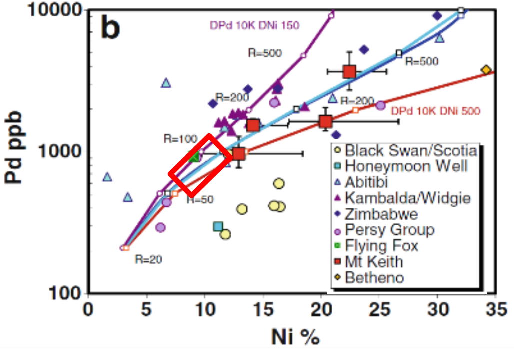


Komatiite Jess-o-Gram





b
DPd 10K DNi 150
R=500
R=500
R=200
R=200
DPd 10K DNi 500
R=100
R=50
R=20
Pd ppb
10000
1000
100
0
5
10
15
20
25
30
35
Ni %
Black Swan/Scotia
Honeymoon Well
Abitibi
Kambalda/Widgie
Zimbabwe
Persy Group
Flying Fox
Mt Keith
Betheno

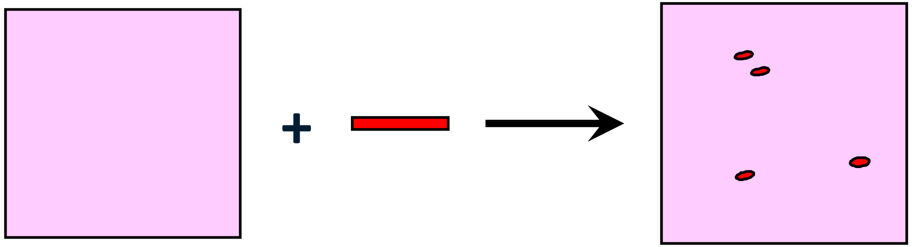


The R factor

$$Y^{i}_{SUL} = X^{i}_{SIL} \frac{D.(1 + R)}{(R+D)}$$

Mass balance (conservation of mass)

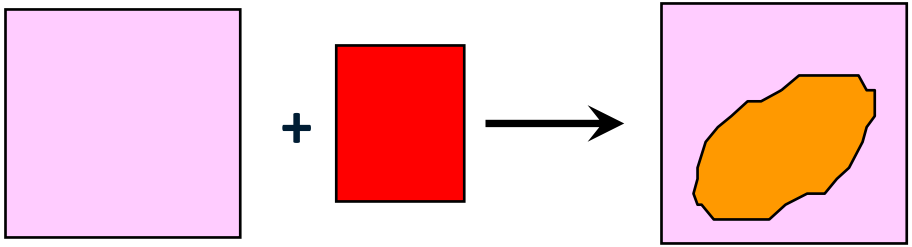
Partition coefficient – conc of i in sulfide = D x conc in magma



High R

$Y_{SUL} \approx D.X_{SIL}$

PGE, Ni rich sulphide



Low R

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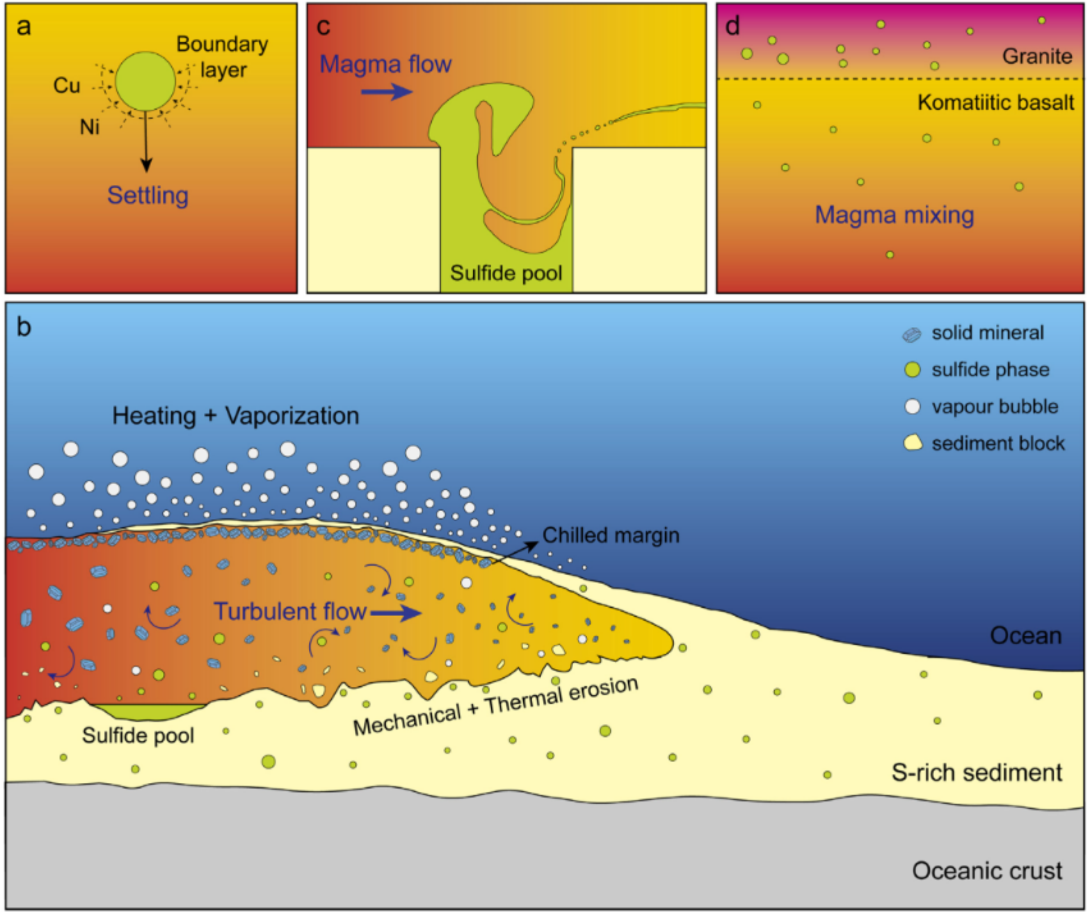

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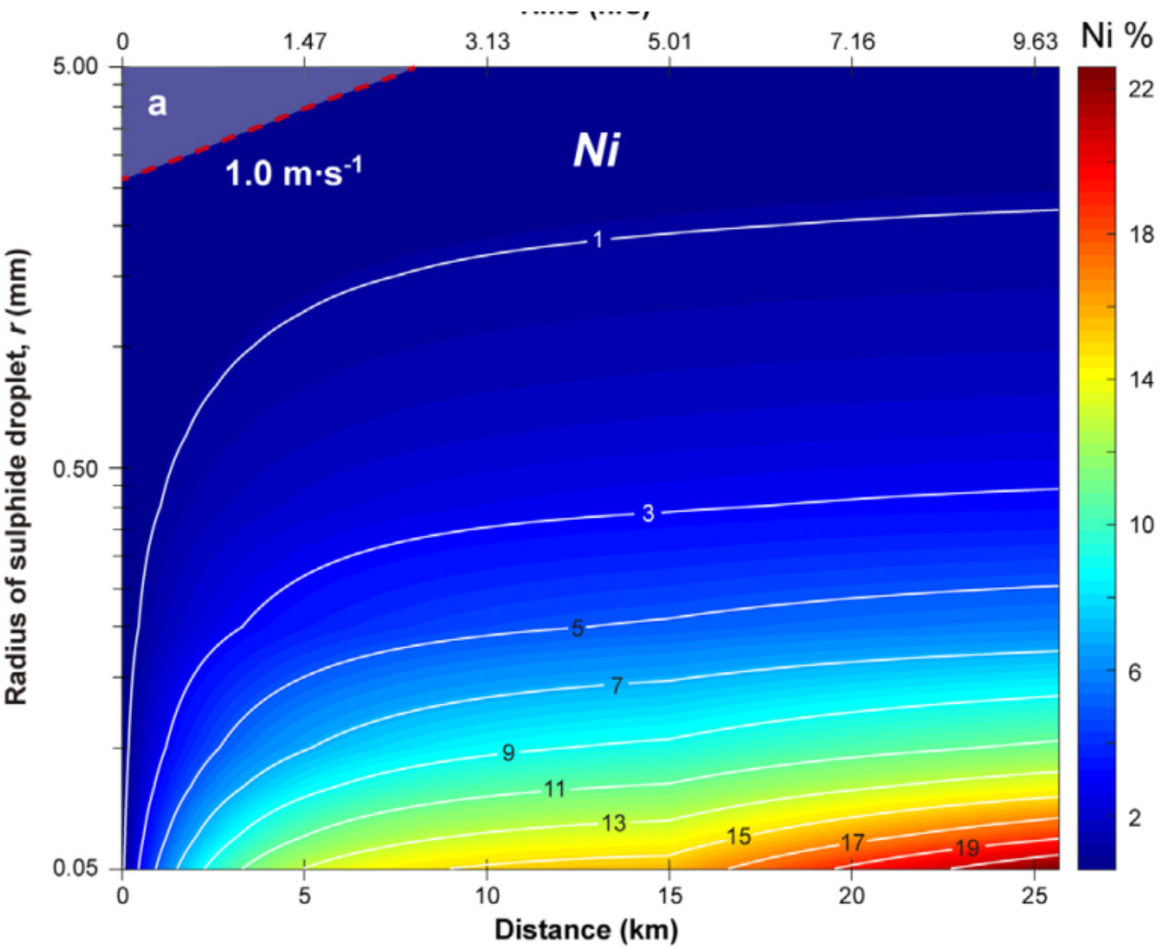
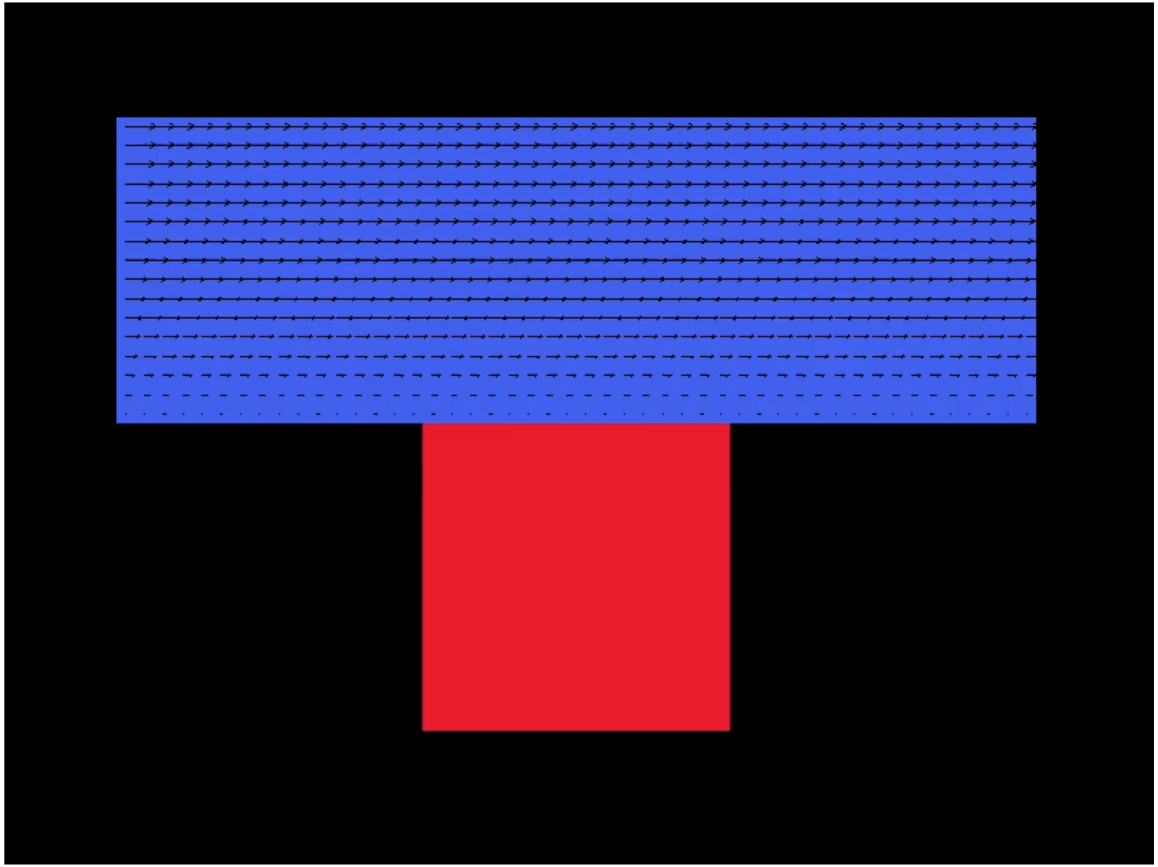
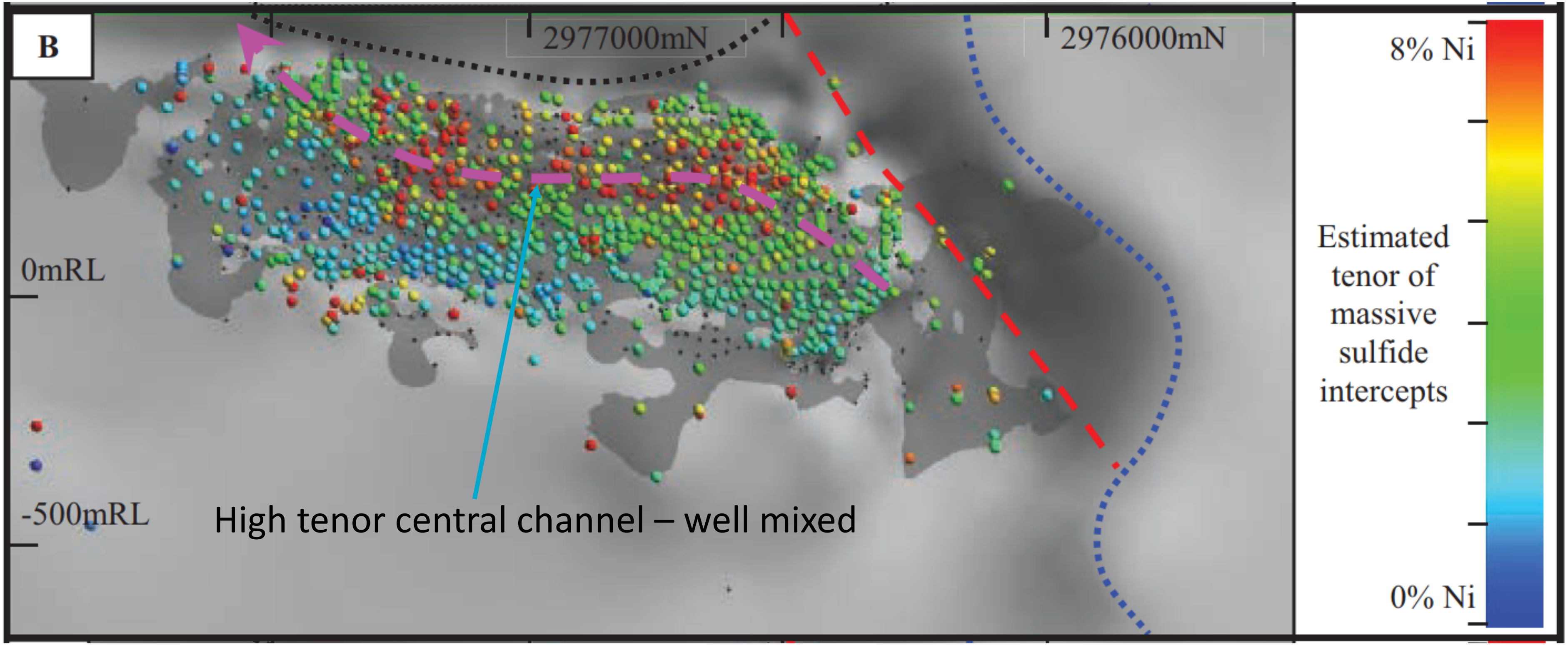


Time (hrs)
0
1.47
3.13
5.01
7.16
9.63
Ni %
22
18
14
10
6
2
a
1.0 m·s-1
Ni
1
3
5
7
9
11
13
15
17
19
5.00
0.50
0.05
Radius of sulphide droplet, r (mm)
0
5
10
15
20
25
Distance (km)

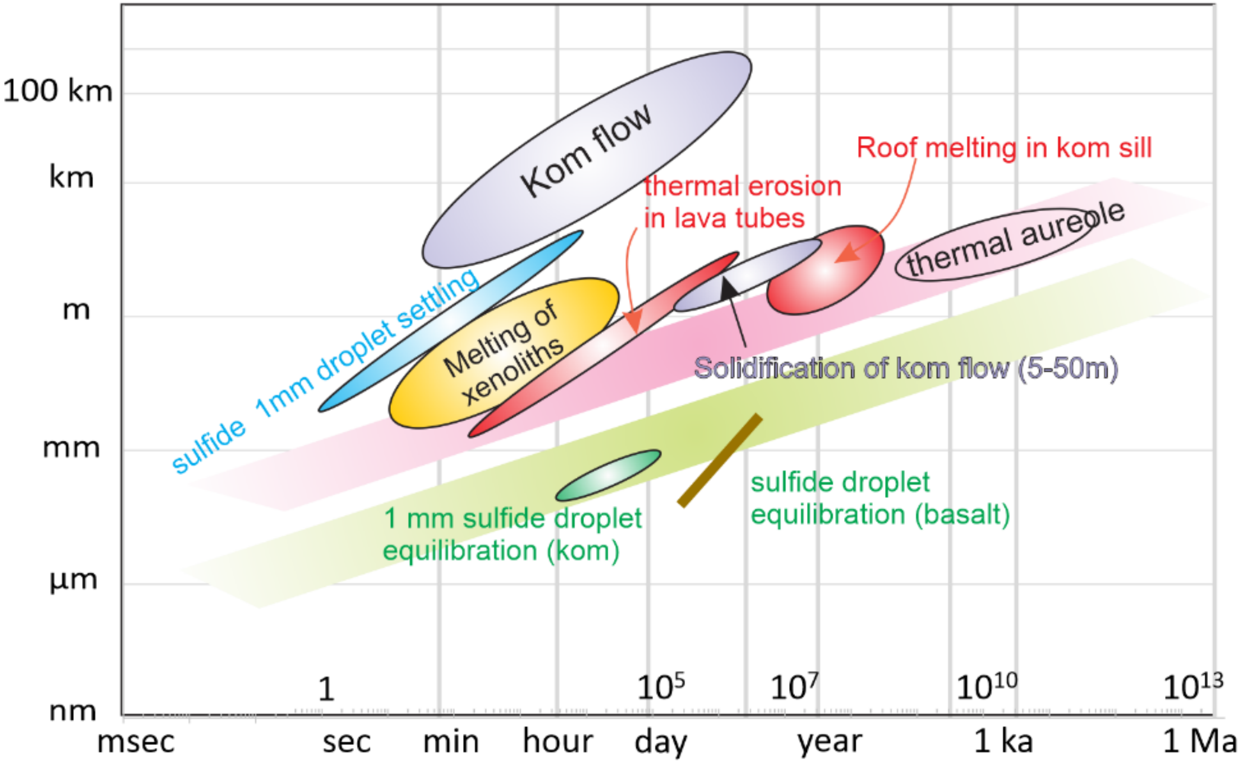
Re-entrainment and upgrading



Tenor variation within the Cliffs massive sulfide shoot (Perring 2015)



Take-aways:

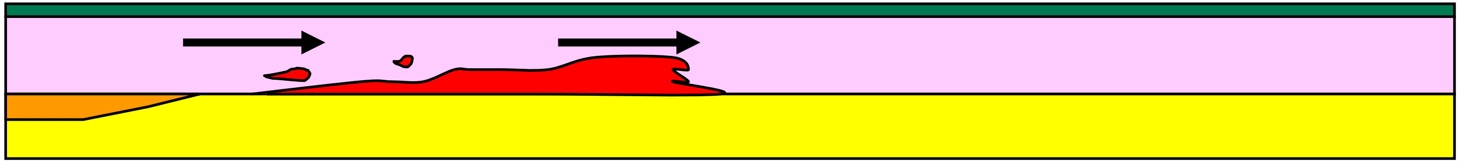


- Sulfides are deposited km from original assimilation site
- Sulfide tenors controlled by fluid dynamics of transport

Sulfide transport and deposition mechanisms

Deposition and recycling

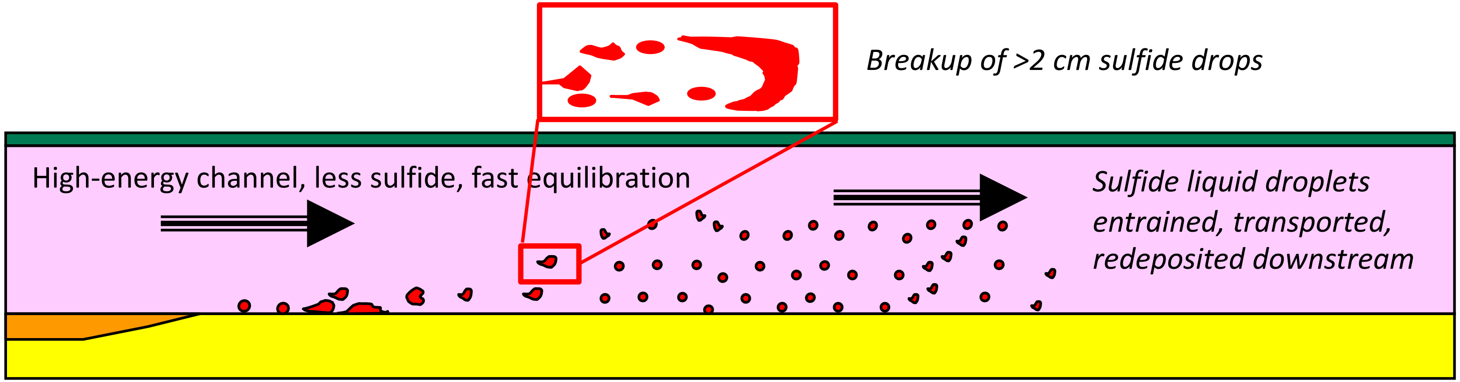
Low-energy channel, abundant sulfide, slow equilibration = low R



Sed S source

Entrained bed-load sulfide liquid – Ni, PGE poor

Breakup of >2 cm sulfide drops



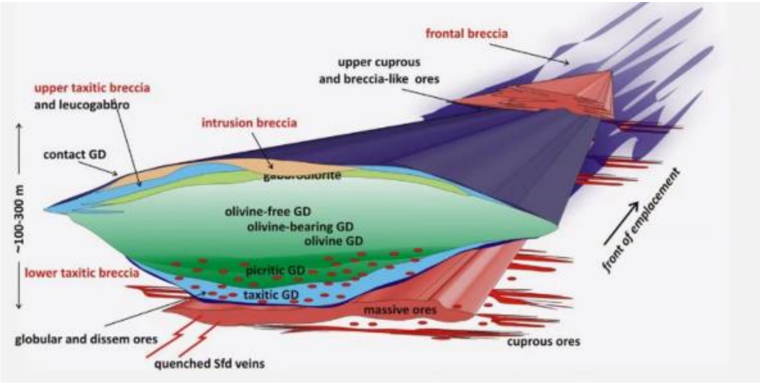
Sed S source

Entrained sulfide liquid droplets – Ni, PGE rich

Ore compositions controlled by fluid dynamics more than by magma composition

Komatiite hosted and mafic intrusion hosted ores: similarities, differences

Mafic intrusion-hosted



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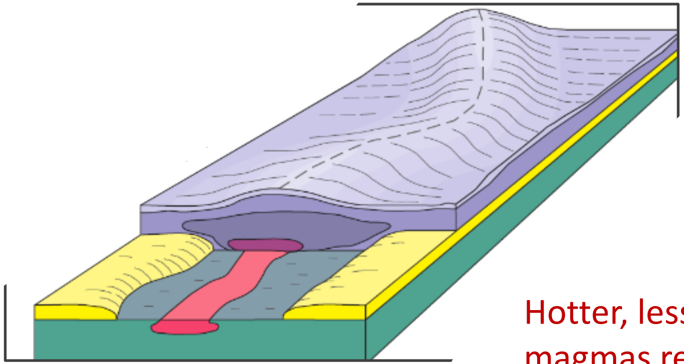
Komatiite-hosted



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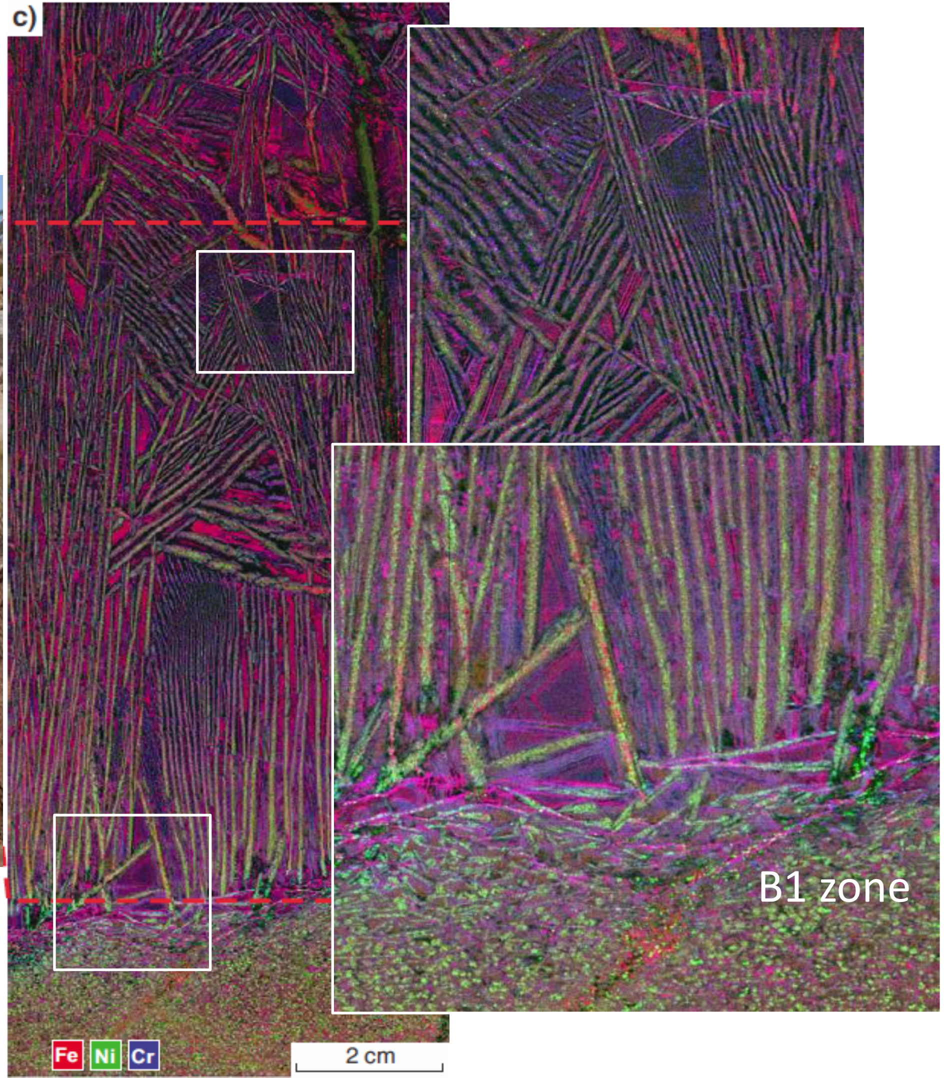
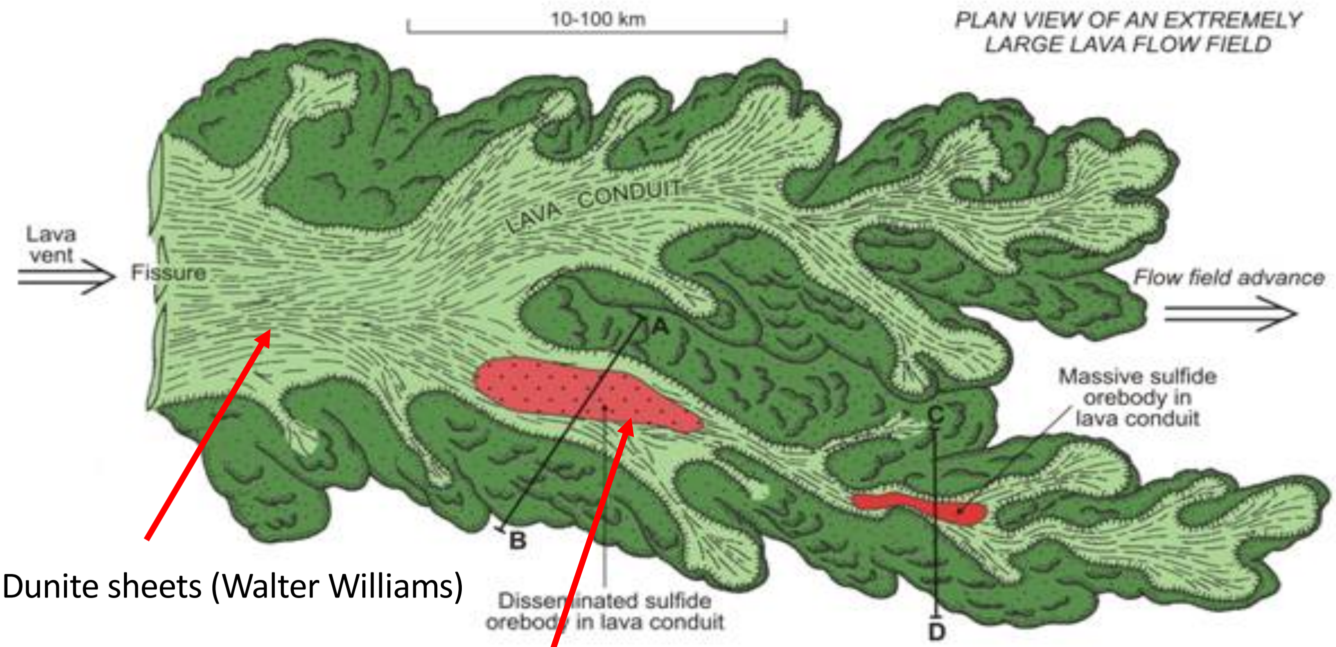
Hotter, less viscous magmas result in

- Easier assimilation of country rock
- More rapid assimilation of xenoliths and equilibration of sulfide droplets
- Faster cooling means less time for post-emplacement sulfide infiltration/melting

Komatiites - developments



Hill et al CSIRO flow-field model ~1995. Dunites extrusive in (relatively) proximal environment, feeding more distal sheet flows and thin flow fields

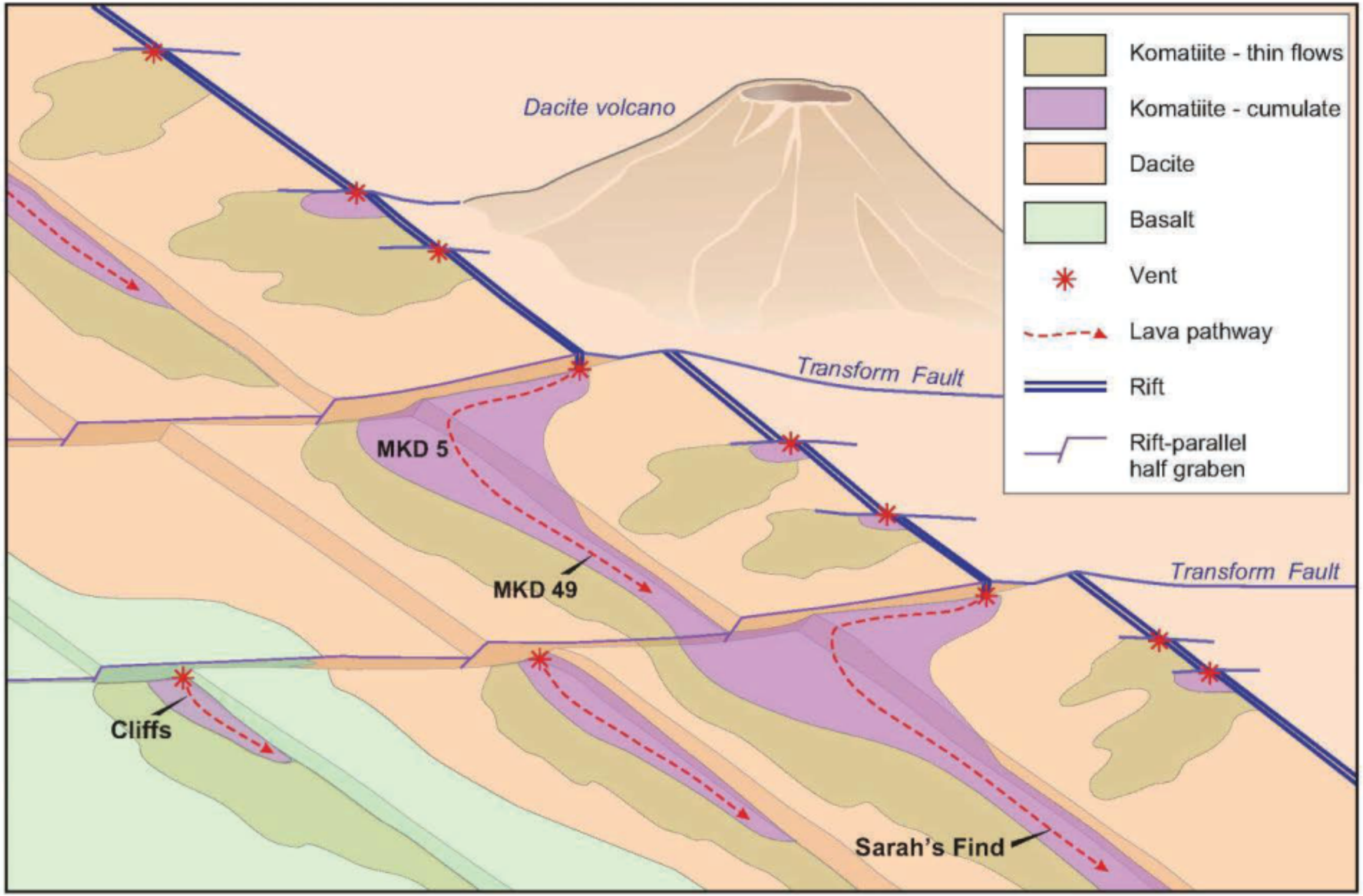


Dunite sheets (Walter Williams)

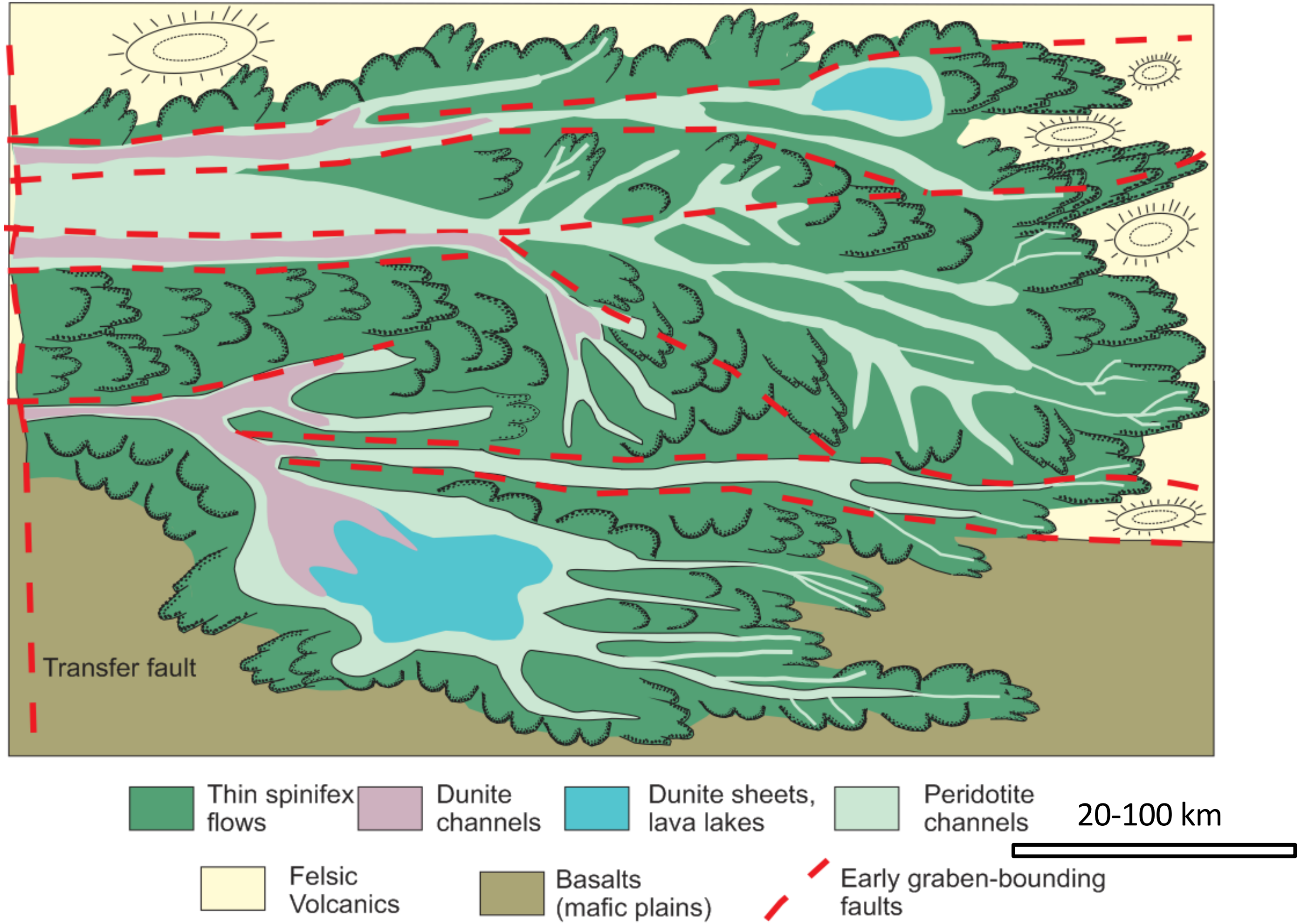
Dunite lenses in entrenched rilles

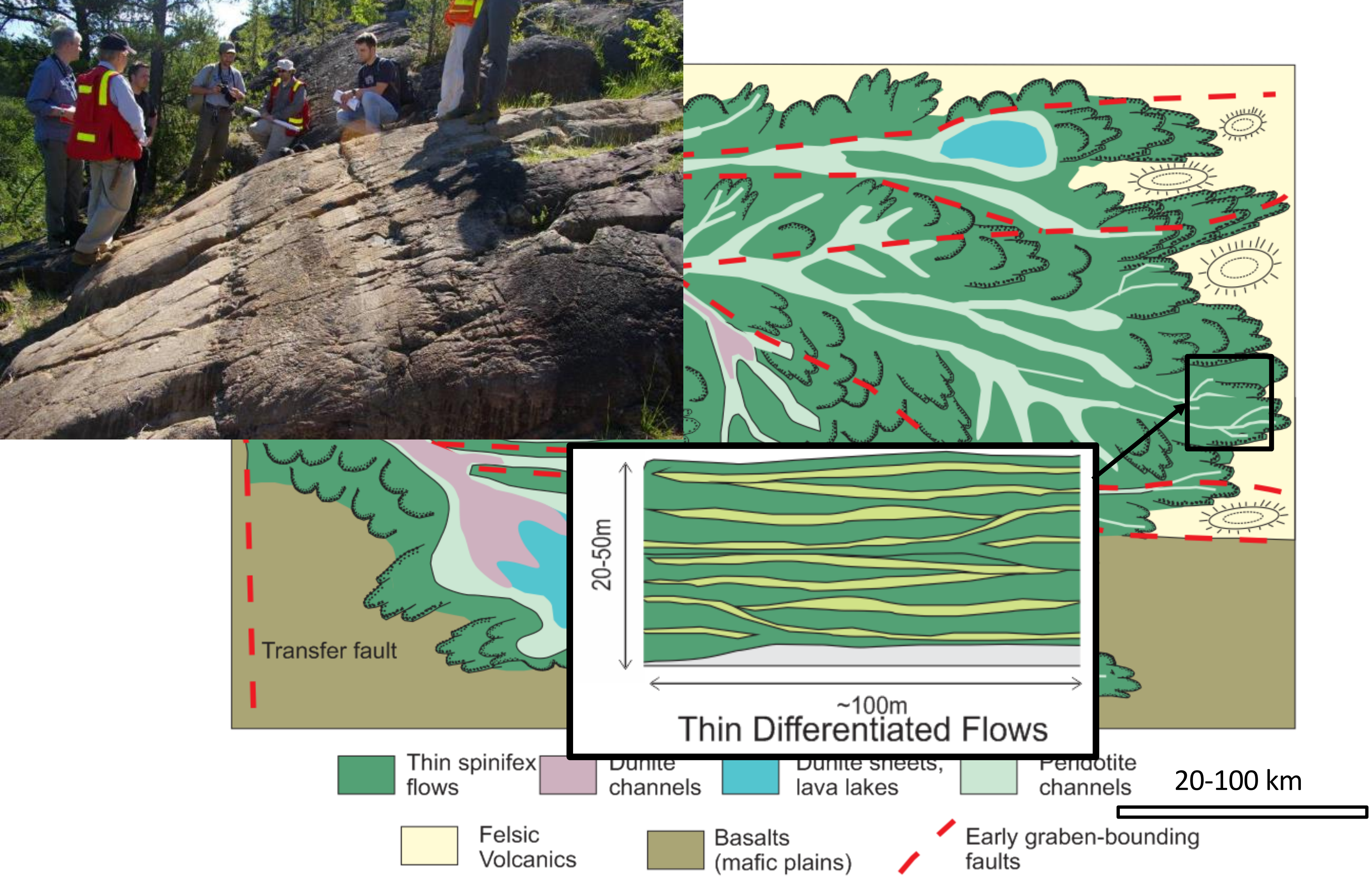
Compound sheet flows and flanking thin flow facies

Setting of Mt Keith camp (Perring 2015)

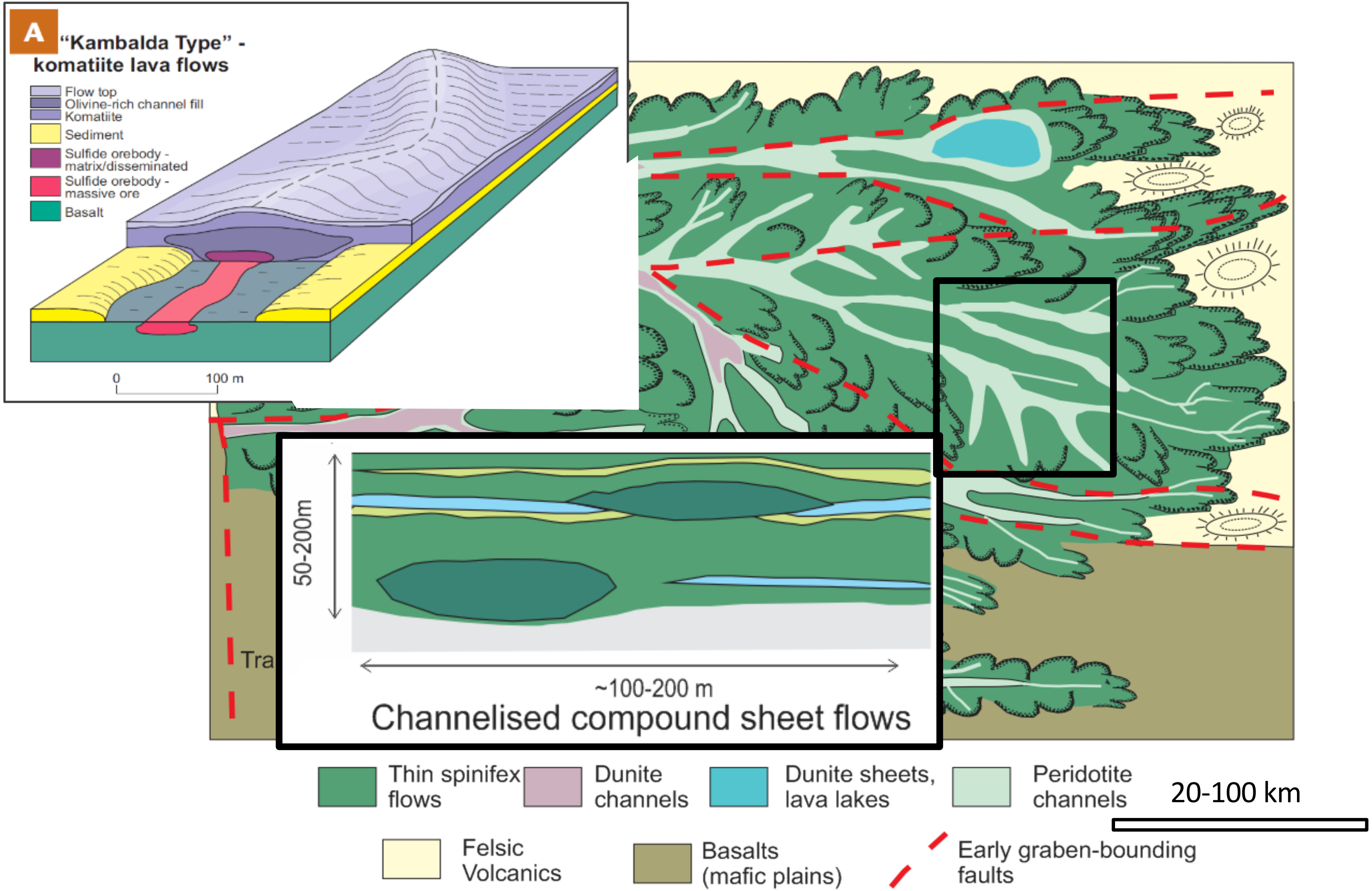


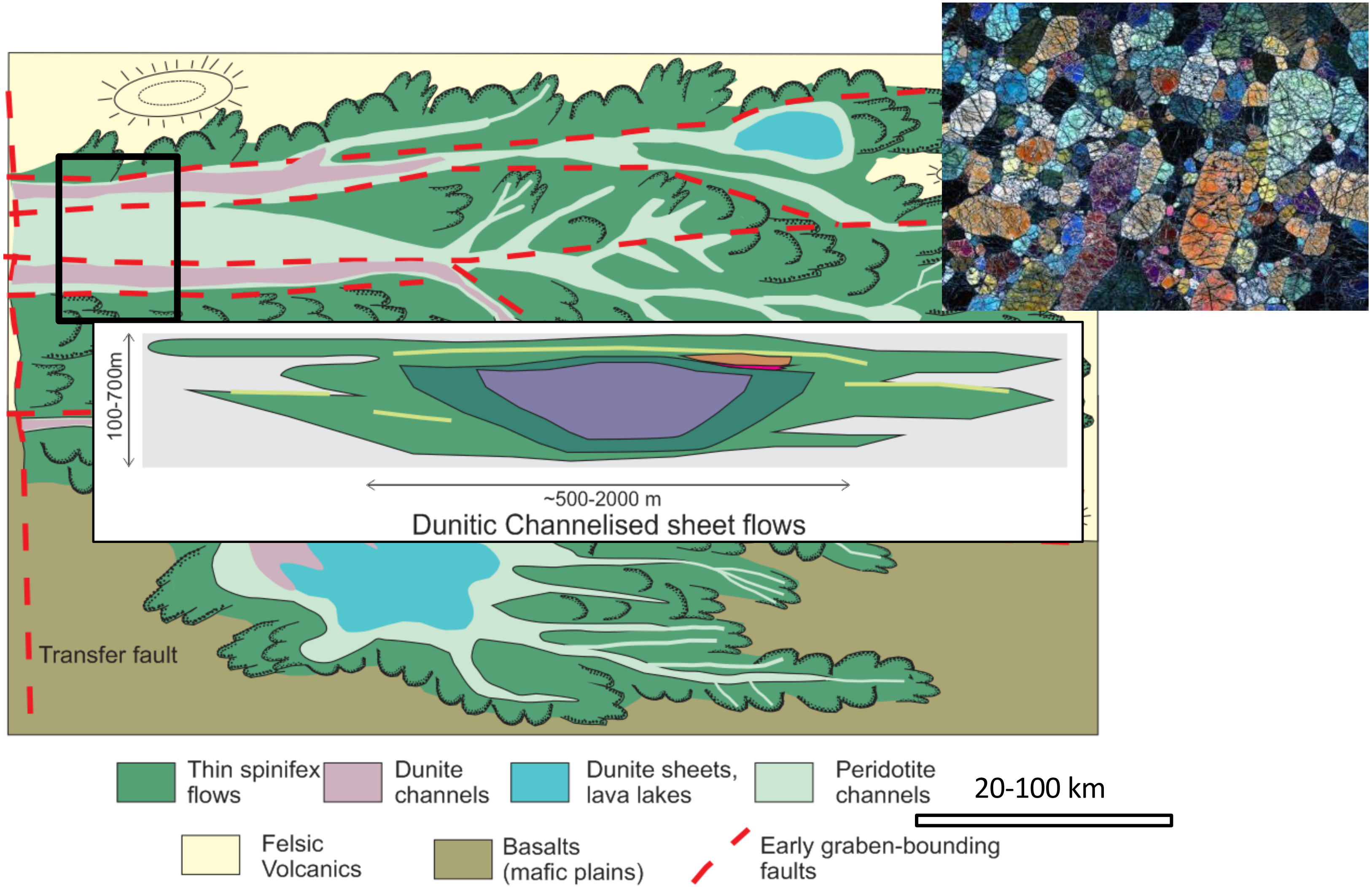
Komatiite flow field model (Gole and Barnes 2020 OGR)



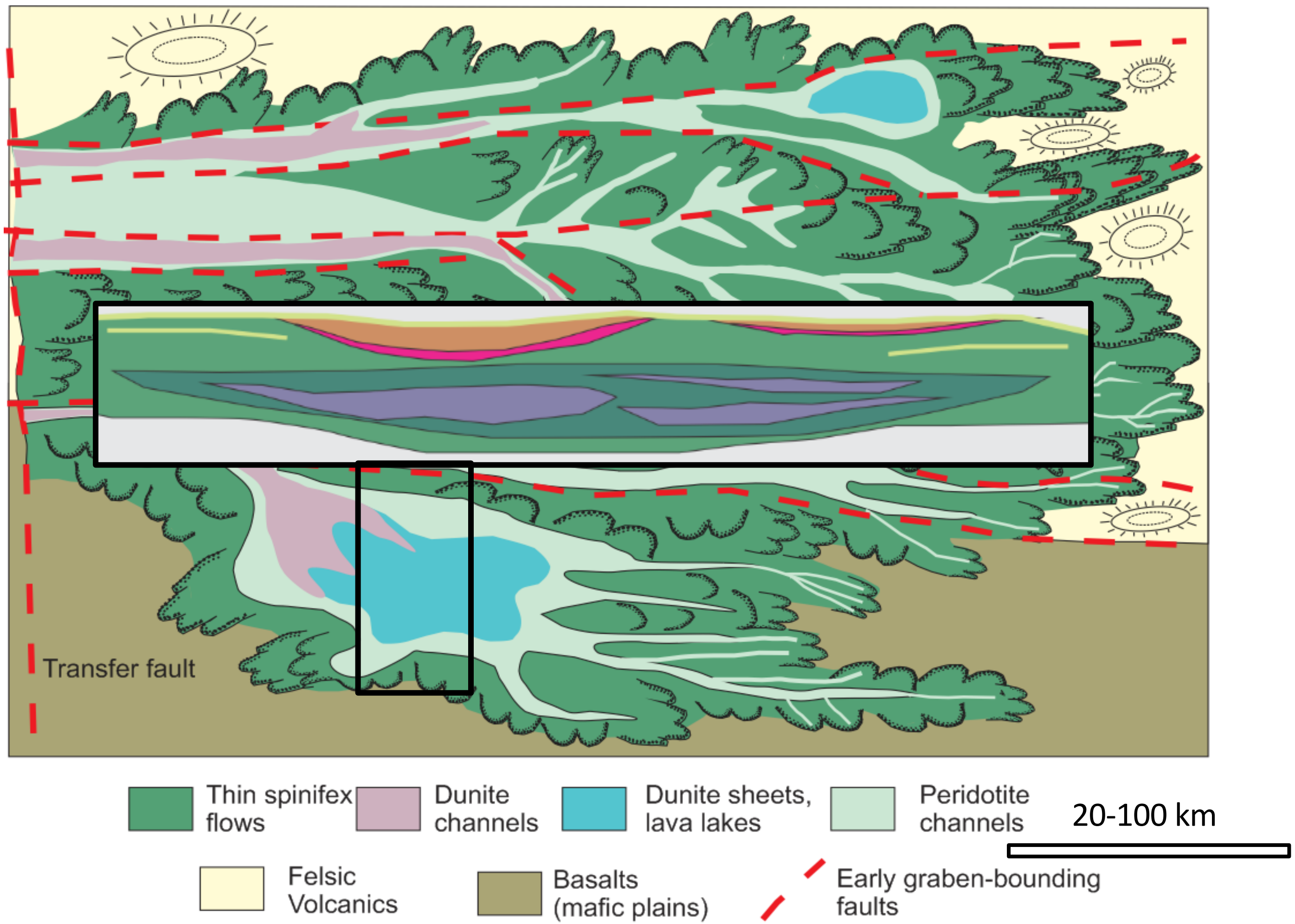


Transfer fault
20-50m
~100m
Thin Differentiated Flows
Thin spinifex flows
Dunite channels
Dunite sheets, lava lakes
Peridotite channels
20-100 km
Felsic Volcanics
Basalts (mafic plains)
Early graben-bounding faults


A
"Kambalda Type" - komatiite lava flows
Flow top
Olivine-rich channel fill
Komatiite
Sediment
Sulfide orebody - matrix/disseminated
Sulfide orebody - massive ore
Basalt
0
100 m
50-200m
~100-200 m
Channelised compound sheet flows
Tra
Thin spinifex flows
Dunite channels
Dunite sheets, lava lakes
Peridotite channels
20-100 km
Felsic Volcanics
Basalts (mafic plains)
Early graben-bounding faults



Transfer fault
100-700m
~500-2000 m
Dunitic Channelised sheet flows
Thin spinifex flows
Dunite channels
Dunite sheets, lava lakes
Peridotite channels
20-100 km
Felsic Volcanics
Basalts (mafic plains)
Early graben-bounding faults


Transfer fault
Thin spinifex flows
Dunite channels
Dunite sheets, lava lakes
Peridotite channels
20-100 km
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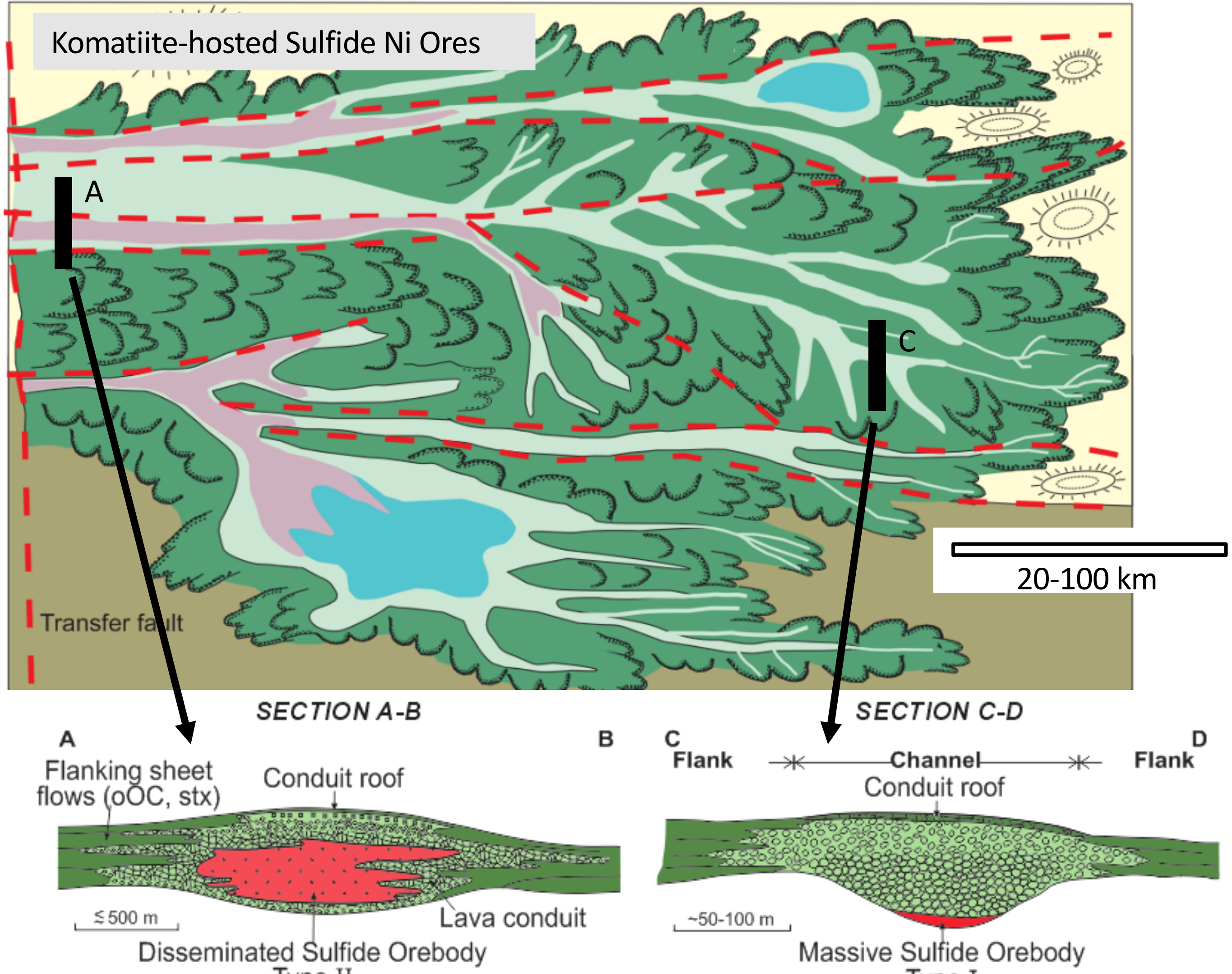
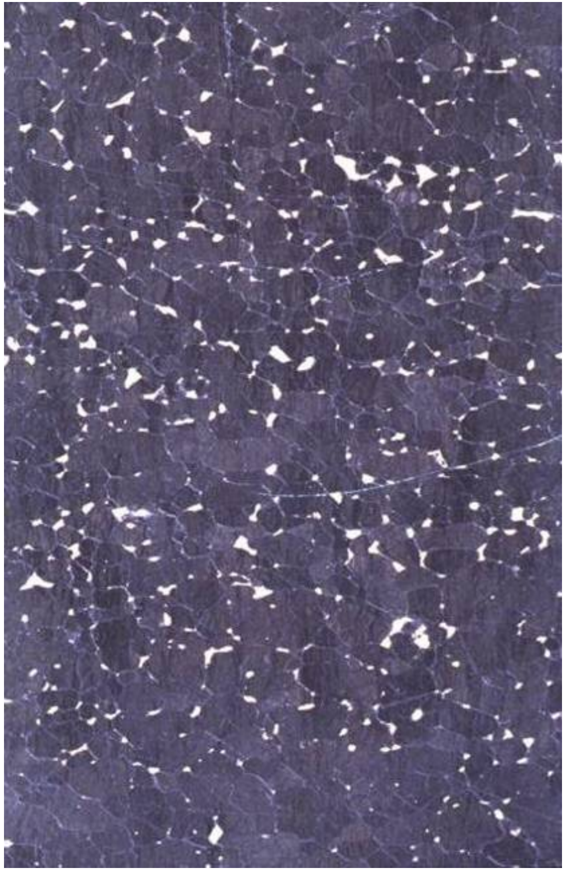
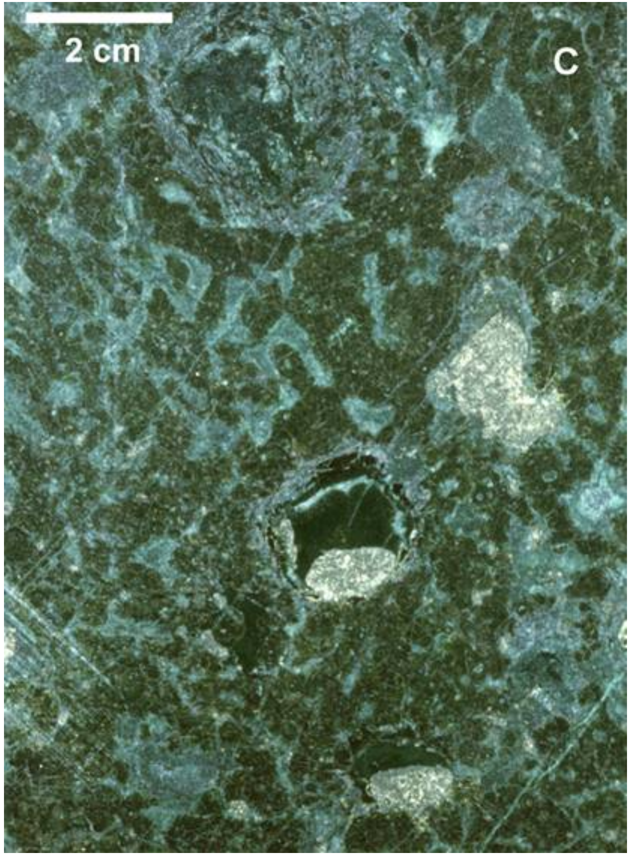
Komatiite-hosted Sulfide Ni Ores

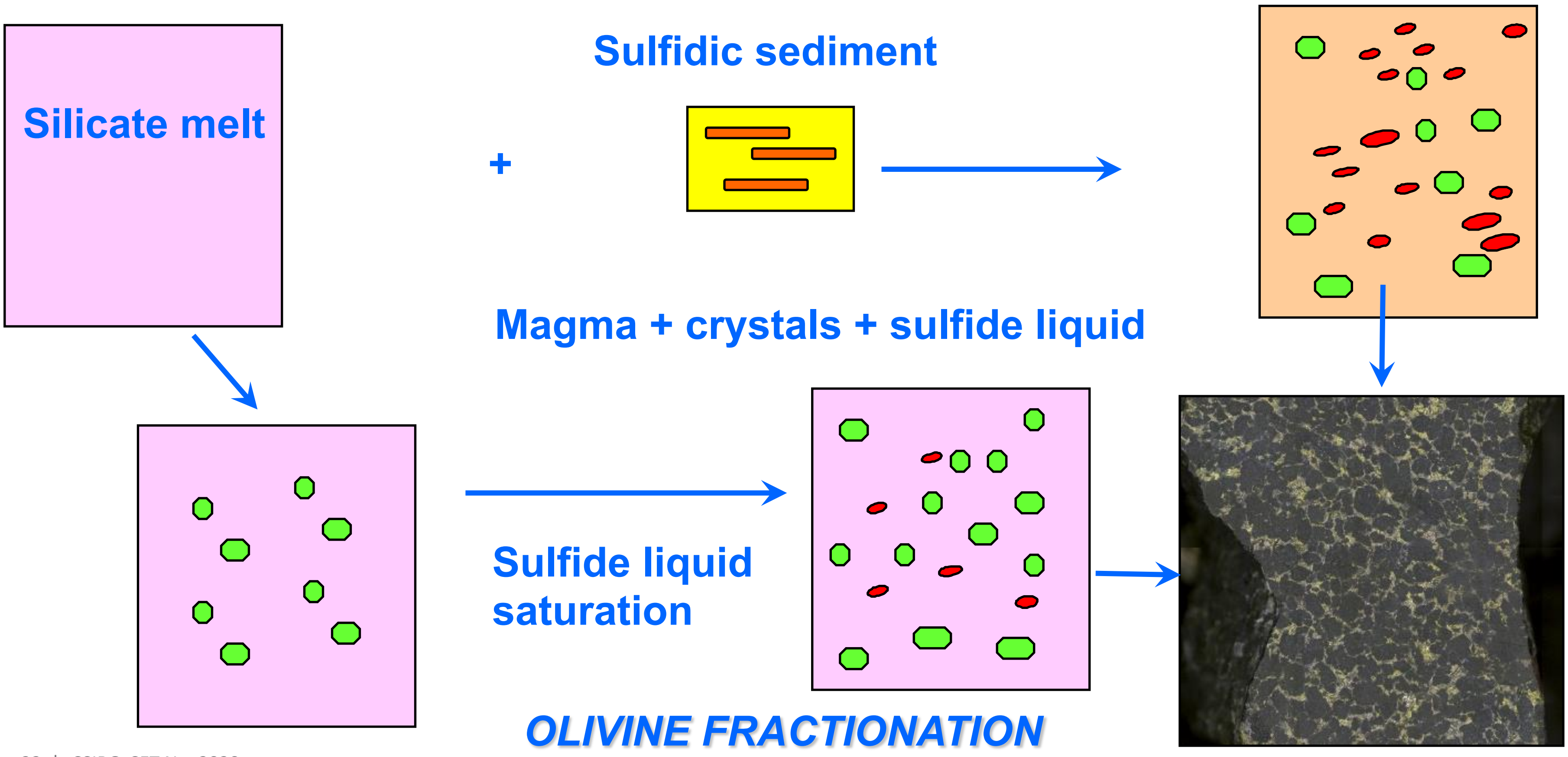


Disseminated ores in komatiitic olivine cumulates: genetic clues from sulfide textures

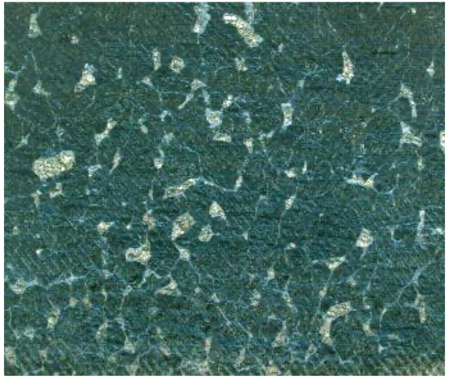




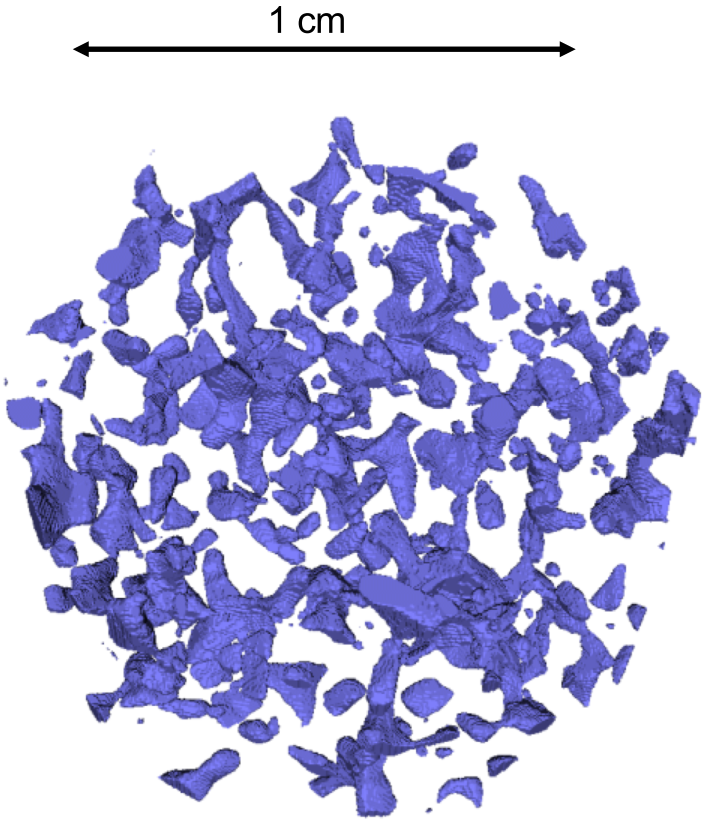
ASSIMILATION + CRYSTALLISATION



microCT visualisation of magmatic Ni sulfides - nickel sulfide ore, Mt Keith

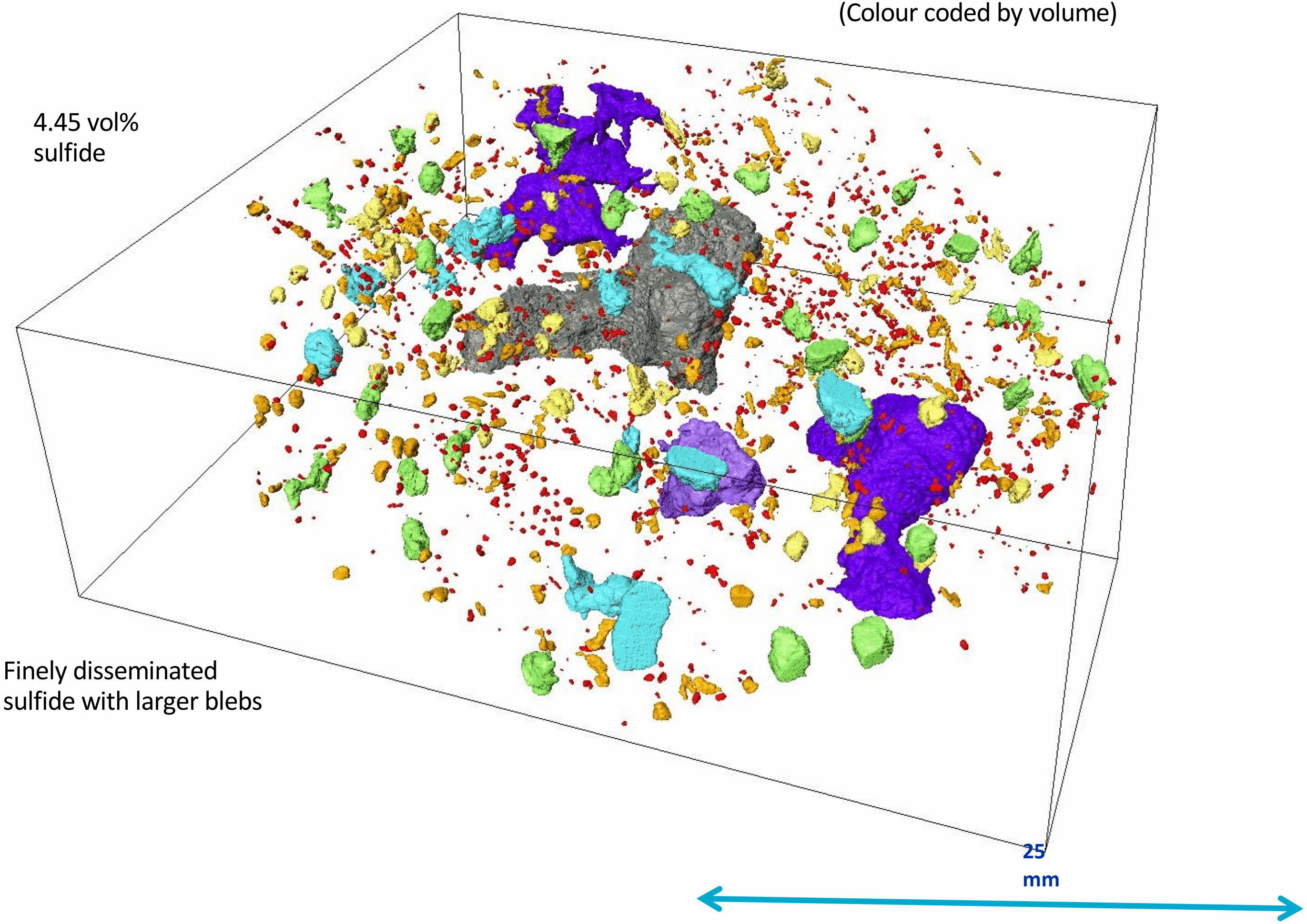


- Sample is “adcumulate = 100% olivine + ~ 3.5% sulfide liquid – no interstitial silicate magma



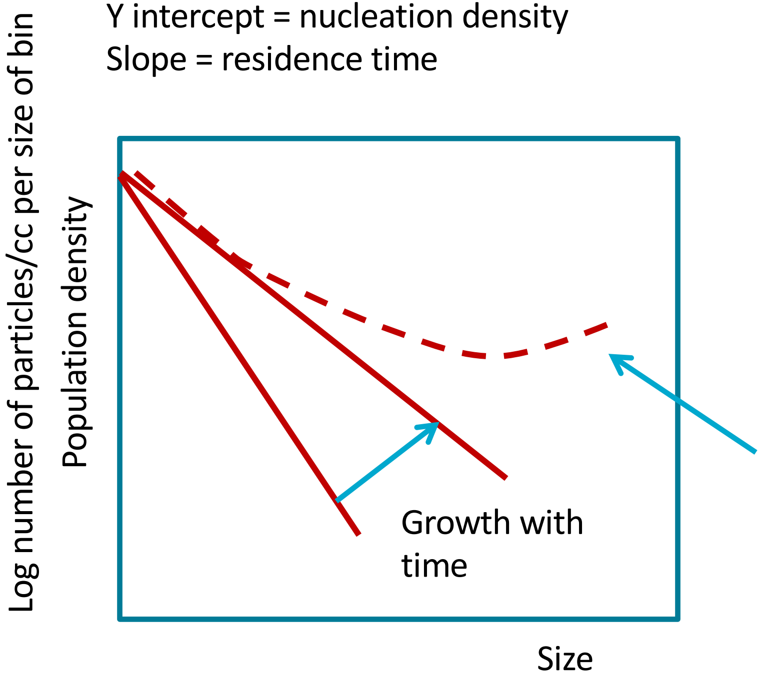
“Bleb” size and distribution of nickel sulfides (Mount Keith – Yakabindie deposits)

(Colour coded by volume)

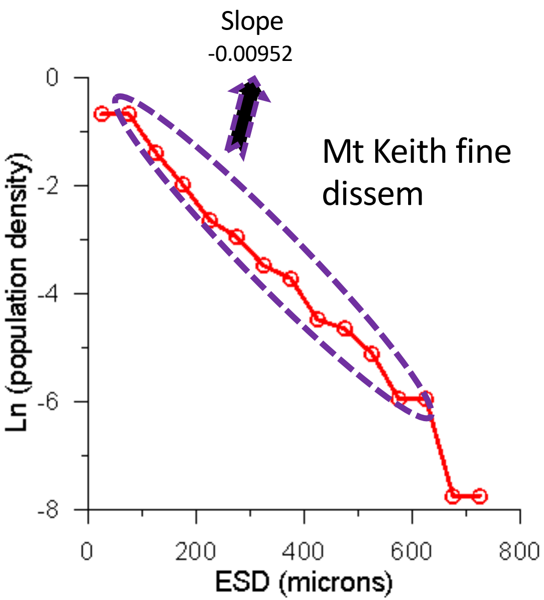


Particle size analysis (CSD, crystal size distribution)
“Bleb” size and distribution of nickel sulfides

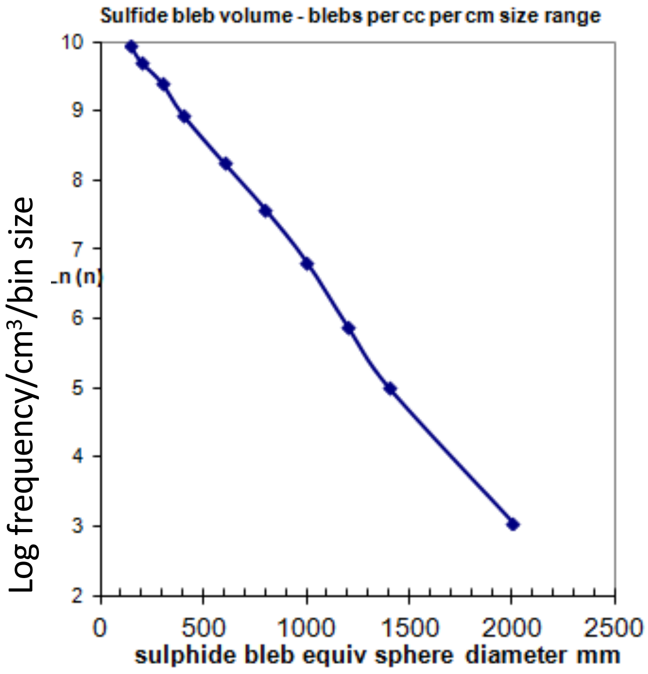
Straight line implies homogenous population of crystals/droplets with constant growth rate
Y intercept = nucleation density
Slope = residence time

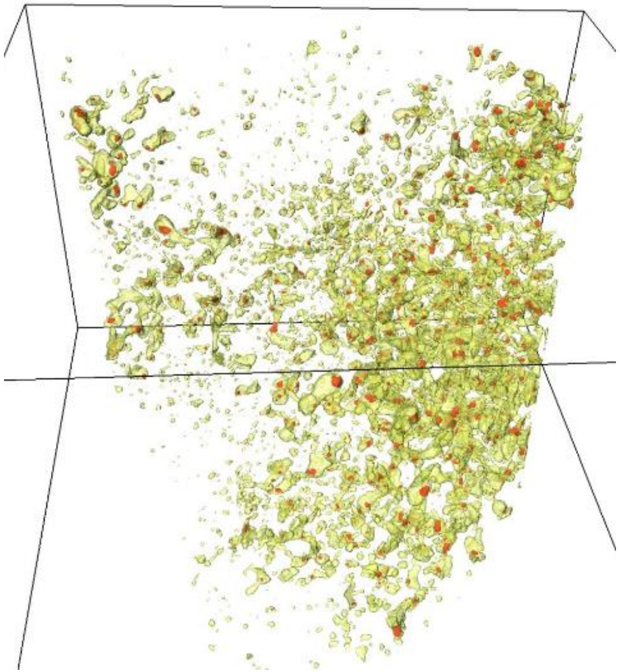


Kinked curve = mechanical sorting (adding large drops/crystals)



Size distributions of sulfide droplets.
Need to measure in 3D

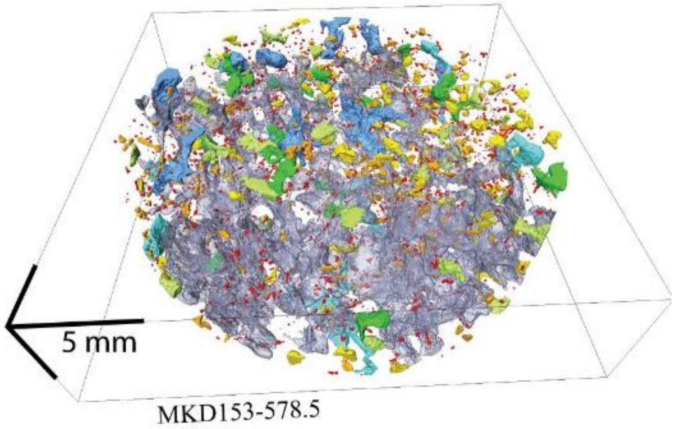


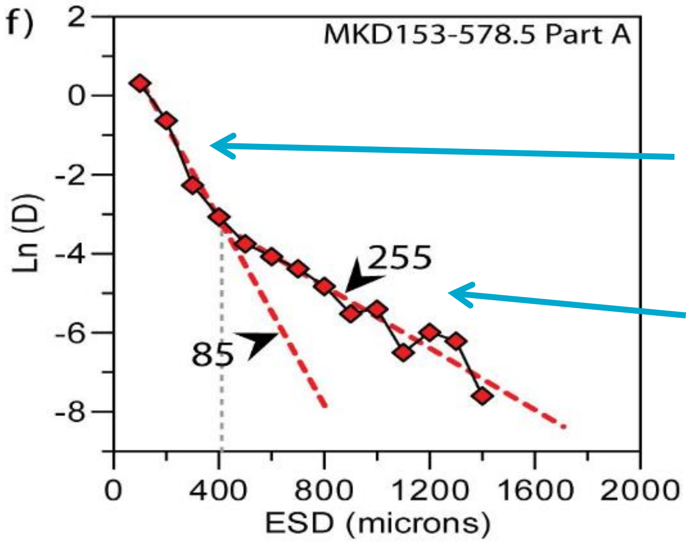


(Assume bleb size = droplet size)
Droplet sizes have semi-log distributions like populations of growing crystals

Size-distribution of sulfides: coarse sulfide samples

Two populations – both with semi-log distribution. Why?



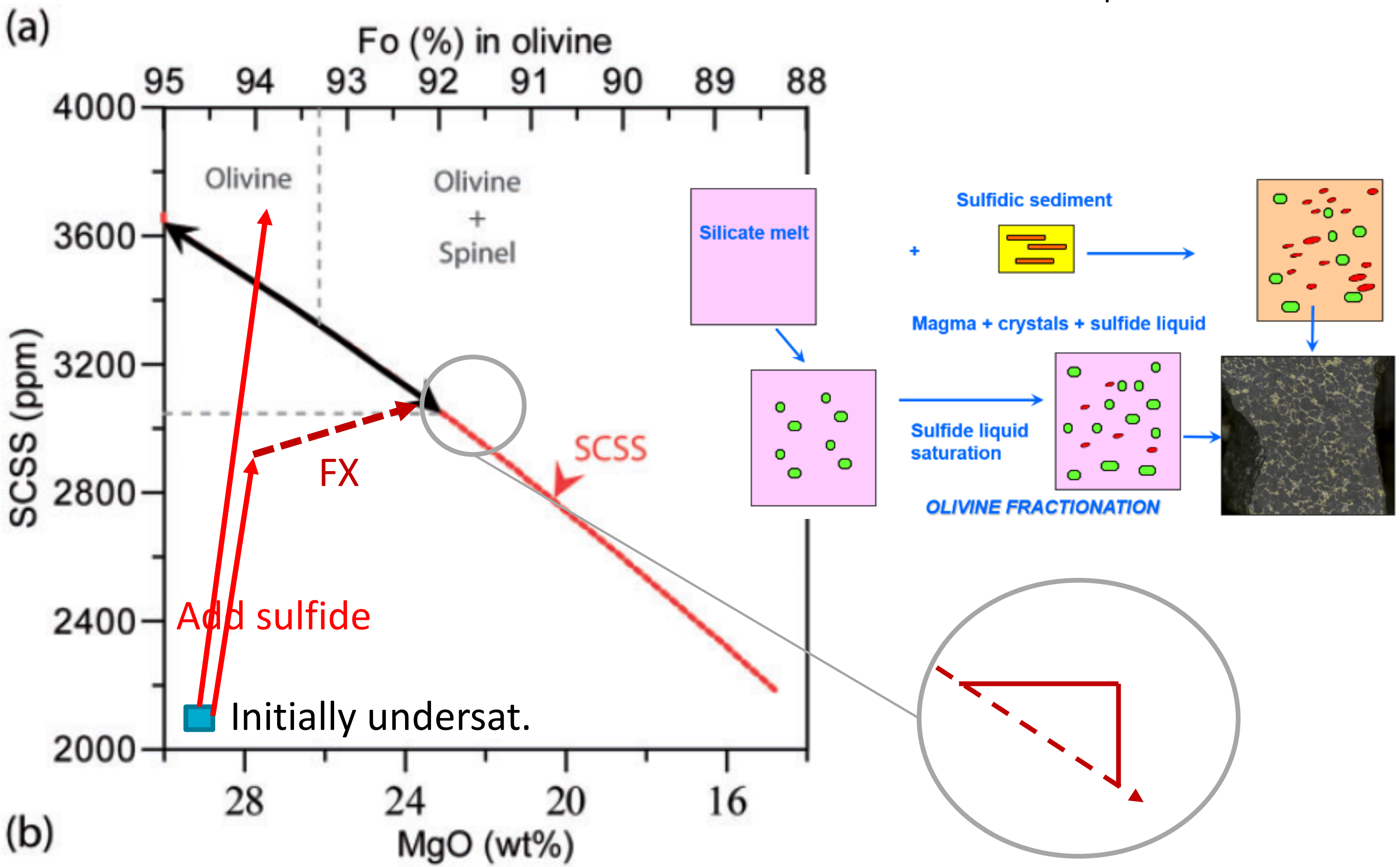


Population 1, fine droplets

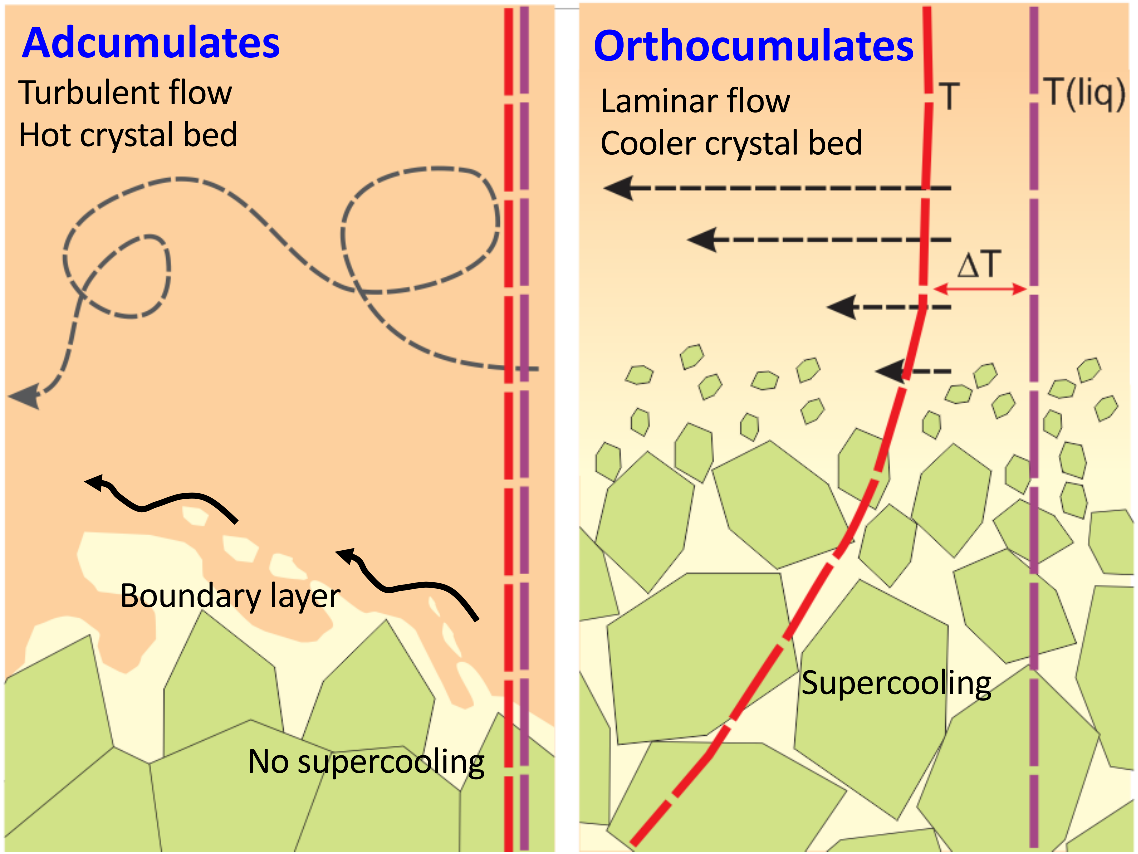
Population 2, larger blebs

Belinda Godel, SJ Barnes and S-J Barnes (J Pet 2013)

SCSS = S content at sulfide liquid saturation

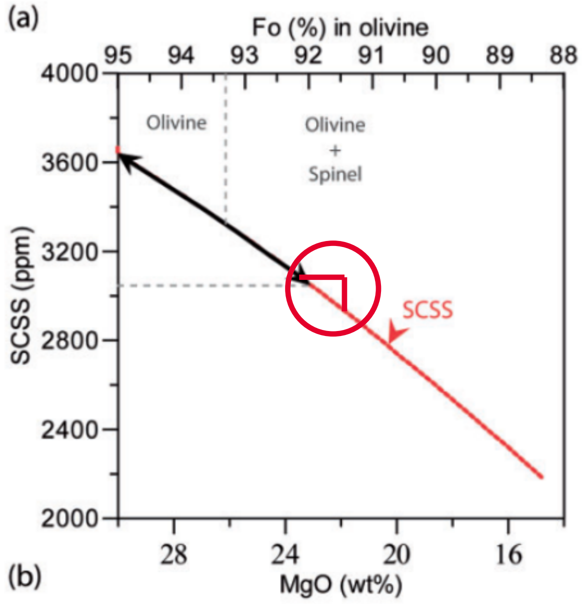


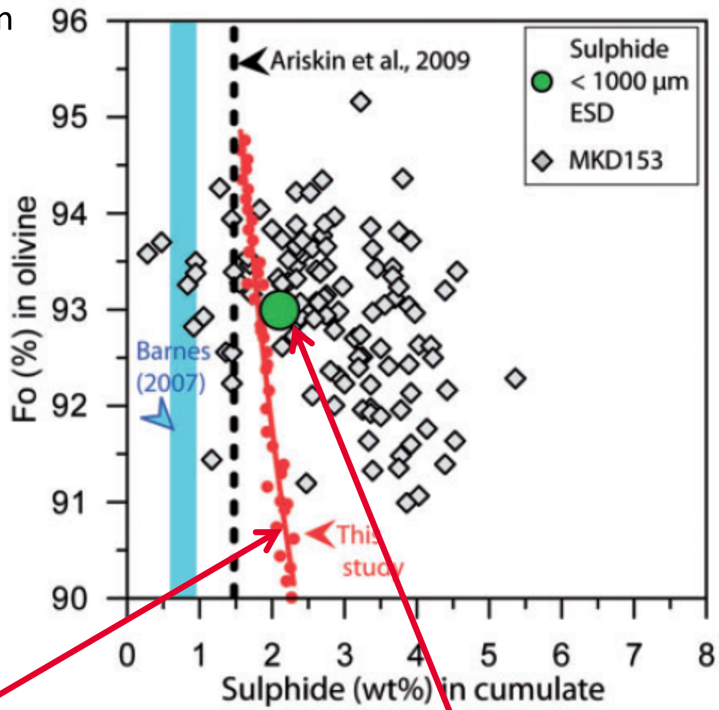
In-situ nucleation-growth mechanism for cumulates



Adcumulates: Prolonged turbulent flow of lava over a bed of hot crystals.

SCSS = S content at sulfide liquid saturation



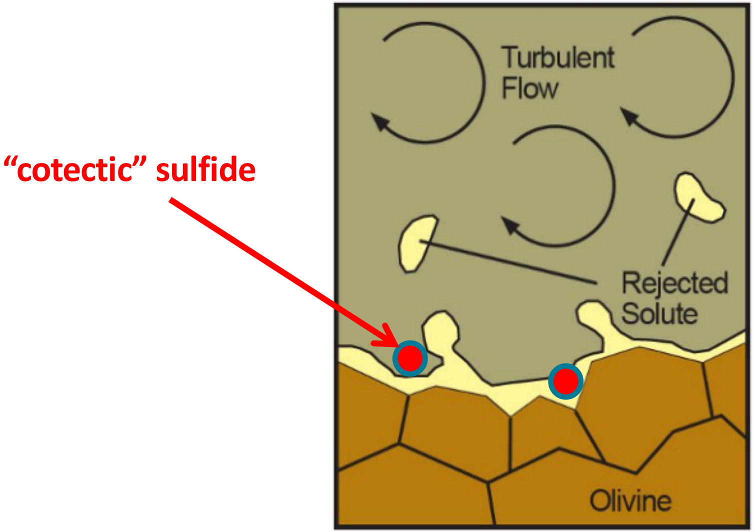


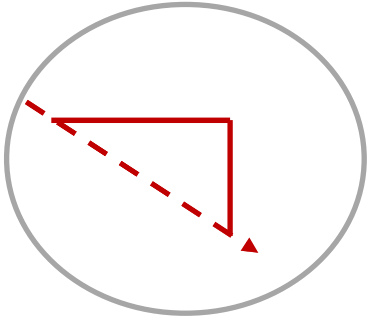
Slope of SCSS with MgO defines expected cotectic proportion of olivine to sulfide during fractional crystallisation (Li and Ripley model)

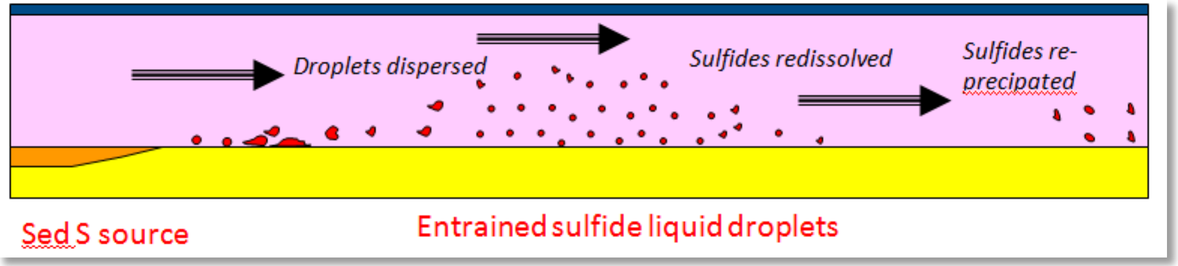
Measured mode of small sulfide blebs (<1 mm equiv sphere diameter)

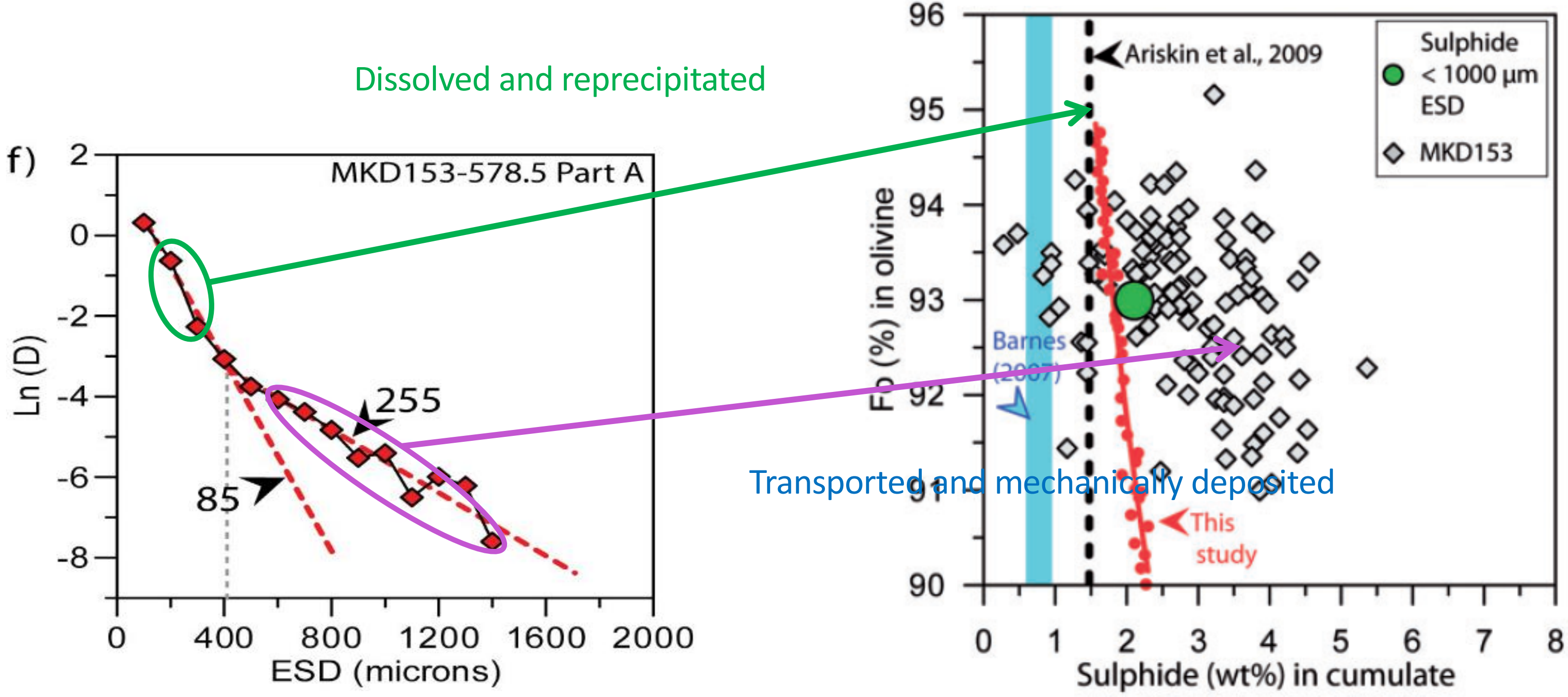
Hypothesis: small blebs are the result of in situ nucleation/growth....

The modal % of small sulfide blebs in the adcumulate should match the predicted cotectic proportion between olivine and sulfide





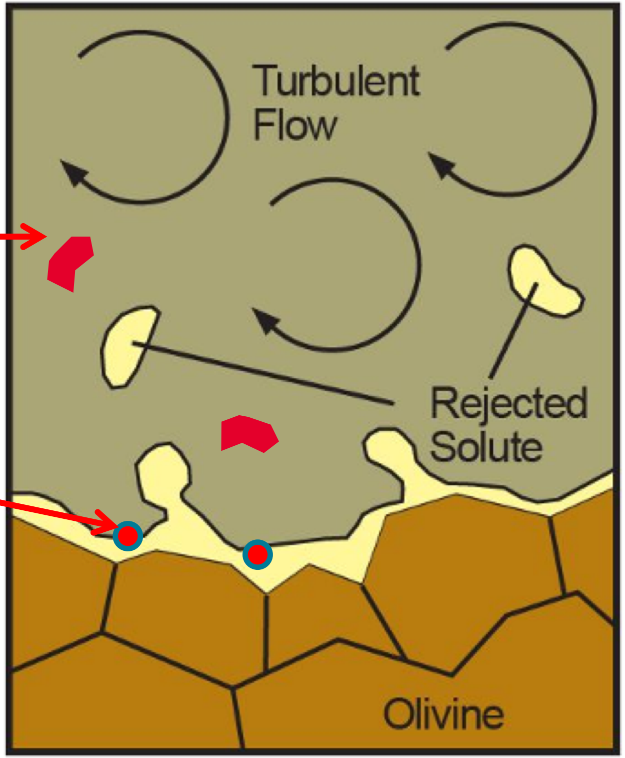

Droplets dispersed
Sulfides redissolved
Sulfides re-precipated
Sed S source
Entrained sulfide liquid droplets


Dissolved and reprecipitated
f)
MKD153-578.5 Part A
255
85
Ln (D)
ESD (microns)
0
400
800
1200
1600
2000
2
0
-2
-4
-6
-8
Ariskin et al., 2009
Sulphide
< 1000 µm
ESD
MKD153
Barnes
(2007)
Fo (%) in olivine
Transported and mechanically deposited
This
study
Sulphide (wt%) in cumulate
96
95
94
93
92
91
90
0
1
2
3
4
5
6
7
8

Conclusion : small blebs are the result of in situ nucleation/growth....

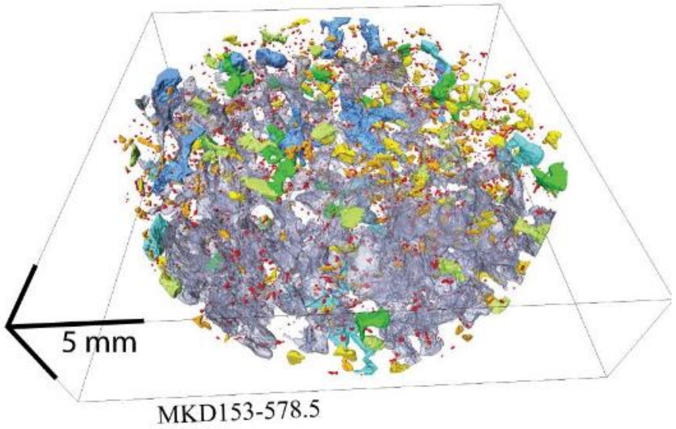
Transported and deposited sulfide droplets

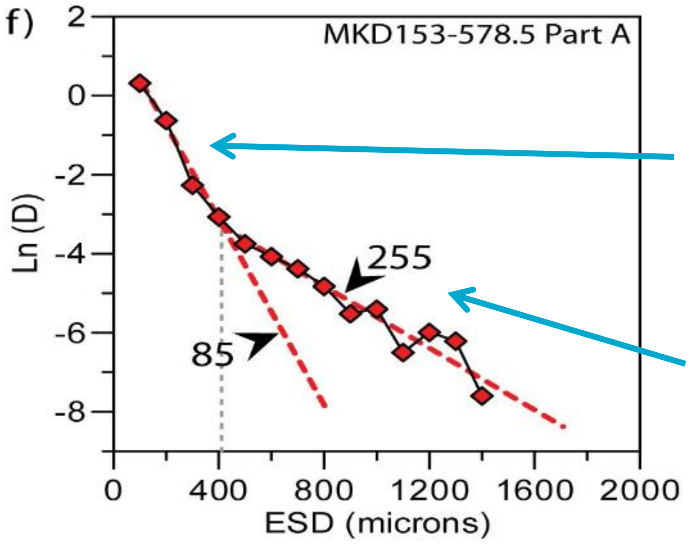
"in situ" cotectic sulfide



Size-distribution of sulfides

Two populations – both with power law distribution. Why?
Both in situ nucleation and growth and droplet breakup generate power-law size distributions





In situ nucleation and growth of droplets at deposition site

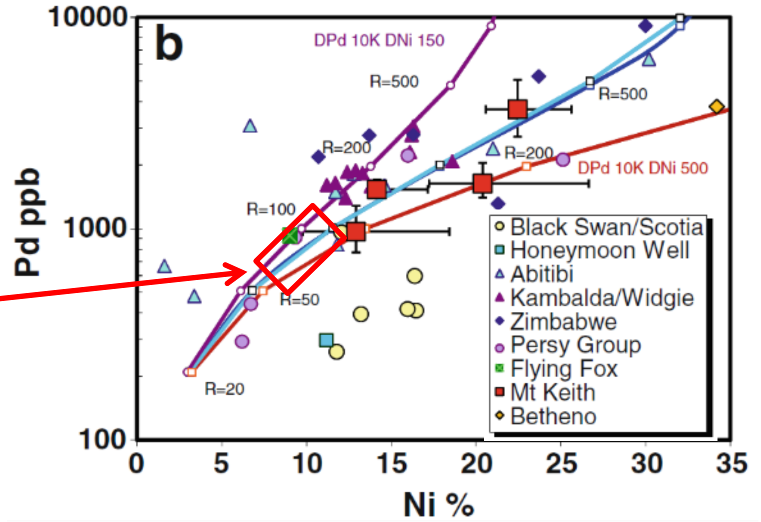
Power-law size distribution generated by breakup of large droplets during transport?

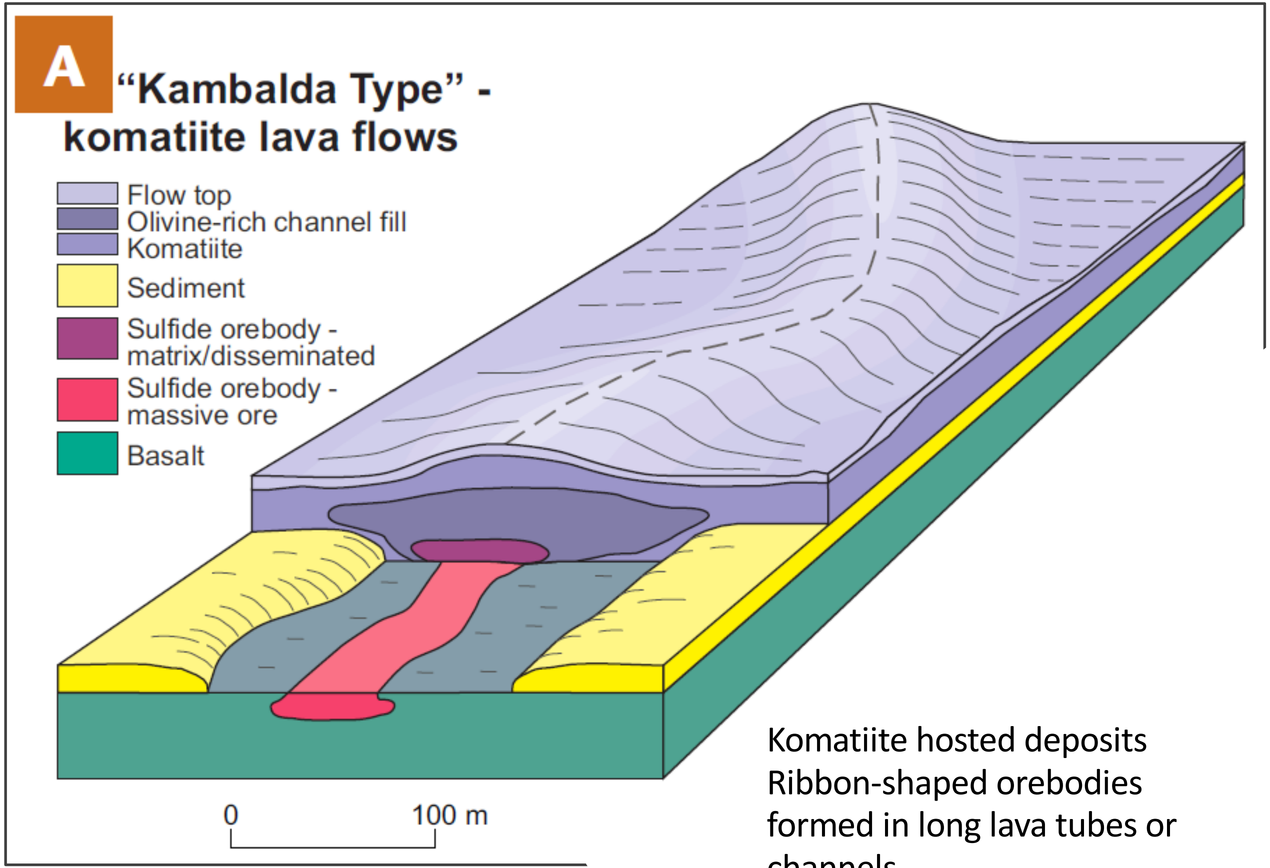
(Godel et al., J Pet 2013)

So what?

- Disseminated ores are mixture of in-situ cotectic and transported entrained droplet populations
- Ore deposition can happen a long way from the original S source
- Purely cotectic sulfides are not a good indicator of proximity to high grade ore – although they may have reasonably high tenors (R = 100-200). Coarse blebs with high (> 2 ppm) Pd are better indicators of proximity to high-grade ore

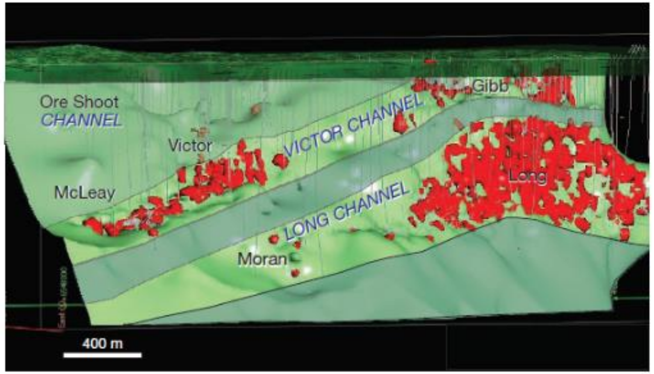
Characteristic tenor range of purely cotectic sulfides in komatiites

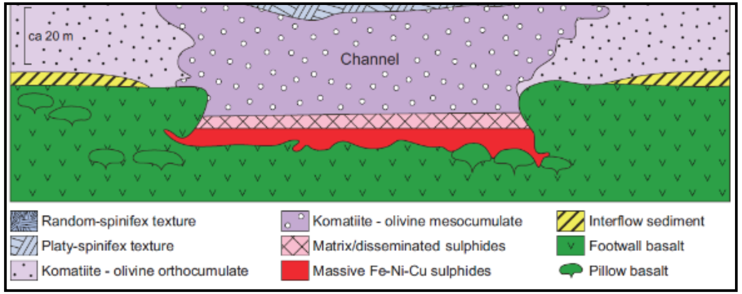


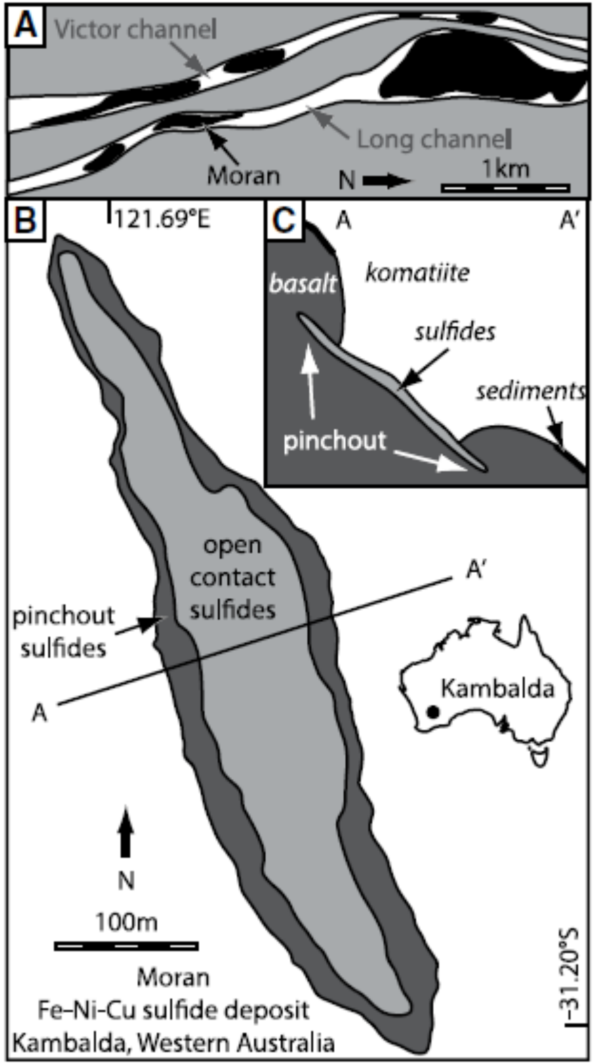


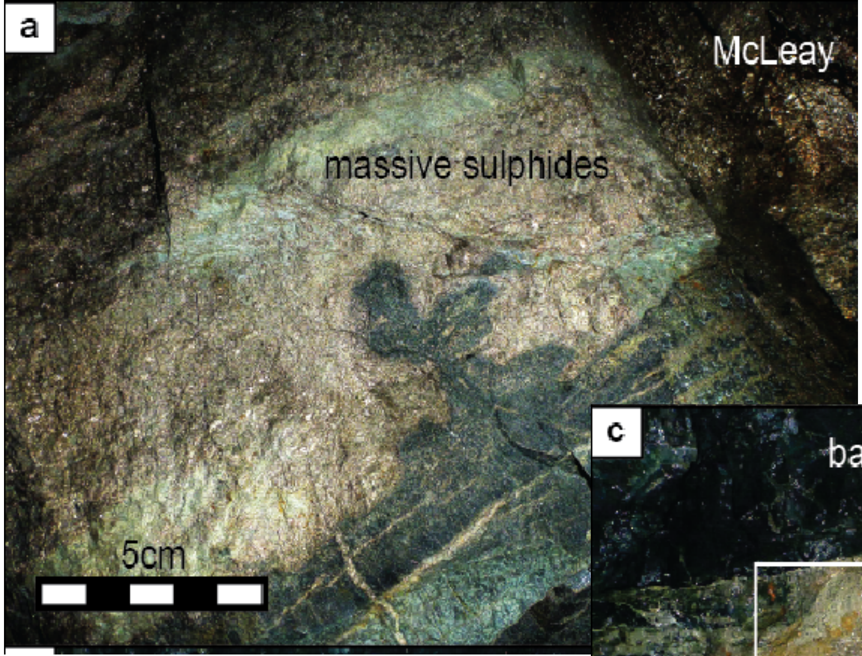
Komatiite hosted deposits
Ribbon-shaped orebodies formed in long lava tubes or channels

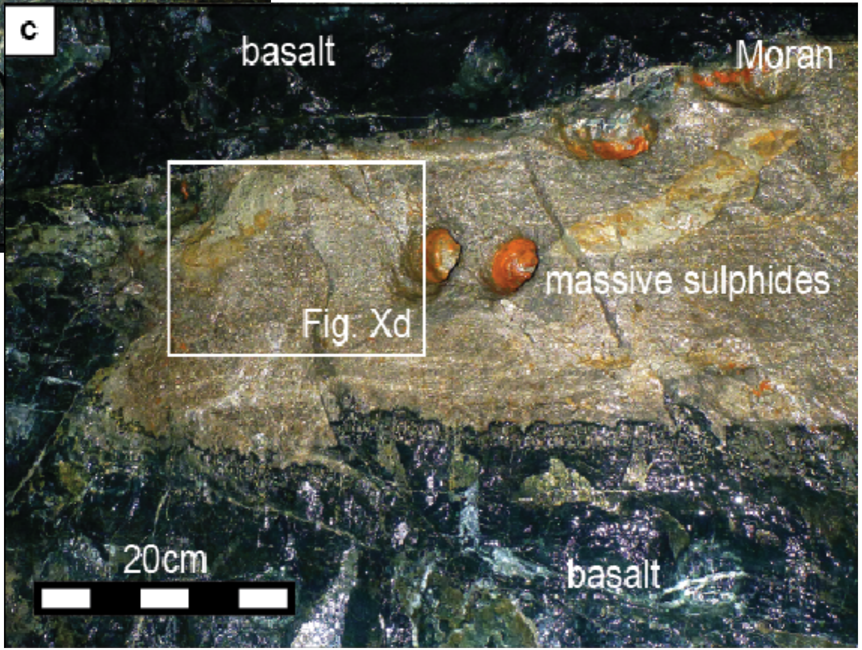
Emulsion textures and breccias at a sulfide-silicate infiltration-melting front: Moran Shoot, Kambalda









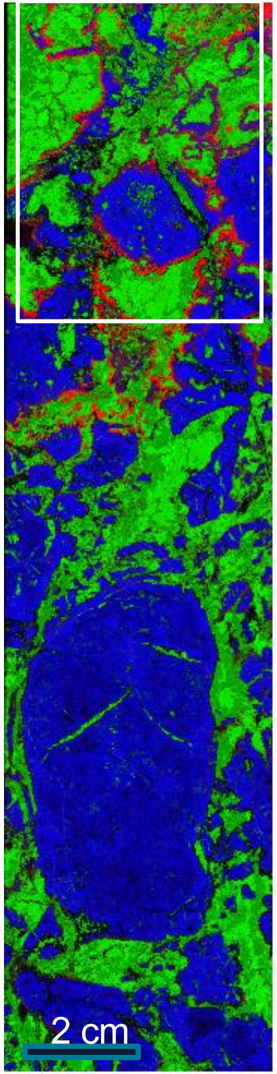


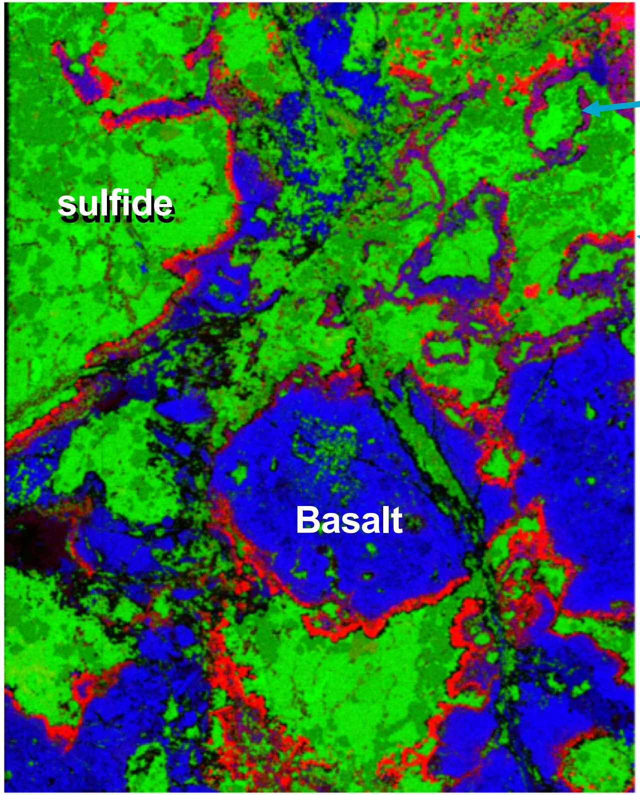
Thermomechanical erosion of footwall basalts at Kambalda

(Staude et al., 2016, 2017)

Sulfide-silicate infiltration-melting front: Moran Shoot, Kambalda

(False colour image, Cr red, S green and Si blue)

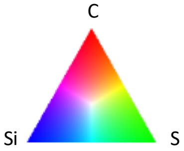




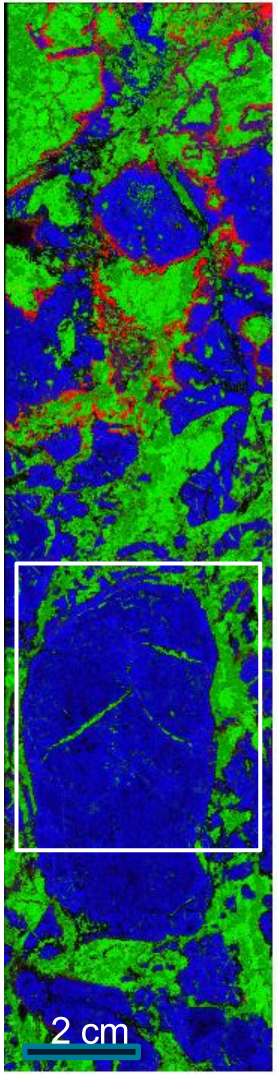
“Floating” basalt plumes

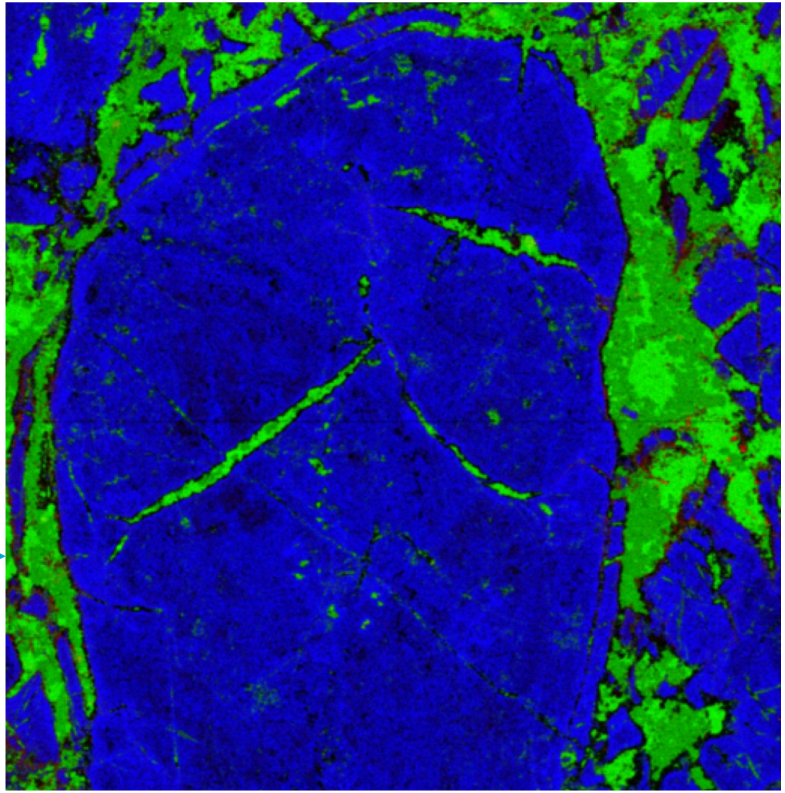
Chromite (formed at silicate-sulfide melt interfaces

Basalt fragments melting at the margins



Sulfide-silicate infiltration-melting front: Moran Shoot, Kambalda

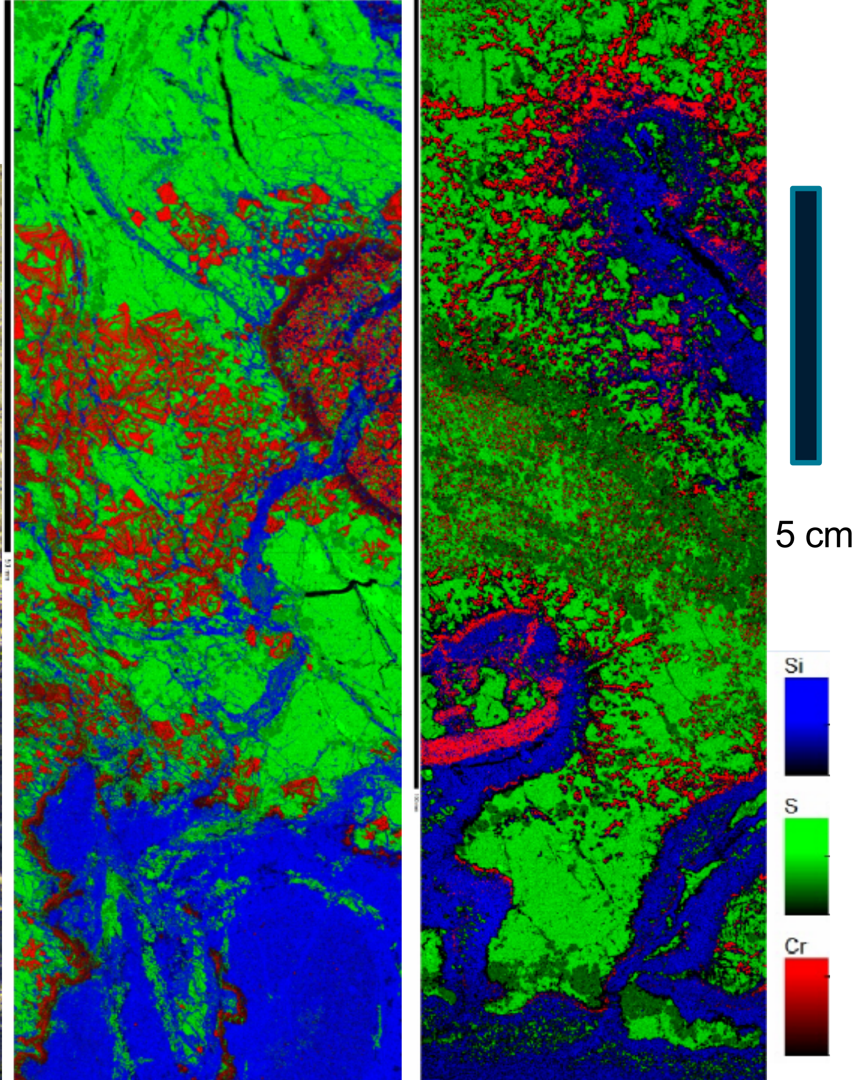




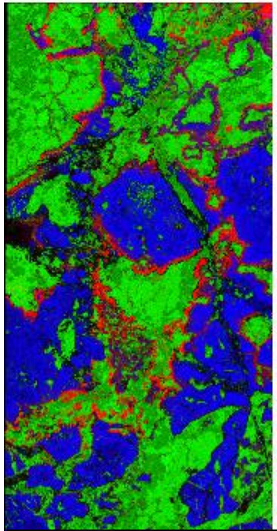
Hydrofractured basalt clasts with sulfide penetrating along fractures

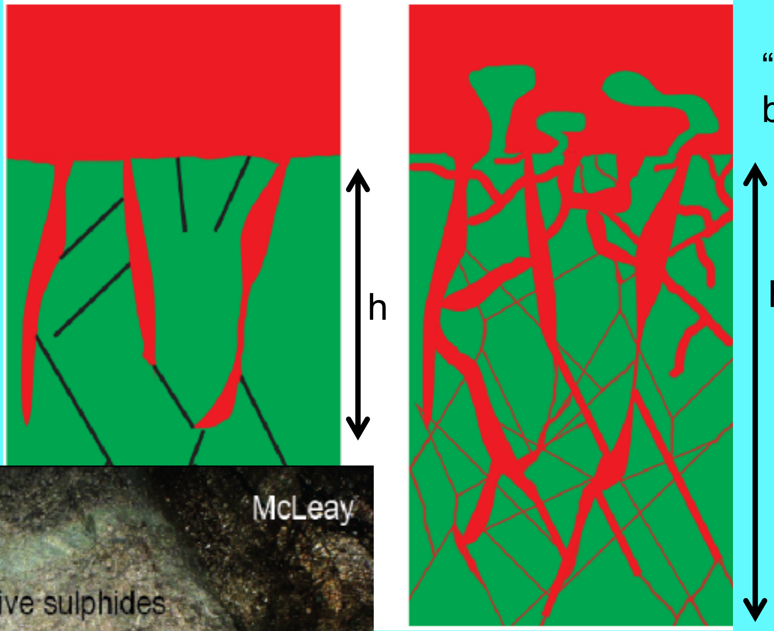
Chromite disappearing downwards

Basalt melt plumes



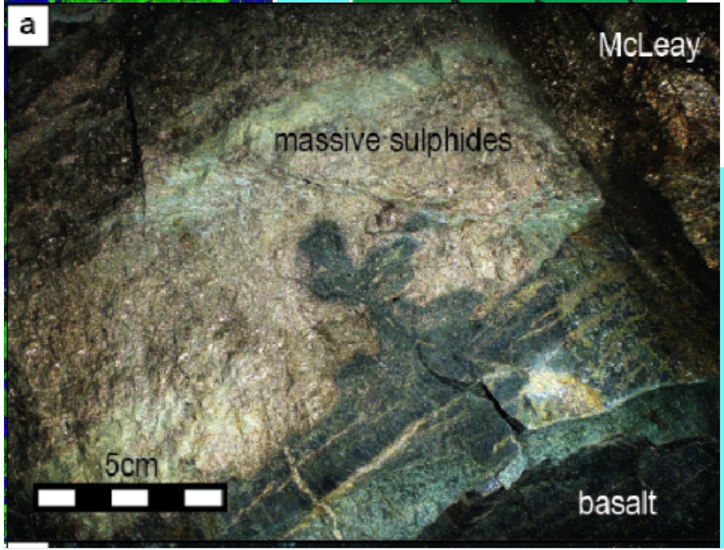
Sulfide-silicate infiltration-melting front: Moran Shoot, Kambalda





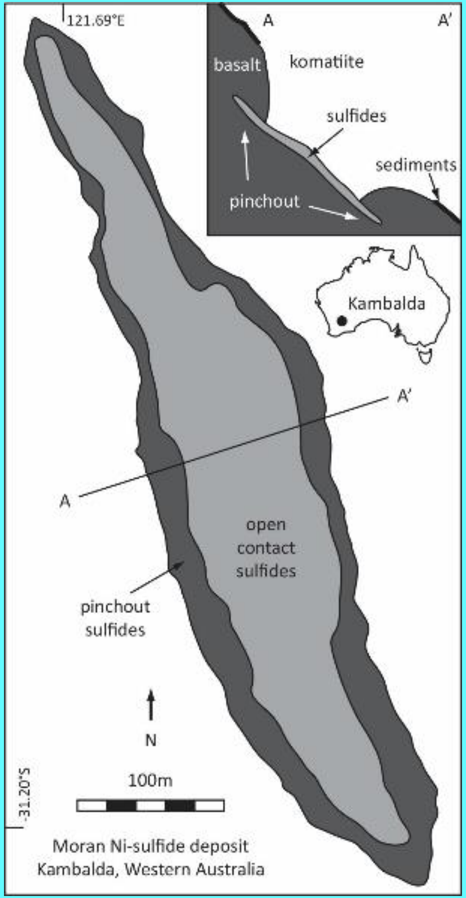
“Floating” basalt plumes

“Hydrostatic” Differential pressure at tip of sulfide network increases as veins propagate downwards

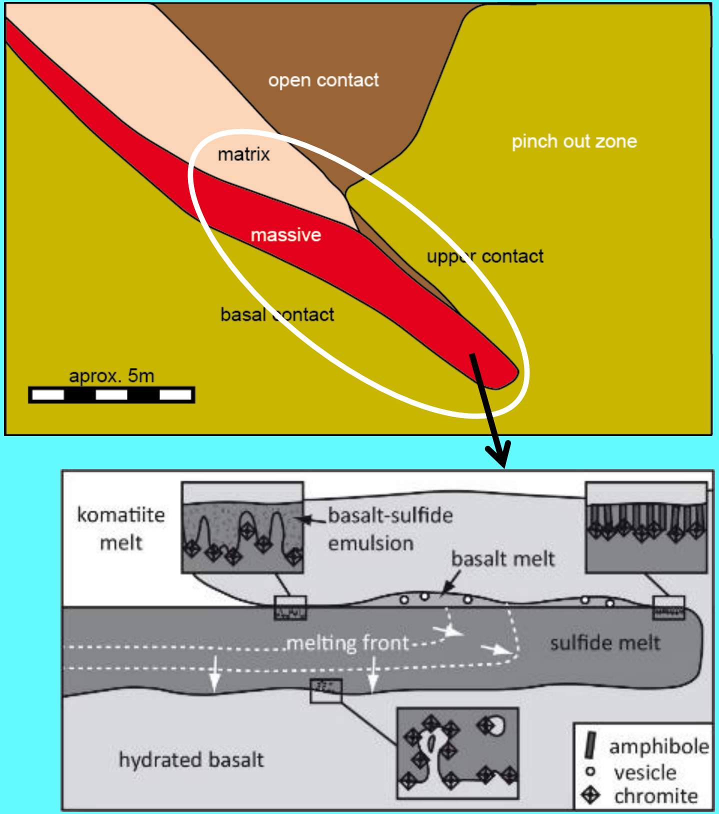


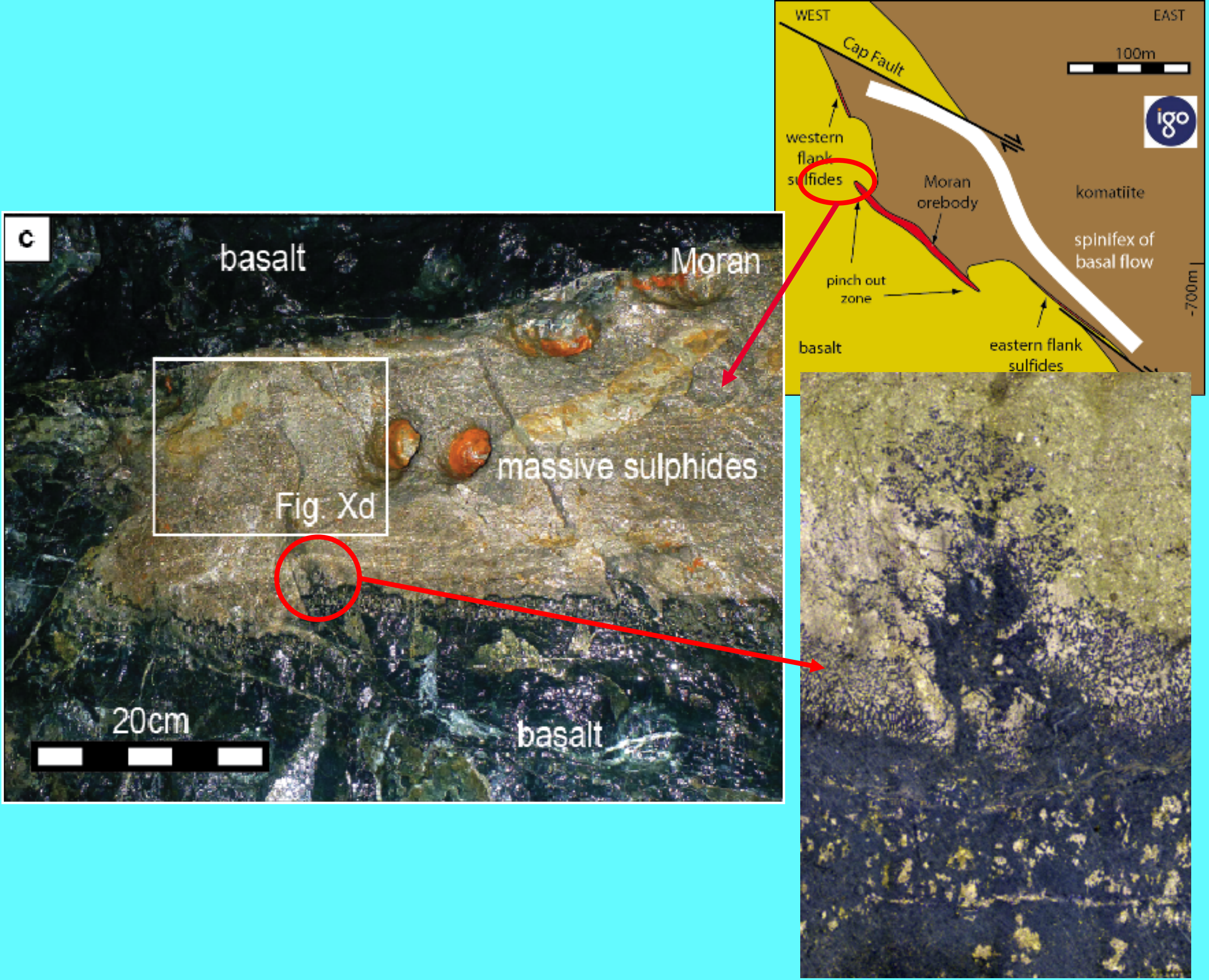
Hydrofractured basalt with sulfide penetrating along fractures

Moran Shoot pinchout zone

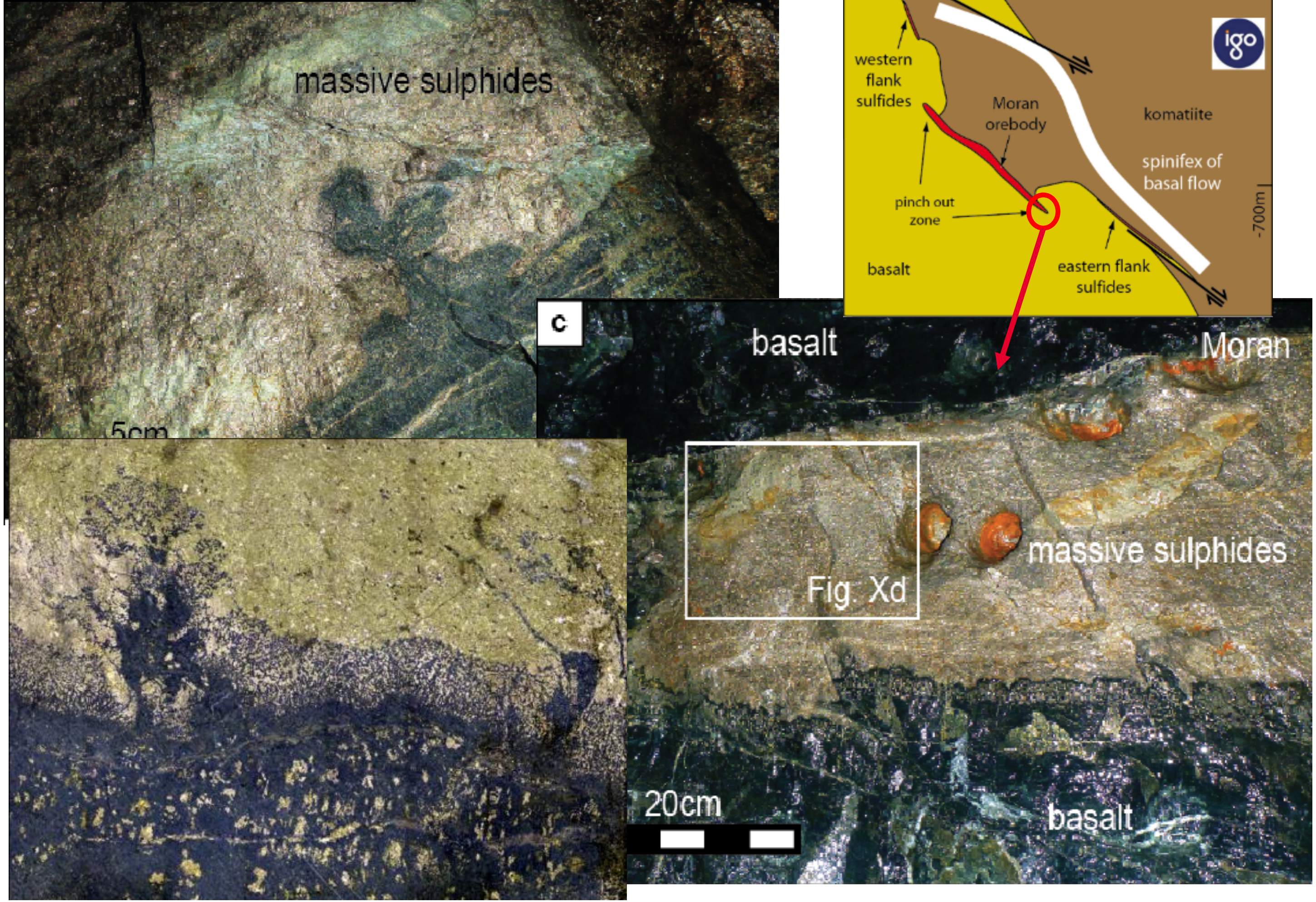


Silicate-sulfide melting front



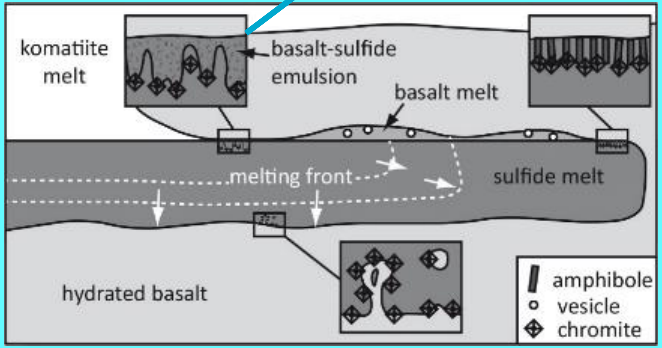

c
basalt
Moran
massive sulphides
Fig. Xd
20cm
basalt
WEST
EAST
Cap Fault
100m
western flank sulfides
Moran orebody
komatiite
spinifex of basal flow
pinch out zone
-700m
basalt
eastern flank sulfides

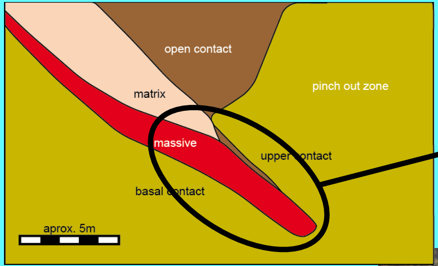
Moran and McLeay

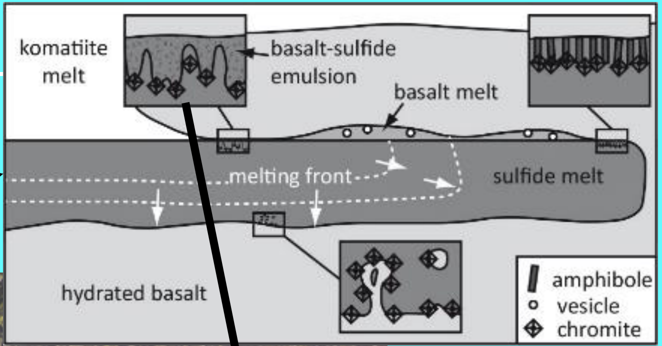


Silicate-sulfide emulsion texture

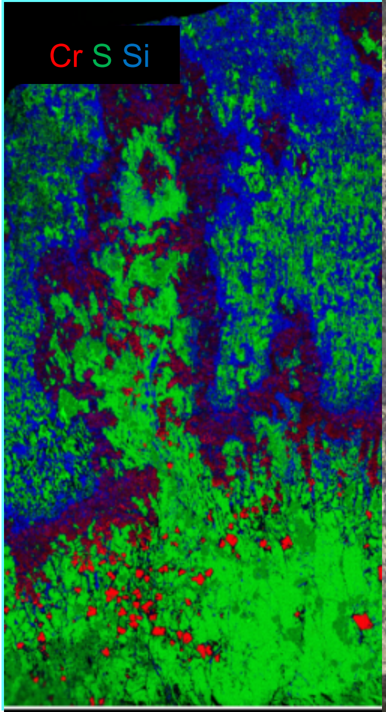
Moran Shoot pinchout zone

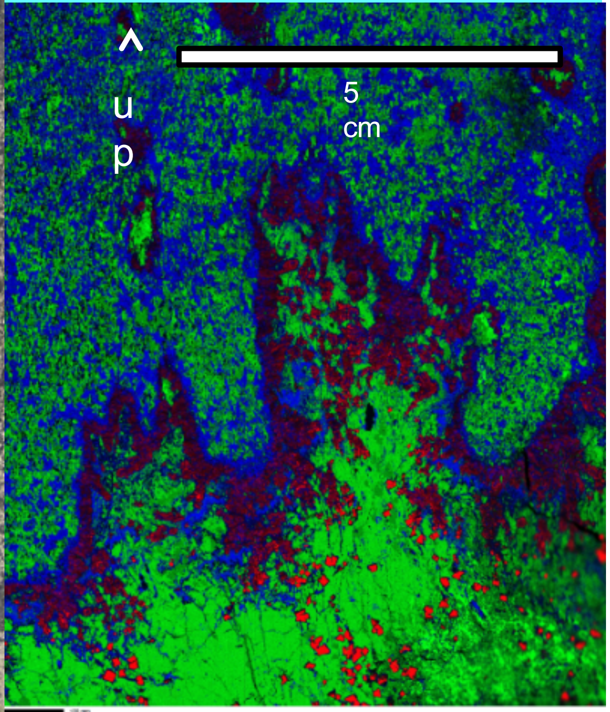


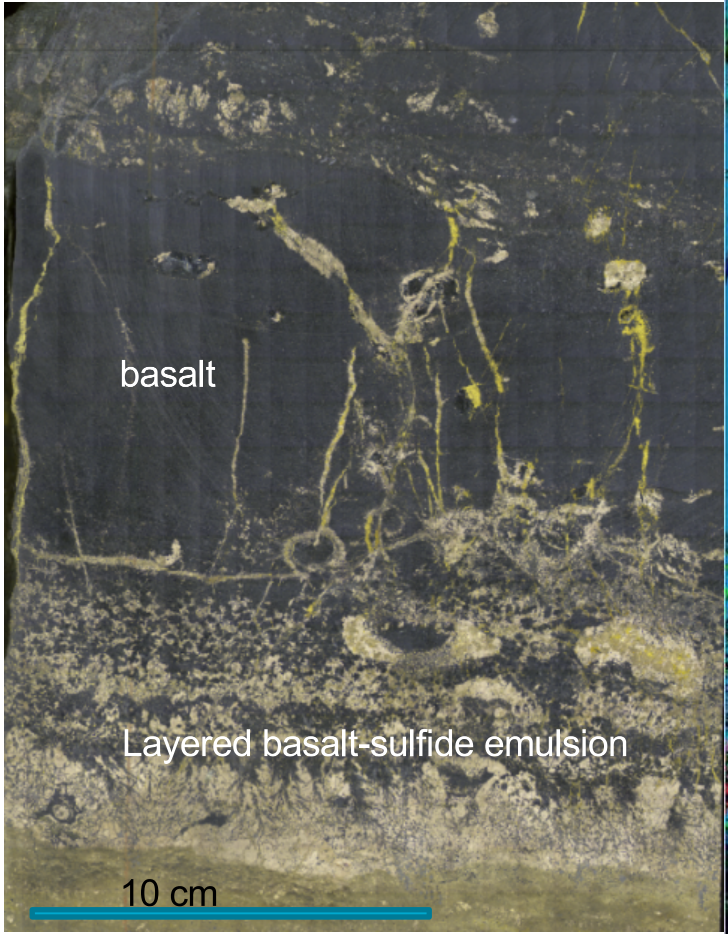


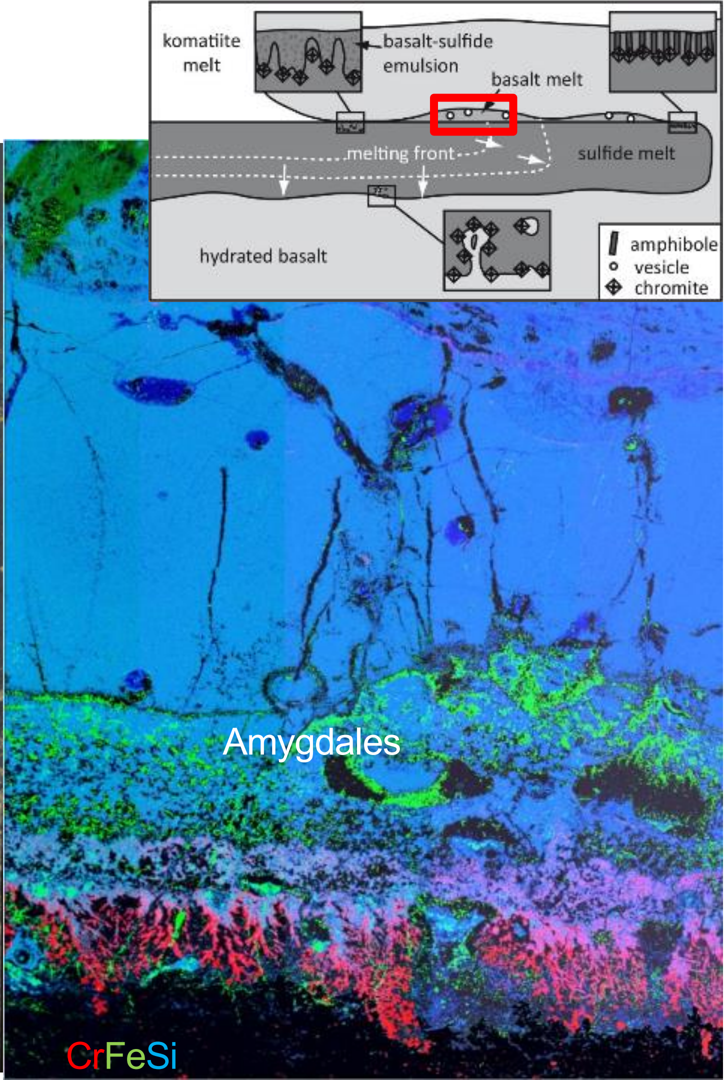


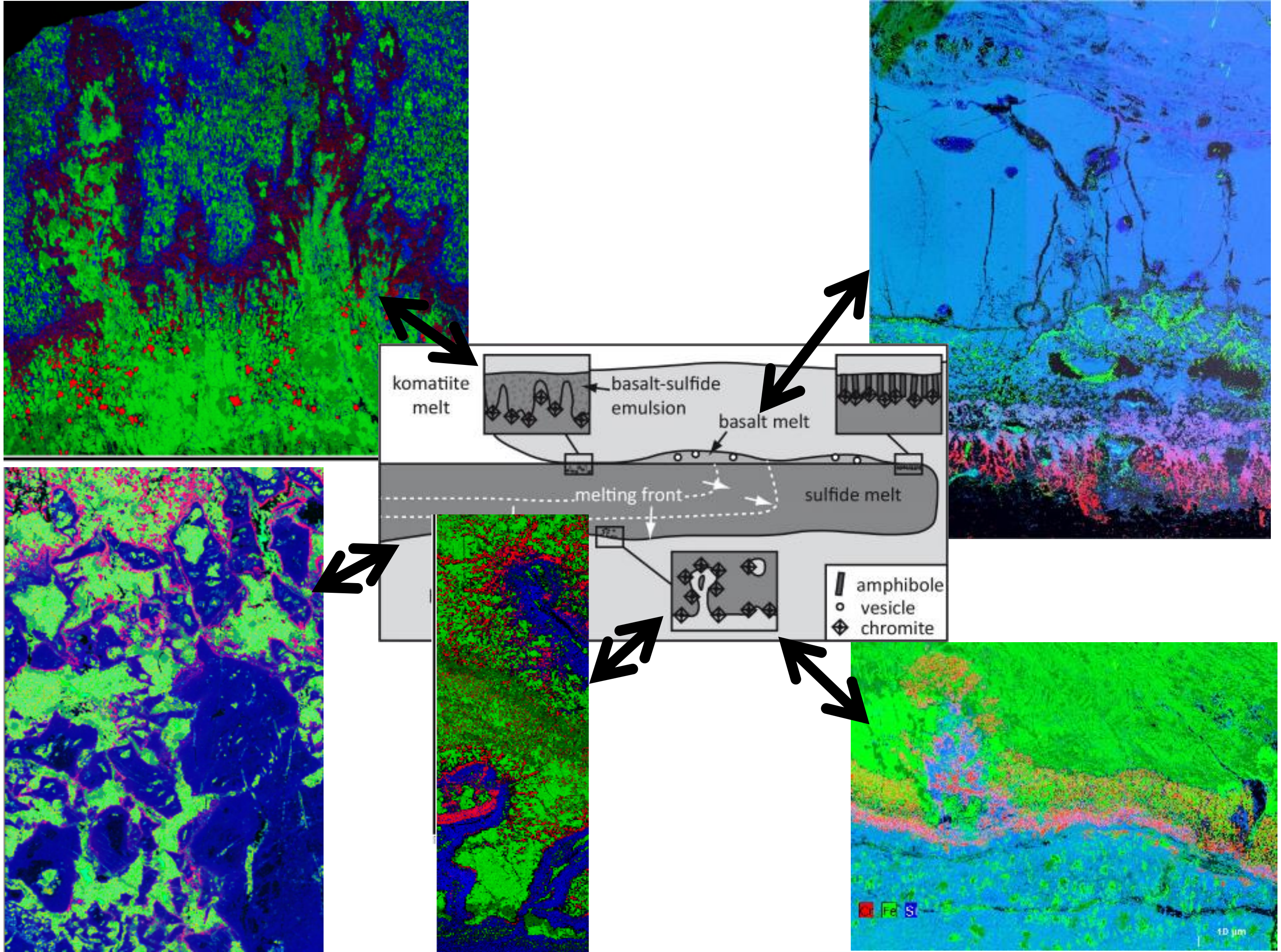
Staude Barnes and Le Vaillant, Geology 2016



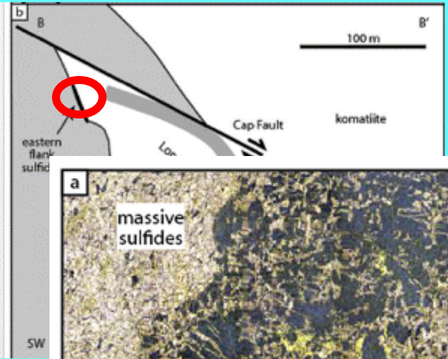


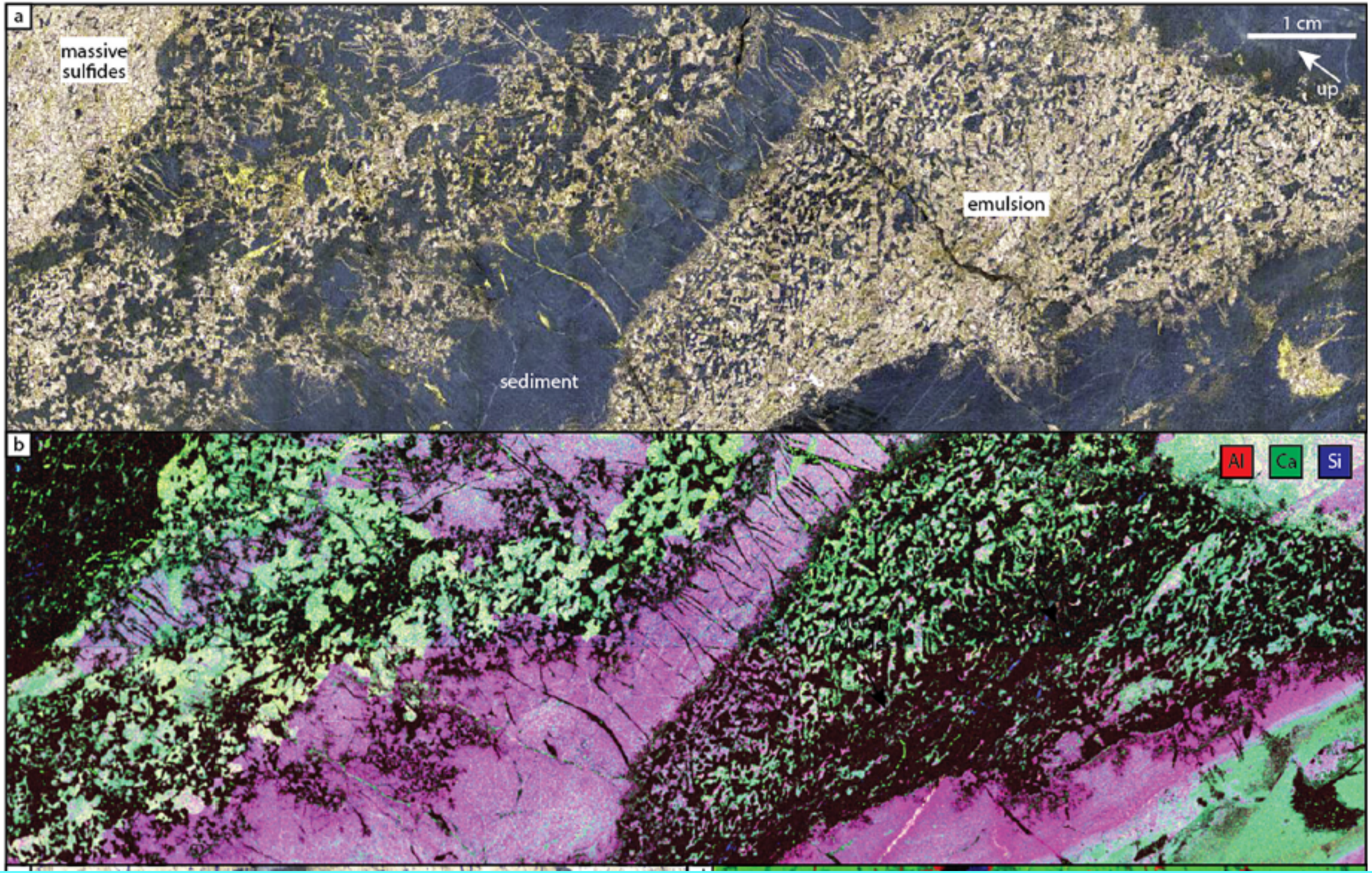

basalt
Layered basalt-sulfide emulsion
10 cm

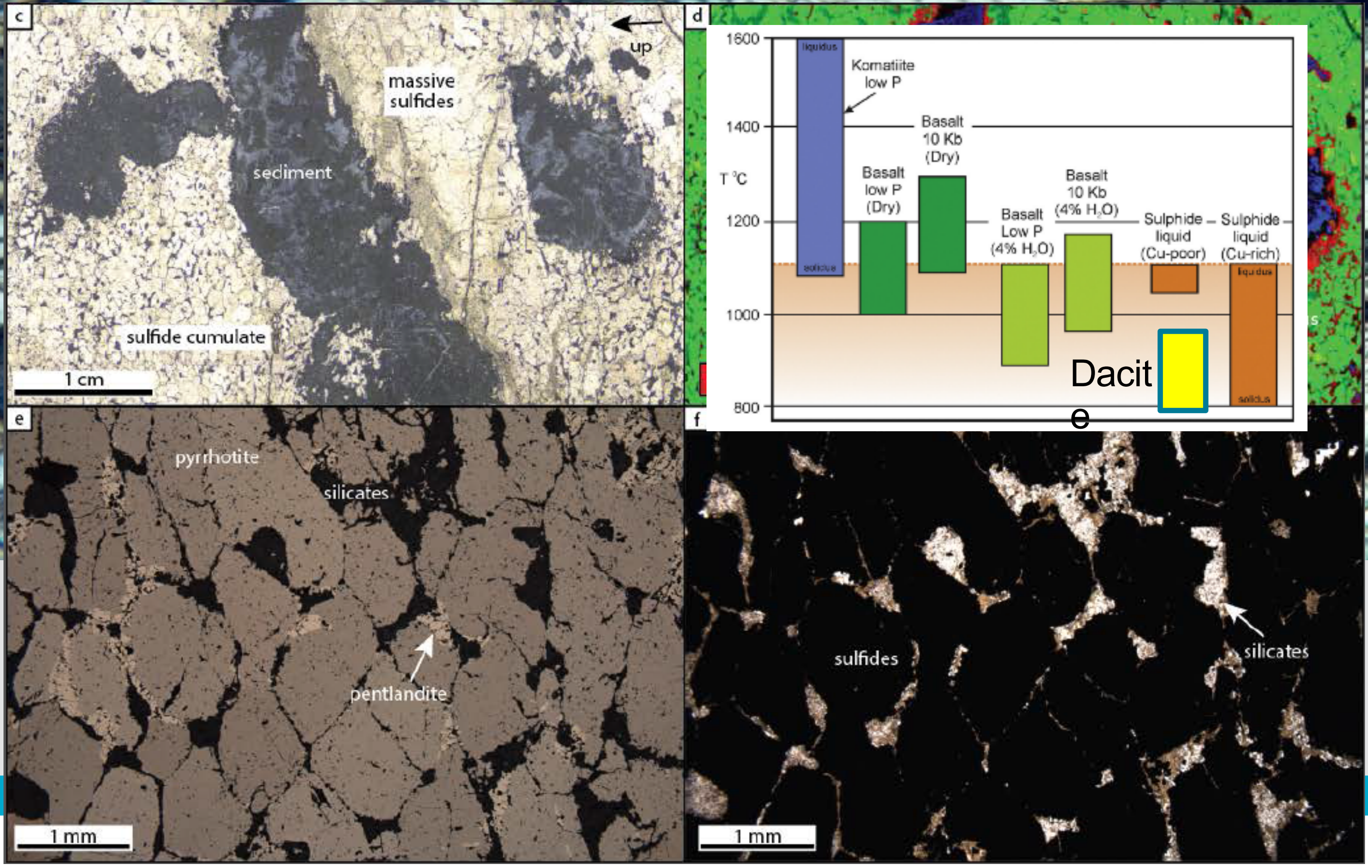

Amygdales
CrFeSi
komatiite melt
basalt-sulfide emulsion
basalt melt
melting front
sulfide melt
hydrated basalt
amphibole
vesicle
chromite


komatiite melt
basalt-sulfide emulsion
basalt melt
melting front
sulfide melt
amphibole
vesicle
chromite

Sulfide melting into sediments







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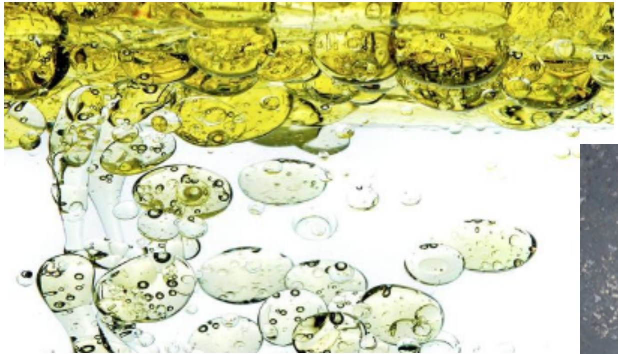
Minerals Down Under

CSIRO

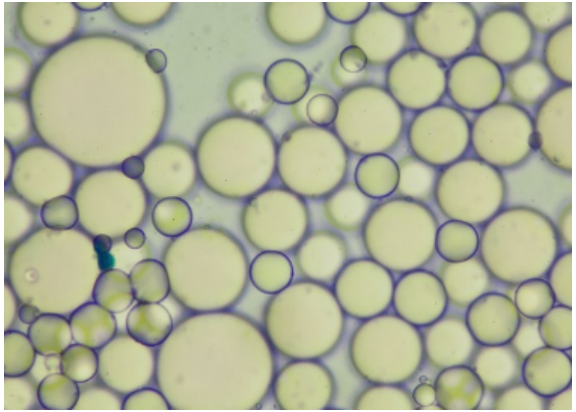
Emulsions – vinaigrette or mayonnaise?

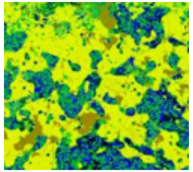
Vinaigrette…

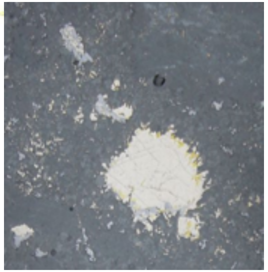
Oil droplets in water…



Mayonnaise – water droplets in oil…

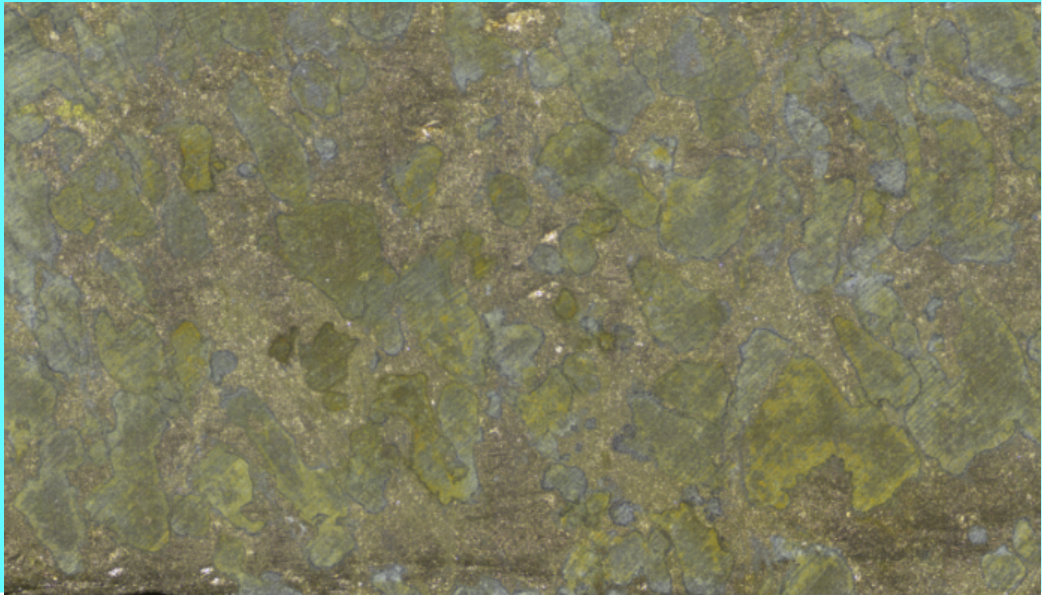


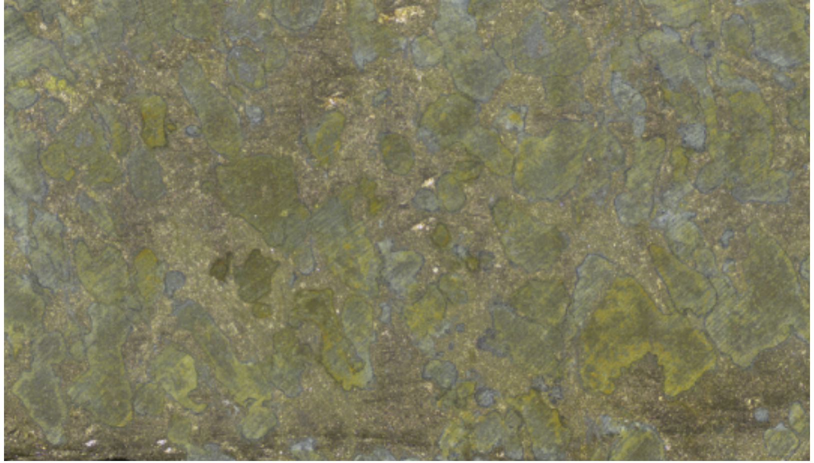




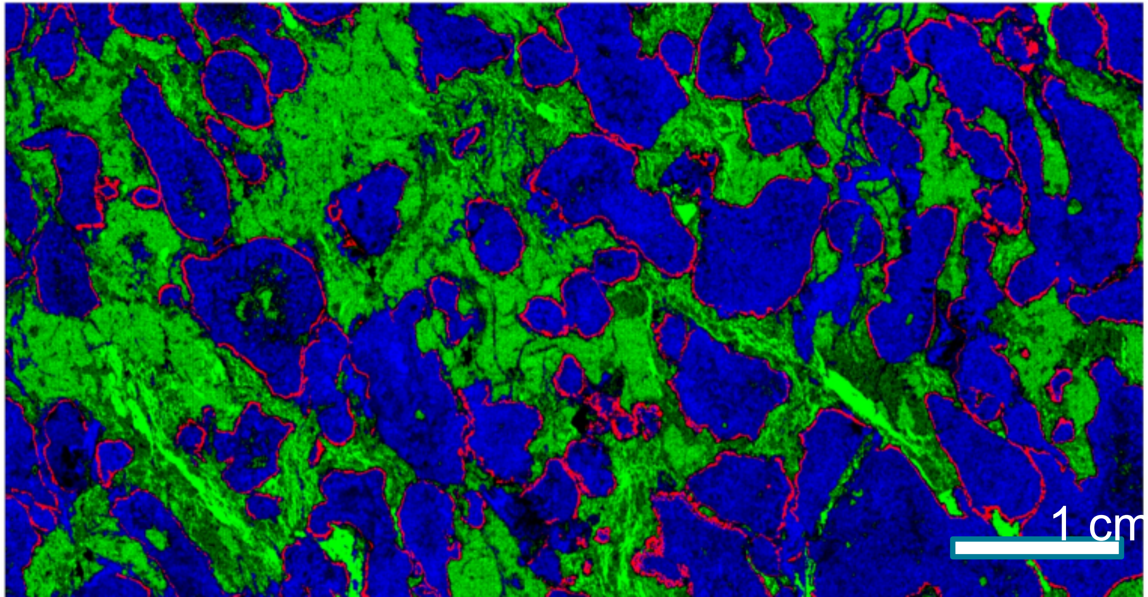
Sulfide in silicate (basalt) liquid
(Mayonnaise)

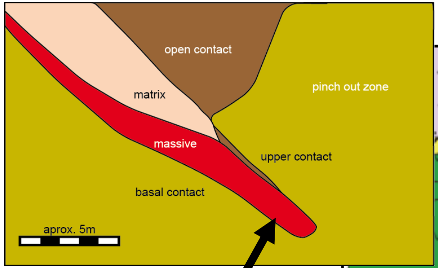
Silicate (basalt) in sulfide liquid
(Vinaigrette)

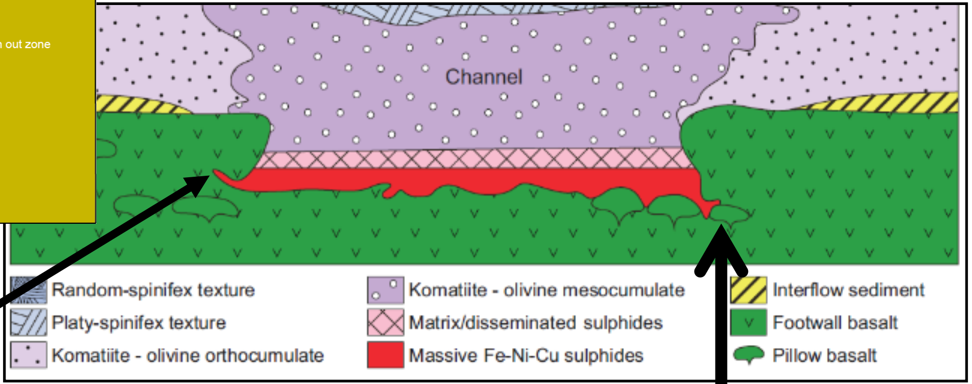





Cr
Si
S

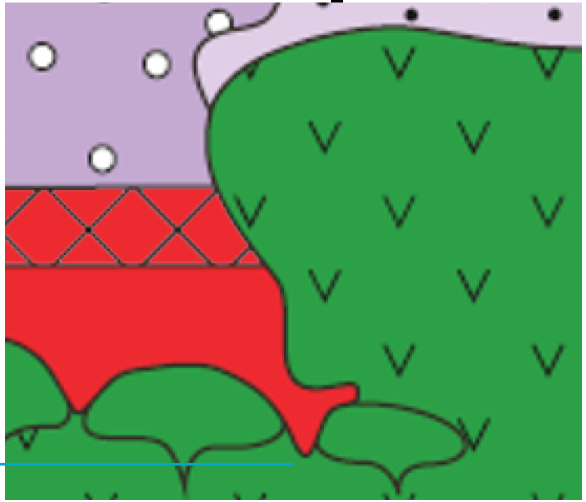

1 cm

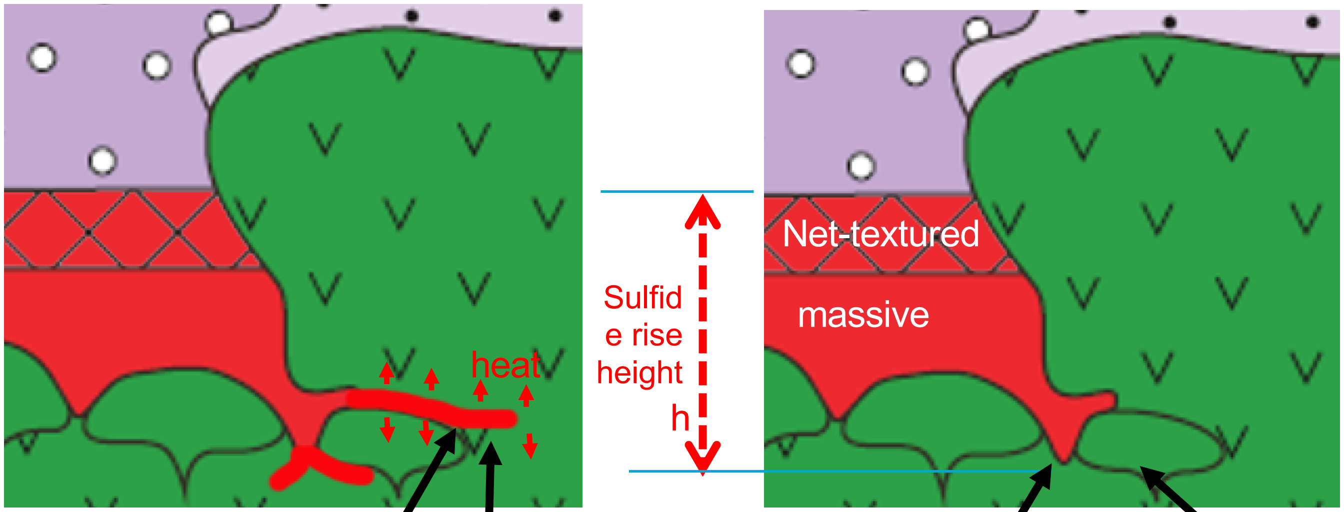




What drives lateral erosion here?

Excess "magmastatic" pressure due to sulfide rise height





Efficient heat transfer to roof causes further melting here

Excess pressure here $\mathbf{hg(\rho_{sul}-\rho_{bas})}$

Causes sulfide liquid to propagate into cracks laterally and vertically here

…relative to here

Sulfide melt can excavate its own “traps”

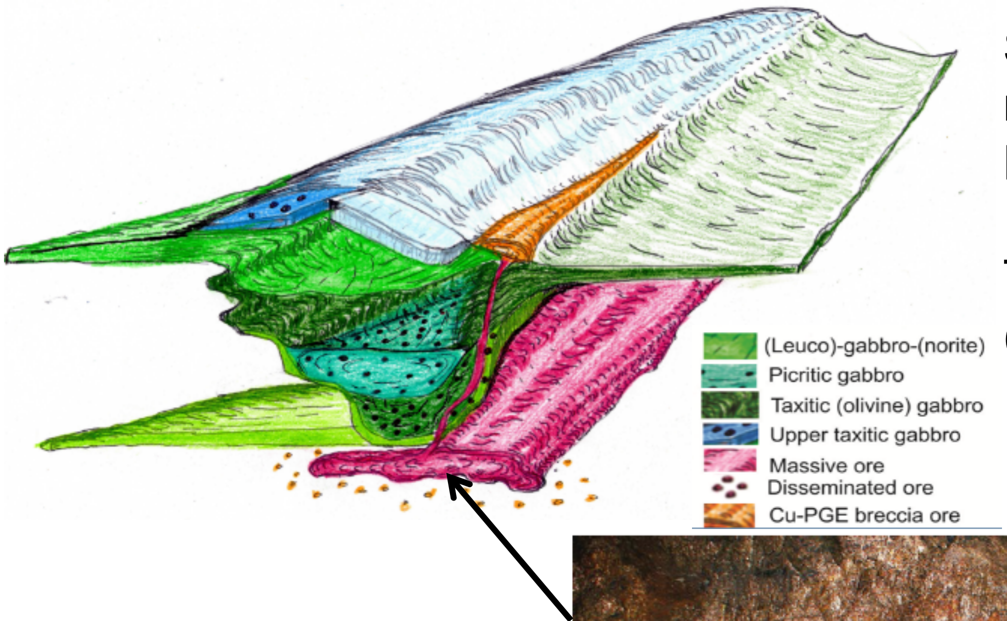
Physical properties of silicate and

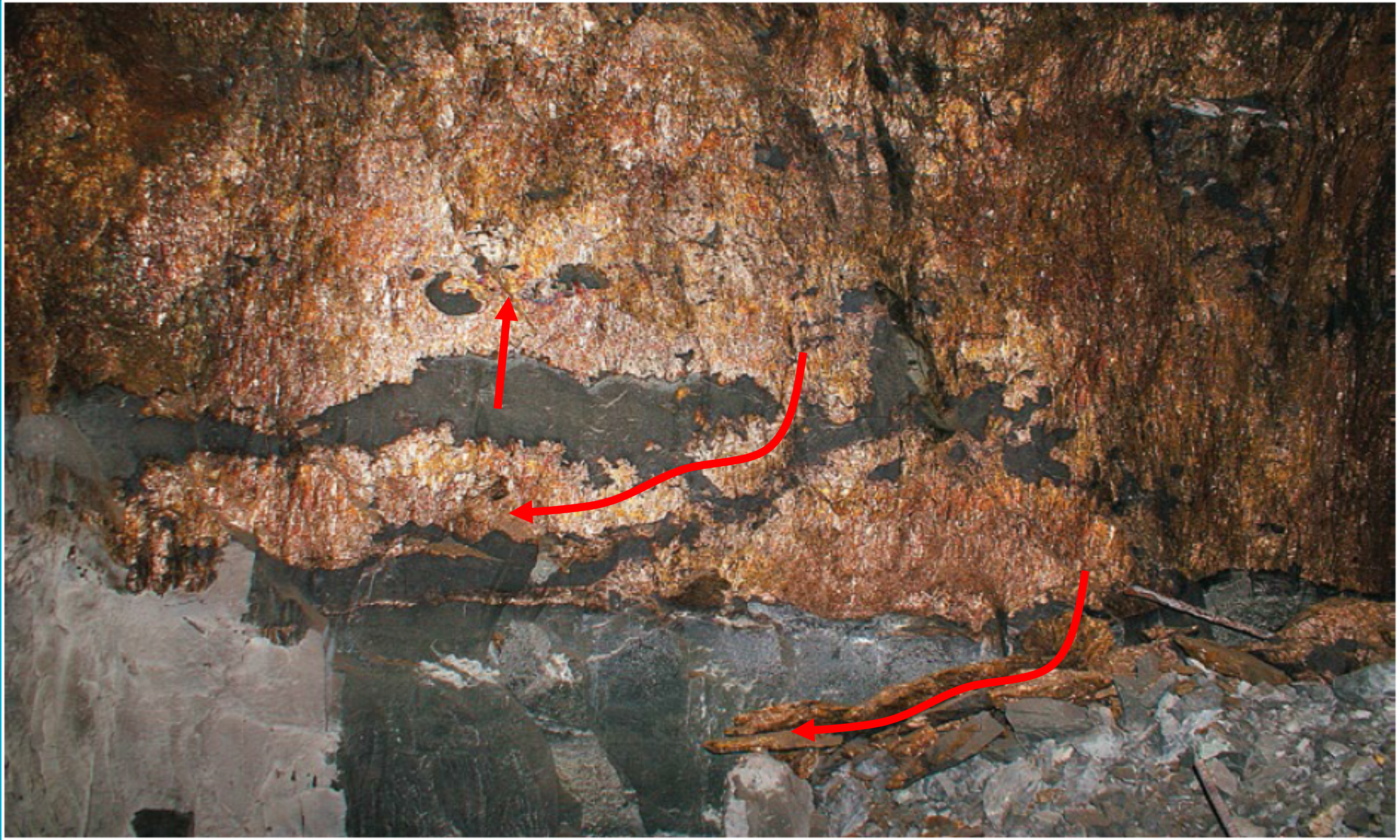
Melt type	Density (ρ) ($kg\ m^{-3}$)	Dynamic viscosity (μ) (Pa s)	Kiner (m^2 s
Fe sulphide	4000	2×10^{-2}	5 ×
Cu sulphide	5200	2×10^{-2}	3·8 ×
Komatiite	2800	1	3·5 ×
Basalt	2600	100	3·8 ×
Dacite	2000	1×10^{4}	5 m^2

Melt type	Prandtl number Pr	Schmidt number Sc	Lewis
Komatiite	350		7100
Basalt	38000		1000
Dacite	5×10^{6}		1000

Sulfide liquids are
VERY dense
VERY runny
VERY efficient carriers of heat

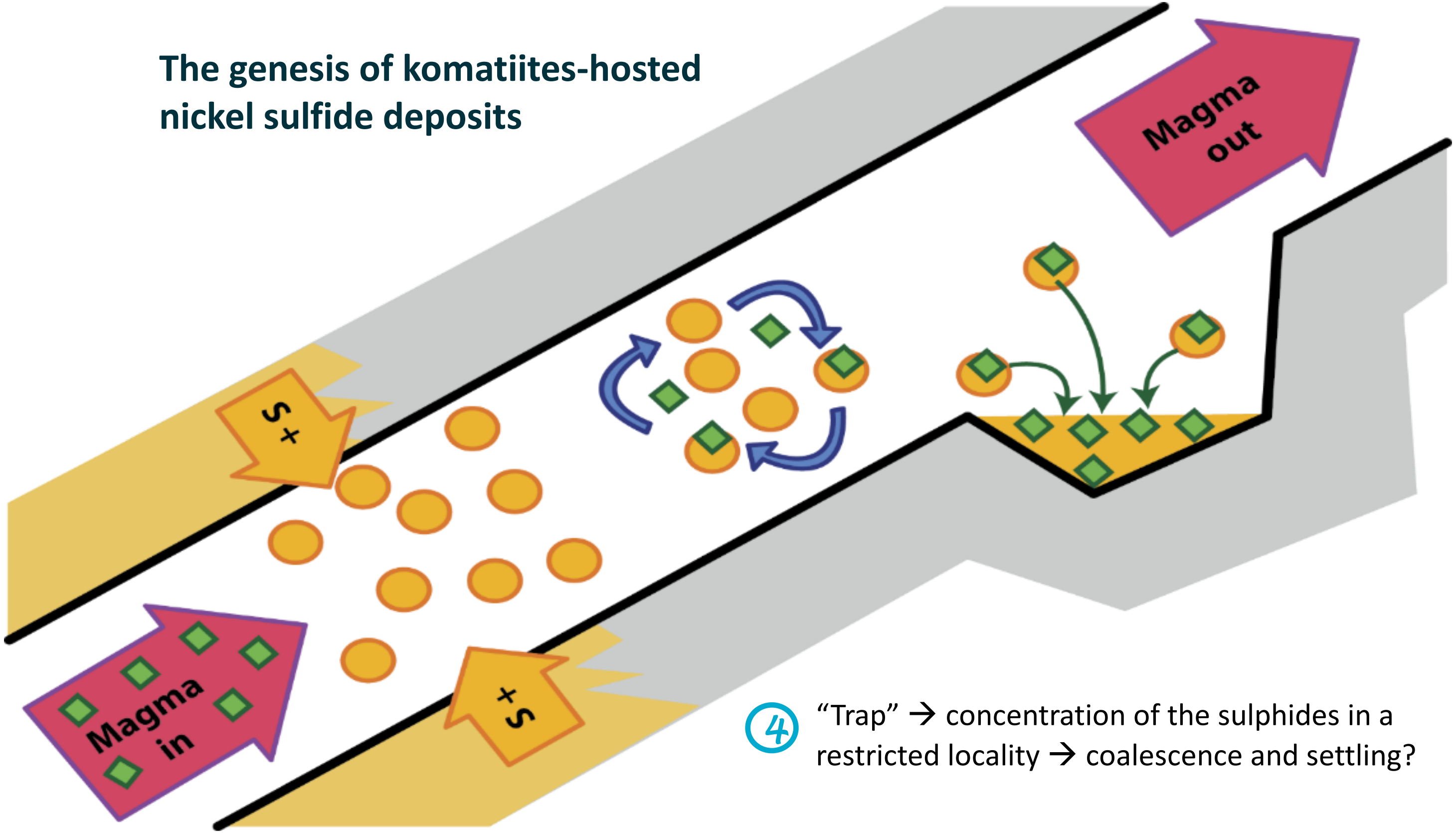
Sulfide – silicate melting fronts Kharealakh Intrusion, Talnakh (Noril'sk)





Sulfide melt infiltration front, base of the Oktyabrysky massive sulfide sheet. This is a melting raft of footwall metasediment floating up into sulfide but still attached to the floor. Photo courtesy of Nadya Krivolutskaya and organising team of 13th International Pt Symposium, Russia, 2013.

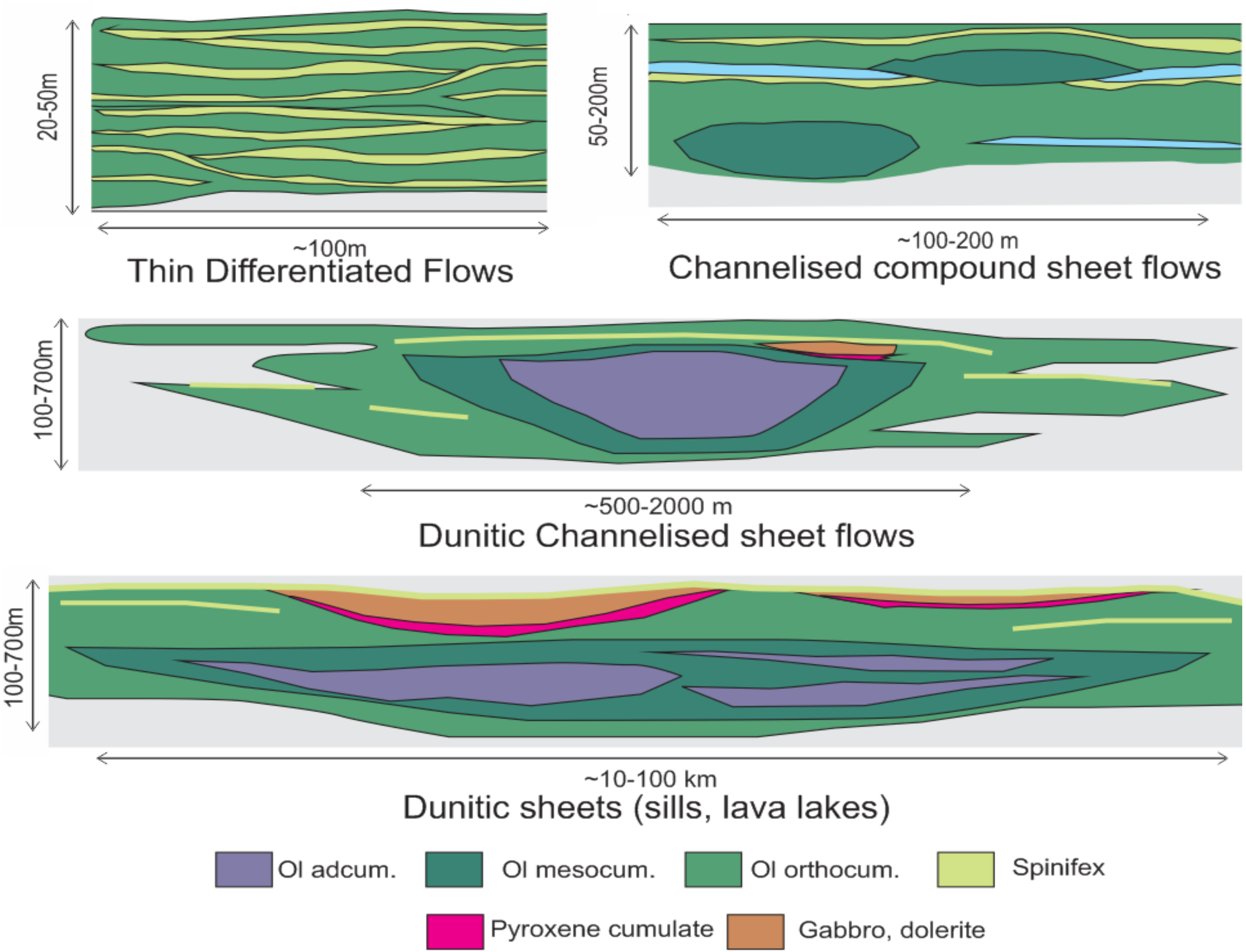
The genesis of komatiites-hosted nickel sulfide deposits



④ "Trap" → concentration of the sulphides in a restricted locality → coalescence and settling?

Komatiite facies model

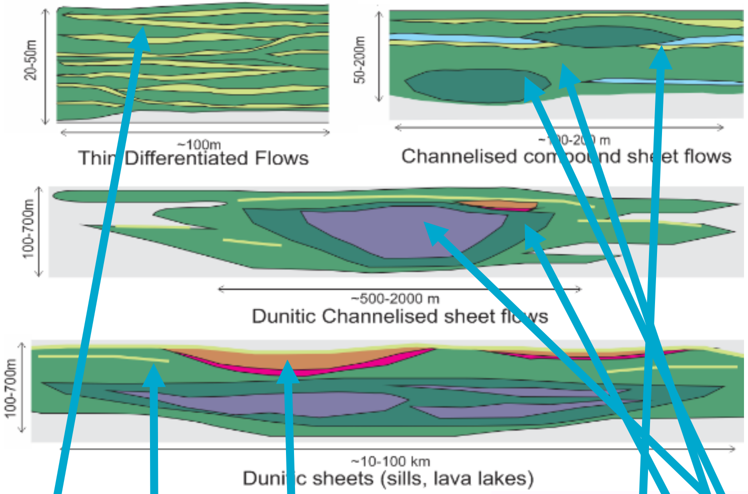
Recognising favourable volcanology



Deposit Scale

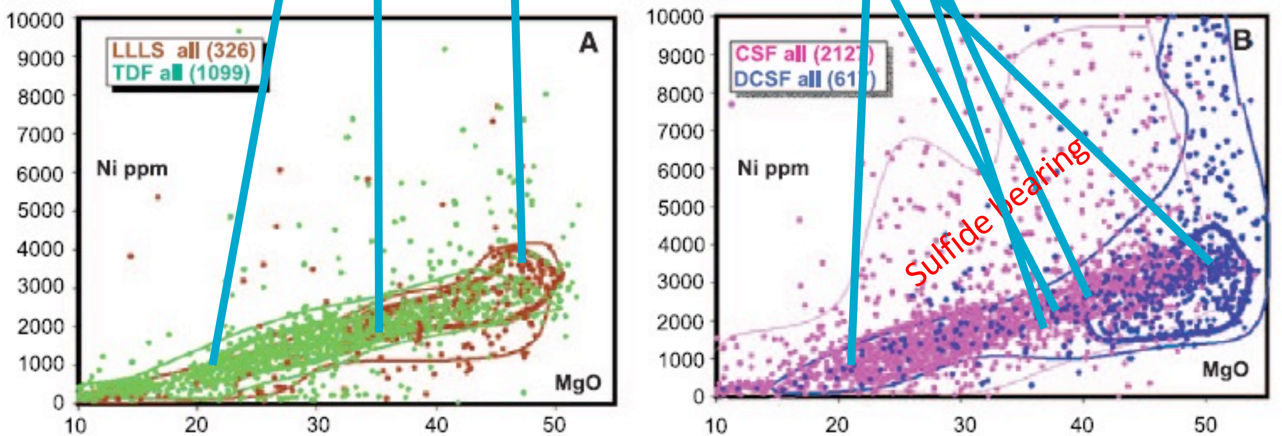
MgO changed by alteration

MgO leached during weathering



Talc-carb
High MgO rocks – MgO 20-25% low

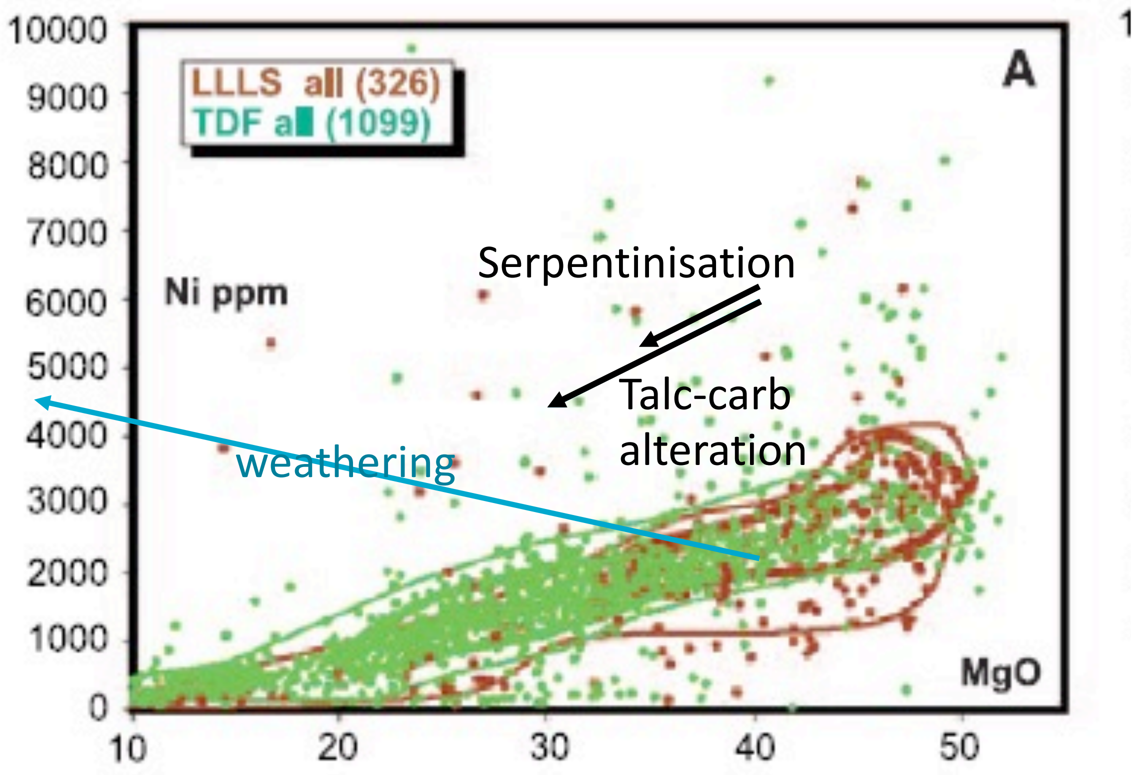
Serpentinite
High MgO rocks – MgO 10-15% low



Unprospective settings

Prospective settings

In komatiites, Ni & MgO= strong correlation (fractionation and accumulation of olivines) → **Ni-MGO plots**



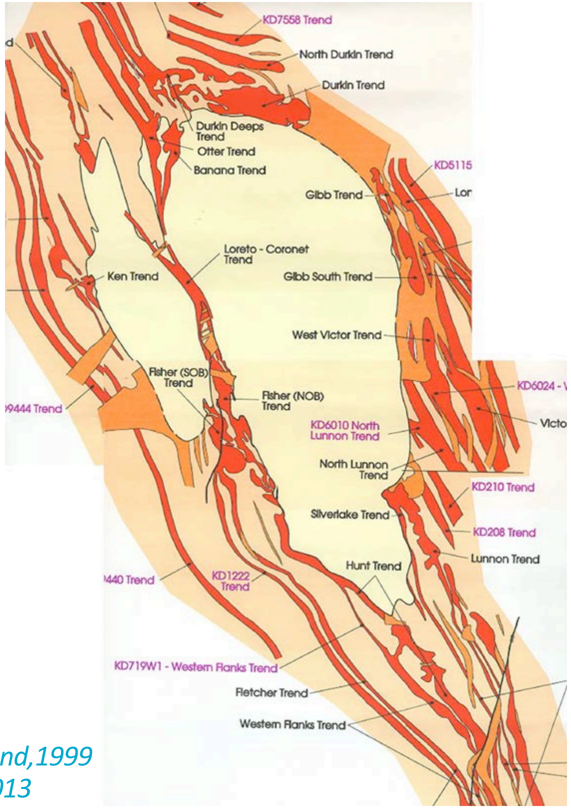
Lithogeochem on weathered rocks
(saprolite, saprock, TOFR)
Conserved Element Ratios
Ti, Cr, Ni

WMC approach 70s-80s

Ni/Cr ratios used to delineate ore-related channels

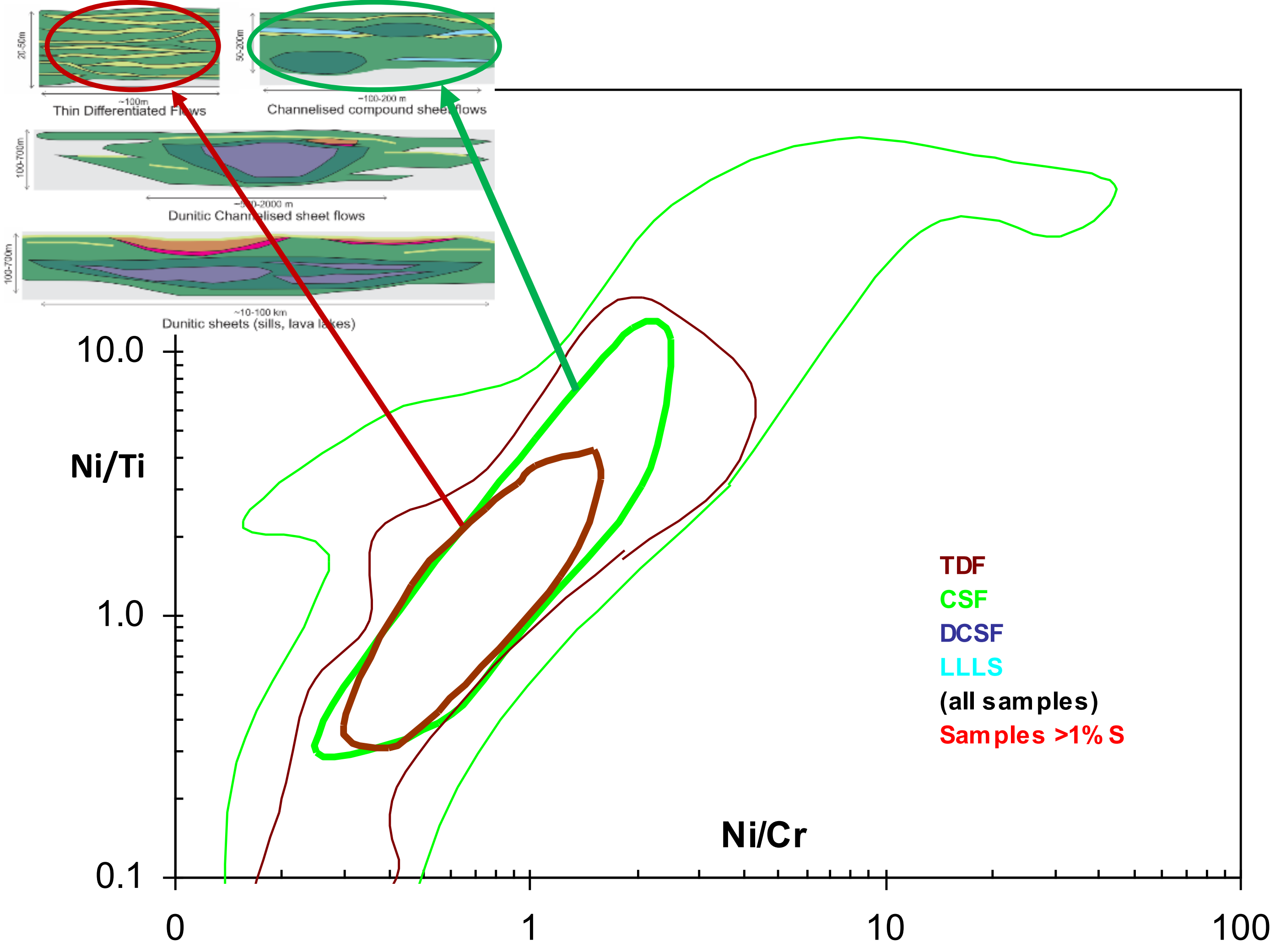
Picks up olivine and nickel sulphide rich channel facies

→Not much more efficient than Ni alone

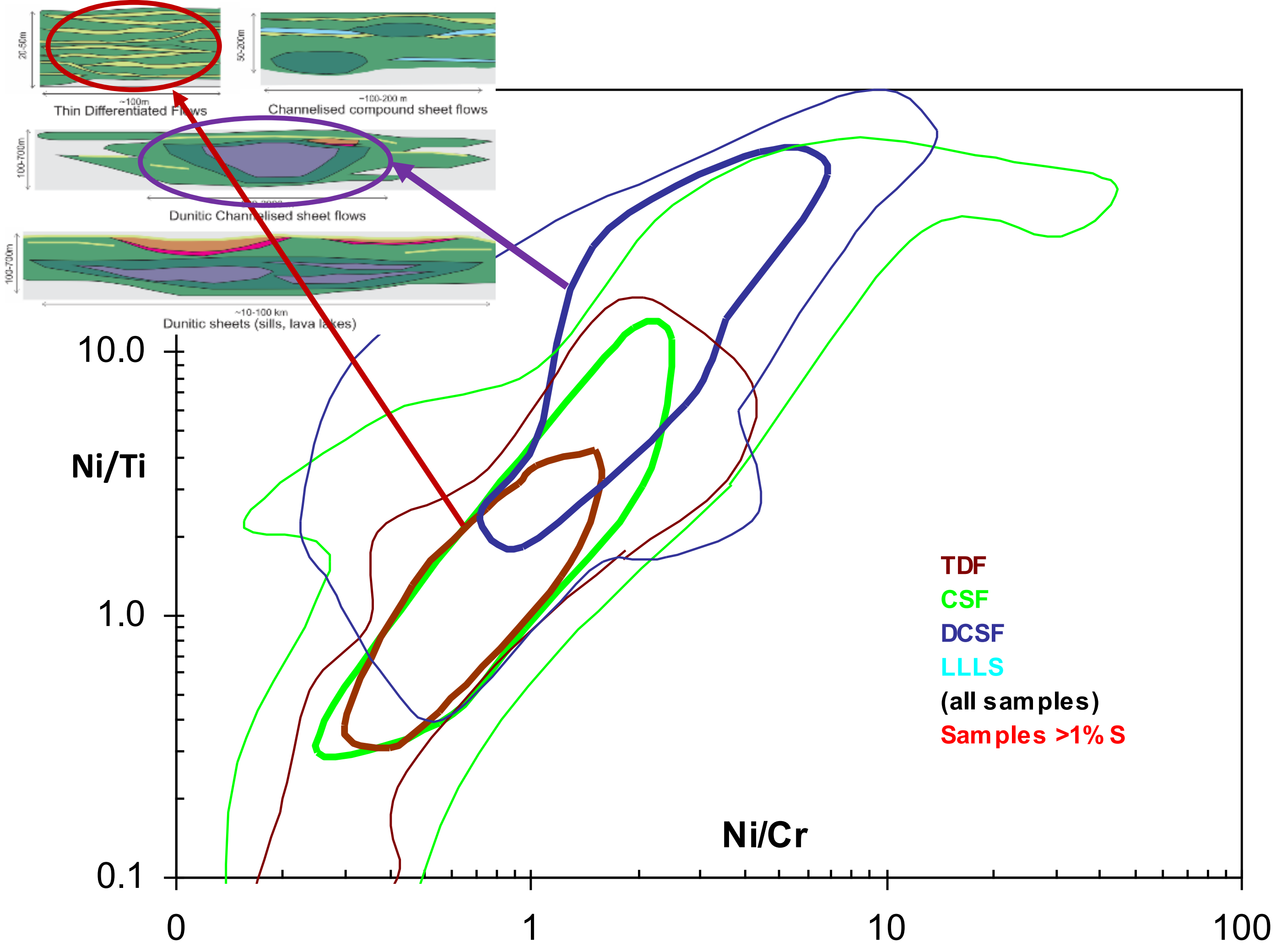


Brand, WMC
Barnes and Brand,1999
Barnes et al.,2013
Barnes et al.,2004

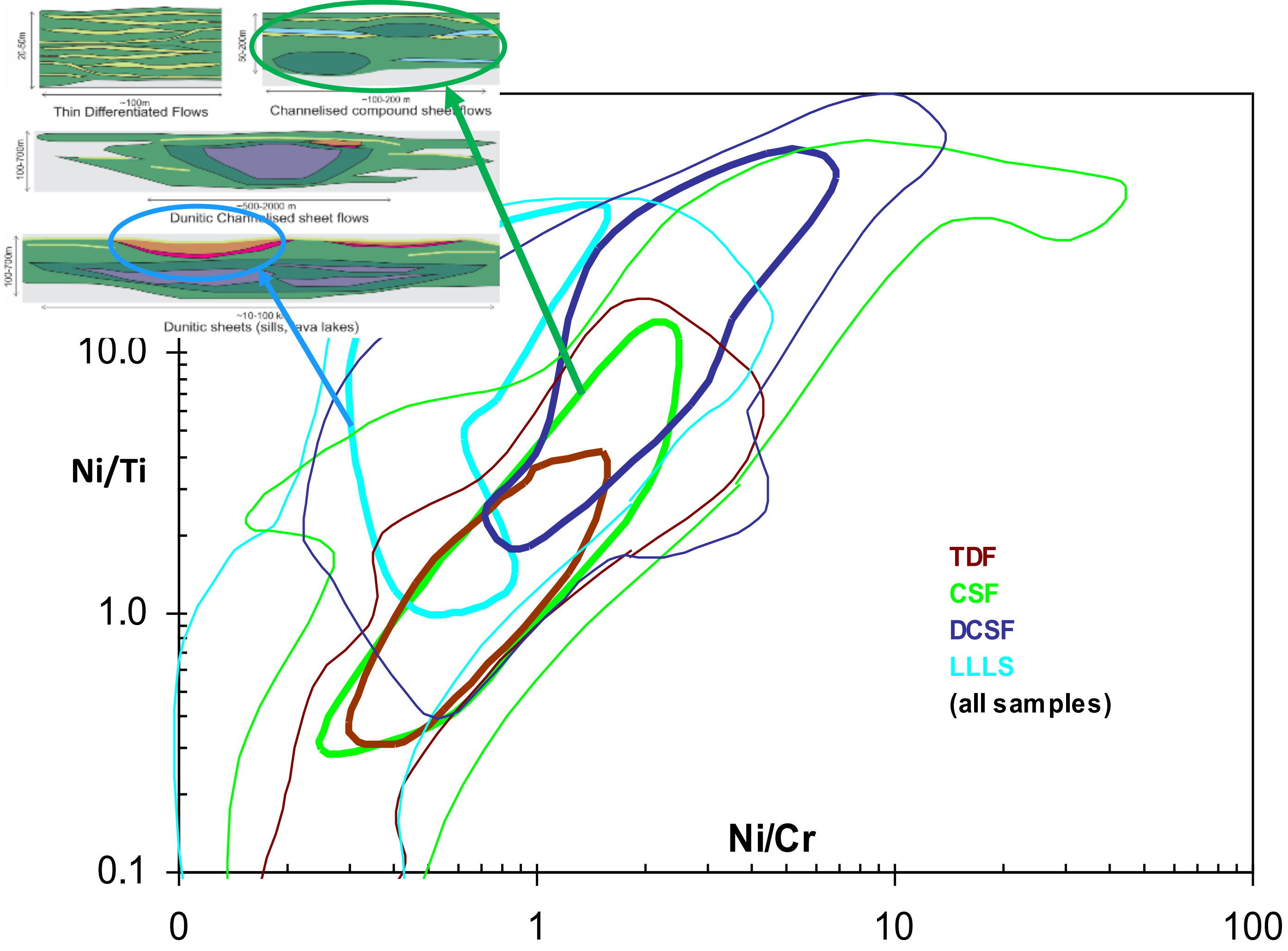
High Ni/Cr ratio in red



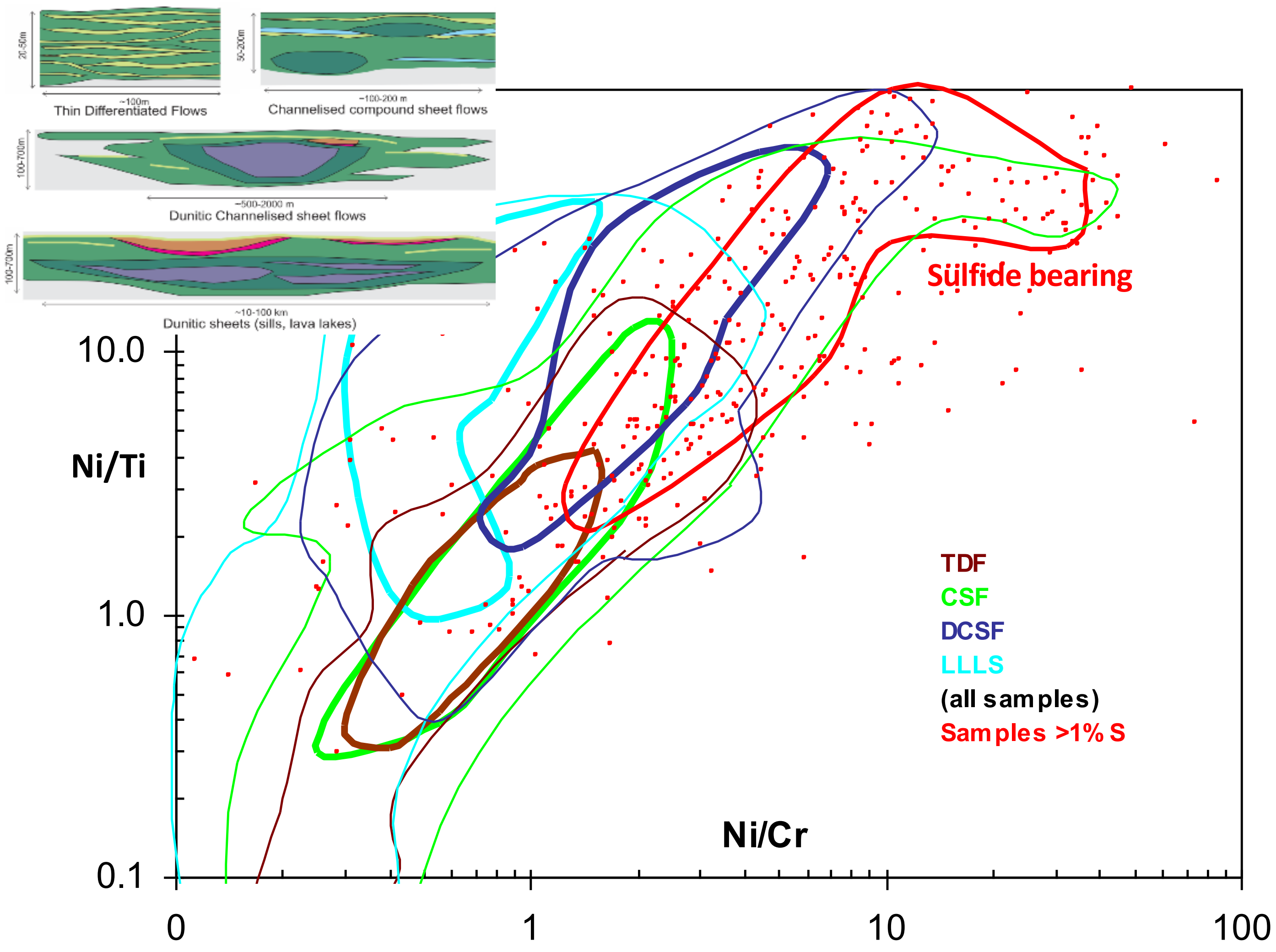
Thin Differentiated Flows
Channelised compound sheet flows
Dunitic Channelised sheet flows
Dunitic sheets (sills, lava lakes)
10.0
1.0
0.1
Ni/Ti
Ni/Cr
0
1
10
100
TDF
CSF
DCSF
LLLS
(all samples)
Samples >1% S

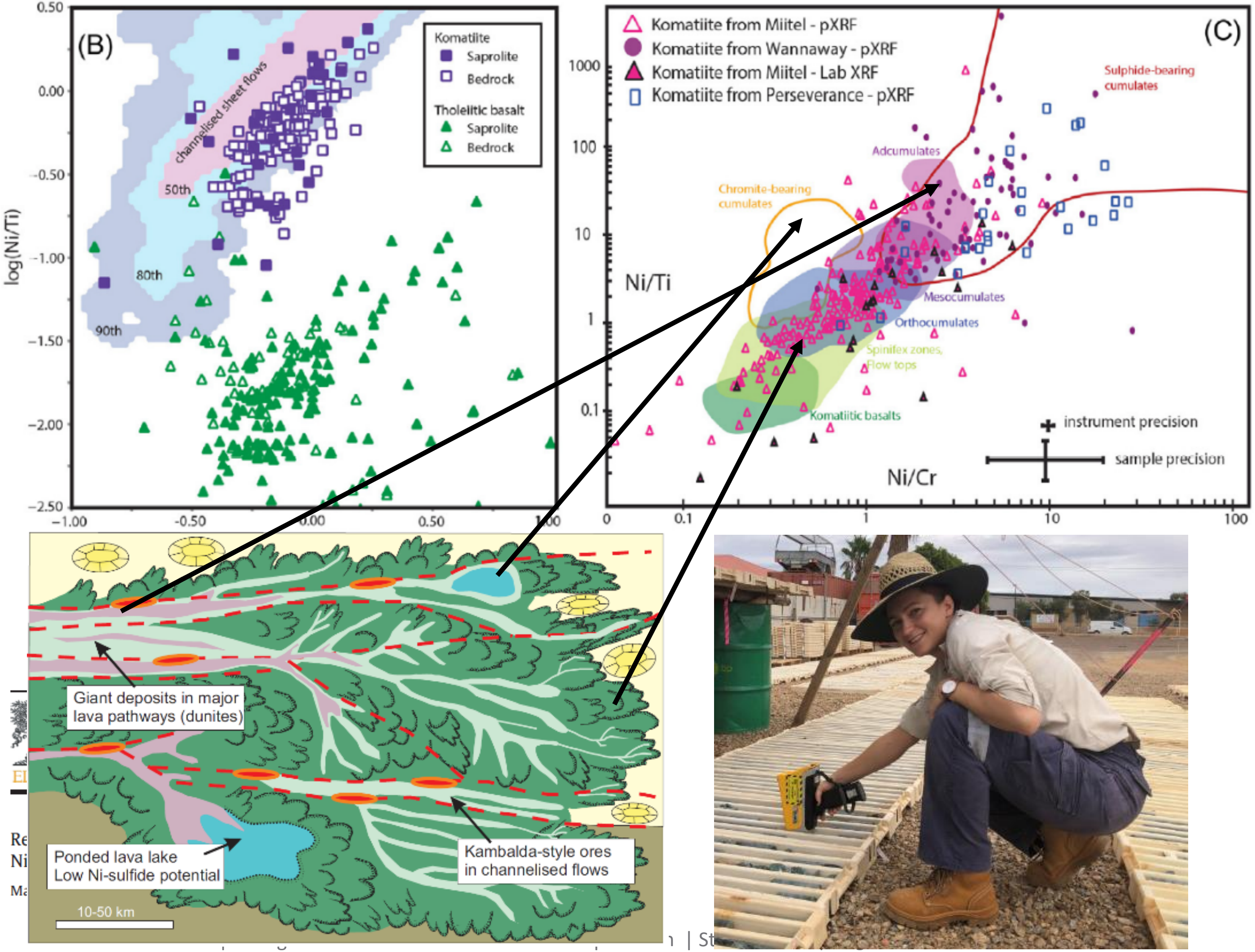


Thin Differentiated Flows
Channelised compound sheet flows
Dunitic Channelised sheet flows
Dunitic sheets (sills, lava lakes)
~100m
~100-200 m
~10-100 km
Ni/Ti
10.0
1.0
0.1
Ni/Cr
0
1
10
100
TDF
CSF
DCSF
LLLS
(all samples)
Samples >1% S



Thin Differentiated Flows
Channelised compound sheet flows
Dunitic Channelised sheet flows
Dunitic sheets (sills, lava lakes)
Ni/Ti
10.0
1.0
0.1
Ni/Cr
0
1
10
100
TDF
CSF
DCSF
LLLS
(all samples)


20-50m
~100m
Thin Differentiated Flows
50-200m
~100-200 m
Channelised compound sheet flows
100-700m
~500-2000 m
Dunitic Channelised sheet flows
100-700m
~10-100 km
Dunitic sheets (sills, lava lakes)
Sulfide bearing
10.0
1.0
0.1
Ni/Ti
Ni/Cr
0
1
10
100
TDF
CSF
DCSF
LLLS
(all samples)
Samples >1% S



(B)
log(Ni/Ti)
channelised sheet flows
50th
80th
90th
Komatiite
Saprolite
Bedrock
Tholeiitic basalt
Saprolite
Bedrock
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-1.00
-0.50
0.00
0.50
1.00
(C)
Komatiite from Miitel - pXRF
Komatiite from Wannaway - pXRF
Komatiite from Miitel - Lab XRF
Komatiite from Perseverance - pXRF
Sulphide-bearing cumulates
Adcumulates
Chromite-bearing cumulates
Mesocumulates
Orthocumulates
Spinifex zones, Flow tops
Komatiitic basalts
instrument precision
sample precision
Ni/Ti
Ni/Cr
1000
100
10
1
0.1
0
0.1
1
10
100
Giant deposits in major lava pathways (dunites)
Ponded lava lake
Low Ni-sulfide potential
Kambalda-style ores in channelised flows
10-50 km

Rock and mineral chemistry to detect orebodies

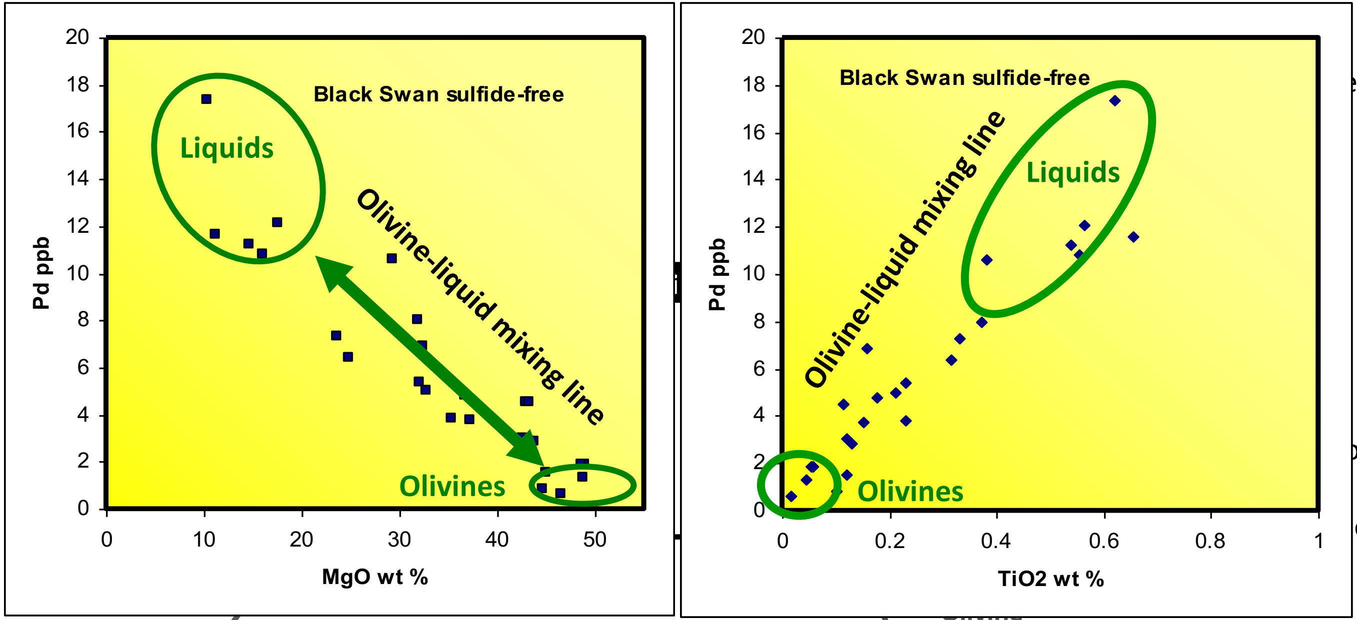
- Detect favourable hosts
- Detect distal footprints of ore formation – e.g. PGE, Ni depletion
- Detect vectors towards ore – trace PGE enrichments/depletions
- Distal resistate mineral indicators – Ni and Ru in chromite

For whole rock major elements: need to correct for volatile addition (correct to 100% H2O-CO2 free) and for sulfide component.

Deposit Scale

5 **Subtle positive and negative anomalies in PGE (Pd-Pt in particular) in komatiites host units**

Heggie et al., 2012
Barnes et al., 2013

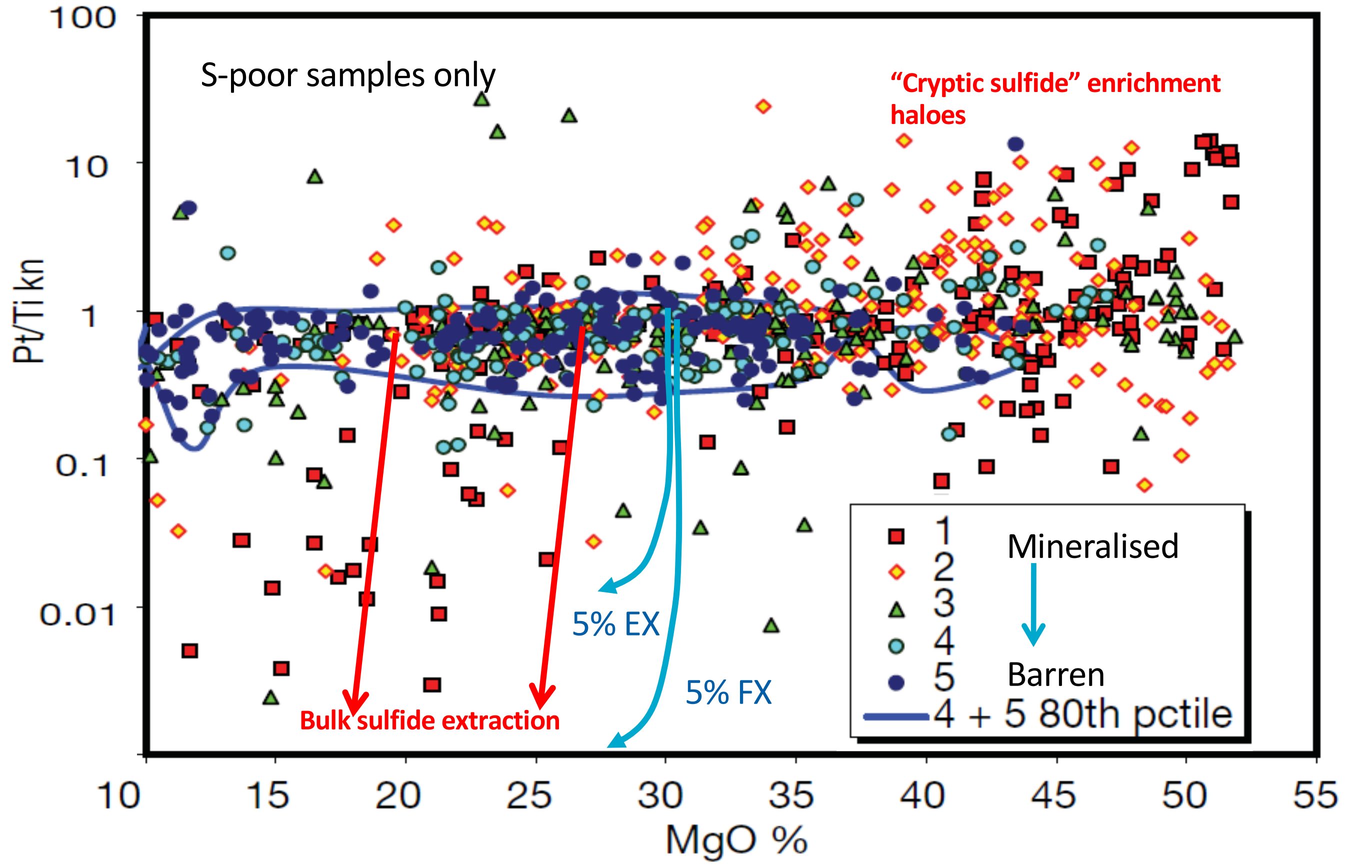


Thin Differentiated flows

rich cumulates

Use ratios Pt/Ti, Pd/Ti to take out the effect of olivine fractionation

Komatiites and komatiitic basalts

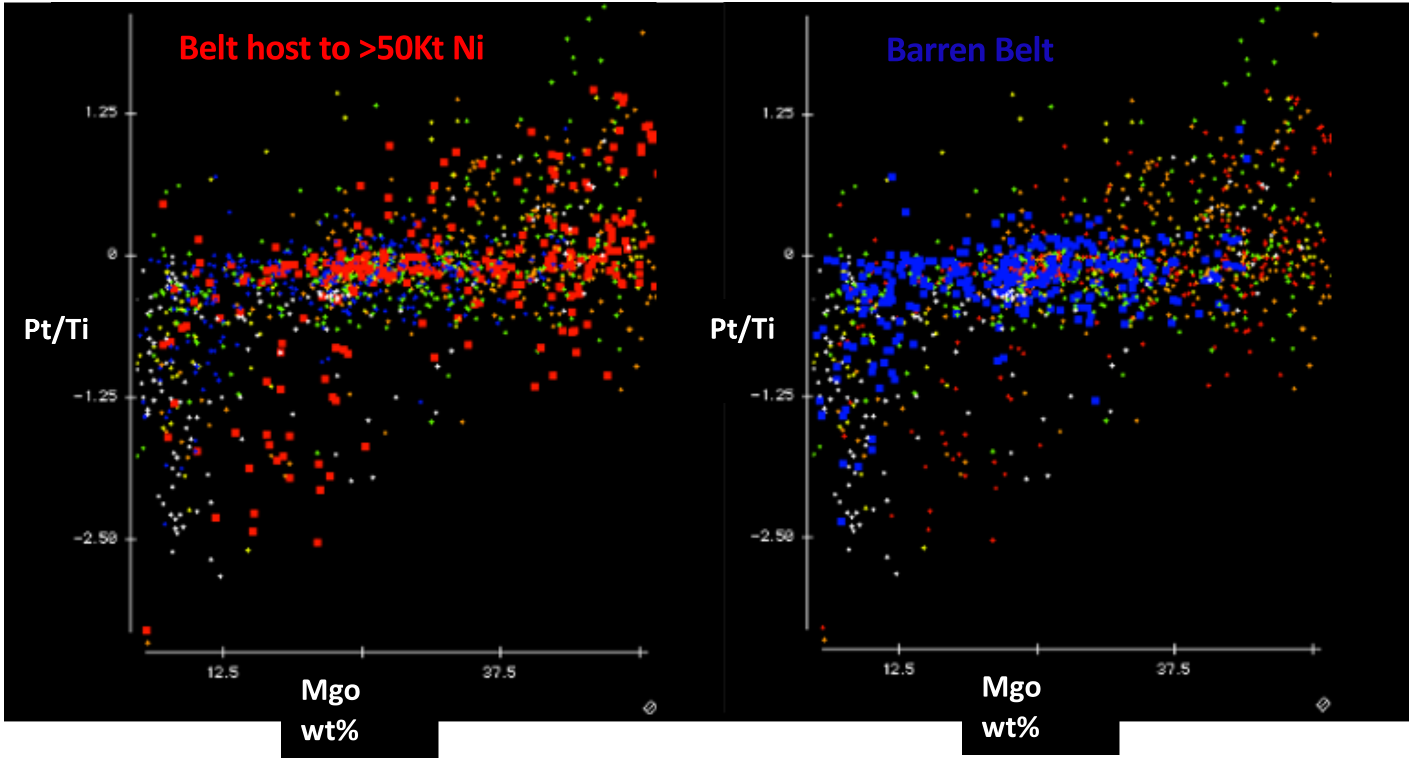


Very small amount of sulfide extraction has a very big depletion effect

Greenstone belt scale

⑤ **Subtle positive and negative anomalies in PGE (Pd-Pt in particular) in komatiites host units**

Heggie et al., 2012
Barnes et al., 2013

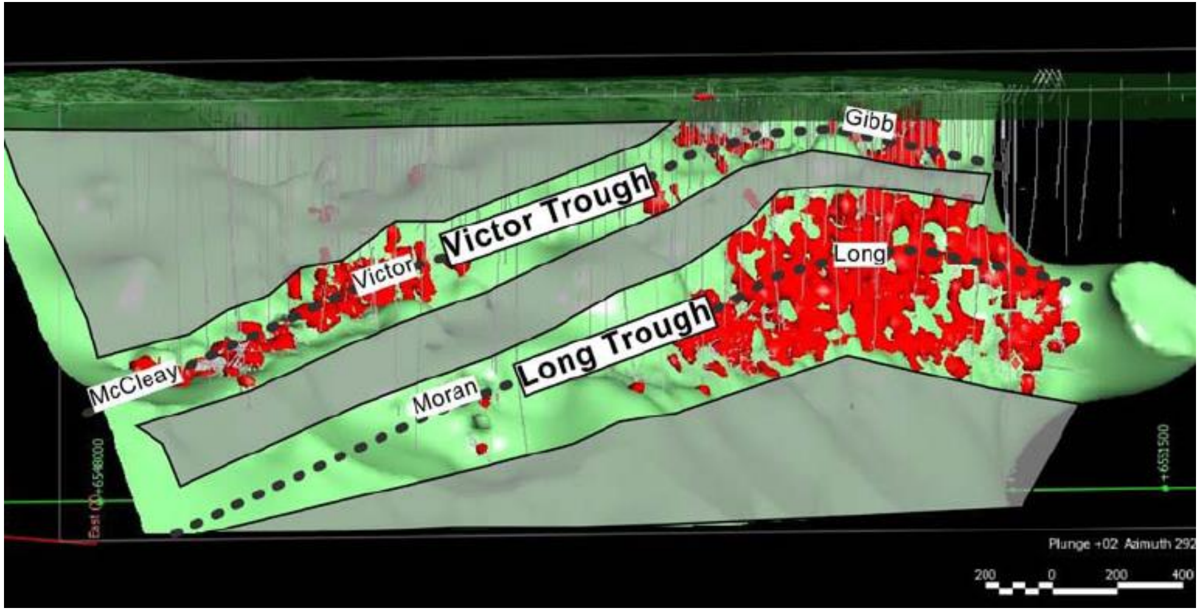


Deposit Scale

⑤ **Subtle positive and negative anomalies in PGE (Pd-Pt in particular) in komatiites host units (remember that the PGE content of komatiites will depend on their age)**

Heggie et al., 2012
Barnes et al., 2013

→ Example at Long Victor : subtle anomalies extending up to 400m away from the massive sulphides



Deposit Scale

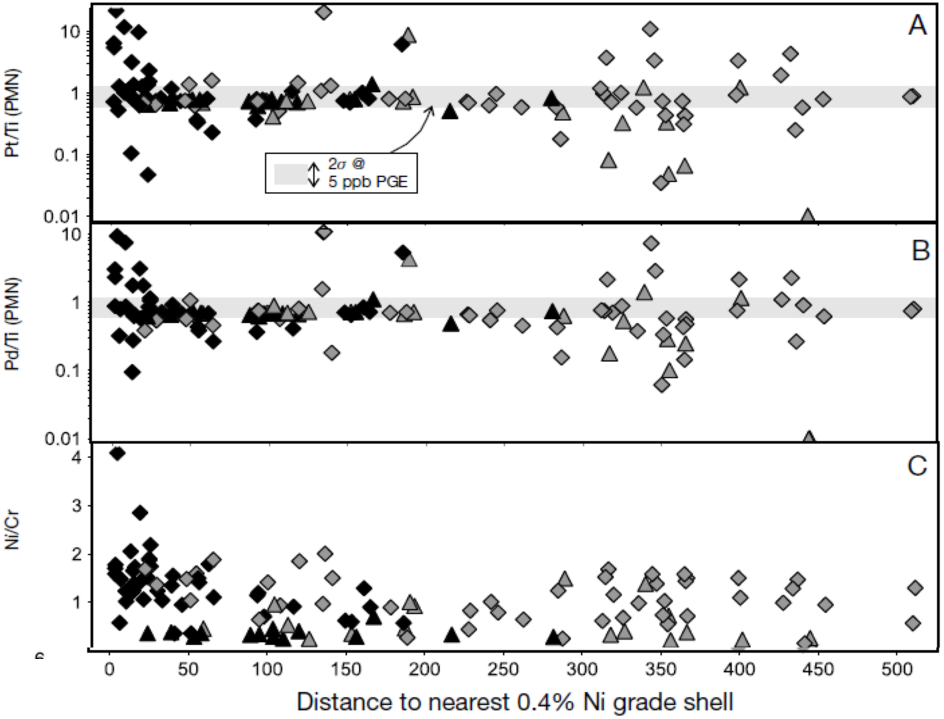
5 **Subtle positive and negative anomalies in PGE (Pd-Pt in particular) in komatiites host units**

Heggie et al., 2012
Barnes et al., 2013

Whole rock chemistry in relation to distance from ore shell

▲ ◆ Channel zones

△ ◇ Flank zones

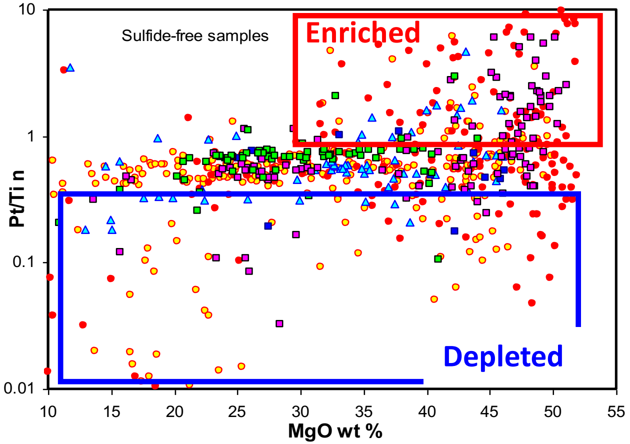


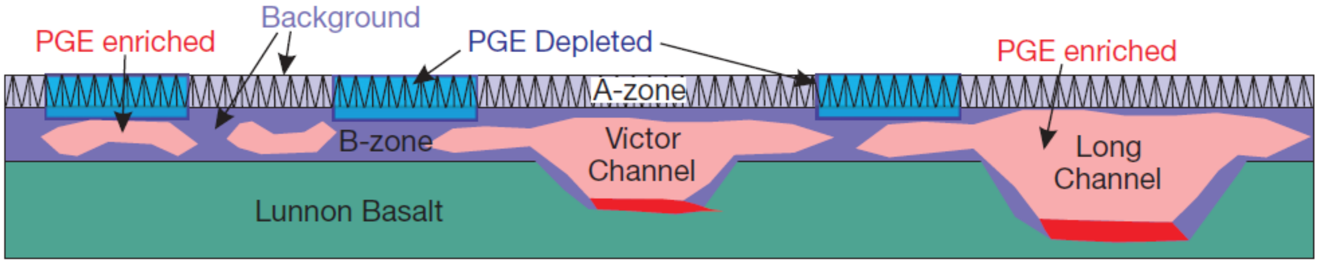
Deposit Scale

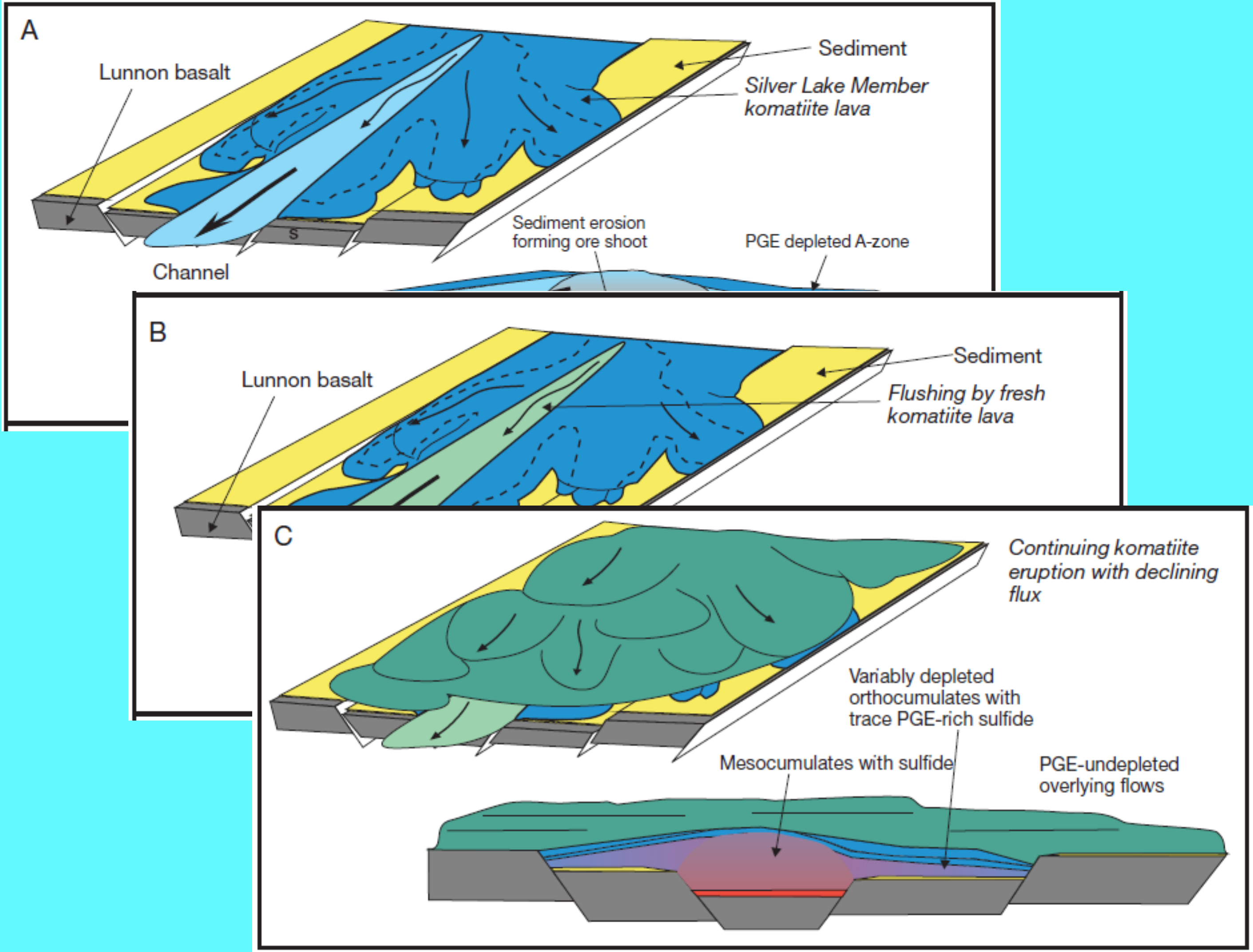
⑤ **Subtle positive and negative anomalies in PGE (Pd-Pt in particular) in komatiites host units**

Heggie et al., 2012
Barnes et al., 2013

→ *Example at Long Victor:*

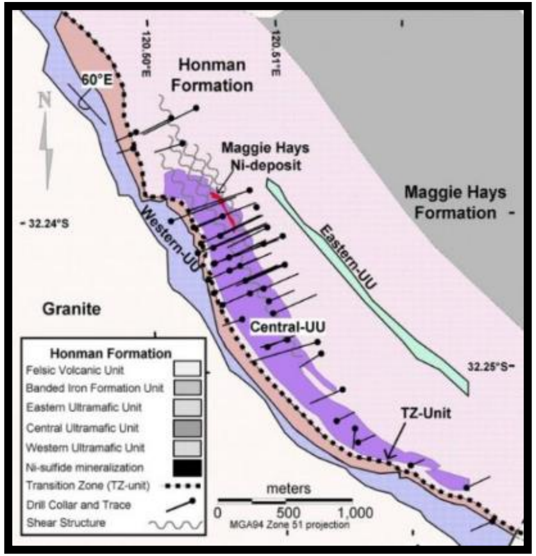




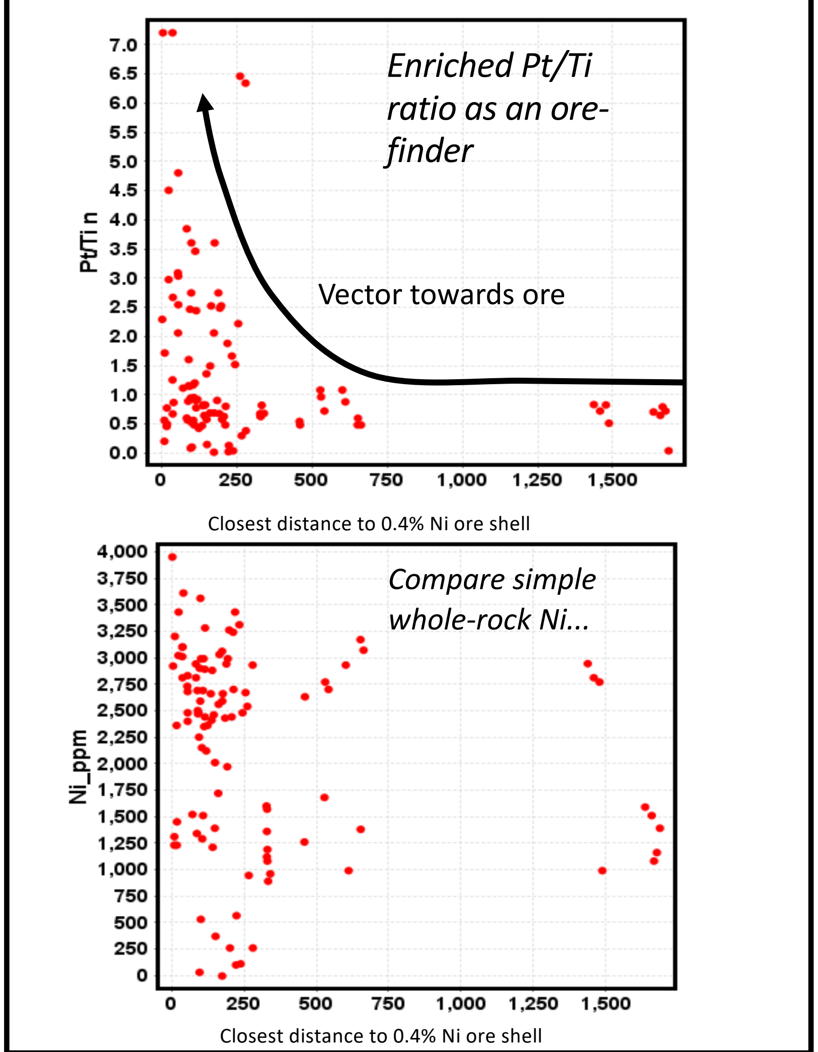

A
Lunnon basalt
Sediment
Silver Lake Member
komatiite lava
S
Sediment erosion
forming ore shoot
PGE depleted A-zone
Channel
B
Lunnon basalt
Sediment
Flushing by fresh
komatiite lava
C
Continuing komatiite
eruption with declining
flux
Variably depleted
orthocumulates with
trace PGE-rich sulfide
Mesocumulates with sulfide
PGE-undepleted
overlying flows

Lithogeochemical vectoring, Maggie Hays deposit, Lake Johnston Belt, WA

The ratio Pt/Ti provides a much more effective and recognisable geochemical halo around Ni sulfide orebodies than simple Ni concentration, which has a wide variability in the background host rock. Pt/Ti anomaly extends ~250 m from orebody (defined by 0.4% Ni ore shell).
Data from Heggie et al., 2012, Economic Geology.



(Heggie et al,in prep)



Sampling probability

Kambalda example

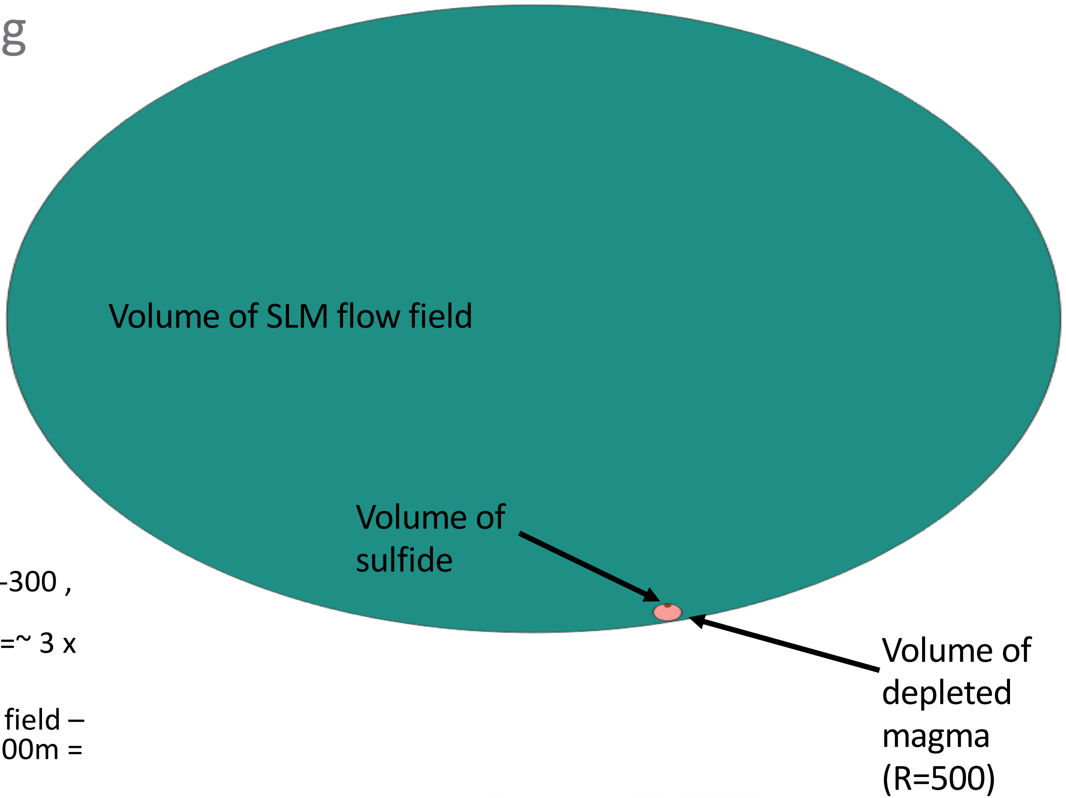
SLM contains ~ 1.5 mtonnes contained Ni, average tenor around 15% in sulfide, = ~ 10^7 tonnes sulfide

Typical R factor range 100-500 , implies volume of magma involved in ore formation =~ 3×10^8 to 2×10^9

Estimated volume of flow field – SLM – 100 km x 50 km x 200m = 10^{12} m^3

Depleted magma represents ~ .03 to .2 % of total volume of flow field.

The sampling problem...



- Typical R factor range 100-300 , implies volume of magma involved in ore formation =~ 3 x 10^8 to 2 x 10^9
- Estimated volume of flow field – SLM – 100 km x 50 km x 200m = 10^{12} m^3
- Depleted magma represents ~ .03 to .17 % of total volume of flow field.