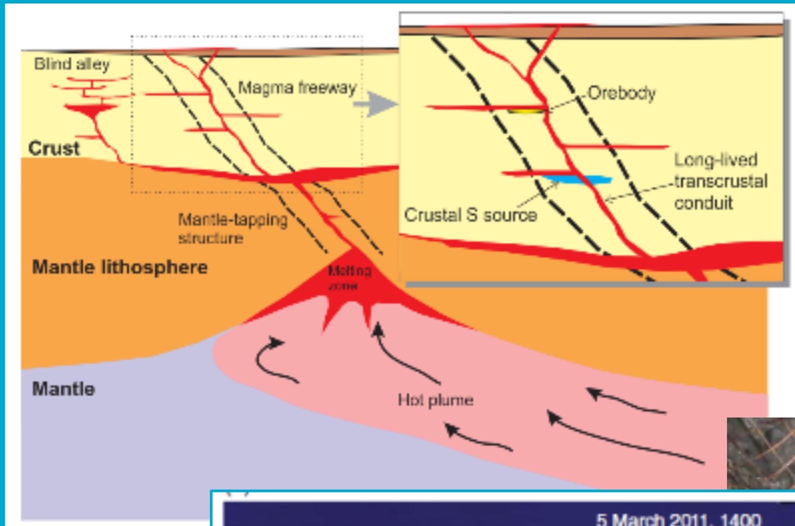
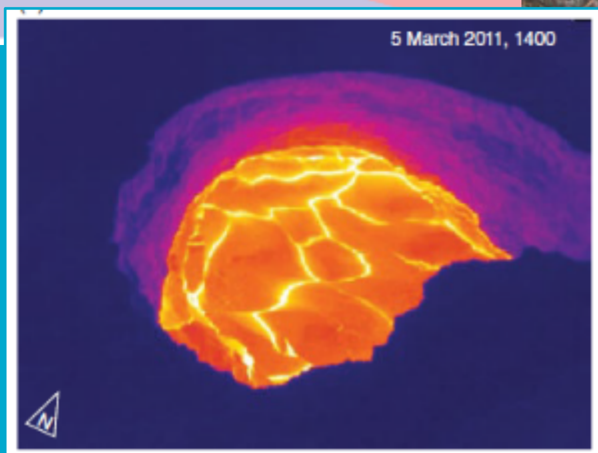
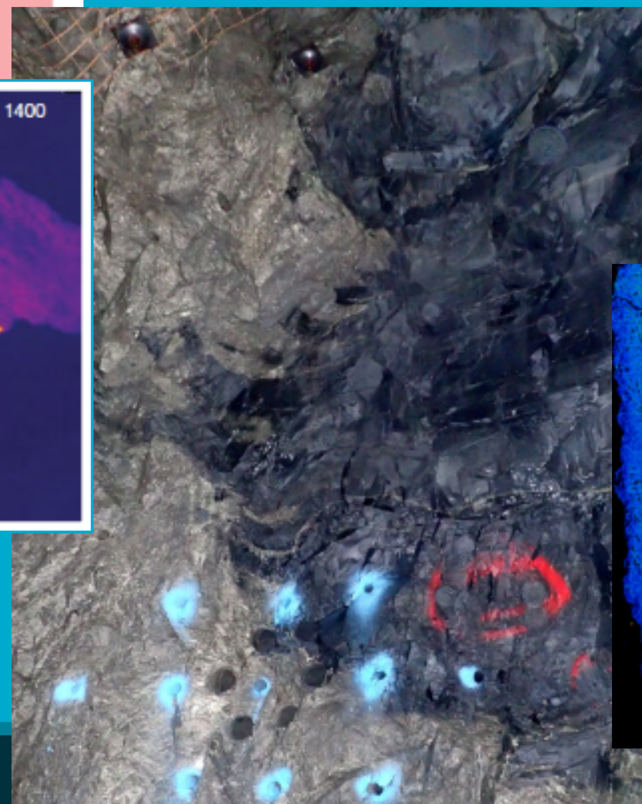
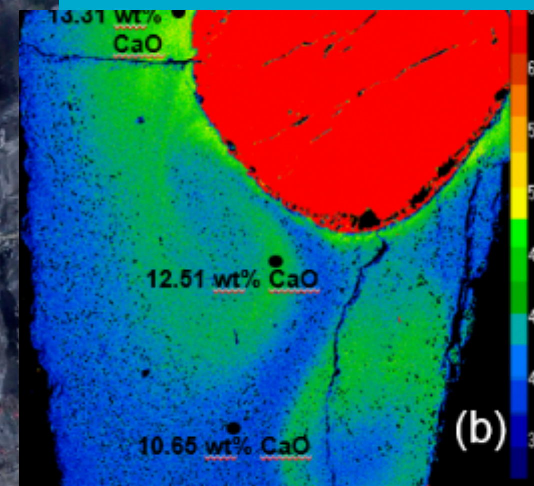








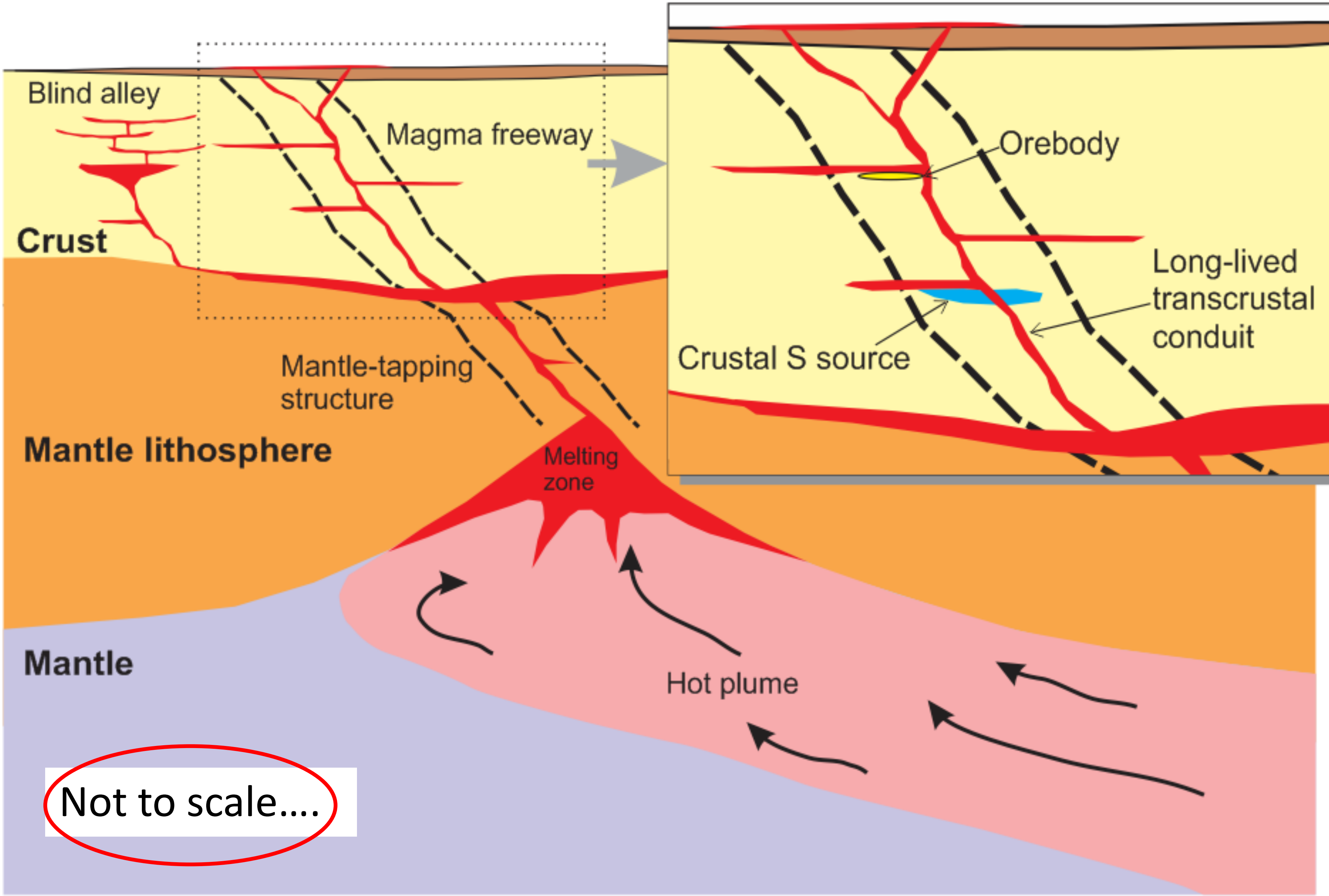
Length and time scales and genetic models for magmatic Ni-Cu sulphide mineral systems

Barnes and Robertson
Geoscience Frontiers 2018

CSIRO MINERAL RESOURCES
www.csiro.au

Sudbury Magmatic Ore Deposits Short Course
April 2018

Steve Barnes
steve.barnes@csiro.au

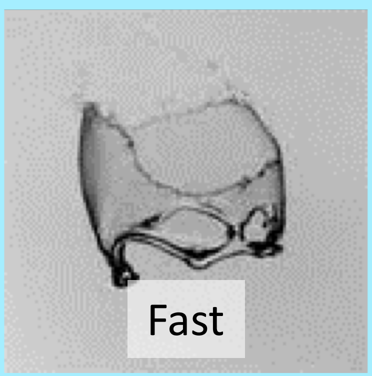

Blind alley
Magma freeway
Crust
Mantle-tapping structure
Mantle lithosphere
Melting zone
Mantle
Hot plume
Orebody
Long-lived transcrustal conduit
Crustal S source
Not to scale….


Dynamic physical systems
• 1000s of km scale
• Focus mass, momentum and heat into one place
• Multi-scale processes: fast processes at small scale, slow processes at large scales

Timescales and lengthscales

HARES

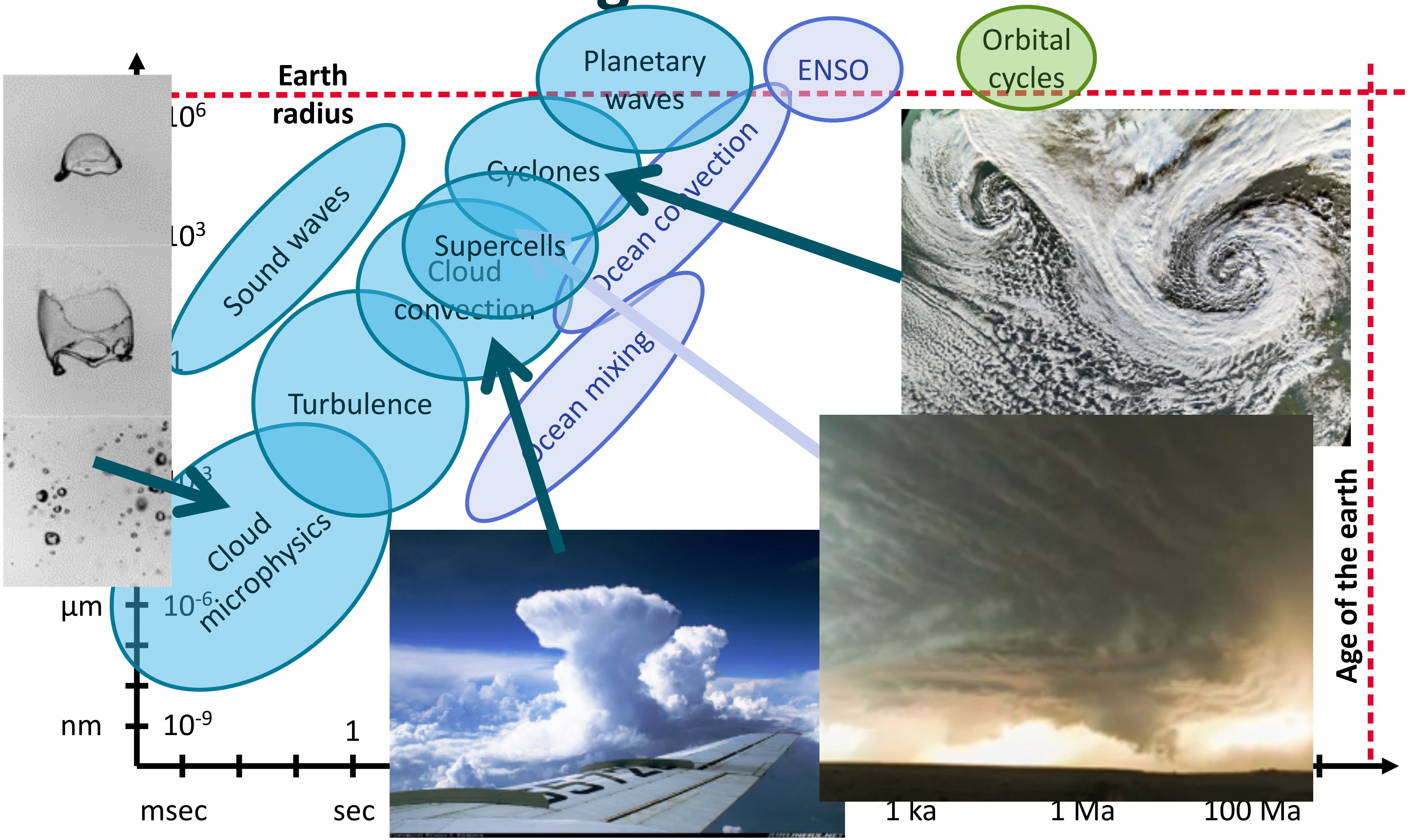
TORTOISES

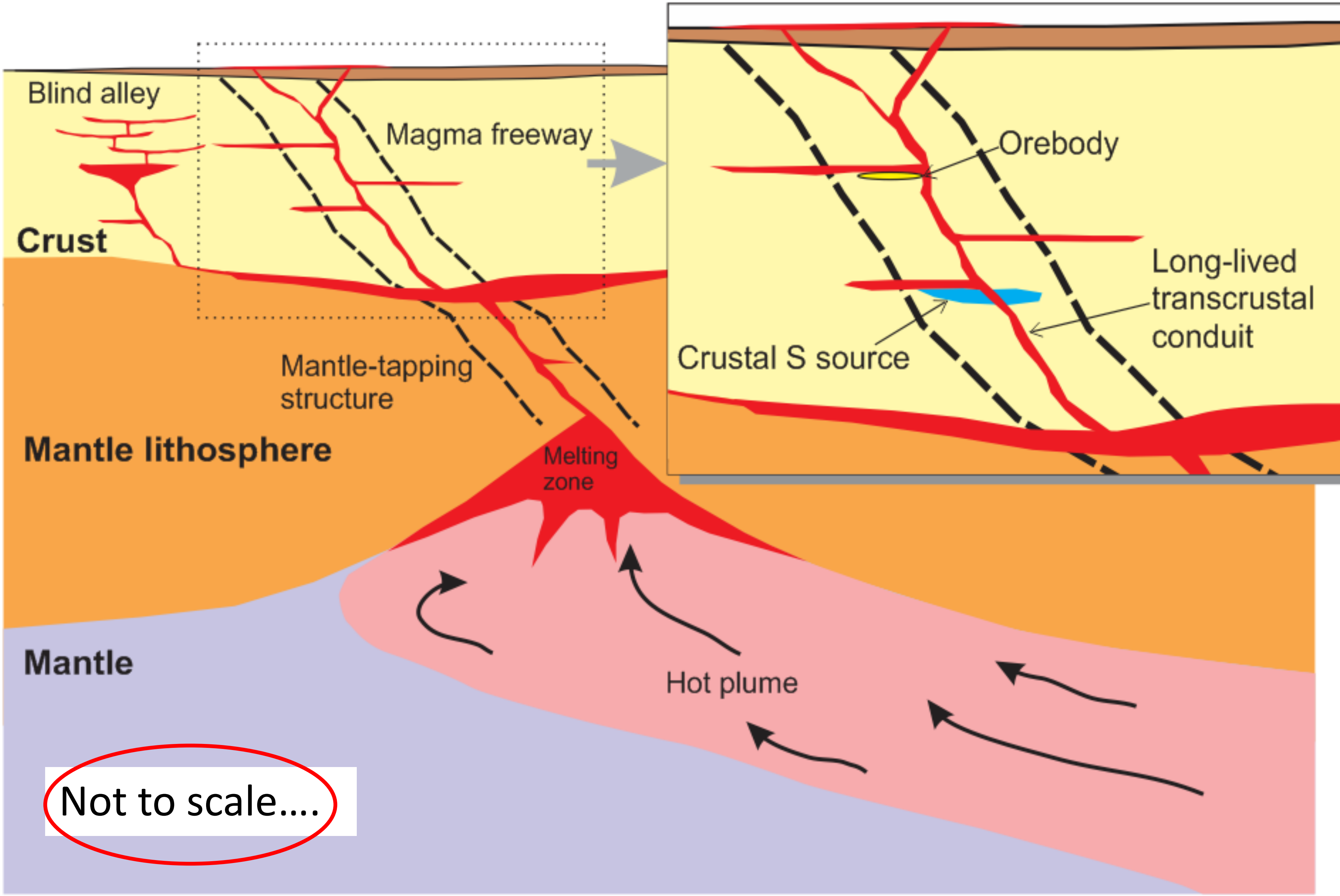


Fast processes operating at small scales

Slow processes operating at large scales

Timescales and lengthscales




Blind alley
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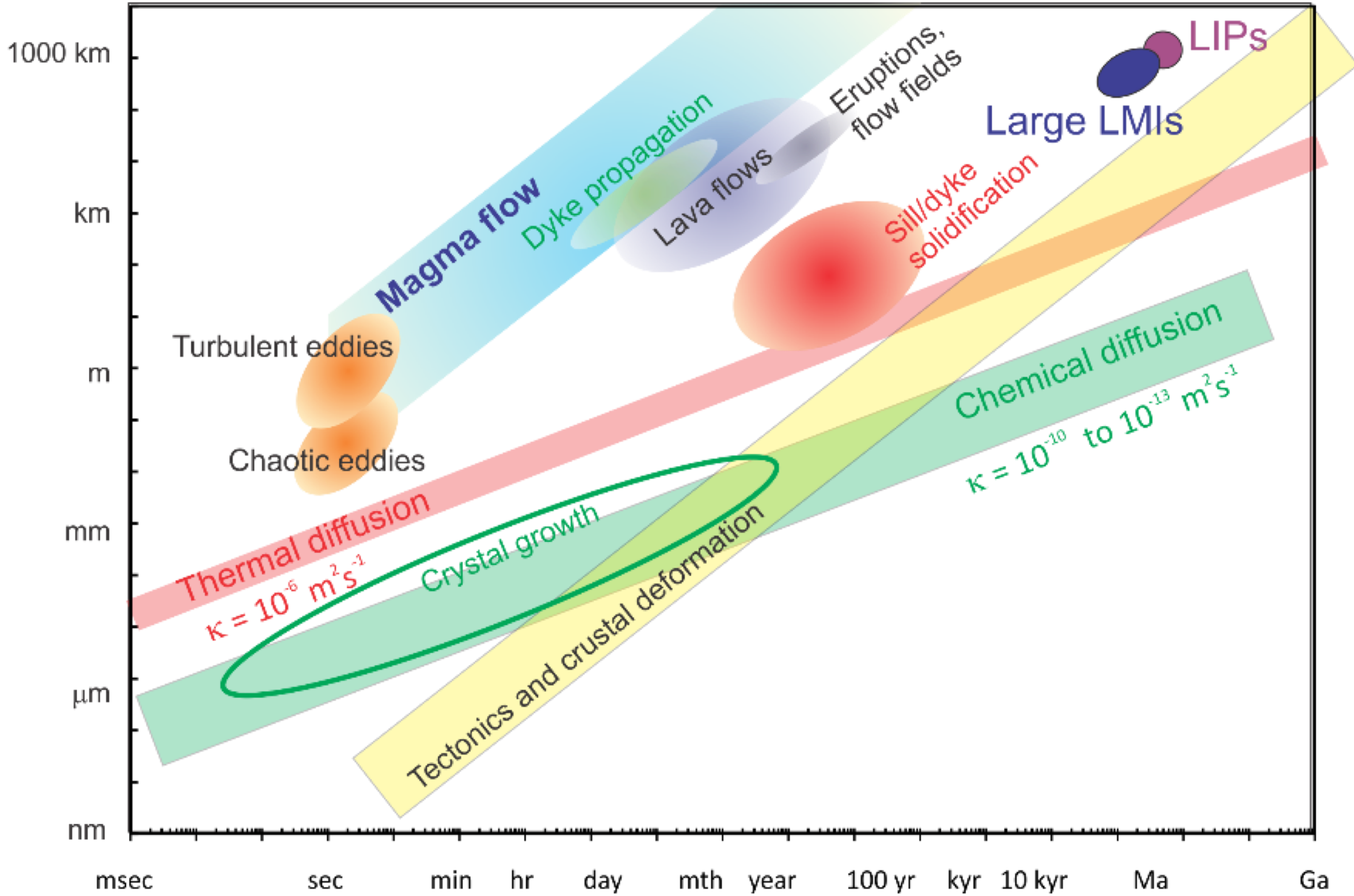
Not to scale….



1000 km
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day
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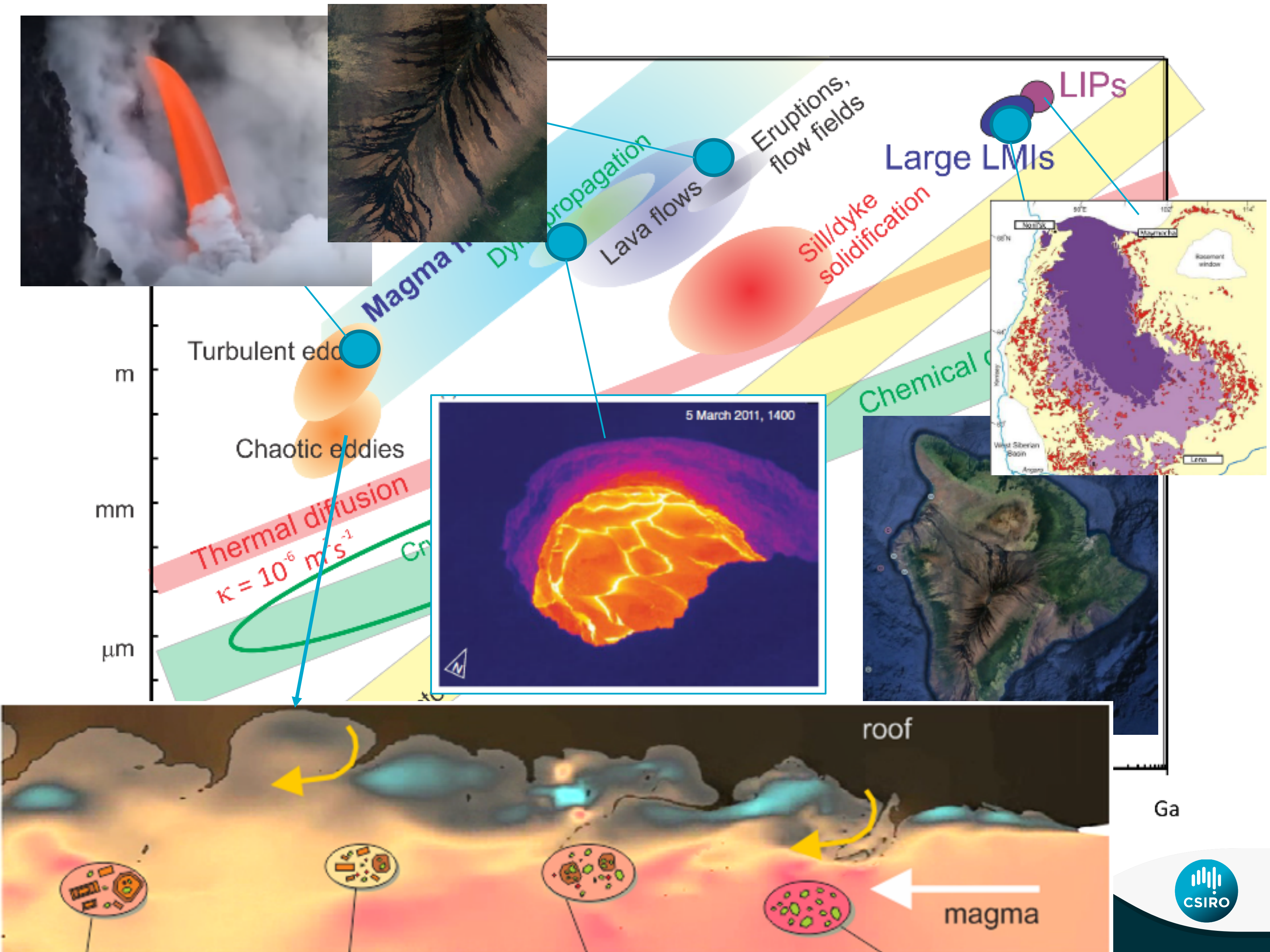
year
100 yr
kyr
10 kyr
Ma
Ga
Magma flow
Dyke propagation
Lava flows
Eruptions, flow fields
LIPs
Large LMIs
Sill/dyke solidification
Turbulent eddies
Chaotic eddies
Thermal diffusion
κ = 10^-6 m^2 s^-1
Crystal growth
Tectonics and crustal deformation
Chemical diffusion
κ = 10^-10 to 10^-13 m^2 s^-1



LIPs
Large LMIs
Eruptions,
flow fields
Lava flows
Dy propagation
Magma
Sill/dyke
solidification
Turbulent edd
Chaotic eddies
Thermal diffusion
κ = 10⁻⁶ m²s⁻¹
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5 March 2011, 1400
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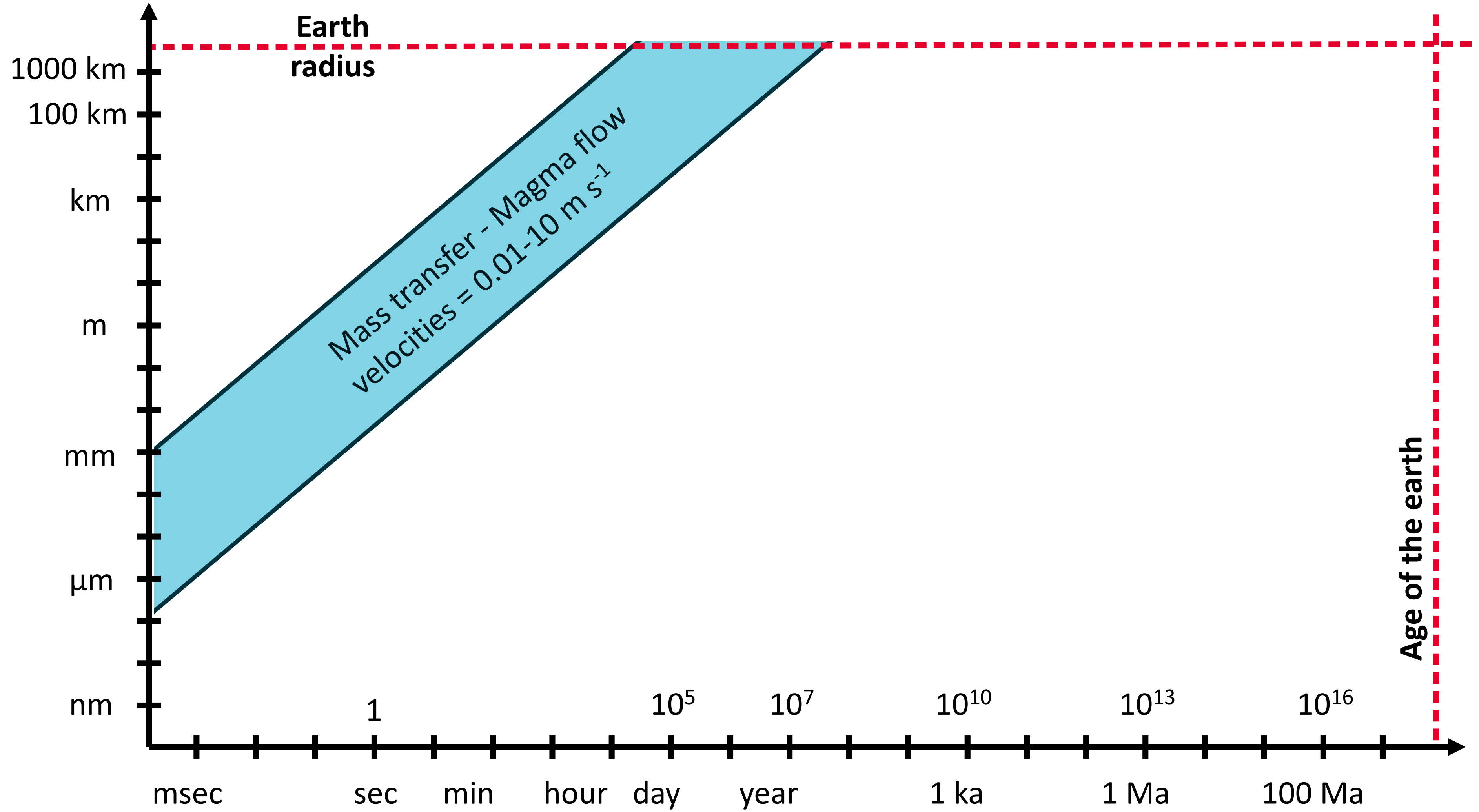
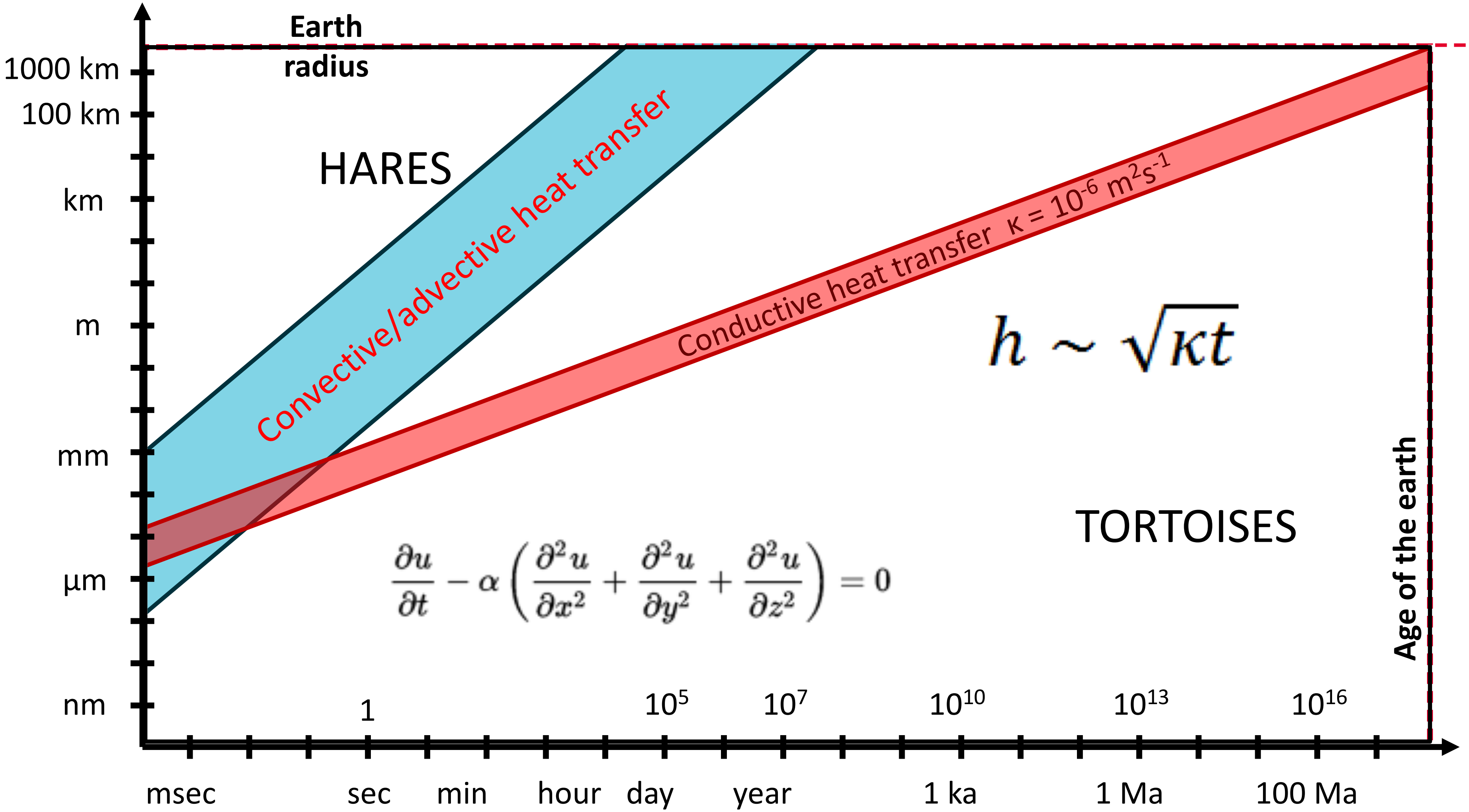
roof
magma
CSIRO

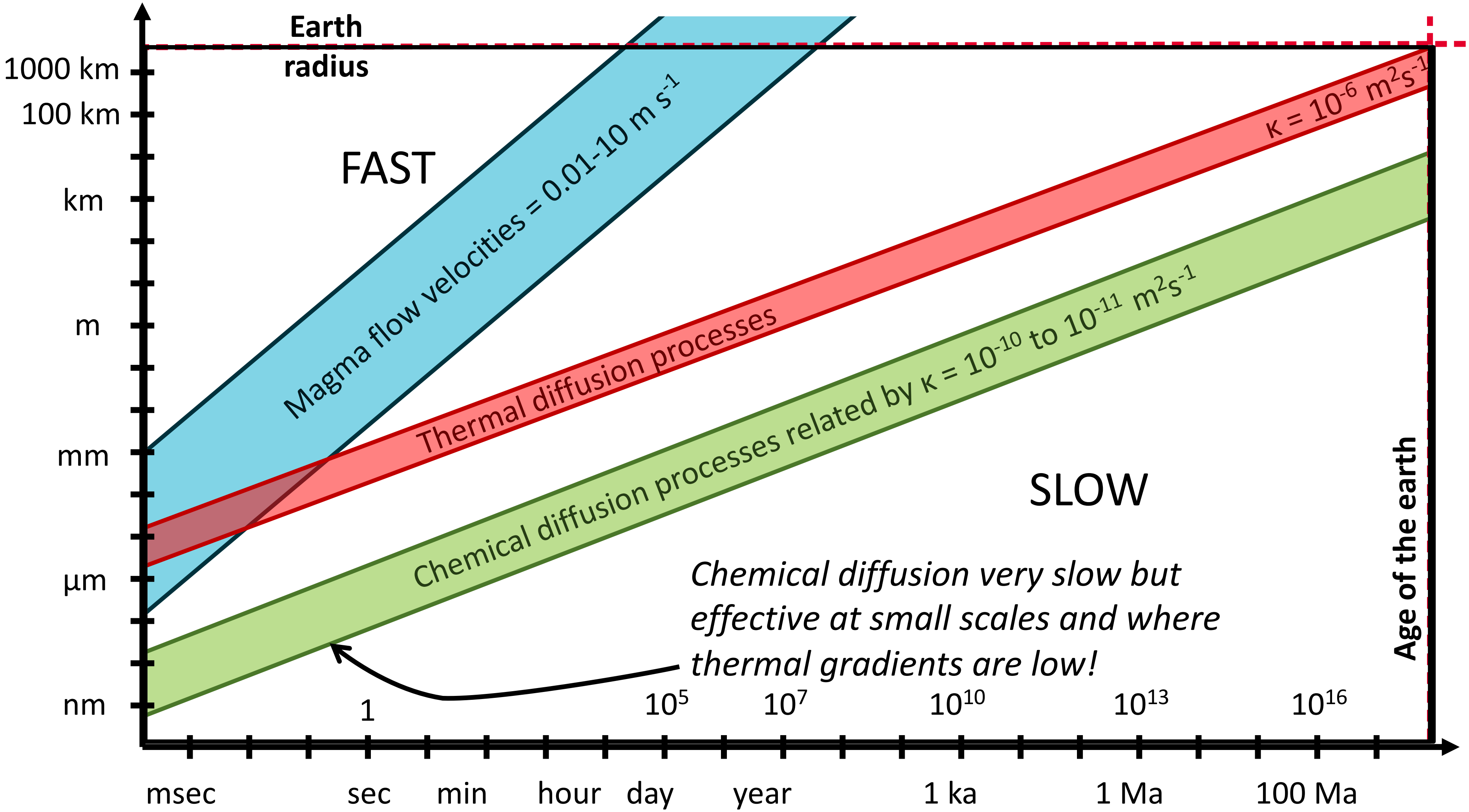
Scales of magmatic processes



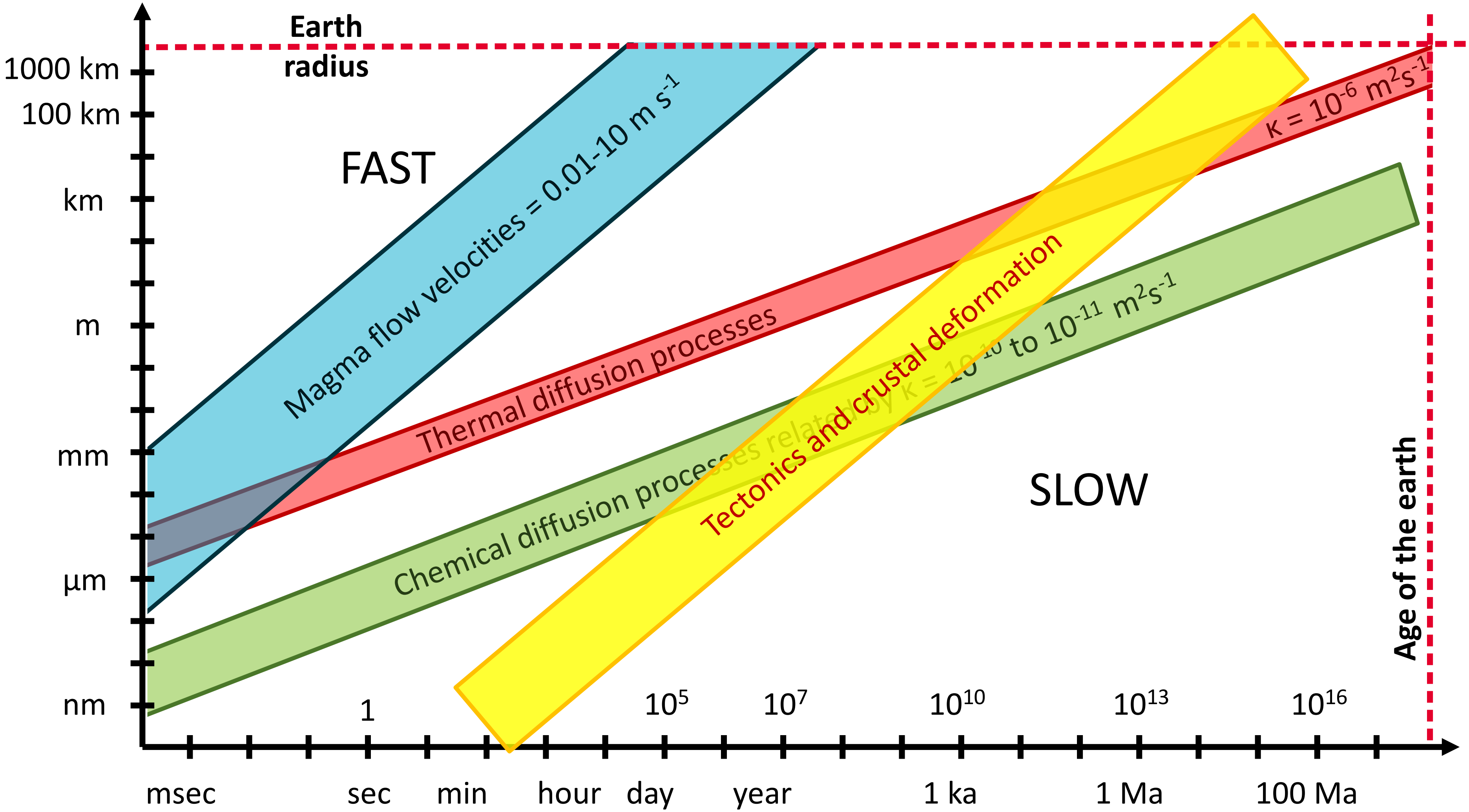
Heat transfer

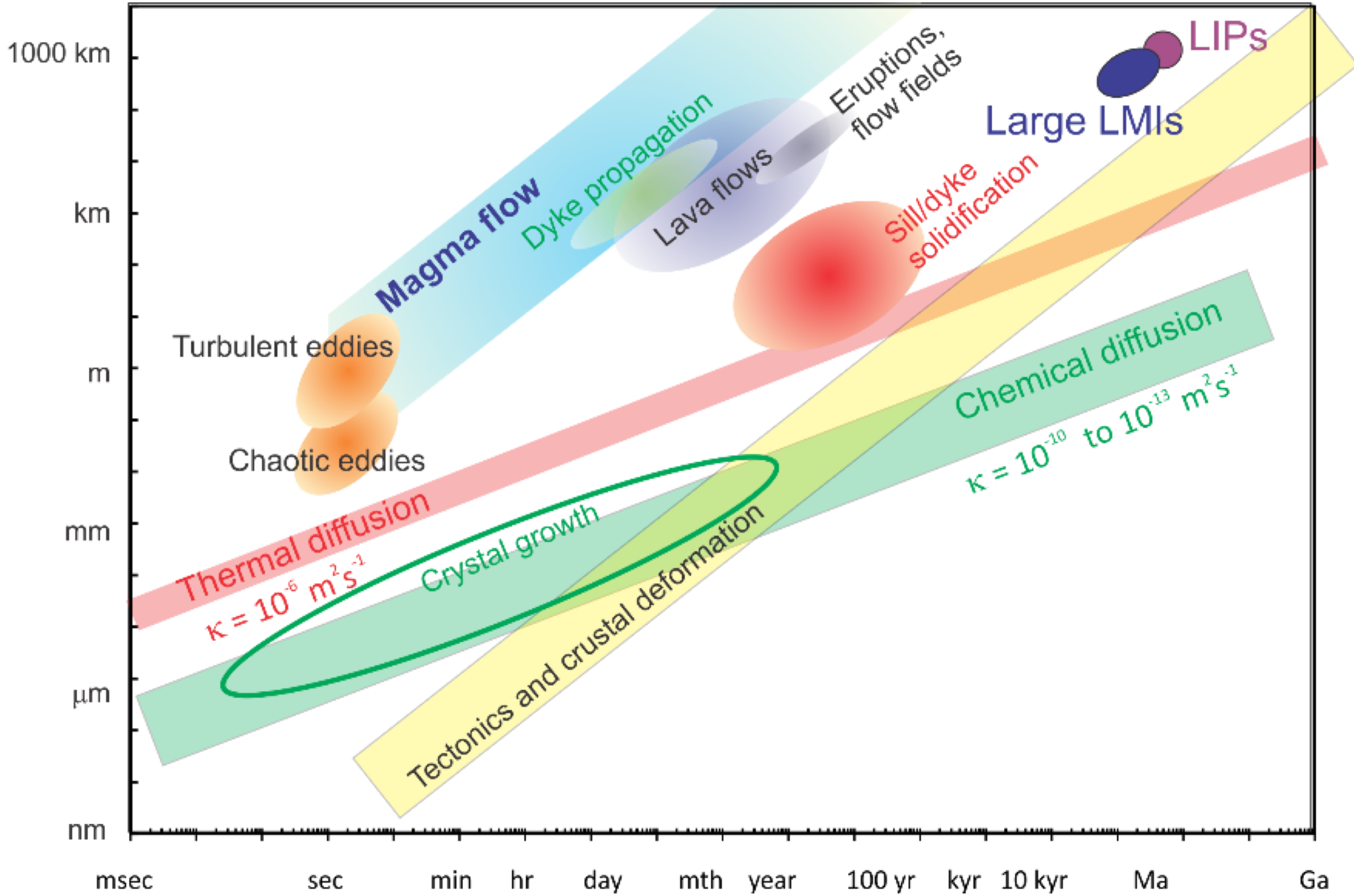


Fast and Slow processes



Scales of magmatic processes





1000 km
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min
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day
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Magma flow
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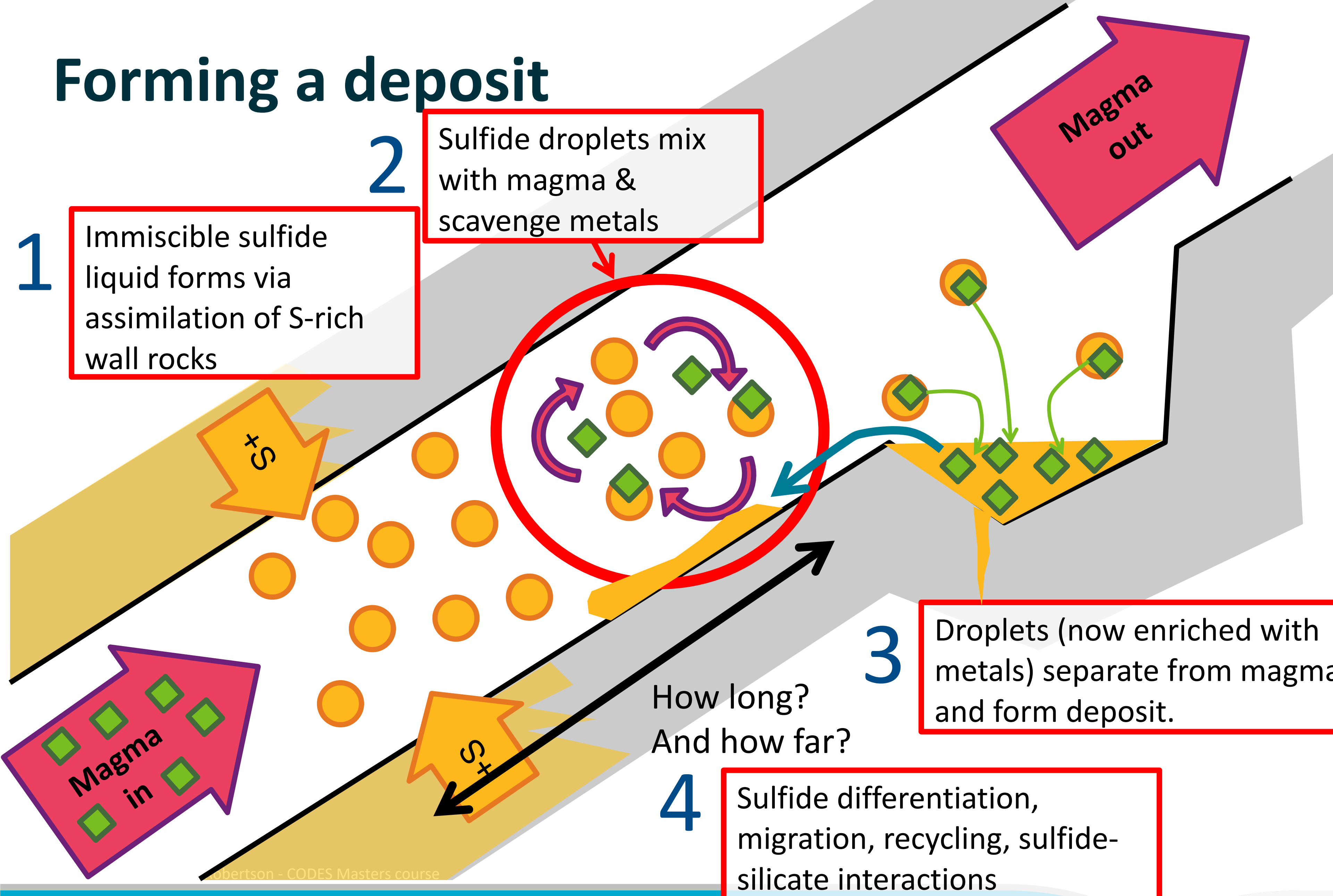
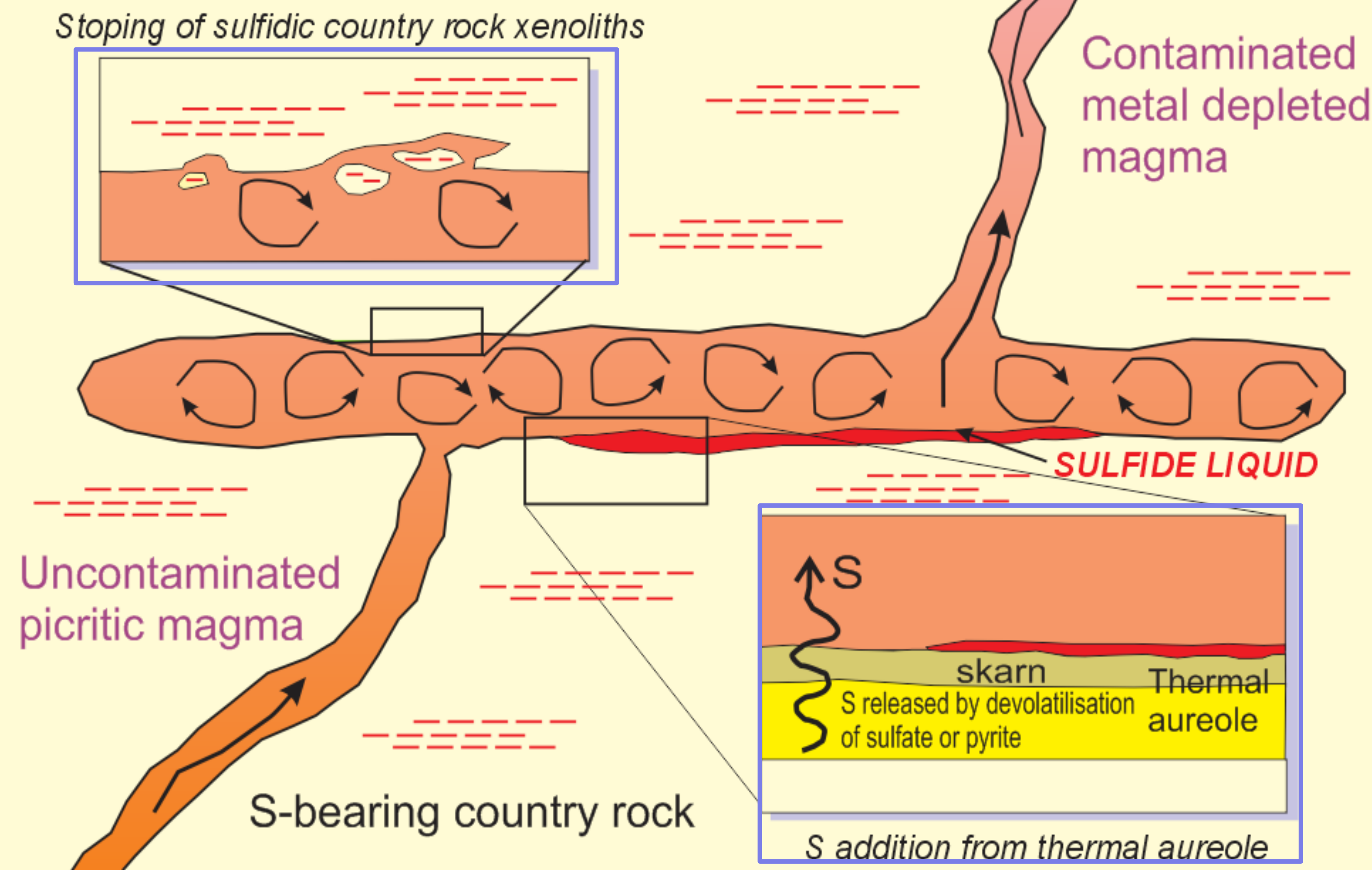
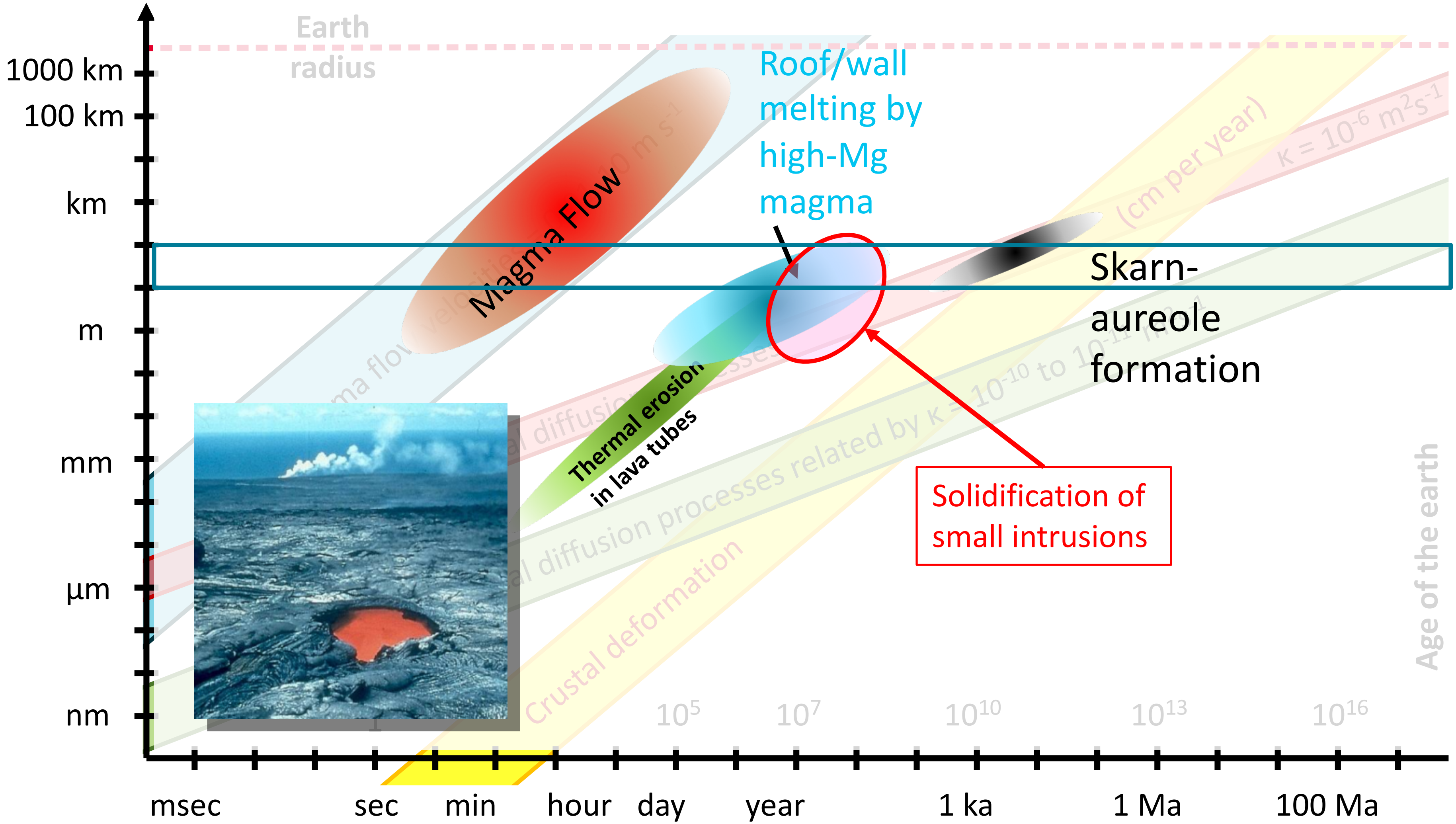
Forming a deposit



How do we get the extra S into the magma?

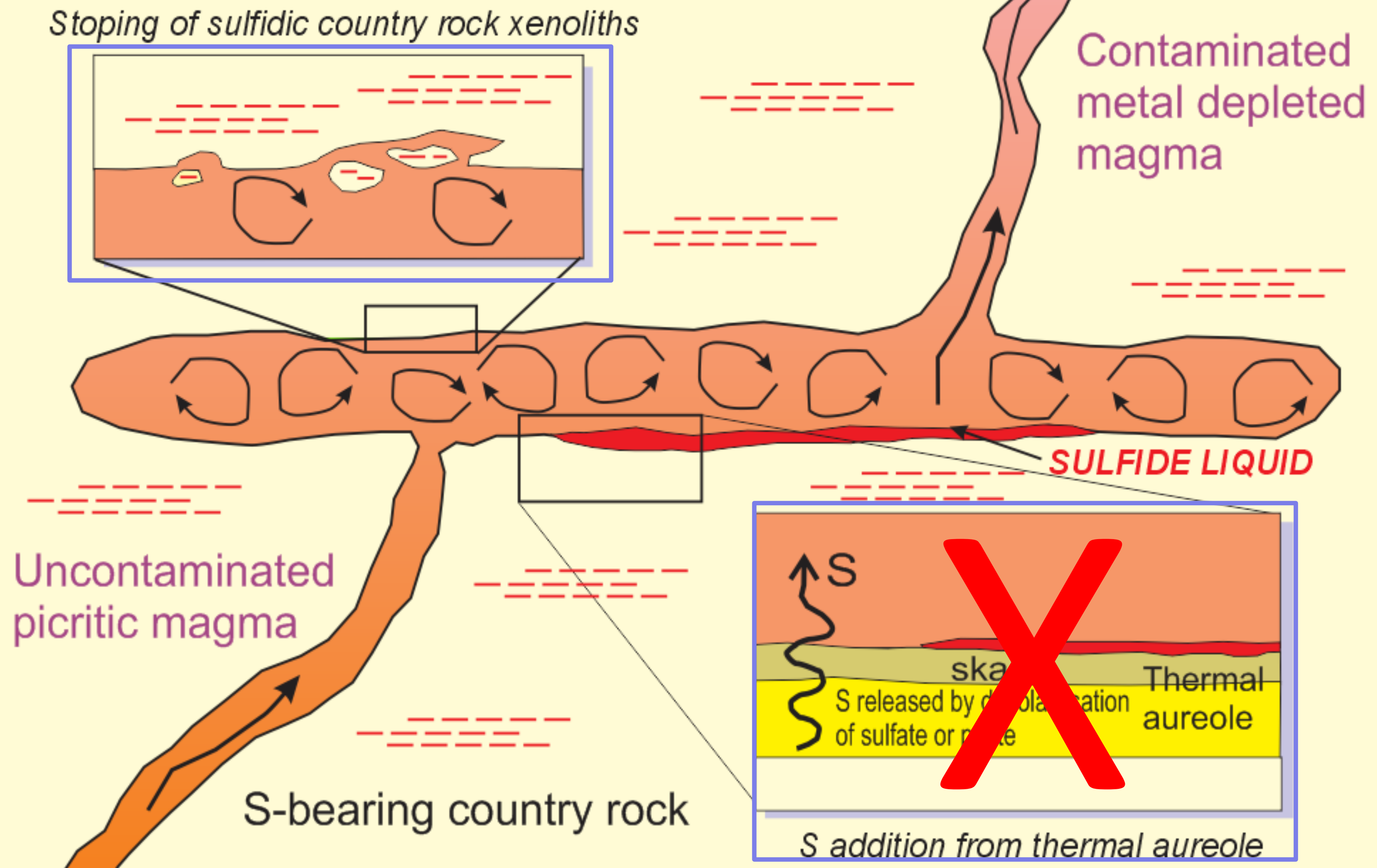


Modified from Lesher and Keays, 2002



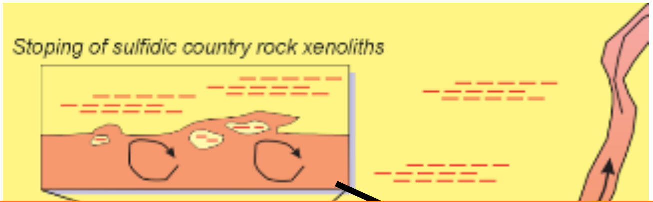
First conclusion: the quickest way to add S to magma is by direct incorporation of country rock (Robertson et al., Economic Geology, 2015)

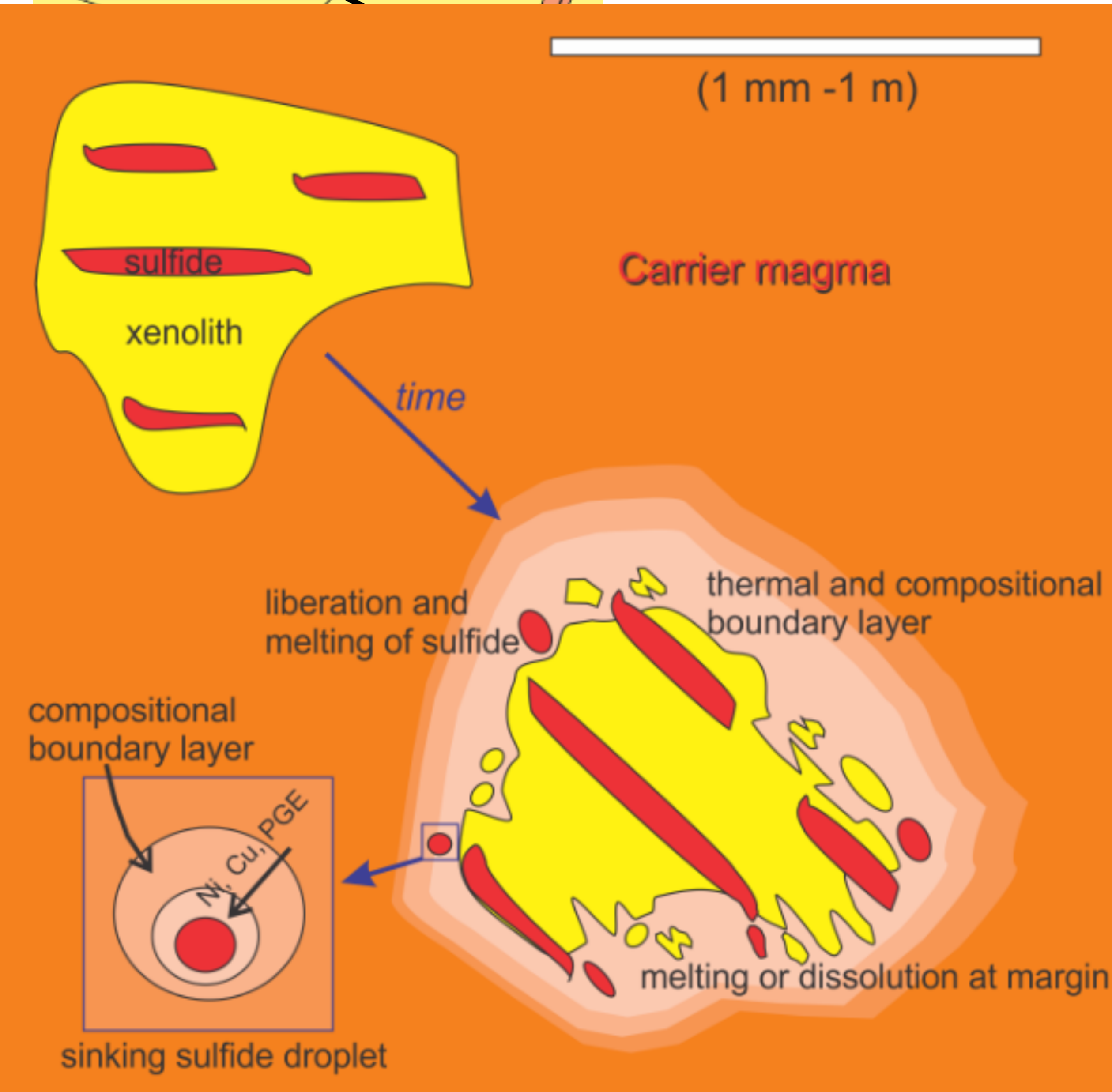
How do we get the extra S into the magma?

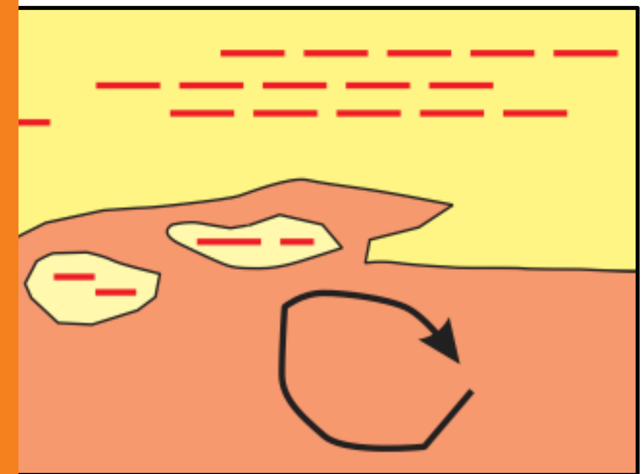


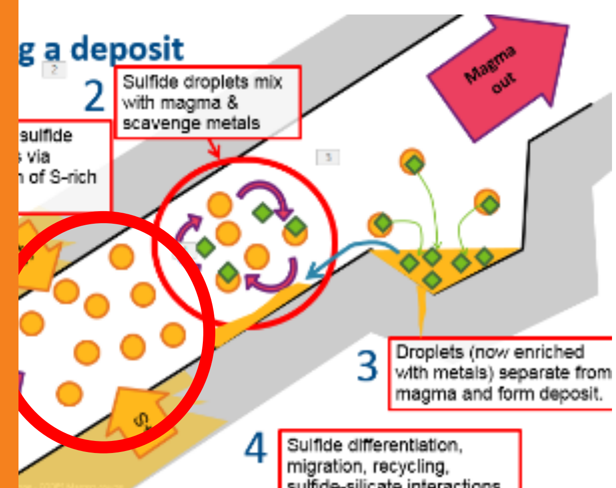
Modified from Lesher and Keays, 2002

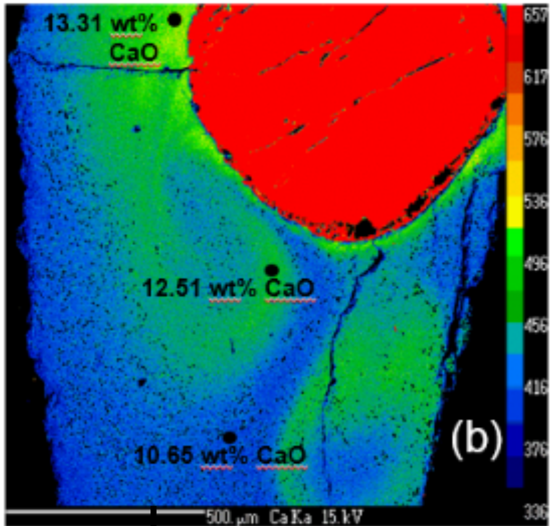
Disaggregation and transport of xenoliths







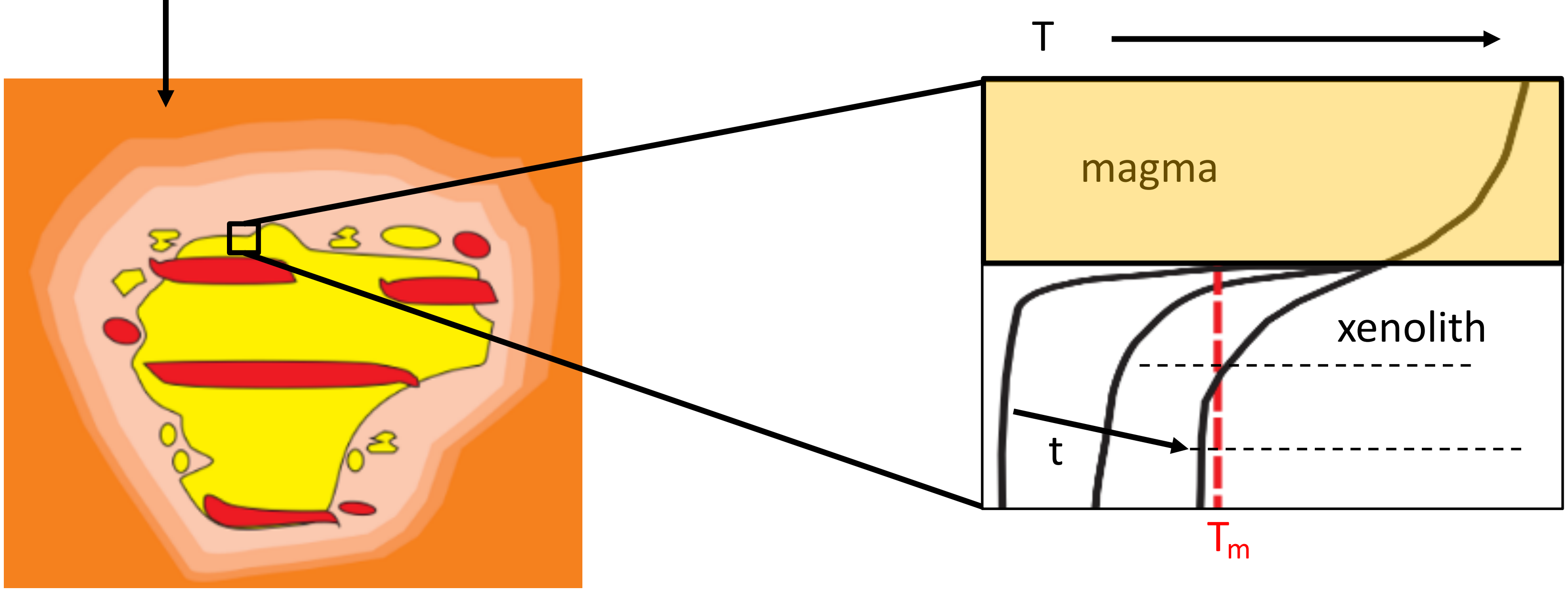


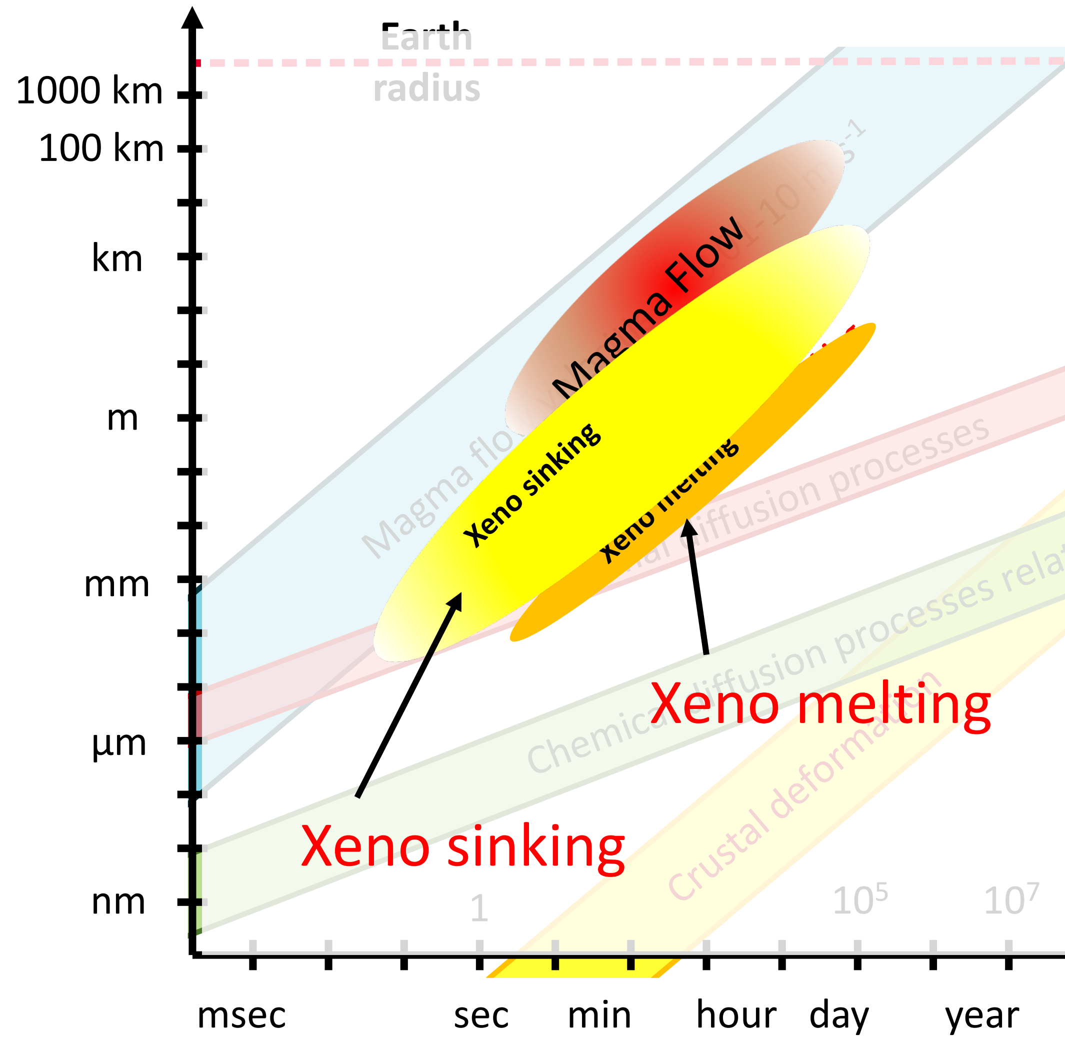


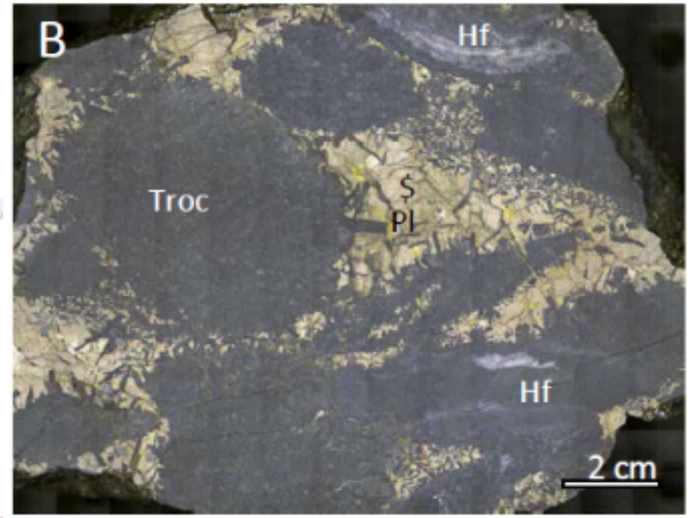
Convective mixing in a boundary layer around anhydrite dissolving into mafic magma (Iacono-Marziano, 2017, in press)

Heat conduction from magma into xenolith (slow) causing melting in narrow boundary layer at contact

- Stirring speeds the process
- Stirring favoured by low viscosity, turbulent flow, sinking of xenolith



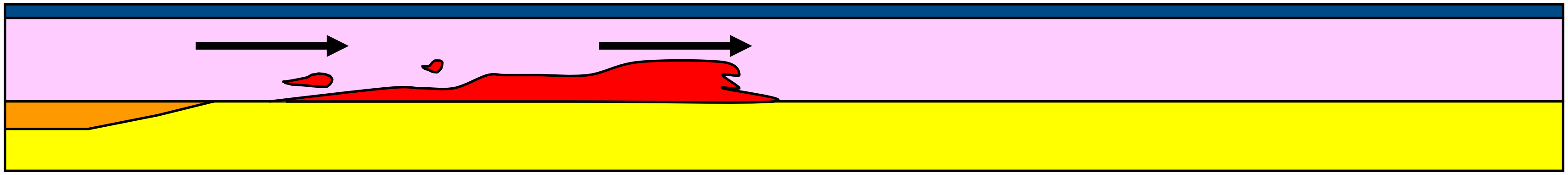




Conclusion: xenoliths (and sulfide) might be transported a long way before they melt

Sulfide liquid transport might be primarily within disaggregating xenoliths, rather than as free droplets

Bed load drag mechanism

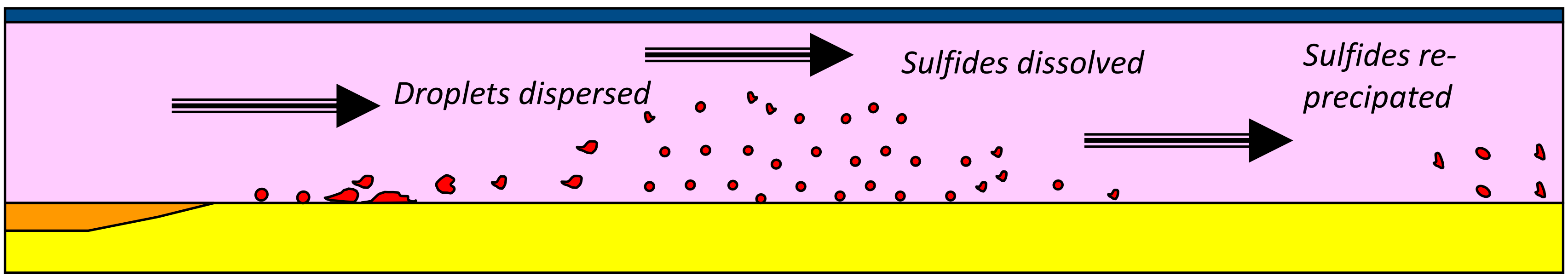


Sed S source

Entrained bed-load sulfide liquid – low R, Ni, PGE poor

Dispersion, suspension, dissolution

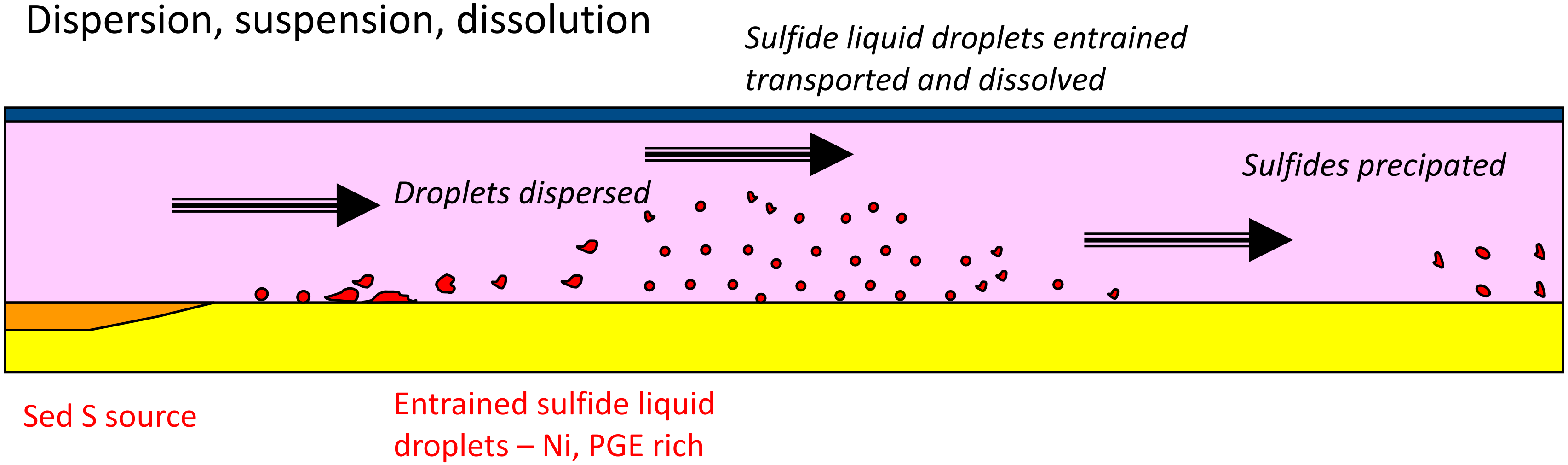
Sulfide liquid droplets entrained transported and dissolved



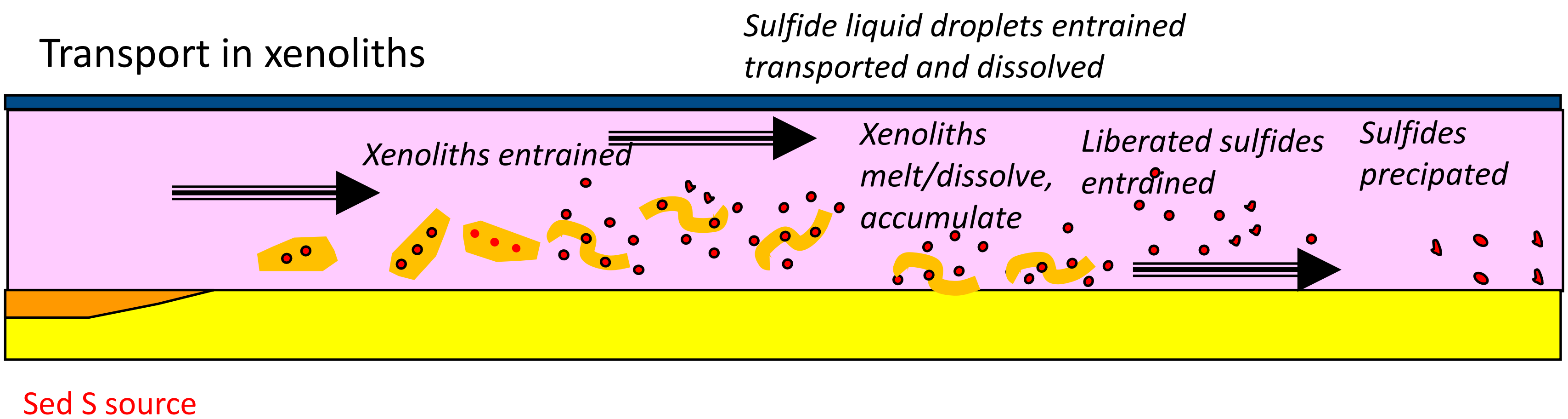
Sed S source

Entrained sulfide liquid droplets – Ni, PGE rich

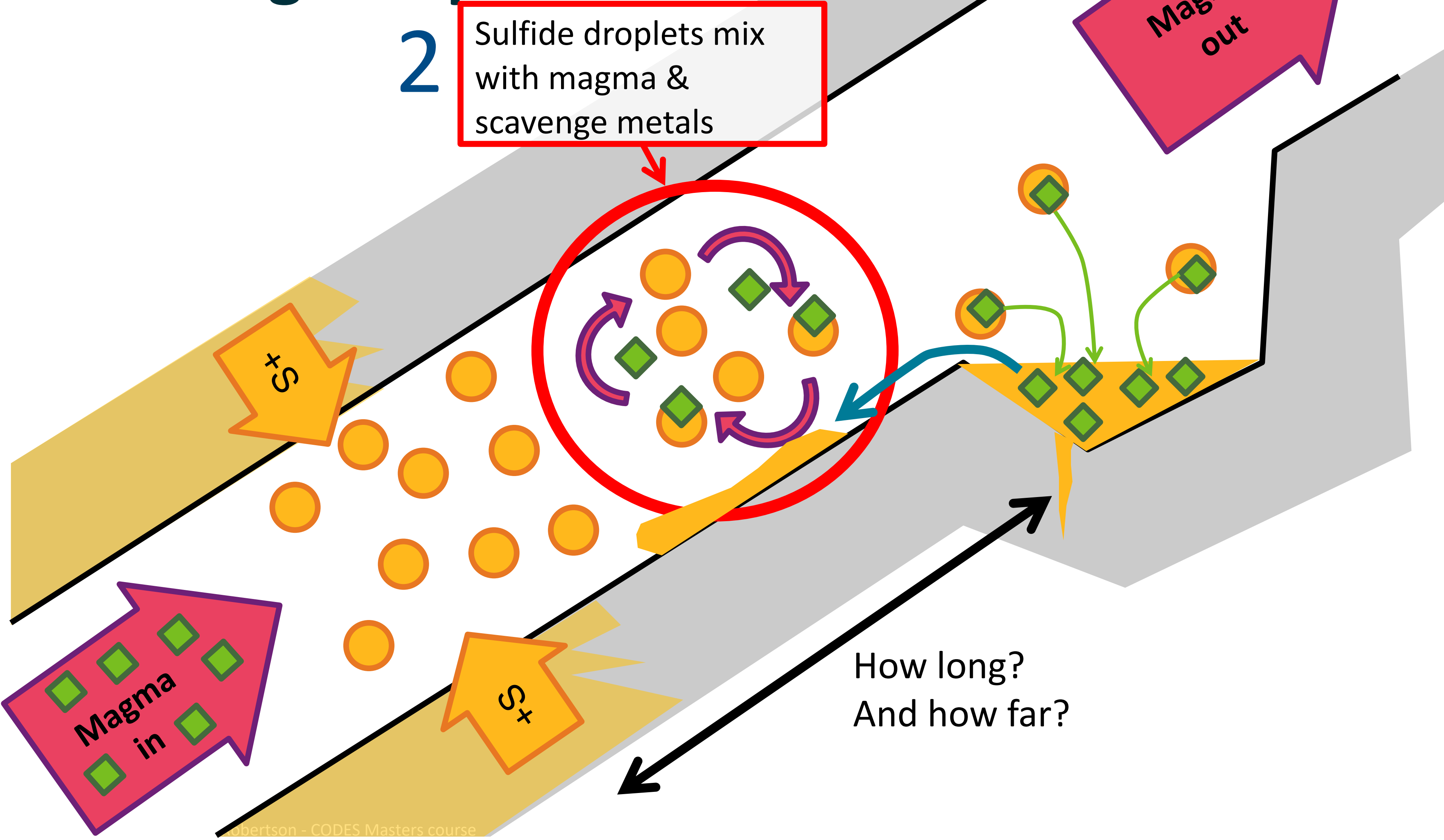
Dispersion, suspension, dissolution



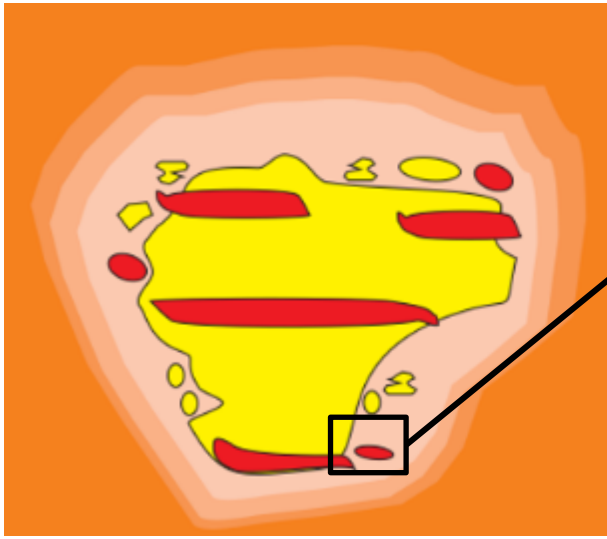
Transport in xenoliths

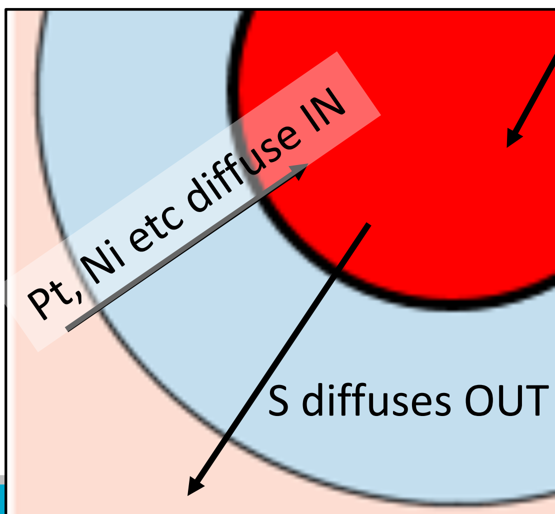


Forming a deposit

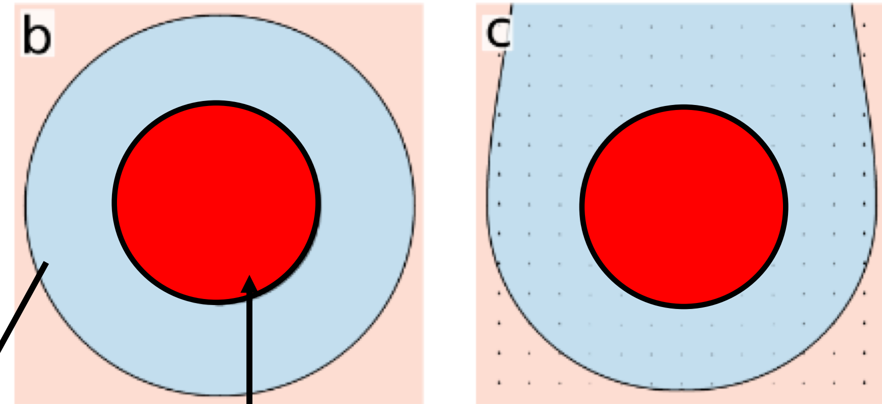


Detachment, sinking and upgrading of dense sulfide droplet

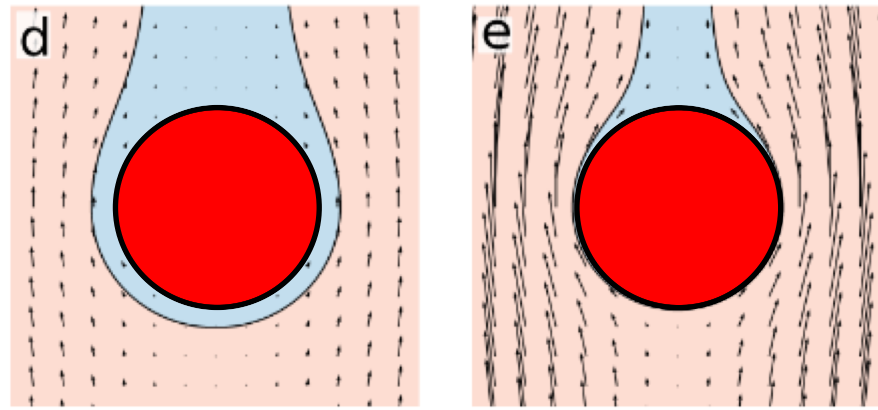




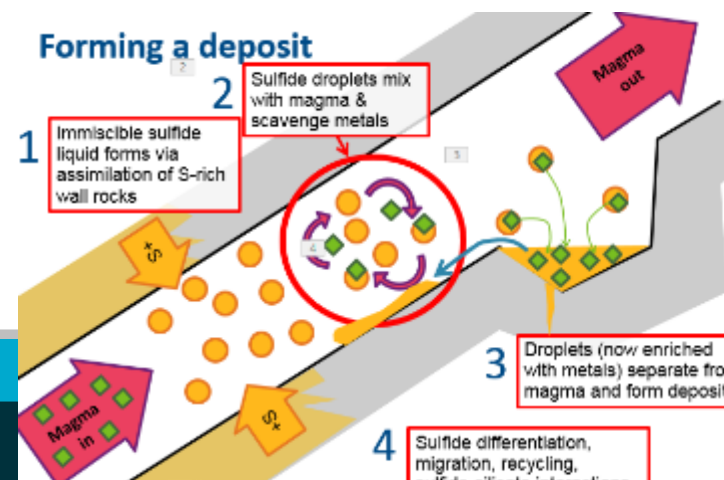
SLOW



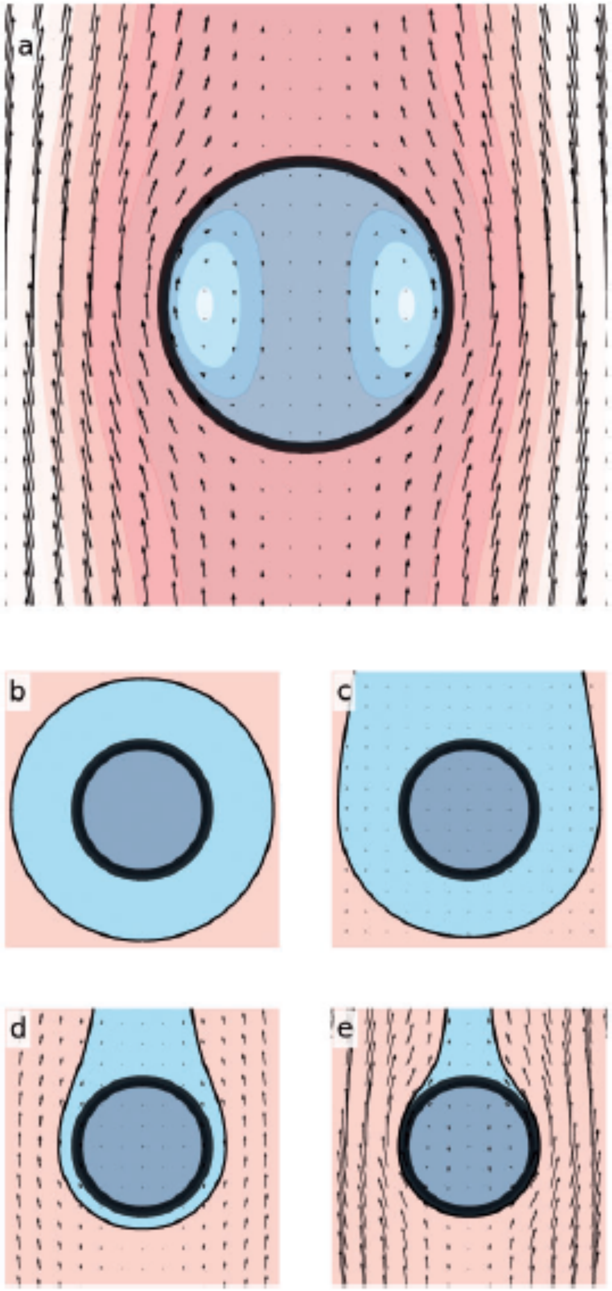
Compositional boundary layer around sulfide droplet

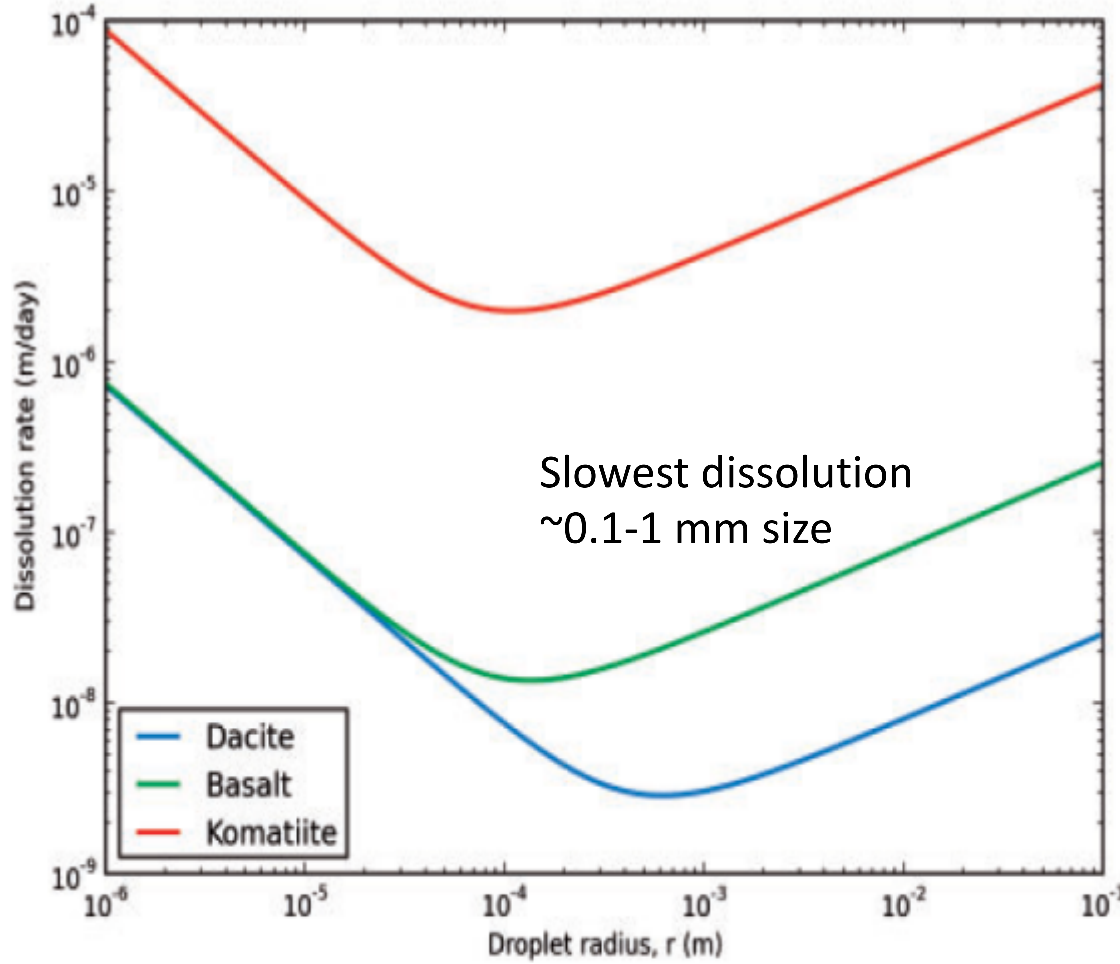


Sinking sulfide droplet disrupts its own boundary layer



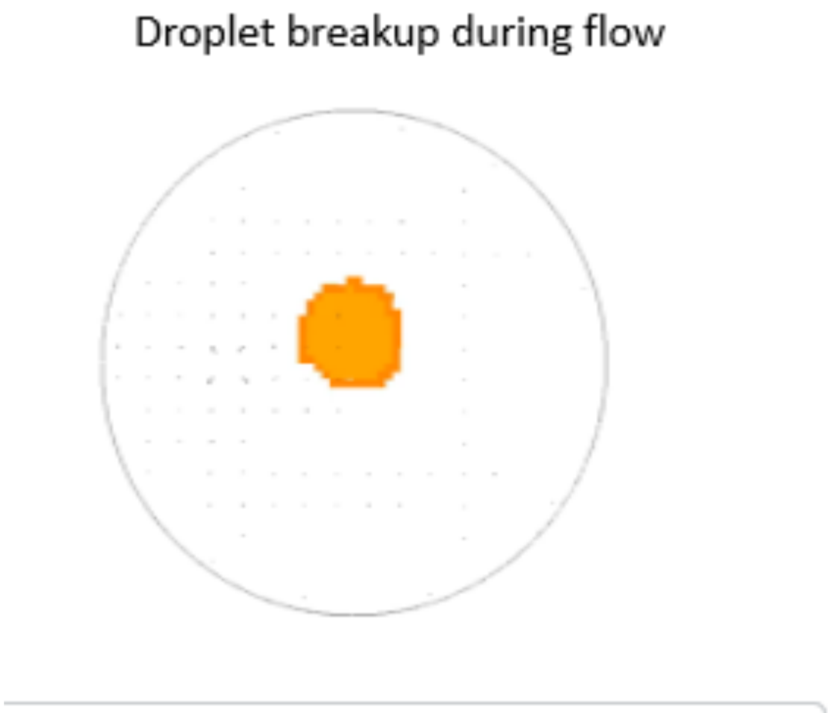
Robertson et al., 2016, J Petrology



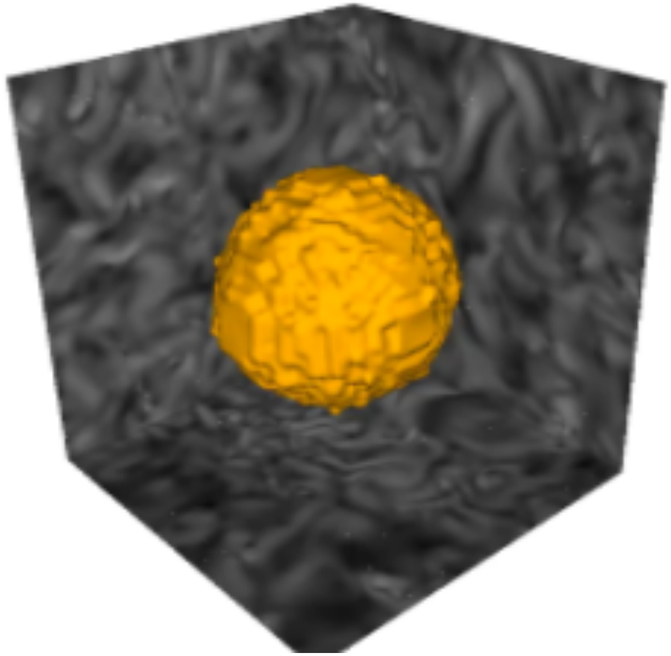


Robertson et al 2016

Droplet breakup during flow

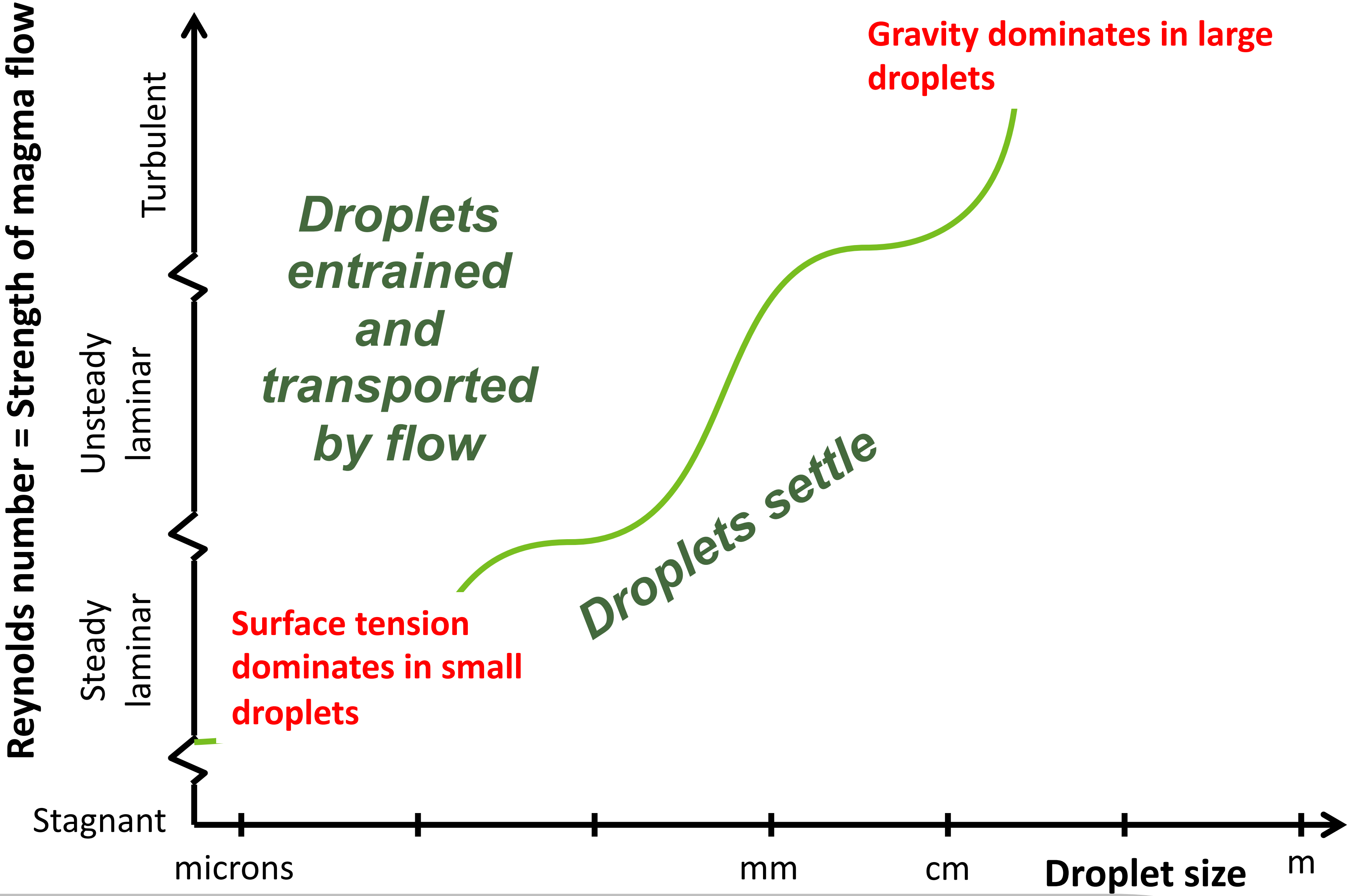


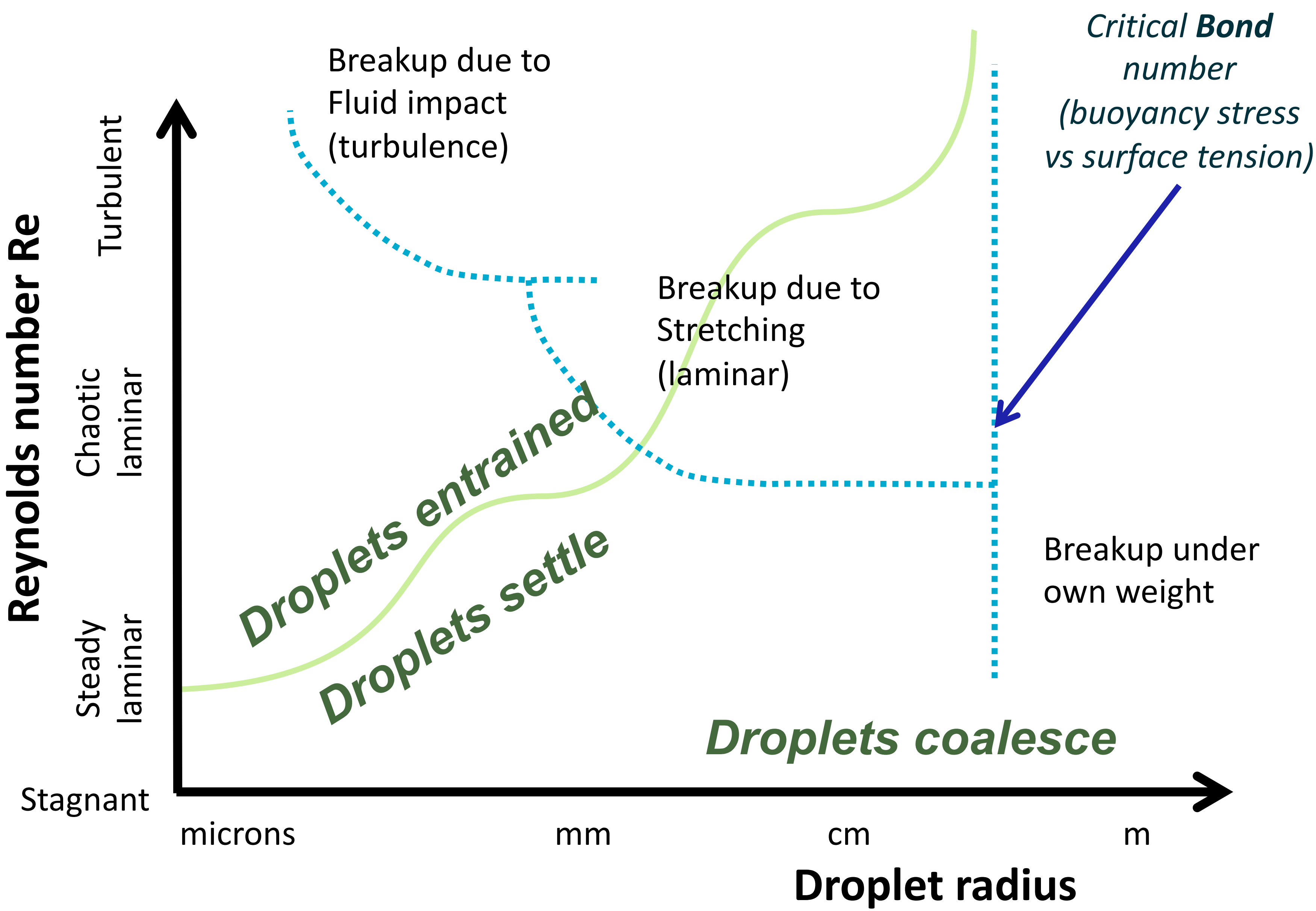
Chaotic laminar flow



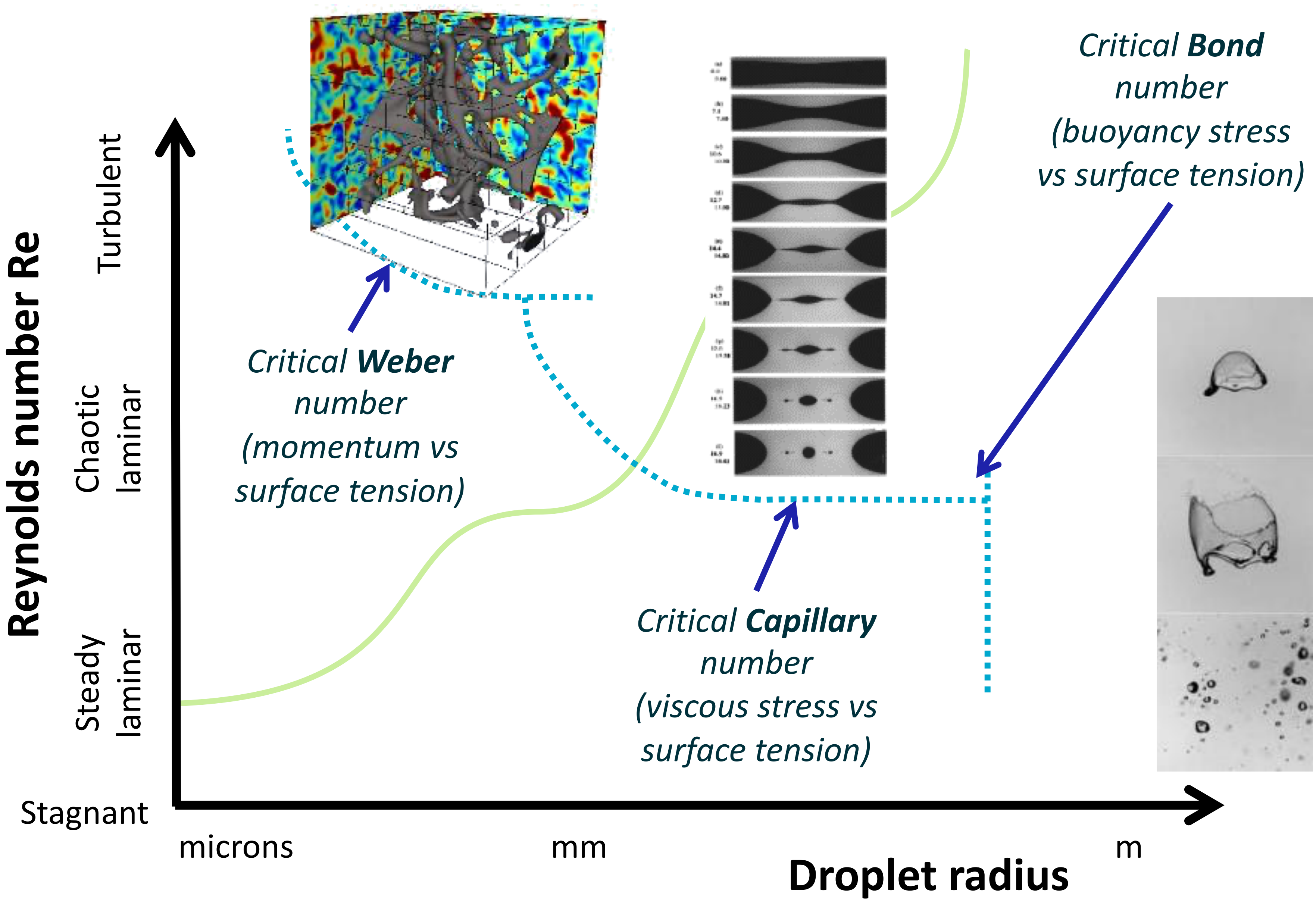
Fully turbulent

Droplets may SETTLE, BREAK UP or COALESCE during transport



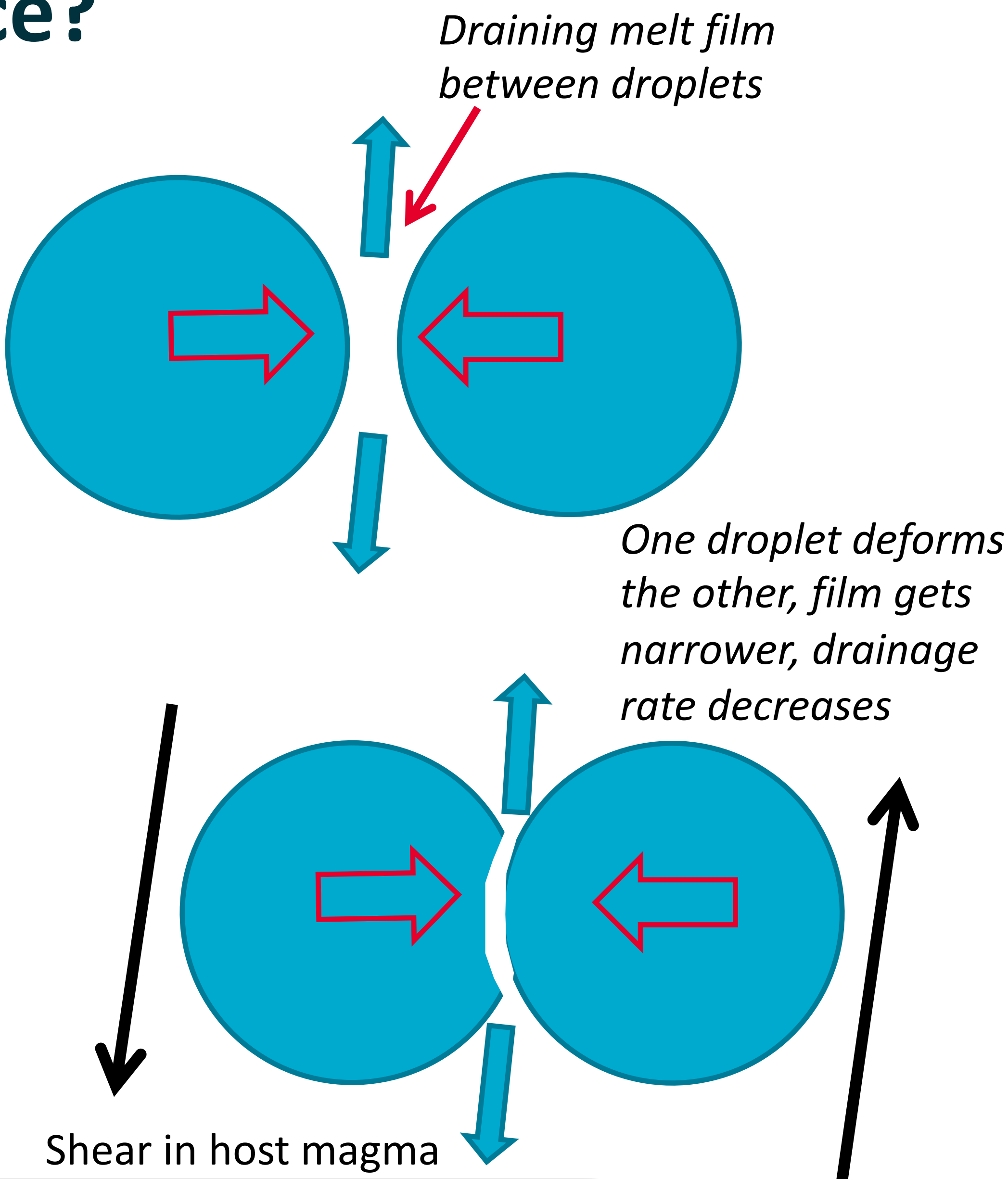


Critical **Bond** number (buoyancy stress vs surface tension)
Breakup due to Fluid impact (turbulence)
Breakup due to Stretching (laminar)
Breakup under own weight
Droplets entrained
Droplets settle
Droplets coalesce
Reynolds number Re
Turbulent
Chaotic laminar
Steady laminar
Stagnant
microns
mm
cm
m
Droplet radius


Reynolds number Re
Turbulent
Chaotic laminar
Steady laminar
Stagnant
microns
mm
m
Droplet radius
Critical **Weber** number (momentum vs surface tension)
Critical **Capillary** number (viscous stress vs surface tension)
Critical **Bond** number (buoyancy stress vs surface tension)
CSIRO

Can droplets coalesce?

- Coalescence favoured in large droplets, much less likely in small ones
- Droplets don't coalesce during flow unless droplet density is very high
- Significant coalescence probably only occurs after droplets have accumulated in high abundance



De Bremond d'Ars et al, 2001 EPSL

Coalescence?

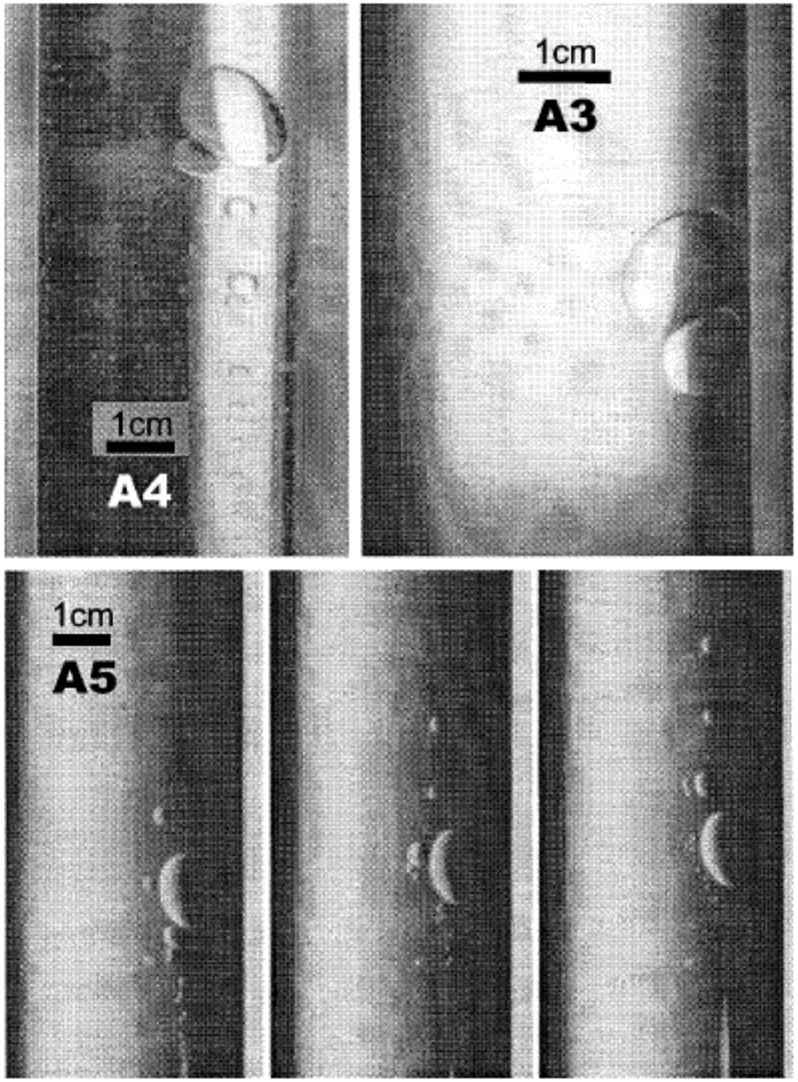
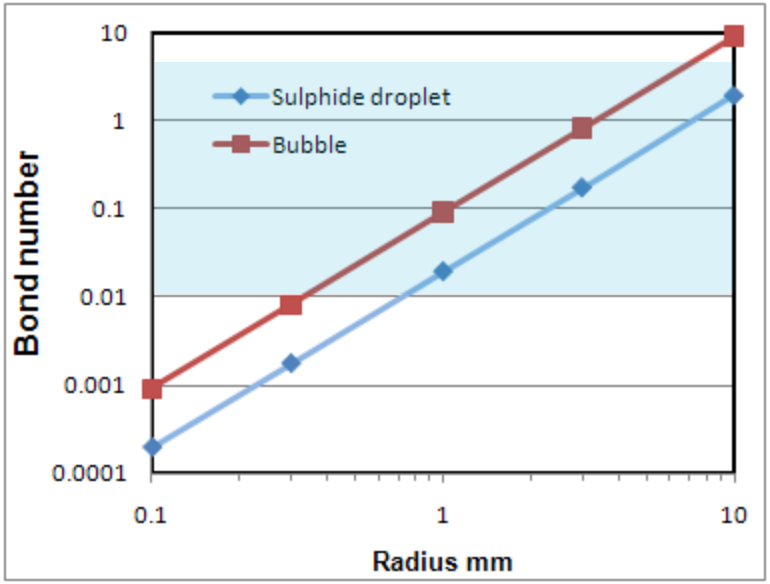


Fig. 3. Photographs of three experiments showing the absence of coalescence in host fluids of different viscosities (A3: 0.13 Pa s; A4: 0.45 Pa s; A5: 0.30 Pa s) whatever the size of the drops.

De Bremond d'Ars et al 2001 EPSL

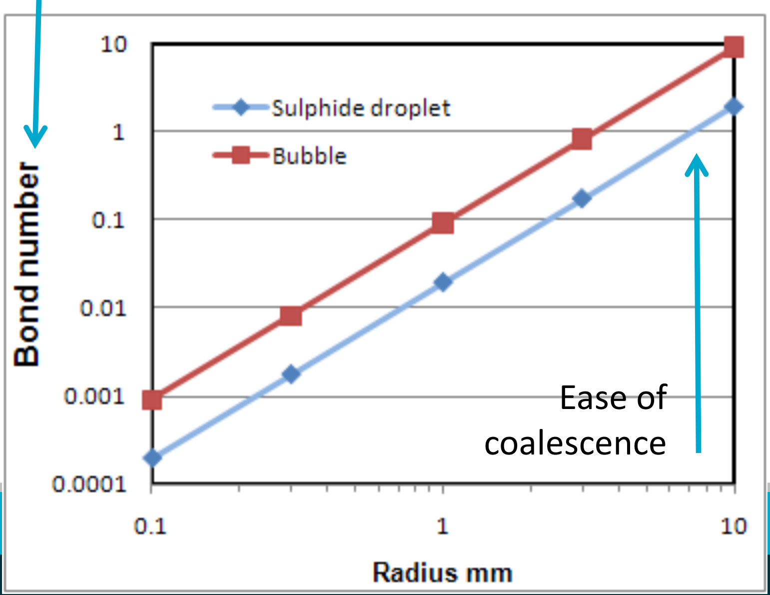
Experimental result: no coalescence of droplets during vertical transport for Bond numbers 0.01-5



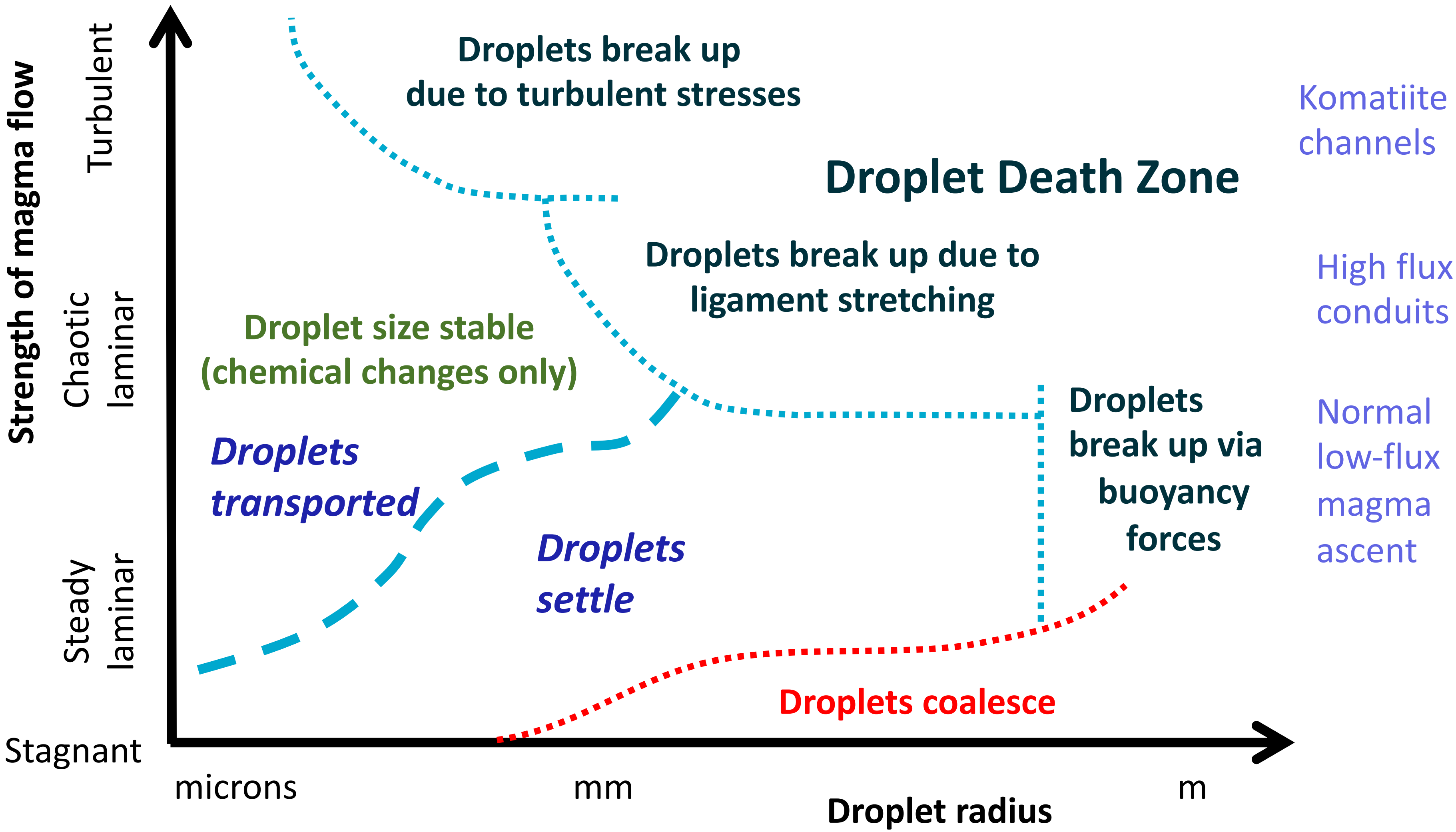
Vesicles as analogues of sulfide droplets – non-coalescence behaviour

Sulfide droplet ~ 1 cm has similar "deformability" as a bubble ~ 4 mm

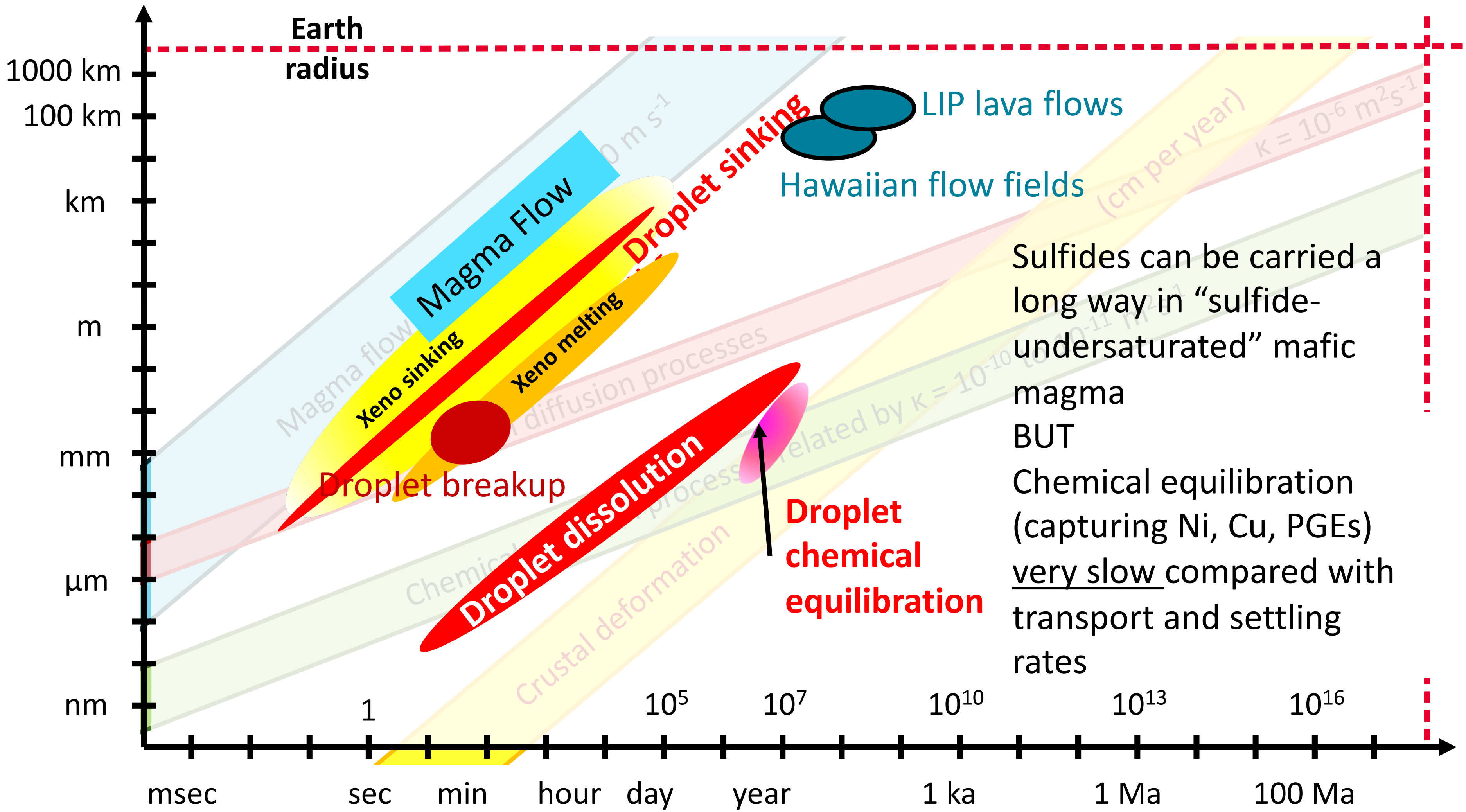
$$\frac{\Delta \rho g a^2}{\sigma}$$



Regimes of droplet behaviour



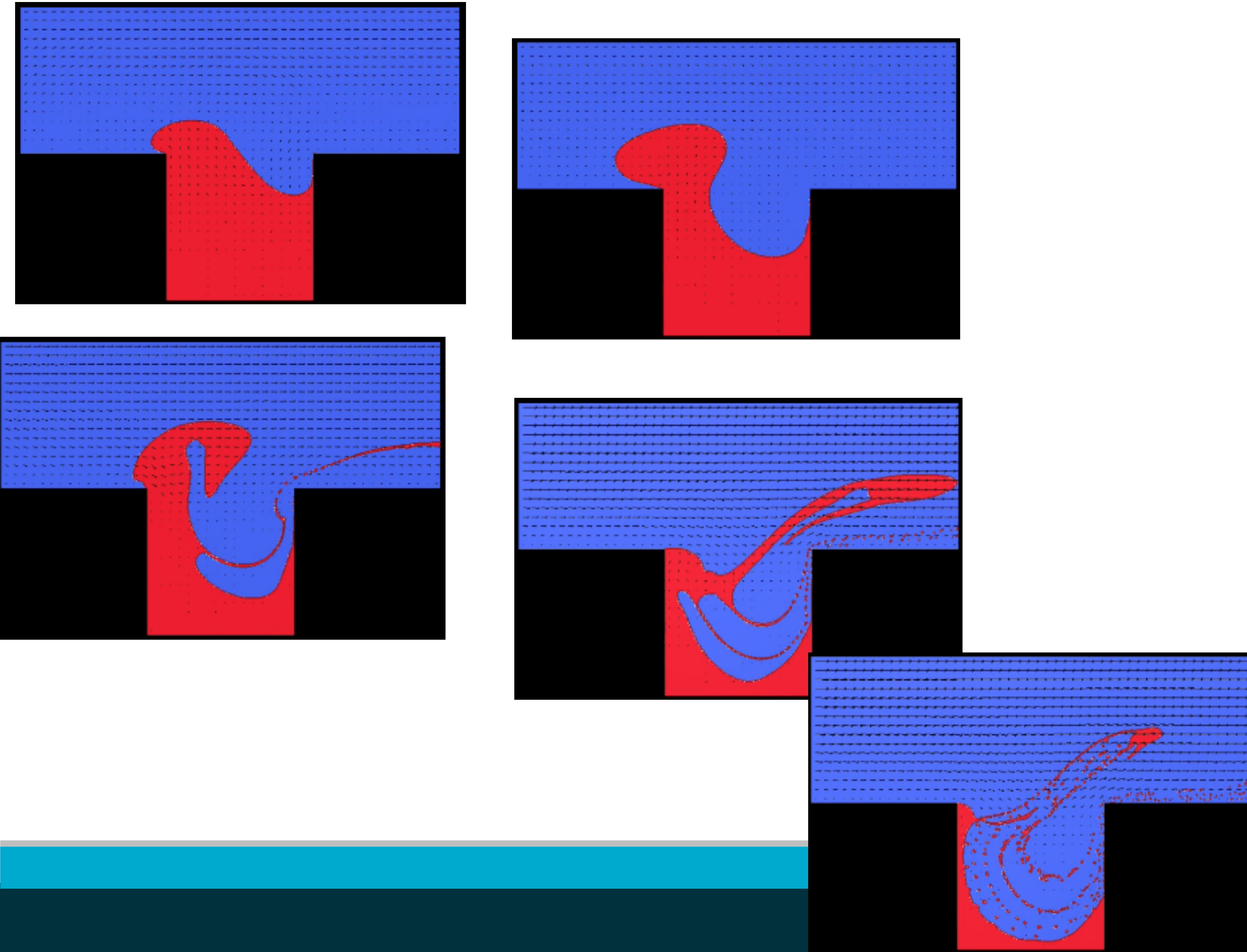
Conclusion: breakup, not coalescence , dominates during droplet transport

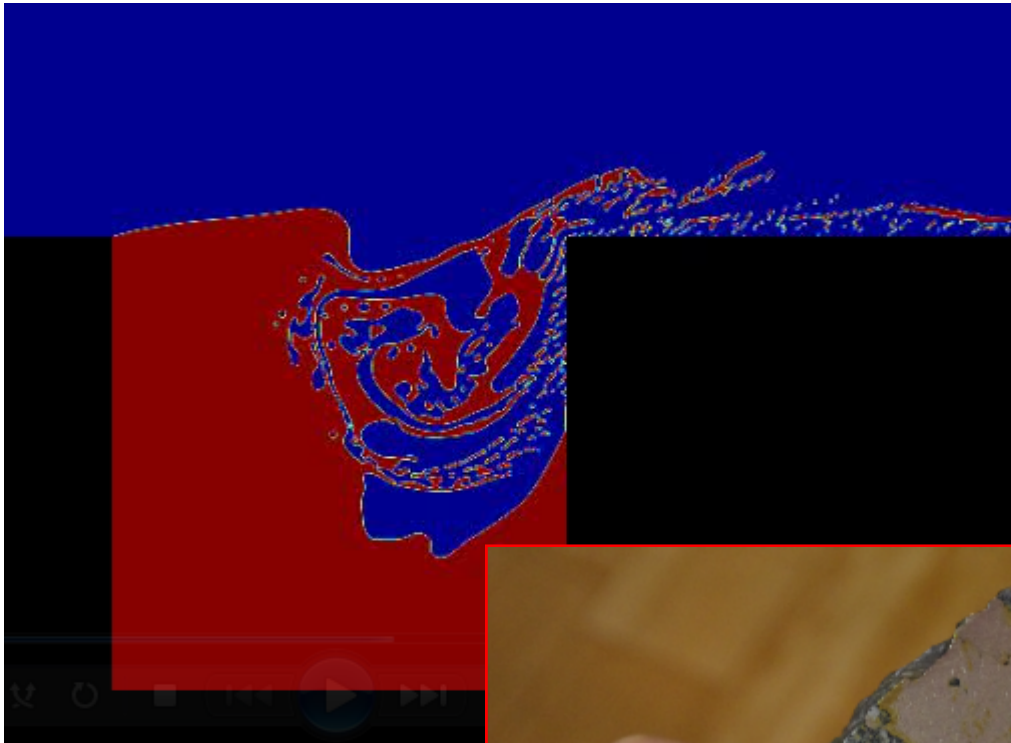


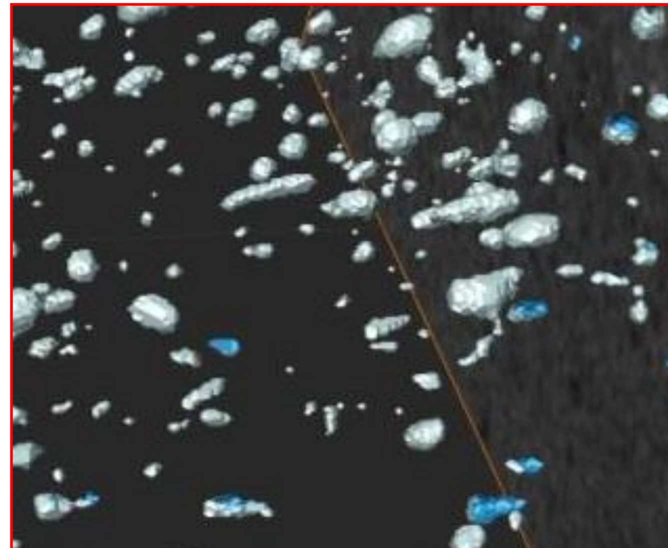
Sulfides can be carried a long way in "sulfide-undersaturated" mafic magma

BUT

Chemical equilibration (capturing Ni, Cu, PGEs) very slow compared with transport and settling rates





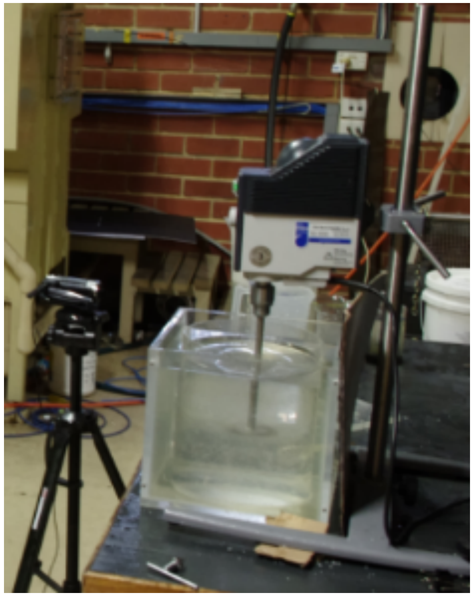


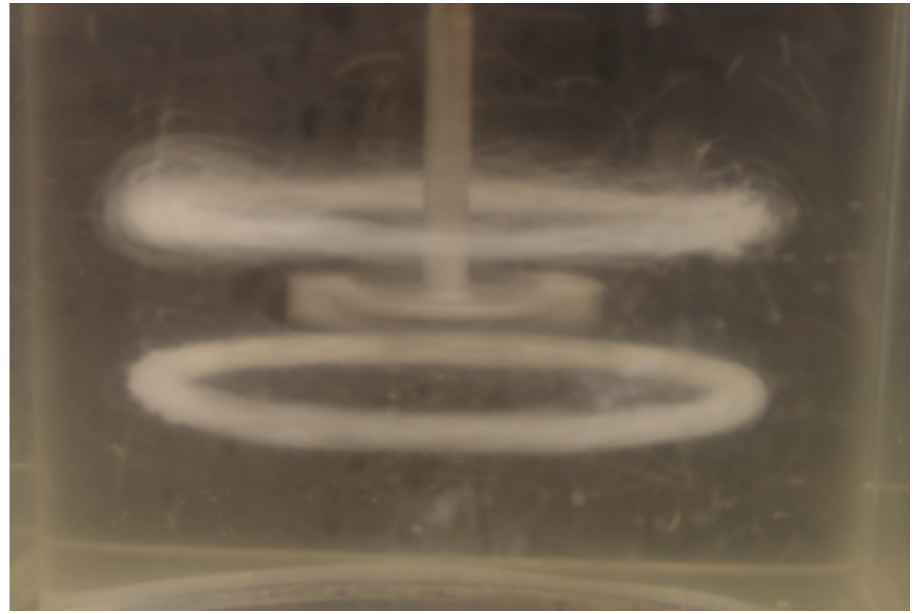
How do we deposit droplets?

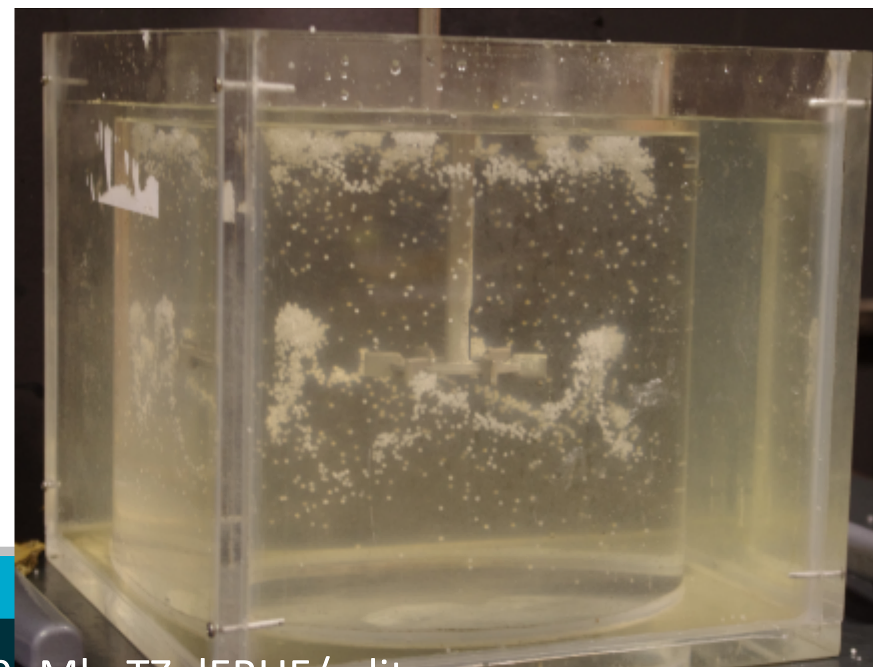
- When you have lots of droplets and crystals they interact!
- At high particle densities, the dynamics of the suspension take over from the individual particles

Trapping and concentrating droplets in chaotic laminar flows

Analogue fluid experiments

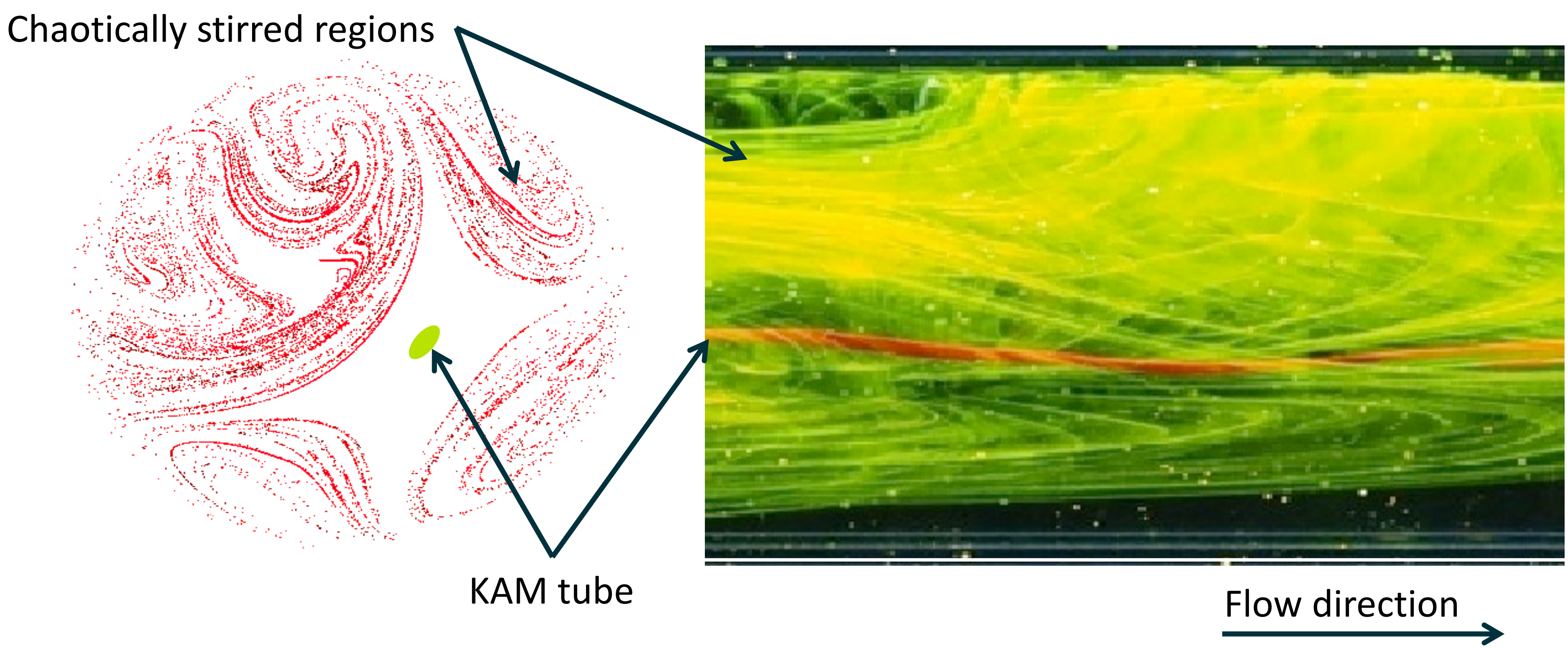


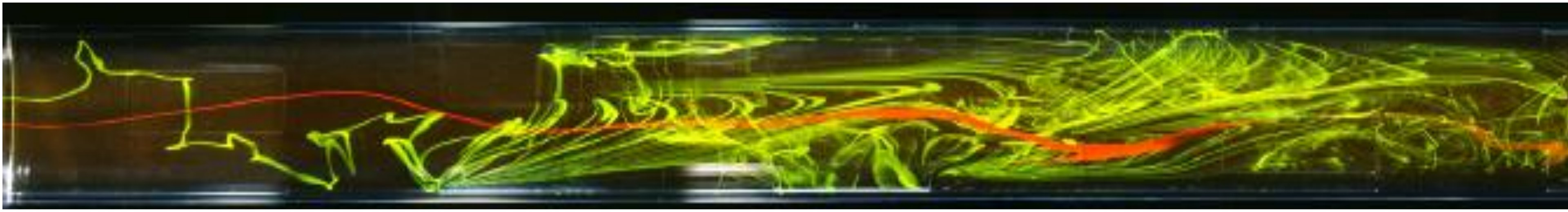




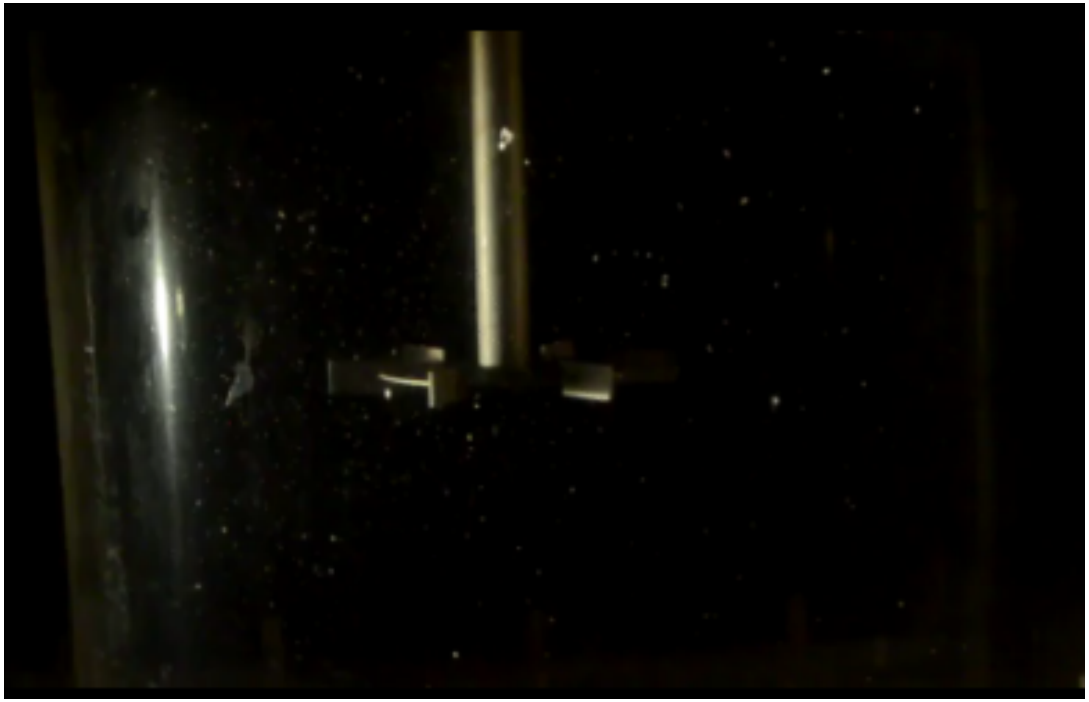
https://docs.google.com/file/d/0Bye8F7kyztwOc29pMkpTZnlERUE/edit

Mixing in chaotic conduit flows



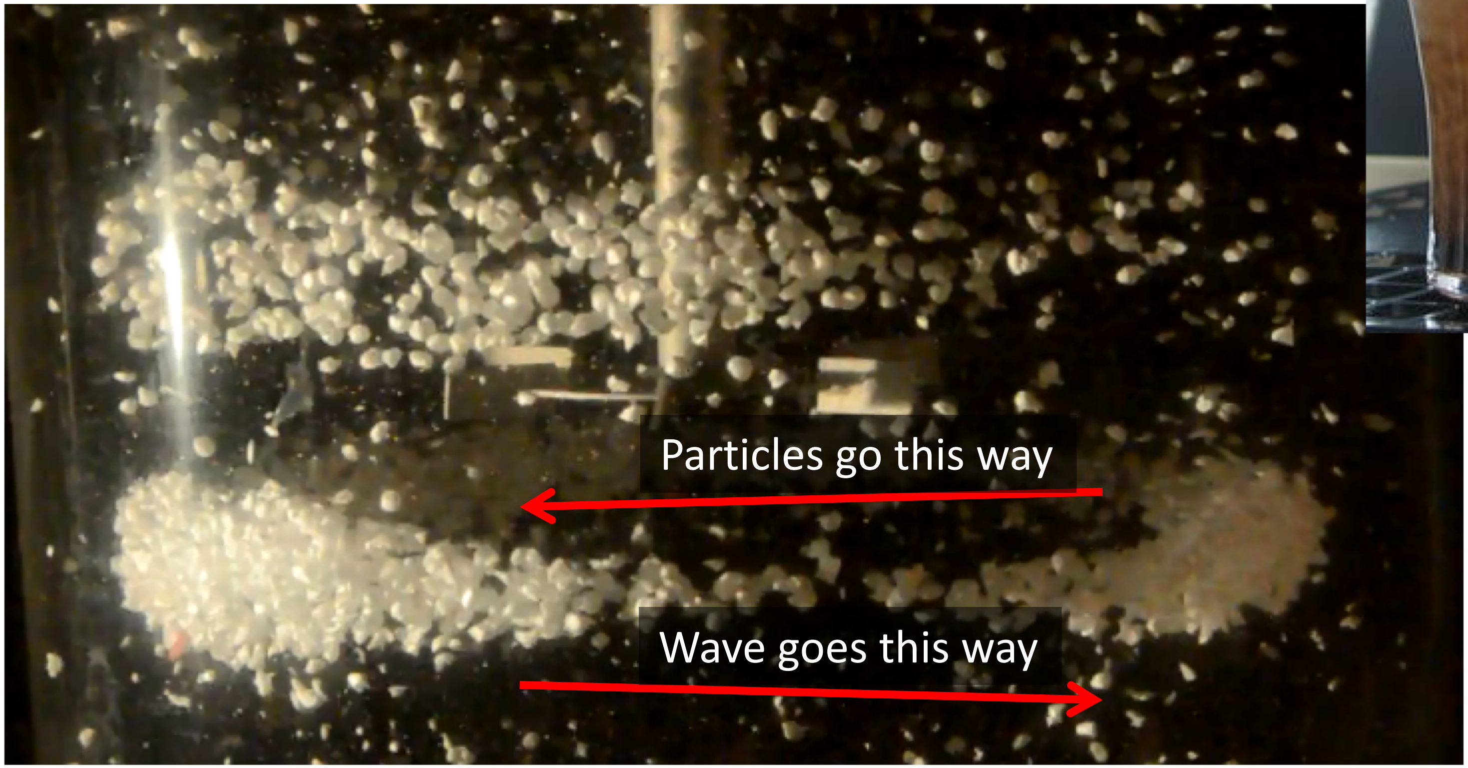


Droplet trapping https://www.youtube.com/watch?v=PWUFm0PUUjQ movie



Secondary instabilities

Local particle density affects particle velocities
"Traffic jam dynamics" – particle waves propagate through KAM regions.

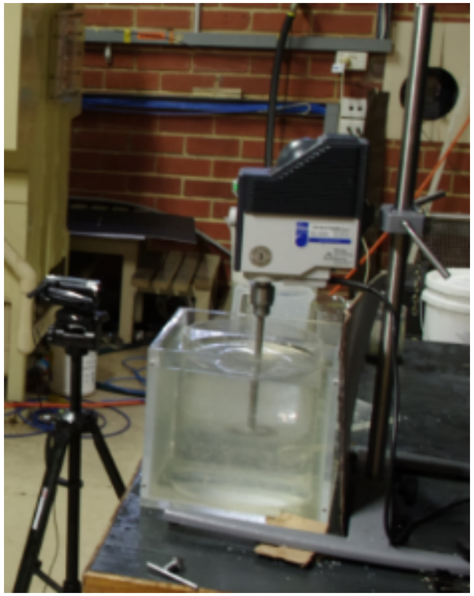


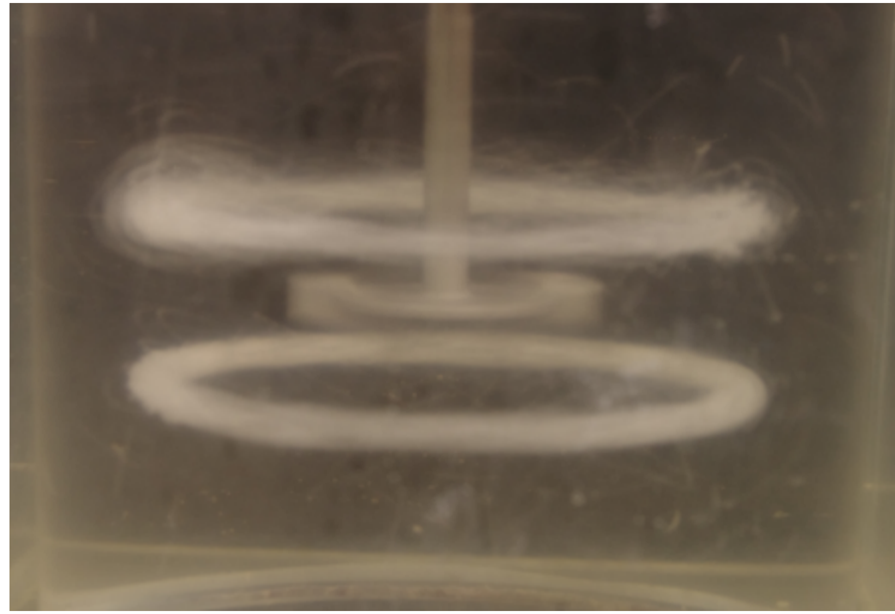
Have a Guinness for science

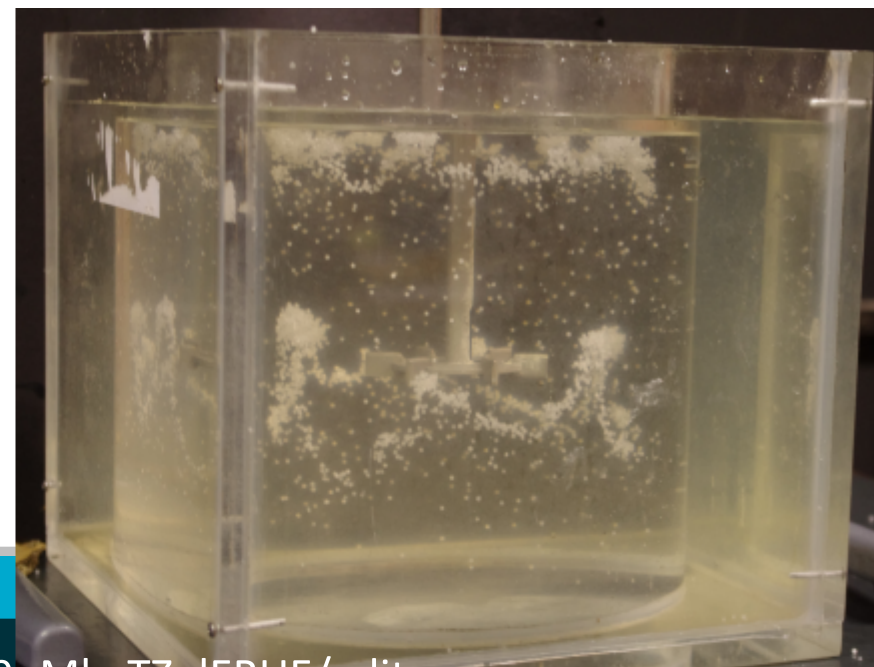
Jump to movie

Trapping and concentrating droplets in chaotic laminar flows

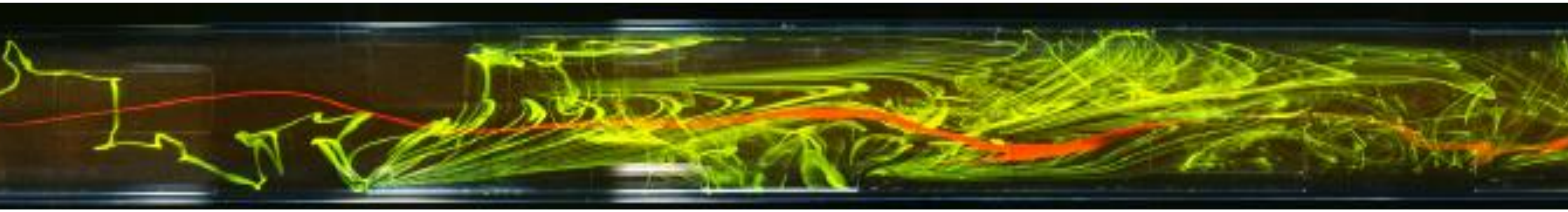
Analogue fluid experiments





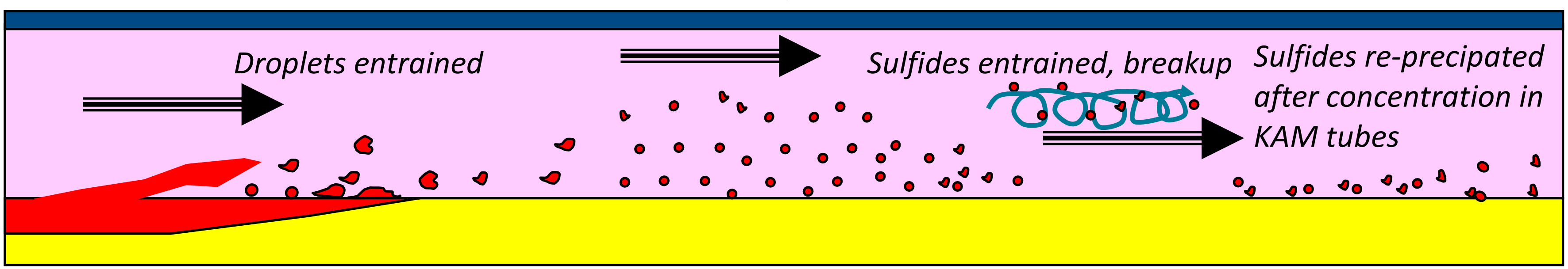


https://docs.google.com/file/d/0Bye8F7kyztwOc29pMkpTZnlERUE/edit

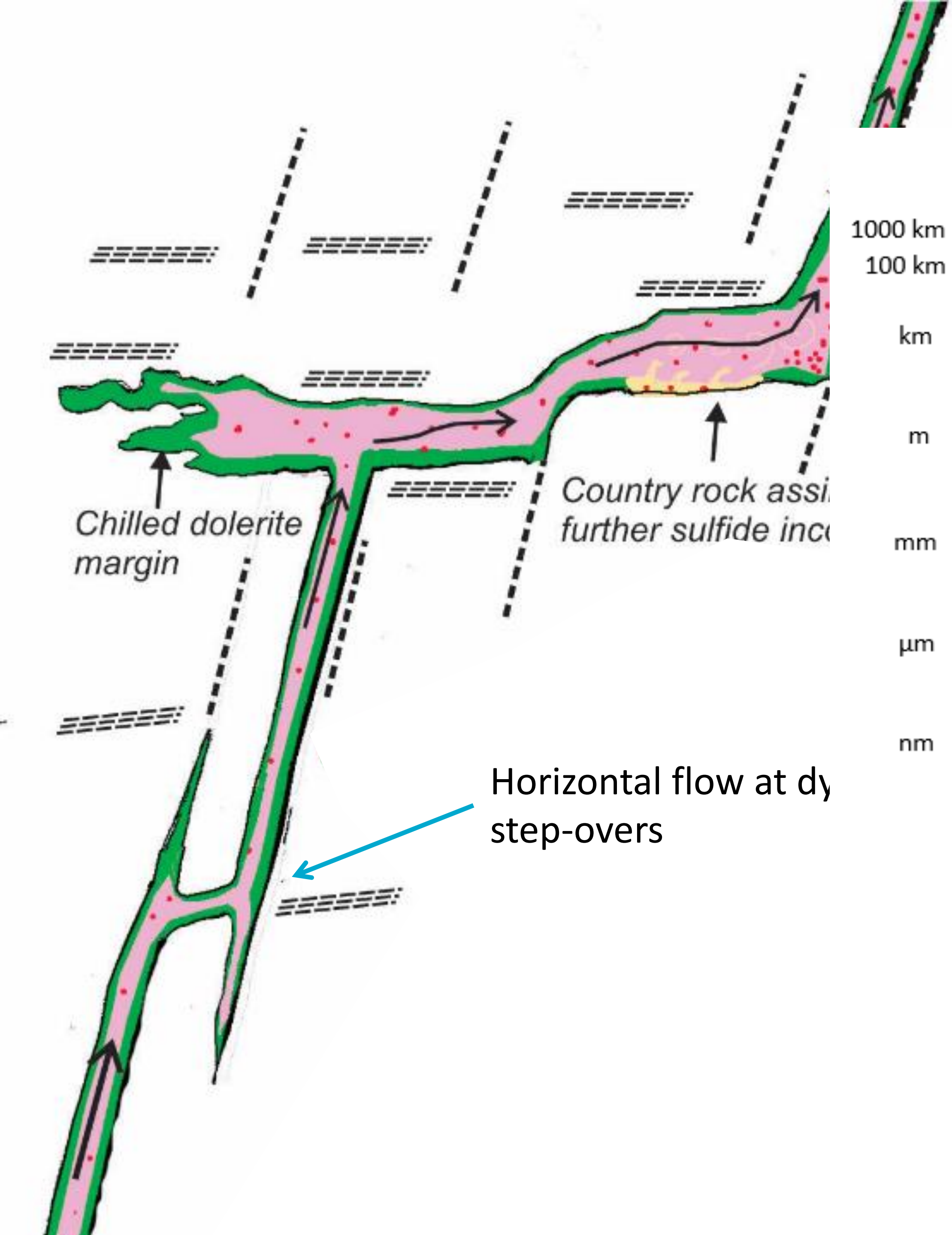


Dispersion, suspension, dissolution

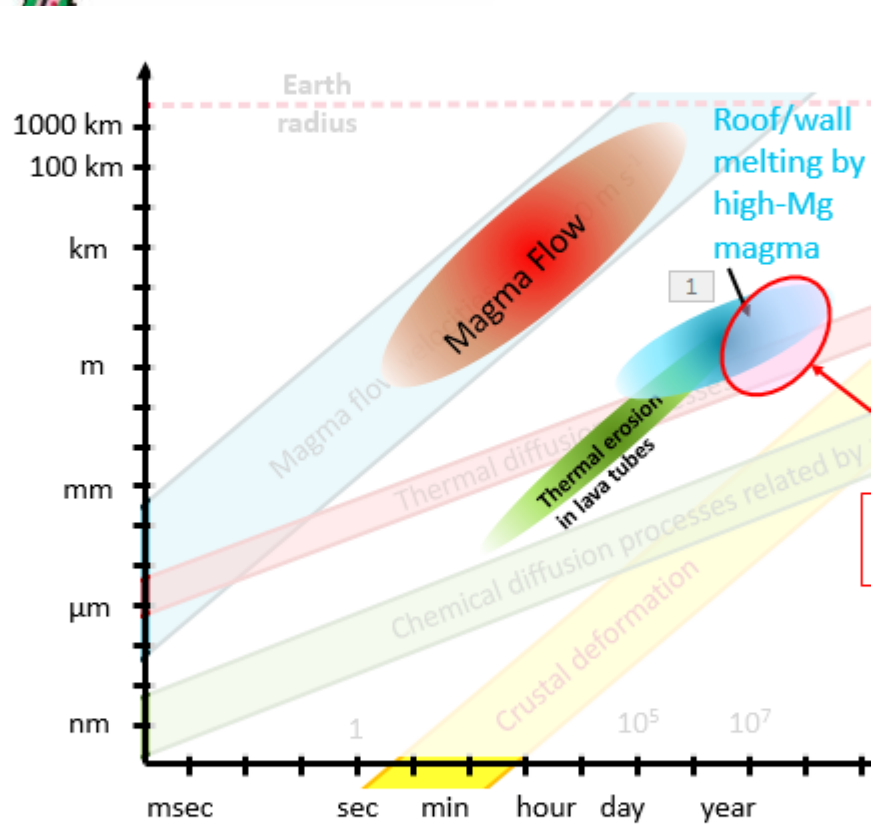
Sulfide liquid droplets entrained and transported



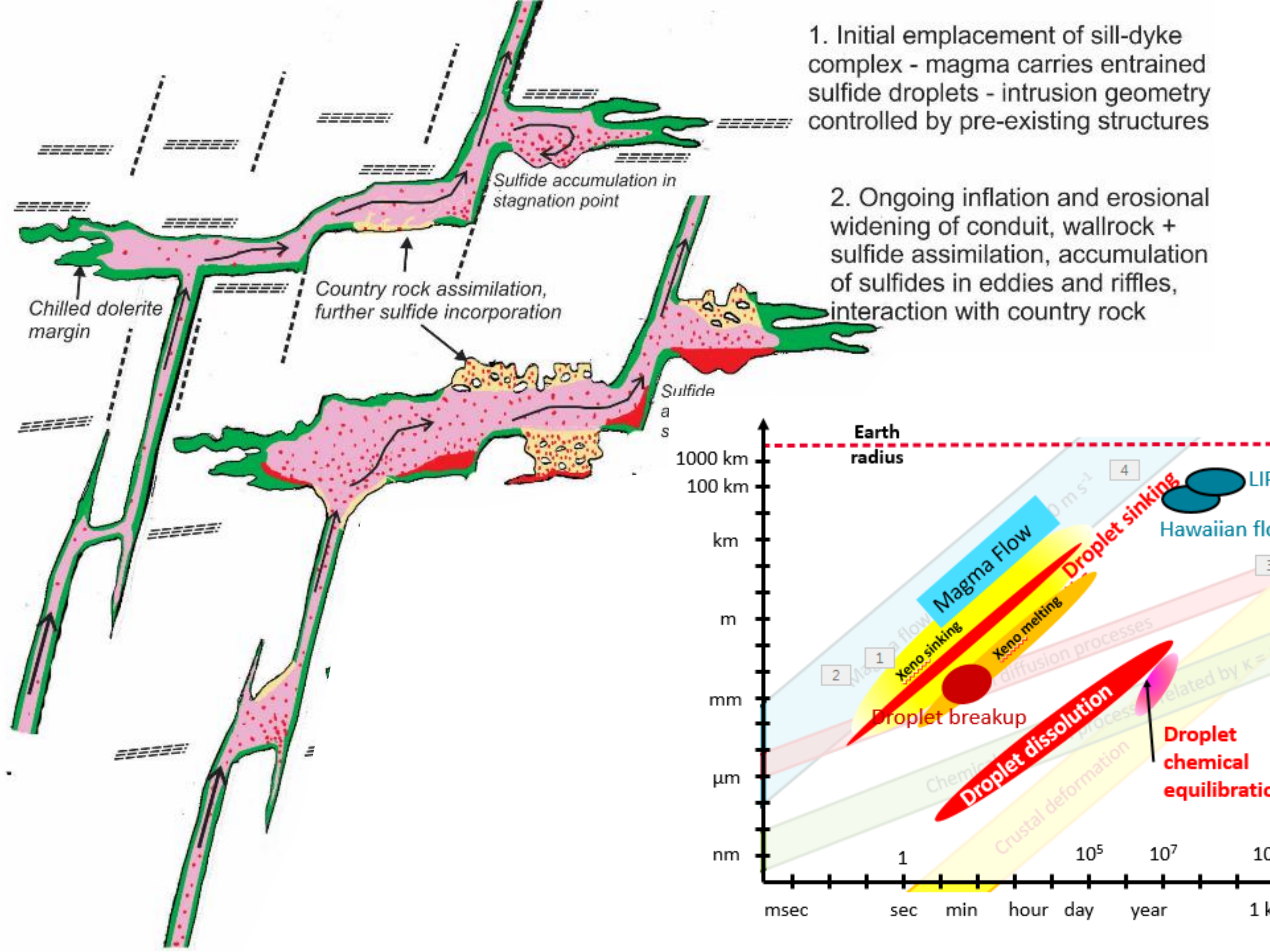
Sulfide liquid pool



Chilled dolerite margin
Country rock assi
further sulfide inc
Horizontal flow at dy
step-overs

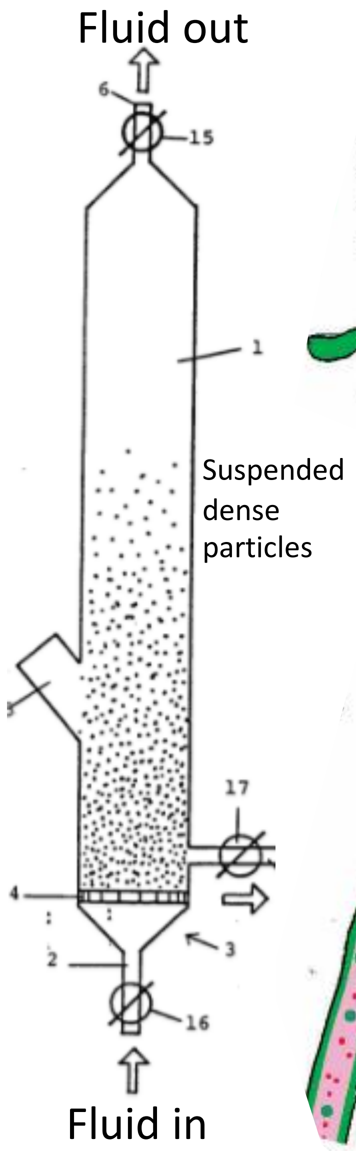


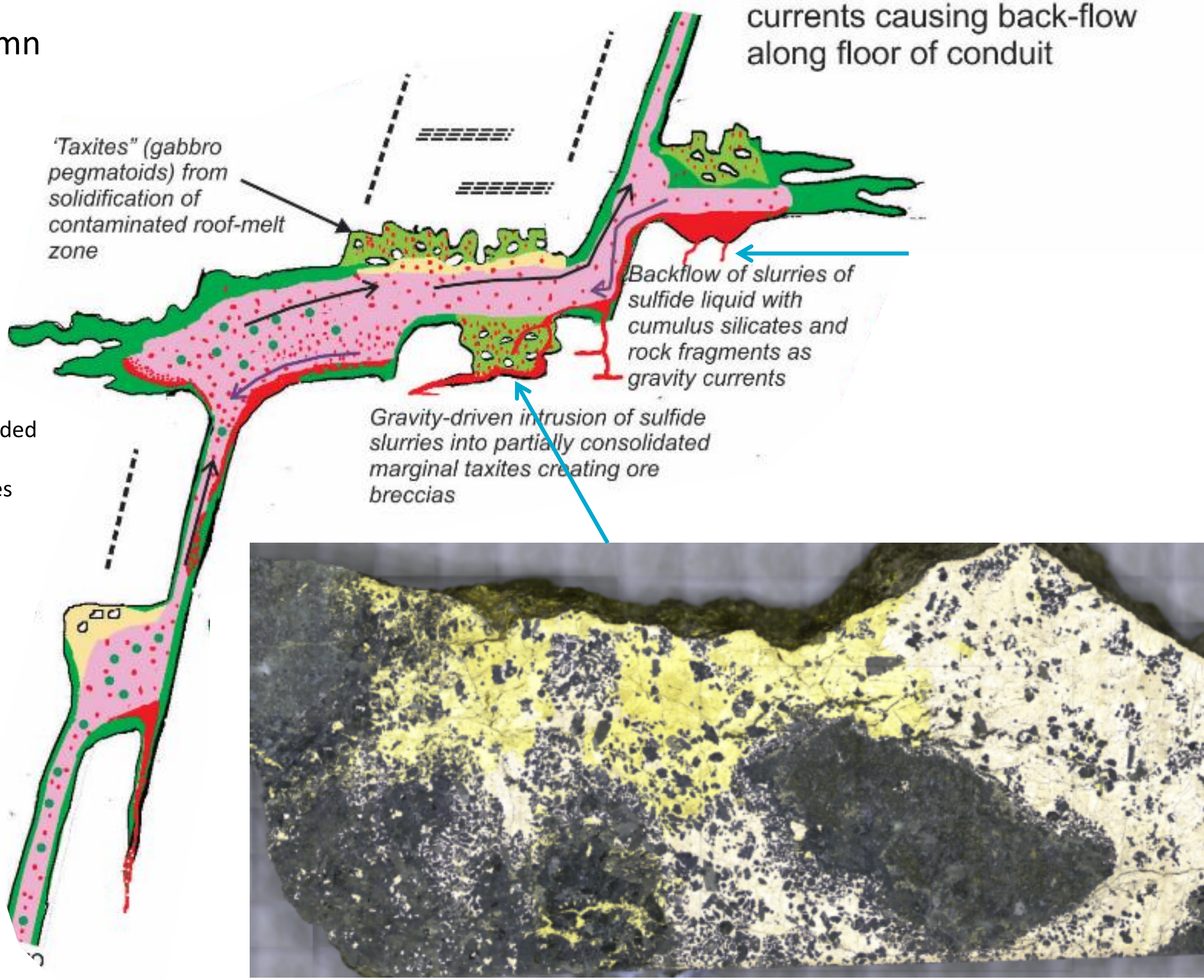
Earth radius
1000 km
100 km
km
m
mm
µm
nm
msec
sec
min
hour
day
year
1
10^5
10^7
Roof/wall melting by high-Mg magma
Magma Flow
Magma flow
Thermal diffusi
Thermal erosion in lava tubes
Chemical diffusion processes related by
Crustal deformation


1. Initial emplacement of sill-dyke complex - magma carries entrained sulfide droplets - intrusion geometry controlled by pre-existing structures
2. Ongoing inflation and erosional widening of conduit, wallrock + sulfide assimilation, accumulation of sulfides in eddies and riffles, interaction with country rock
Sulfide accumulation in stagnation point
Country rock assimilation, further sulfide incorporation
Chilled dolerite margin
Sulfide
Earth radius
1000 km
100 km
km
m
mm
µm
nm
Magma Flow
Xeno sinking
Xeno melting
Droplet sinking
Droplet breakup
Droplet dissolution
Droplet chemical
diffusion processes
Crustal deformation
1
10^5
10^7
msec
sec
min
hour
day
year
1
2
4

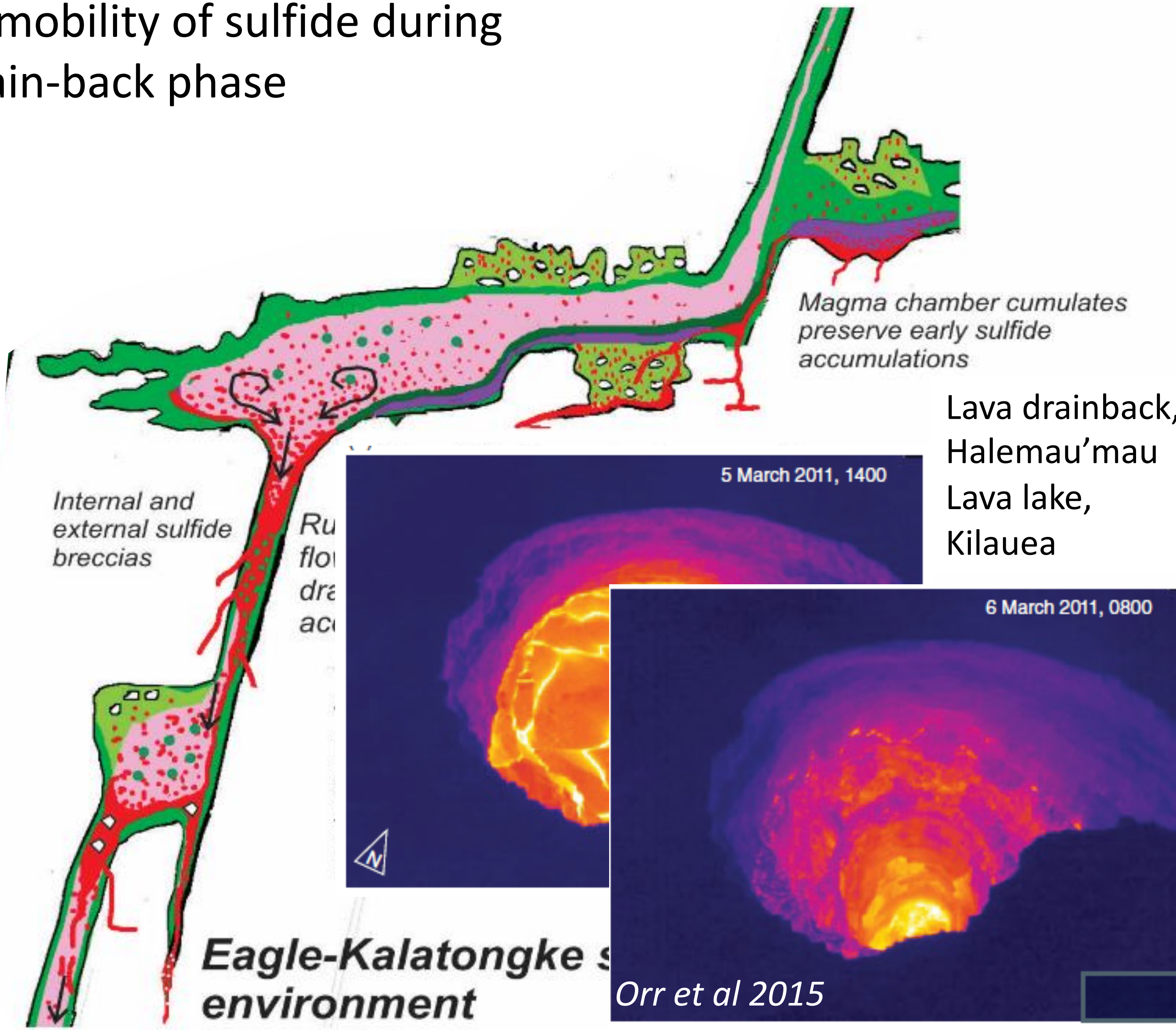
3. Development of density driven sulfide rich gravity currents causing back-flow along floor of conduit

Elutriation column



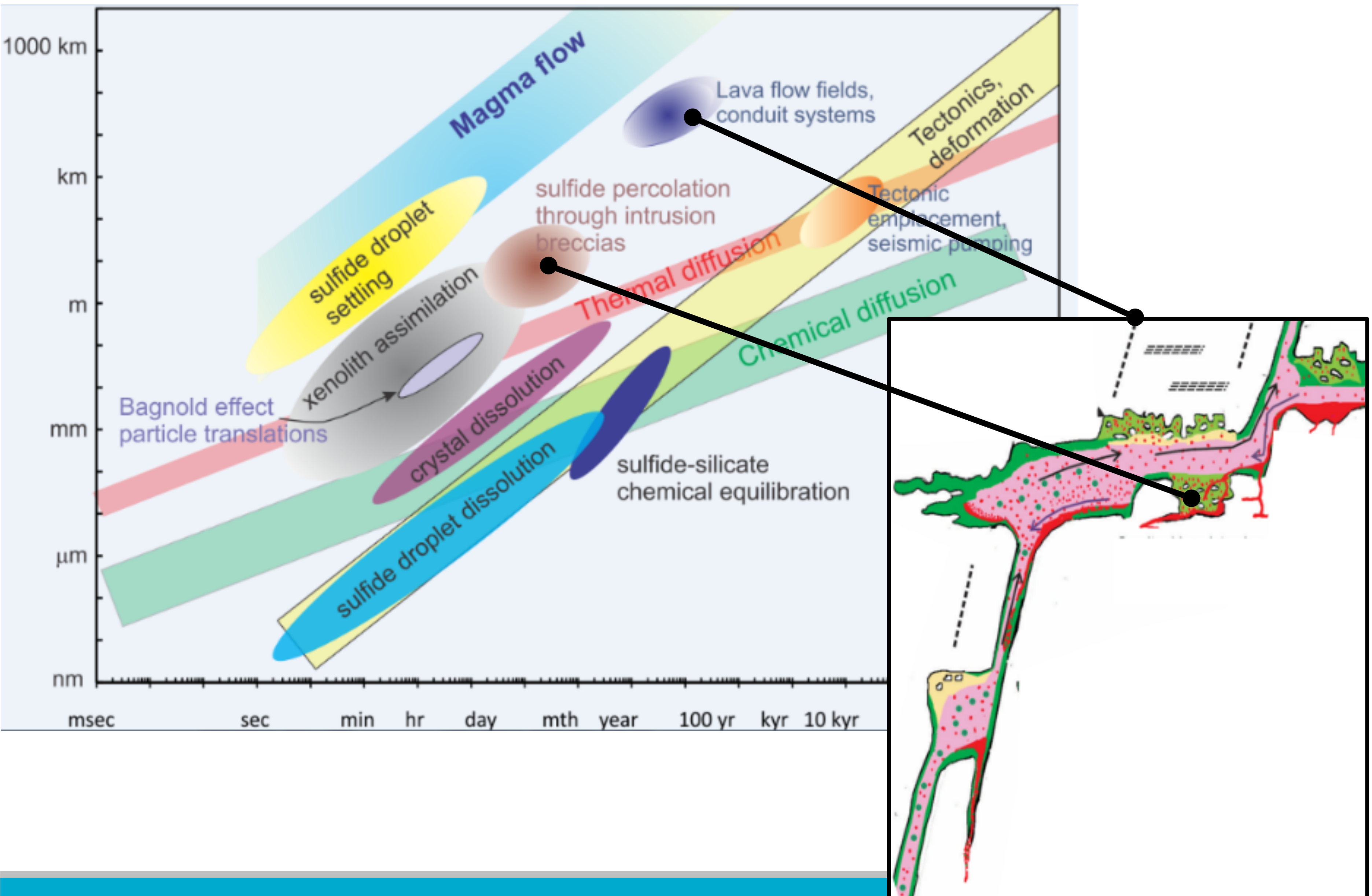


Late stage mobility of sulfide during magma drain-back phase



Lava drainback, Halemau’mau Lava lake, Kilauea

Orr et al 2015


1000 km
km
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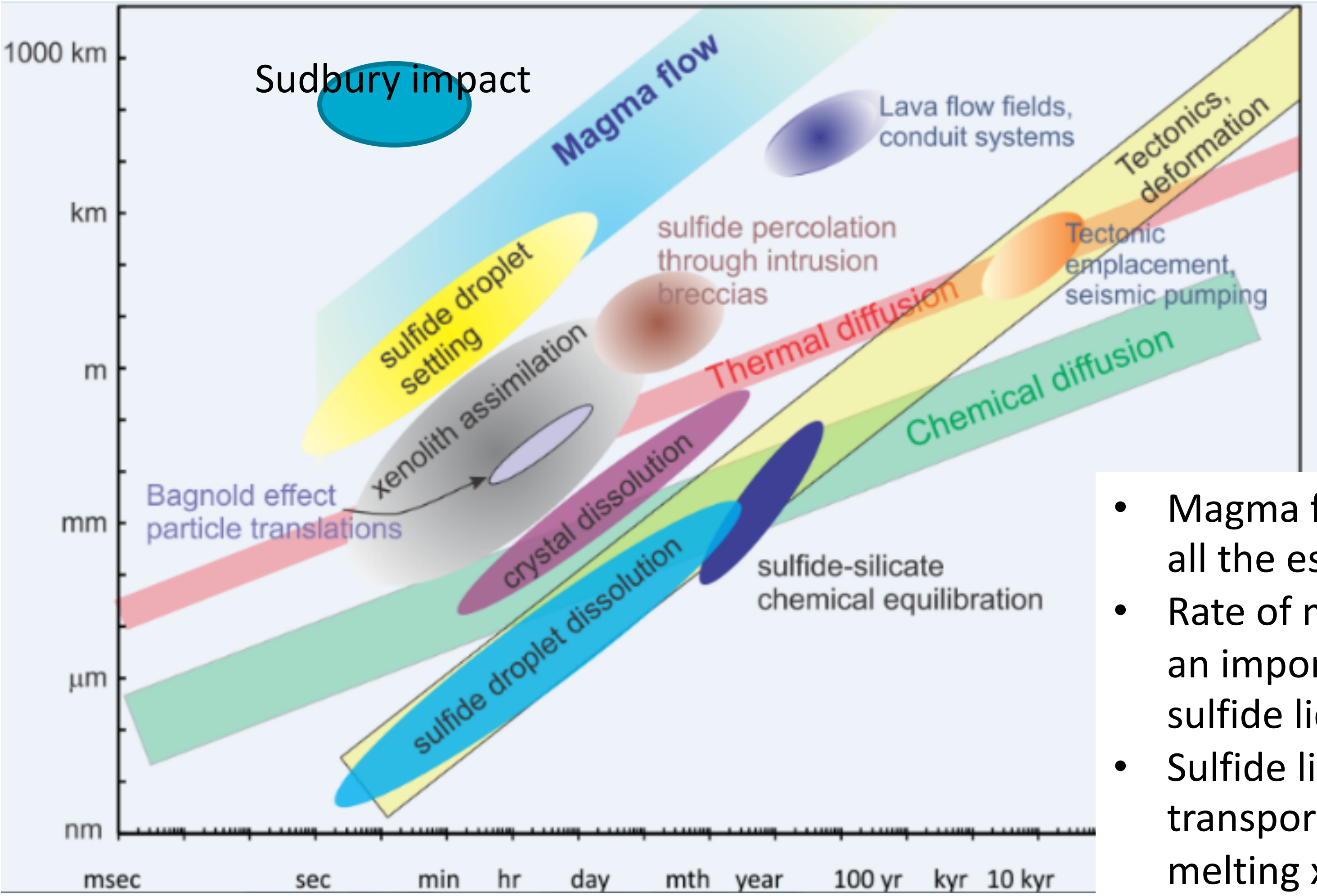
year
100 yr
kyr
10 kyr
Magma flow
Lava flow fields, conduit systems
Tectonics, deformation
sulfide percolation through intrusion breccias
Tectonic emplacement, seismic pumping
sulfide droplet settling
Thermal diffusion
xenolith assimilation
Chemical diffusion
Bagnold effect particle translations
crystal dissolution
sulfide-silicate chemical equilibration
sulfide droplet dissolution

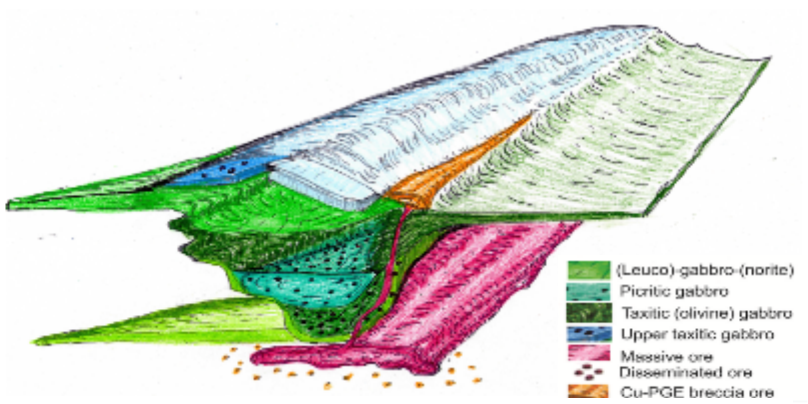


Take home messages:
Scaling relationships are key
Kinetics matter

- Magma flow is the fastest of all the essential processes
- Rate of melting of xenoliths is an important control on sulfide liquid generation
- Sulfide liquid may be transported largely within melting xenoliths
- Sulfide droplets settle or segregate much faster than they can equilibrate
- Ore formation requires multi-stage recycling in long lived trans-crustal conduit systems

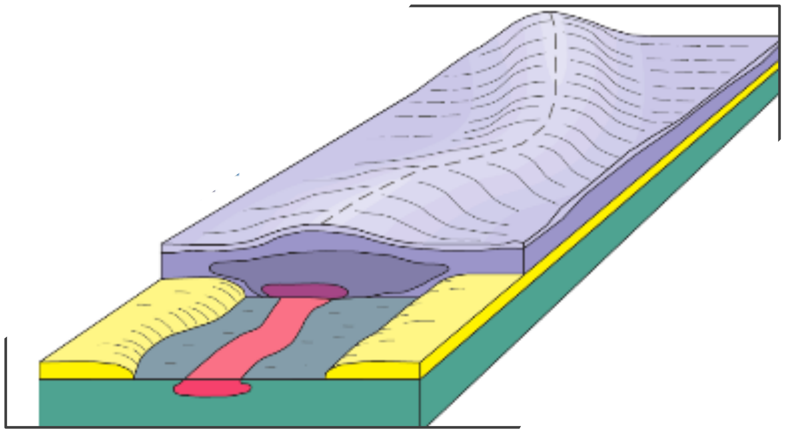
Komatiite hosted and mafic intrusion hosted ores: similarities, differences

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

Komatiite-hosted

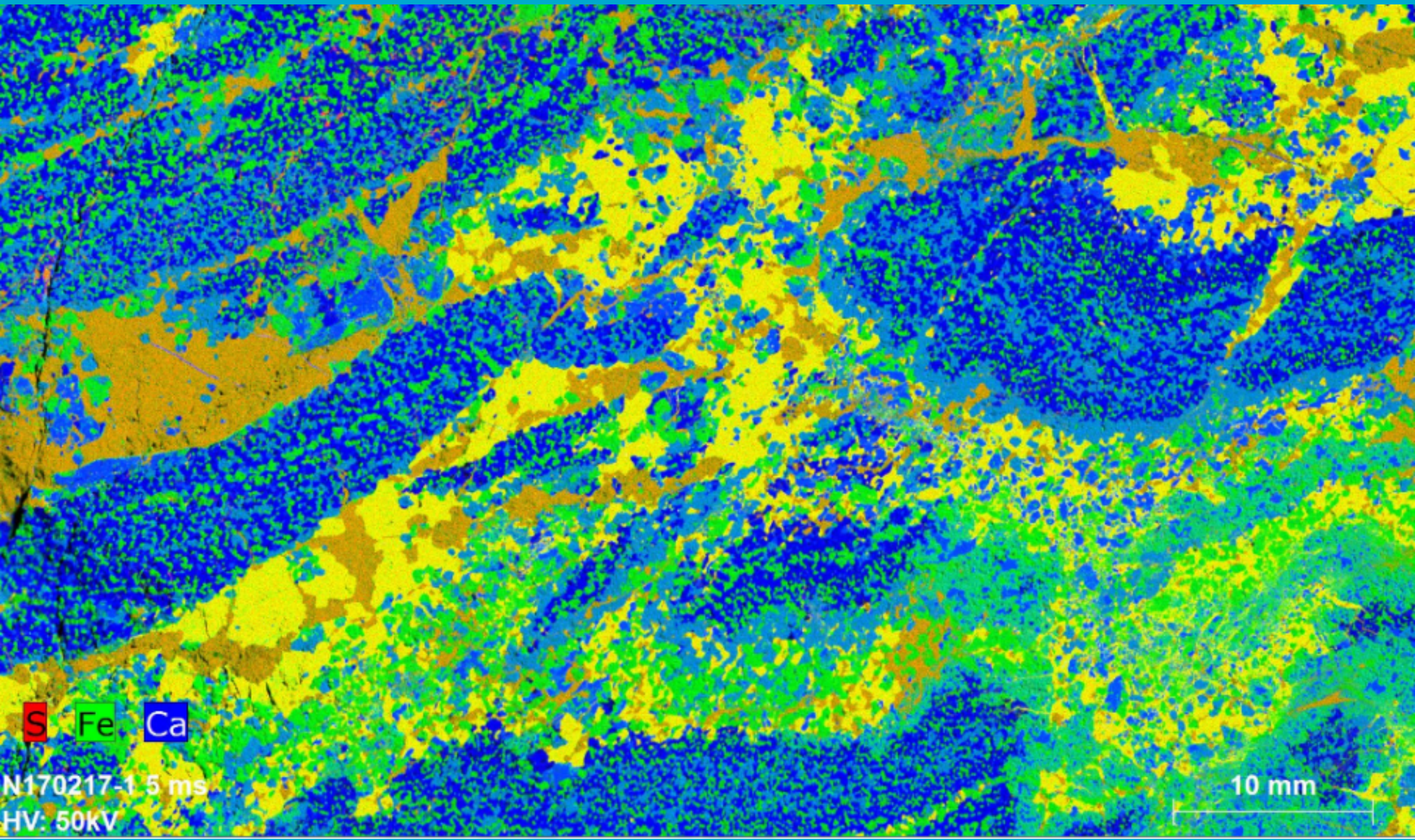


- Lava tubes or channels
- Thermal/mechanical erosion of floor and roof rocks
- Mainly conformable ores at basal contacts
- No “taxites” – contaminated pyroxenites sometimes
- Breccia ores rare, restricted to passive intrusion breccias

Can we explain some of these differences?

Detection and evaluation criteria – silicate signals

- High abundances of cumulate rocks, particularly olivine and chromite bearing cumulates.
- Characteristic tube-like morphologies, forming a continuum with elongate boat-shaped flared or blade-shaped dykes, in otherwise more convoluted intrusive systems.
- Evidence for strong interactions with country rocks such as xenoliths (particularly strongly reacted xenoliths showing evidence of extensive melt extraction, as at Voisey's Bay); marginal breccias; large thermal aureoles; pegmatoidal marginal rocks ("taxites"); characteristic zoning patterns in cumulus silicates
- Proxies for anomalously slow magmatic cooling rates in relation to small size of intrusion such as well developed coarse-grained poikilitic textures; extensive thermal aureoles;.
- Evidence of sulphide liquid fractionation into Cu-Pt-Pd rich and Ni-rich, Cu poor components, a process that requires environments of slow and prolonged cooling.



Thanks for listening!

steve.barnes@csiro.au