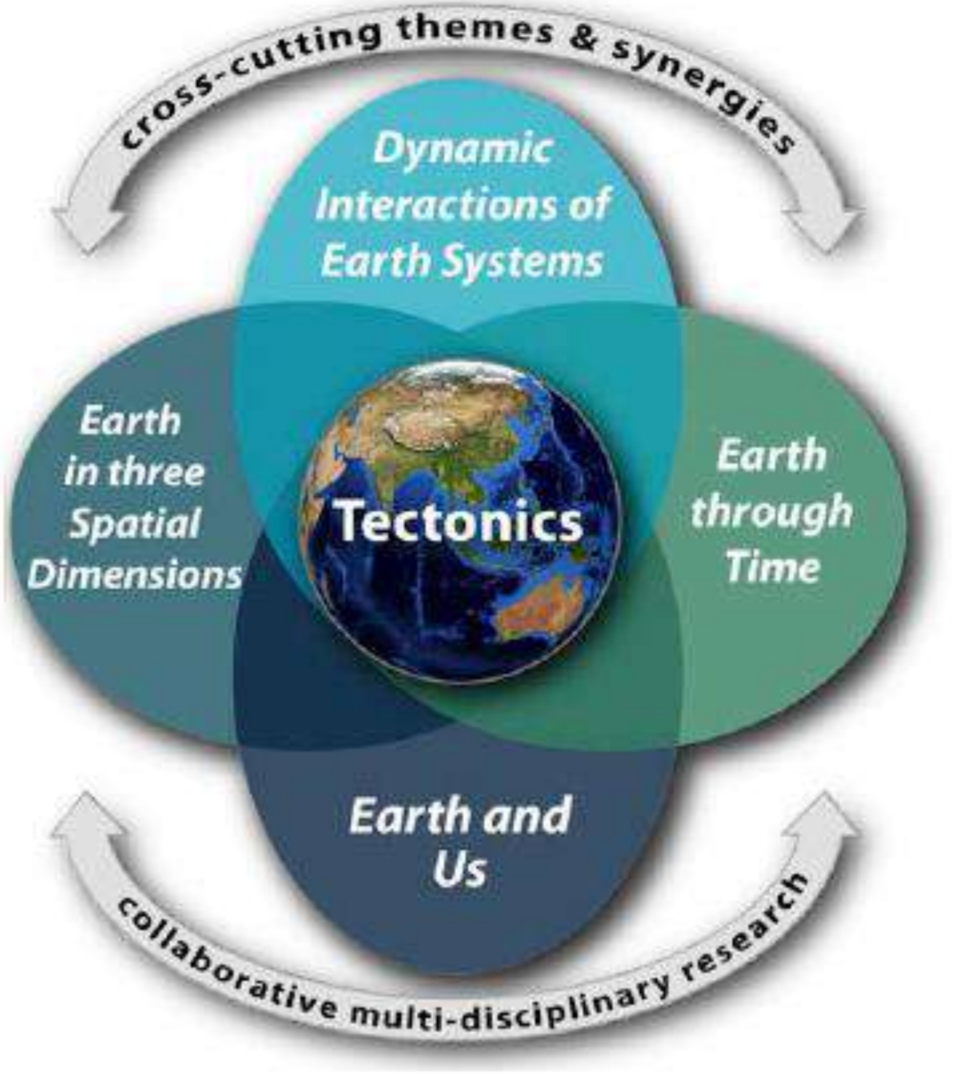
Rheology of the Lower Crust:
Concepts, Methods, Observations

1) Lecture 1: Rheology of the Lower Crust: General importance & Recap of Solid state deformation mechanism and flow laws

2) Quantitative Orientation Analysis: How does it work? How can it help me to understand the Lower Crust – rheology and evolution

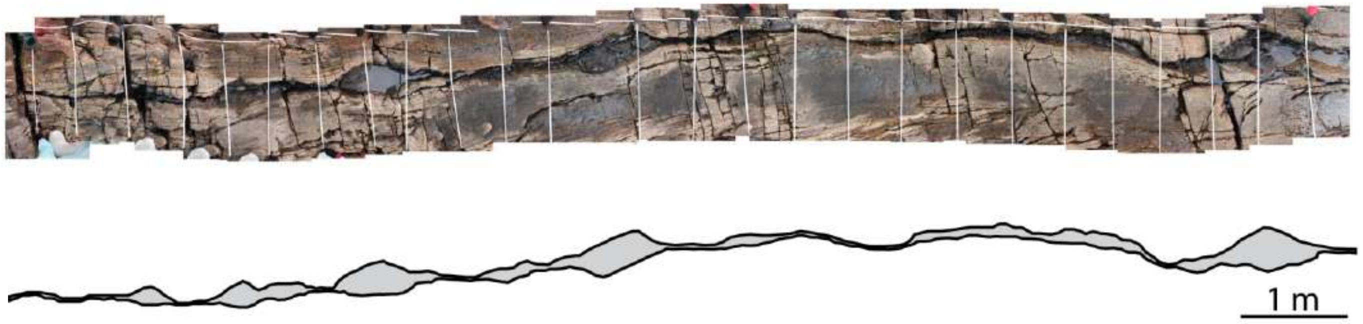
3) Quantitative Orientation Analysis: Examples and Opportunities - Rheology of the Lower Crust

4) Rheology of the Lower Crust: Other measurements and considerations



Modified after Huntington & Klepeis et al. 2017

Lecture 4: Rheology of the Lower Crust: Other measurements and considerations



1. Case study - Rheology from pinch and swell structures
2. Case study – Melt presence in the lower crust -> rheology and signatures
3. Link Orientation/Phase analysis and seismic signature

Gardner et al. JSG 2015, 2016

1) Case study - Rheology from pinch and swell structures

Gardner et al. JSG 2015, 2016

Rheology of the lower crust

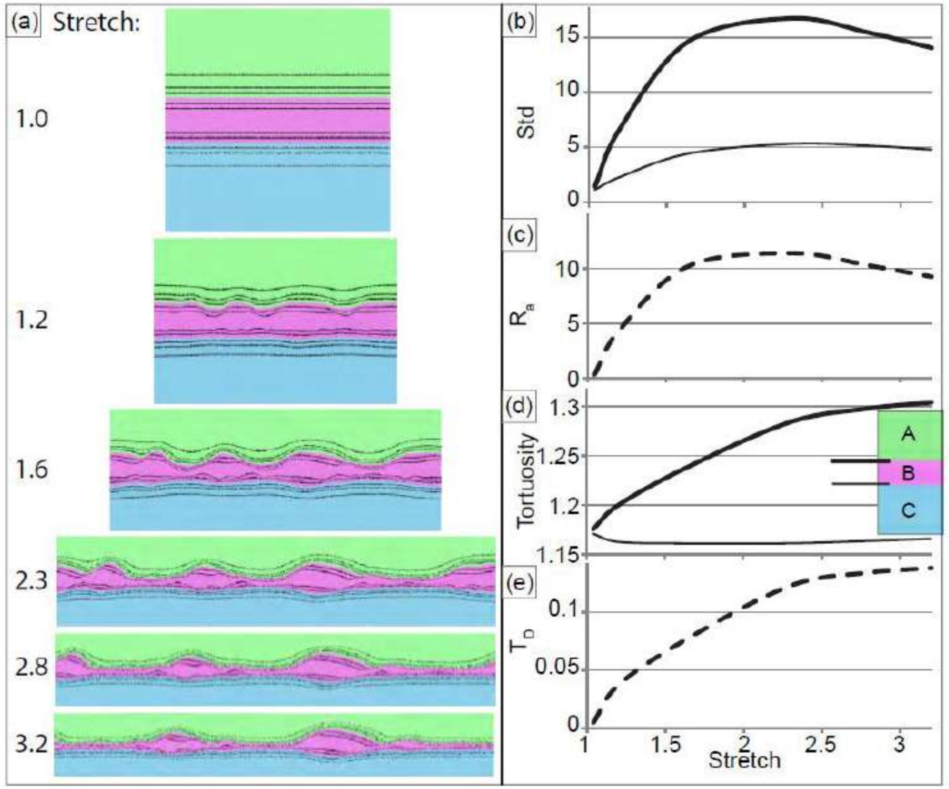
Problem:

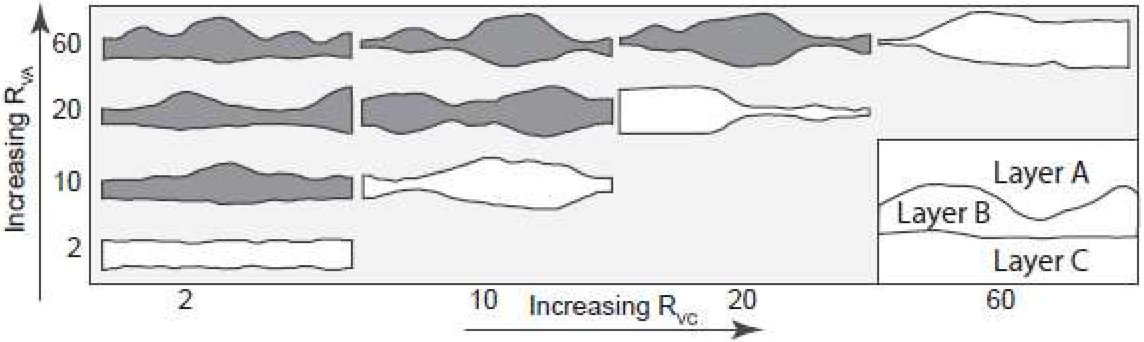
- Most experiments are done on monomineralic rocks
- BUT most rocks are polymineralic
- What is the rheology of a polymineralic rock then????

Idea: Using Pinch and Swell structures

1) Take three lithologies (one near monomineralic) deforming in the field – determine general flow law using microstructure
2) Using monomineralic lithology to calculate viscosity of one of the layers
3) Use numerical models to calculate viscosity difference of A/B and B/A
(combined Mohr-coloumb ("brittle") behavior with viscous flow)

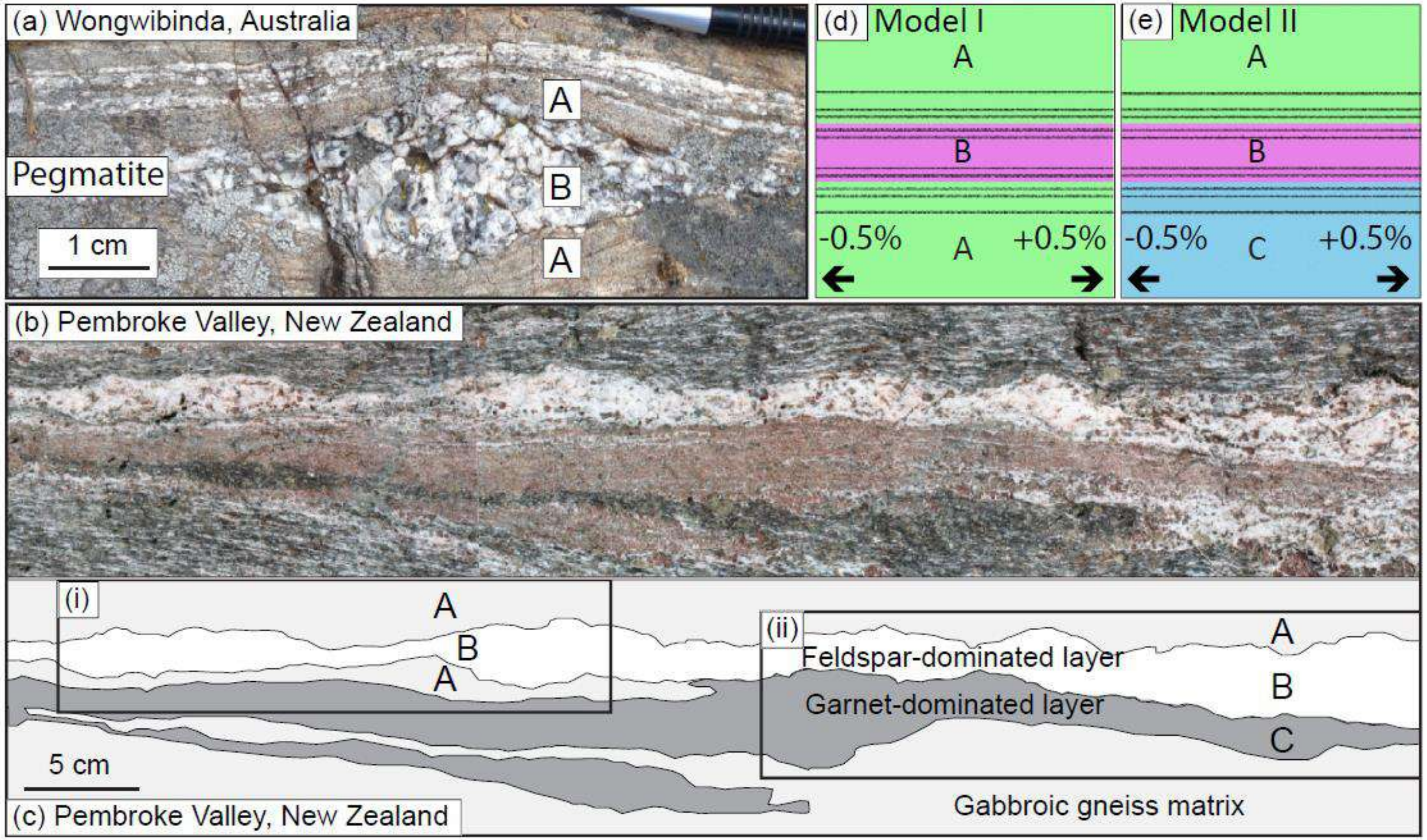
=> Rheological property of polymineralic rocks!!





1) Case study - Rheology from pinch and swell structures

Gardner et al. JSG 2016



Step 1
Identify the three lithologies – determine general flow law using microstructure

A) gabbroic-gneiss (poly)

B) Anorthosite (mono)

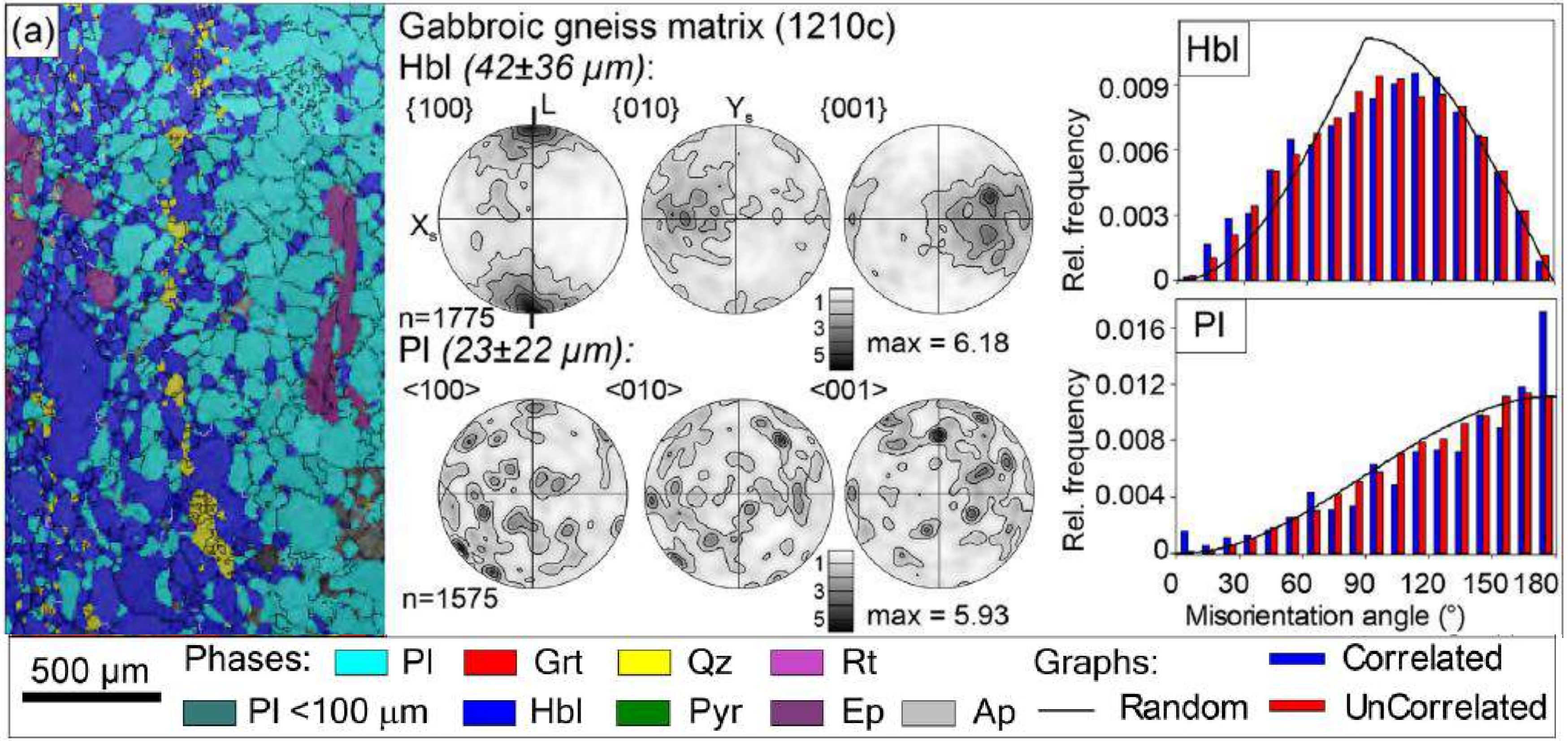
C) Grt-Fsp-gneiss (poly)

Step 2
Determine general flow law using microstructure for each -> identify deform. mechanisms

1) Case study - Rheology from pinch and swell structures

Gardner et al. JSG 2016

A) gabbroic-gneiss (poly) B) Anorthosite (mono) C) Grt-Fsp-gneiss (poly



Step 2

Determine general flow law using microstructure for each -> identify deform. mechanisms

Bulk flow law:
Diffusion creep/GBS
Neutonian flow, n=1

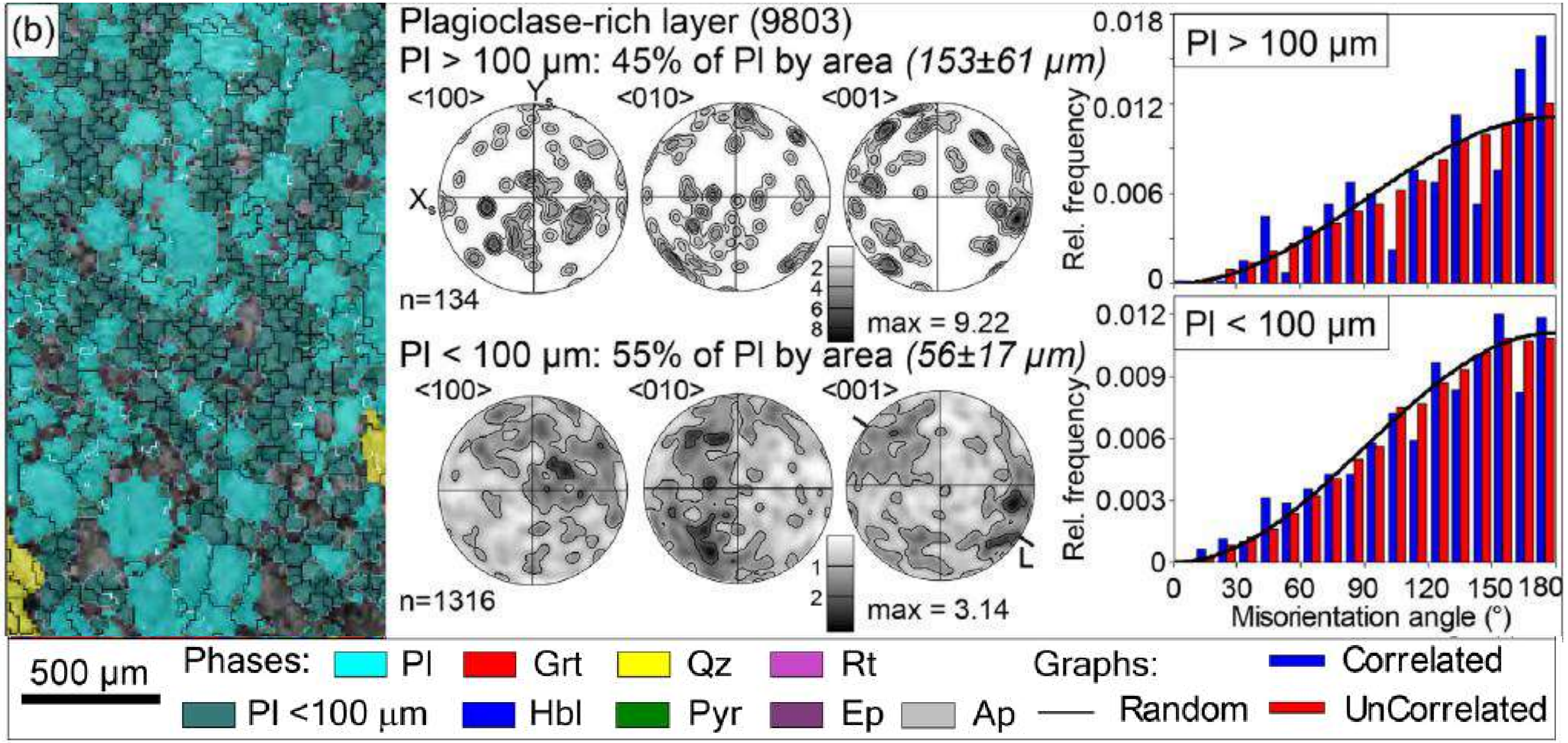
Hrbl: -> CPO characteristics for diffusion creep (anisotropic diffusion rates relative to axes)

Plag-> Lack of CPO characteristics for GBS

1) Case study - Rheology from pinch and swell structures

Gardner et al. JSG 2016

A) gabbroic-gneiss (poly) **B) Anorthosite (mono)** C) Grt-Fsp-gneiss (poly



Step 2
Determine general flow law
using microstructure for each
-> identify deform. mechanisms

Bulk flow law:
Diffusion creep/GBS
Neutonian flow, n=1

Plag (small and large)
-> Lack of CPO characteristics for GBS/Diffusion creep

Large grains: Take up little deformation (no Disloc creep)
-> small grains form IWL – take up all the strain

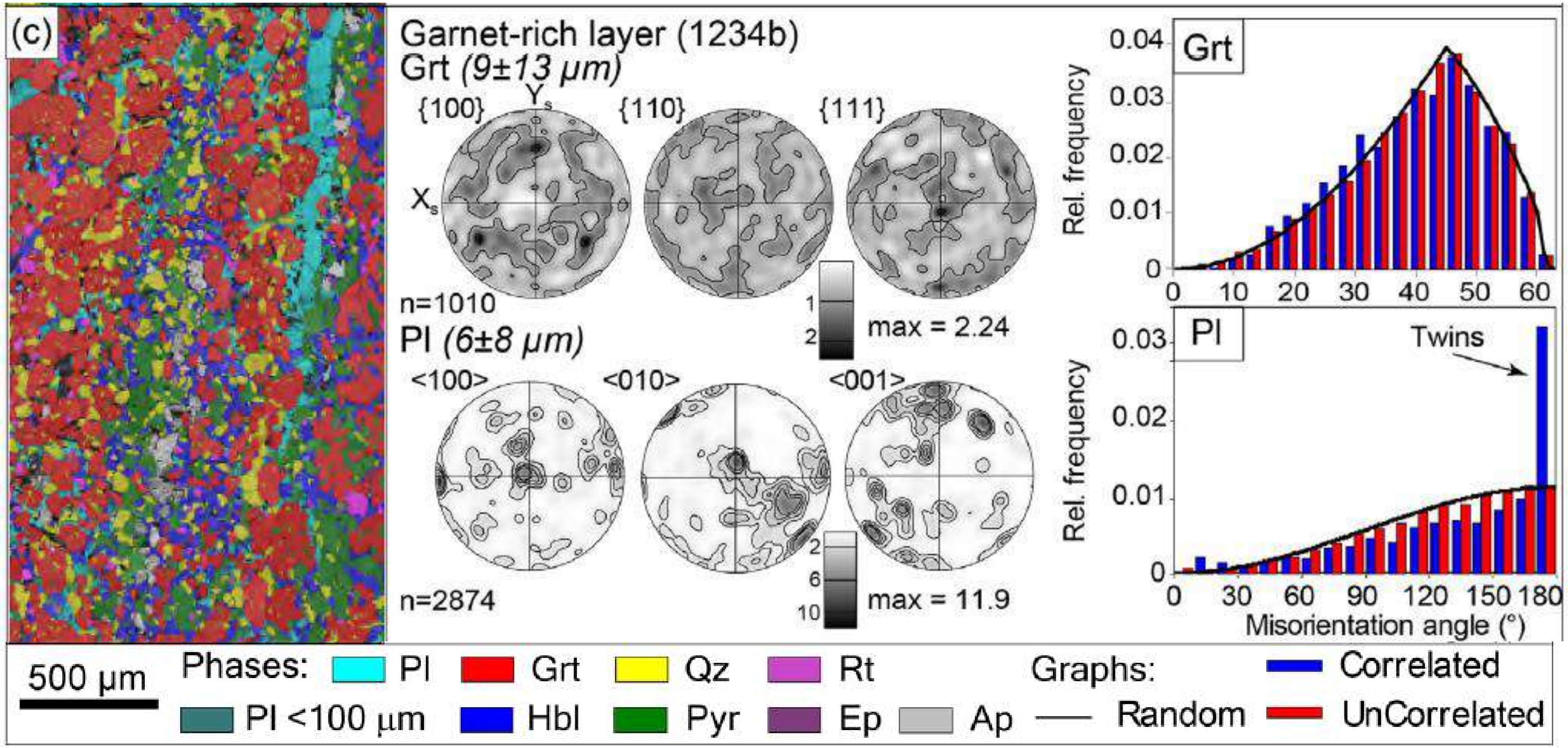
1) Case study - Rheology from pinch and swell structures

Gardner et al. JSG 2016

A) gabbroic-gneiss (poly)

B) Anorthosite (mono)

C) Grt-Fsp-gneiss (poly



Step 2

Determine general flow law using microstructure for each -> identify deform. mechanisms

Bulk flow law:

Diffusion creep/GBS

Neutonian flow, n=1

Grt/Pl: -> CPO characteristics for diffusion creep

Step 3

Use monomineralic rock type to determine viscosity of that layer using experimental data

Monomineralic rock type: Plag rich, anorthositic layer

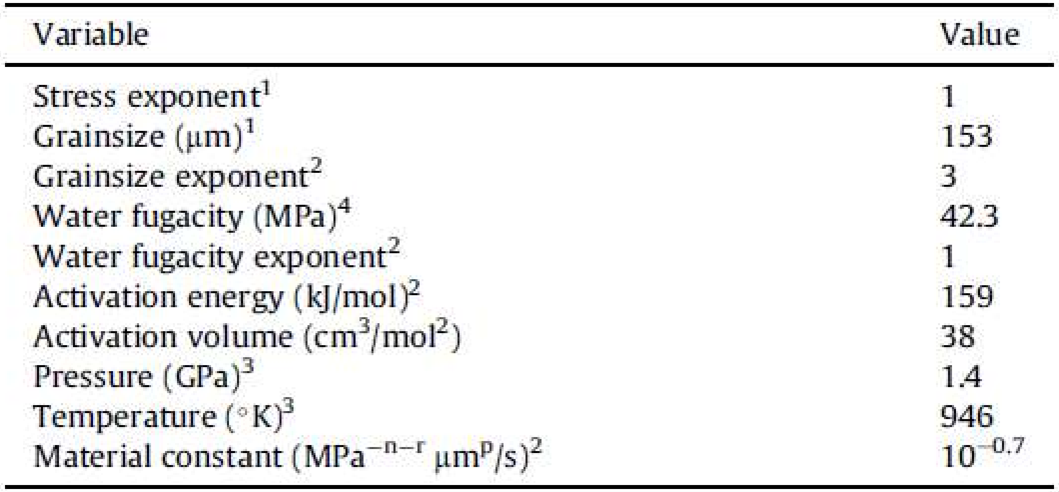
General flow law

$$\eta = 1/2\left(Ad^{-p} f_{\mathrm{H_2O}}^{r} \exp\left(-\frac{E^* + PV^*}{RT}\right)\right)$$

based on experiments of Rybacki et al. 2006

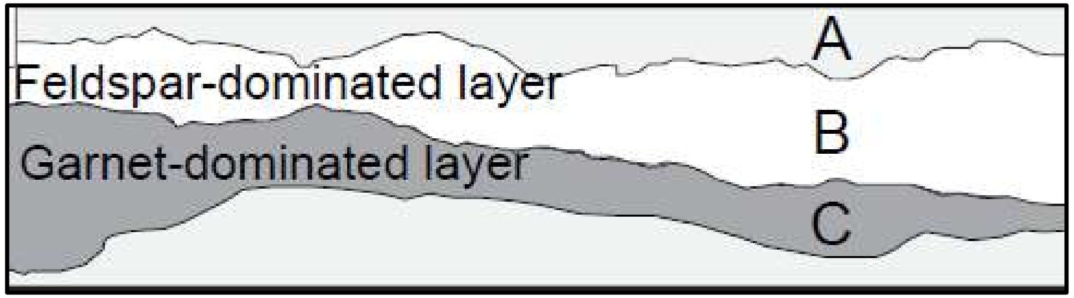
Values from

- Microstructures
- PT of other work (e.g. Daczko et al. 2002, Smith, Piazolo et al. 2015)



Variable	Value
Stress exponent[1]	1
Grainsize (μm)[1]	153
Grainsize exponent[2]	3
Water fugacity (MPa)[4]	42.3
Water fugacity exponent[2]	1
Activation energy (kJ/mol)[2]	159
Activation volume (cm^3/mol^2)	38
Pressure (GPa)[3]	1.4
Temperature (°K)[3]	946
Material constant ($MPa^{-n-r}\ \mu m^p/s$)[2]	$10^{-0.7}$

viscosity of ~1.1×10^{17} Pa s



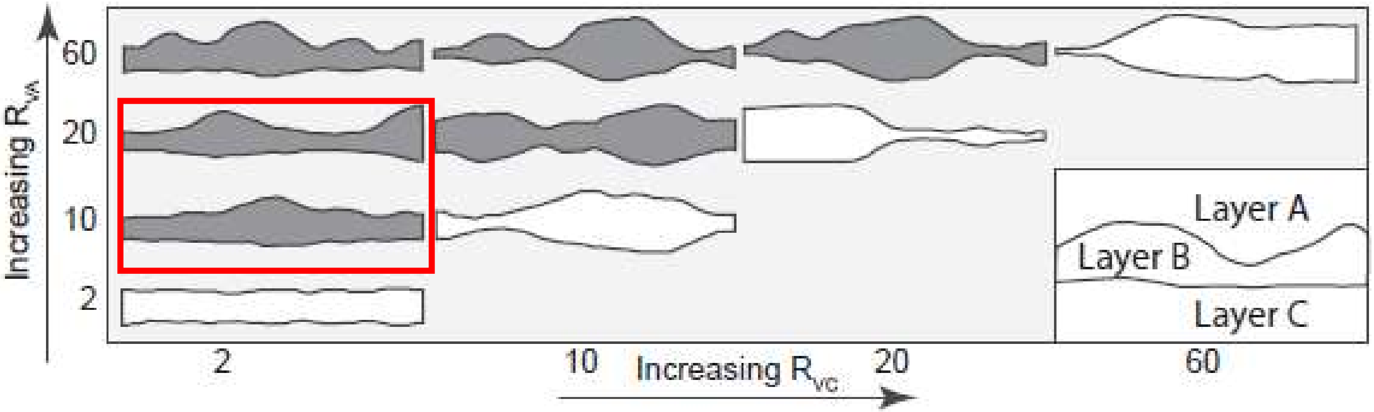
Layer B:

viscosity of ~1.1×10^{17} Pa s

Step 4

Use geometry of the three layers A, B, C

-> determine in comparison with numerical model relative viscosities R_{VA} & R_{VC}



Layer A: using R_{VA} = 10 - 40

2.8×10^{15} to 1.1×10^{16} Pa s

Layer C: using R_{VC} = 2

~5.6×10^{16} Pa s,

Post-seismic viscosity mid/lower crust

~10^{18}–10^{19} Pa s

Tibetian plateau (Clark & Royden,2000)

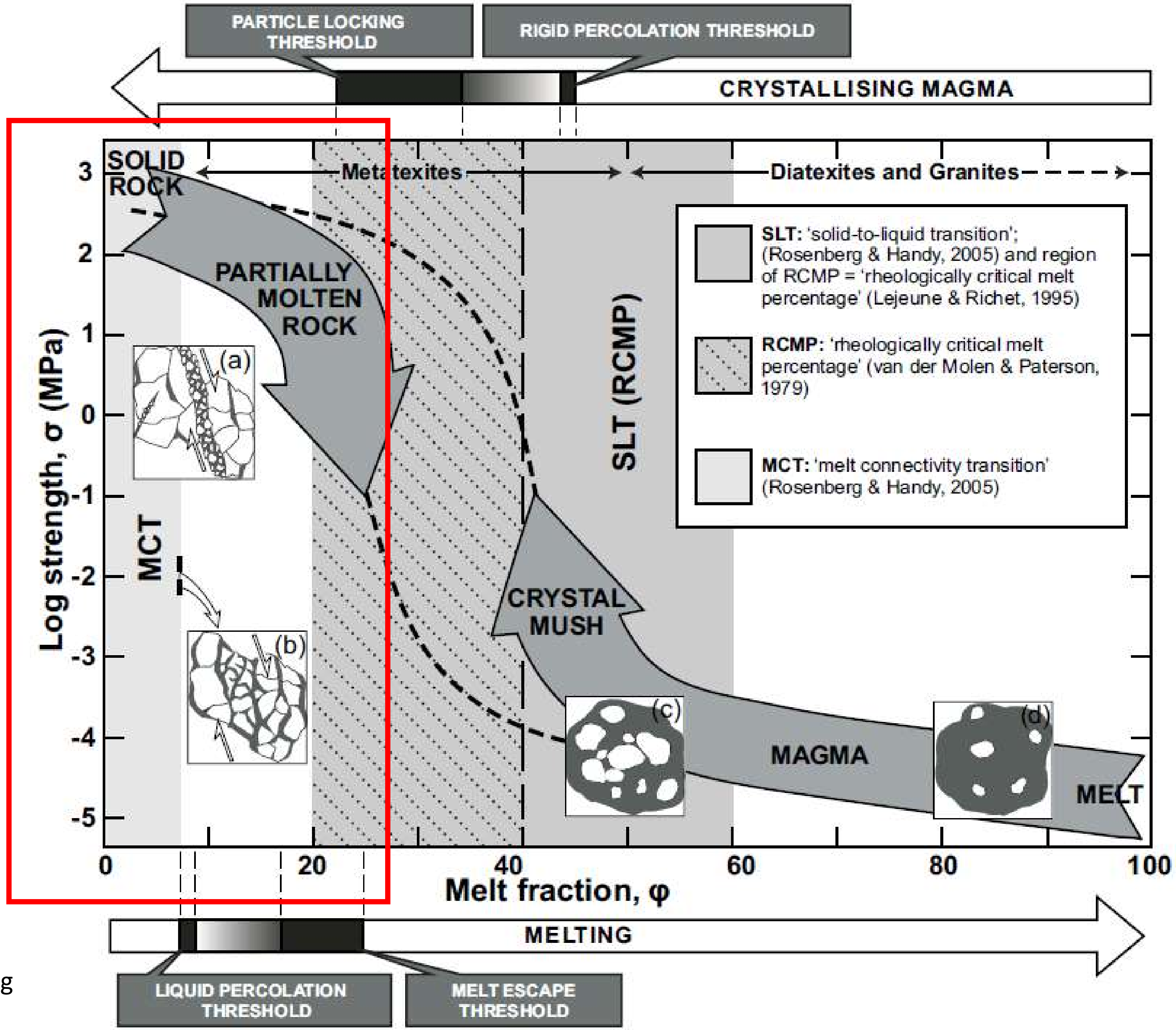
10^{16} to 10^{18}

Take home message:

Grt bearing rocks not always strong, Arc root can be quite soft

2) Case study – Melt presence in the lower crust - Rheology

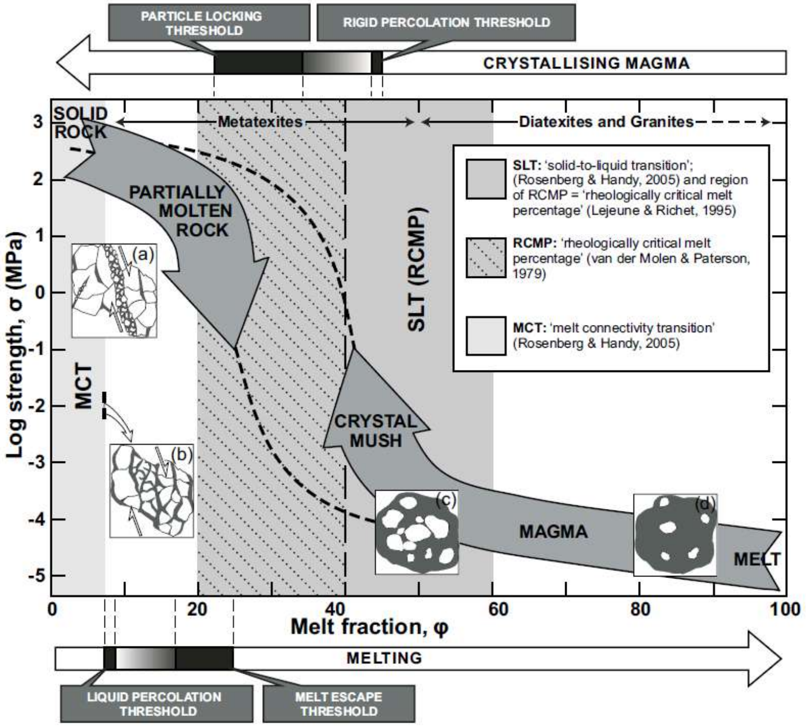
Characteristics of melt – rock mixtures– experimental/ Theoretical?

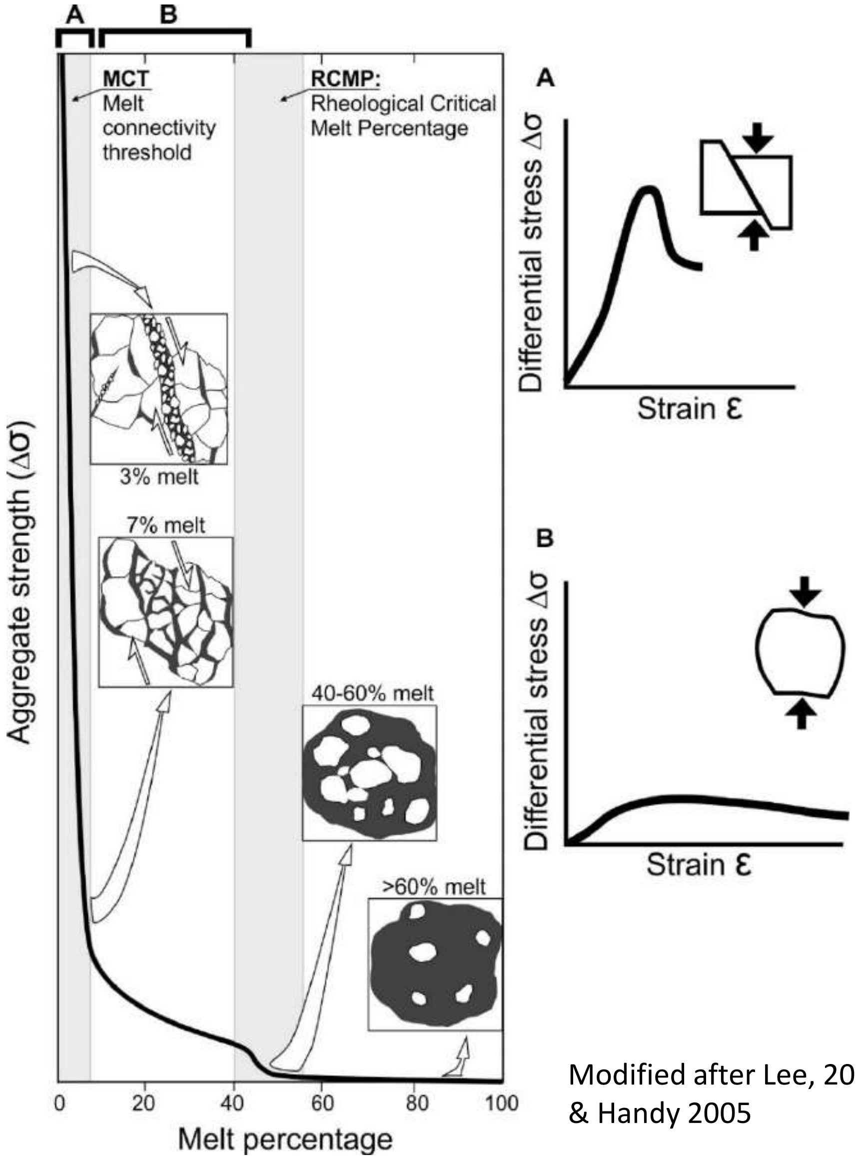


Modified after Lee, 2019 & Rosenberg & Handy 2005, Tikoff et al. 2013, ref. therein

2) Case study – Melt presence in the lower crust - Rheology

Characteristics of melt – rock mixtures– experimental/ Theoretical?



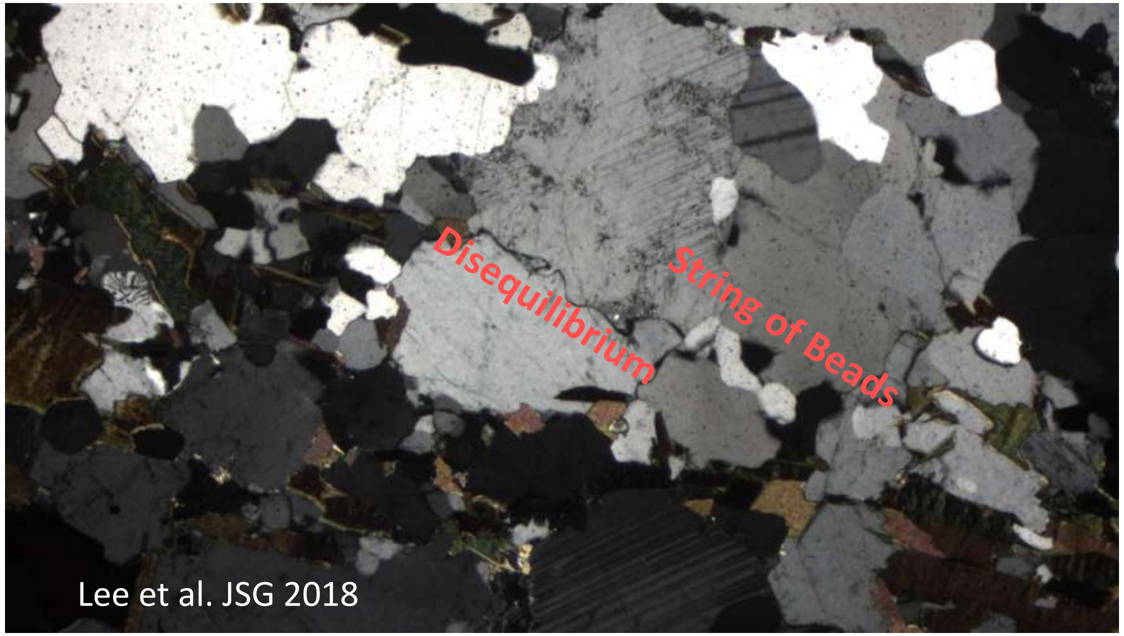


Small amount of melt = big rheological effect

How can we recognize melt presence if only small amounts?

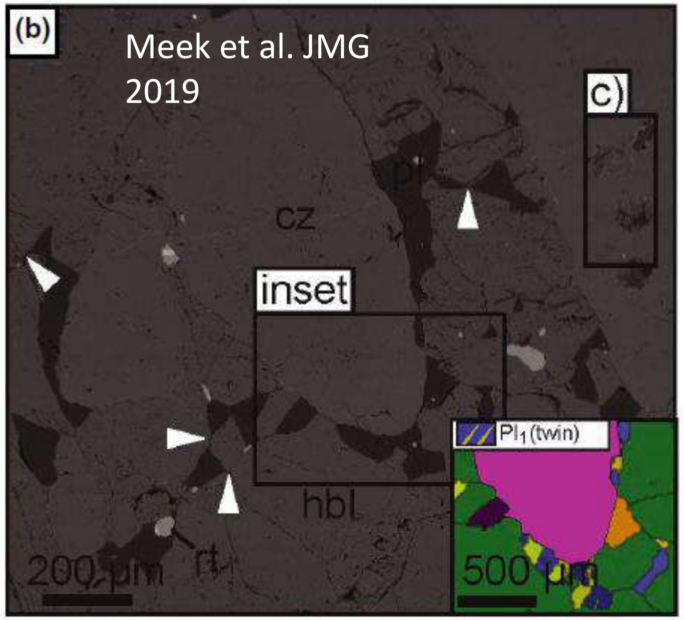
Modified after Lee, 2019 & Rosenberg & Handy 2005

How can we recognize melt presence if only small amounts?



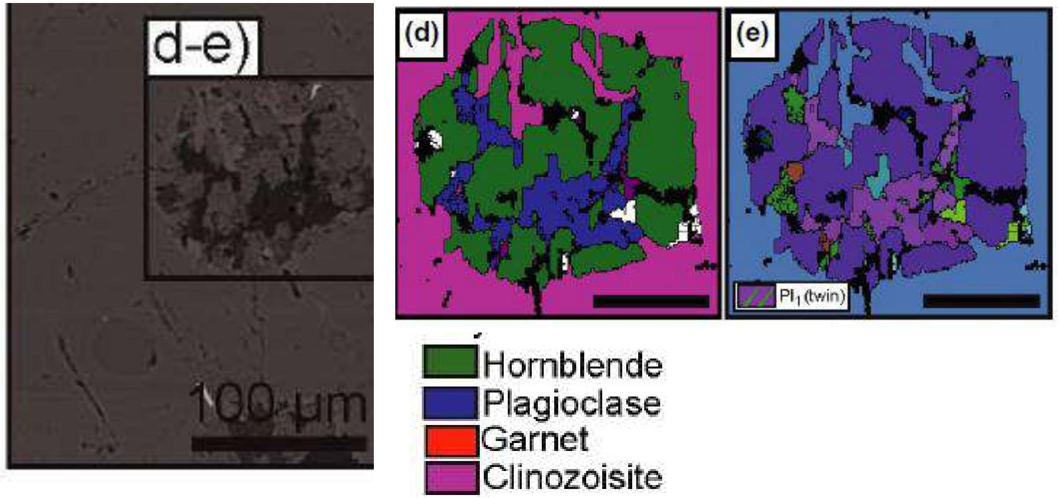
Lee et al. JSG 2018

Interstitial phases
Same orientation=>
3D connection

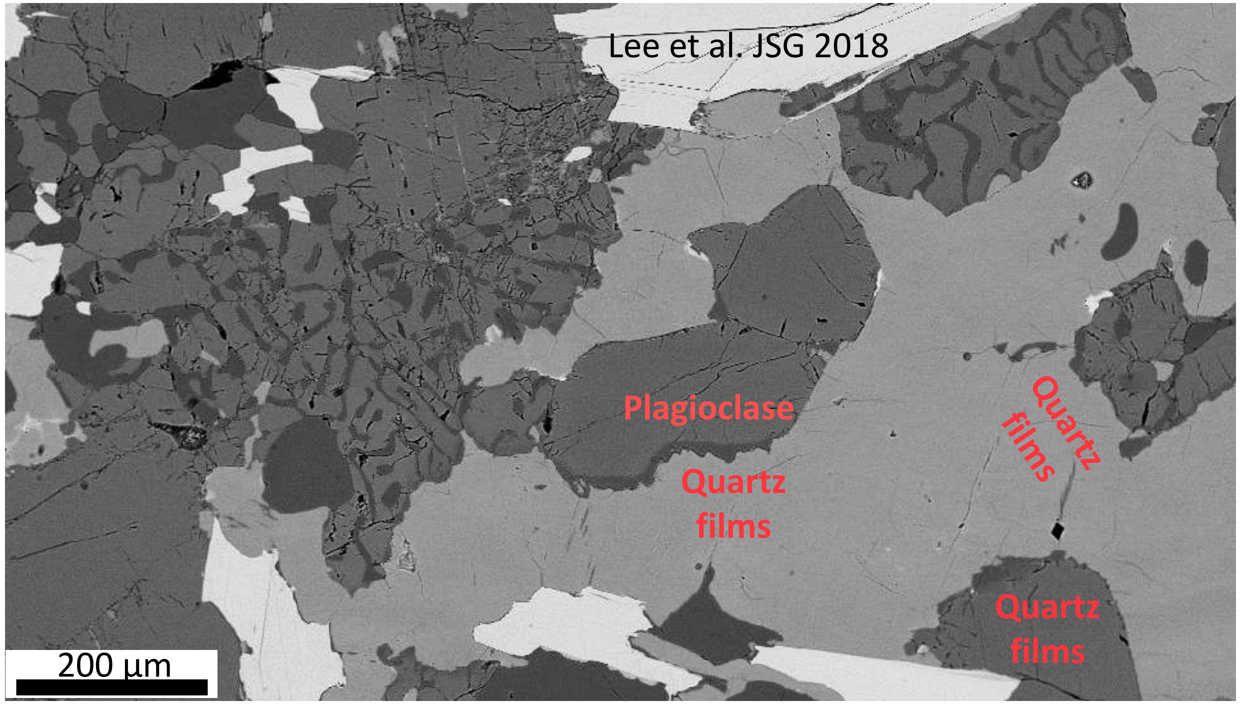


Meek et al. JMG 2019

Melt inclusions



Meek et al. JMG 2019



Lee et al. JSG 2018

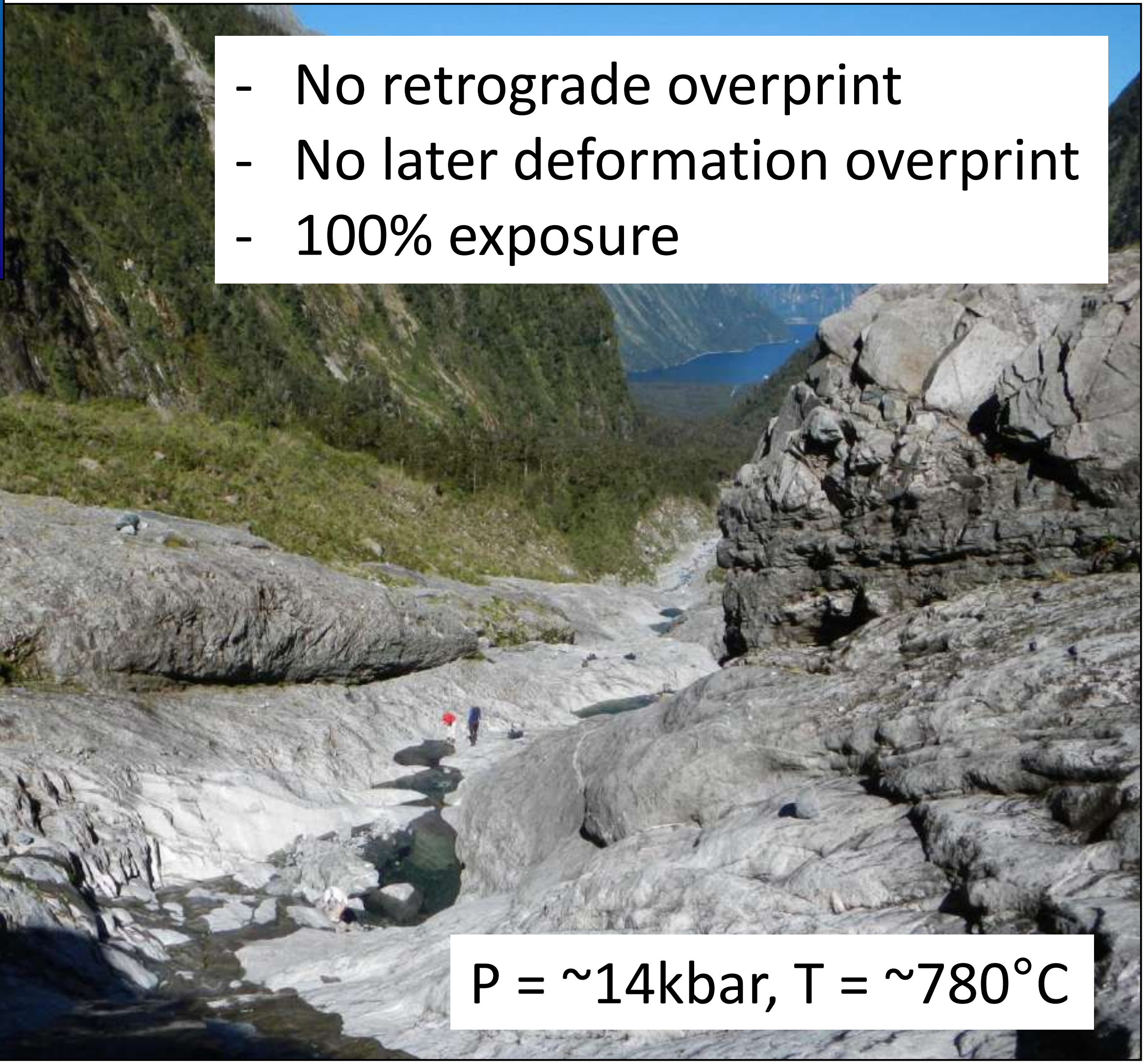
Melt in the Lower crust

Stuart et al. (2016), G^3

Stuart et al. (2018) JPet
Stuart et al. (2017) JMG

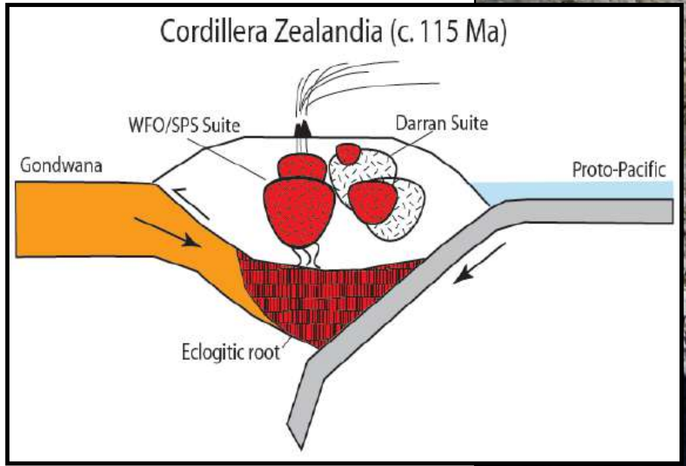
M. Jackson:
Kohistan Arc =
Fiordland

Deep
Continental Arc



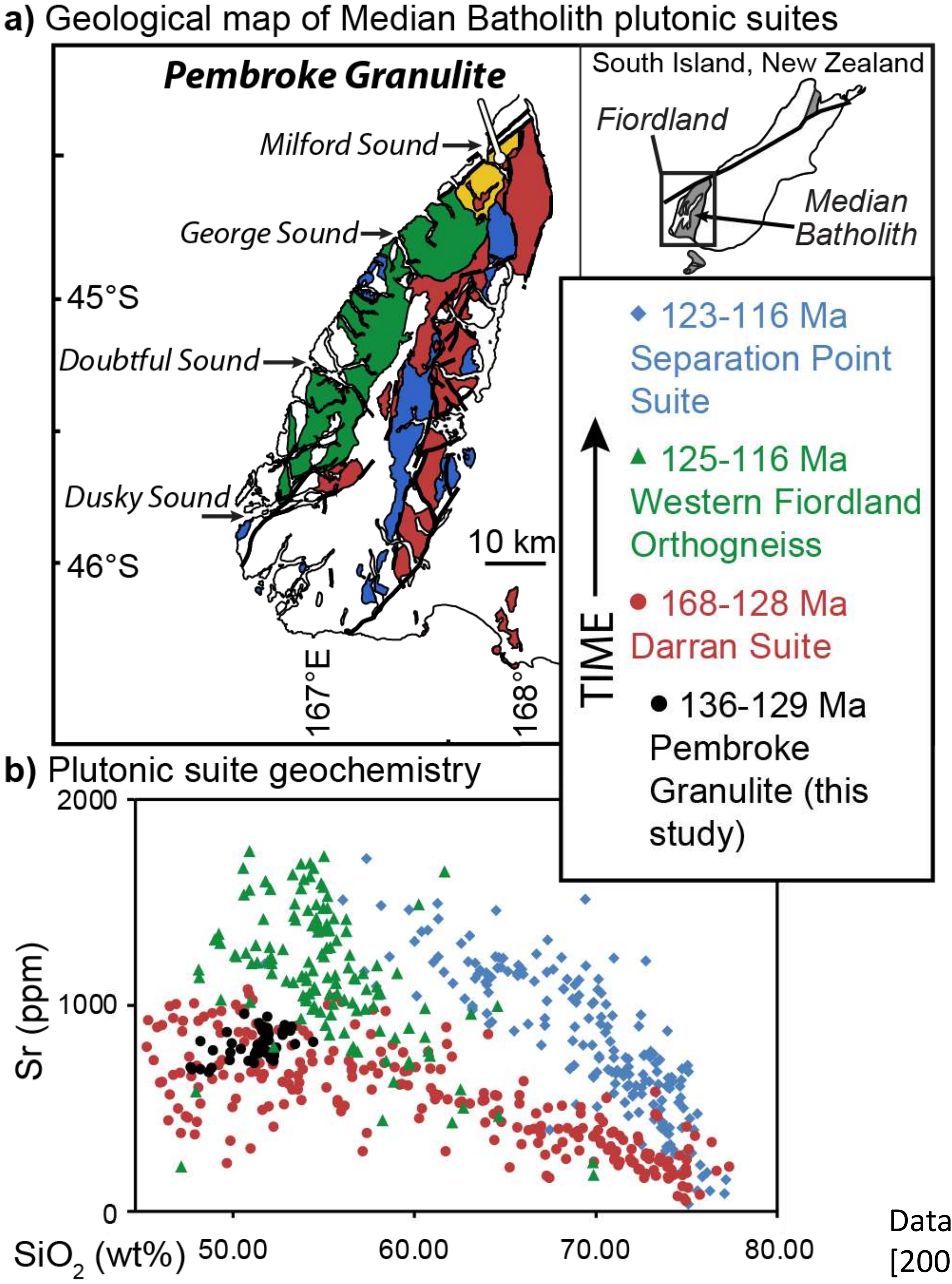
- No retrograde overprint
- No later deformation overprint
- 100% exposure

P = ~14kbar, T = ~780°C



Milan et al. Sci. Reports 2017

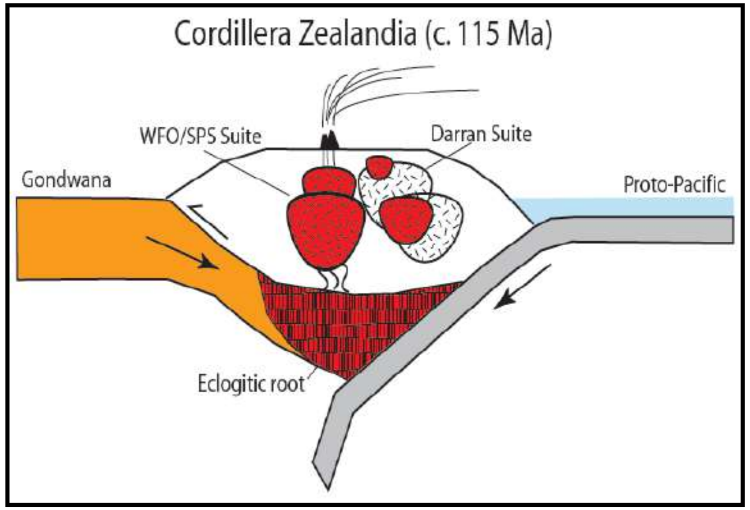
Pembroke Valley, Fiordland, NZ



PEMBROKE VALLEY

- >127 Ma Low-Sr
- Low flux ~14 km^3/my/km arc

- <127 Ma High-Sr
- Flare-up >100 km^3/my/km arc (Milan et al. Sci. Reports 2017)

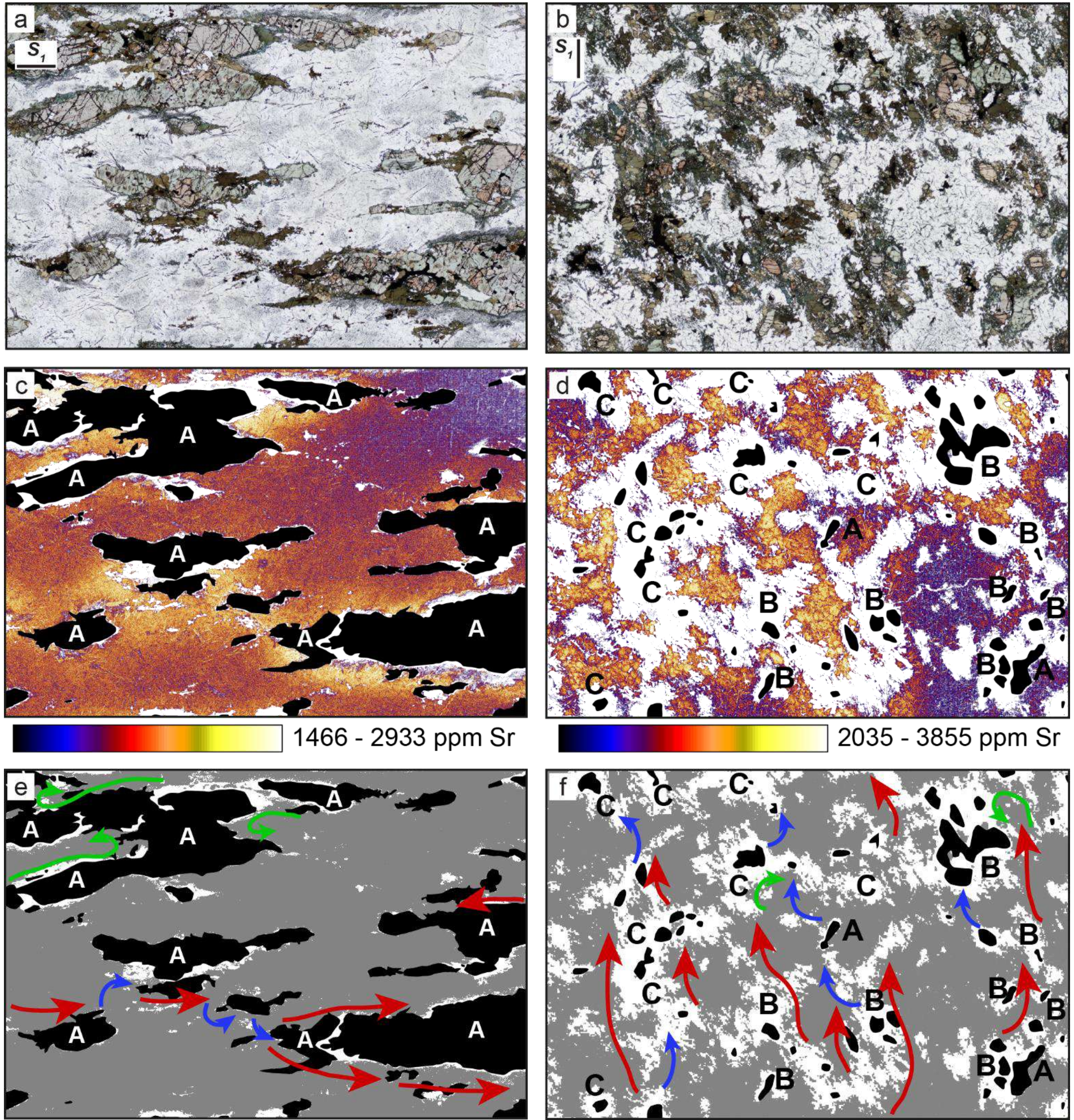


Data: this study; Allibone et al. [2009a]; Allibone et al. [2009b]; Hollis et al. [2003]

How can we recognize melt presence if in situ or external melt?

(Assymmetric) Reaction textures and chemistry
-> metasomatism
-> fluxing melt

Do we have similar structures in e.g. mafic complex? (Kohistan – seems yes….)



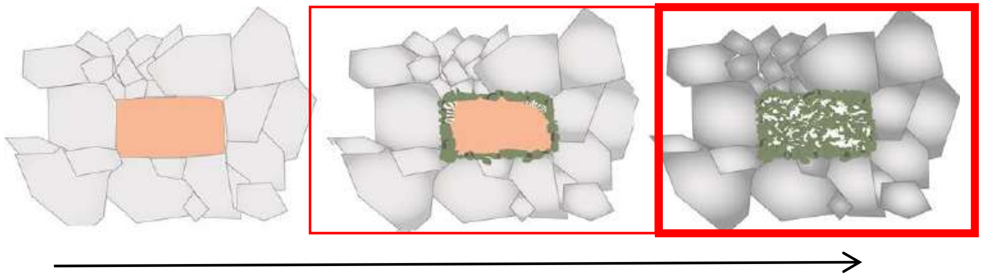
Synchrotron mapping: patterns of Sr variation in plag

- FOV = 18 & 12 mm
- Px = black
- Corona = white
- Coloured = plag
- Sr enriched next to coronas
- S_1 parallel = red
- Embayment = green
- Bridges = blue

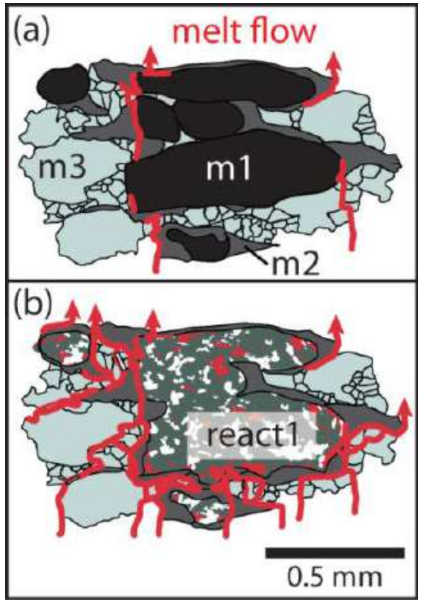
Stuart et al. (2016), G^3

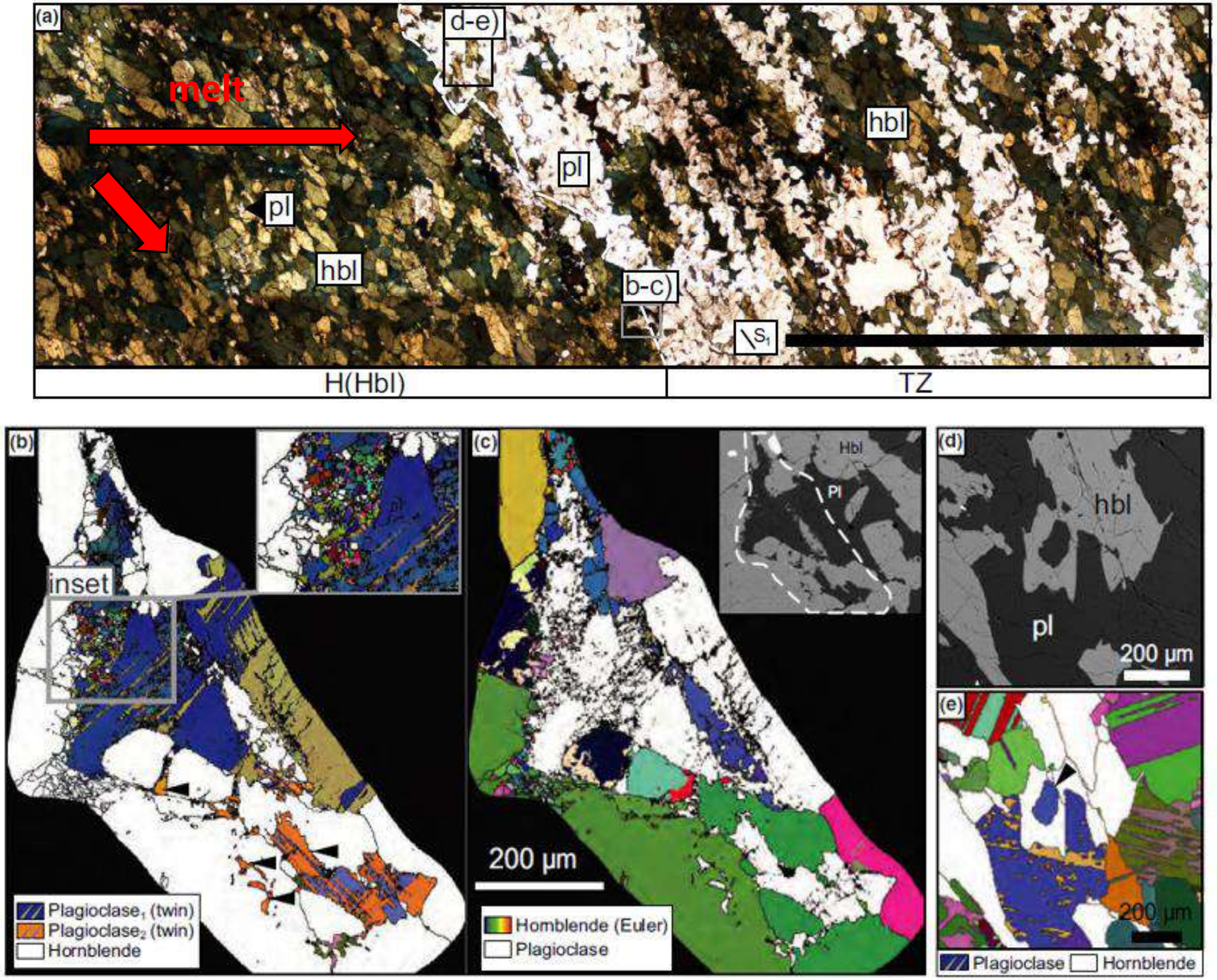
Metasomatism via diffuse porous melt flow of external melt -> More common than we think?

Hydrous Melt
-> reaction in open system



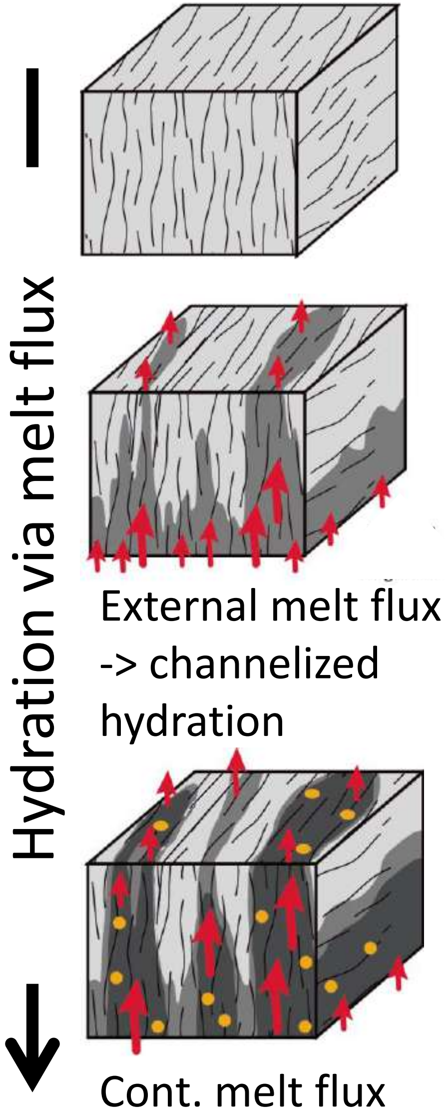
Stuart et al. JMG 2018





Meek et al. JMG 2019

Daczko et al. (2016)
Scientific Reports



External melt flux
-> channelized
hydration

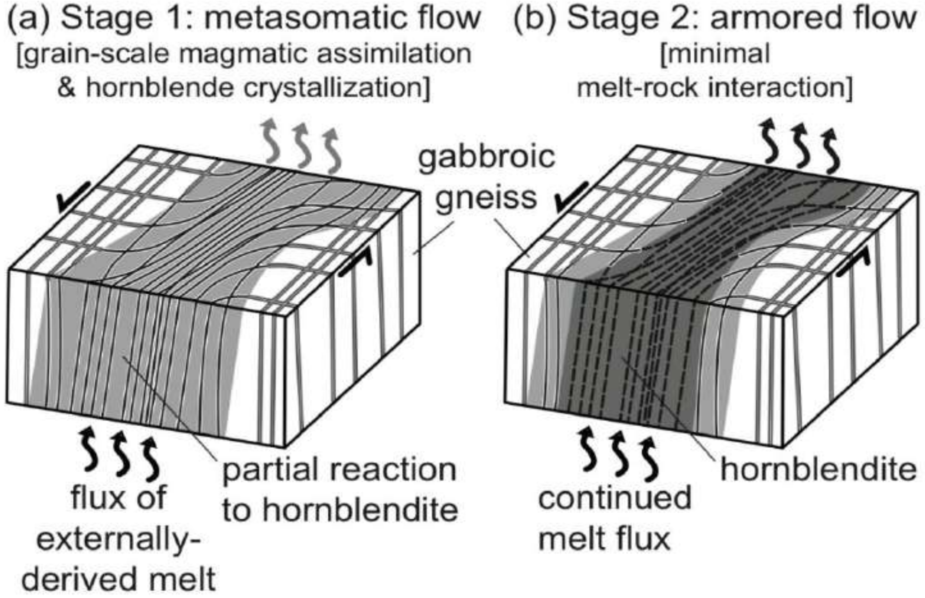
Cont. melt flux

Stuart et al. JMG 2018

- **Key features**
- 30-40 m wide
- Irregular boundaries

Take home message

-> Channelized melt flux zone
-> rheologically soft
-> Shear zone as melt “pump”
-> High volume through-put

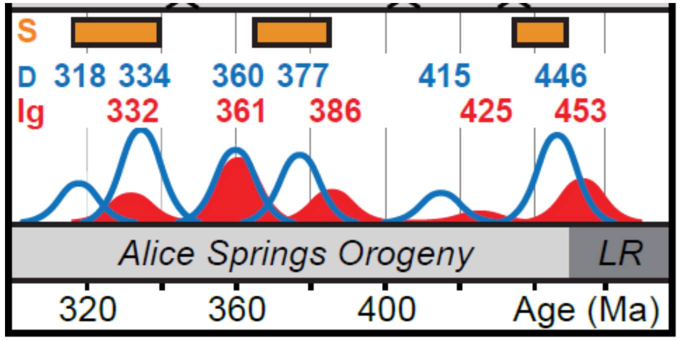

(a) Stage 1: metasomatic flow
[grain-scale magmatic assimilation & hornblende crystallization]

(b) Stage 2: armored flow
[minimal melt-rock interaction]

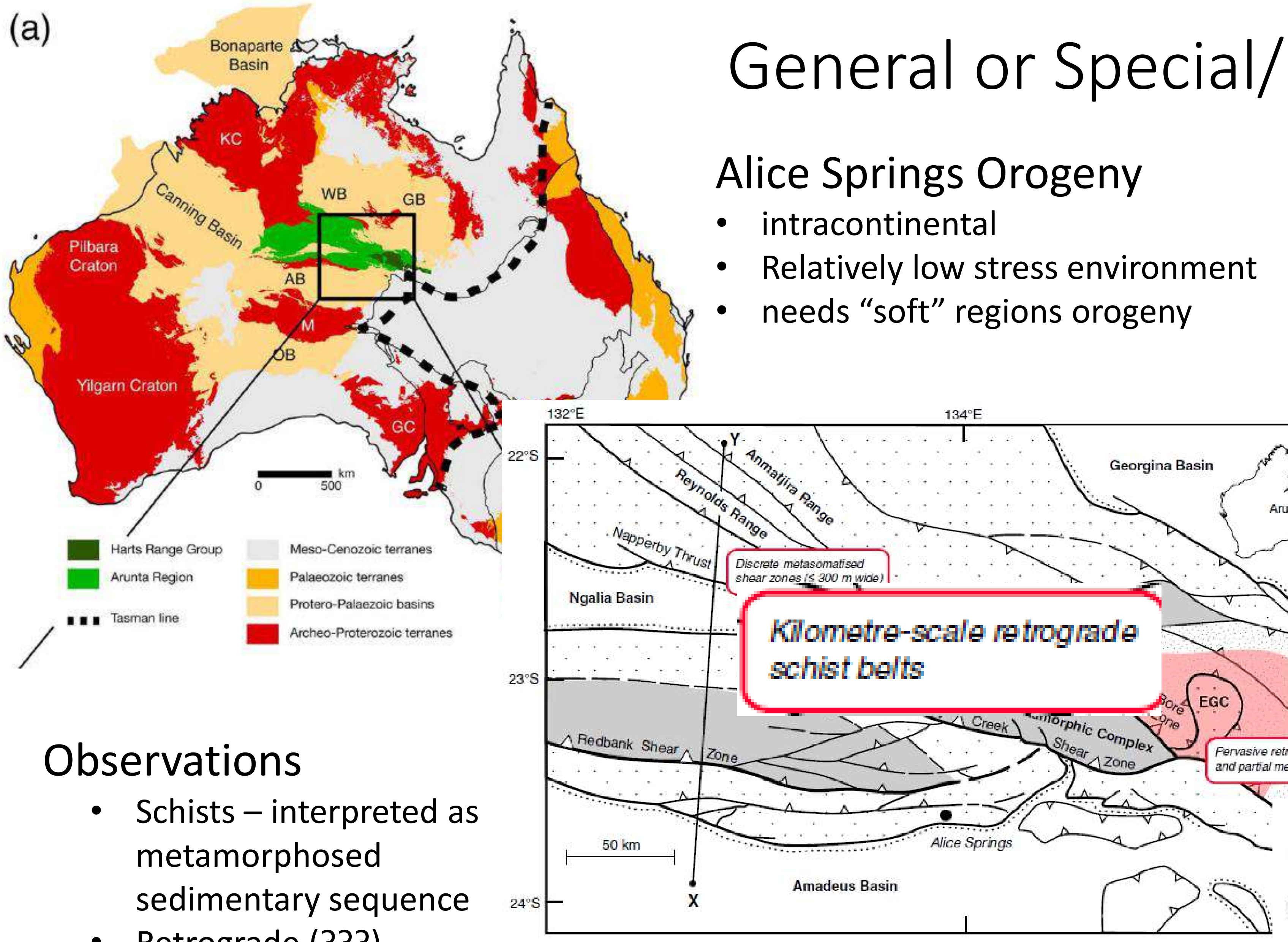
General or Special/Rheology?

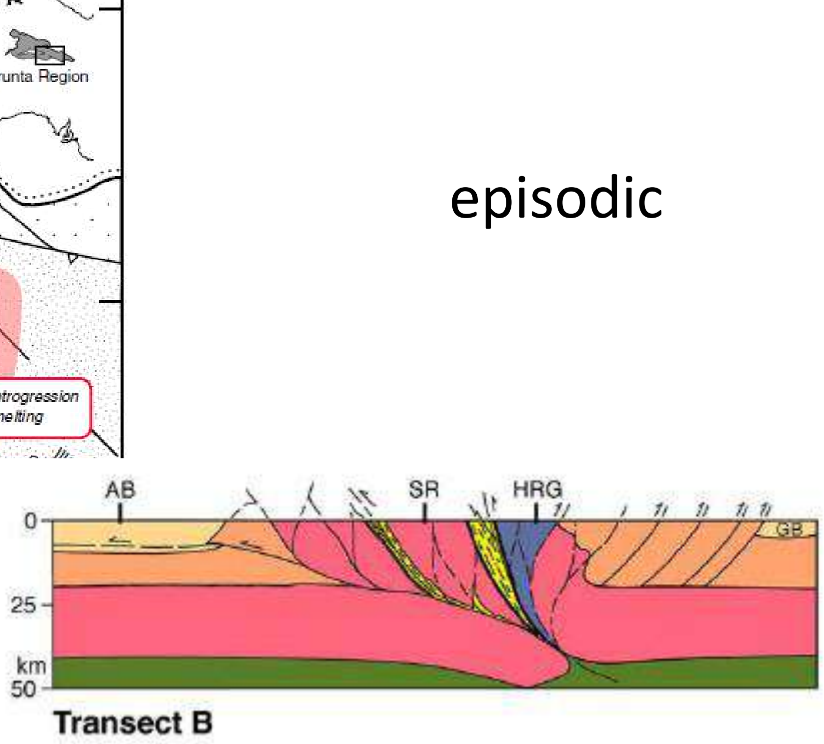
Alice Springs Orogeny

- intracontinental
- Relatively low stress environment
- needs "soft" regions orogeny



episodic





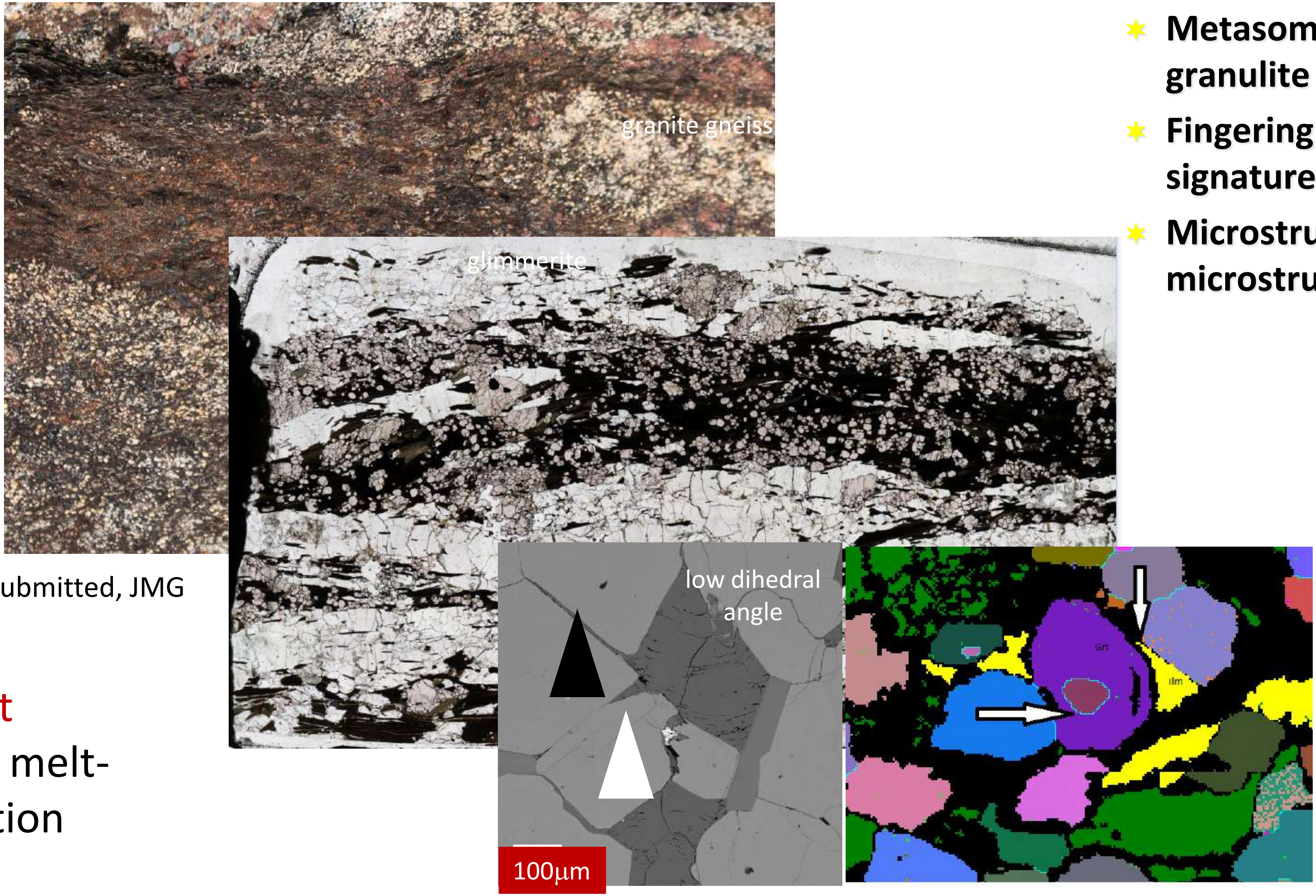
Observations

- Schists – interpreted as metamorphosed sedimentary sequence
- Retrograde (???)

Silva et al. Tectonics 2018

Schist belt: Grt-Sill schists

- **No clear igneous component in field**
- **Metasomatism: felsic granulite vs Grt schist**
- **Fingering – reactive flow signature?!**
- **Microstructures – melt microstructures**



Ghatak et al. submitted, JMG

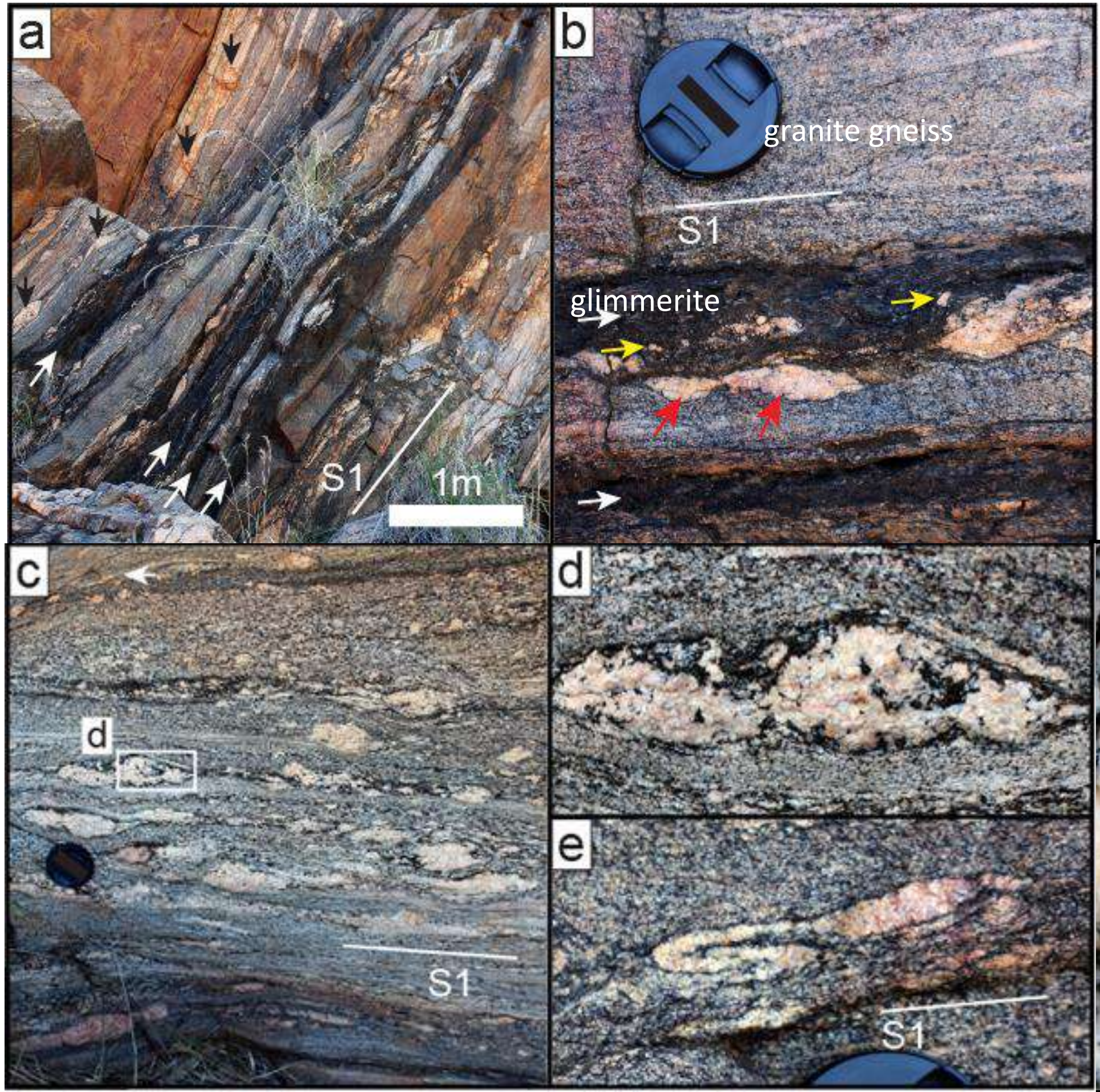
Ilm interstitial

Grt replacment

Grt-Sill schist
= Product of melt-rock interaction

Schist belt: glimmerite

Piazolo et al., in prep, Silva in revision, JPet

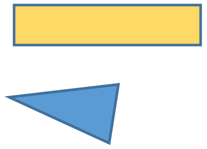


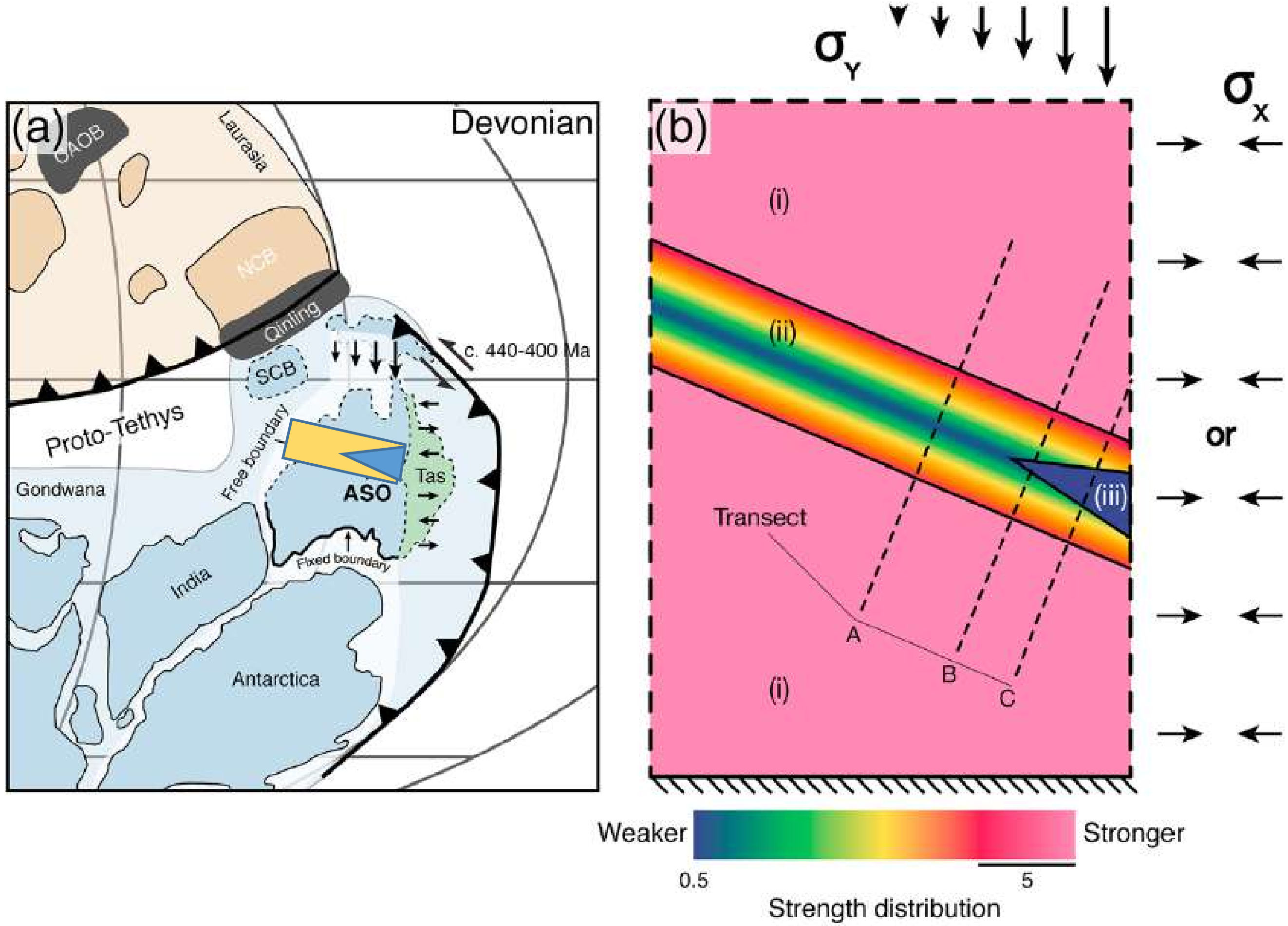
- **Recognisable igneous component**
- **Other relationships are the same**
- **Metasomatism: granite gneiss vs glimmerite**
- **Deformation not solid state**
- **Melt trapped**

Glimmerite = Product of melt-rock interaction

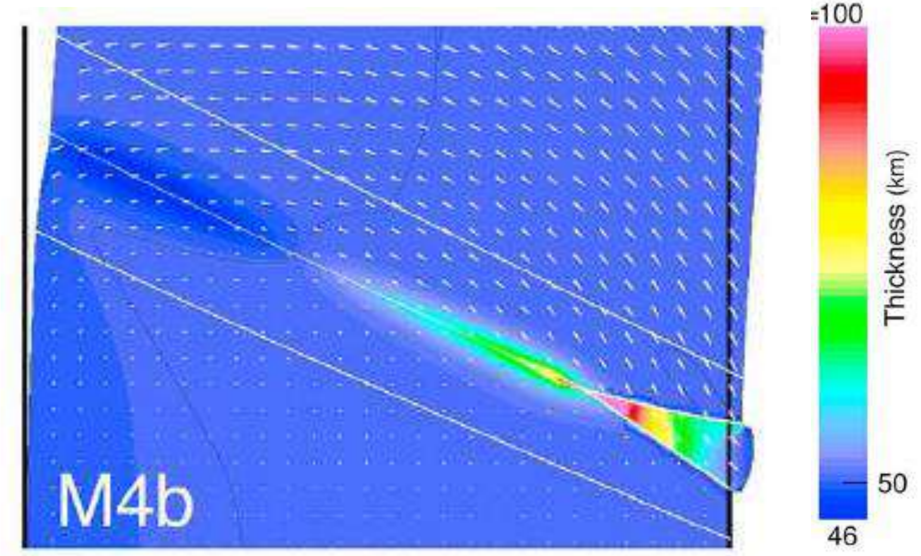
Model

- Reactivation of pre-existing Basin across Australia - soft
- On east side – deep rift sequence – very soft - melt
- Squeeze





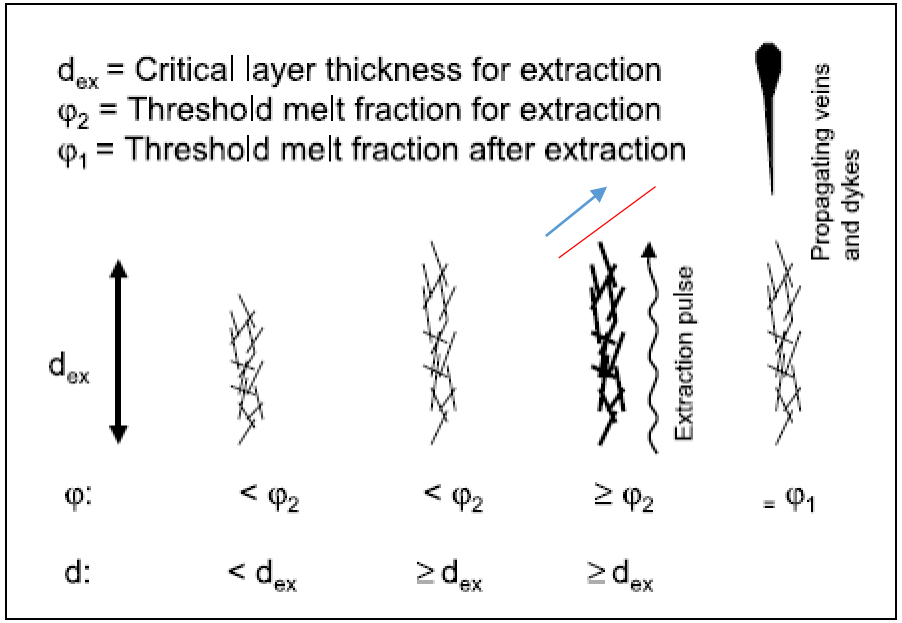
Basil modelling:
Silva et al. Tectonics 2018



Meek et al. JMG 2019

Model

- Reactivation of pre-existing Basin across Australia - soft
- On east side – deep rift sequence – very soft - melt
- Squeeze



Modified after Schmeling, JGR, 2006

-> High topography where deep rift sequence is -> highest erosion – deepest portion exposed -> high grade rocks

-> Episodic nature – melt production through underthrusting of wet sediments

-> production of melt & simultaneous

-> external stress – below failure

-> melt pressure -> failure and melt present shear and reaction (Glimmerite, Grt- sill gneiss)

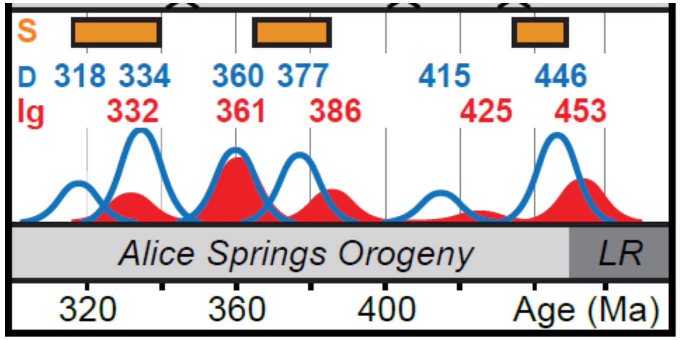
-> very soft -> high deformation rate (sedimentation external basins)

-> melt drainage -> stop of activity

-> slow melt pressure built up & stress built – up

-> cycle starts again

Piazolo et al. in review, Geology



Implications – melt in the lower crust

- Diffuse porous melt flow: pervasive flux of hydrous silicate melt may produce “pseudo-retrograde” hydration textures

Valle de Sesia (?), yesterday

- Hydration through channelized porous melt flow can lower its rheology substantially

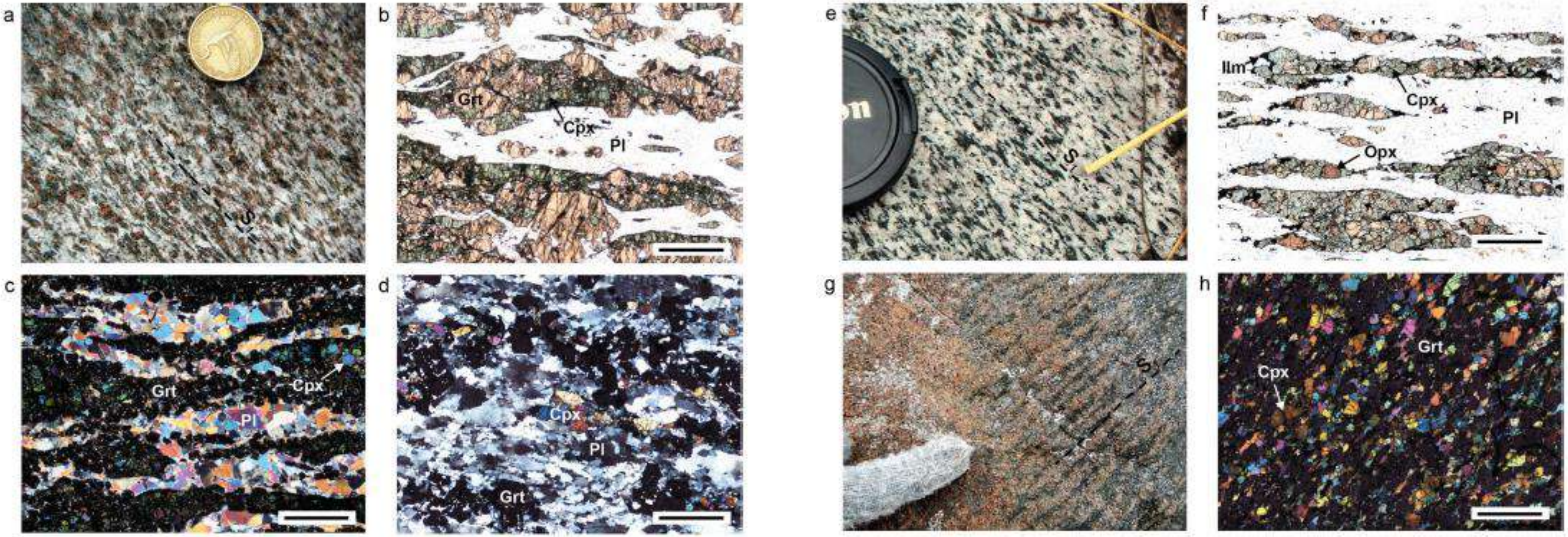
- Hornblendite: Invites a reevaluation of the significance of basic to ultrabasic bodies in exposures of lower crust, emphasizes their importance in delineating zones of mass transfer “feeder dykes”, and therefore may help resolve the cryptic pathways of melt migration at depth

- Melt fluxed shear zones maybe be highly episodic and at the center of mountain building

3) Case study – How to interpret Seismic data

What rocks are down there? What state are they in? What is their history?

Typical lower crustal rocks: Grt, pyx, fsp rich, layered



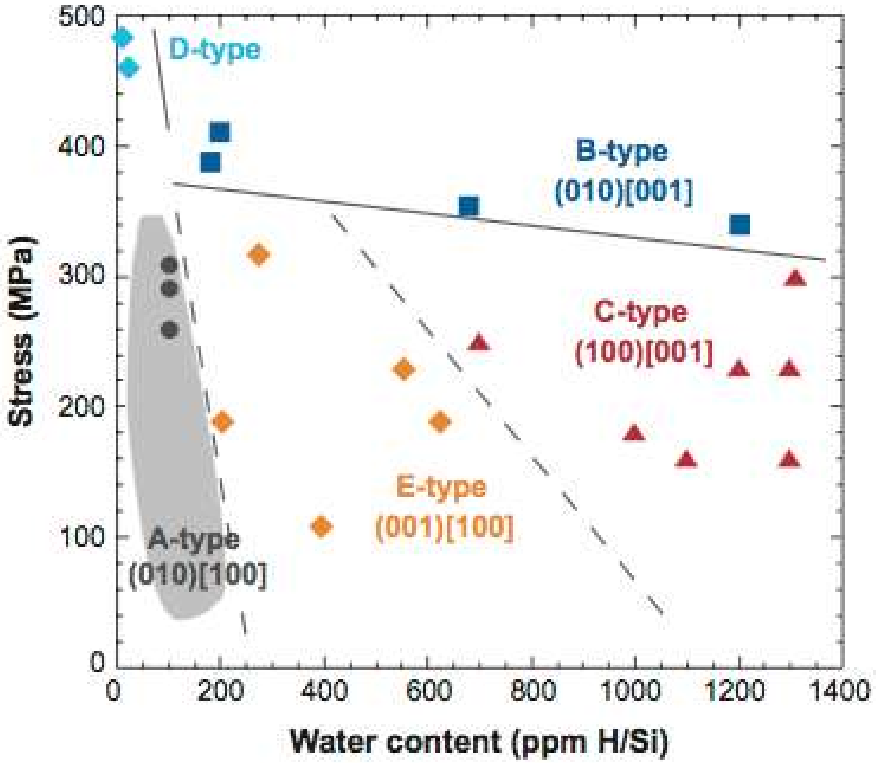
Cyprych et al. 2017

How would they look like seismically?

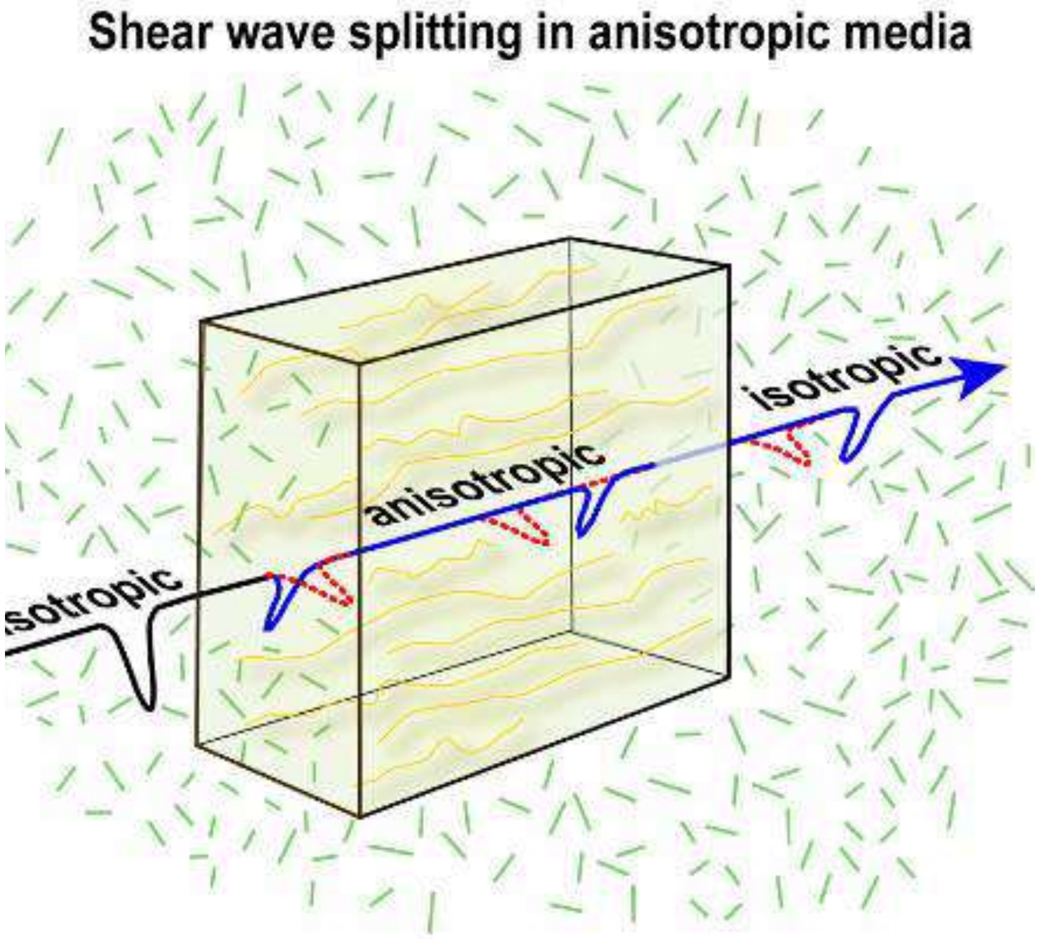
in terms of: flow direction,

stress & wet/dry conditions

seismic measurements



Karato et al. 2008



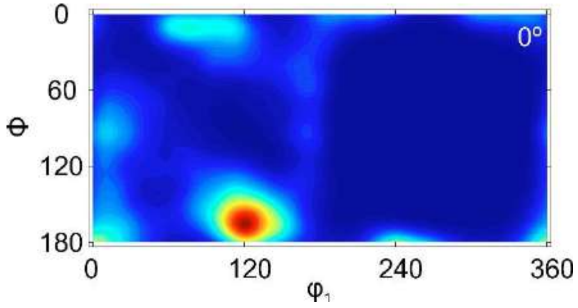
(After Crampin, 1981)

How would they look like seismically?

See review Almquist & Mainprice, 2017

Classic/Traditional way to calculate seismic properties (VHR method):

Mineral orientation distribution function (ODF) EBSD → Elastic stiffness matrix of mineral → Single phase polycrystal Voigt tensor → Model specific calculations giving aggregate Voigt tensor



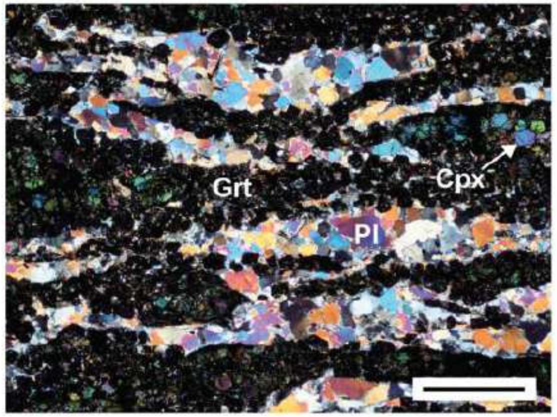
$$\begin{bmatrix} 86.8 & 7.04 & 11.91 & -18.04 & 0 & 0 \\ 7.04 & 86.8 & 11.91 & 18.04 & 0 & 0 \\ 11.91 & 11.91 & 105.75 & 0 & 0 & 0 \\ -18.04 & 18.04 & 0 & 58.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 58.2 & -18.04 \\ 0 & 0 & 0 & 0 & -18.04 & 39.88 \end{bmatrix}$$

e.g. Quartz: McSkimin et al. (1965)

$$\begin{bmatrix} 99.9 & 6.29 & 5.19 & -1.91 & 0.88 & 2.59 \\ 6.29 & 100 & 6.33 & 0.52 & -1.2 & -2.85 \\ 5.19 & 6.33 & 105 & -0.16 & 0.77 & 0.26 \\ -1.91 & 0.52 & -0.16 & 49.4 & 0.26 & -0.94 \\ 0.88 & -1.2 & 0.77 & 0.26 & 47.4 & -2.79 \\ 2.59 & -2.85 & 0.26 & -0.94 & -2.79 & 46.3 \end{bmatrix}$$

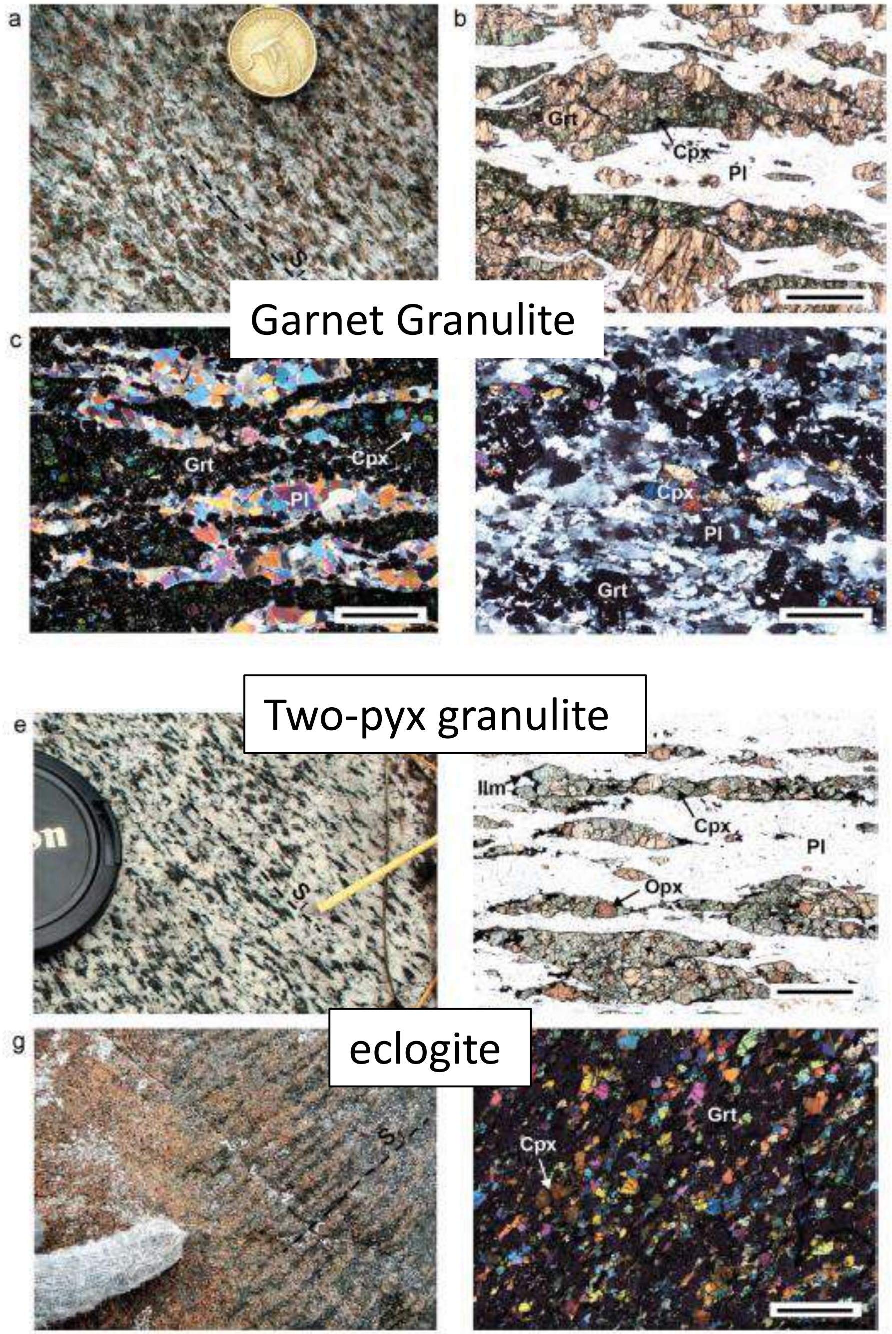
Asymptotic Expansion Homogenisation – Finite Element (AEH-FE) method

\+ Phase boundary data i.e. microstructure



Vel et al. 2016

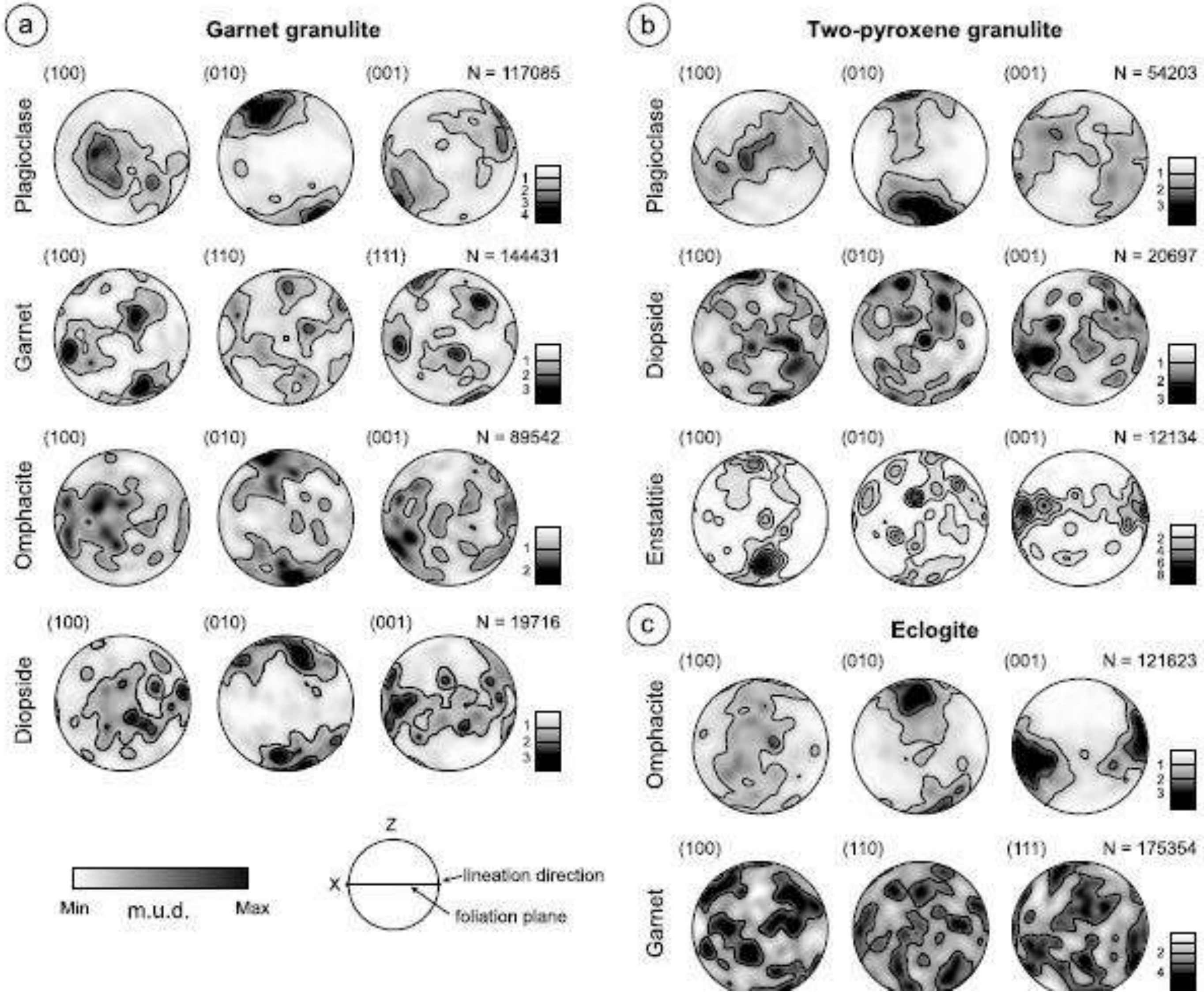
EBSD



Garnet Granulite

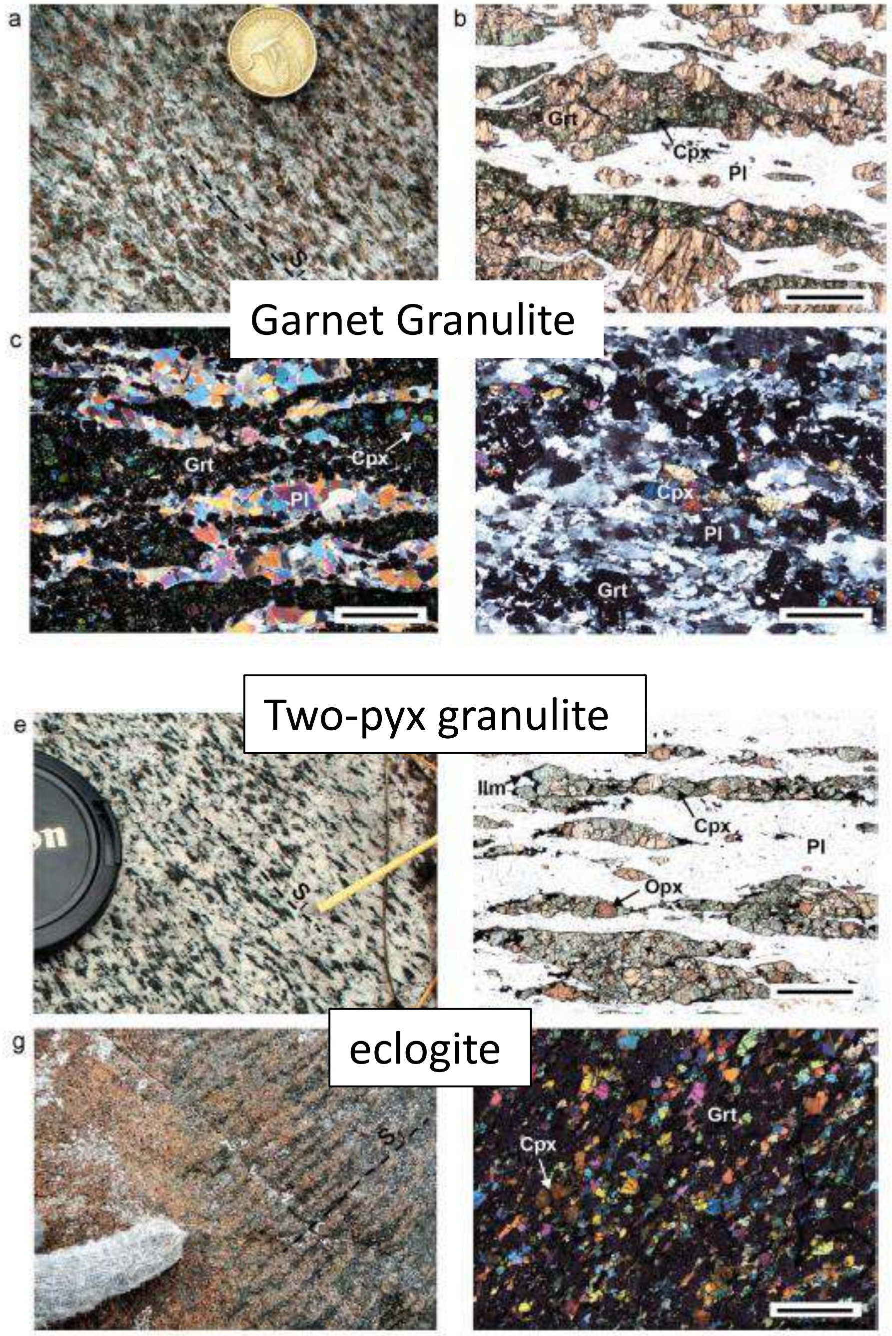
Two-pyx granulite

eclogite



Cyprych et al., EPSL 2017

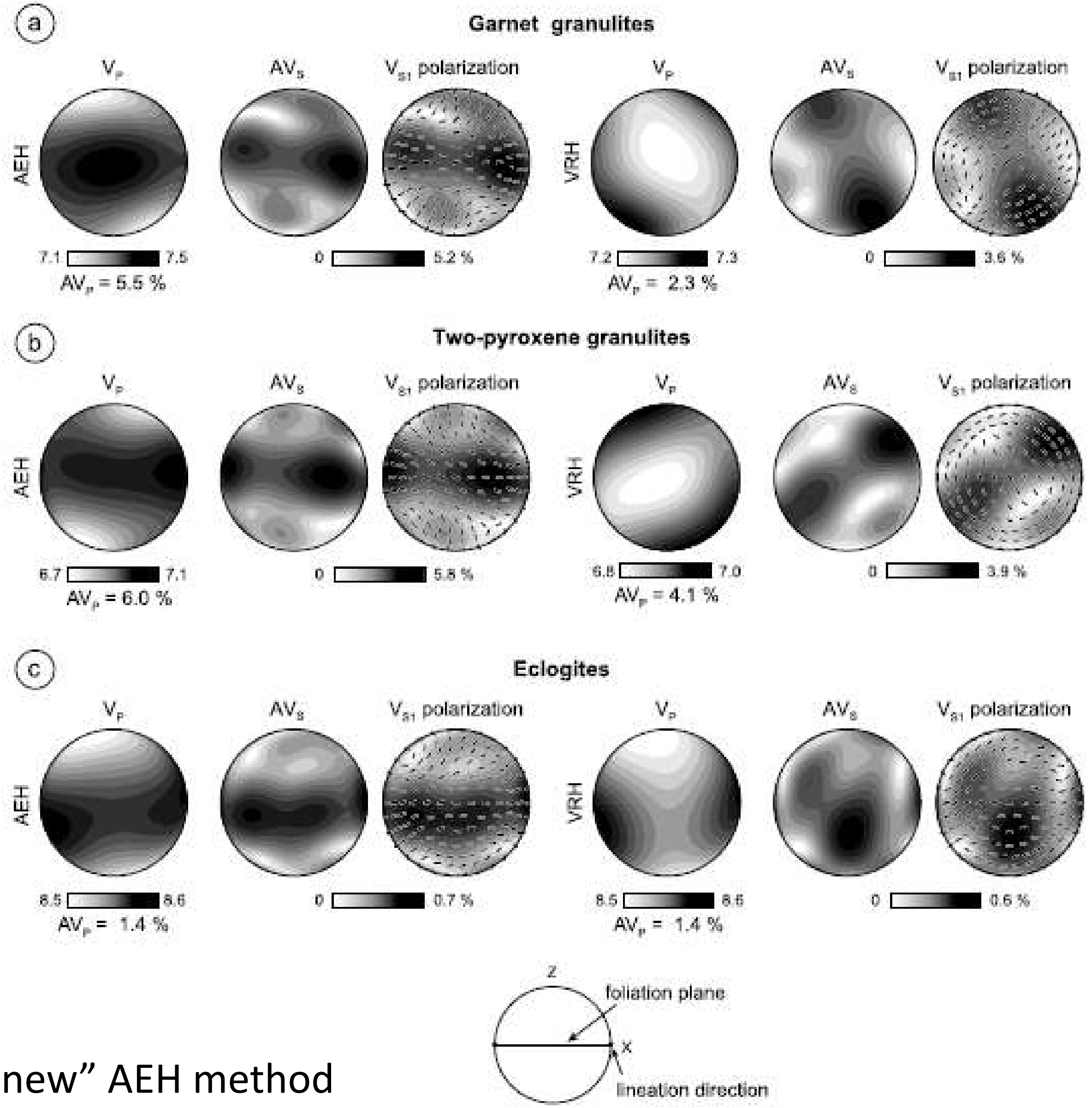
Seismic properties



Garnet Granulite

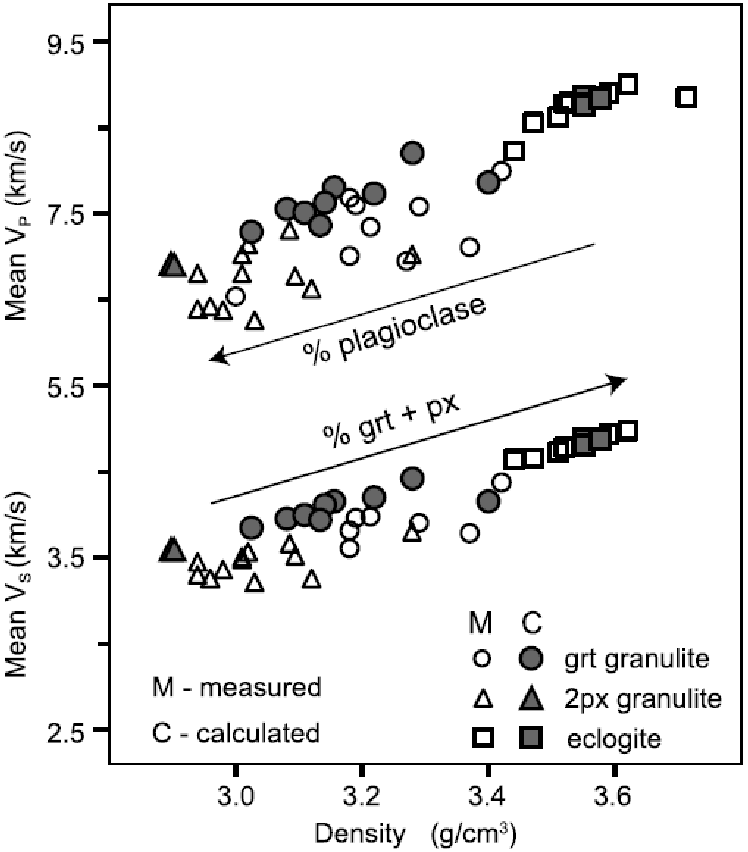
Two-pyx granulite

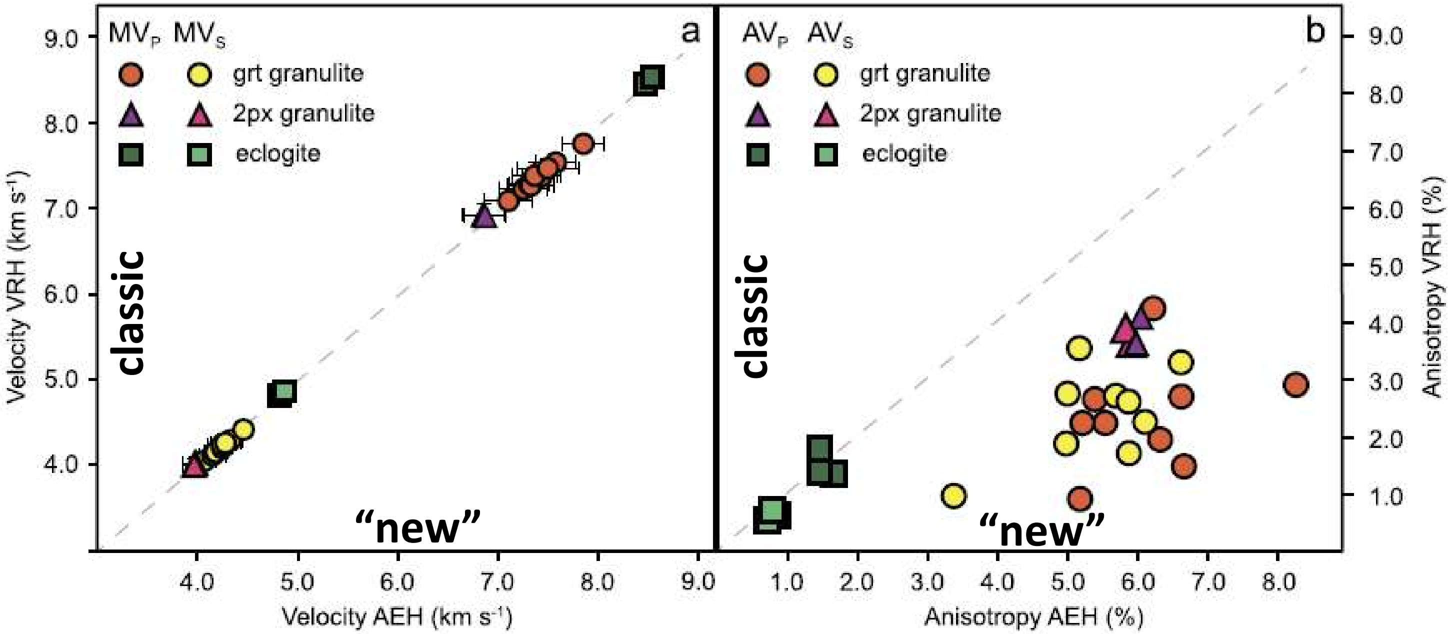
eclogite



“new” AEH method

Cyprych et al., EPSL 2017





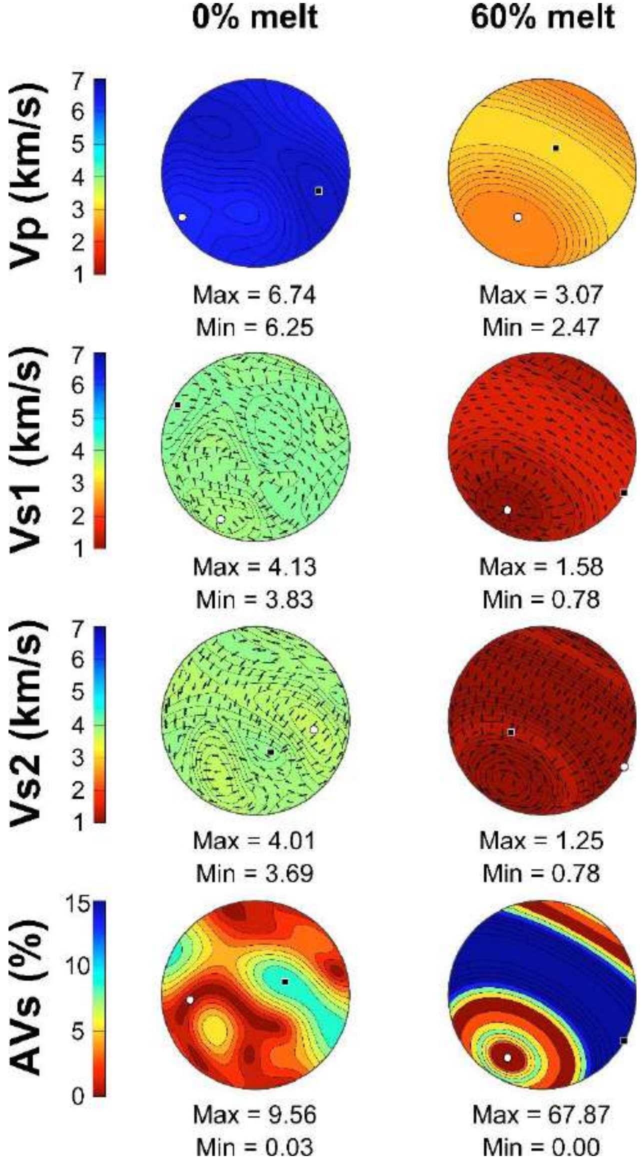
- For S and P wave velocities not much difference between the two models and measured velocitites

- For Anistotropy – big difference
“thin layer effect”

Cyprych et al., EPSL 2017

Influence of melt on Seismic response

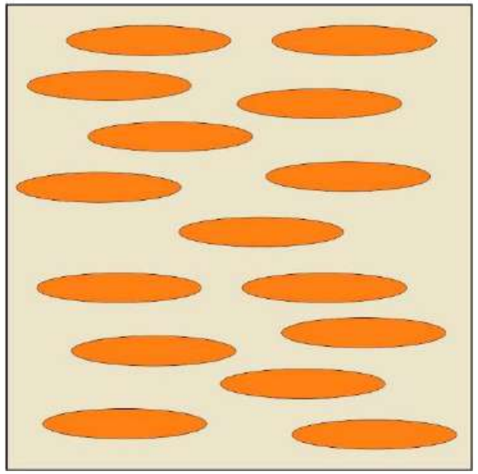
MIGMATITE



ISOTROPIC SOLID ROCK

+

ISOTROPIC ALIGNED MELT WITH DEFINED SHAPE



Lee et al. G3 (2017)
Took some natural examples

SHEAR ZONE