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Volcanic Processes: a Variety of Length and Time Scales

Rheology of Crystal-Rich Magmas

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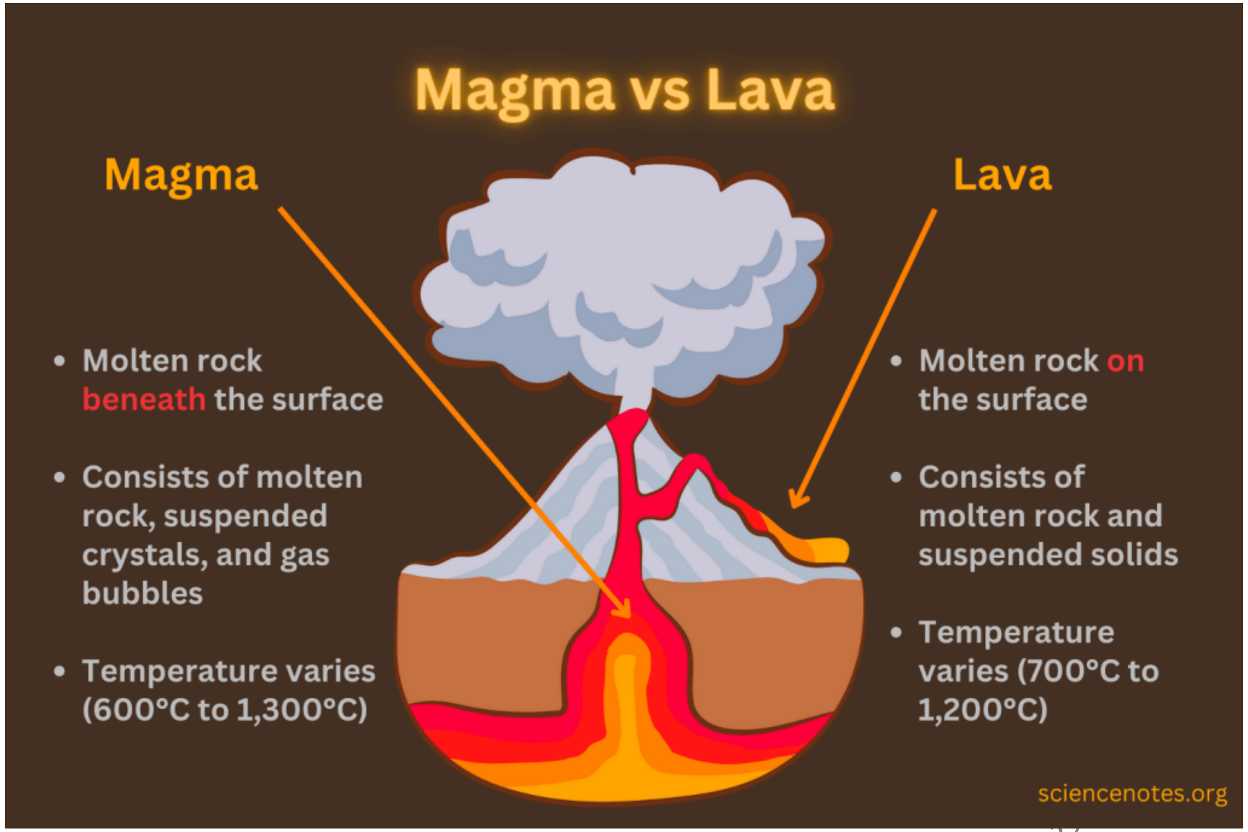
UNIVERSITY of RWANDA

Magma is liquid rock with crystals. Approaching the surface, gas bubbles form as pressure drops, so magma can contain solid, liquid, and gas.

- Magma = liquid rock + crystals
- Pressure drops near surface → gases bubble out
- Magma becomes solid + liquid + gas



It's all about *viscosity*

- Melt composition
- Temperature
- Crystals (content, shape, size distribution)
- Strain rate
- Vesicles
- …

Effusive

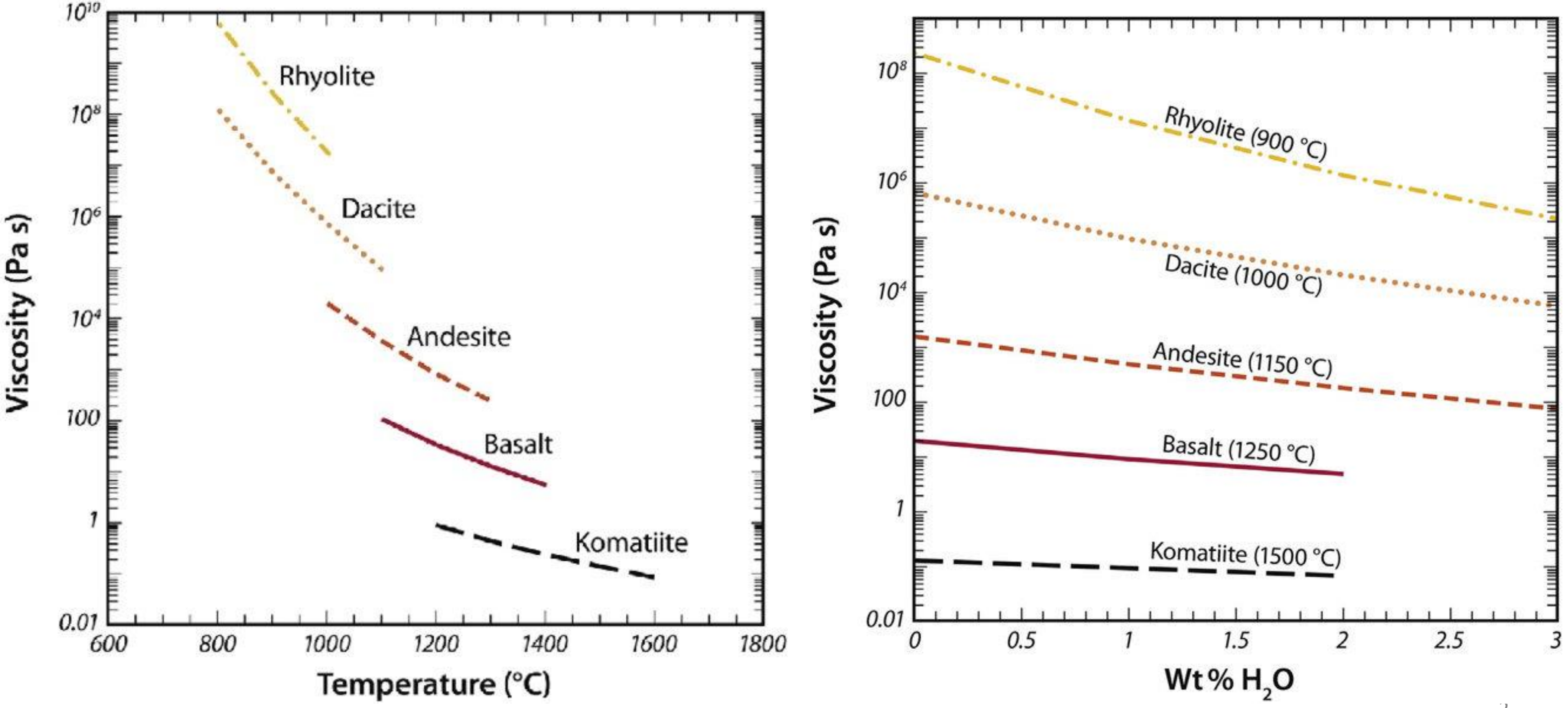
from Etna Volcano Live Webcam

Explosive

It can vary over 20 orders of magnitude!

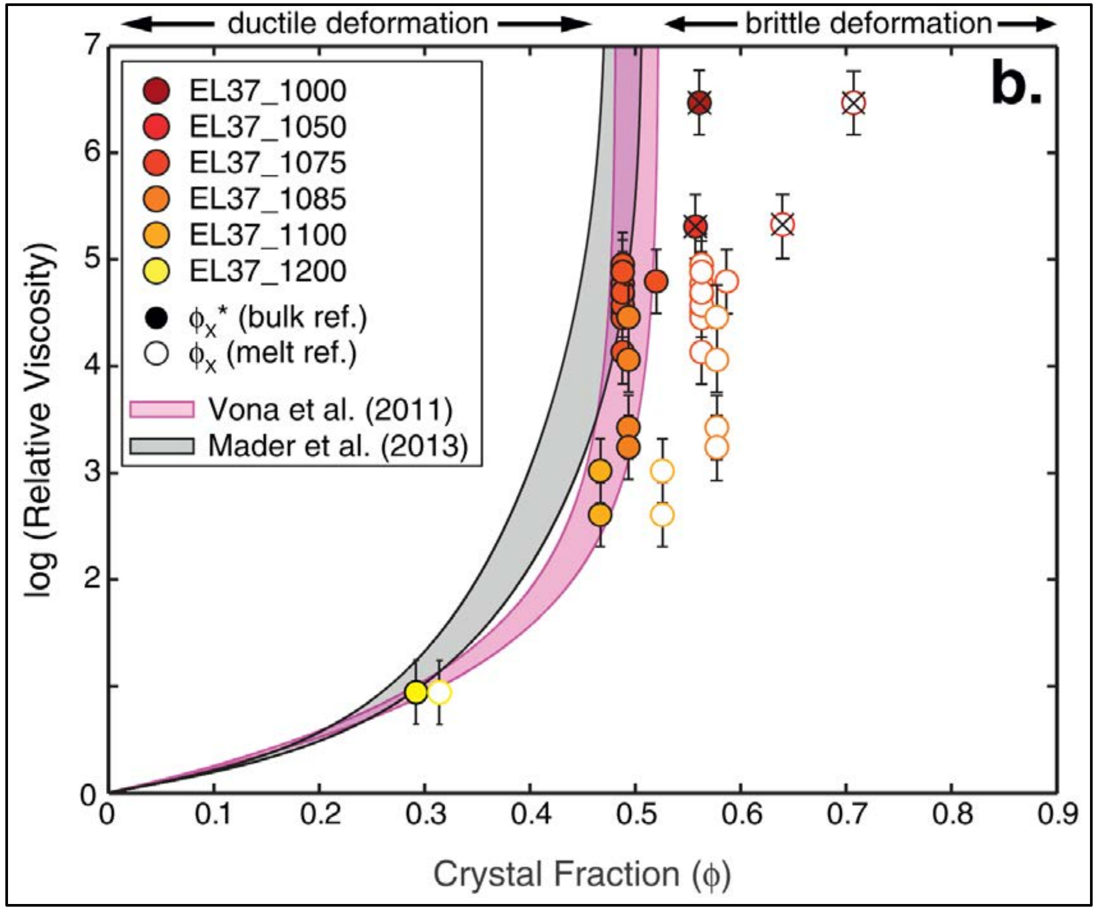
All this contributes to the different responses of magma rheology and eruption styles!

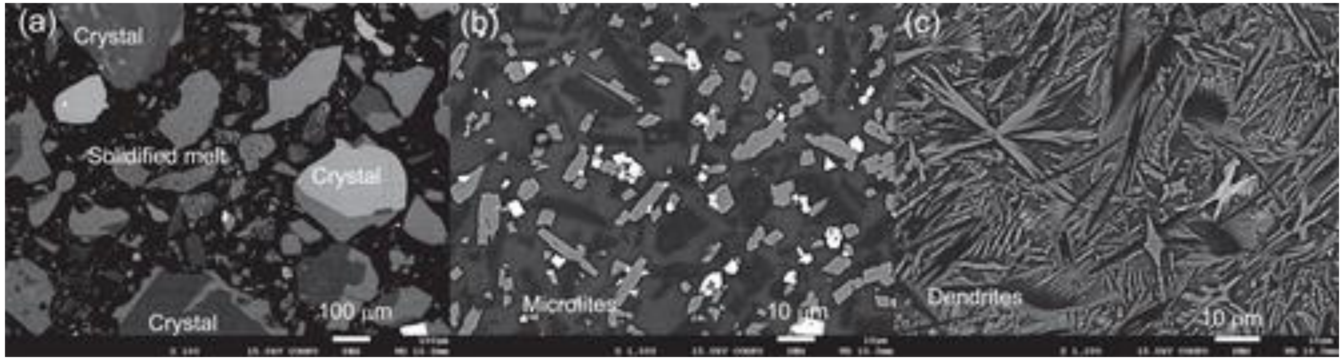
Melt viscosity (e.g., Spera, 2000; Giordano, Russell, Dingwell, 2008)



Effects of crystal content

Rheological
literature





Namiki et al. (2025). Crystal-rich magma is solid-like and liquefies when deformed. J. Geophys. Res., 130, e2024JB030483.

Relative viscosity =
magma viscosity/melt viscosity (η_m/η_l)

Relative viscosity increase with the solid phase concentration

No focus on rheology above critical crystal fraction (e.g. maximum packing fraction)!

Many studies… *but* no systematic results on strain rate and Aspect Ratio!

Effects of crystal content

Focusing on particle-bearing systems rheology:

- Database from rheological literature covering all the natural volcanic parameters.

- Systematic model of relative viscosity (η_r) as function of :

- apparent viscosity η_a
- melt viscosity η_l
- crystal concentration ϕ
- crystal shape R
- and strain rate $\dot{\varepsilon}$

- Quantitative description of the rheological behavior of *crystal-bearing magmatic systems*.

Low R

High R

Low $\dot{\varepsilon}$

High $\dot{\varepsilon}$

Effects of crystal content

Sigmoidal shape proposed by Lejeune and Richet (1995) and then described by Costa et al. (2007,2009):

$$\eta_r(\phi) = \frac{1+\varphi^{\delta}}{[1-F(\varphi,\varepsilon,\gamma)]^{B\phi_*}} \qquad F = (1-\xi)\mathrm{erf}[\frac{\sqrt{\pi}}{2(1-\xi)}\varphi(1+\varphi^{\gamma})]$$

R =1 only!

B = Einstein coefficient = 2.5

$\varphi = \phi/\phi_*$ → ϕ= solid fraction

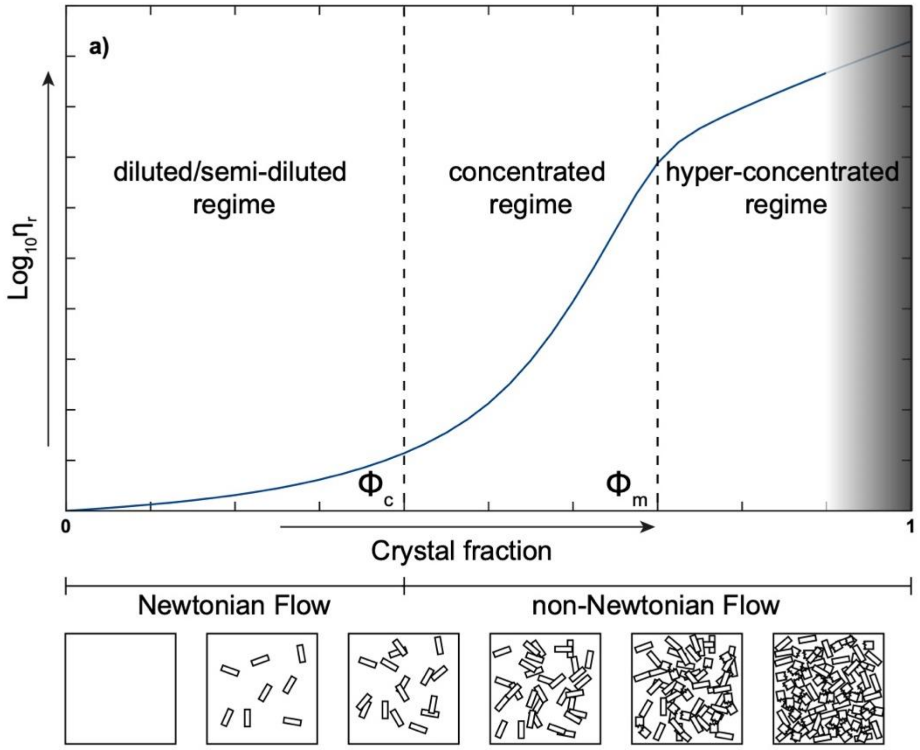
ϕ_*= critical solid fraction

γ = steepness of the curve near ϕ_*

δ and ξ = steepness and height

of the iper-concentrated region

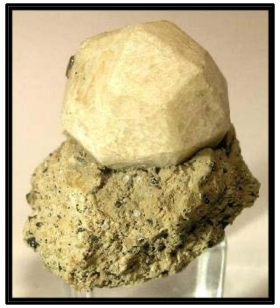
erf = error function



Four different flow regimes: diluted, semi-diluted, concentrated and hyper-concentrated

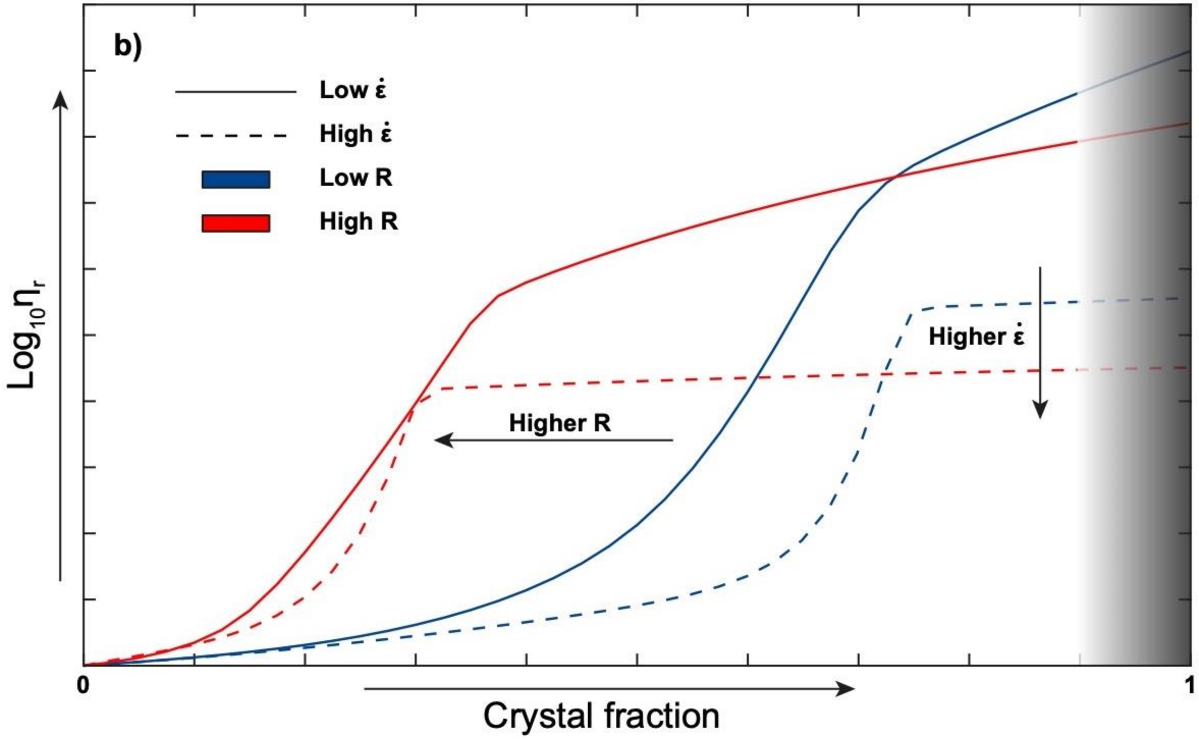
Effects of crystal content

Viscosity varies with particles shape and strain rate!



Spherical (Leucite)

Elongated (Plagioclase)



- Different elongation of crystals in nature
- Need to take into account the elongation (Aspect Ratio *R*)

Effects of crystal content

Database: construction (over 1400 rheological data) and classification

- **Material type** (natural, synthetic or analogue)
- **Chemical composition**
- **Experimental methodology**
  - Temperature
  - Applied strain rate
  - Confining pressure
- **The phase components**
  - Crystal content and mean aspect ratio *R*

Results:

- Apparent viscosity η_a
- Melt viscosity η_l
- Relative viscosity $\eta_r = \eta_a / \eta_l$

Effects of crystal content

Data correction

Common issues in reporting data:

- Deformation mechanisms; → $\eta_{eff} = \frac{\sigma}{\dot{\varepsilon}}$ vs $\eta_{eff} = \frac{m\, g\, h^2}{3V \frac{\delta h}{\delta t}}$
- Relative viscosity of NATURAL SAMPLES experiments; → Natural vs residual melt
- Missing information → (R, $\dot{\varepsilon}$, Chemistry and/or T…)
- Viscous heating → For high particle fraction, high R and high $\dot{\varepsilon}$

Effects of crystal content

$$\phi_*(\dot{\varepsilon}, R) = \left[\phi_m + \Delta\phi \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right]$$

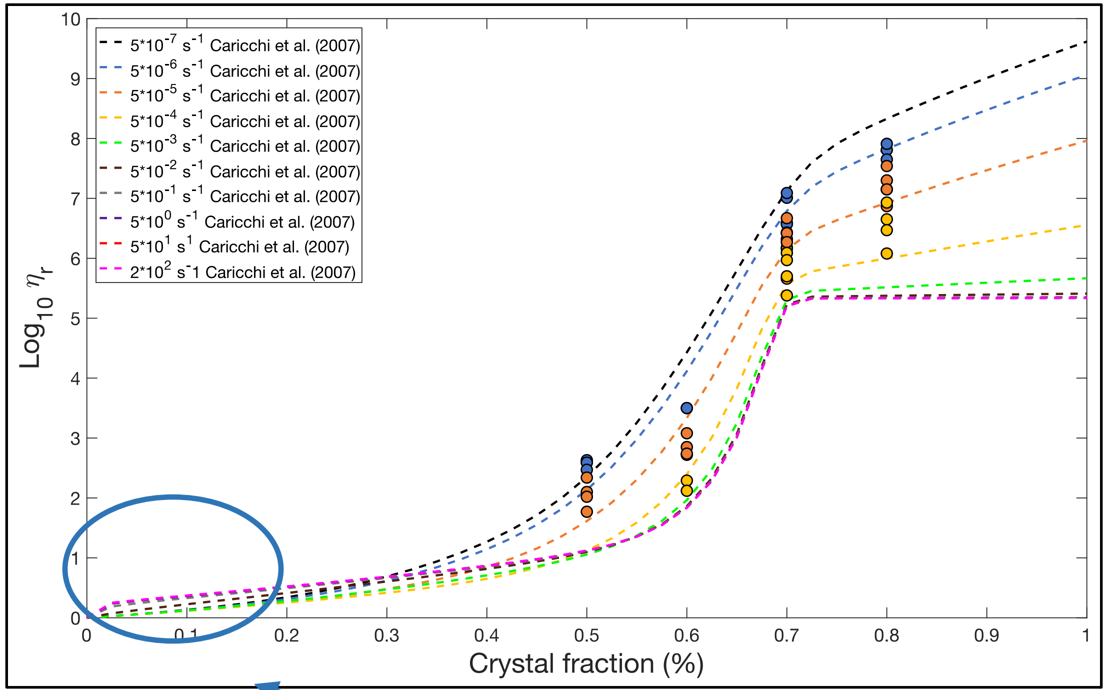
$$\delta(\dot{\varepsilon}, R) = \left[\delta_m - \Delta\delta \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right]$$

$$\xi(\dot{\varepsilon}, R) = \left[\xi_m + \Delta\xi \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right]$$

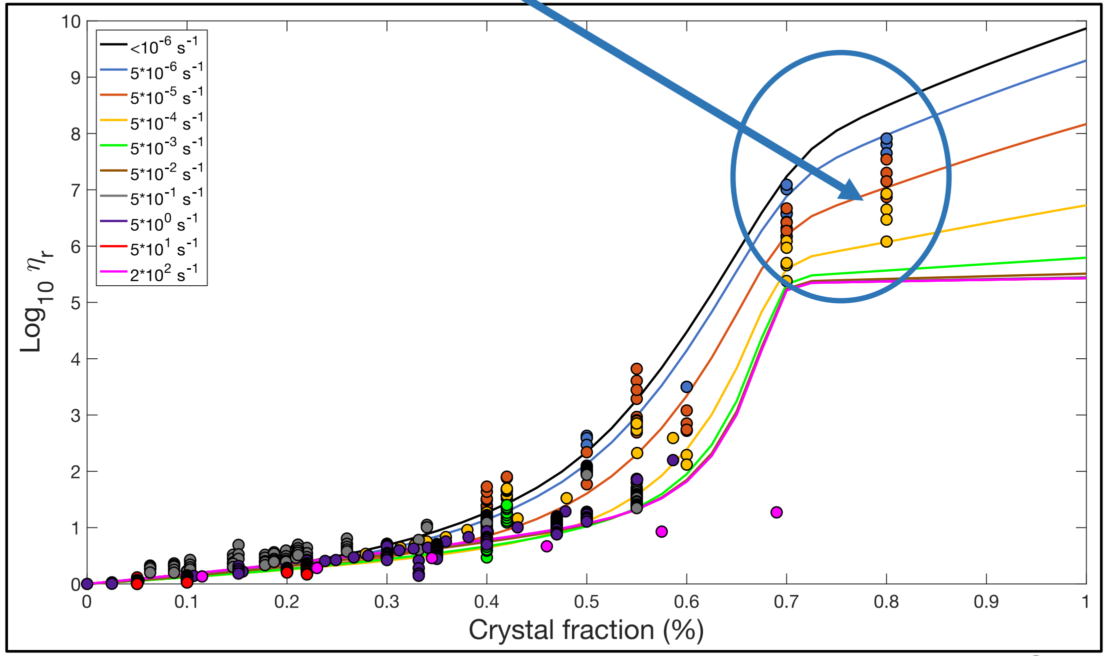
$$\gamma(\dot{\varepsilon}, R) = \left[\gamma_m + \Delta\gamma \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right]$$

Spherical particles and wide range of strain rates

$\delta = \delta_m - \Delta\delta$ → $\delta_m = 7.73$ (previously 6.78)



Better fit for the upper plateau



Avoid sharp increase at very low particle concentration

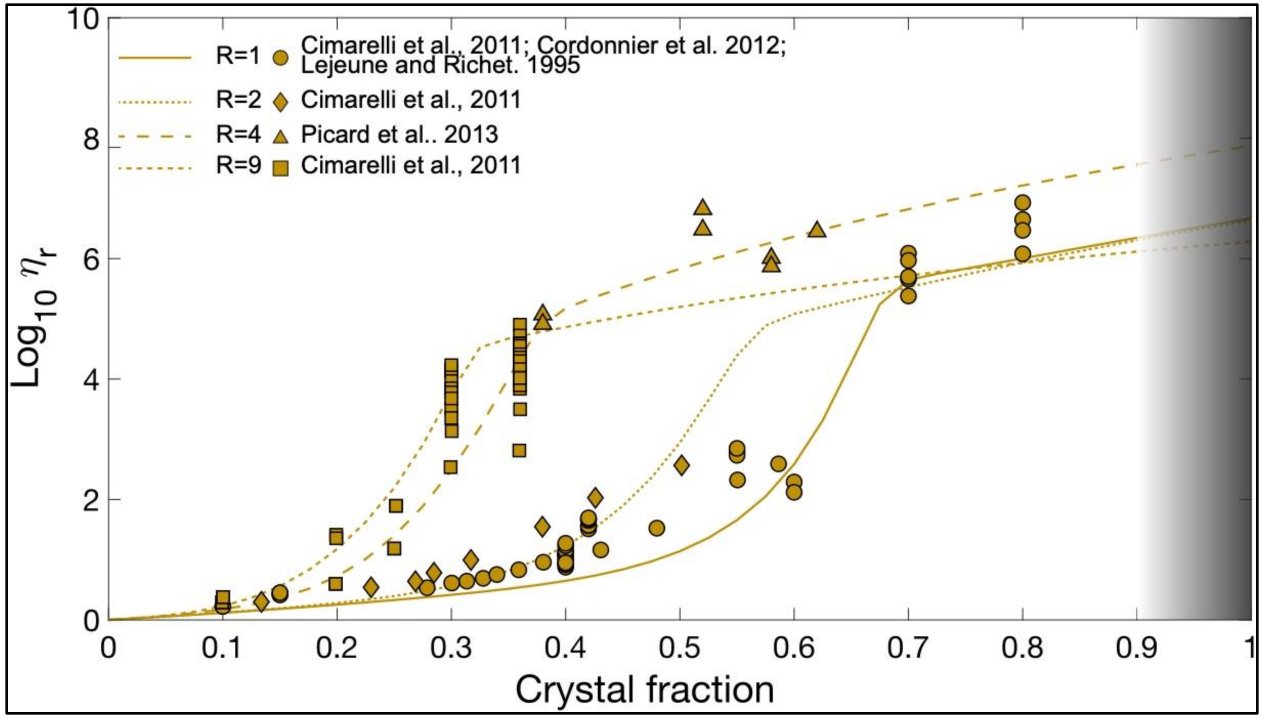
Effects of crystal content

$$\phi_*(\dot{\varepsilon} = 10^{-4}\ s^{-1}; R) = \left(\frac{1}{R^{b_1}}\right)\phi_s\ (10^{-4}\ s^{-1})$$

$$\delta(\dot{\varepsilon} = 10^{-4}\ s^{-1}; R) = \delta_m e^{b_2(R-1)}(10^{-4}\ s^{-1})$$

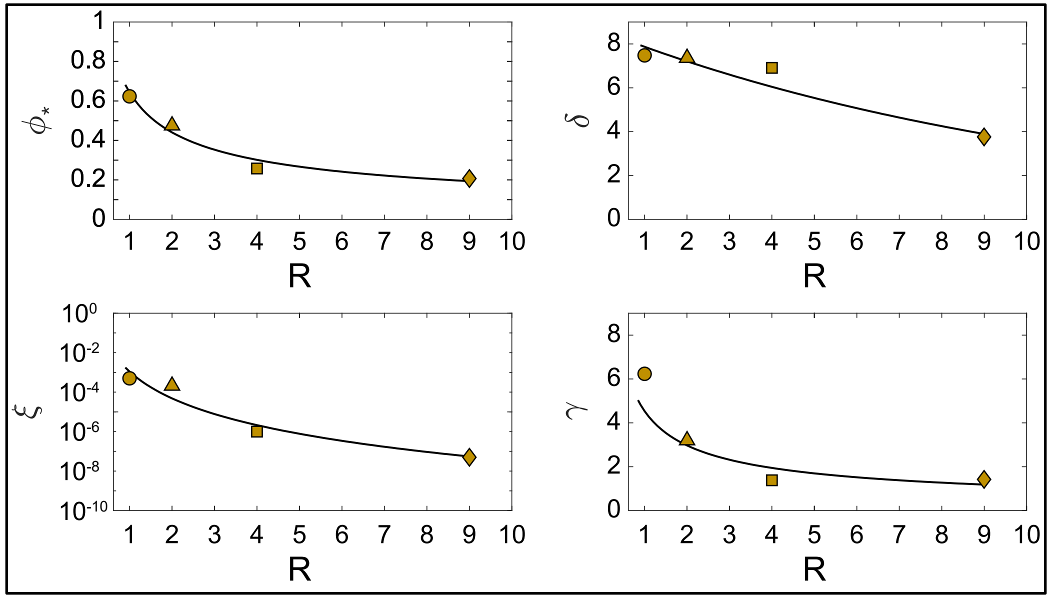
$$\xi(\dot{\varepsilon} = 10^{-4}\ s^{-1}; R) = \left(\frac{1}{R^{b_3}}\right)\xi_m\ (10^{-4}\ s^{-1})$$

$$\gamma(\dot{\varepsilon} = 10^{-4}\ s^{-1}; R) = \left(\frac{1}{R^{b_4}}\right)\gamma_m\ (10^{-4}\ s^{-1})$$



$\dot{\varepsilon}$=10^{-4} s^{-1}

Entire range of *R*

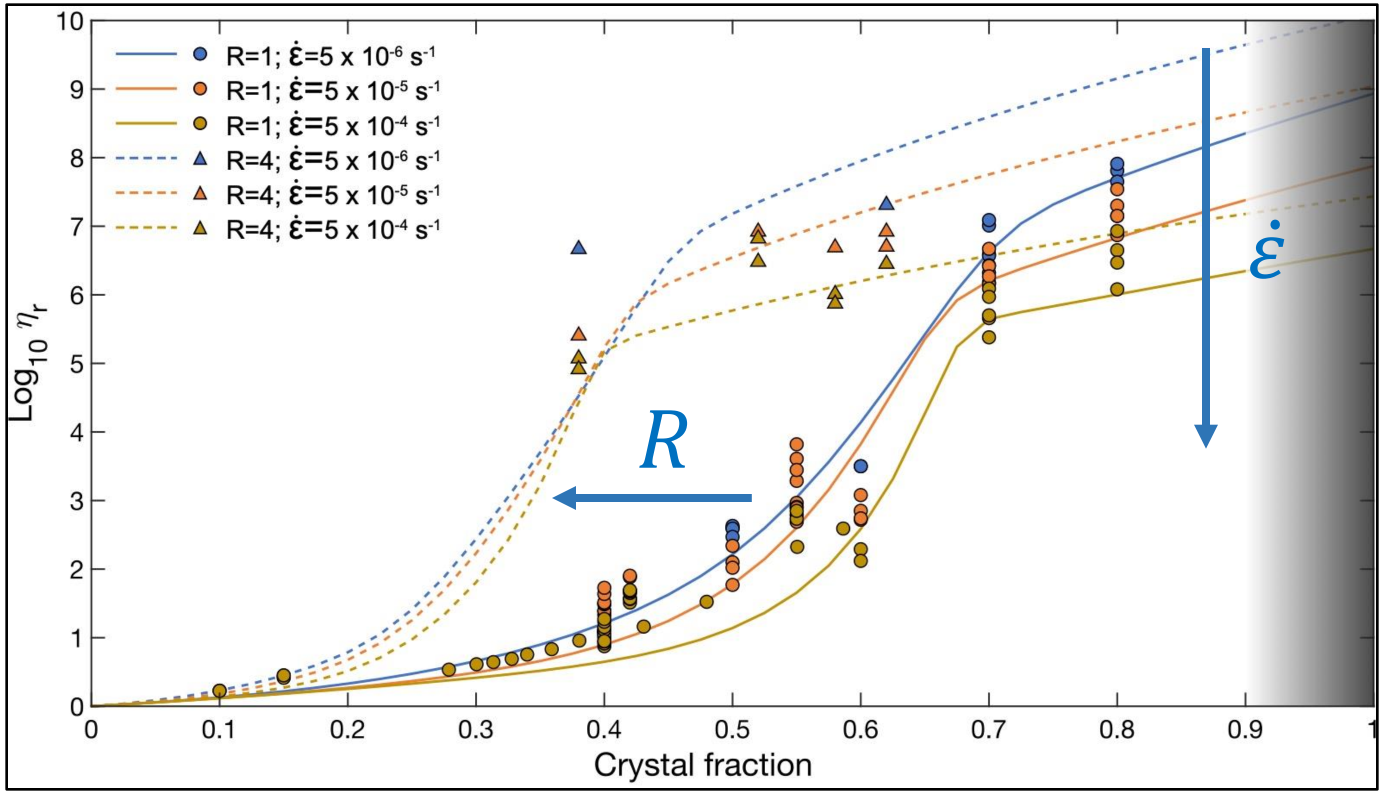


b_1=0.538 b_2=0.092

b_3=4.568 b_4=0.718

Effects of crystal content

- High crystal fraction plateau-like relative viscosity region
- For a given *R*, this plateau-like region is higher as the strain rate decreases
- For a given *strain rate,* the curves are shifted towards the lower crystal fractions as *R* increases .



$$\eta_r(\dot{\varepsilon}, R) = \frac{1 + \varphi^{\delta(\dot{\varepsilon},R)}}{[1 - F(\dot{\varepsilon}, R)]^{B\phi_*(\dot{\varepsilon},R)}}$$

$$\phi_*(\dot{\varepsilon}, R) = \left[\phi_m + \Delta\phi \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right] * R^{-b_1}$$

$$\delta(\dot{\varepsilon}, R) = \left[\delta_m - \Delta\delta \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right] * e^{-b_2(R-1)}$$

$$\xi(\dot{\varepsilon}, R) = \left[\xi_m + \Delta\xi \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right] * R^{-b_3}$$

$$\gamma(\dot{\varepsilon}, R) = \left[\gamma_m + \Delta\gamma \frac{(\dot{\varepsilon}/\varepsilon_c)^n - (\varepsilon_c/\dot{\varepsilon})^n}{(\dot{\varepsilon}/\varepsilon_c)^n + (\varepsilon_c/\dot{\varepsilon})^n}\right] * R^{-b_4}$$

Conclusion and future work

- Building wide rheological database:

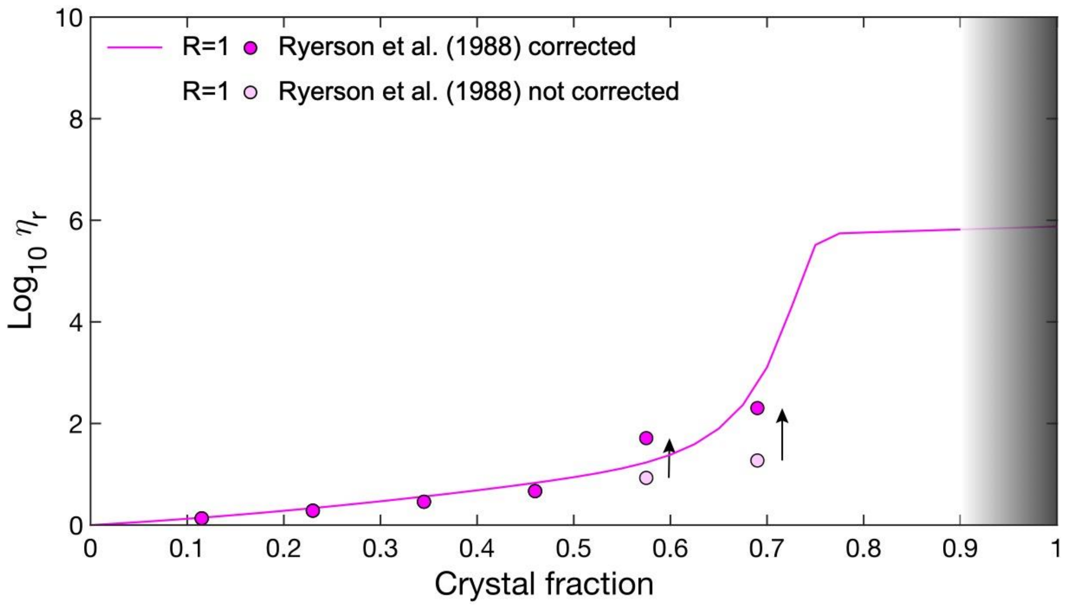
https://doi.org/10.6084/m9.figshare.16886155.v1

- Identification of issues in reporting data
- Extension of the model of Costa et al. (2009) to all the natural strain rates ($\dot{\varepsilon}$) for spherical particles (R=1)
- Generalization of the model for all the aspect ratios (R) and strain rates ($\dot{\varepsilon}$) pertinent to natural environment

Conclusion and future work

Scientific community should:

- adopt measurement standardization
- fill the gaps in the poorly characterized parameter space;
- carry experiments to characterize viscous dissipation effects (e.g. focusing on the regime explored by Ryerson et al., 1988)



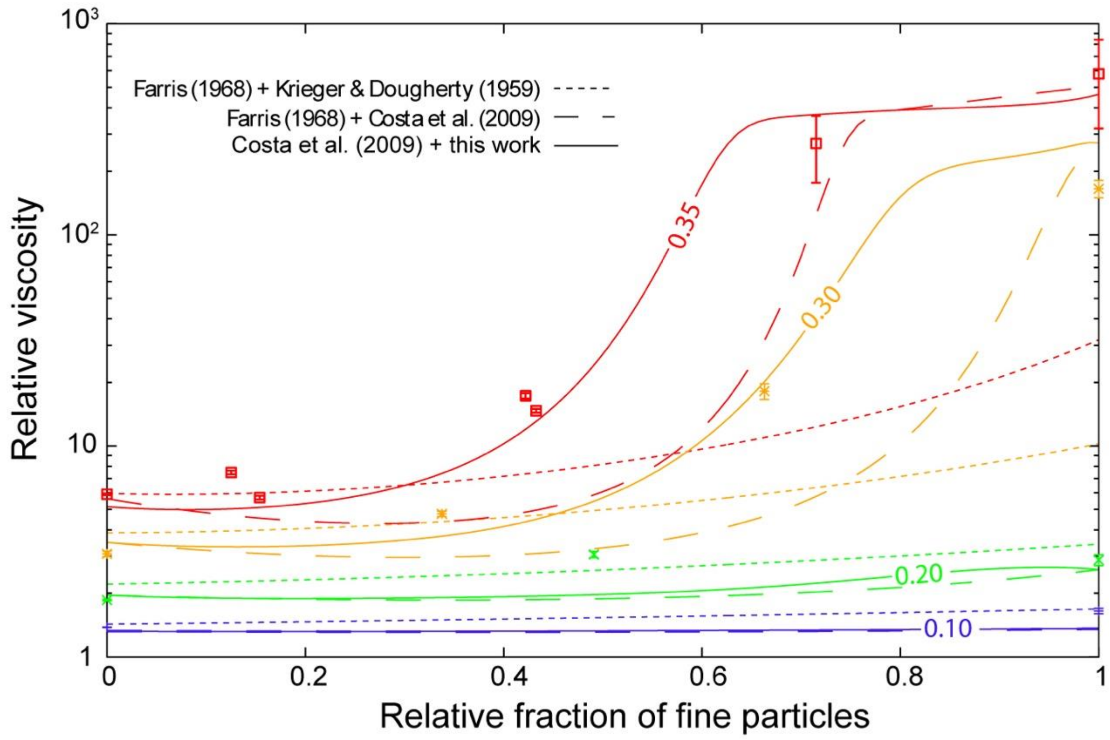
$T_{max} - T_0 = \ln(\mathrm{Na})/b$

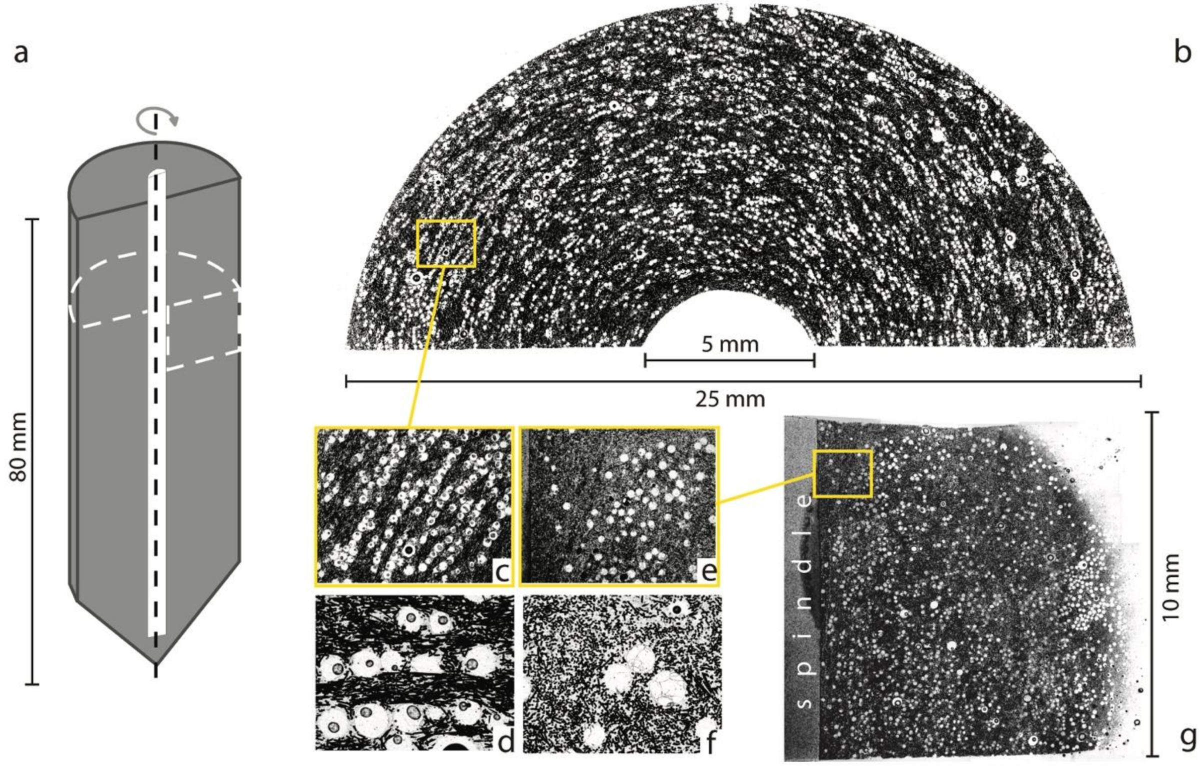
T_{max} = max temperatura
T_0 = considered temperature
Na = Nahme number
b = rheological sensitivity to temperature

Conclusion and future work

Scientific community should:

- better characterizing the effects of crystal-size distribution (fine vs coarse), fluid-solid interactions, and hysteresis relevant for elongated particles (Cimarelli et al., 2011)





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DATA DESCRIPTOR

A comprehensive database of crystal-bearing magmas for the calibration of a rheological model

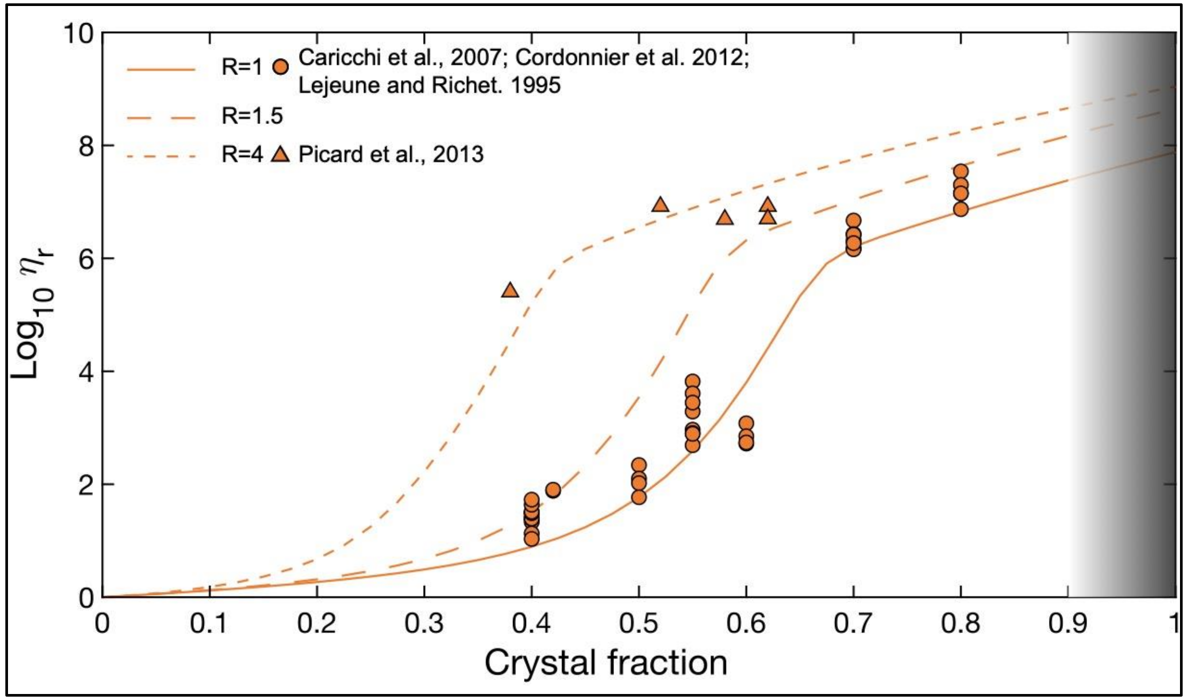
Alessandro Frontoni[1] ✉, Antonio Costa[2], Alessandro Vona[1] & Claudia Romano[1]

In this work, we present a comprehensive rheological database including most of the existing data relevant for crystal-bearing magmas collected from the scientific literature, covering the entire range of natural volcanic conditions, in terms of crystal content (1–80%), crystal shape (aspect ratio R from 1 to 13), and strain rate (between 10^{-7} and $10^{2}\,s^{-1}$). Datasets were collected and discerned as a function of the information which we considered necessary for building a general systematic model describing relative viscosity of crystal-bearing magmas, such as the apparent and melt viscosity, the crystal concentration, crystal shape, and the strain rate. The selected dataset was then used for modelling the relative viscosity of a liquid-solid mixture having different concentrations of particles with different R, subjected to different strain rates. The proposed model allows us to quantitatively describe the rheological behaviour of crystal-bearing magmatic systems.

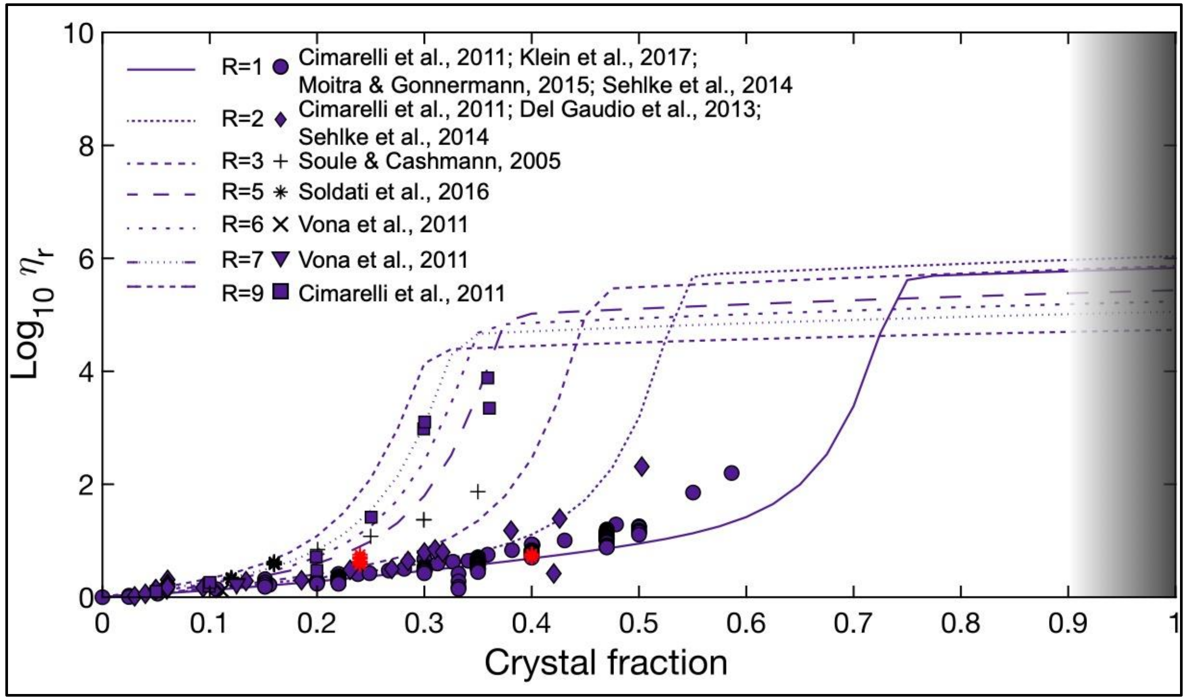
Thank you for your attention!

Effects of crystal content

- $\dot{\mathcal{E}}$=5 x 10^{-5} s^{-1}

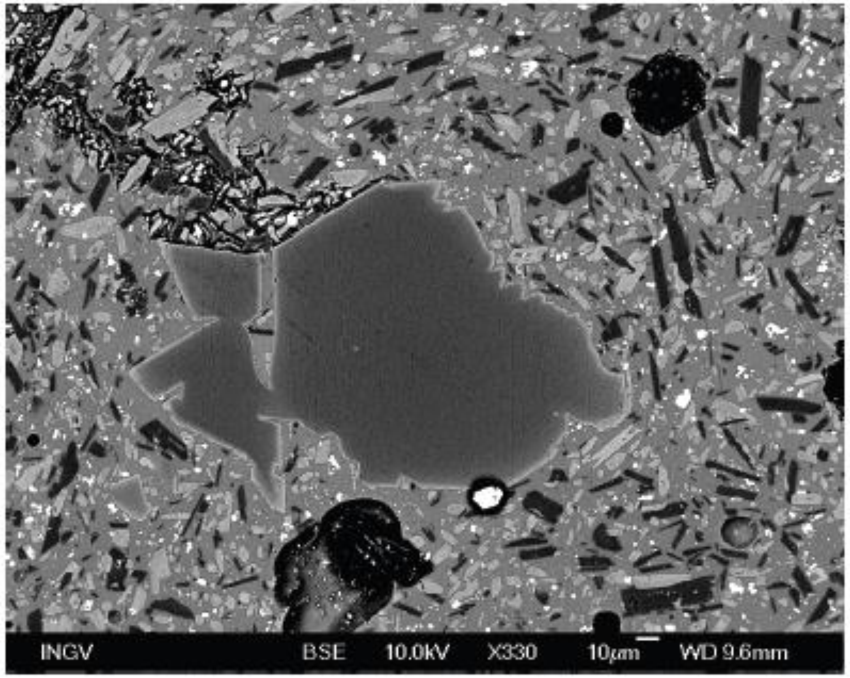


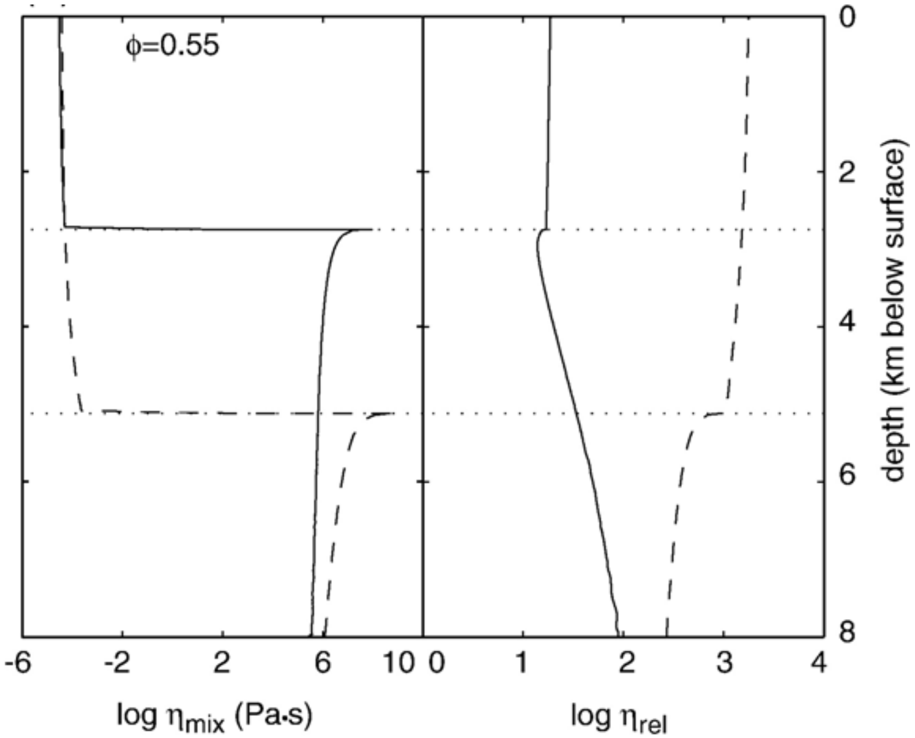
- $\dot{\mathcal{E}}$=5 x 10^{0} s^{-1}



Application to *all the strain rates*, crystal content and aspect ratios of volcanological interest!

Rationale





Caricchi et al. 2007

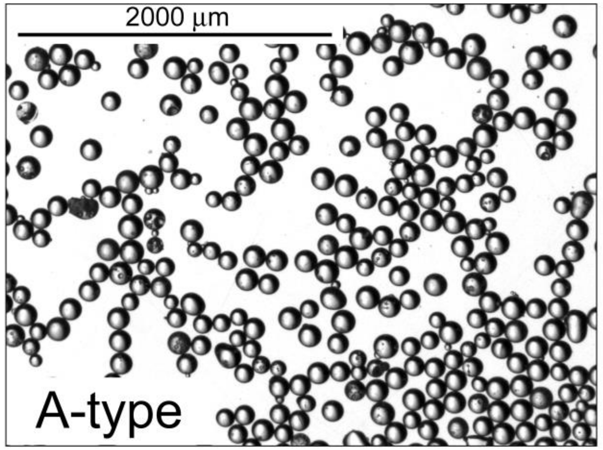
Complex history of crystallization (microlites + phenocrysts)

Increasing crystallinity changes rheology (non-Newtonian)

Influence on magma flow and eruptive style.

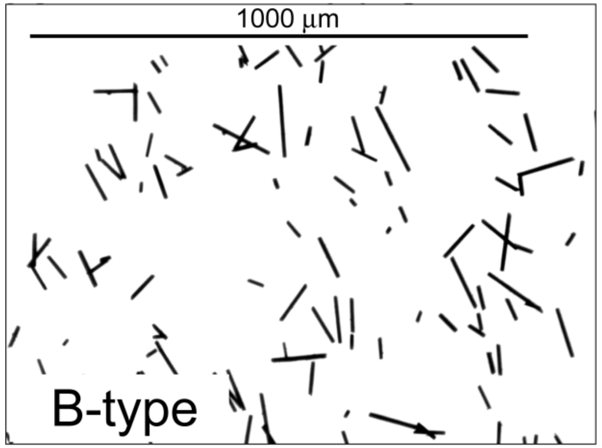
Analogues

Suspensions of particles in Newtonian silicone oil

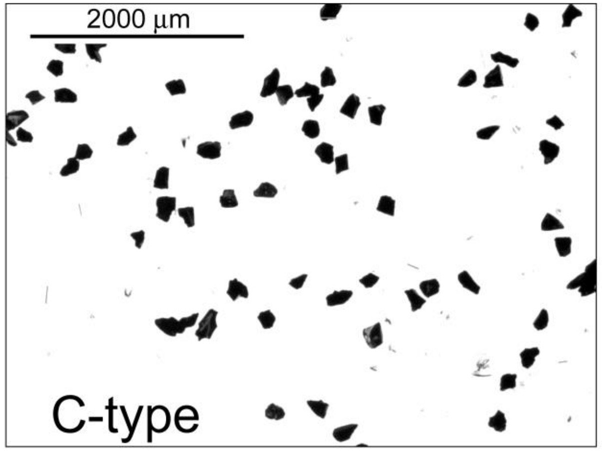


glass beads: ⟩= 2.448 g/cm^3; d=125⌠m

+

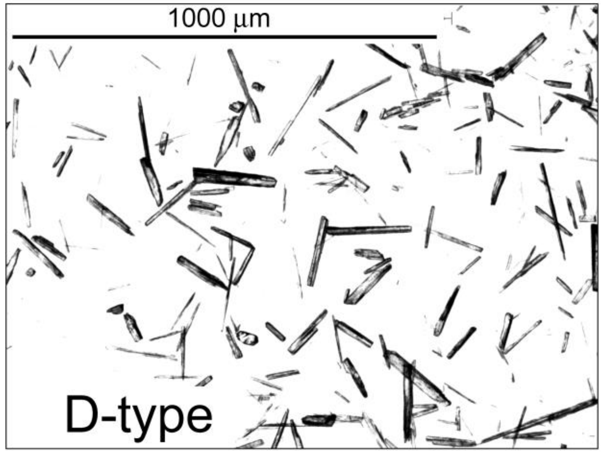


carbon fibres: ⟩= 1.740 g/cm^3; r=9.05



SiC grit: ⟩= 3.166 g/cm^3; r=1.8

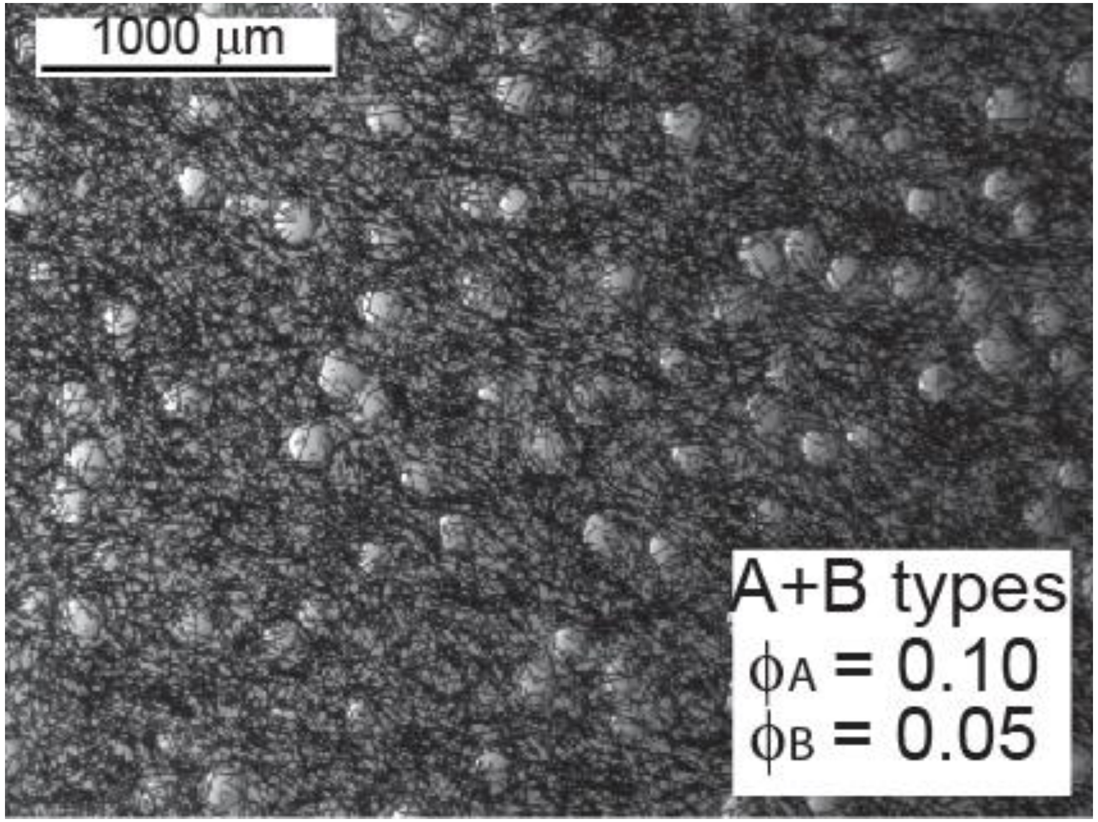
+



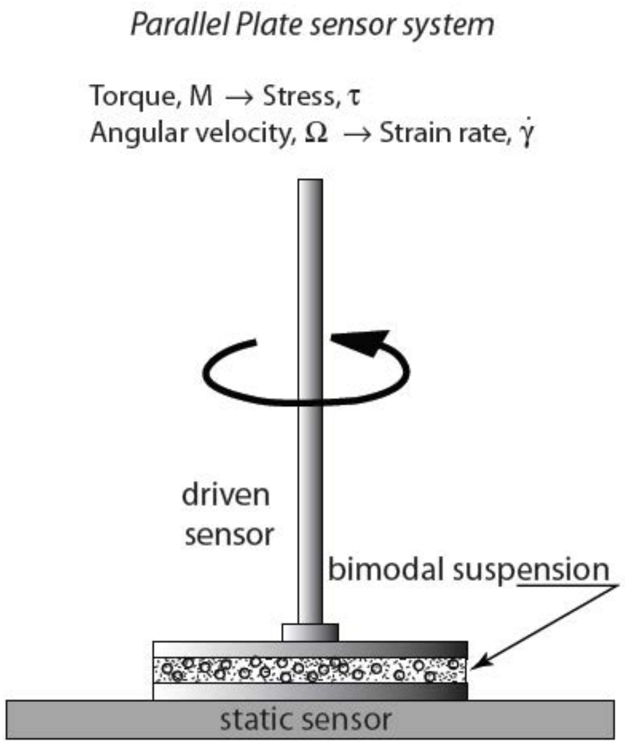
wollastonite: ⟩= 2.750 g/cm^3; r=8.50

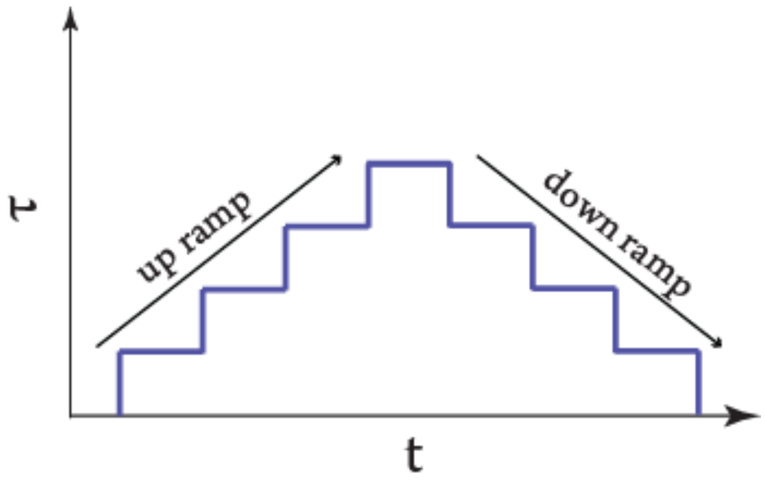
Analogues

Bimodal suspensions of particles with different shape and size



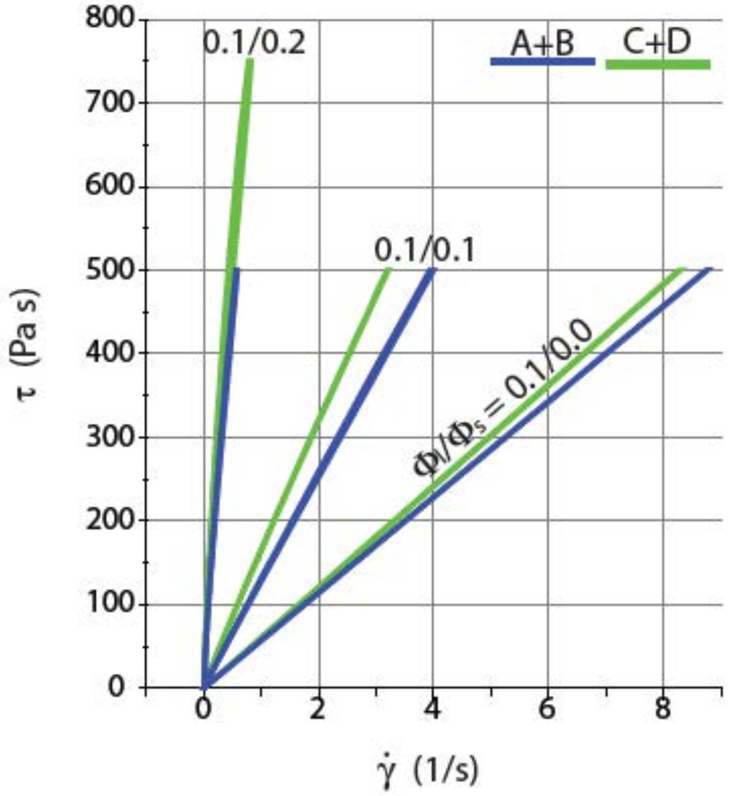
Measurements





Measurements

Flow curve $\tau = f(\dot{\gamma})$



$$\tau = \tau_0 + K\dot{\gamma}^n$$

Herschel-Bulkley model

τ_0: yield strength (Pa)

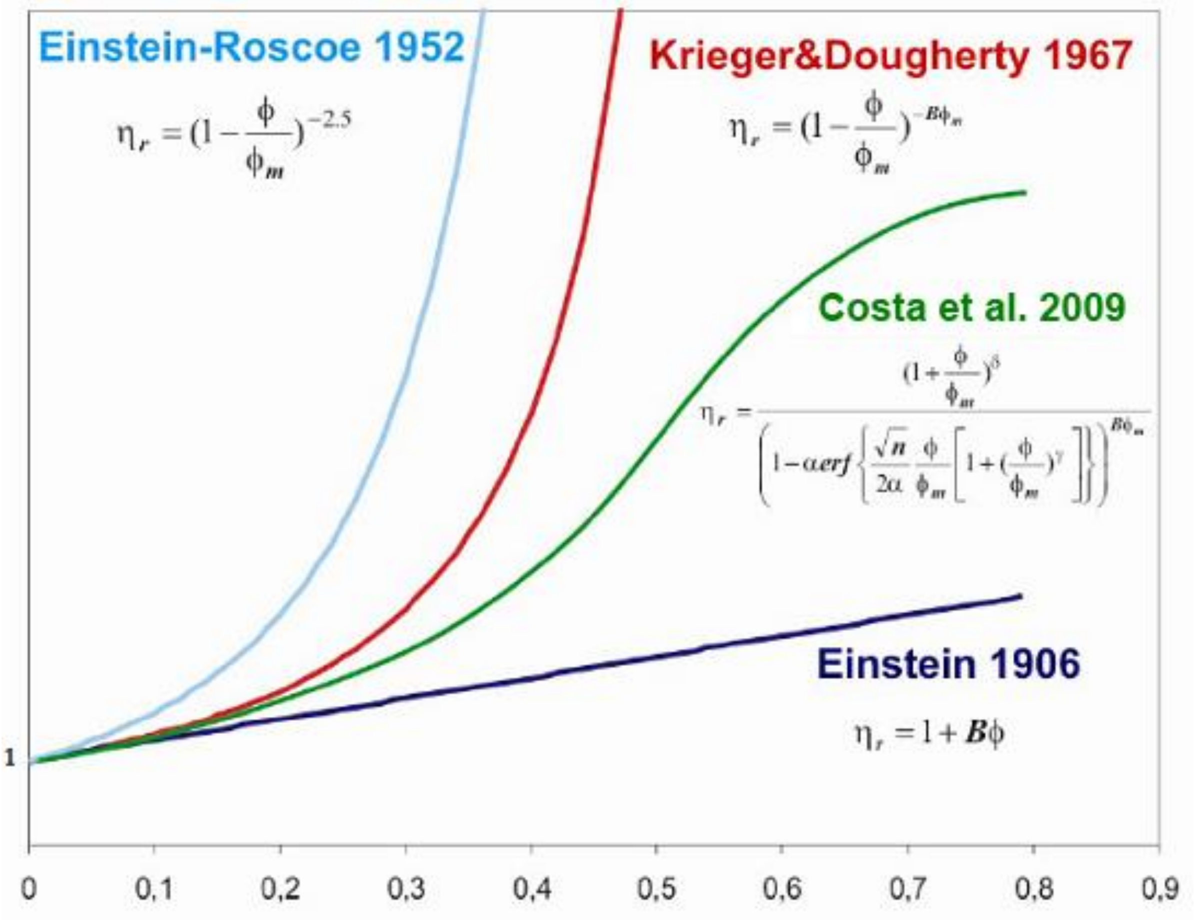
K: consistency (Pa s^n)

n: flow index

effective relative viscosity

$$\eta_r \equiv \frac{1}{\mu_l}\left(\frac{\tau - \tau_0}{\dot{\gamma}}\right) = \frac{K\dot{\gamma}^{n-1}}{\mu_l}$$

Models for $\eta_r(\phi)$



<u>Monodisperse suspensions:</u>

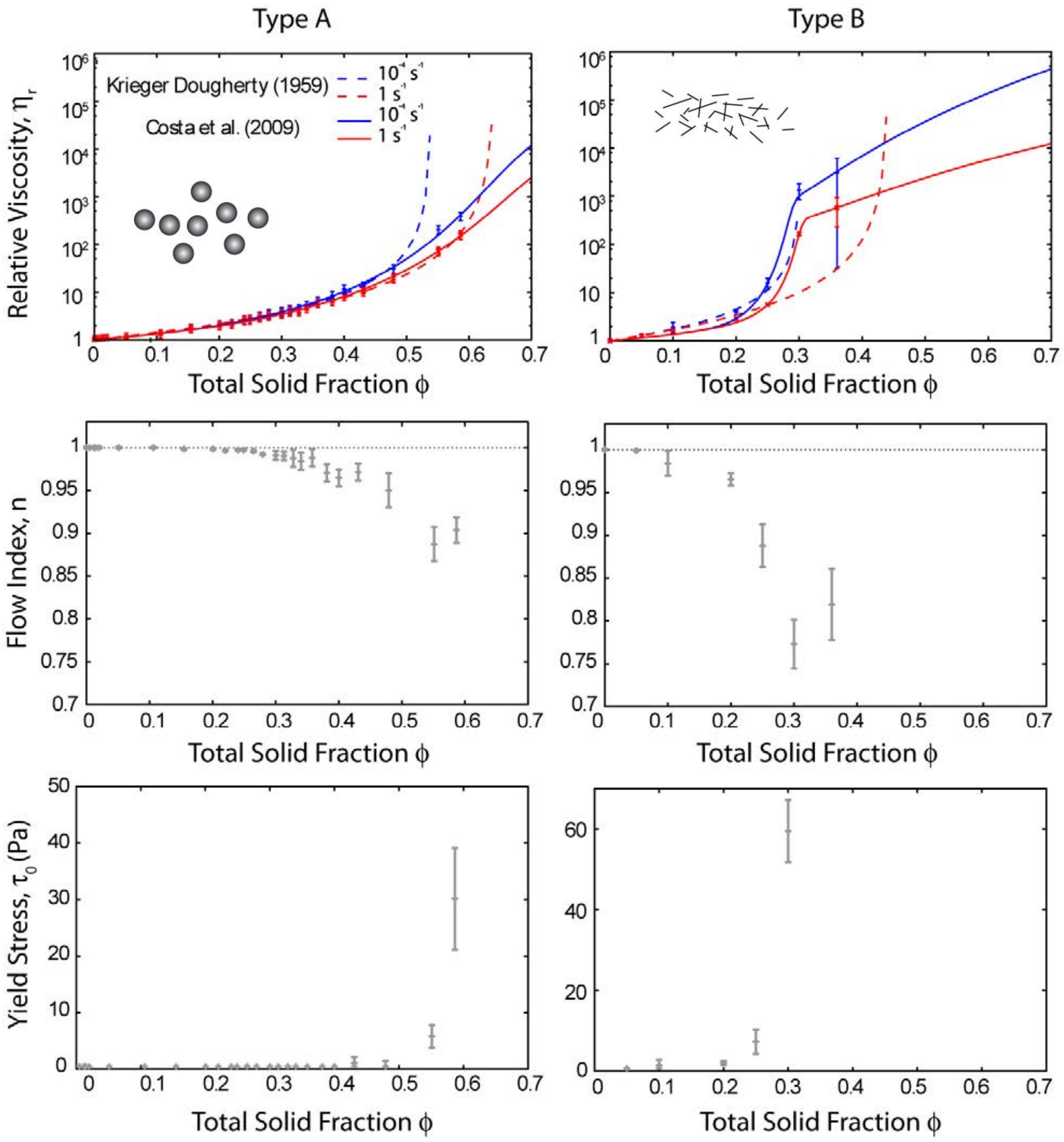
Einstein 1906
Theoretical, linear, dilute suspensions
B 'intrinsic viscosity' = 2.5 for spheres

Einstein-Roscoe 1952
Power-law, ϕ_m = max. particle concentration

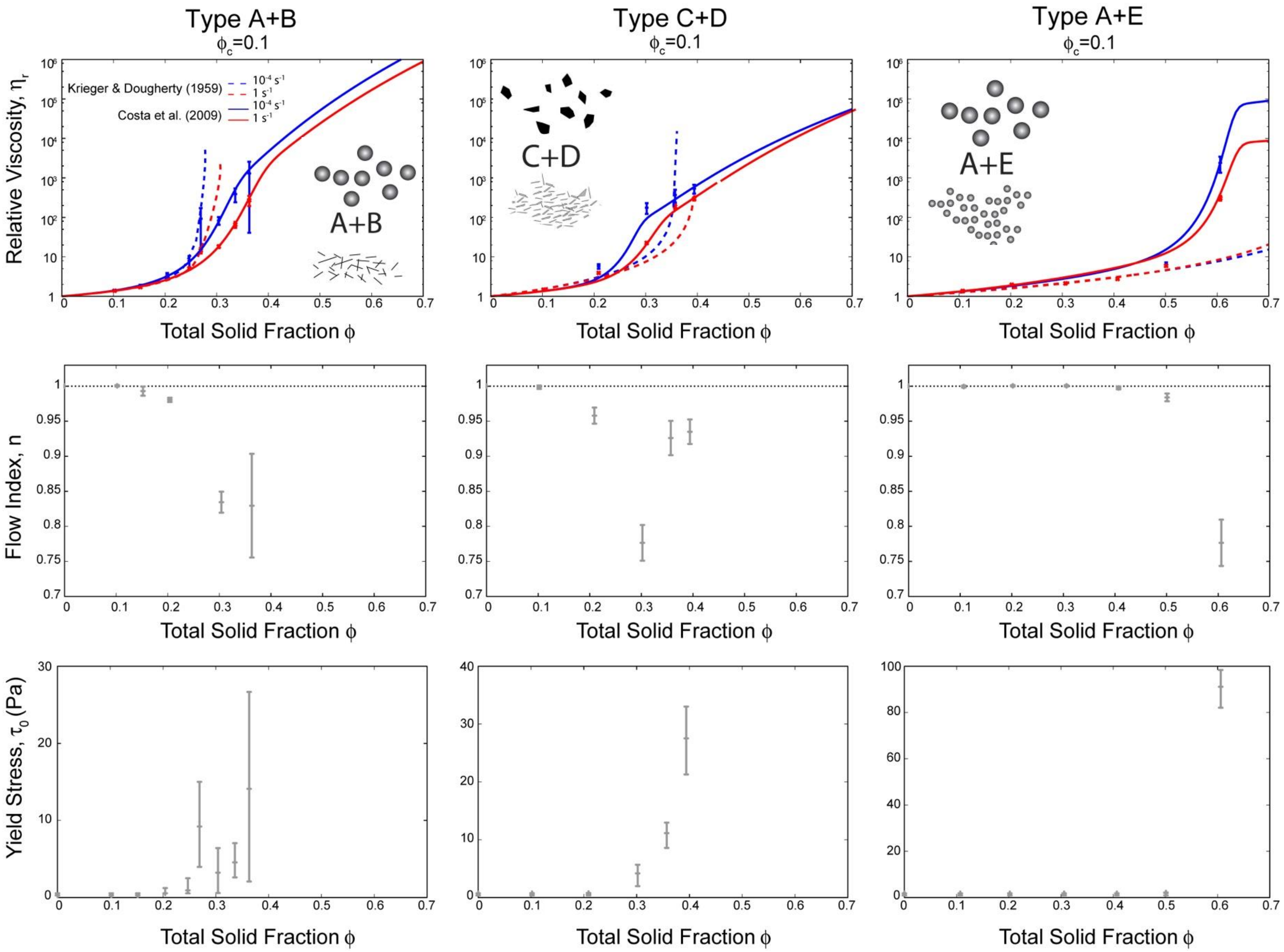
Krieger & Dougherty 1967
Power-law, exponent modified by ϕ_m

Costa et al. 2009
sigmoidal semi-empirical 3-parameter equation

Monodisperse

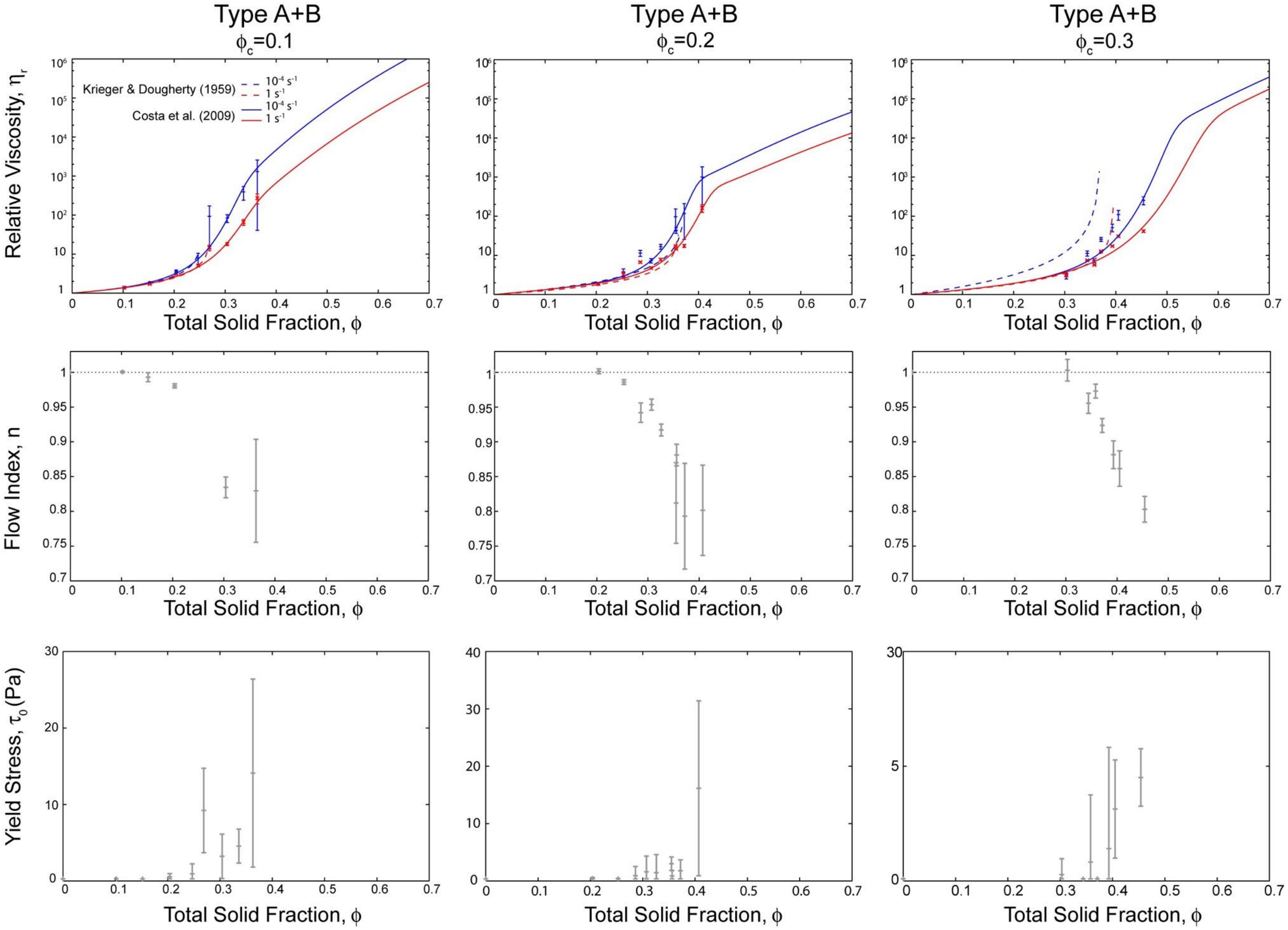


Bidisperse



Type A+B
ϕc=0.1
Type C+D
ϕc=0.1
Type A+E
ϕc=0.1
Relative Viscosity, ηr
Krieger & Dougherty (1959)
Costa et al. (2009)
10⁻⁴ s⁻¹
1 s⁻¹
A+B
C+D
A+E
Total Solid Fraction ϕ
Flow Index, n
Yield Stress, τ0 (Pa)

Bidisperse



Type A+B
ϕc=0.1
Type A+B
ϕc=0.2
Type A+B
ϕc=0.3
Krieger & Dougherty (1959)
Costa et al. (2009)
10-4 s-1
1 s-1
Relative Viscosity, ηr
Flow Index, n
Yield Stress, τ0 (Pa)
Total Solid Fraction, ϕ

Monodisperse