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Shear localization during magma ascent: results from quasi-2D numerical simulations

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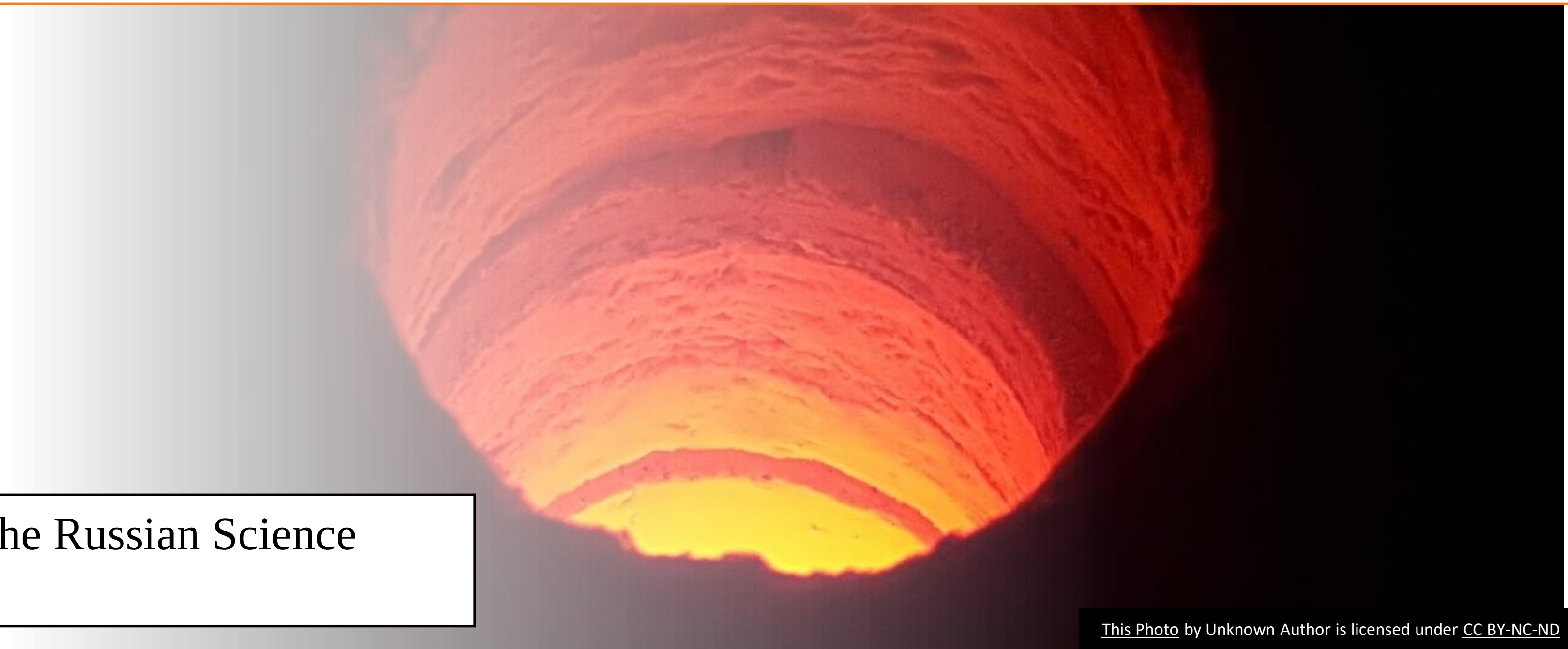

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Abstract

- At large crystal contents magma exhibits non-Newtonian behavior, typically shear thinning due to crystal orientation along streamlines. 1D models widely used for extrusive eruption simulations cannot capture efficiently the complexity of cross-conduit variations of the properties of magmas as they assume parabolic velocity profile and averaged properties of magma. Large aspect ratios of volcanic conduits (length/diameter) makes use of fully 2D numerical models computationally expensive and not reliable because of extremely large cross-conduit variation of parameters.

- Here we present results of numerical simulations of a quasi-2D model that accounts for magma crystallization with the release of the latent heat, shear thinning rheology, heat transfer and viscous dissipation. Simulated velocity profile is far from parabolic. Shear layers form initially near the wall of the conduit and migrate towards the interior as magma ascends. Shear heating results in significant increases in temperature of the magma in narrow shear bands. There is a drastic difference between the predictions of 1D and quasi-2D models in terms of pressure-discharge rate relations. Lava dome morphology can be strongly affected by the formation of shear zones inside volcanic conduits during magma ascent.

Examples of flow localization – spine extrusion

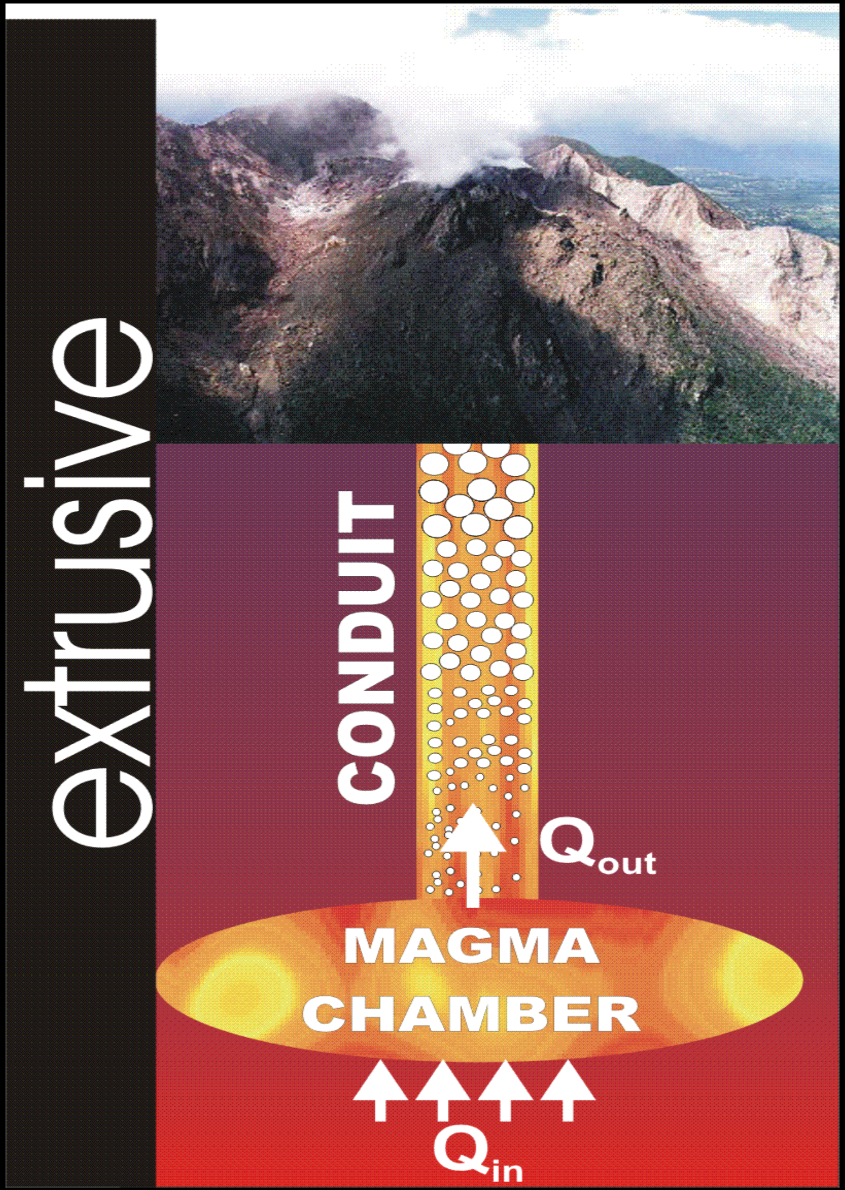
A volcanic spine at the summit of the Mt. Pelee. Photograph by Angelo Heilprin (United States, 1853-1907).

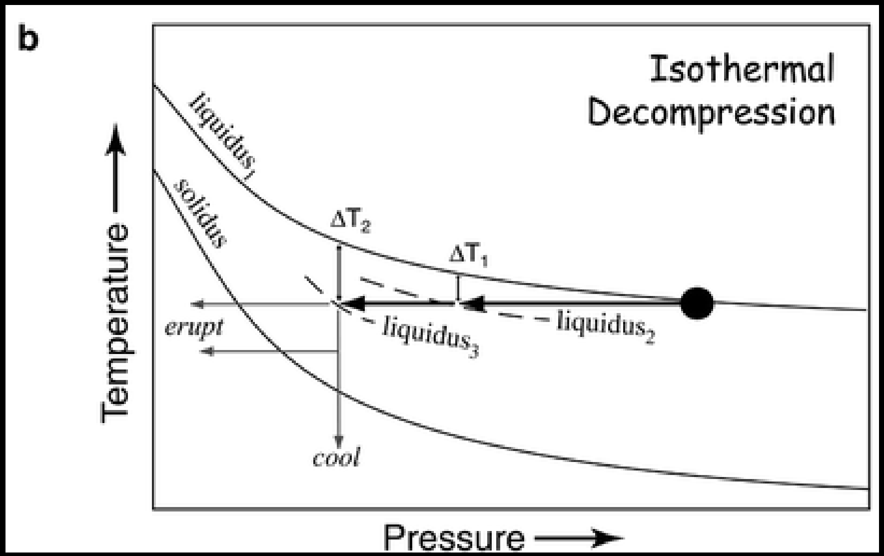
Watts R. B. et al. Growth patterns and emplacement of the andesitic lava dome at Soufriere Hills Volcano, Montserrat //Geological Society, London, Memoirs. – 2002. – T. 21. – №. 1. – C. 115-152.

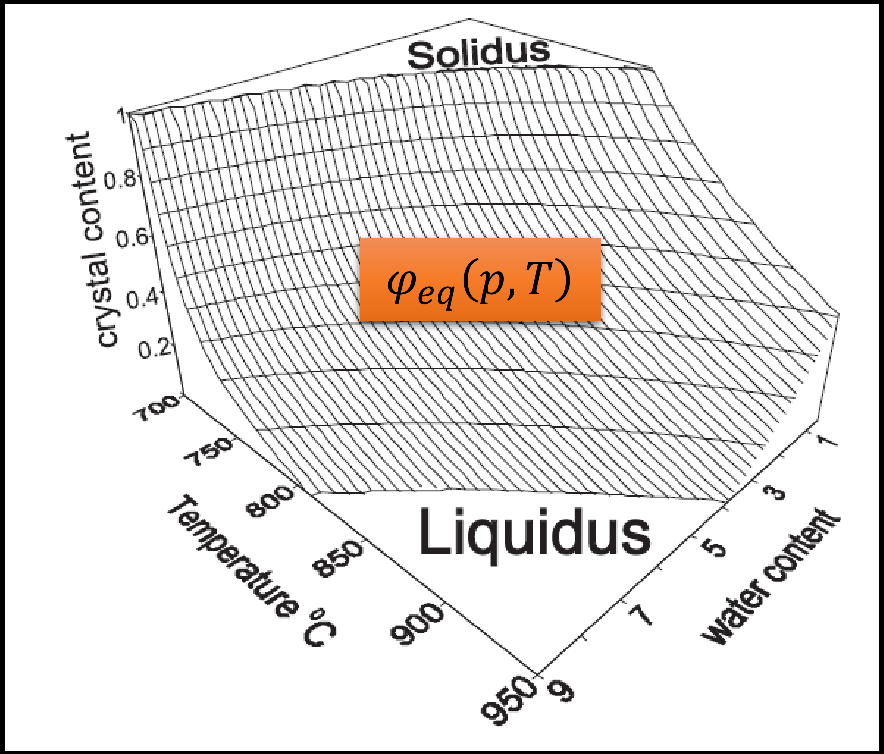
Main features of extrusive eruptions

Slow ascend velocity
(0.1-30 mm/s)

- ✓ Magma parcel spends weeks to months in the conduit.
- ✓ Degassing induced crystallization leads to viscosity increase.
- ✓ At high crystal content magma exhibits non-Newtonian properties.
- ✓ Heat conduction to the country rocks, latent heat release and shear heating lead to strong temperature variations.
- ✓ Magma properties across the conduit change dramatically leading to shear localization and flow instabilities.
- ✓ Magma recharge can play a significant role during eruptions.





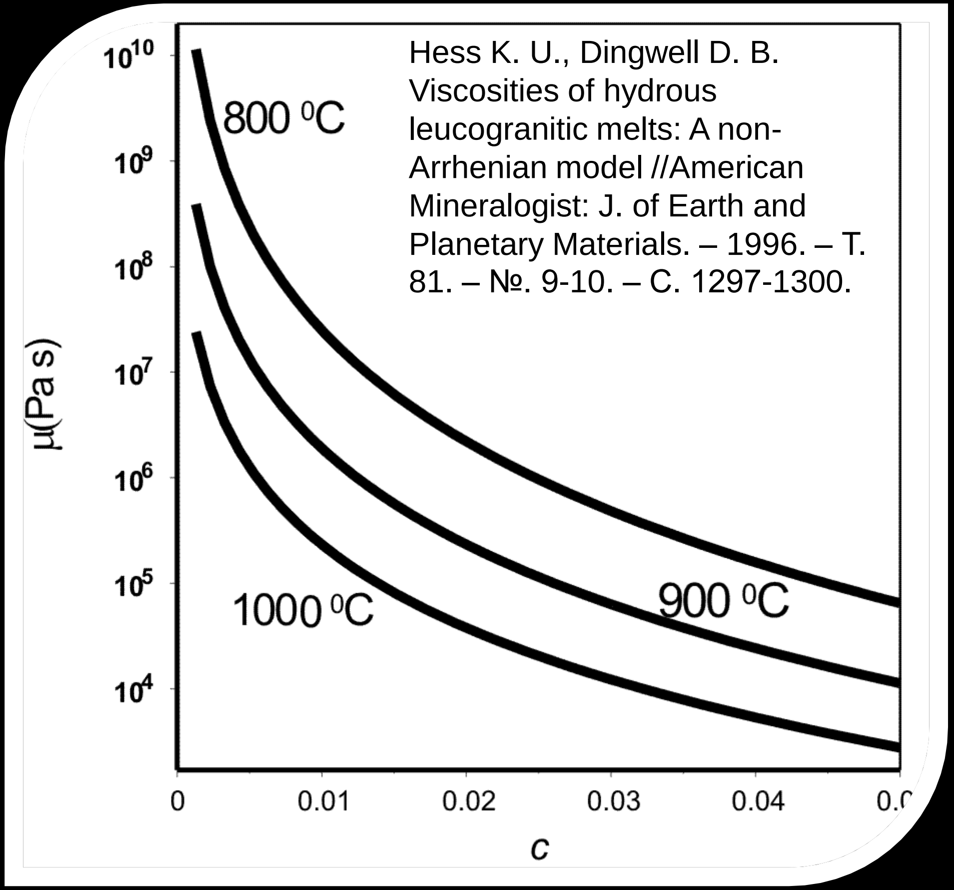


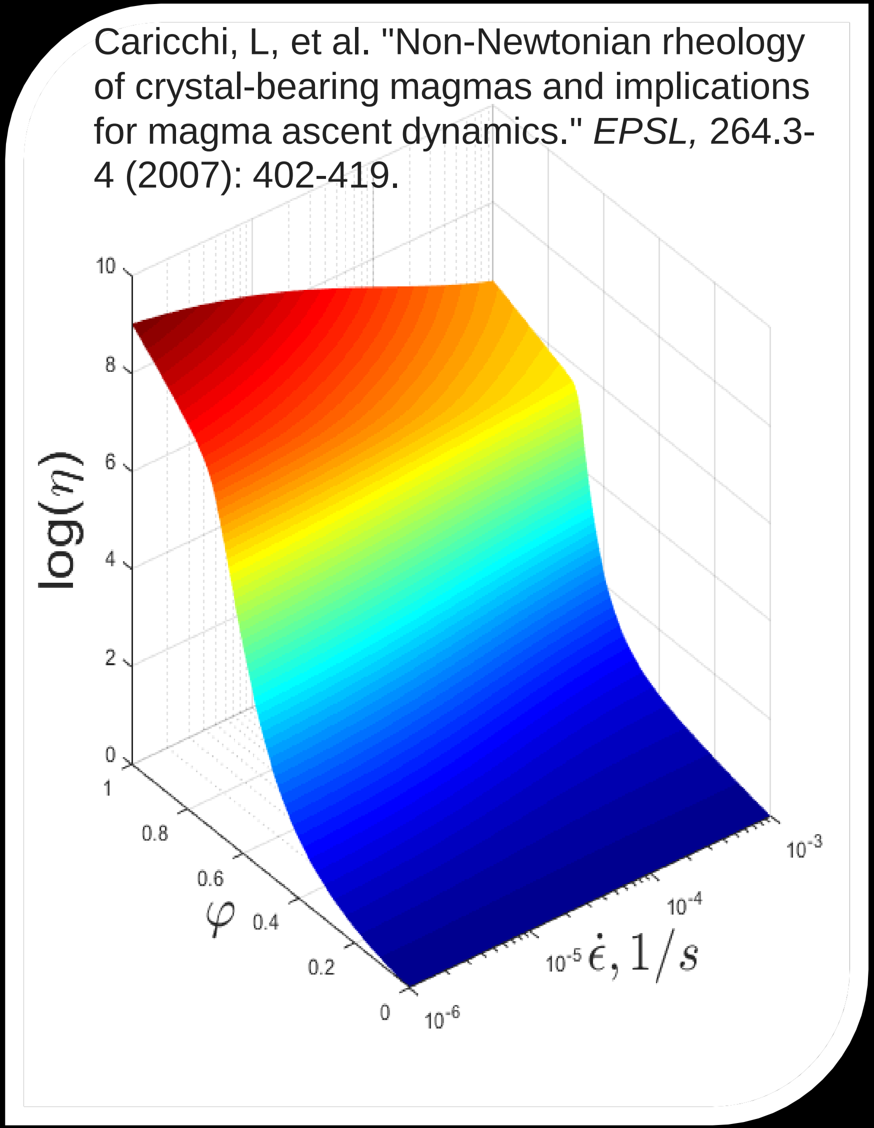
$$\frac{d\varphi}{dt} = -\frac{\varphi - \varphi_{eq}(p,T)}{\tau(p,T)}$$

Degassing induced crystallization

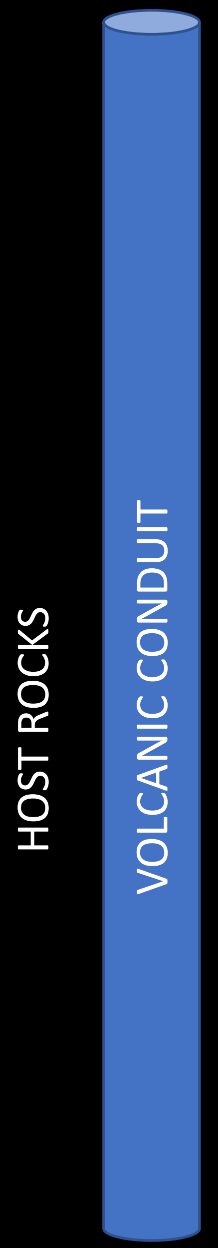
Melnik O., Sparks R. S. J. Controls on conduit magma flow dynamics during lava dome building eruptions //Journal of Geophysical Research: Solid Earth. – 2005. – T. 110. – №. B2.

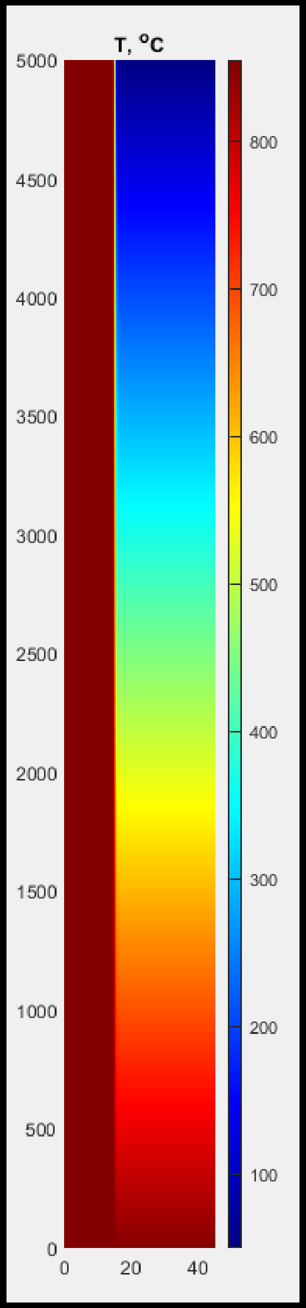
$$\mu = \mu_m(p, T, x_i) \bullet \eta(\varphi, \dot{\varepsilon})$$





Magma viscosity





Model setup

- Cylindrical volcanic conduit is surrounded by cold host rocks
- Magma is an incompressible, non-Newtonian fluid
- Velocity has only vertical component that depends on radial coordinate.
- Fixed influx rate into the conduit from the magma chamber
- Pressure at the top of the conduit is fixed at 10 MPa due to the load of the lava dome.
- Heat transfer to surrounding rocks occurs due to heat conduction.
- Shear heating and latent heat release are accounted

System of equations

$$2\pi\int_o^R \rho V r dr = Q - \text{discharge rate}$$

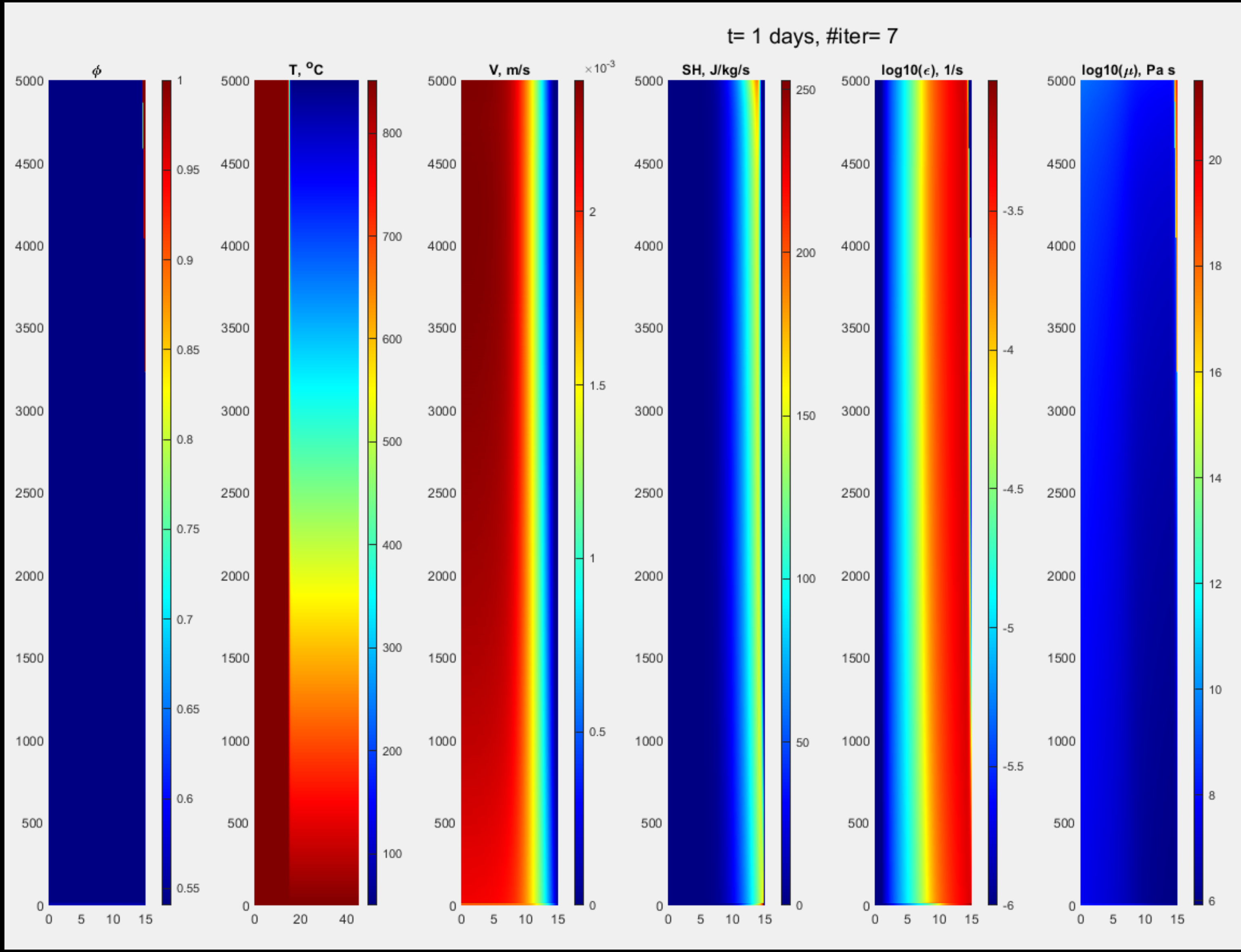
$$\frac{dp}{dz} = \frac{1}{r}\frac{\partial}{\partial r} r\mu\left(p, T, \varphi, \dot{\varepsilon}\right)\frac{\partial}{\partial r}V - \rho g \quad - \text{momentum equation}$$

$$\rho C\left(\frac{\partial}{\partial t}T + V\frac{\partial}{\partial z}T\right) = \frac{1}{r}\frac{\partial}{\partial r} r\kappa\left(T\right)\frac{\partial}{\partial r}T + \mu\left(\frac{\partial}{\partial r}V\right)^2 + L\frac{\partial \varphi}{\partial t} - \text{energy equation}$$

$$\left(\frac{\partial}{\partial t}\varphi + V\frac{\partial}{\partial z}\varphi\right) = -\frac{\varphi - \varphi_{eq}\left(p, T\right)}{\tau\left(p, T\right)} - \text{crystal growth kinetics}$$

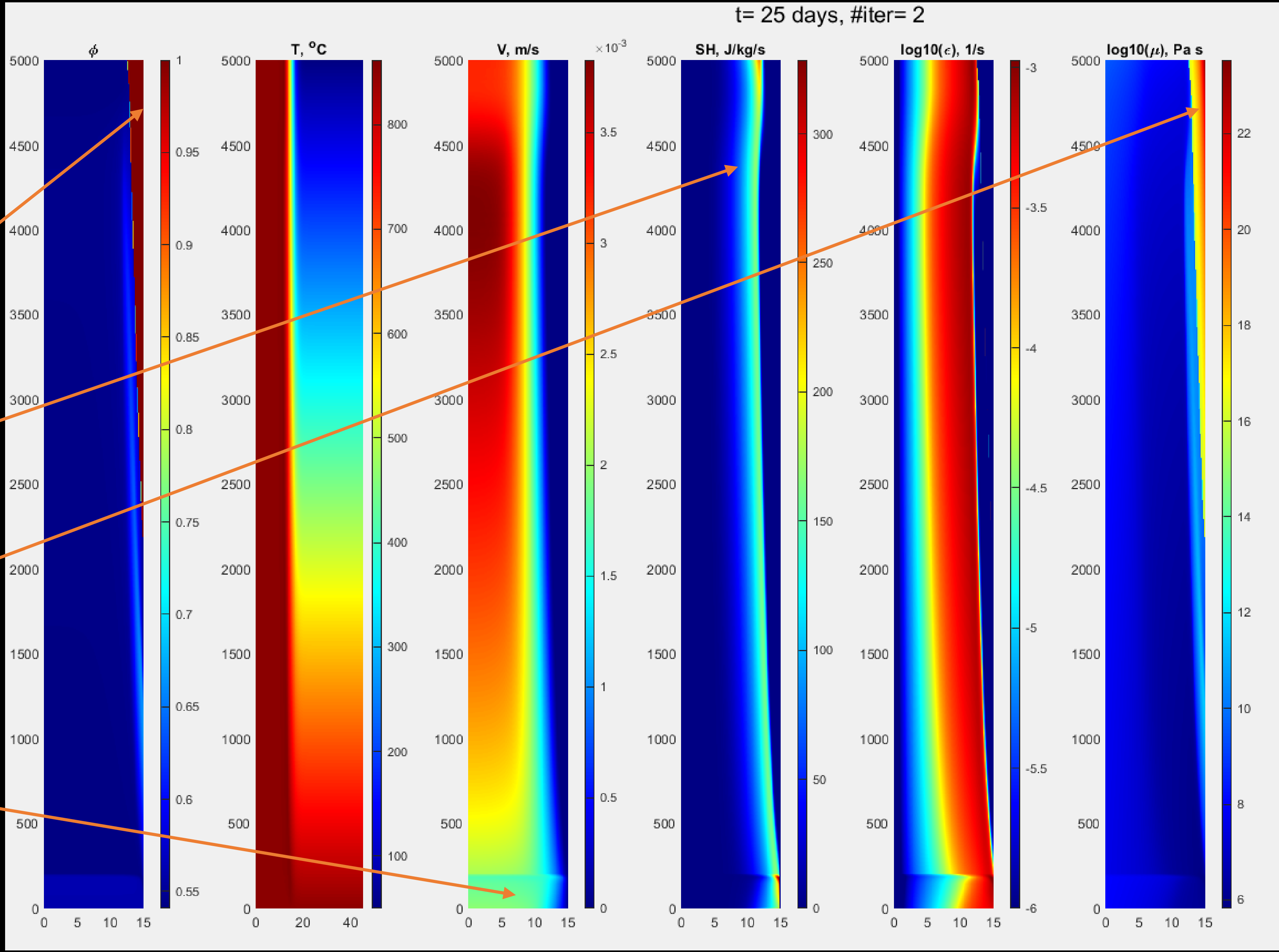
initial conditions

- Uniform crystal content (**φ**) and temperature (**T**) inside the conduit
- Parabolic velocity profile (**V**)
- Shear heating (SH) due to strain rate (**ε**)
- Viscosity (**μ**)as a function of pressure
- Geothermal gradient in host rocks



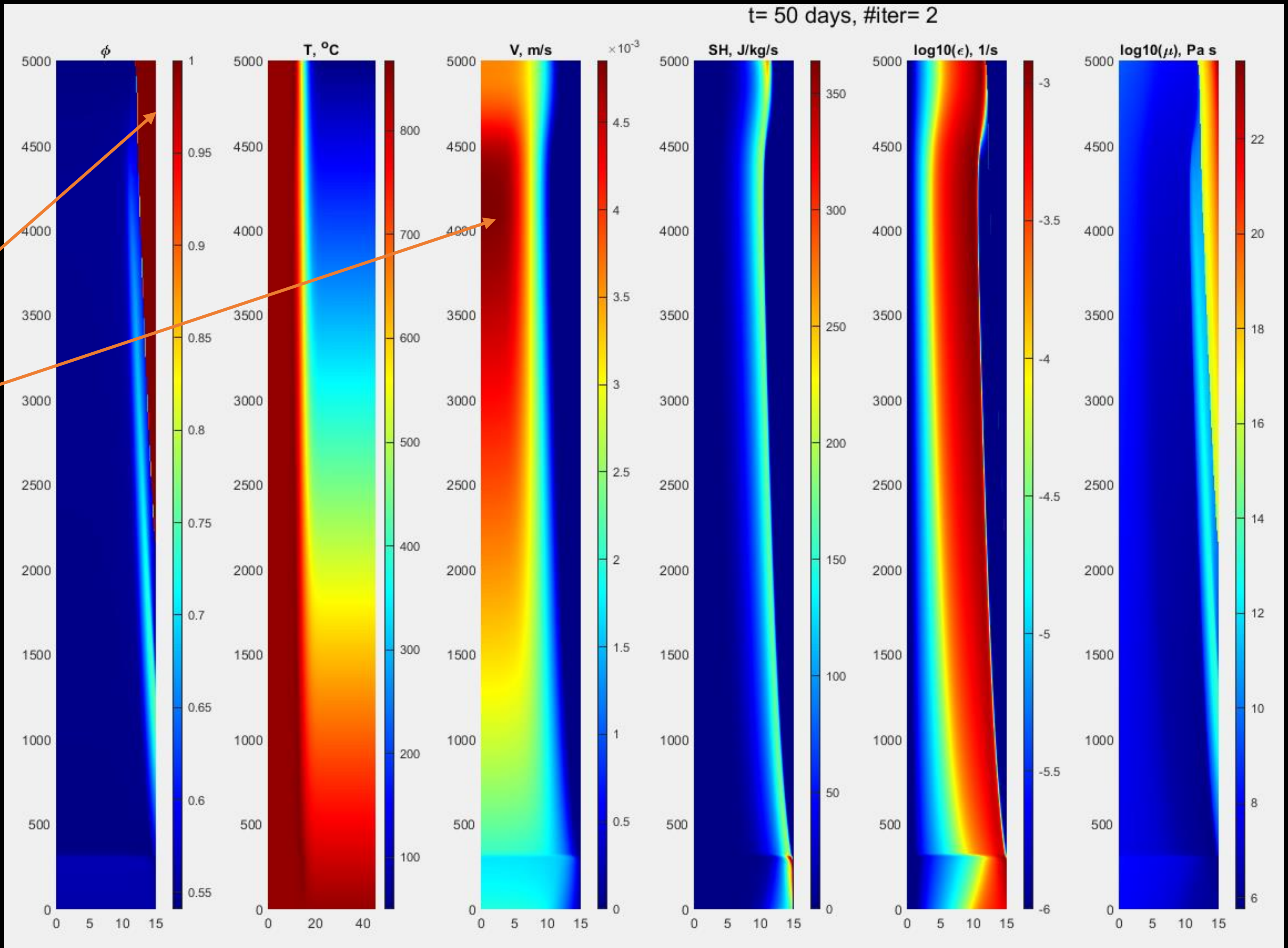
25 days after

- Cold layer of crystallized magma is formed near the top of the conduit
- Shear rate near the conduit walls start to decrease, shear heating localizes in a band
- Viscosity near the wall increases dramatically due to cooling and crystallization
- Magma with different crystal content starts to rise from the chamber



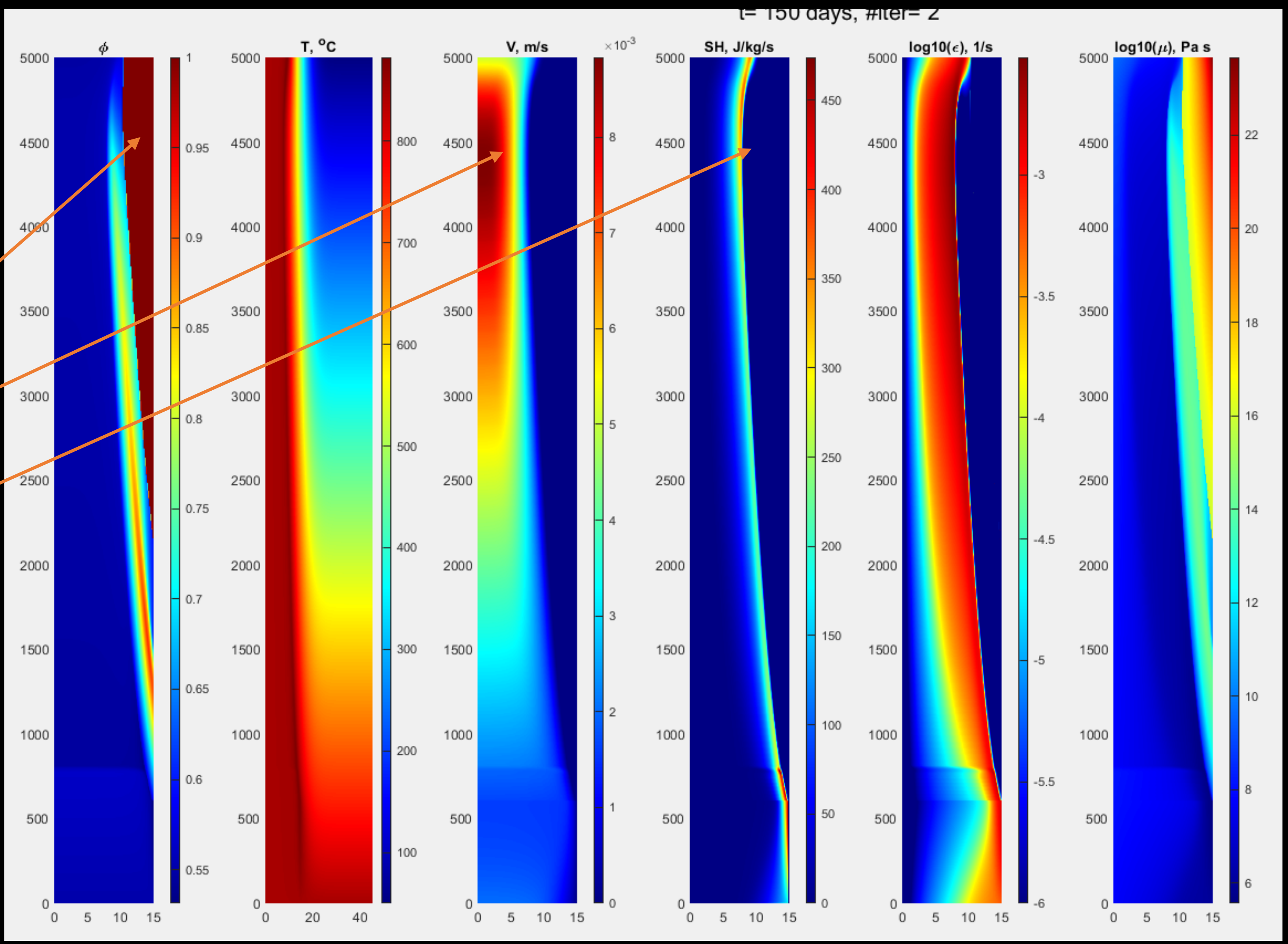
50 days after

- Cold layer thickness increases
- Velocity localizes in the center of the conduit



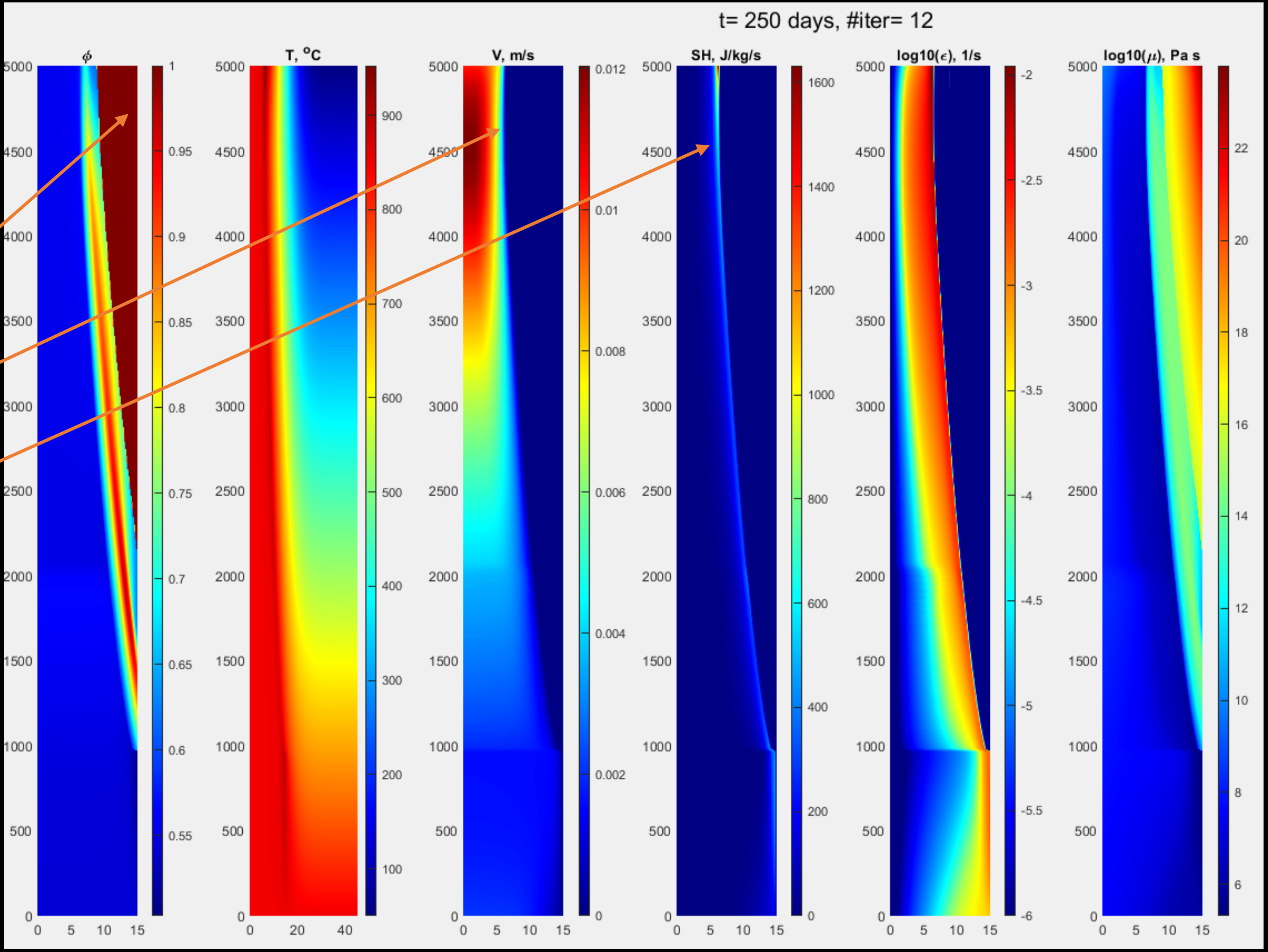
150 days after

- Cold layer thickness increases
- Velocity localizes in the center of the conduit
- Viscous heating localizes in a narrow band



150 days after

- Cold layer thickness increases
- Velocity localizes in the center of the conduit
- Viscous heating localizes in a narrow band
- High viscosity layer occupies significant portion of the conduit leading to the reduction of its effective cross-section area.
- Velocity and shear heating maximum values progressively increase



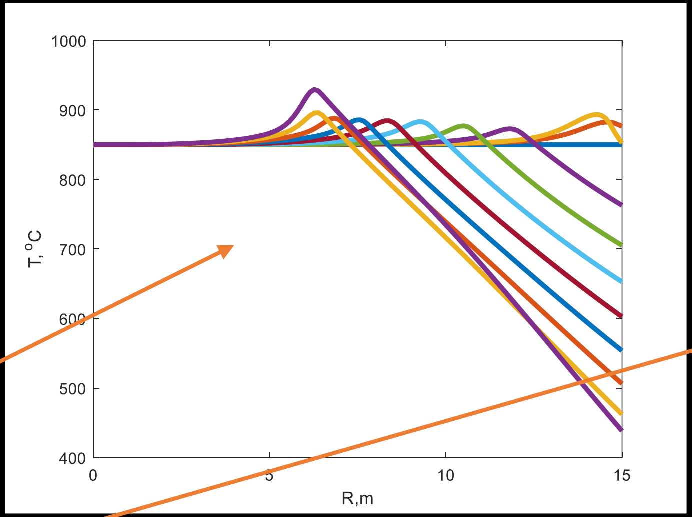
Profiles

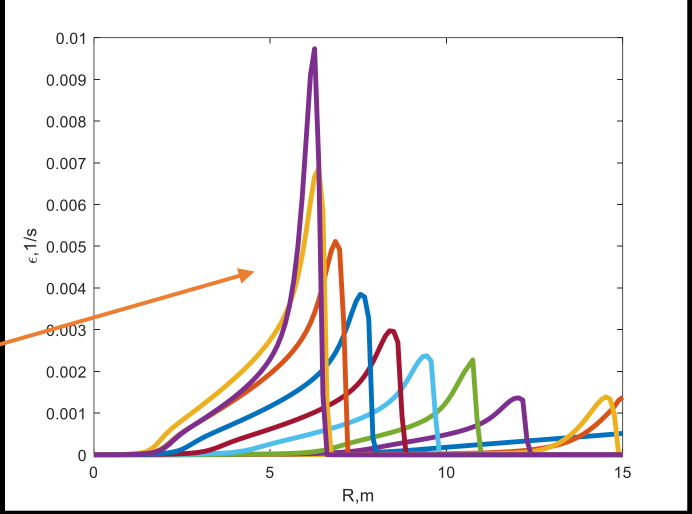
Temperature increases due to shear heating and release of the latent heat and decreases near the wall due to cooling

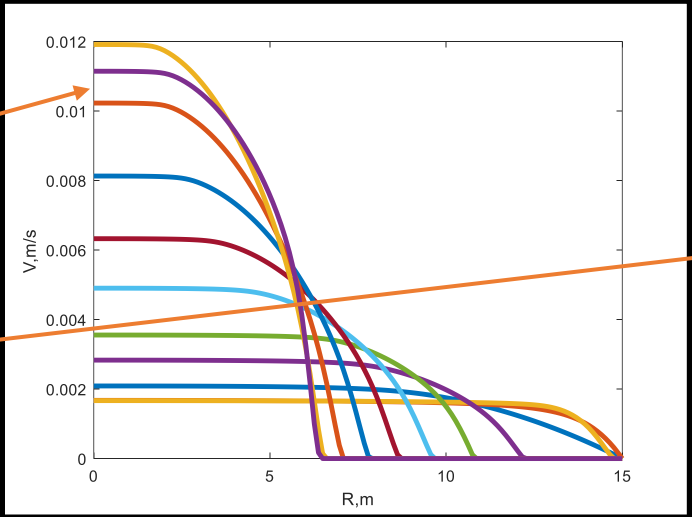
Shear localizes in a relatively narrow band.

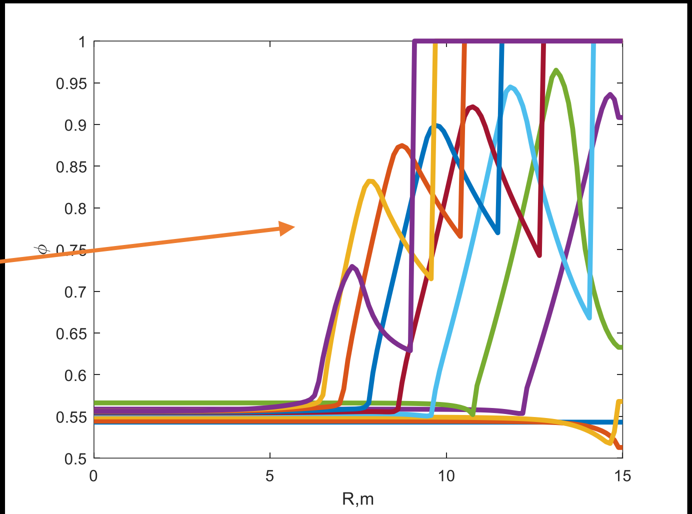
Velocity in the central part of the conduit increases, the plug flow forms

Crystal content profile is not monotonic. Temperature increase leads to decrease in crystal content in the shear layer. Near the wall magma is completely solidified. Due to rapid ascent in the central part crystal growth is not efficient









Thank you for attention!

Questions during online session