Coupled Fluid Flow, Deformation, Heat Transport & Mineral Reactions in Hydrothermal Mineralising Systems

热液成矿系统中流体流动，变形，热传递&矿物反应的耦合过程

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Hefei University of Technology Overseas Masters Program 2015

One Hour Presentations

1. A Systems Approach: The 5 Questions
2. Folding & Boudinage
3. Shear Zones, Fractures, Breccias and Veins.
4. The Regional Scale – Fundamentals
5. The Regional Scale – Applications
6. Synthesis – The Way Ahead

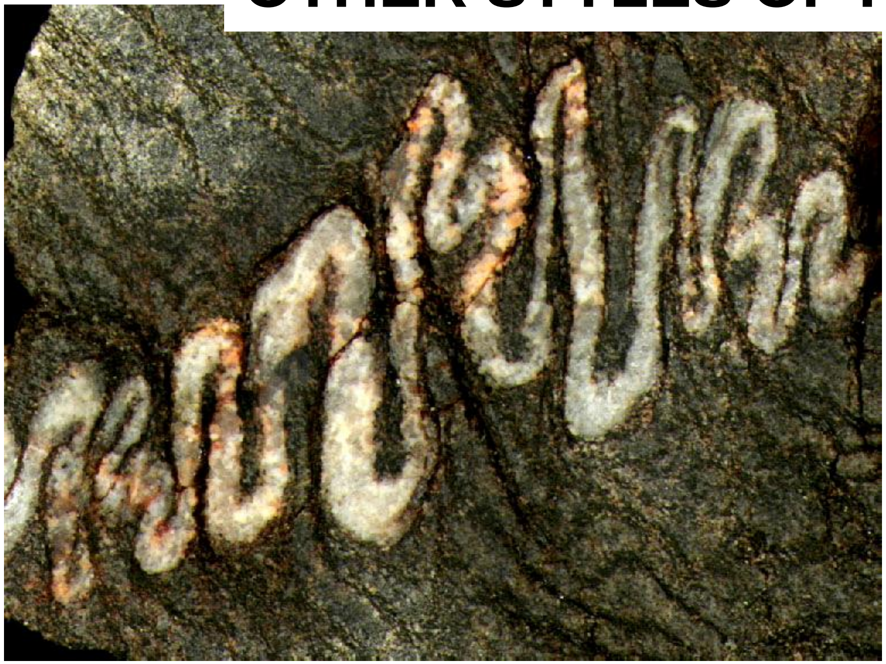
SOME PROBLEMS IN STRUCTURAL GEOLOGY

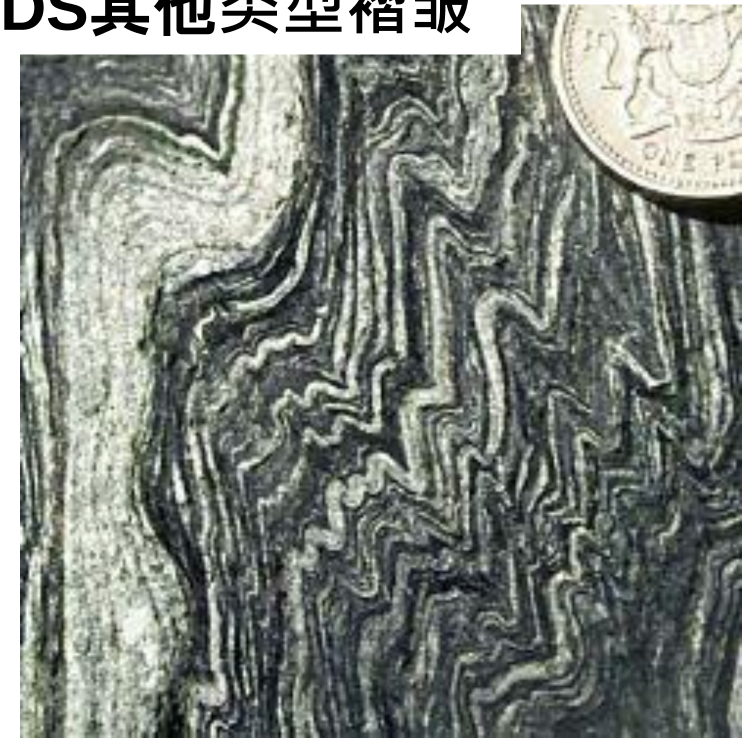
构造地质学中的一些问题

With thanks to Bruce Hobbs, Giles Hunt, Klaus Regenauer-Lieb and Hans Muhlhaus.

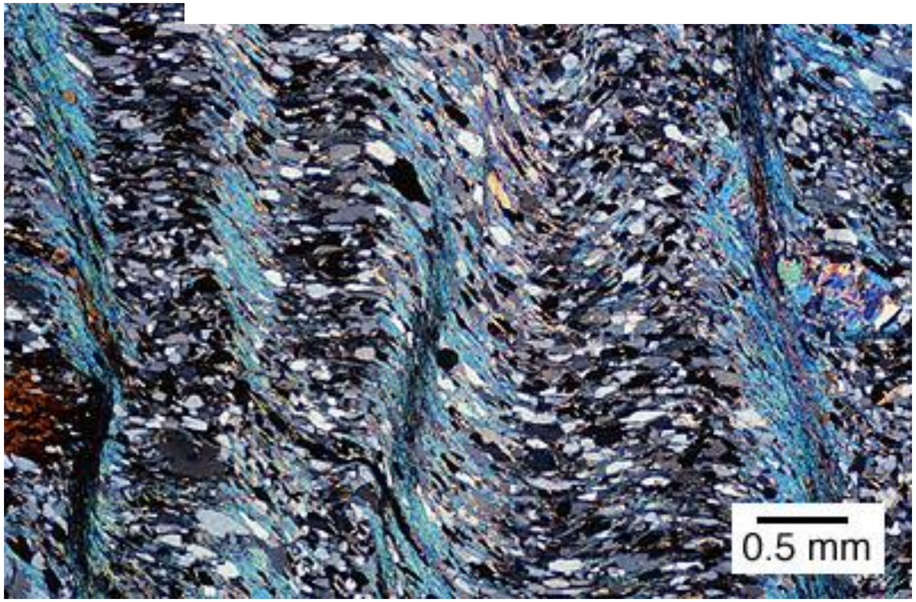
GILES STYLE FOLDS吉尔斯式褶皱

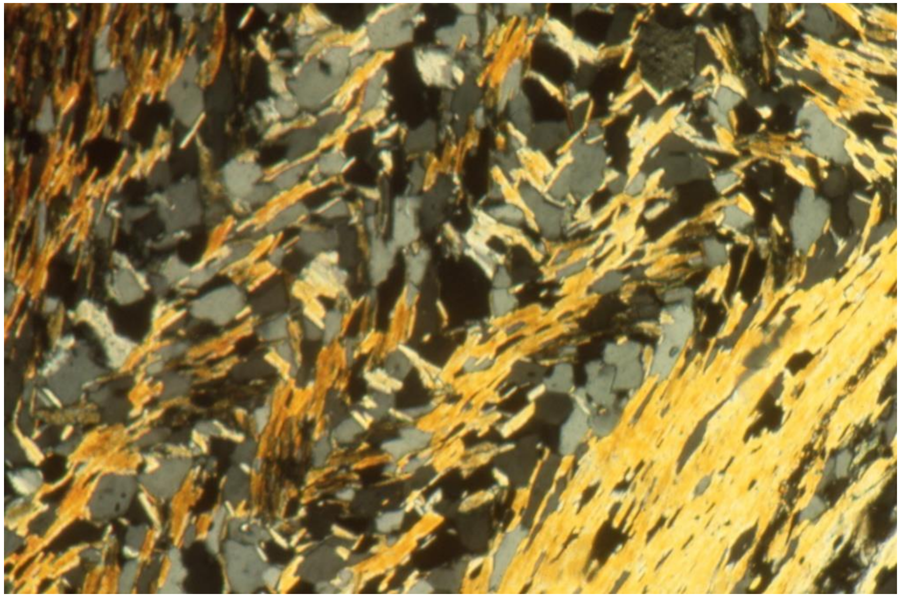
OTHER STYLES OF FOLDS其他类型褶皱

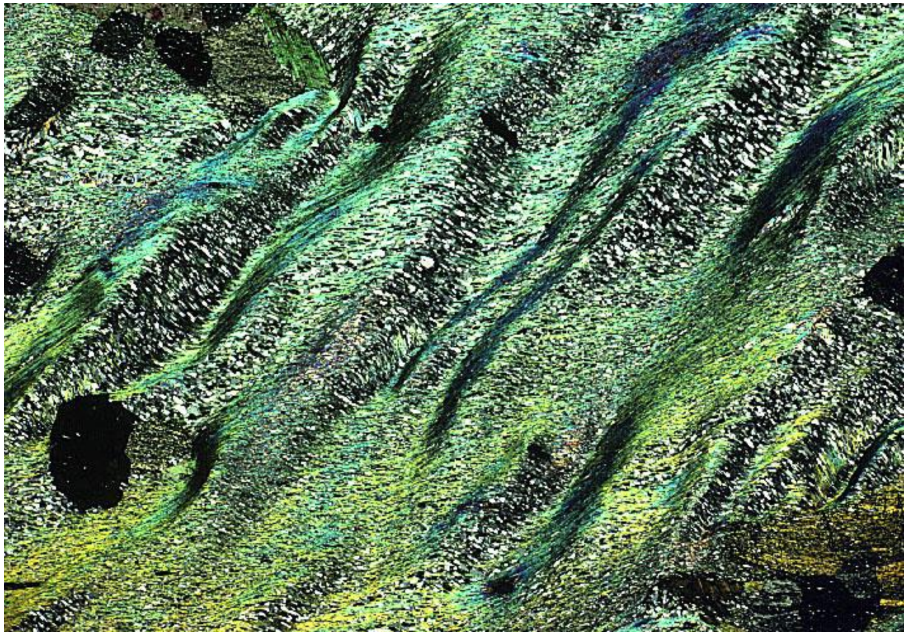




Micro-scale chemical reactions 微观化学反应







SCALE INVARIANCE IN STRUCTURAL GEOLOGY

构造地质中的标度不变性

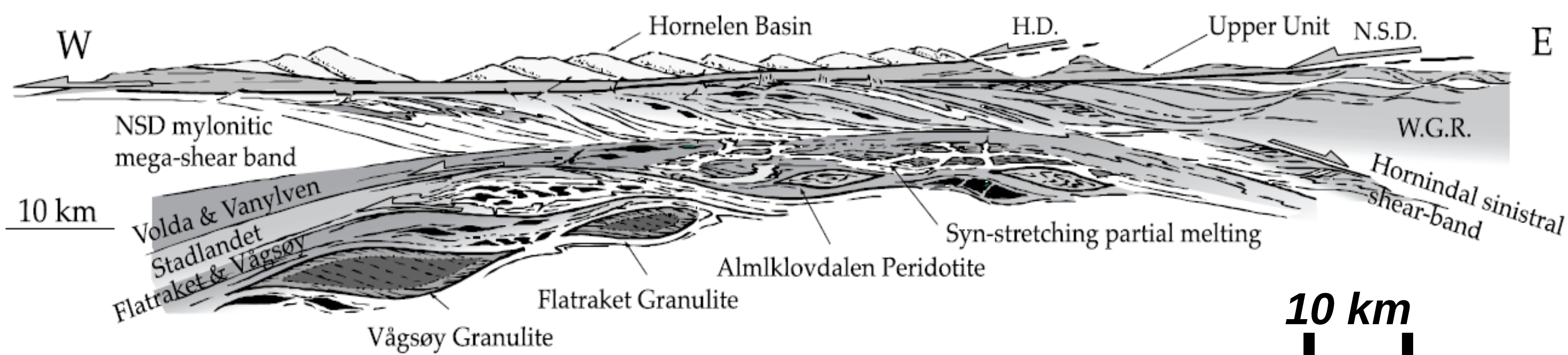
← 10 km →

SIMILAR STRUCTURES AT ALL SCALES

各种尺度下相似结构

← 1m →

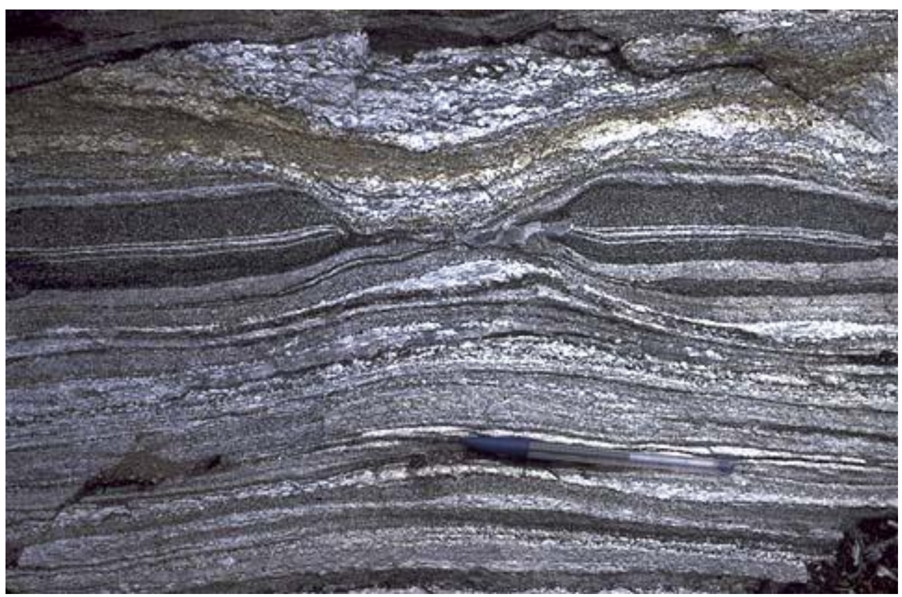
Photos: J-P. Burg



10 km

Fig. 3 Unscaled schematic cross-section showing the different areas and structural relations on a restored vertical profile. The core of the crustal boudin contains granulites and eclogites (black pods), Stadlandet, Vanylven and Volda are partly migmatized rims sheared to the west with amphibolitized eclogites. The Hornindal shear band is the symetrical limit of the boudin. On top, the ductile shear band associated to the NSD crosscuts these structures to the west.

各尺度下石香肠构造与局部熔融



Boudinage and partial melting at all scales

10 cm

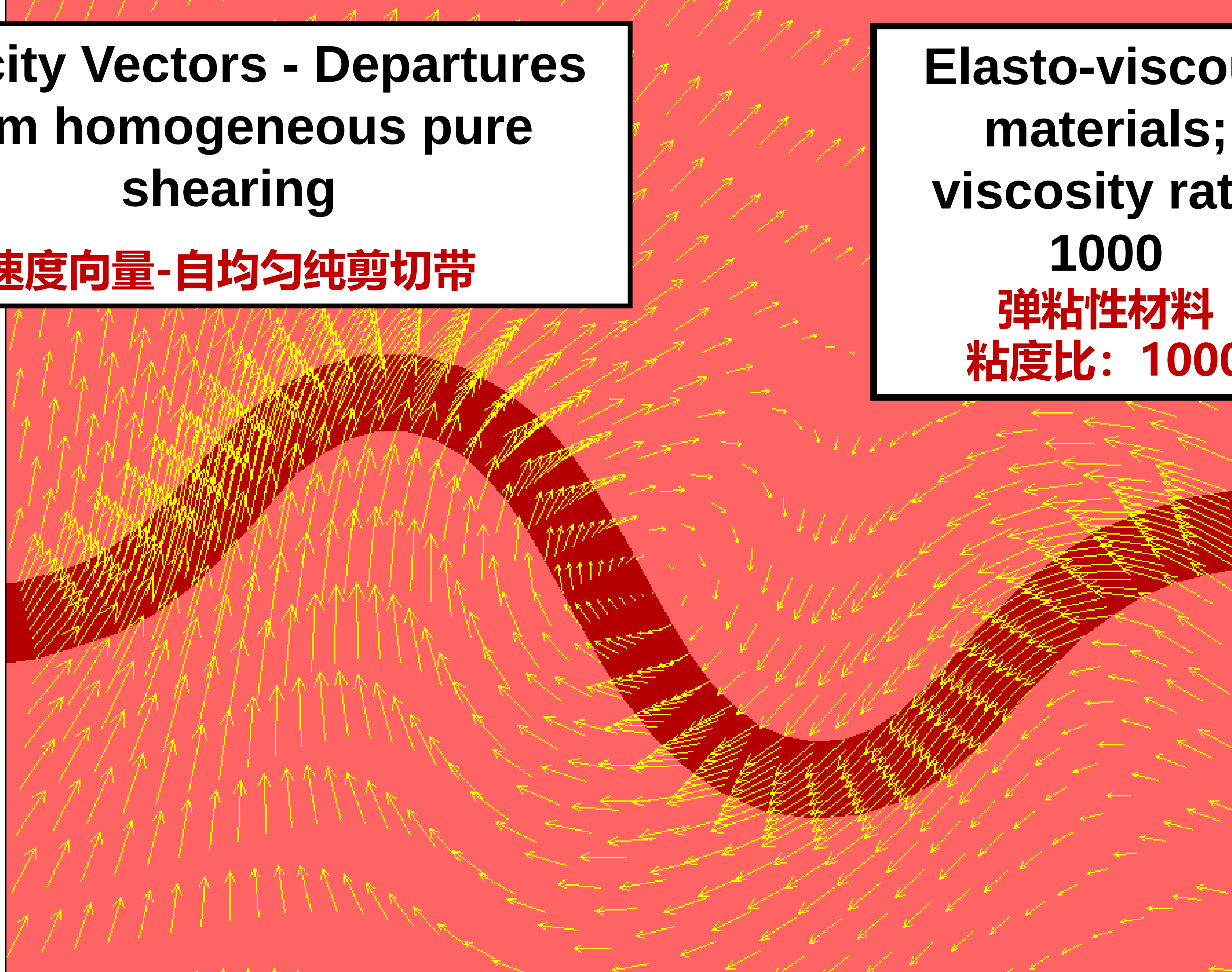
Velocity Vectors - Departures from homogeneous pure shearing

速度向量-自均匀纯剪切带

Elasto-viscous materials; viscosity ratio 1000

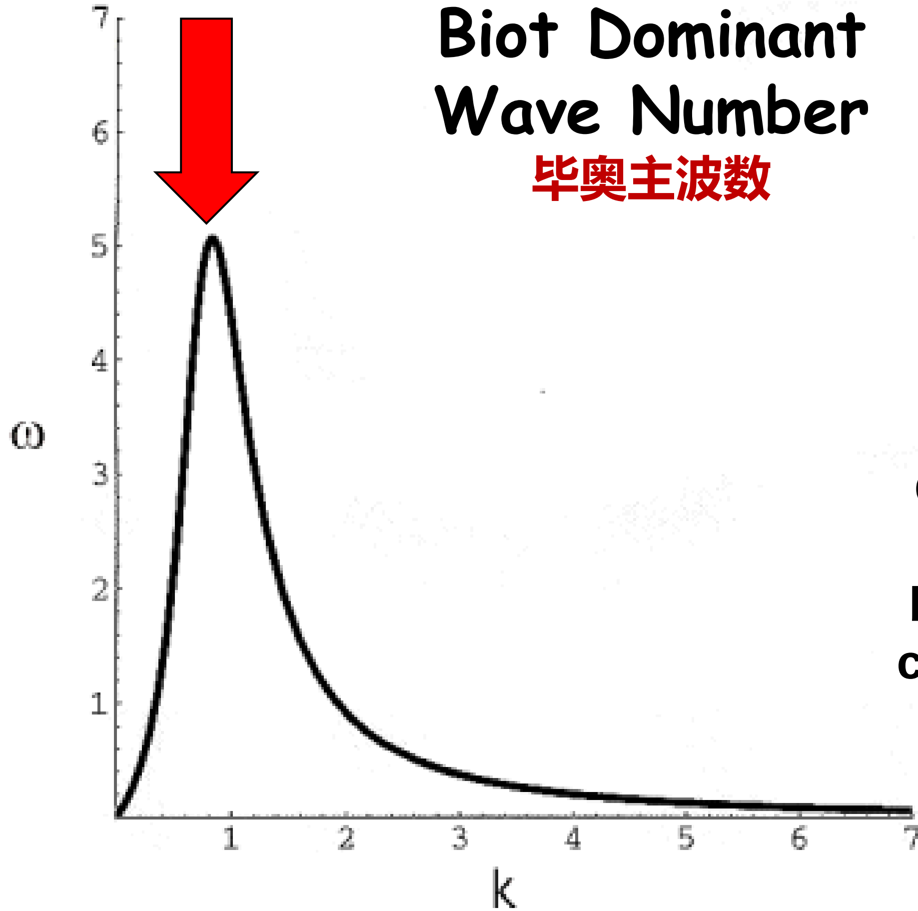
弹粘性材料

粘度比：1000



This vorticity field drives the Biot folding process.

速度场驱动下的Biot褶皱过程



Numerical Solution:
Dominant wavelength wins.

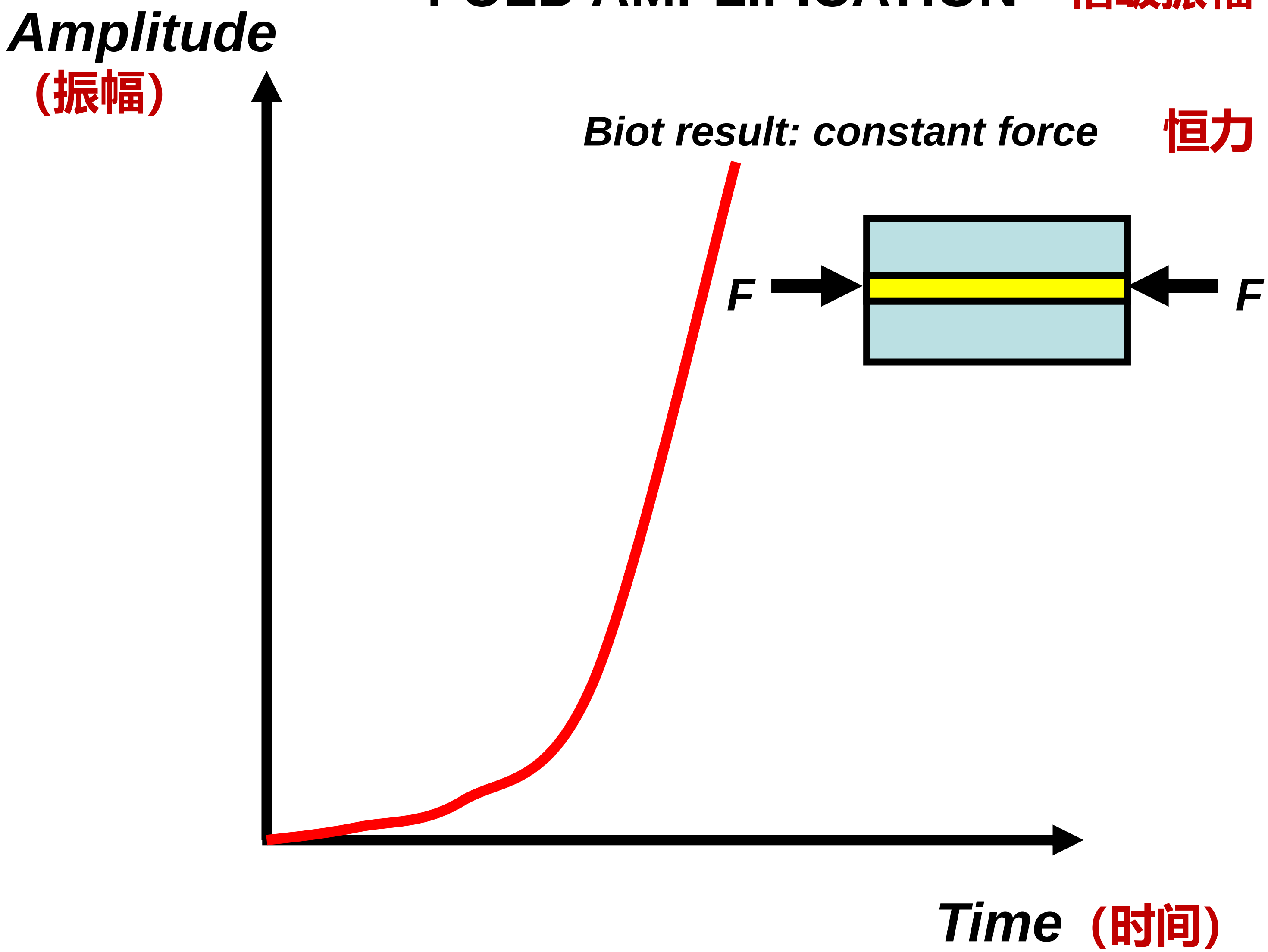
Constant force boundary conditions

恒力边界条件

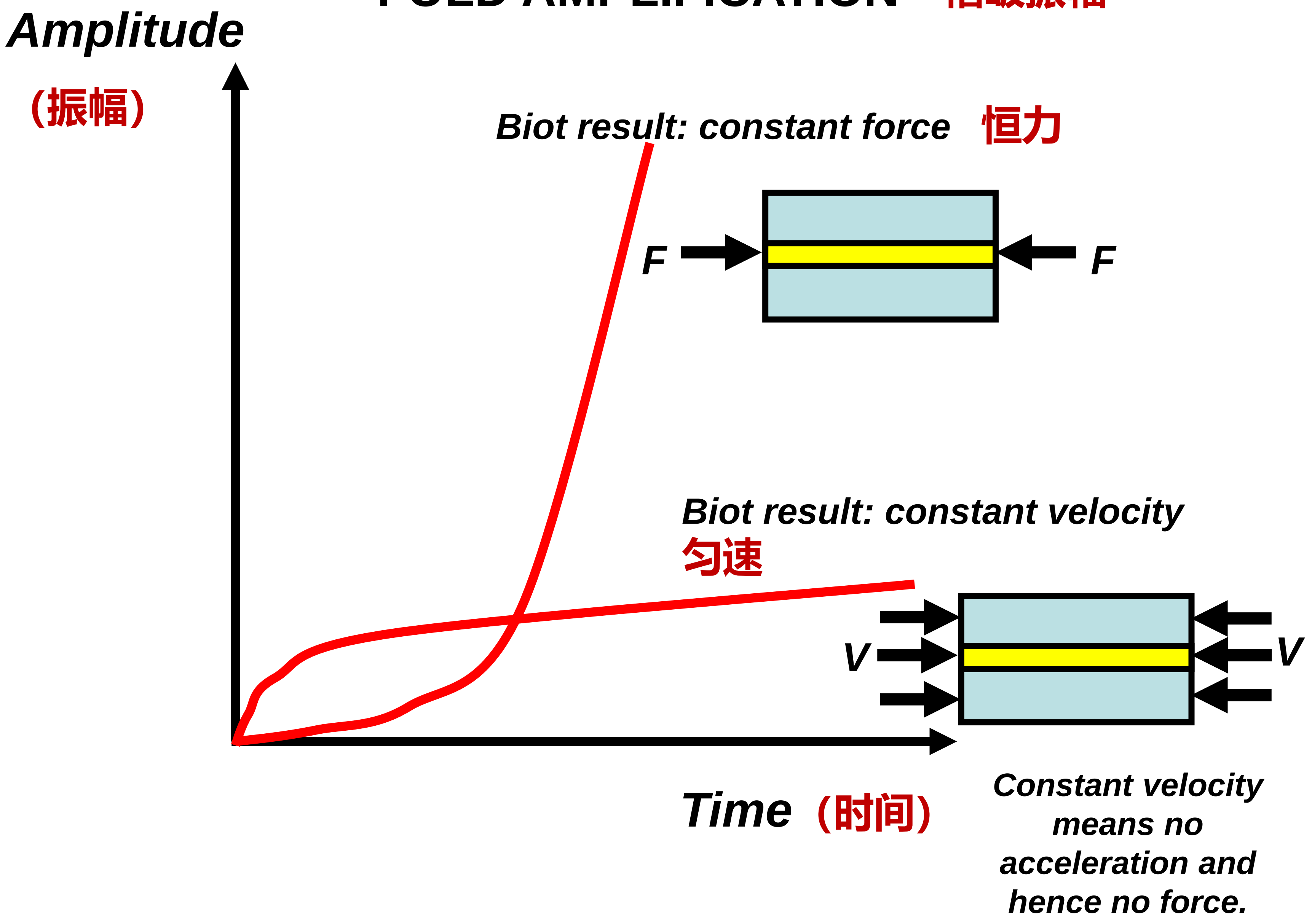
Dispersion Function for Single Isotropic Layer: Plot of growth coefficient, ω, against wave number, $k = 2\pi\ (\text{wavelength})^{-1}$

单一界面扩散方程：生长系数ω，vs , 波数， $k = 2\pi$ (波长)$^{-1}$

FOLD AMPLIFICATION 褶皱振幅

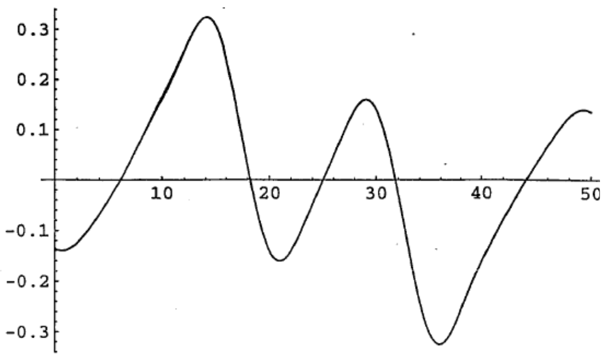


FOLD AMPLIFICATION 褶皱振幅

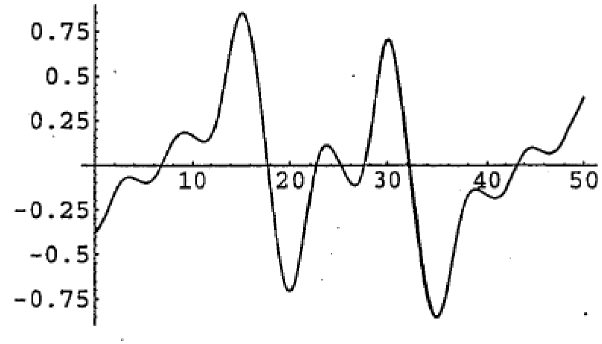


NUMERICAL SOLUTION-CONSTANT VELOCITY BOUNDARY CONDITIONS

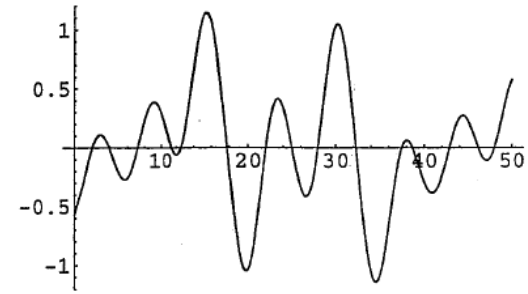
数值解-恒定速度边界条件



initial perturbation t=0

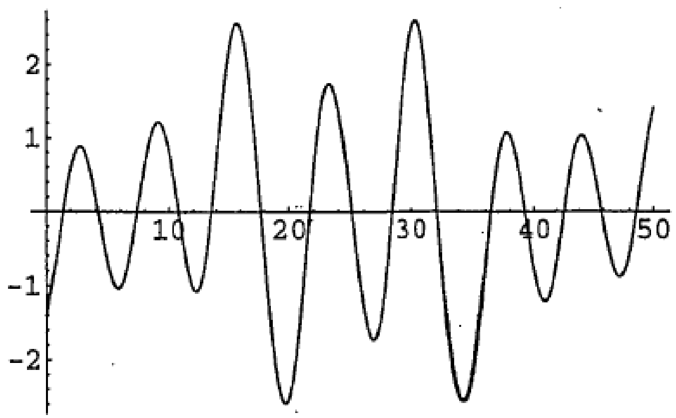


t=0.03 **0.5%**

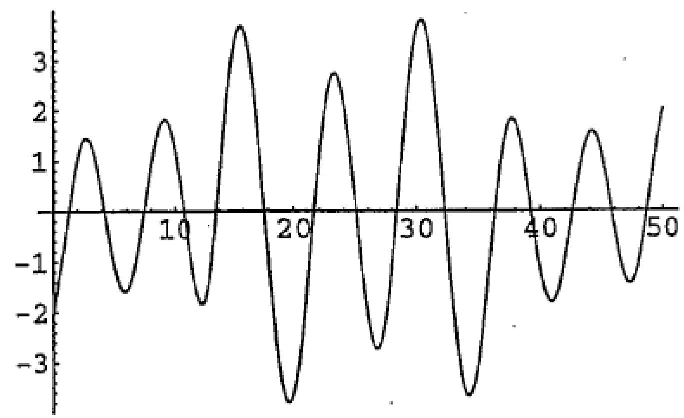


t=0.1

1.8%



t=1 **18%**



t=2.3 **40%**

Red strains assume 1m thick layer, viscosity ratio=100, 10^{-13} s^{-1} strain-rate

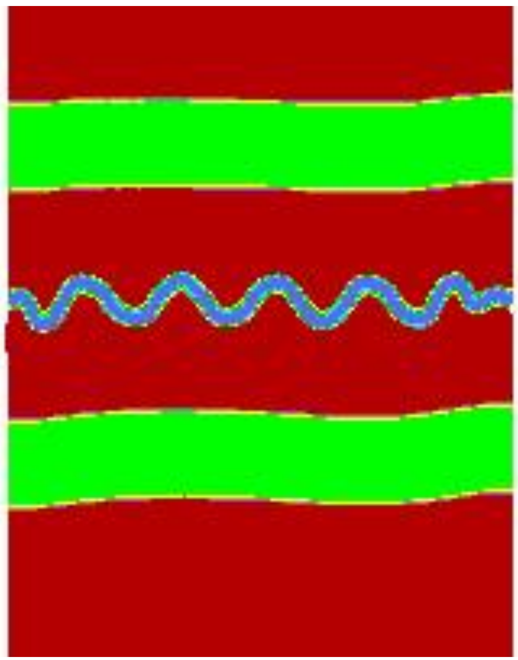
假设 1m层厚，粘度比100， 10^{-13} s^{-1}应变率

VISCOSITY RATIO

粘度比

INITIAL GEOMETRY

初始形态

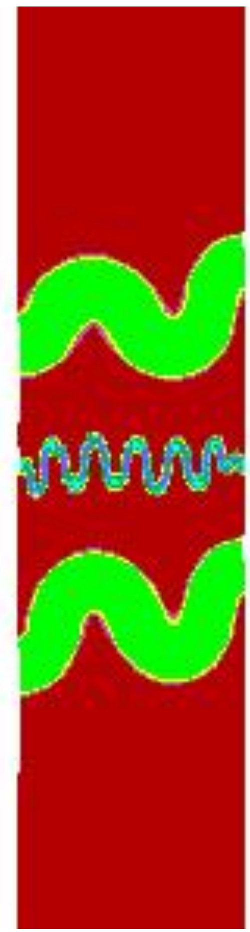


72% SHORTENING

72%压缩

50% SHORTENING

50%压缩



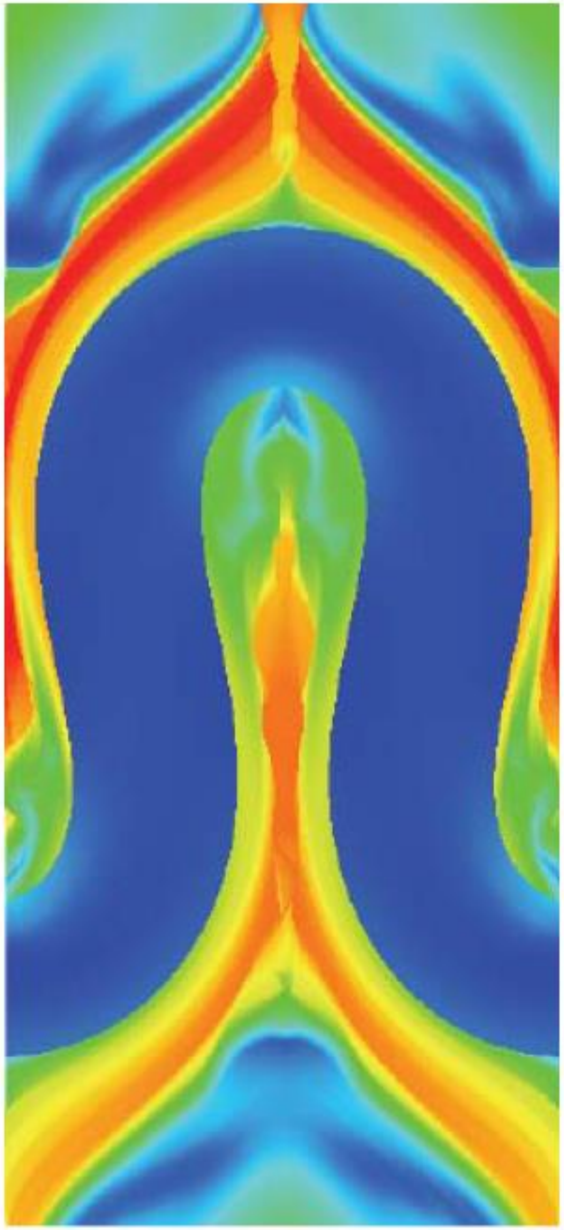
Constant force boundary conditions predict parasitic folds

恒力边界条件预测寄生褶皱

BIOT THEORY: RESULTS OF CONSTANT VELOCITY BOUNDARY CONDITIONS

毕奥理论：恒定速度边界条件结果

NATURAL FOLD



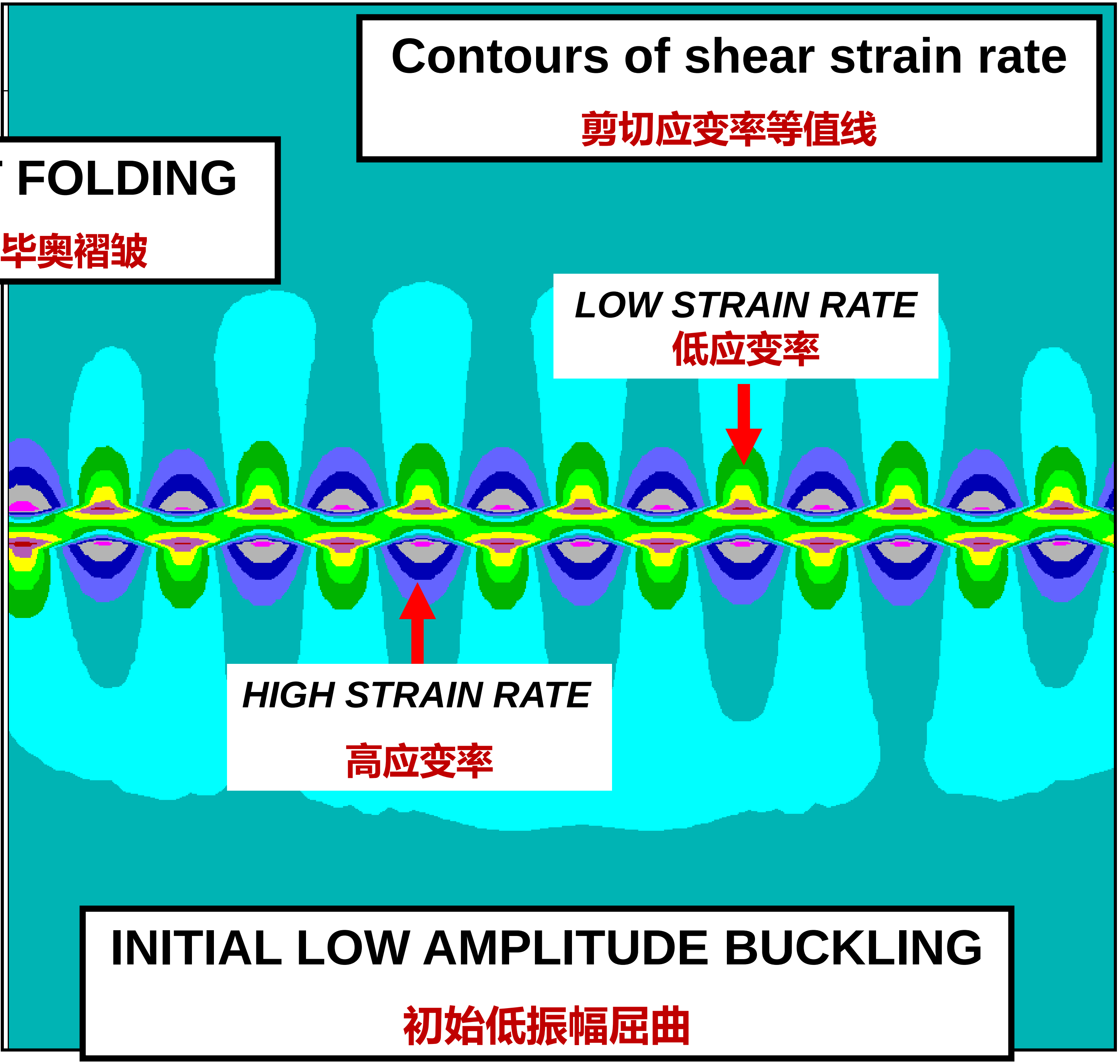
BIOT FOLD

BIOT FOLDING

毕奥褶皱

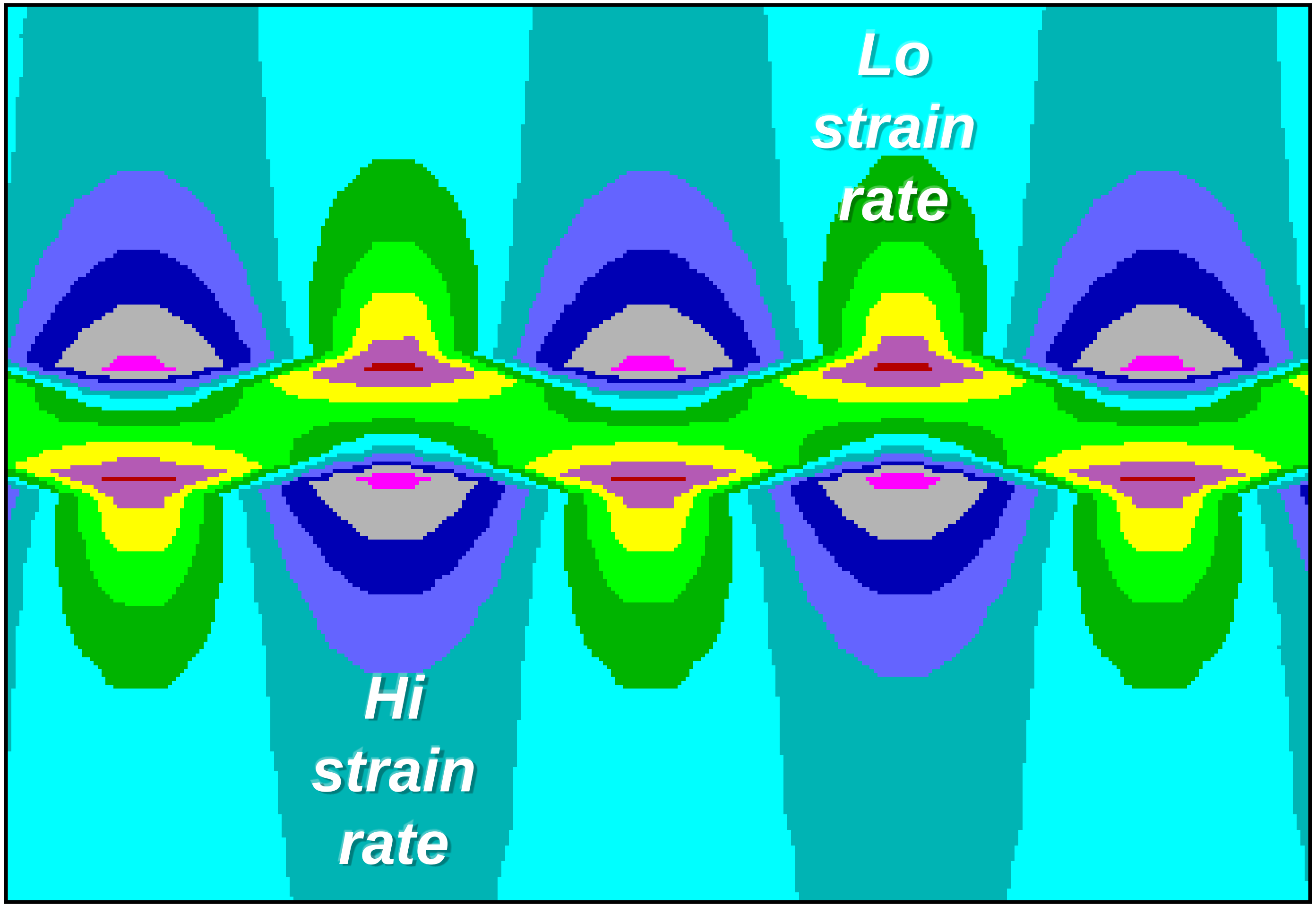
Contours of shear strain rate

剪切应变率等值线



INITIAL LOW AMPLITUDE BUCKLING

初始低振幅屈曲

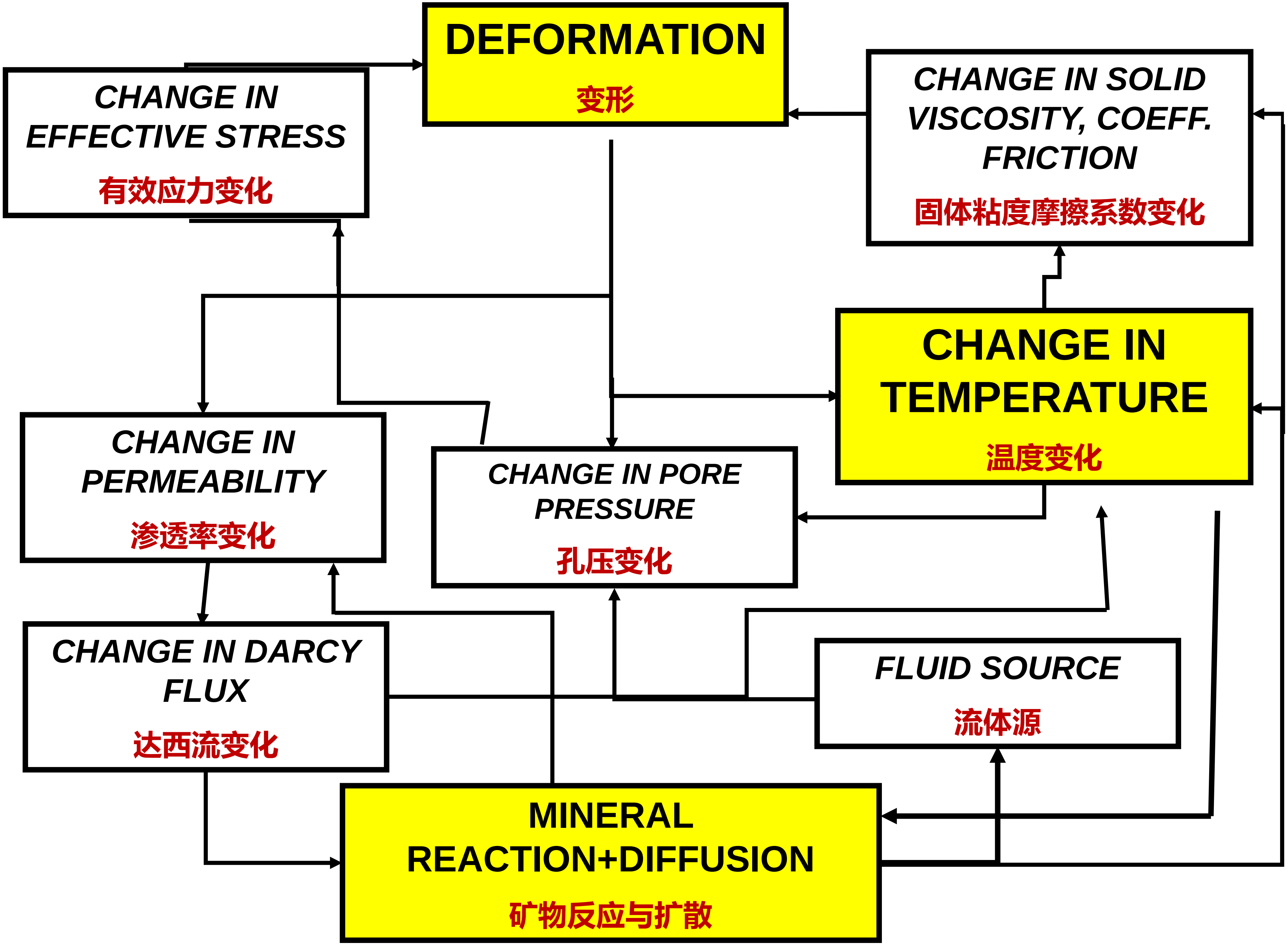


In the Biot theory with constant velocity these high and low strain-rate areas relax with increased shortening and no folds grow.

毕奥理论中，匀速条件下高低应变率区在进一步收缩环境下逐步松弛，无褶皱生长

Any mechanism that enhances strain-rate would make folds continue to grow.

任何应变率的增加机制都会促使褶皱继续生长


DEFORMATION
变形
CHANGE IN EFFECTIVE STRESS
有效应力变化
CHANGE IN SOLID VISCOSITY, COEFF. FRICTION
固体粘度摩擦系数变化
CHANGE IN TEMPERATURE
温度变化
CHANGE IN PERMEABILITY
渗透率变化
CHANGE IN PORE PRESSURE
孔压变化
CHANGE IN DARCY FLUX
达西流变化
FLUID SOURCE
流体源
MINERAL REACTION+DIFFUSION
矿物反应与扩散

Define the Helmholtz free energy as 赫尔姆霍茨自由能

$$\Psi = u - Ts = \Psi(\varepsilon_{ij}^{elastic}, T, m_K, \xi_K)$$

u is specific internal energy; m_K is mass of K^{th} chemical component; ξ_K is extent of K^{th} chemical reaction

Conjugate quantities to state variables are: 共轭物理量

$$\sigma_{ij} = \frac{\partial \Psi}{\partial \varepsilon_{ij}^{elastic}} \qquad s = -\frac{\partial \Psi}{\partial T} \qquad \mu_K = -\frac{\partial \Psi}{\partial m_K} \qquad A_K = -\frac{\partial \Psi}{\partial \xi_K}$$

Cauchy stress	***Specific entropy***	***Chemical potential***	***Affinity of chemical reaction***
柯西应力	比熵	化学势	化学反应亲和势

Second Law of thermodynamics is: 热力学第二定律

$$\rho T\dot{s} = \Phi = \Phi^{mechanical} + \sum_K \Phi_K^{diffusive} + \sum_K \Phi_K^{chemical} + \Phi^{thermal} \geq 0$$

Specific dissipation 耗散比

The various dissipation functions are:

各项耗散方程:

$$\Phi^{mechanical} = \frac{\partial \Psi}{\partial \varepsilon_{ij}^{elastic}} \dot{\varepsilon}_{ij}^{elastic} + \frac{\partial \Psi}{\partial T} \dot{T} + \frac{\partial \Psi}{\partial m_K} \dot{m}_K$$

$$\Phi_K^{diffusive} = -J_K \bullet \{grad\, \mu_K - \frac{\partial \mu_K}{\partial T} grad T\}$$

$$\Phi_K^{chemical} = A_K \dot{\xi}_K + \dot{\mathrm{H}}_K$$

$$\Phi^{thermal} = -\rho \kappa^{thermal} c_p \nabla^2 T$$

$\dot{\mathrm{H}}_K$ ***is the rate of heat release from chemical reaction K***

$\dot{\mathrm{H}}_K$ **是K的化学反应热释放速率**

We assume that

$$\dot{\varepsilon}_{ij}^{total} = \dot{\varepsilon}_{ij}^{elastic} + \dot{\varepsilon}_{ij}^{plastic}$$

Then the energy equation is:

$$\rho c_p \dot{T} = \chi \sigma_{ij} \dot{\varepsilon}_{ij}^{plastic} - \mu^K \dot{m}^K - \left(\sum_K \Phi_K^{diffusive} + \sum_K \Phi_K^{chemical} + \Phi^{thermal} \right)$$

For the isothermal case this becomes

$$\mu_K \dot{m}_K = D_K \frac{\partial^2 m_K}{\partial x^2} + A_K \dot{\xi}_K$$

Which is a coupled set of classical reaction-diffusion equations

典型化学反应-扩散方程耦合集

Thus the case where dissipative deformation is coupled with other processes (thermal, diffusive, chemical) becomes a problem involving reaction-diffusion equations.

耗散变形耦合了其他过程（热，扩散，化学），成为了包含反应-扩散方程的问题

This coupling commonly leads to strain-rate softening.

For instance the isothermal case involving no mass diffusion leads to:

这种耦合通常会导致应变率软化。无物质扩散的等温实例：

$$\sigma_{ij}\dot{\varepsilon}_{ij}^{dissipative} = A_K \dot{\xi}_K$$

Or, in one dimension,

$$\eta\left(\dot{\varepsilon}^{dissipative}\right)^2 = A_K \dot{\xi}_K$$

Thus, for $A\dot{\xi}$ independent of $\dot{\varepsilon}$ strain-rate softening results

$A\dot{\xi}$ **独立于** $\dot{\varepsilon}$ **应变率软化的结果**

Many coupled processes involve mechanisms which result in strain-rate softening.

许多耦合进程包含了导致应变率软化的机制

Another example: exothermic mineral reactions at high strain-rates supply heat that decreases viscosity or the coefficient of friction.

高应变率下放热矿物反应放出热量导致粘度下降、摩擦系数减小

Anhydrous phases $\longrightarrow$ hydrous phases +heat

无水阶段 $\longrightarrow$ 含水阶段+热量

$$\dot{\varepsilon} = A\sigma^N \exp\left(-\frac{Q}{RT}\right)$$

Thus, strain-rate is increased by exothermic mineral reactions

放热反应提高了应变率

LENGTH AND TIME SCALES (长度、时间尺度)

Dominant Length Scale = L = $\sqrt{\dfrac{\kappa^{process}}{\dot{\varepsilon}}}$

κ= *diffusivity* **扩散率**

$\dot{\varepsilon}$=strain-rate **应变率**

Take strain-rate = 10^{-12} s^{-1} (typical tectonic strain-rate)

Thermal diffusivity=10^{-6} m^2 s^{-1} ; L = 1km

Take strain-rate = 10^{-2} s^{-1} (typical seismic strain-rate)
Thermal diffusivity=10^{-6} m^2 s^{-1} ; L = 1cm

Take strain-rate = 10^{-12} s^{-1} (typical tectonic strain-rate)
Chemical diffusivity=10^{-14} m^2 s^{-1} ; L = 0.1m

Take strain-rate = 10^{-2} s^{-1} (typical seismic strain-rate)
Chemical diffusivity=10^{-14} m^2 s^{-1} ; L = 10^{-6} m

The forms of coupling of interest to structural and metamorphic geologists are:

构造/变质岩地质学家们感兴趣的耦合形式：

- **Thermal-mechanical: Dominant at the kilometer scale**

•热-力学耦合：主要用于公里尺度

- **Mineral reactions-mechanical: Dominant at the outcrop scale.**

•矿物反应-力学耦合：主要用于露头尺度

- **Diffusion-mechanical: Dominant at the thin-section scale.**

•扩散-力学耦合：主要用于薄片尺度

- **Fluid-mechanical: Dominant at any scale depending on permeability.**

•流体-力学耦合：依靠渗透率，适用于各种尺度

All produce strain-rate softening and hence produce structures at the relevant scale. 都会产生应变软化，并在相关尺度上产生相应结构

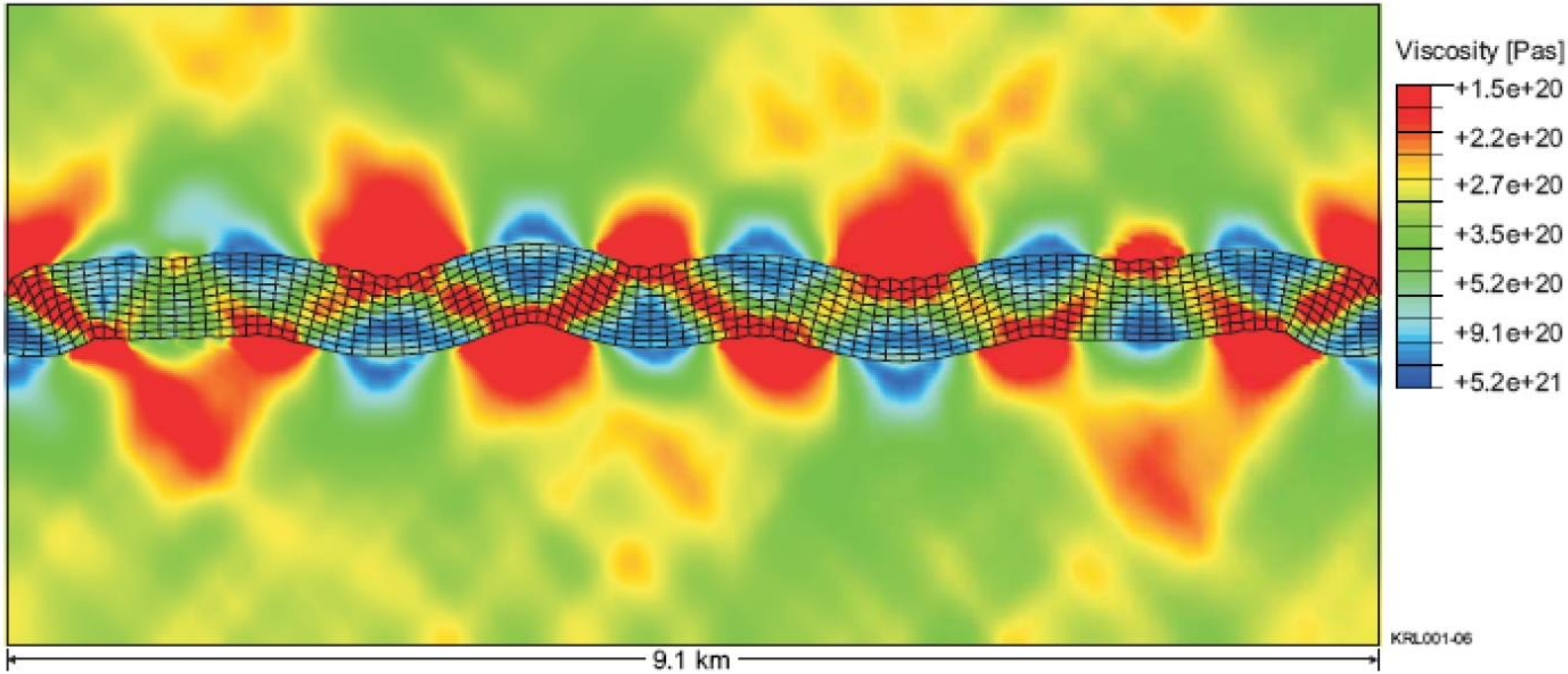
κ= *diffusivity* 扩散率

$\dot{\varepsilon}$ =*strain-rate* 应变率

$$\text{Dominant Length Scale} = \sqrt{\frac{\kappa^{process}}{\dot{\varepsilon}}}$$

热-力学褶皱

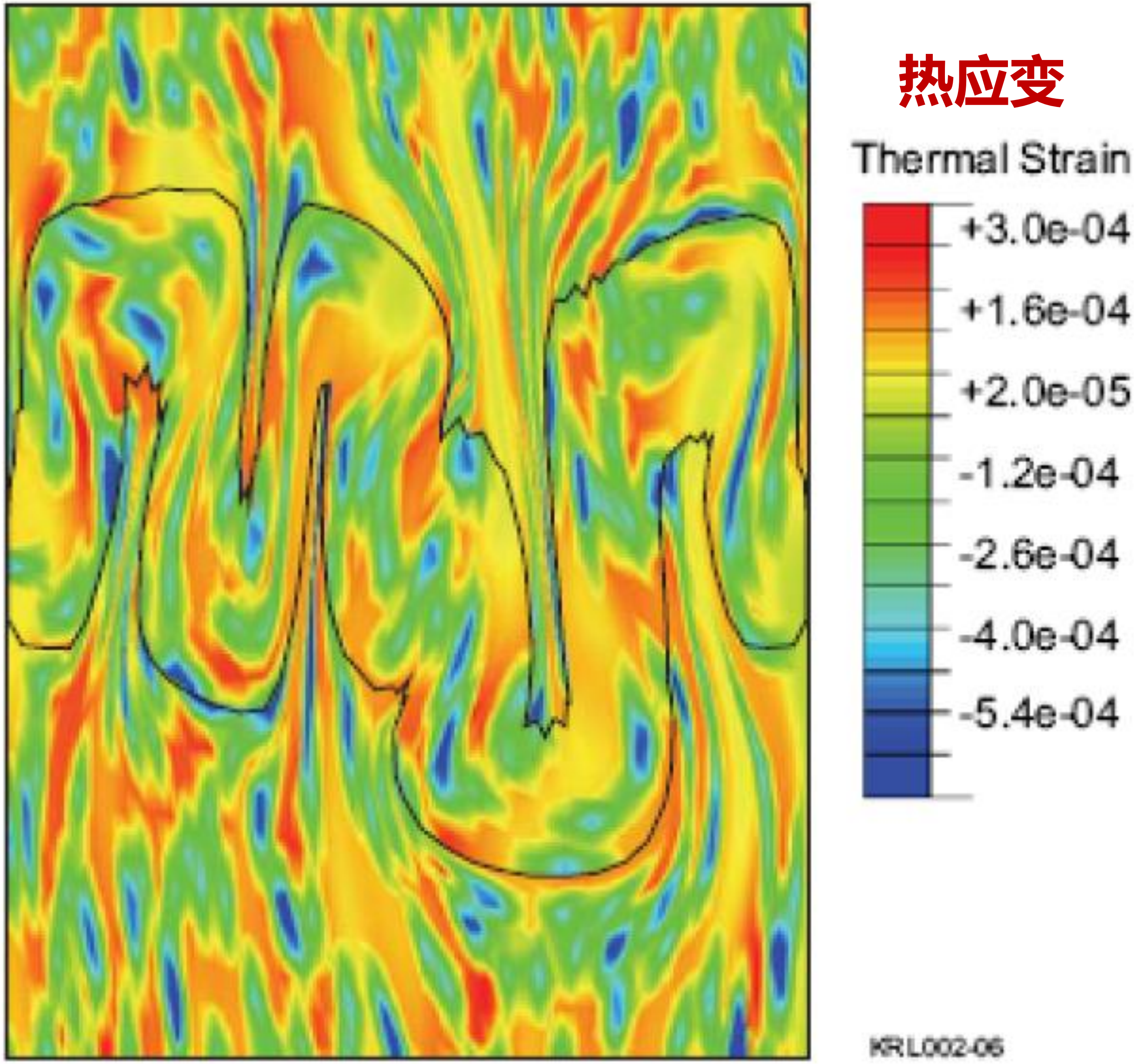
初始粘度比=5

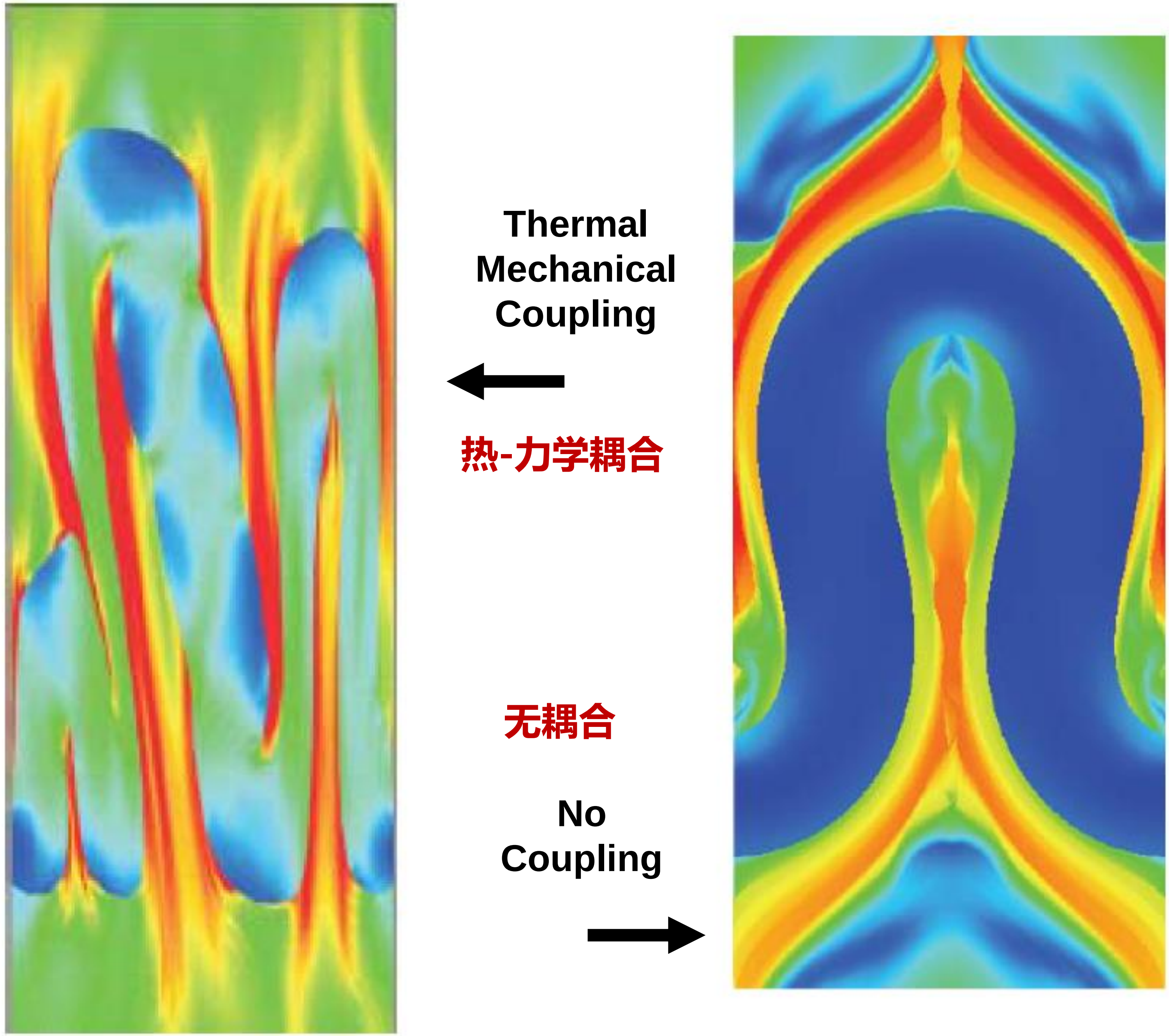


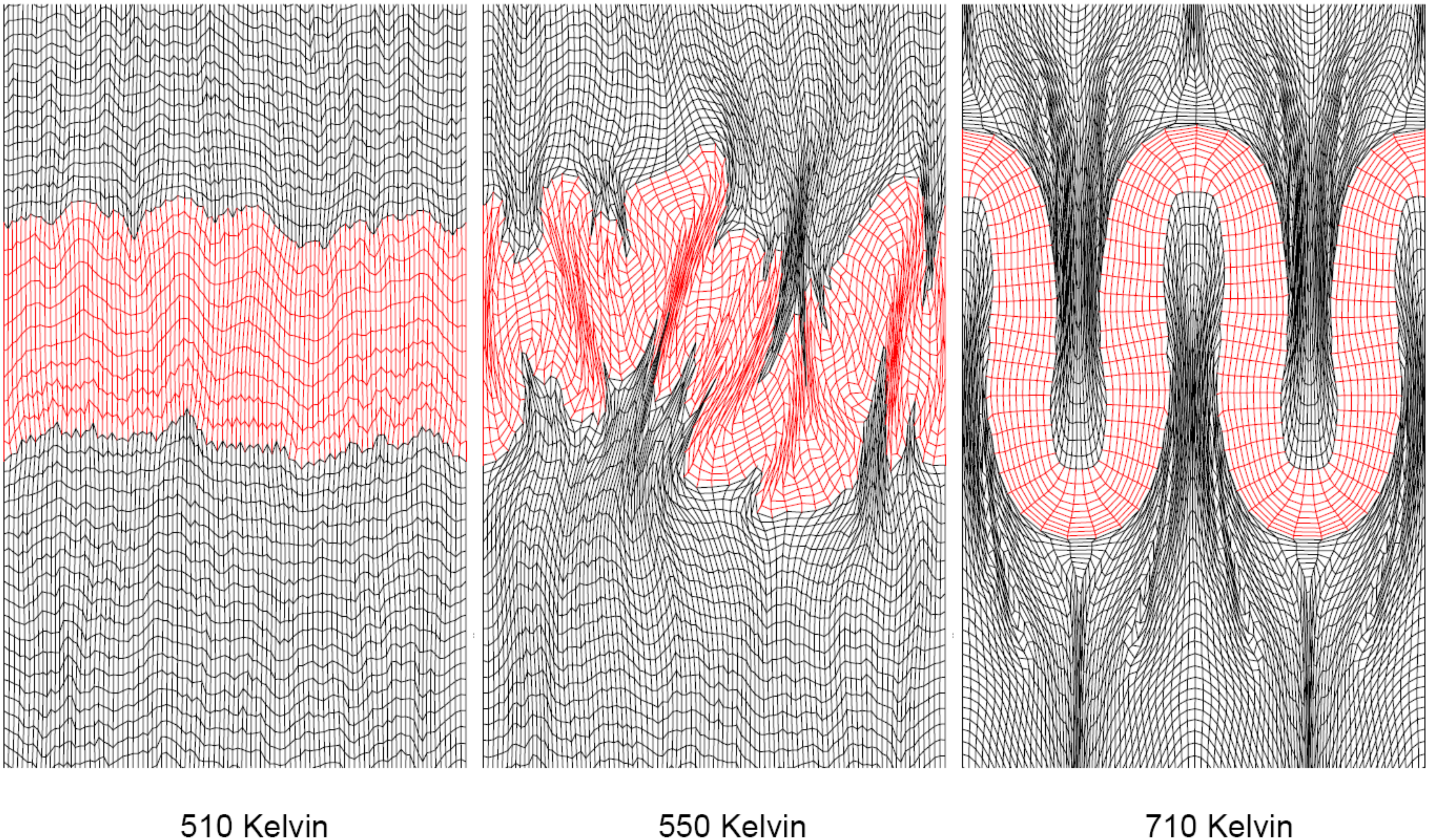
THERMAL-MECHANICAL FOLDING

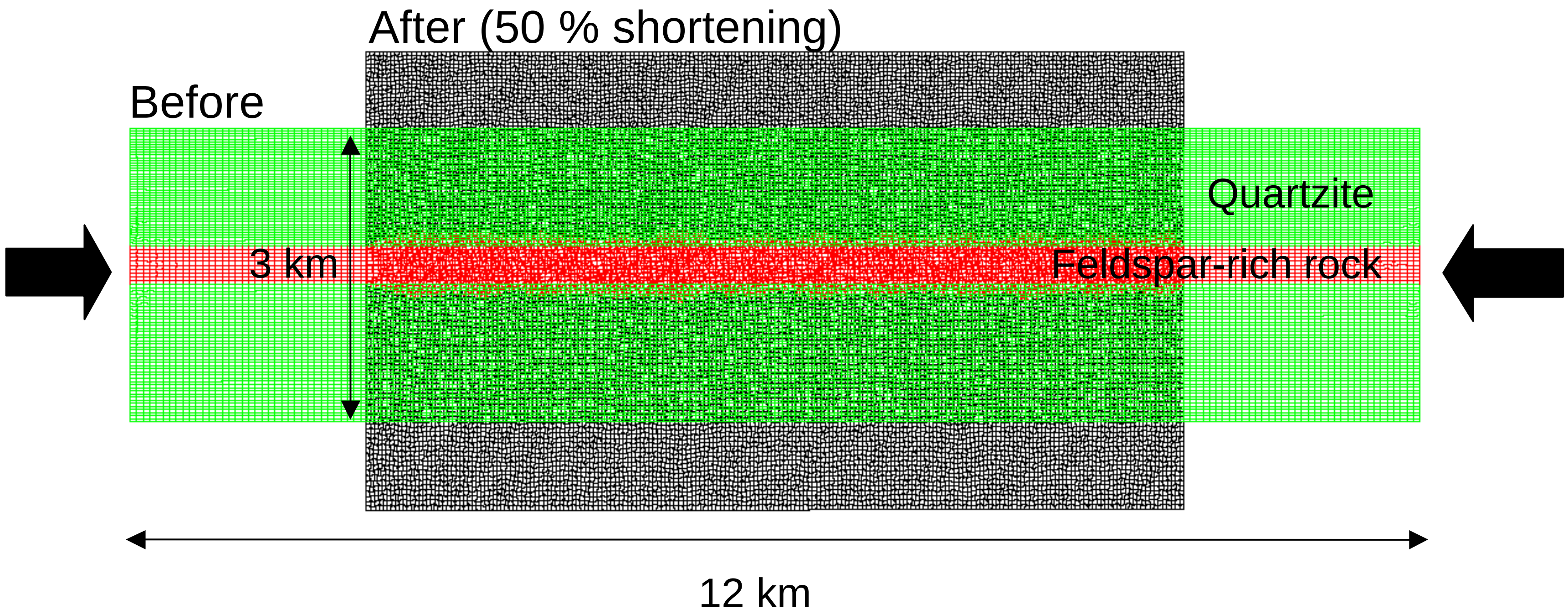
INITIAL VISCOSITY RATIO = 5

热应变


Thermal Strain
+3.0e-04
+1.6e-04
+2.0e-05
-1.2e-04
-2.6e-04
-4.0e-04
-5.4e-04
KRL002-06


Thermal
Mechanical
Coupling
热-力学耦合
无耦合
No
Coupling


510 Kelvin
550 Kelvin
710 Kelvin



Thermal expansion included

MODEL SETUP

Length scale associated with shear zone development = (thermal diffusivity/strain-rate)$^{1/2}$

= $(10^{-6}/10^{-12})^{1/2}$ m = 1km

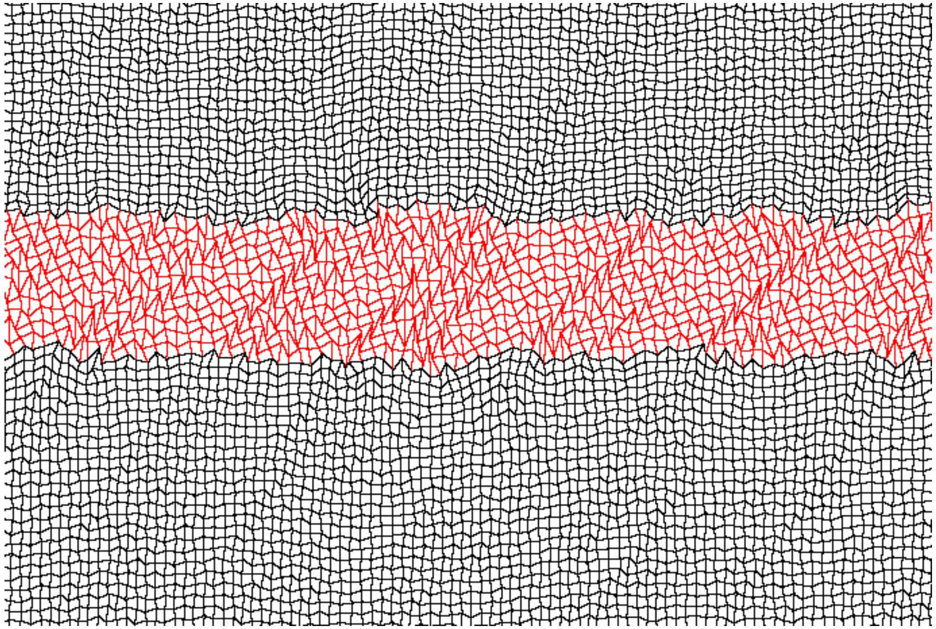
SENSITIVITY OF DEFORMATION TO TEMPERATURE.

变形对温度敏感程度

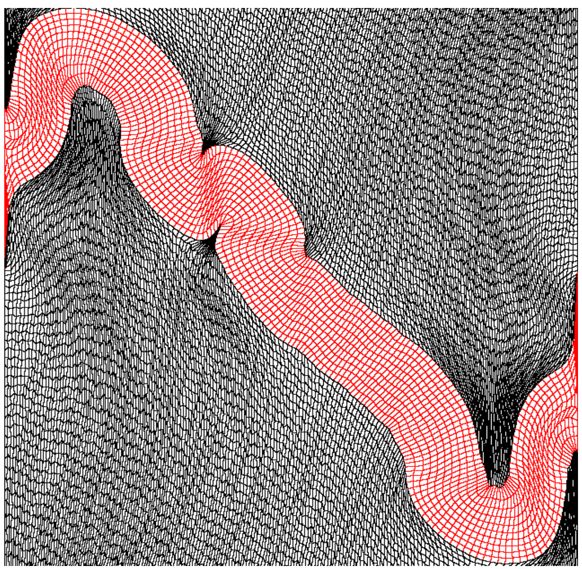
THE “BRITTLE-DUCTILE” TRANSITION.

脆-韧性转换

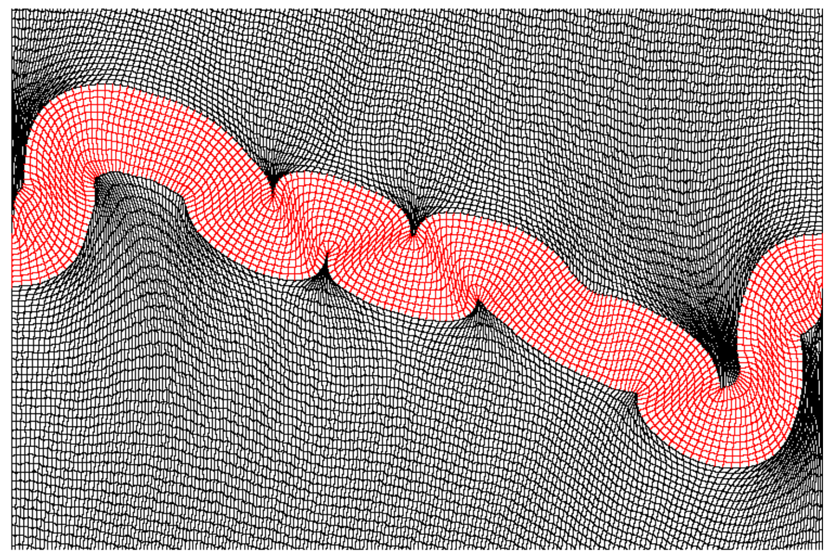
510 K

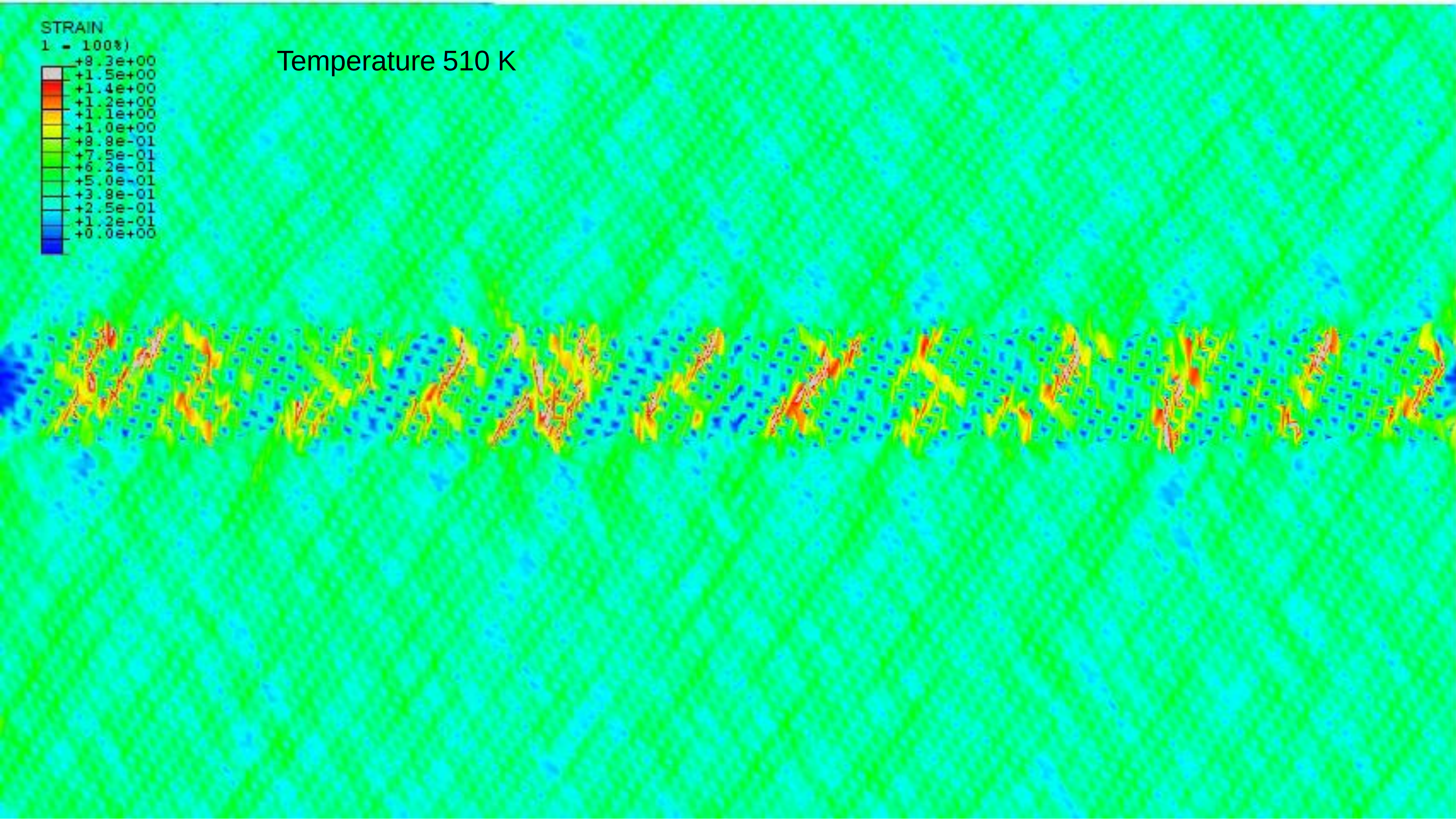


530 K

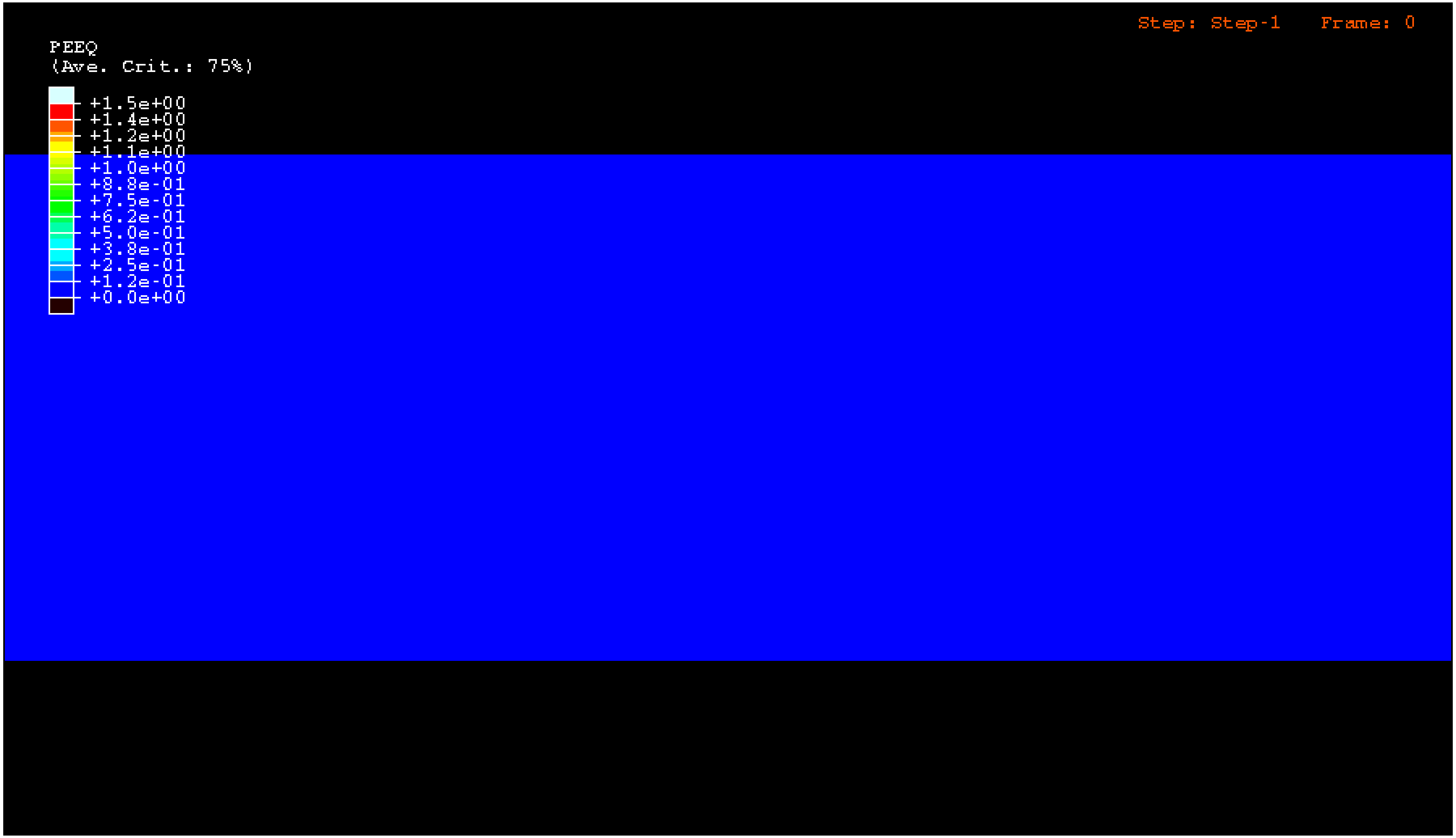


550 K

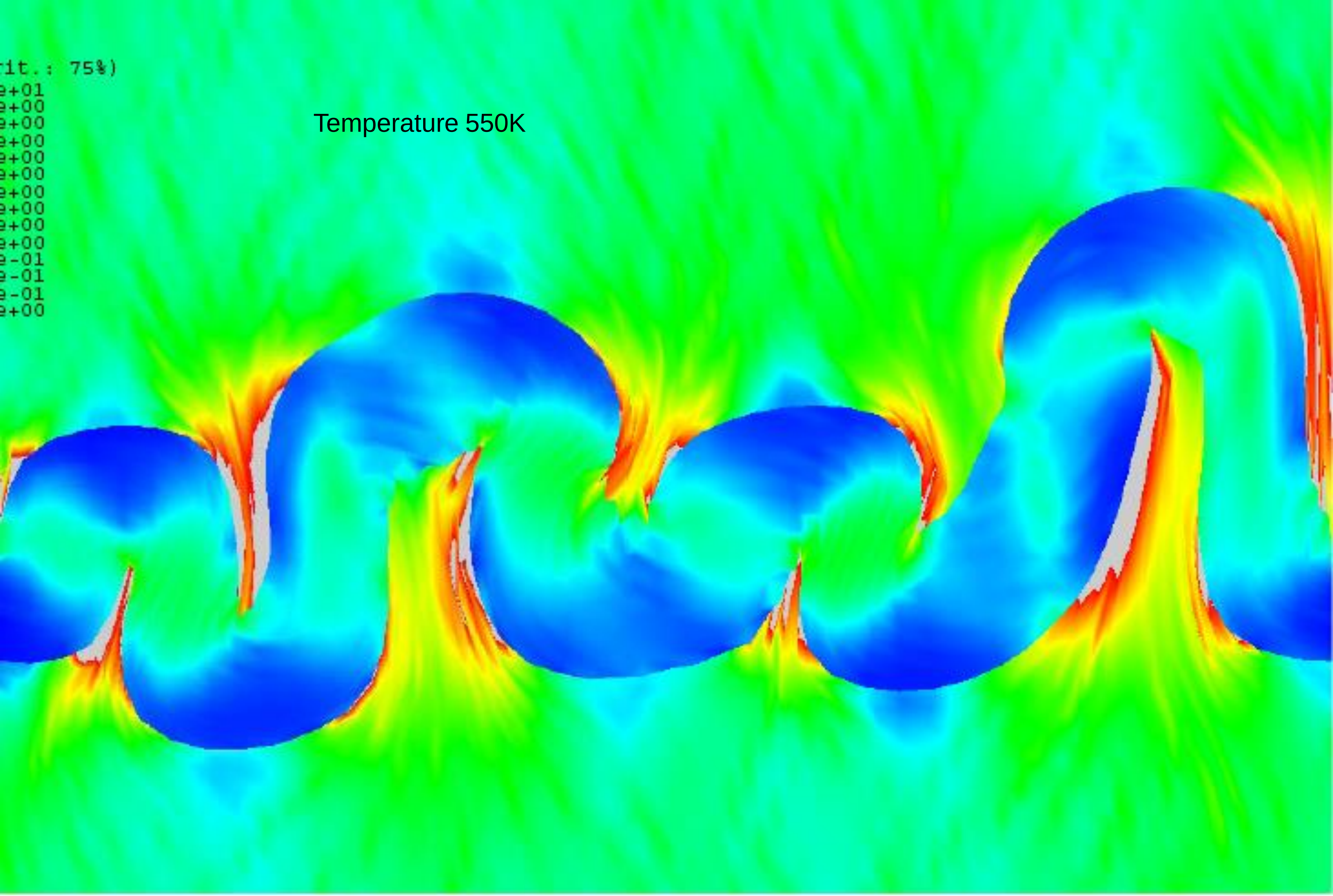



STRAIN
1 = 100%)
+8.3e+00
+1.5e+00
+1.4e+00
+1.2e+00
+1.1e+00
+1.0e+00
+8.8e-01
+7.5e-01
+6.2e-01
+5.0e-01
+3.8e-01
+2.5e-01
+1.2e-01
+0.0e+00
Temperature 510 K

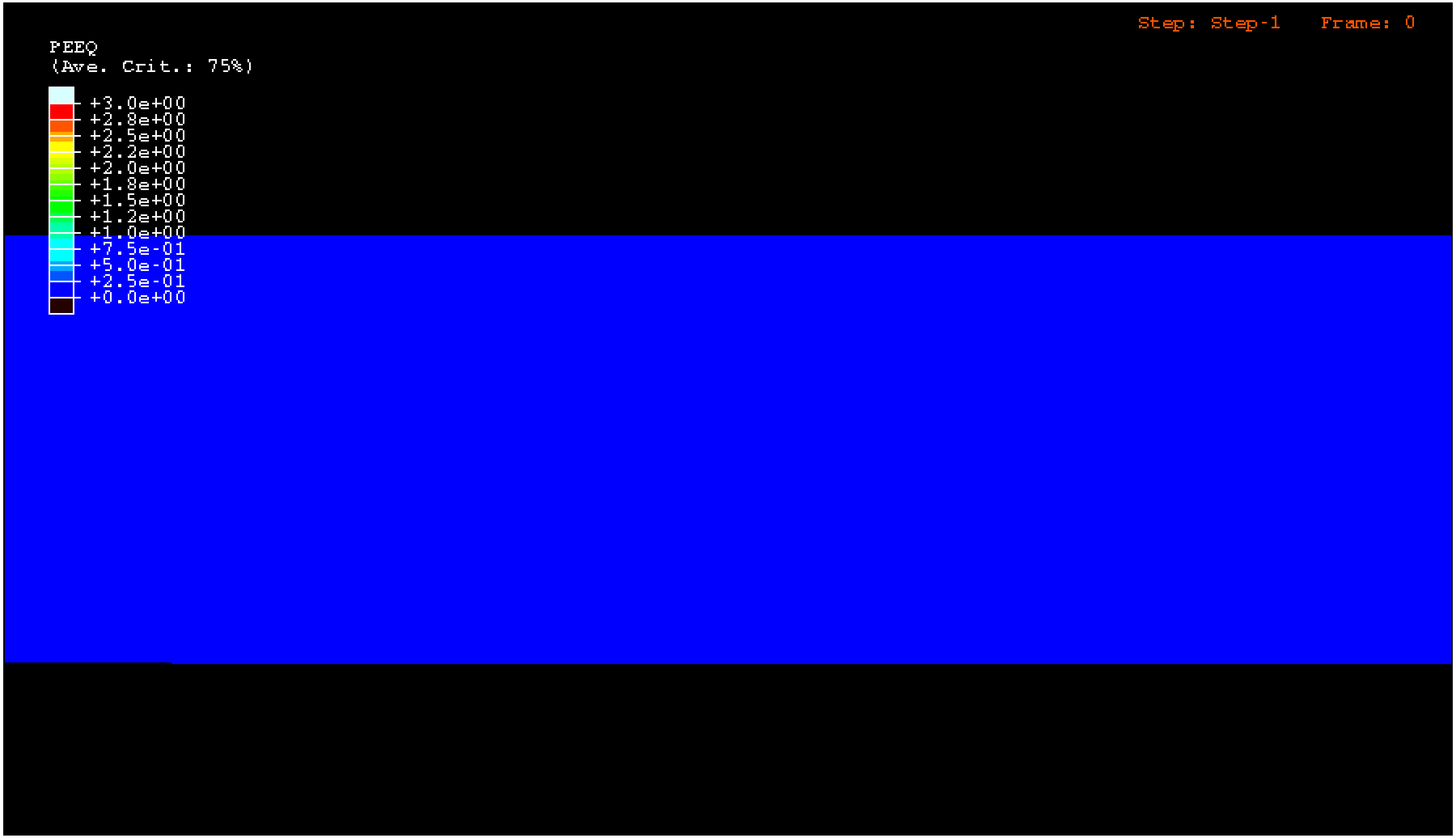
510 K STRAIN

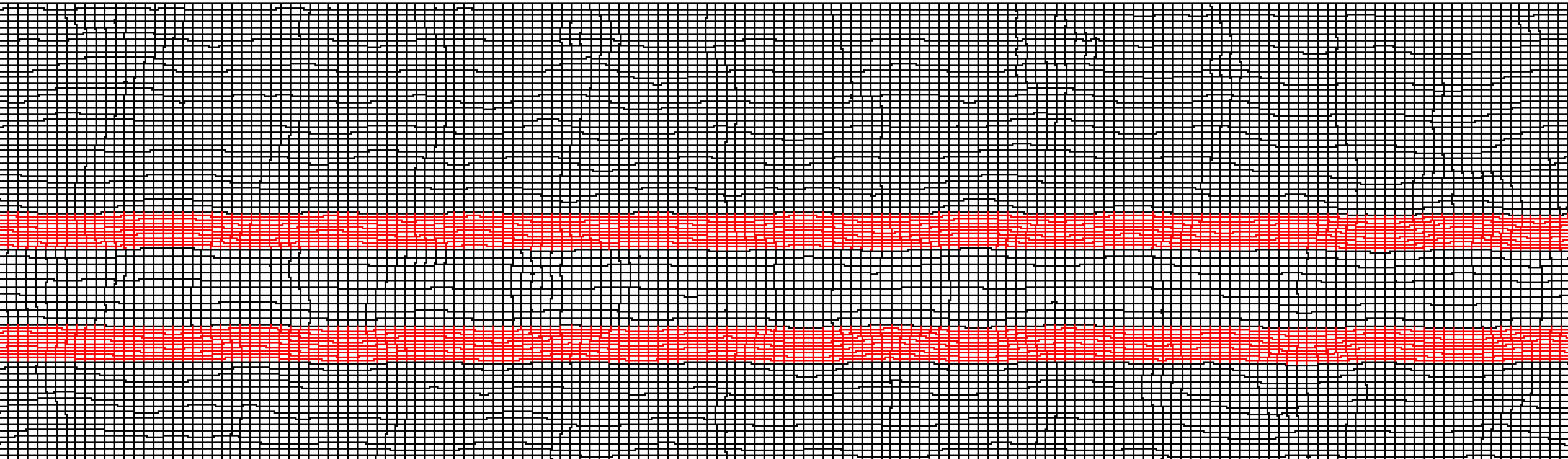


PEEQ
(Ave. Crit.: 75%)
+1.5e+00
+1.4e+00
+1.2e+00
+1.1e+00
+1.0e+00
+8.8e-01
+7.5e-01
+6.2e-01
+5.0e-01
+3.8e-01
+2.5e-01
+1.2e-01
+0.0e+00
Step: Step-1   Frame: 0

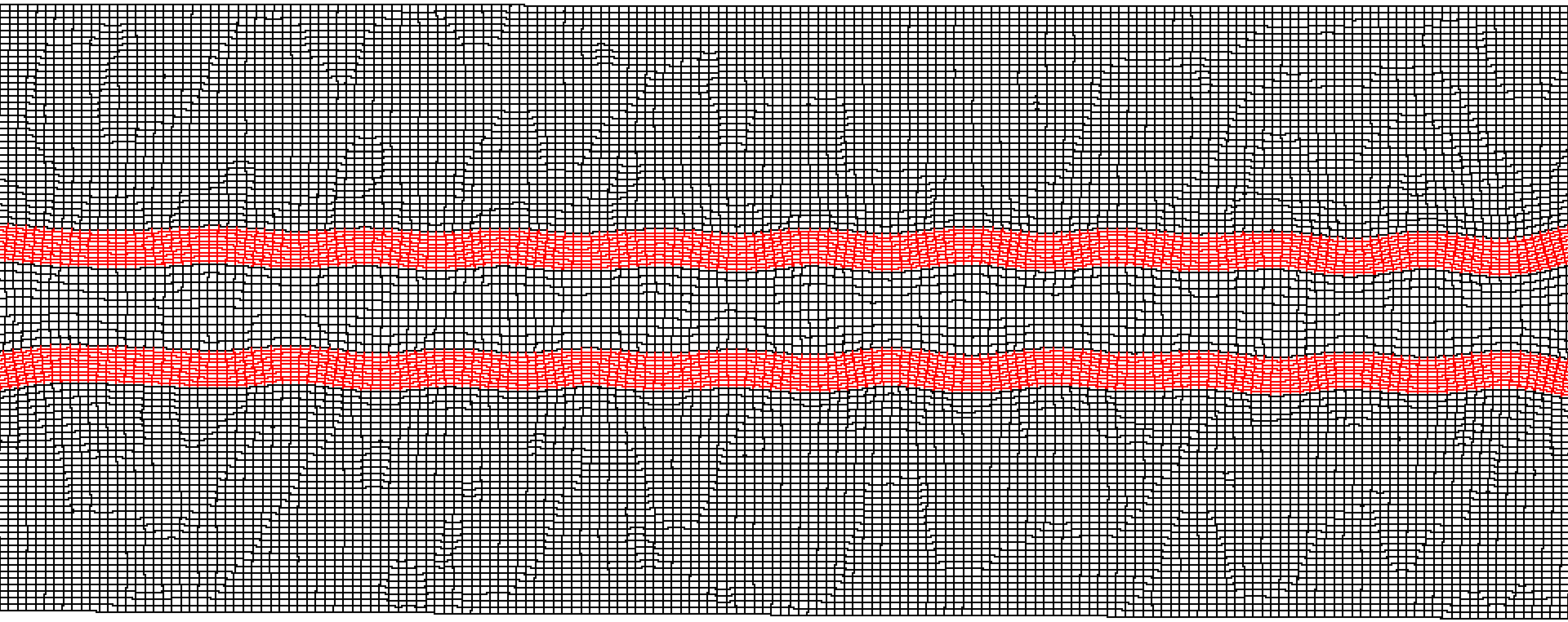

Temperature 550K

550 K STRAIN

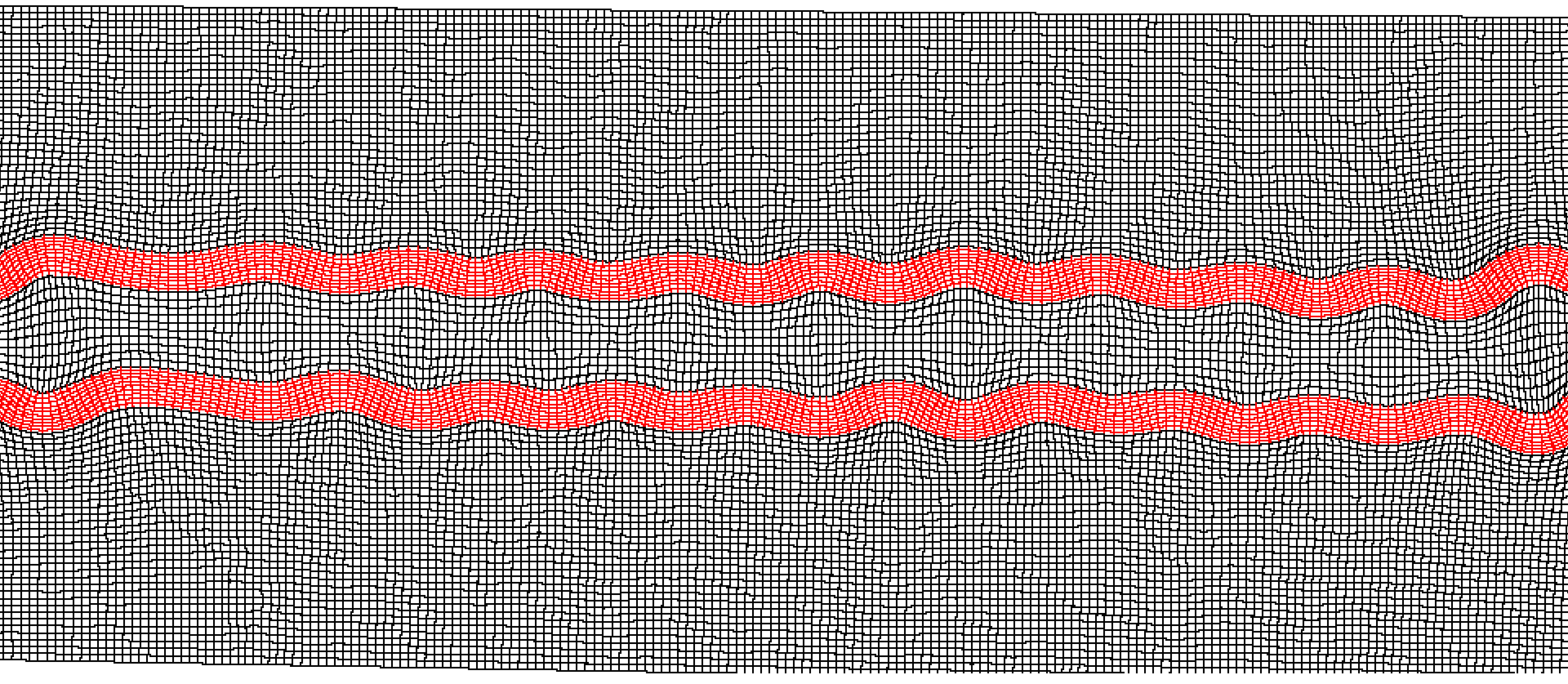

Step: Step-1 Frame: 0
PEEQ
(Ave. Crit.: 75%)
+3.0e+00
+2.8e+00
+2.5e+00
+2.2e+00
+2.0e+00
+1.8e+00
+1.5e+00
+1.2e+00
+1.0e+00
+7.5e-01
+5.0e-01
+2.5e-01
+0.0e+00



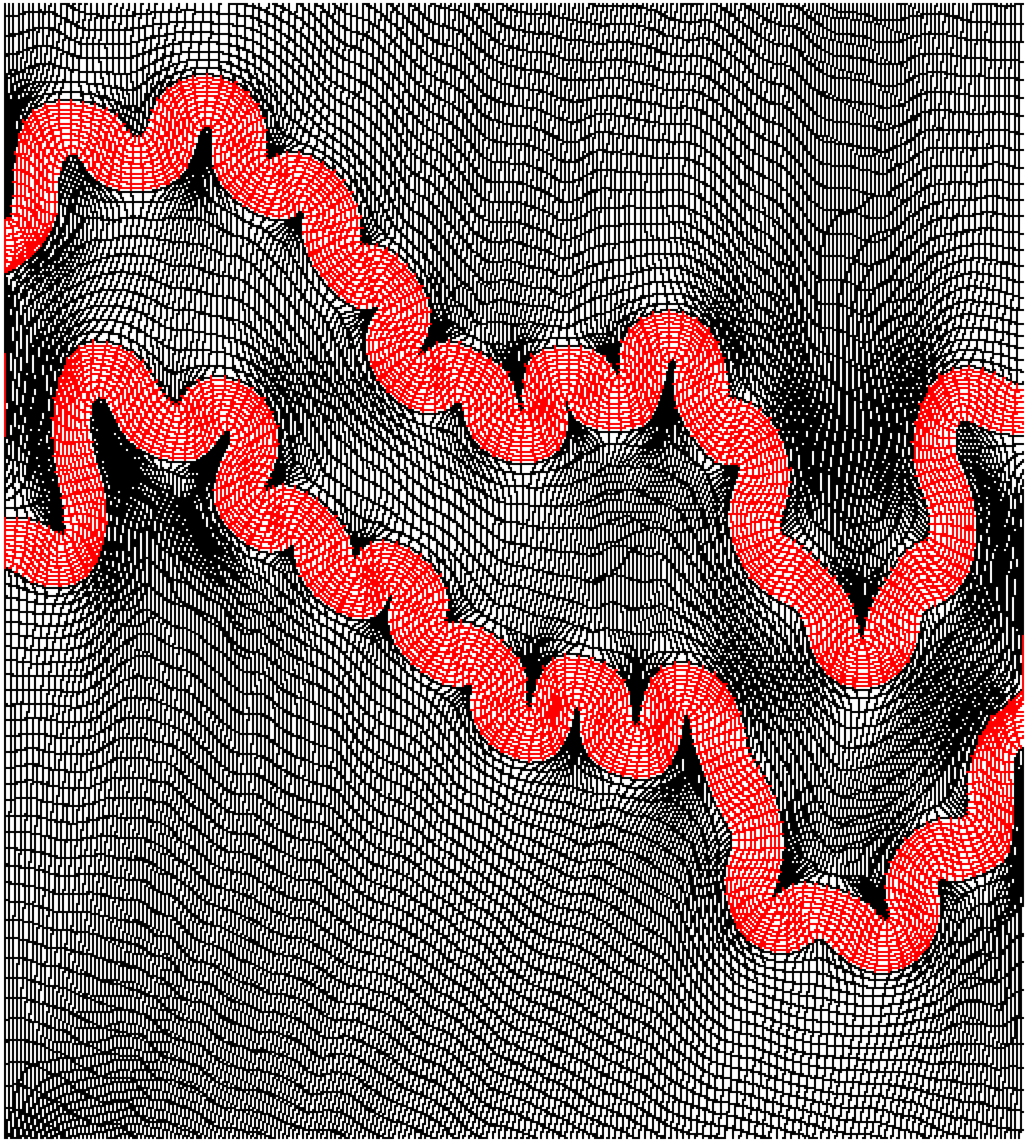
doublemesh1



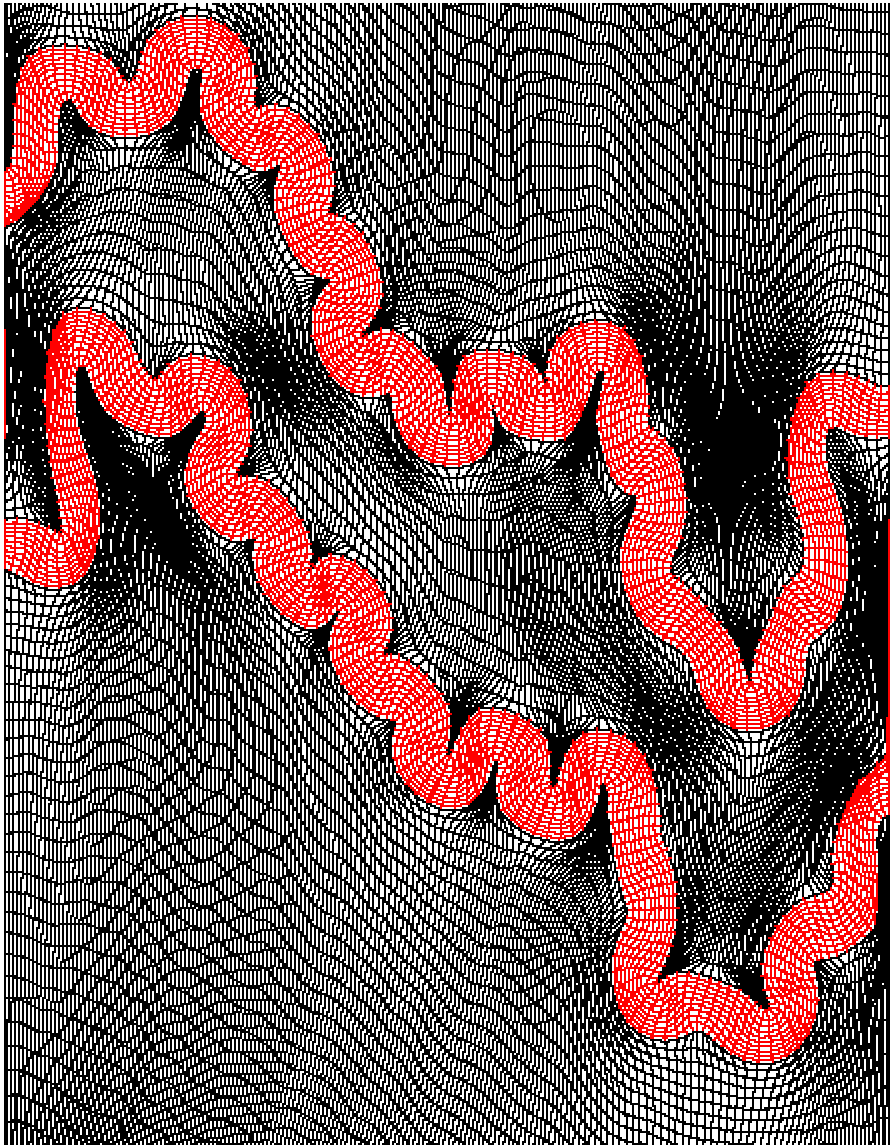
doublemesh2



doublemesh3

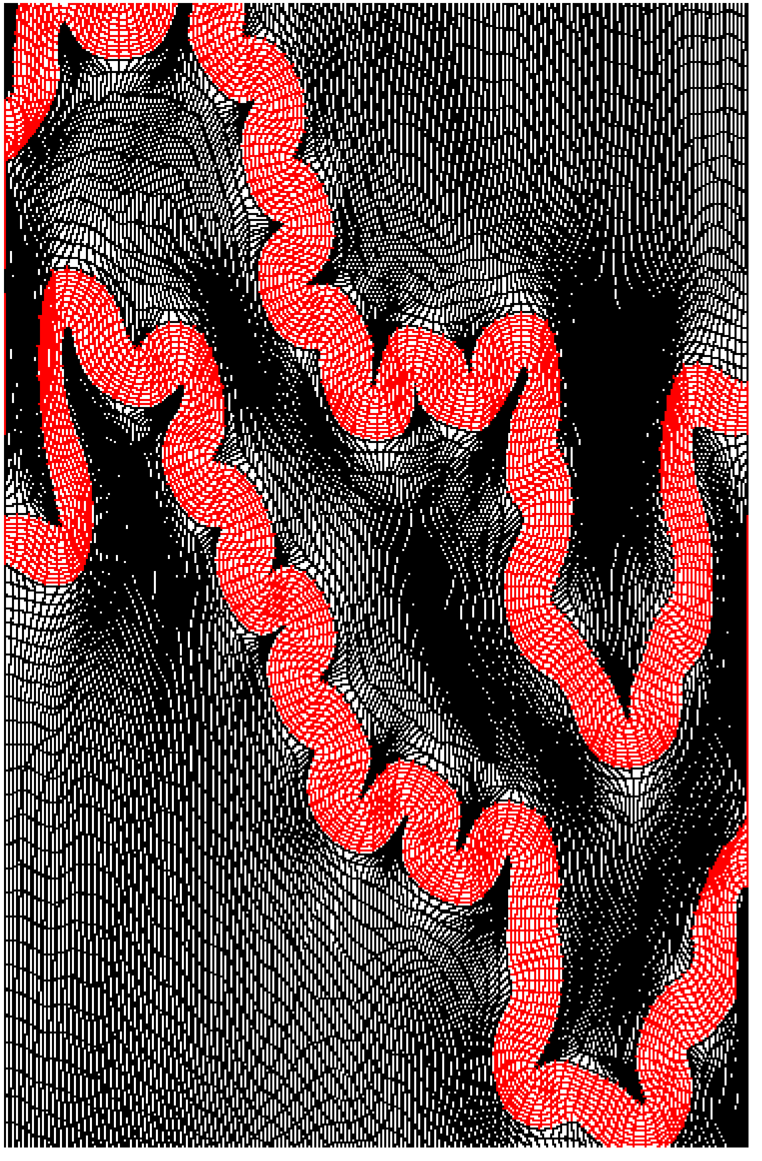


doublemesh4



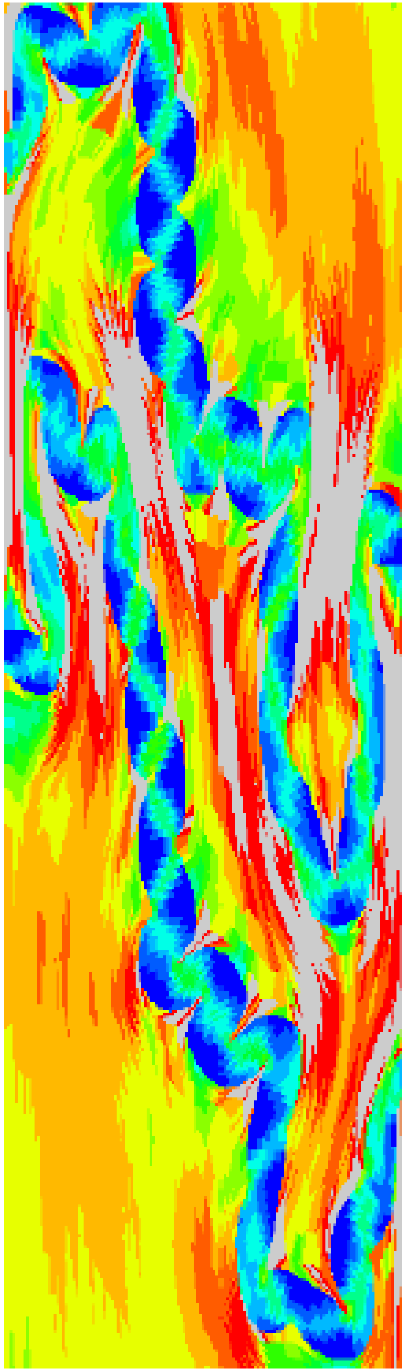
doublemesh5

doublemesh7



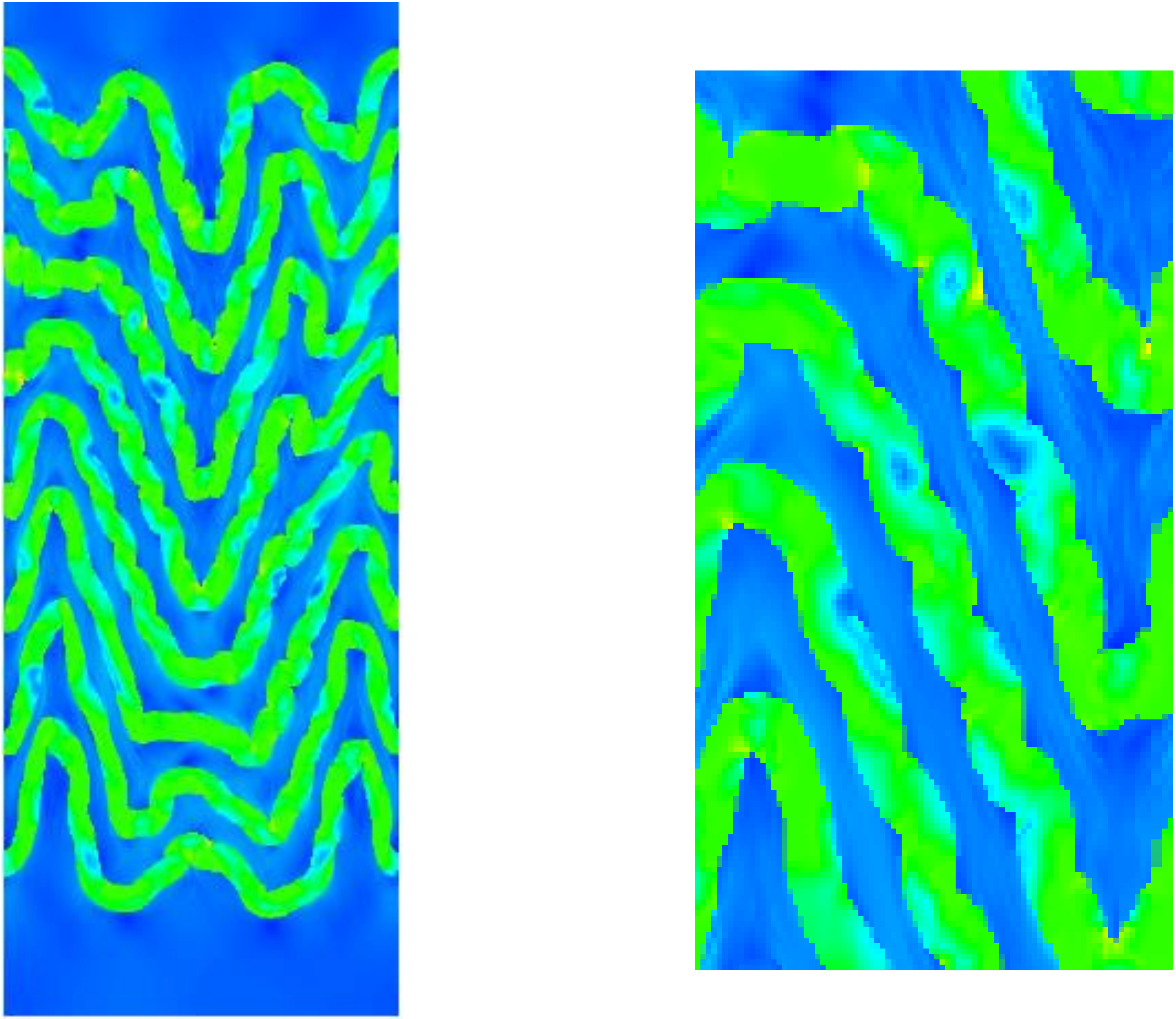
doublemesh8

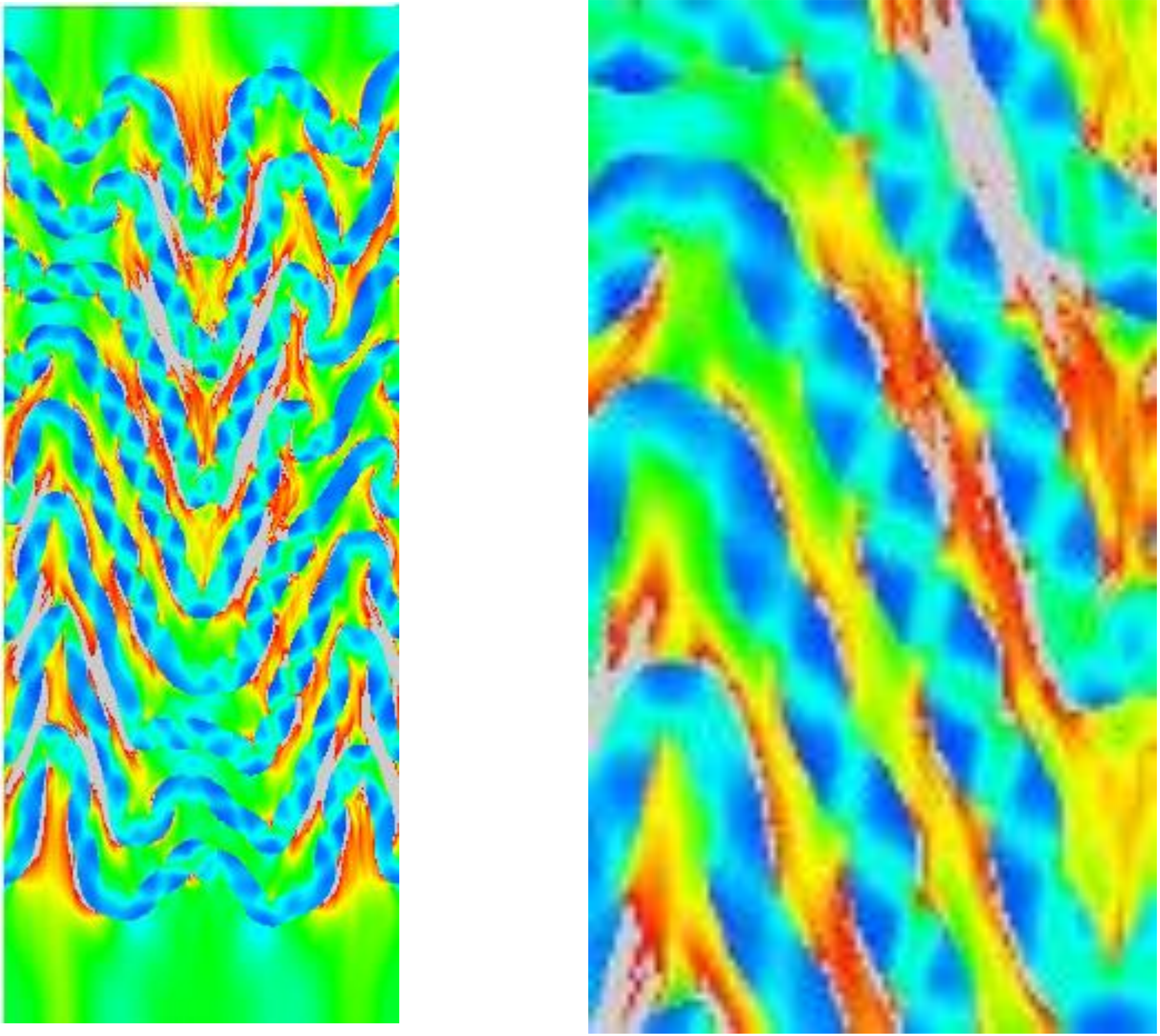
doublemesh10



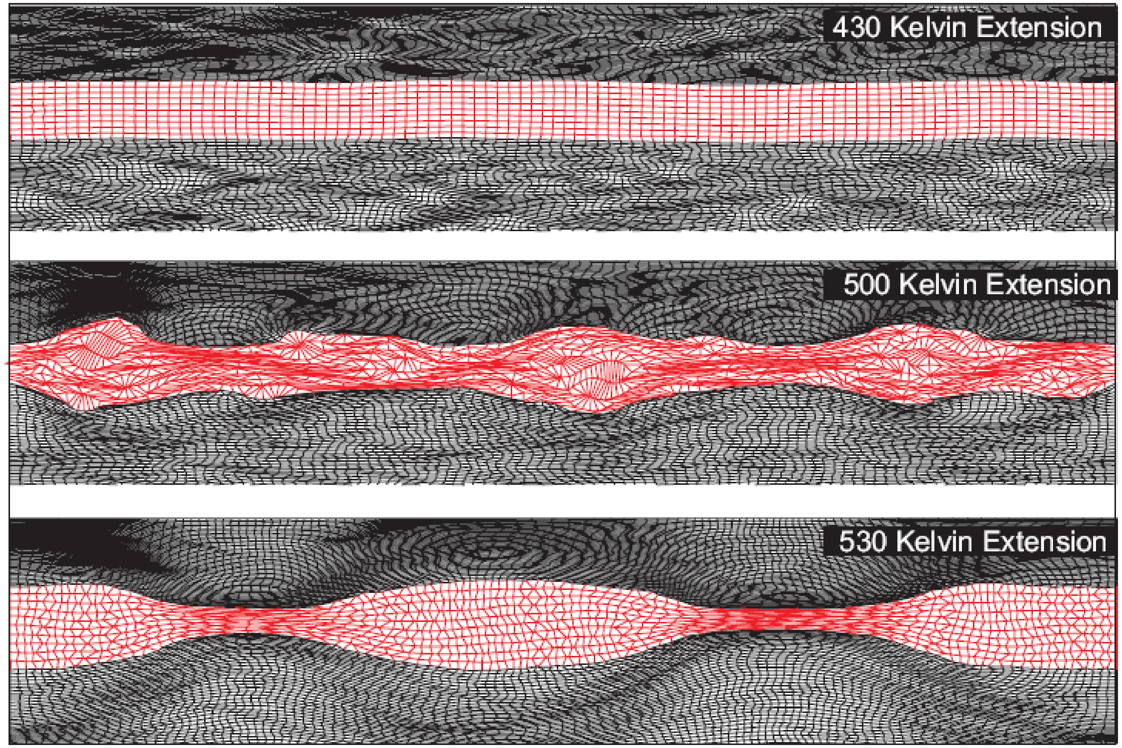
Plot of strain

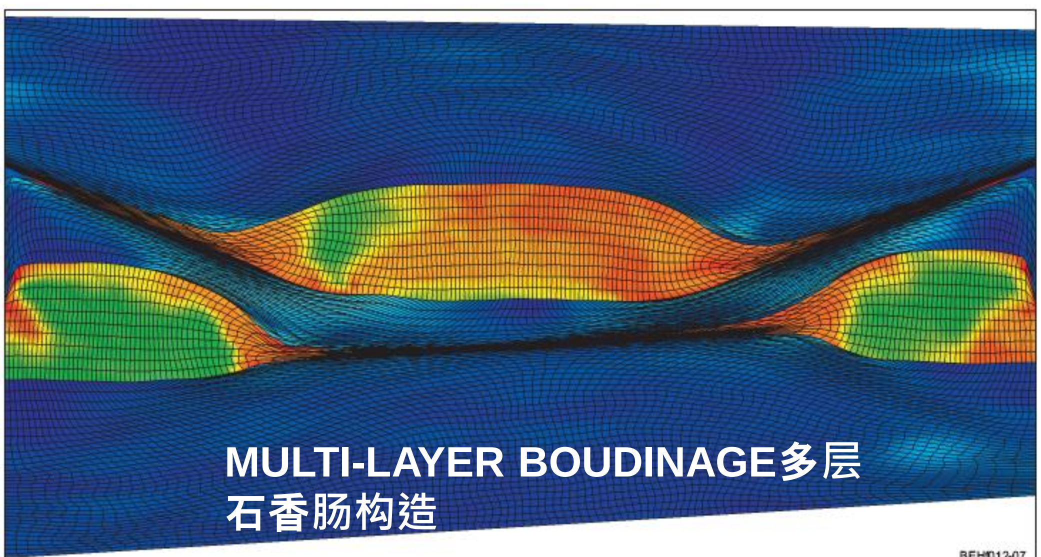
Note zones of localisation
in folded layer





A Extension of a Feldspar layer in Quartz (before: 3.3x12 km; after: 13.2x3 km)





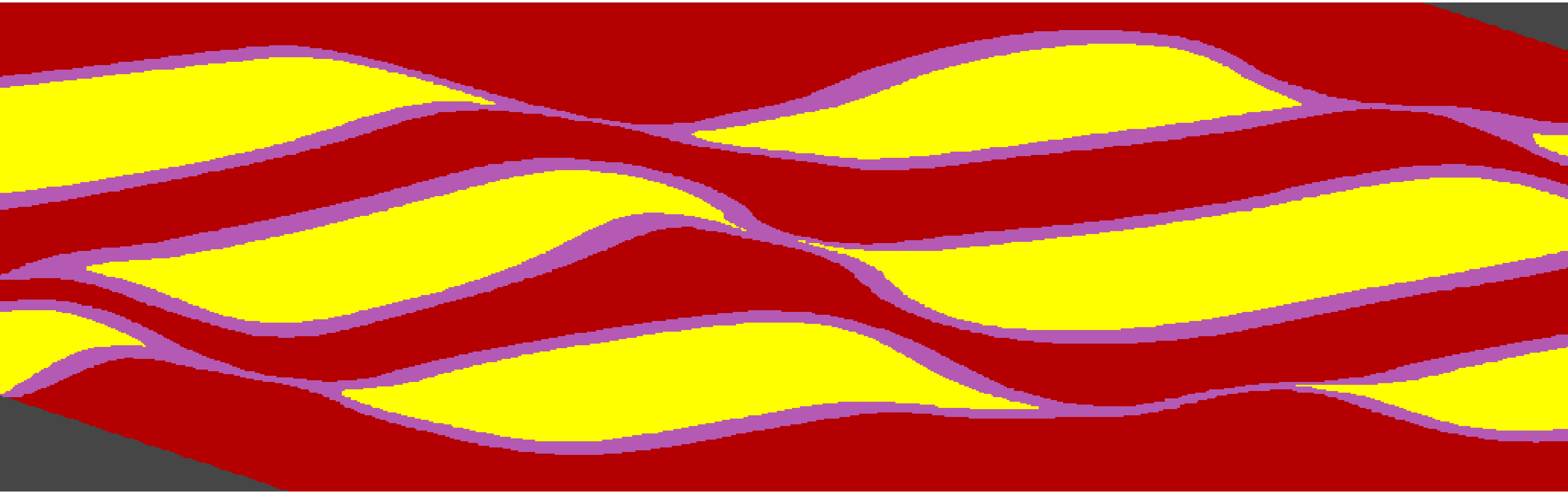
BIOT THEORY PREDICTS NO BOUDINAGE IN THESE MATERIALS

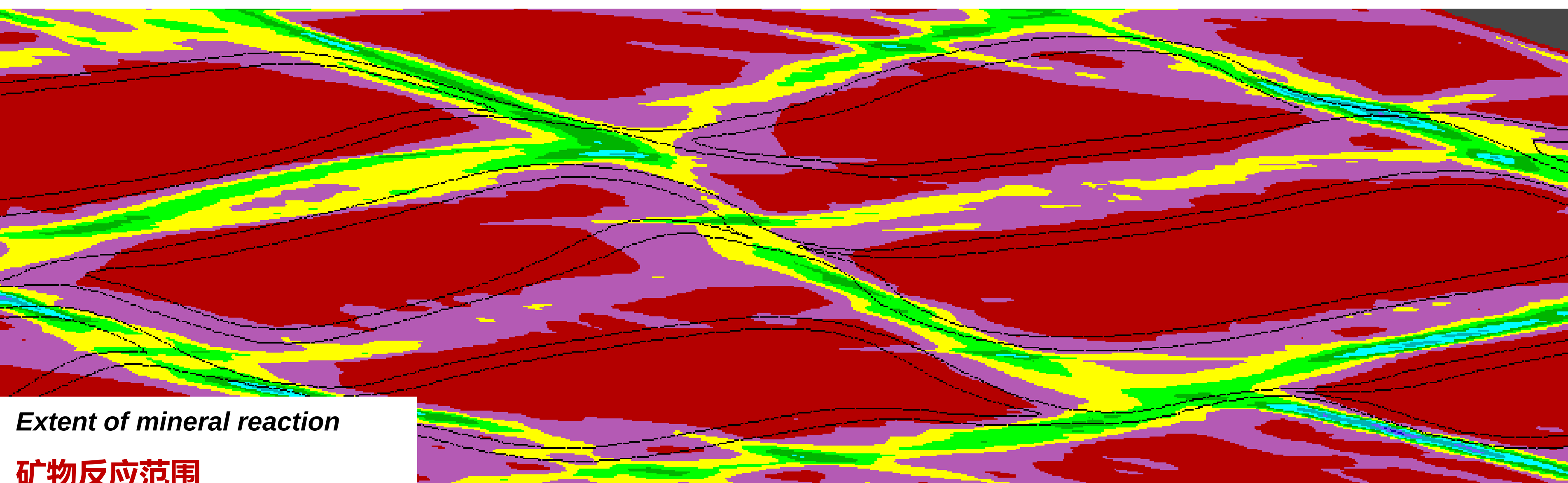
基于毕奥理论在这些材料中无法产出石香肠构造

Deformation of multi-layer sequence; Newtonian viscosity

多层层序：牛顿粘度

***Reaction-deformation coupling* 反应变形耦合**





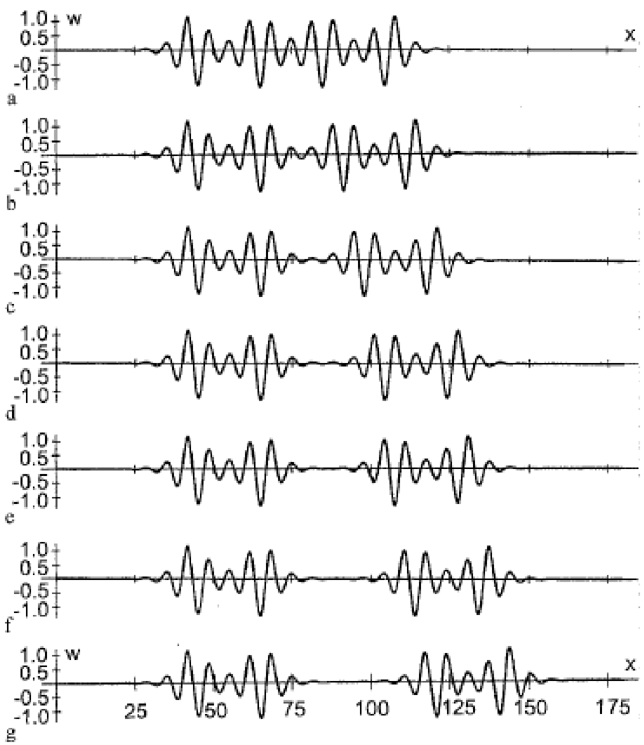
Extent of mineral reaction

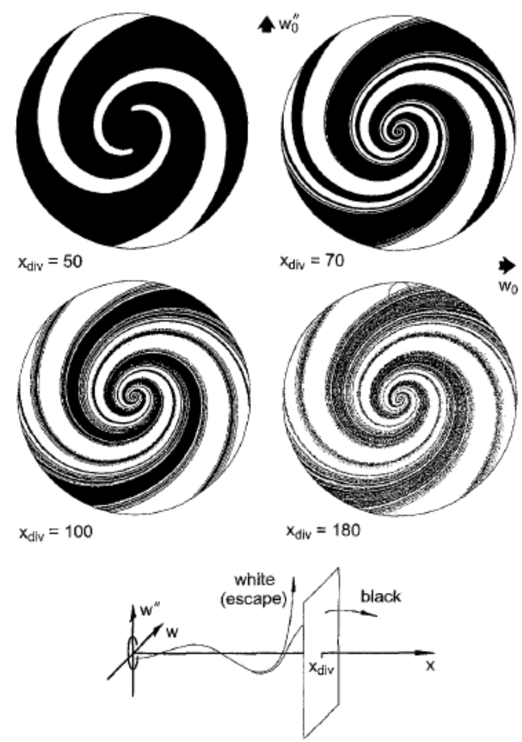
矿物反应范围

In Summary:

Giles Hunt has produced realistic folds in elastic materials and in particular shown that strain-softening leads to localised folding that is characteristic of natural folds.

Giles Hunt基于弹性材料生成了真实褶皱，尤其是揭示了应变软化导致局部褶皱这一自然褶皱的特征





Summary continued.

It appears now that in rate sensitive materials, strain-rate softening is the important ingredient and results from coupling the deformation to other processes that happen during natural deformation.

目前看来，敏感材料的应变率软化是其重要组成部分，这是由于在自然变形过程中，变形常与其他过程相耦合。

The challenge now is to bring these two modes of mechanical behaviour closer together.

目前的挑战是如何把这两种力学行为模式紧密结合


Thank you