ISAP TC on

Constitutive Modelling of Asphaltic Materials

ISAP TC on

Constitutive Modelling of Asphaltic Materials

The TC **co-ordinates activities** in constitutive modelling of asphalt from around the world within the framework of the **I**nternational **S**ociety for **A**sphalt **P**avements (ISAP)

THE SCOPE OF THE TC:

The **encouragement of research** into constitutive modelling of asphalt and the **dissemination of knowledge** into the sector.

Technical Committee on Constitutive Modelling of Asphaltic Materials

TC BOARD

CHAIRMAN
Tom Scarpas

SECRETARY
Niki Kringos

WG01: on Foam Asphalt	Coordinator: A. Loizos
WG02: on Moisture Damage in Asphaltic Mixes	Coordinator: E. Masad
WG03: on Shared Testing for Constitutive Modelling	Coordinator: A. Collop
WG04: on Reinforcement of Asphalt	Coordinator: I. Al-Qadi
WG05: on Re-use of Construction Materials	Coordinator: M. Partl
WG06: on Chemo-Mechanics of Bituminous Materials	Coordinator: J. Youtcheff
WG07: on Bitumen and Mastics	Coordinator: H. Bahia

Technical Committee on Constitutive Modelling of Asphaltic Materials

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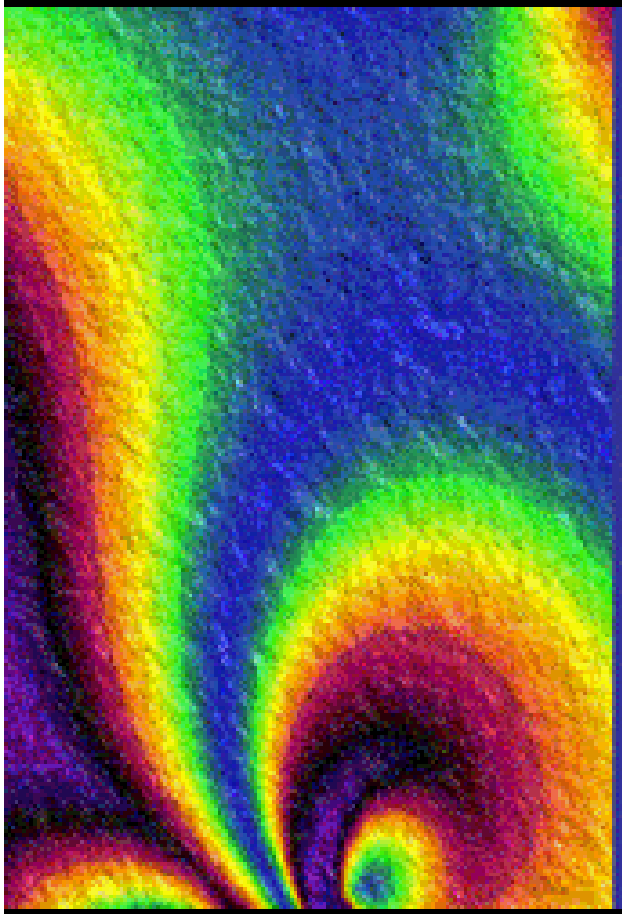


International Course Series on Advanced Constitutive Modeling of Pavement and Soil Engineering Materials

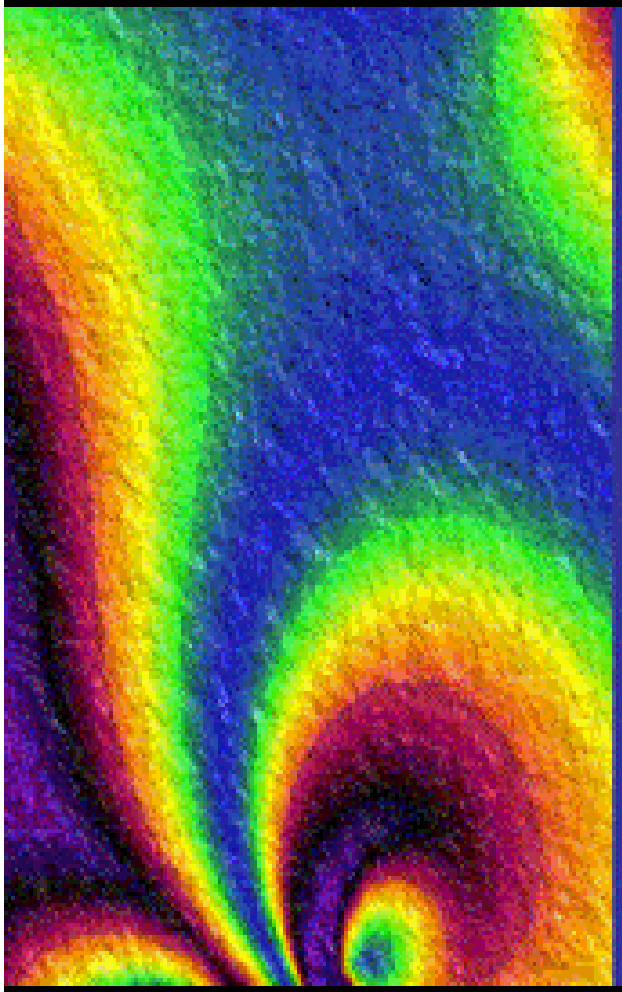
An Intensive Course on:

ADVANCED CONSTITUTIVE MODELING OF ASPHALTIC MATERIALS

5-8 January 2005, Maryland, USA

MORE INFO

Technical Committee on
Constitutive Modelling of Asphaltic Materials



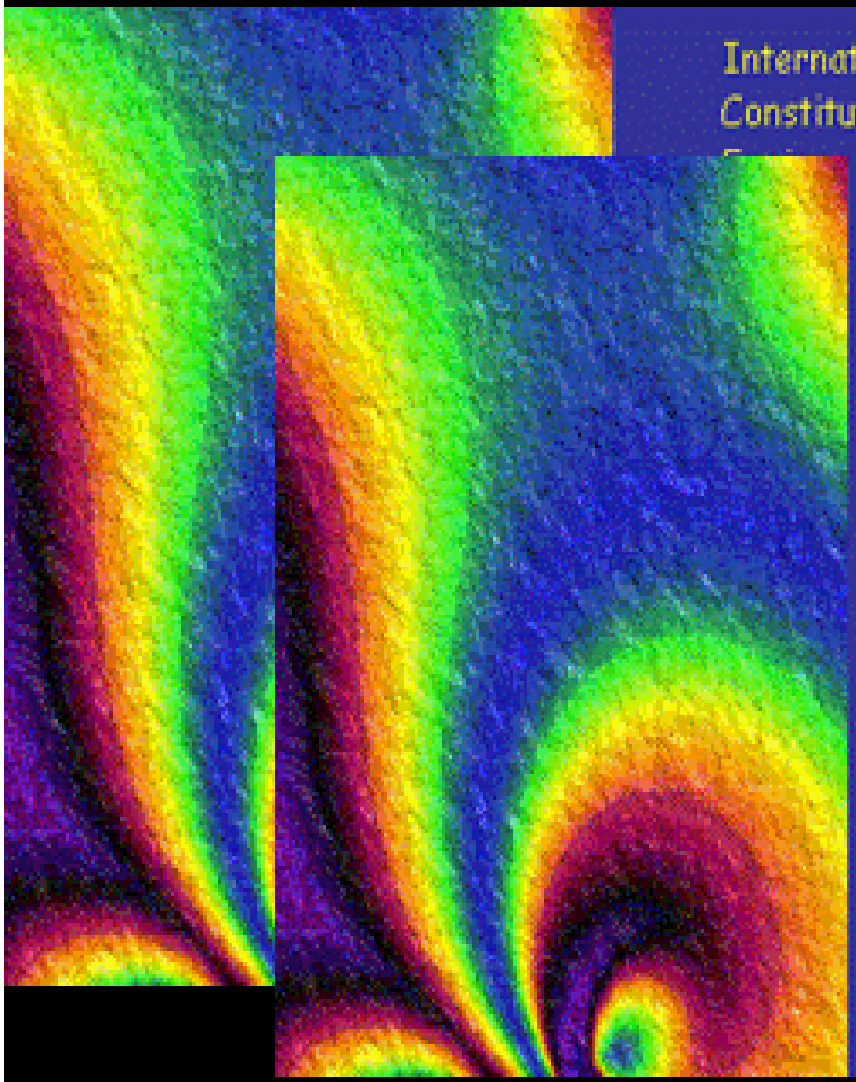
International Course Series on Advanced Constitutive Modeling of Pavement and Soil Engineering Materials

Applied Tensor Analysis for Constitutive Modeling

Delft, June 2004

MORE INFO

Technical Committee on Constitutive Modelling of Asphaltic Materials



International Course Series on Advanced Constitutive Modeling of Pavement and Soil

International Course Series on Advanced Constitutive Modeling of Pavement and Soil
Engineering Materials

An Intensive Course on:

ADVANCED CONSTITUTIVE MODELING OF ASPHALTIC MATERIALS

5-8 January 2005, Maryland, USA

MORE INFO

Technical Committee on Constitutive Modelling of Asphaltic Materials

International Course Series on Advanced Constitutive Modeling of Pavement and Soil

International Course Series on Advanced Constitutive Modeling of Pavement and Soil Engineering Materials

Date and location
The course is under the auspices of the ISAP TC Constitutive Modeling of Asphaltic Materials and shall be held from 21-25 September 2009 in College Station, Texas at the Campus of the Texas A&M University, USA. Details about the location and nearby hotel arrangements are available at www.insapconmod.nl.

Language
All lectures and course handout materials are in English.

Registration
The course fee is US$ 900. A special reduced fee of US$ 700 applies for graduate students.

To register, please visit the course link at www.insapconmod.nl or go directly to https://tti.tamu.edu/conferences/amc09/registration.htm

After registration, participants will receive a letter of confirmation, travel and accommodation suggestions. Registration is final after the course fee has been received. The total number of participants is limited, registration will be accepted according to availability.

The organizers reserve the right to make necessary amendments to the program. For additional information and course news please refer to: www.insapconmod.nl

ISAP TC Constitutive Modeling of Asphaltic Materials

International Course Series on Advanced Constitutive Modeling of Pavement and Soil Engineering Materials

TEXAS A&M UNIVERSITY

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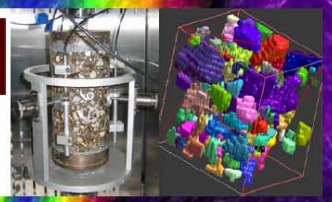
ISAP



TEXAS 21-25 Sept. 2009

AN INTENSIVE COURSE ON:
ADVANCED CONSTITUTIVE MODELING AND CHARACTERIZATION OF ASPHALTIC MATERIALS

Technical Committee on Constitutive Modelling of Asphaltic Materials

Technical Committee on
Constitutive Modelling of Asphaltic Materials

International Workshop on
Moisture Induced Damage of Asphaltic Mixes
Characterization, Visualization and Simulation of the Fundamental Processes

23-25 November 2005

Delft, The Netherlands

Organizers:

A. Scarpas
Delft University of Technology
The Netherlands

www.isap-tc-conmod.org

DCMat
Delft Centre for Materials

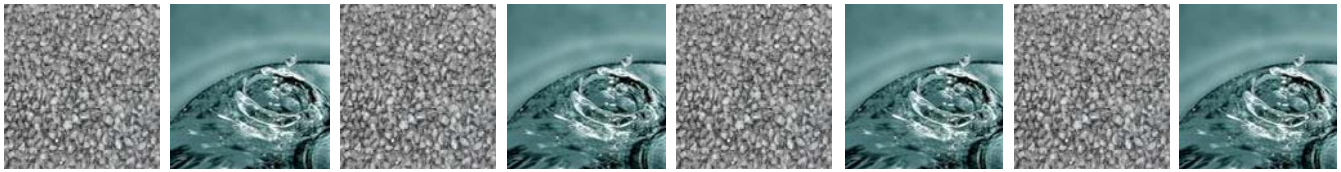
TU Delft
Faculty of Civil Engineering and Geosciences

Second International Workshop on

Moisture Induced Damage of Asphalt Mixes

Characterization, Visualization and Simulation of the Fundamental Processes

September 17-19 2007 **College Station, Texas (USA)**



Organizers

E. Masad
D. Little
R. Lytton
Texas A&M University (USA)

A. Scarpas
Delft University of Technology
(The Netherlands)

A. Papagiannakis
University of Texas San Antonio
(USA)

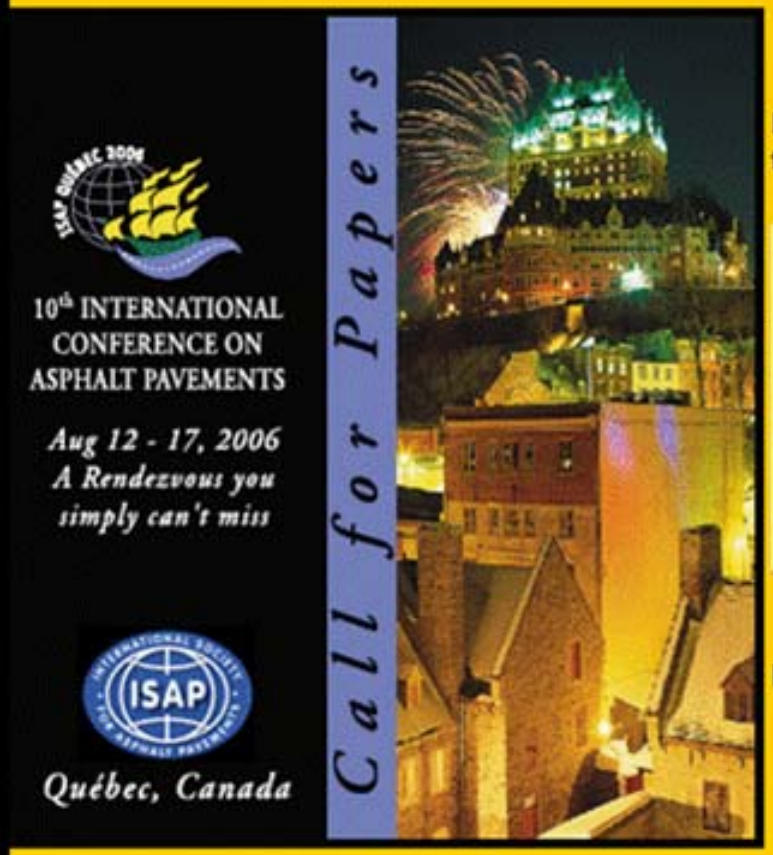
TEXAS A&M UNIVERSITY

Technical Committee on
Constitutive Modelling of Asphaltic Materials

Technical Committee on Constitutive Modelling of Asphaltic Materials

- Foam Asphalt Concrete
  Loizos & Jennings
- Chemo-Mechanics of Bituminous Materials
  Pauli
- Moisture Induced Damage in Asphaltic Materials
  Masad & Kringos
- Micro-Mechanics of Asphalt Concrete Mixes
  Wang

Technical Committee on Constitutive Modelling of Asphaltic Materials

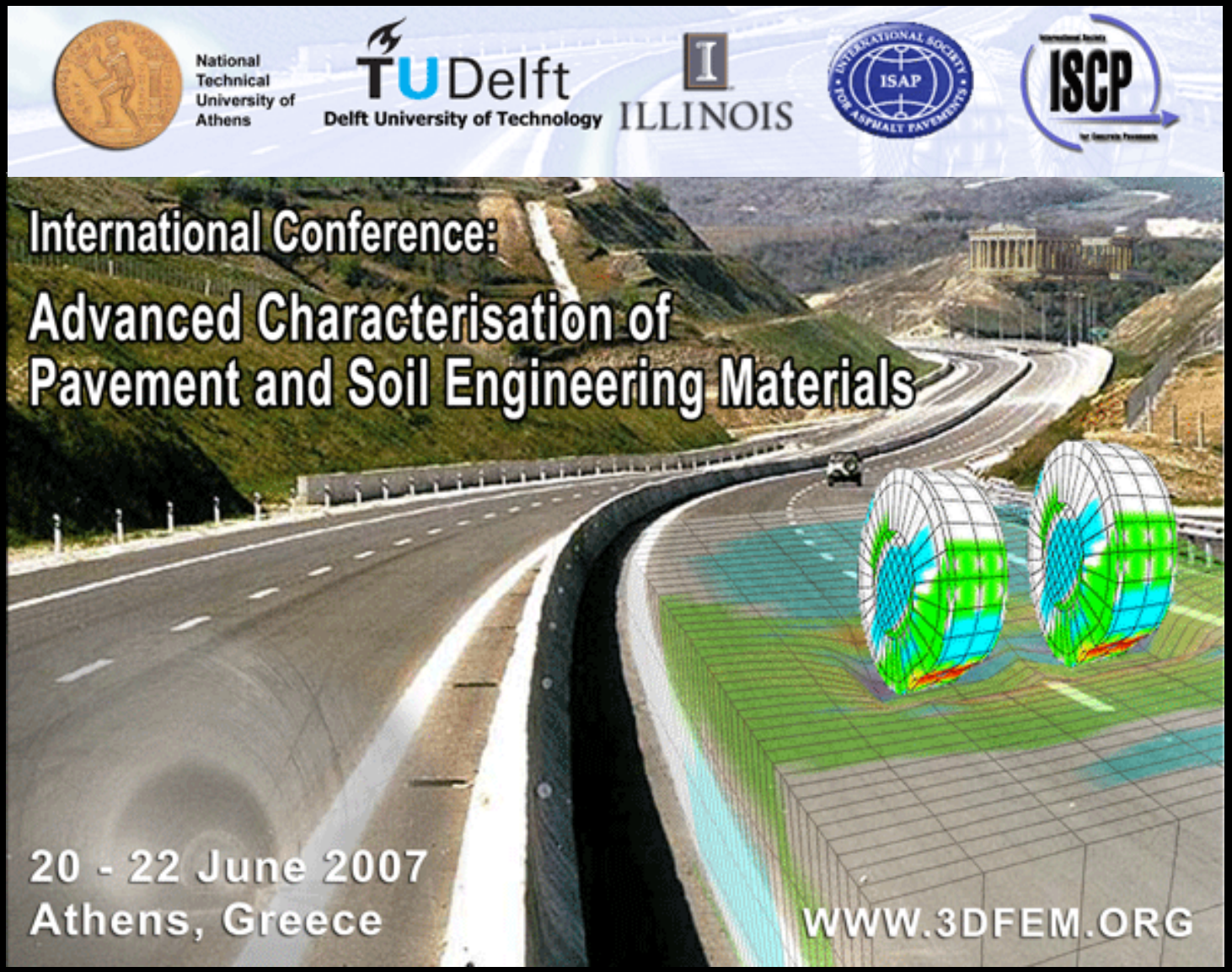


During the 10th ICAP Conference the TC has focussed sessions on:

Session No.	Session Topic	Sponsored by
Session 1.8	Foamed Mix	WG 01
Session 1.9	Water Damage	WG 02
Session 1.10	Asphalt Cracking/ Constitutive Modeling	TC
Session 1.11	Asphalt Reinforcement	WG 04

For more info please visit www.icap2006.fsg.ulaval.ca

Technical Committee on
Constitutive Modelling of Asphaltic Materials



Technical Committee on Constitutive Modelling of Asphaltic Materials

www.isap-tc-conmod.org

HOME | ISAP TC | WG's | EVENTS | NEWS | LINKS | FORUM | CONTACT

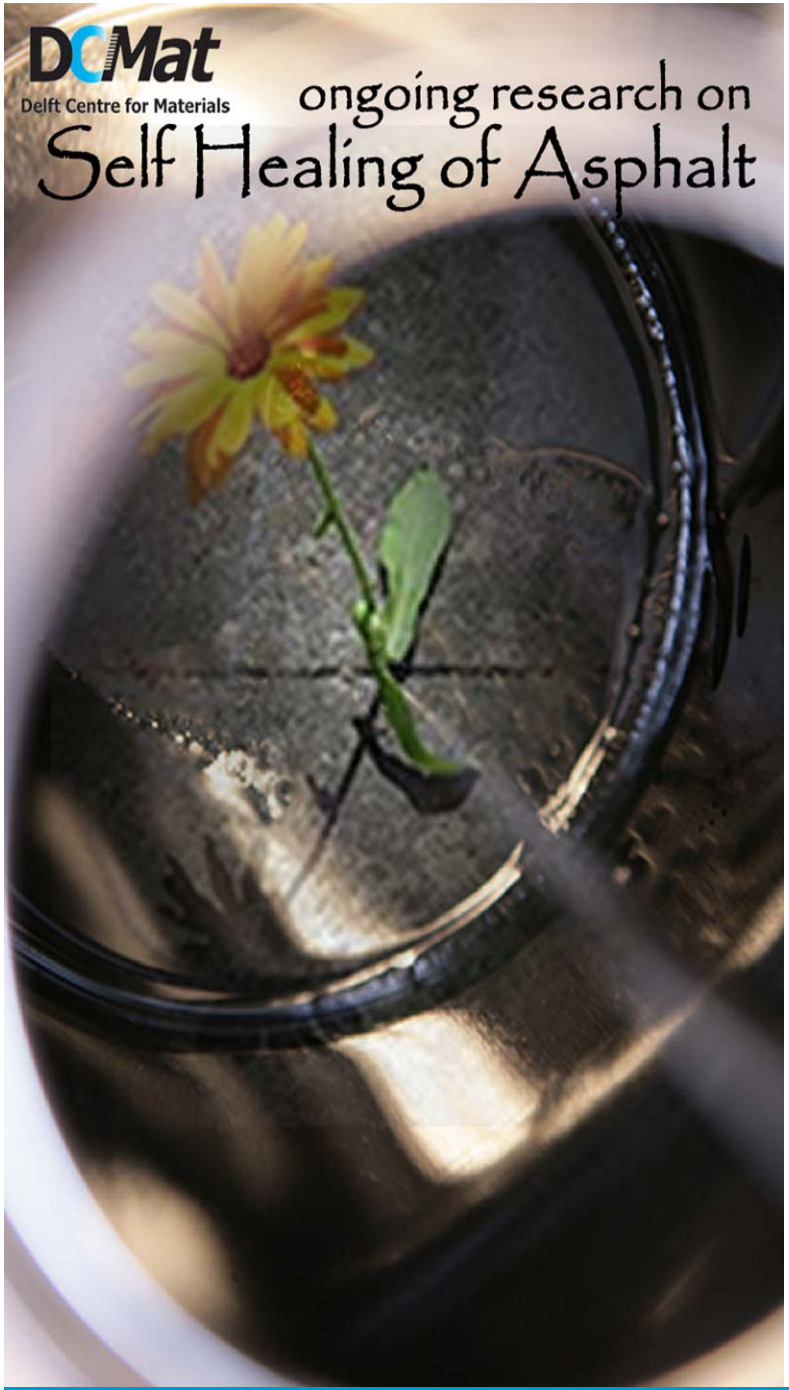
Welcome at the official site of the:

Technical Committee on Constitutive Modelling of Asphaltic Materials.

This ISAP TC was inaugurated
on the 29th of July 2003 in Corfu, Greece.

- 50 members from 12 different countries

- Annual TC Board meeting during TRB



Development of a Physico-Mechanical Healing Model for Bituminous Materials

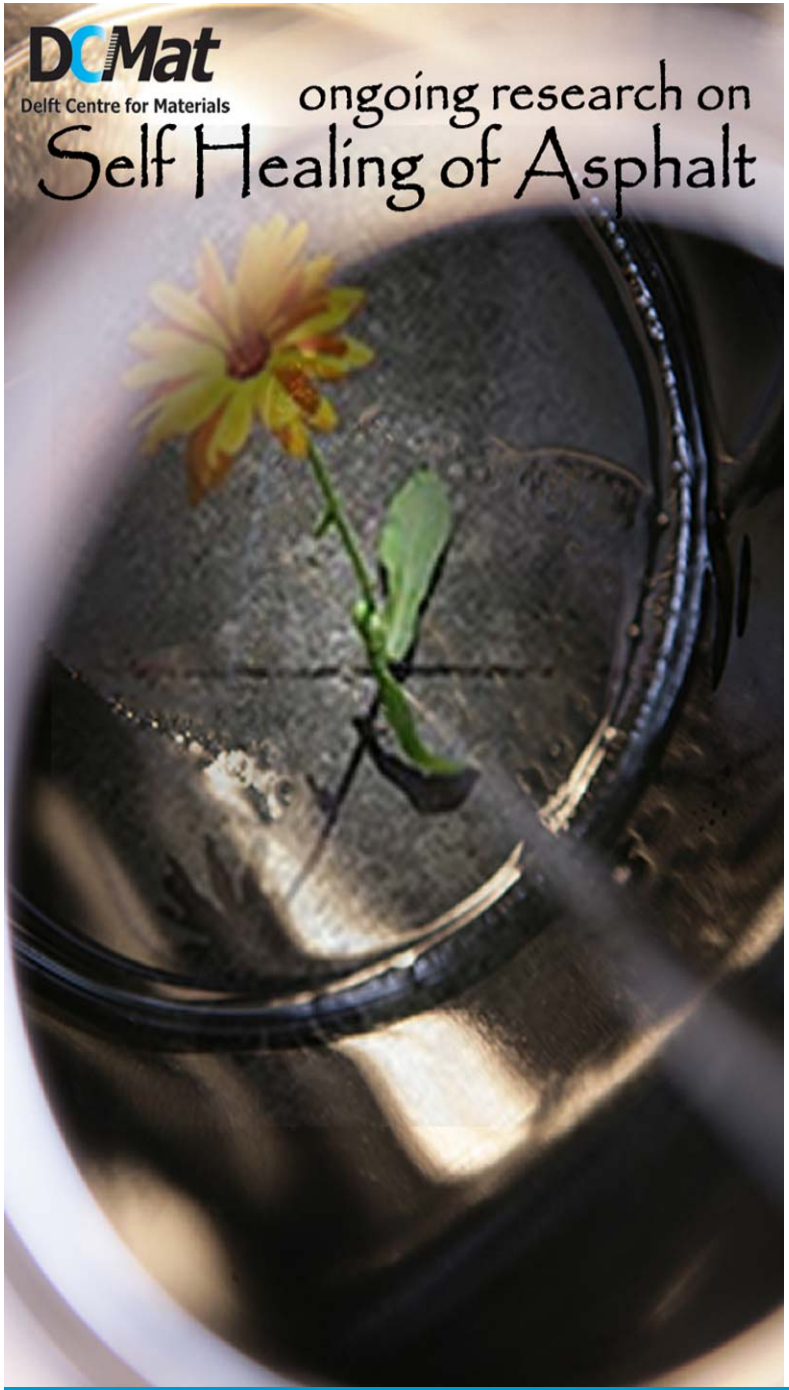
Tom Scarpas

Group of Mechanics of Infrastructure Materials

Section of Structural Mechanics

Faculty of Civil Engineering and Geosciences

TU Delft



Development of a Physico-Mechanical Healing Model for Bituminous Materials

N. Kringos, T. Pauli, A. Schmets

Group of Mechanics of Infrastructure Materials

Section of Structural Mechanics

Faculty of Civil Engineering and Geosciences

TU Delft

Ministerie van Verkeer en Waterstaat
Rijkswaterstaat

Ooms
Avenhorn Groep bv

NYNAS

Western Research
INSTITUTE

TU Delft

U.S. Department of Transportation
Federal Highway Administration

DCMat
Delft Centre for Materials

stw

Development of a Physico-Mechanical Healing Model for Bituminous Materials

Delft Healing Consortium

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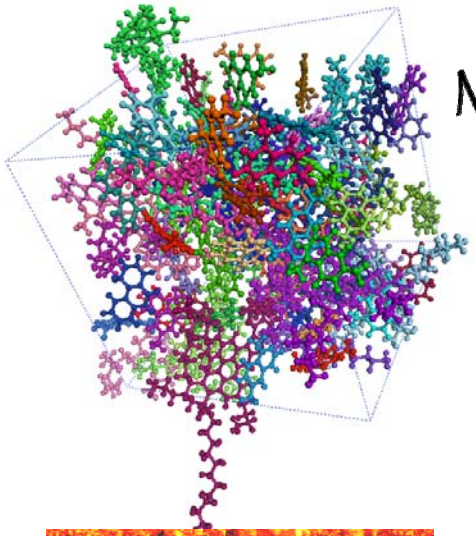
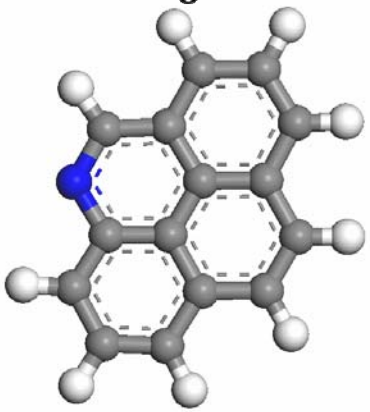
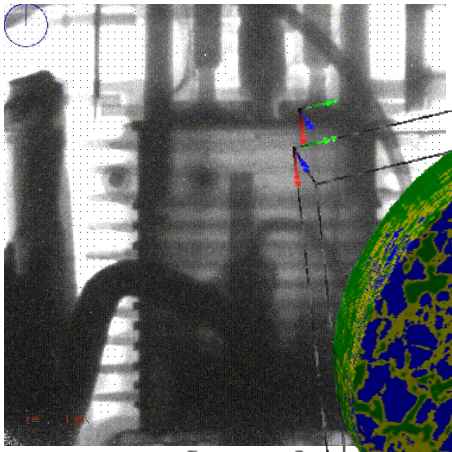


Molecular dynamics

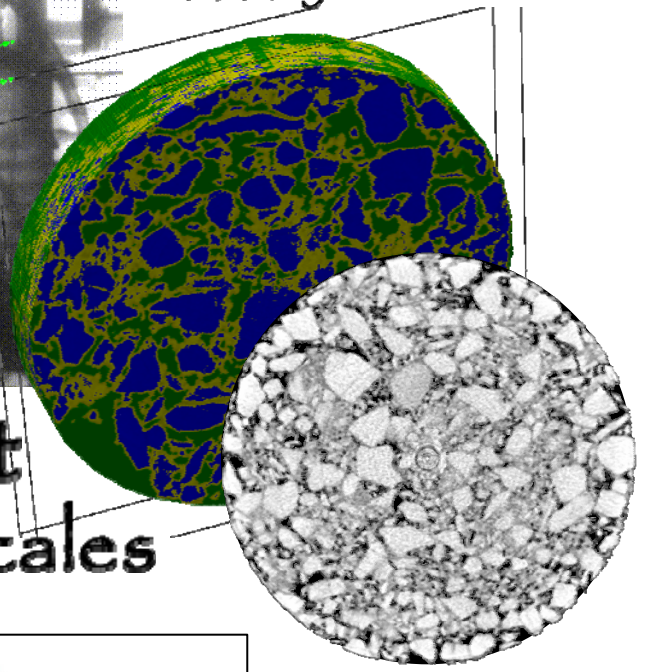


Neutron scattering



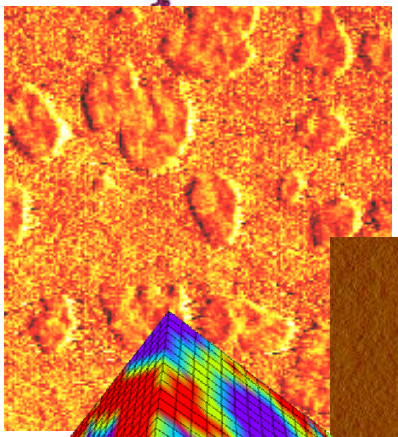
TU Delft

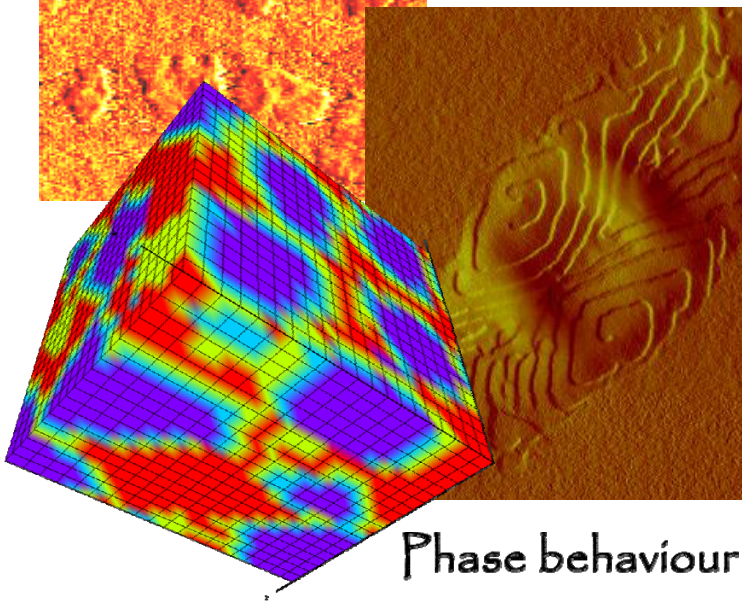
X-Ray scans



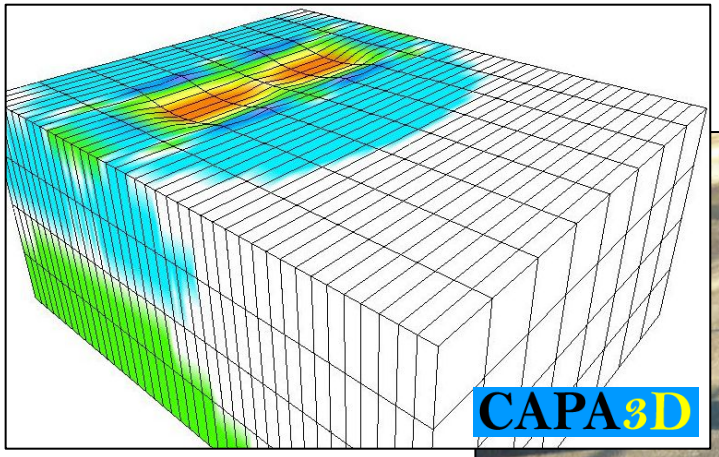
Healing of asphalt

...research on all scales



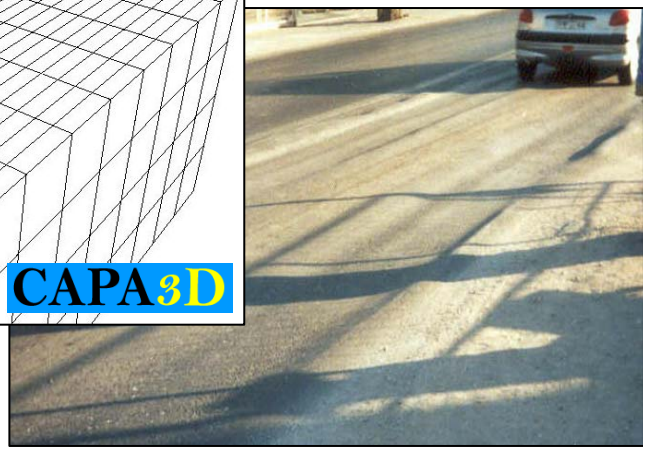


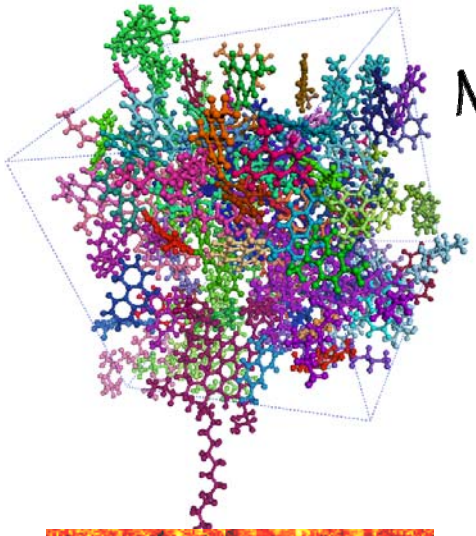
Phase behaviour



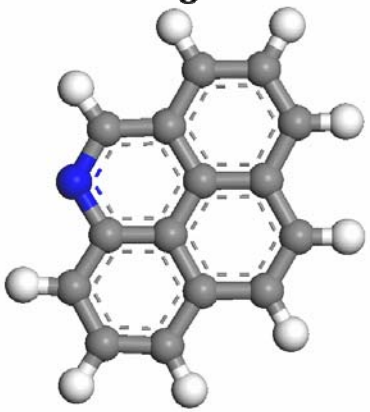
Pavement response

Finite Elements





Molecular dynamics



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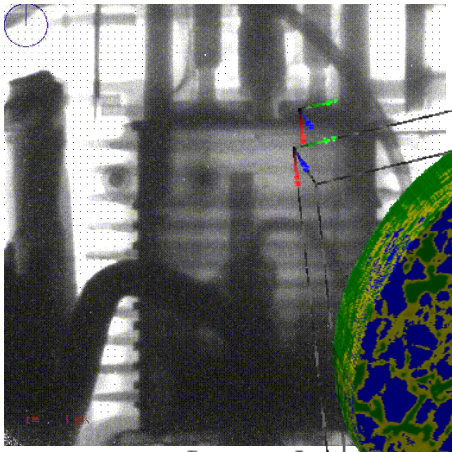
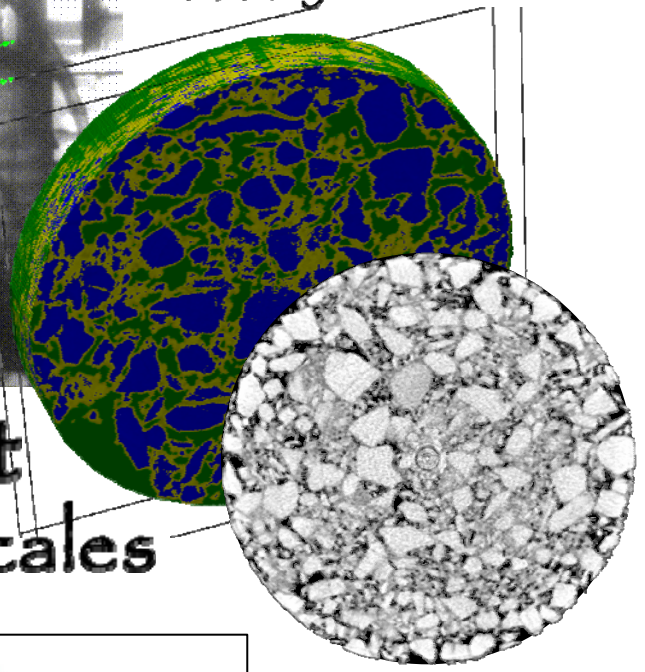


TU Delft

X-Ray scans



Healing of asphalt

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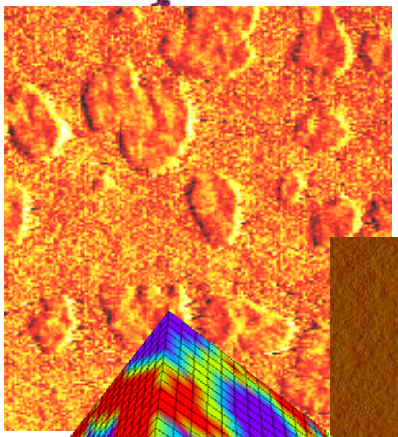

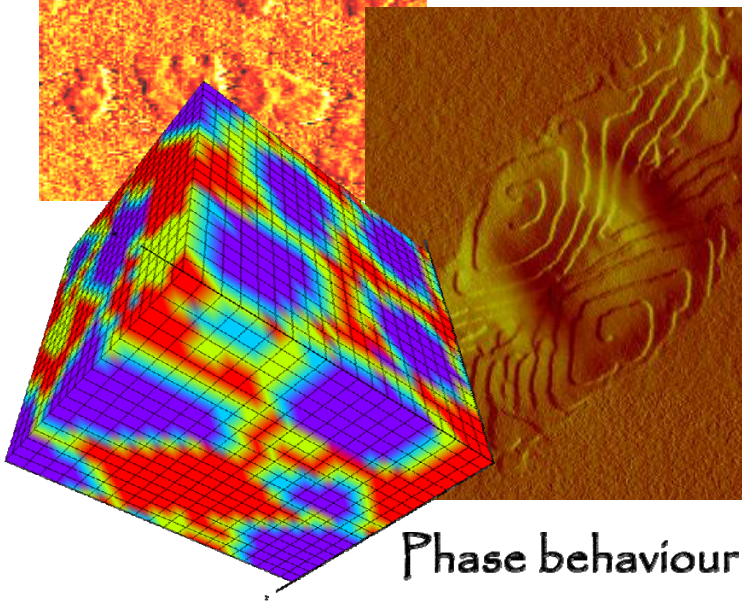

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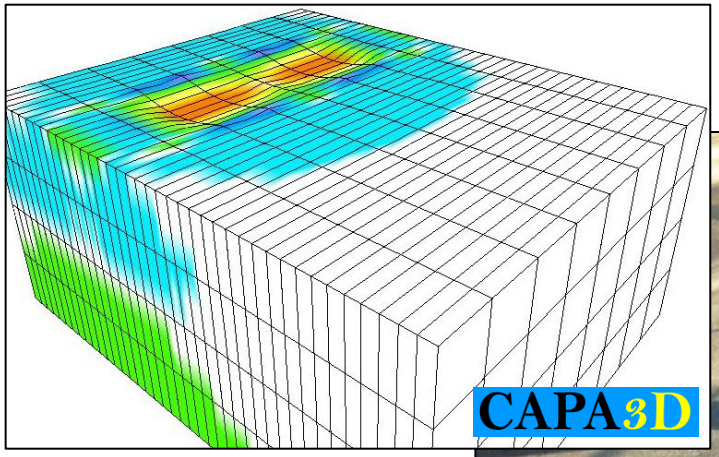

Pavement response

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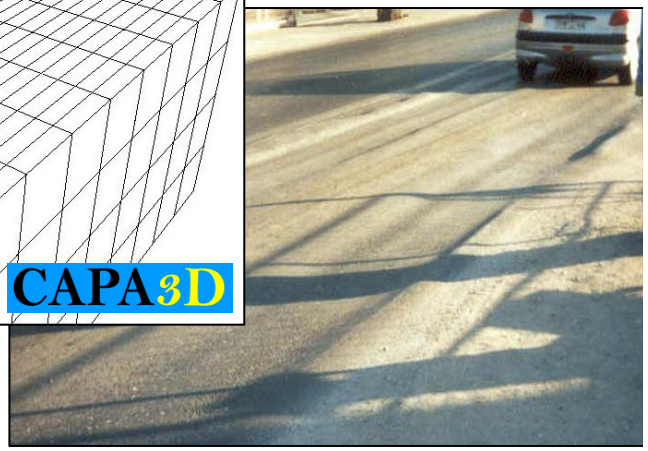
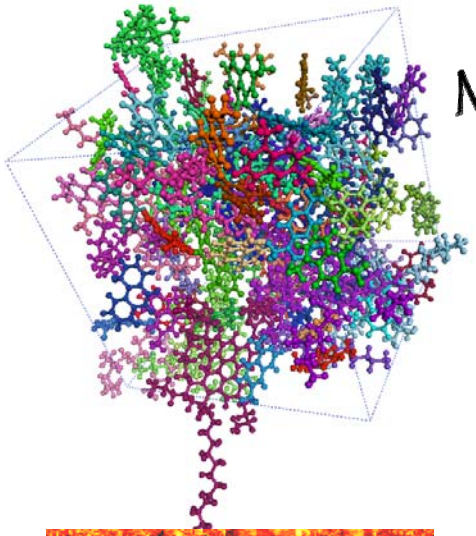
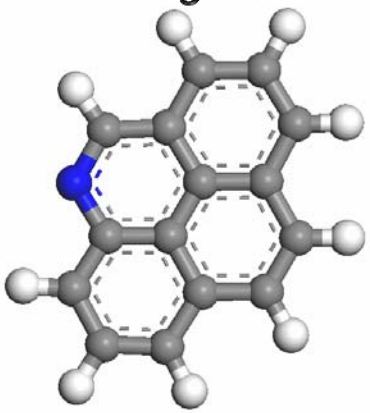
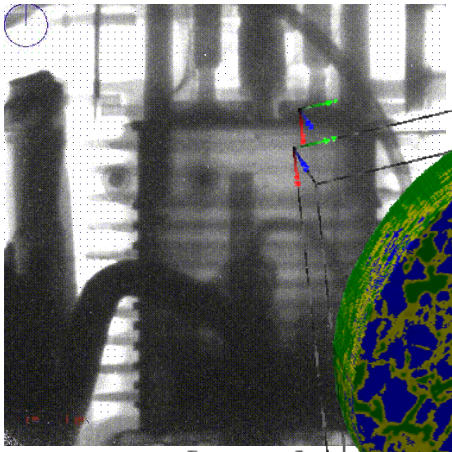




Molecular dynamics

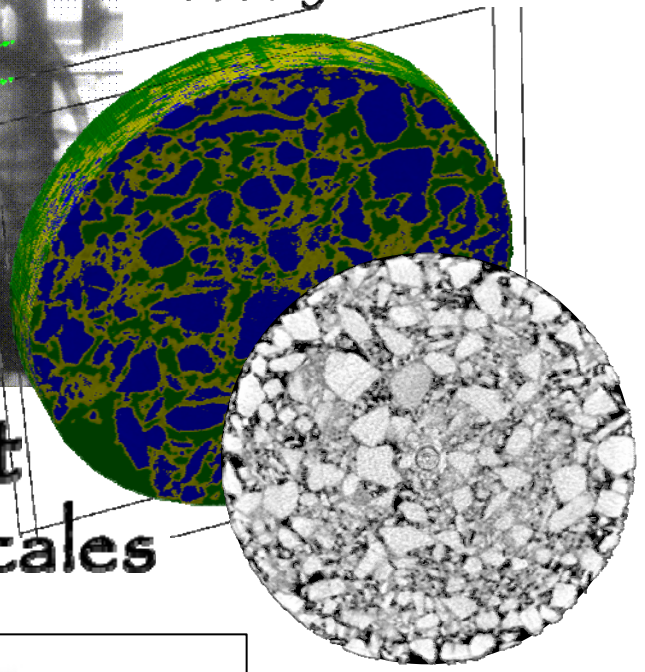


Neutron scattering



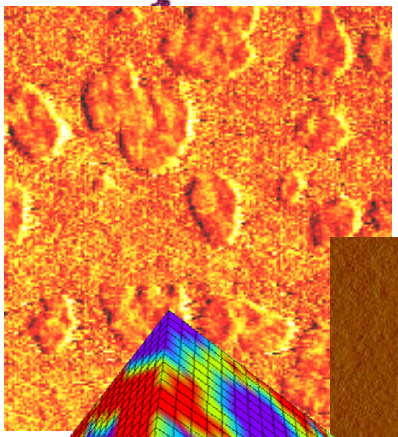
TU Delft

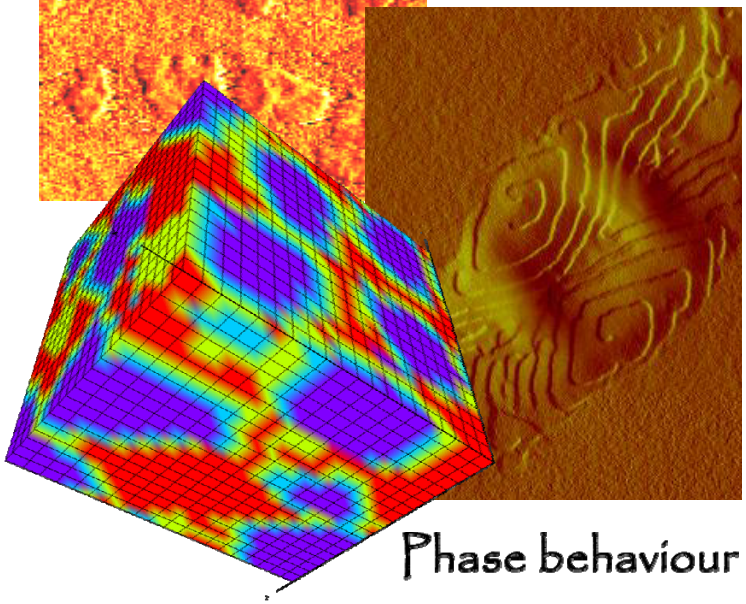
X-Ray scans



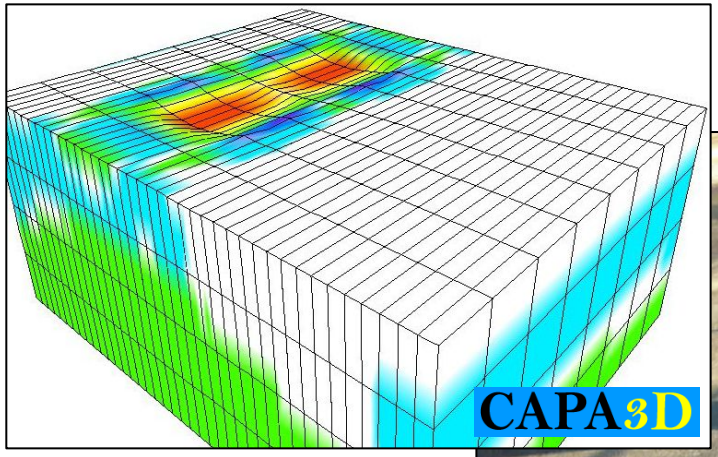
Healing of asphalt

...research on all scales





Phase behaviour



Pavement response

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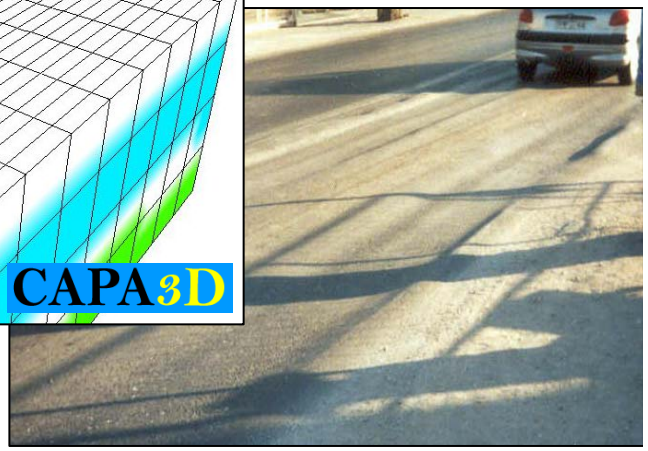
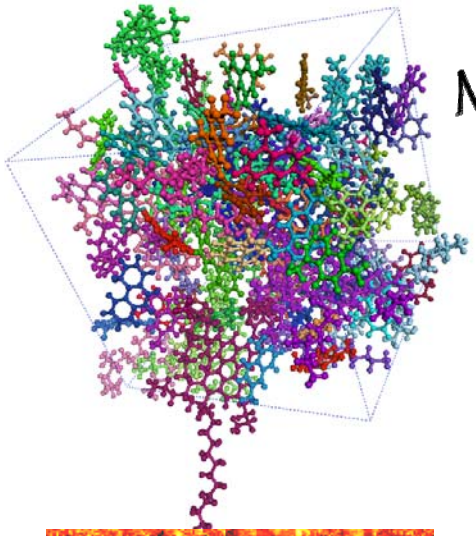
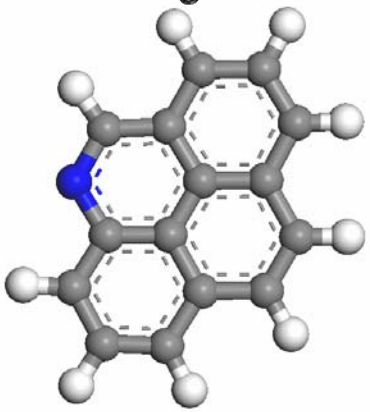
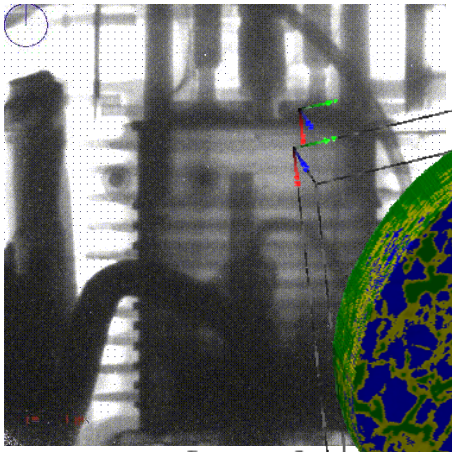




Molecular dynamics

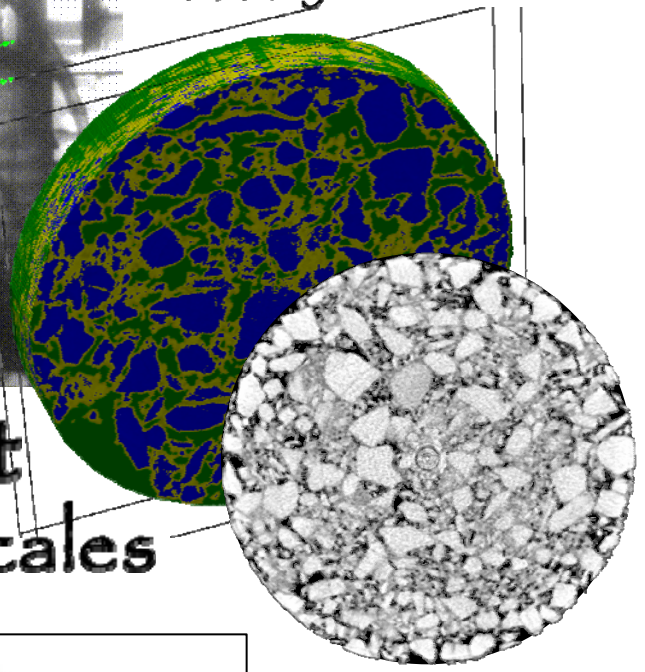


Neutron scattering



TU Delft

X-Ray scans



Healing of asphalt

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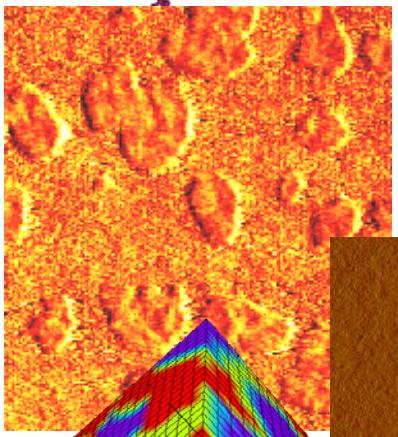
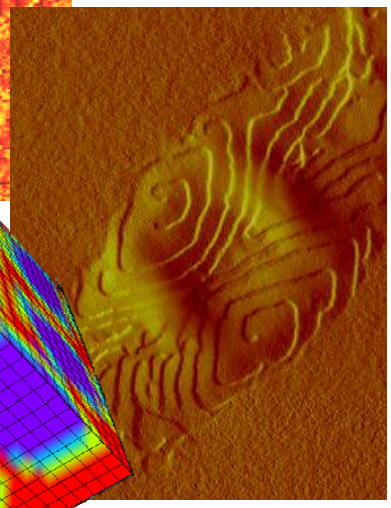
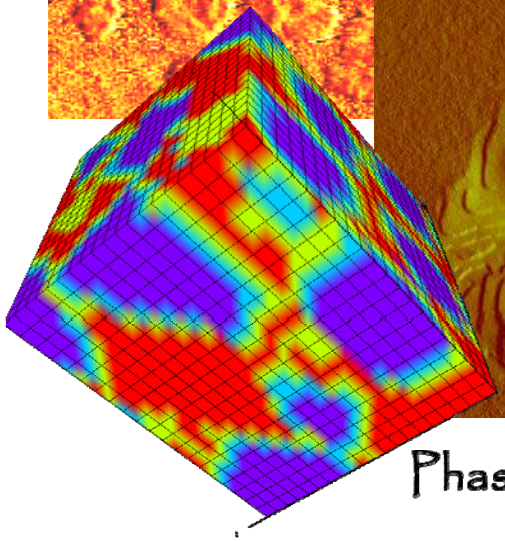
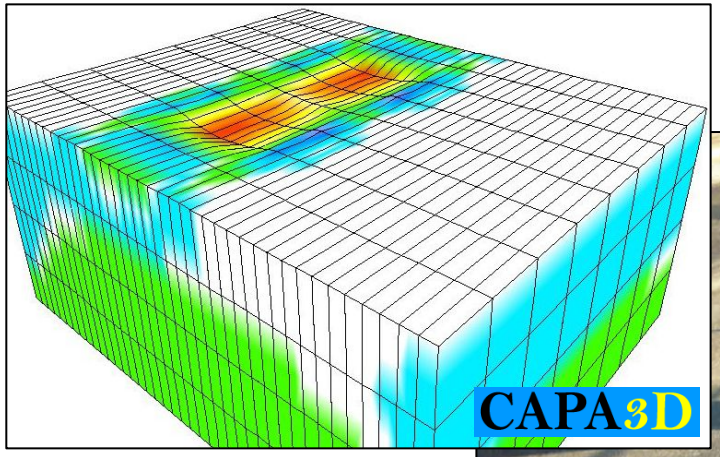




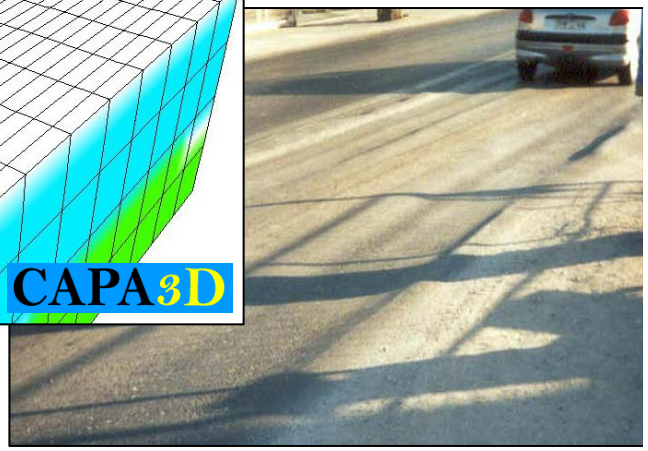


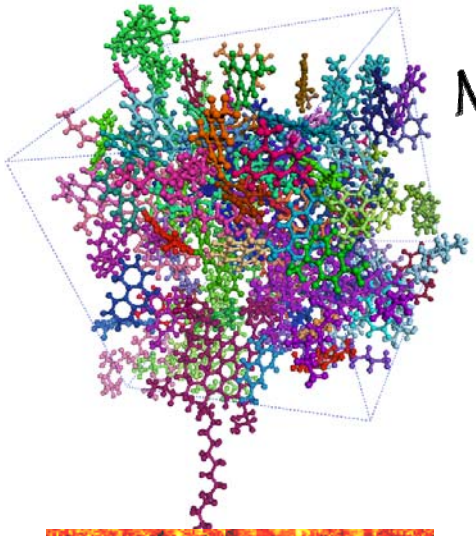
Phase behaviour



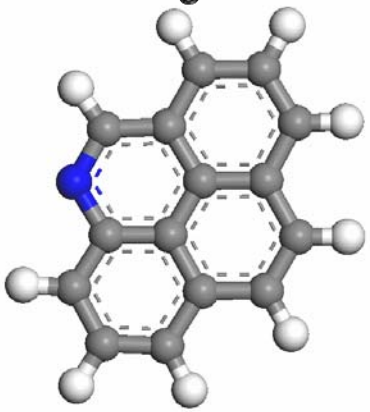
Pavement response

Finite Elements

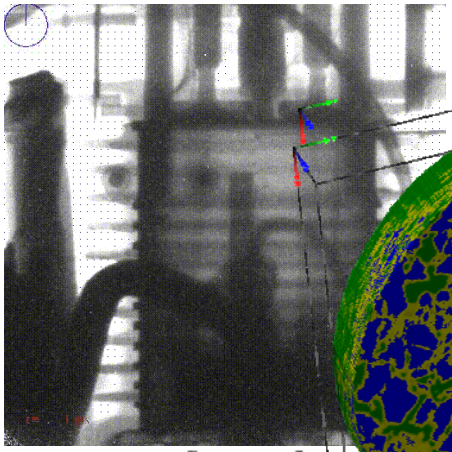




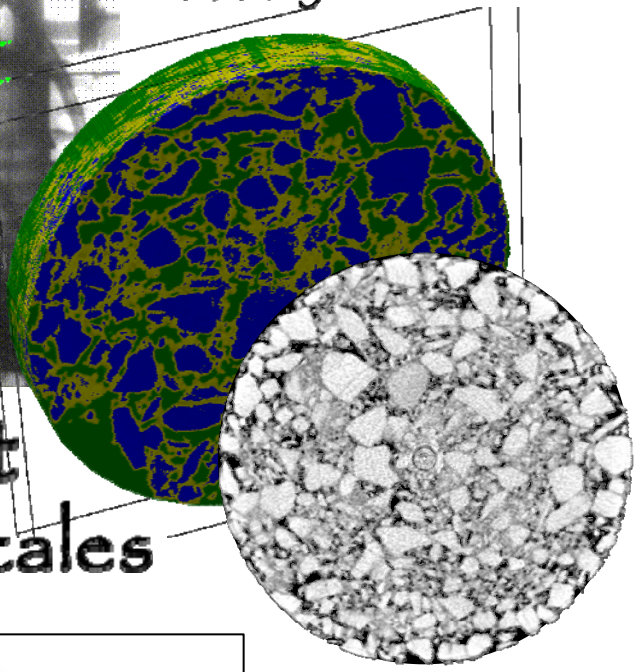
Molecular dynamics



Neutron scattering

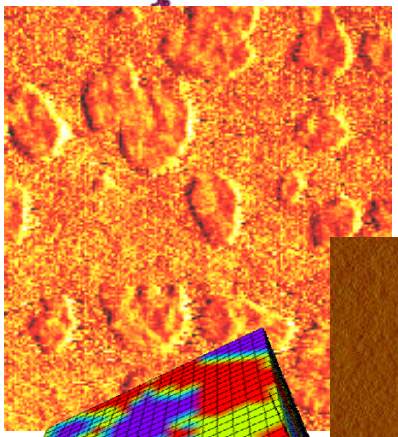


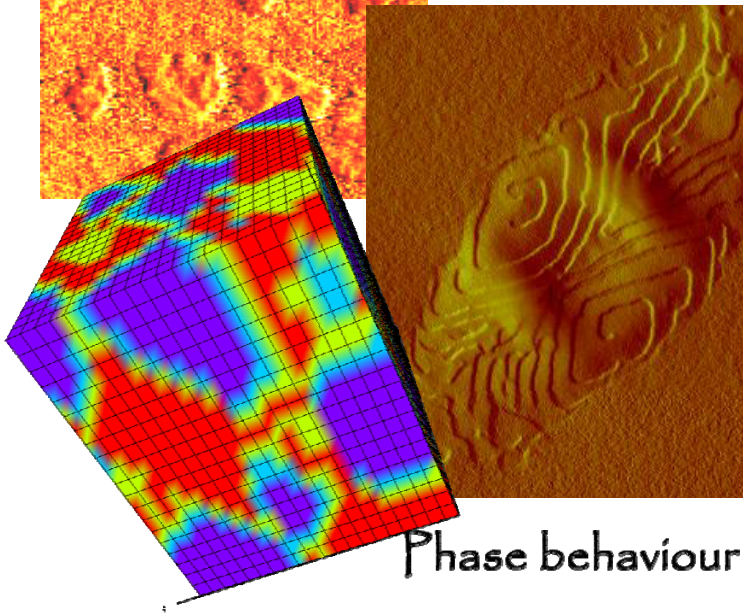
X-Ray scans



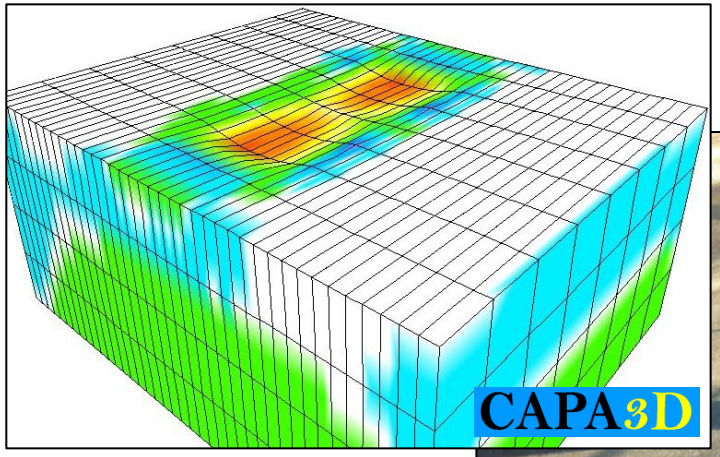
Healing of asphalt

...research on all scales



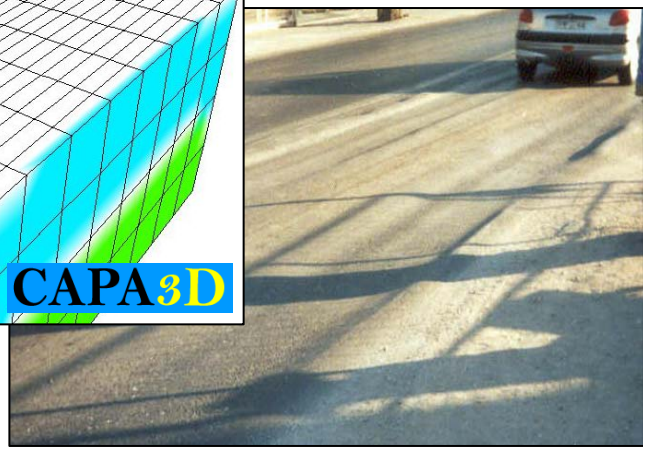


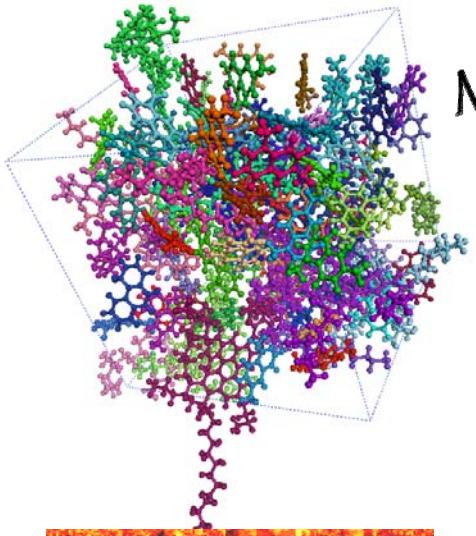
Phase behaviour



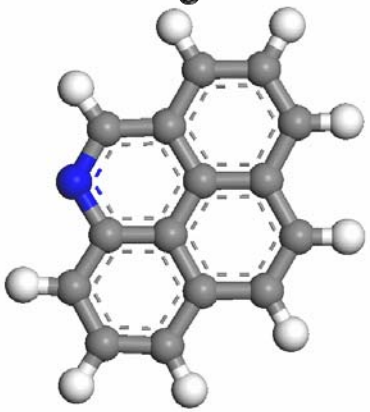
Pavement response

Finite Elements

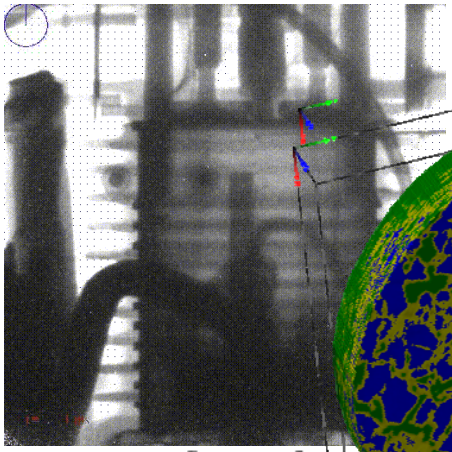




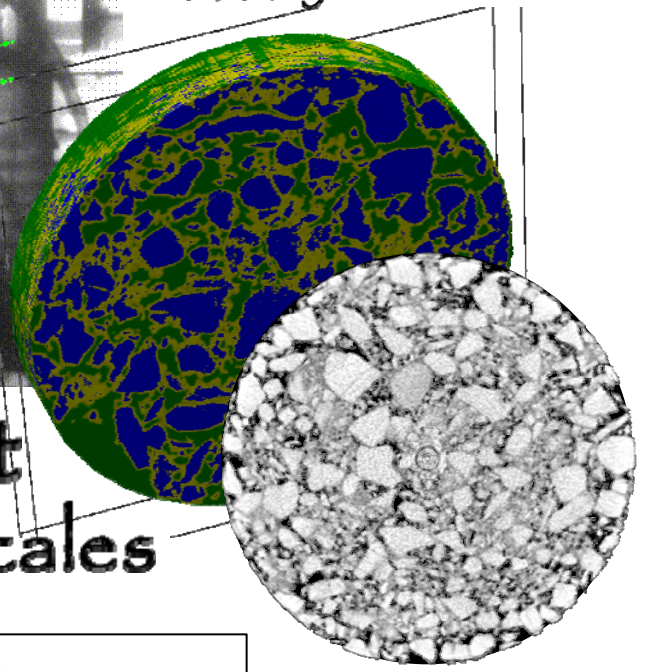
Molecular dynamics



Neutron scattering

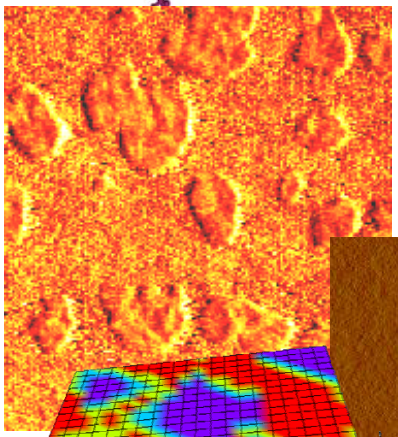


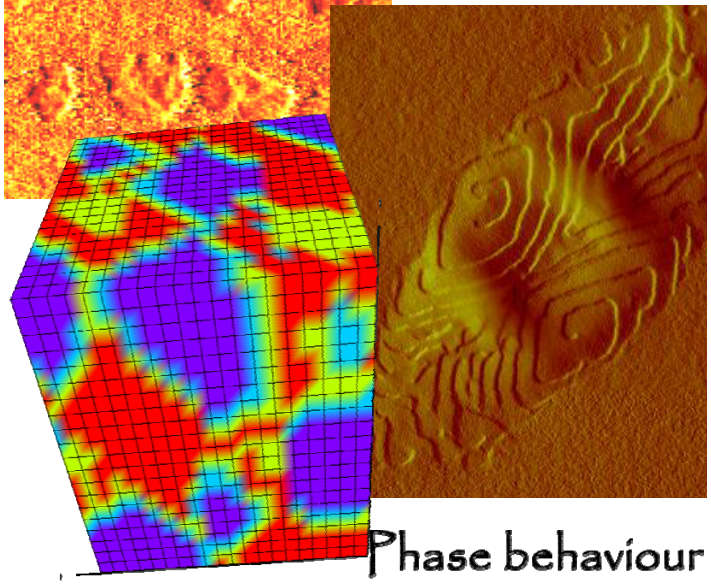
X-Ray scans



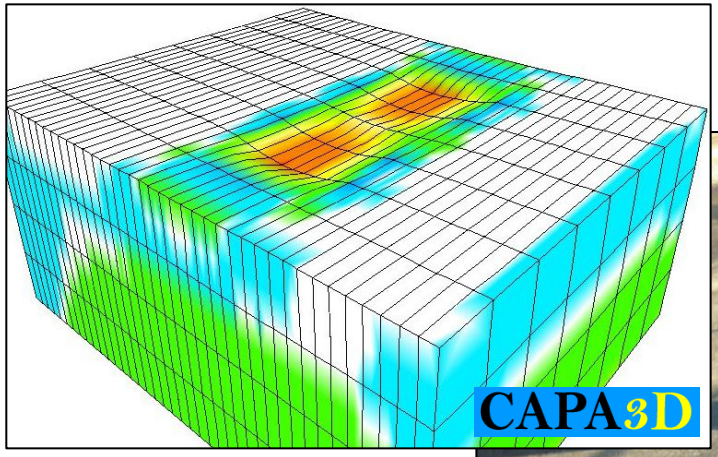
Healing of asphalt

...research on all scales



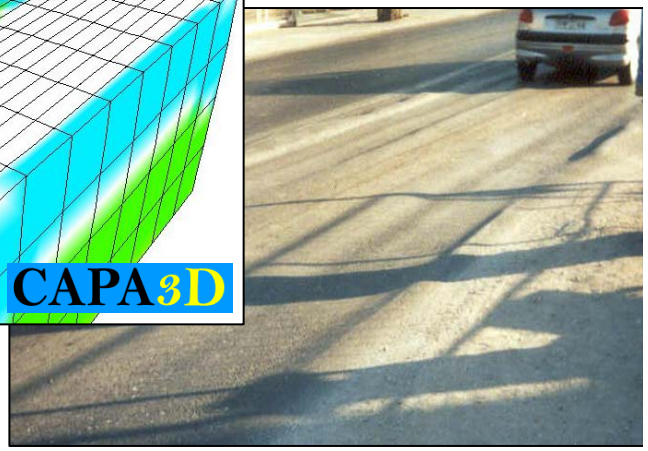


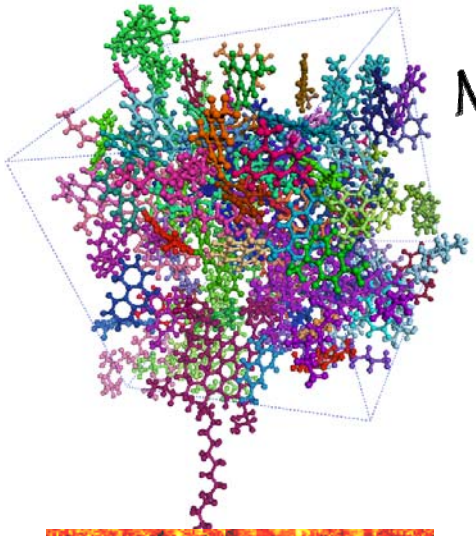
Phase behaviour



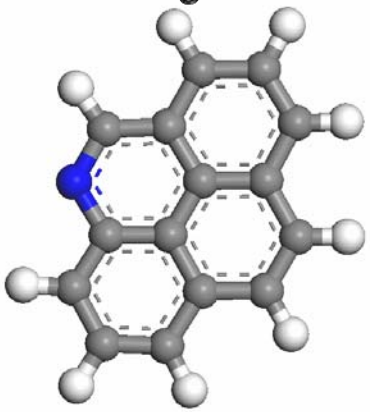
Pavement response

Finite Elements

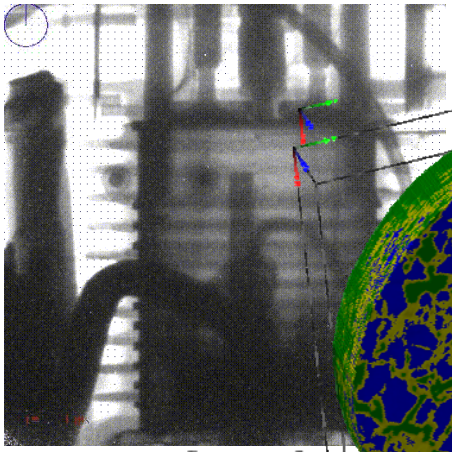




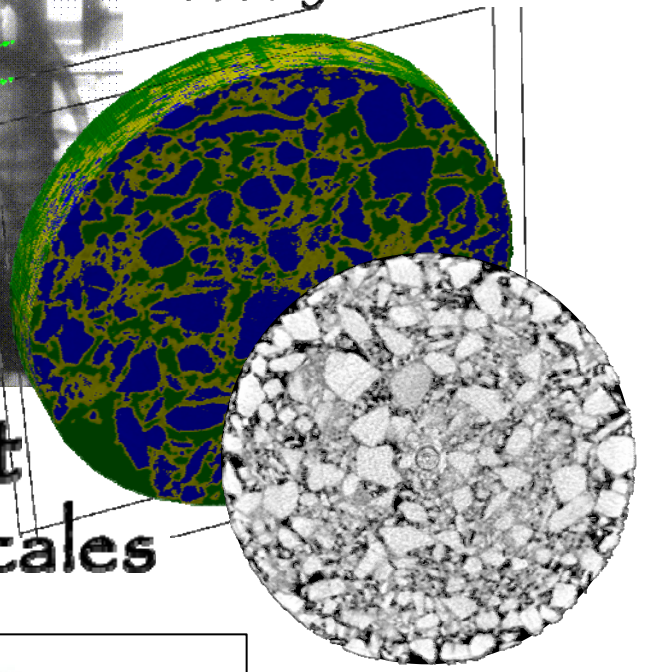
Molecular dynamics



Neutron scattering

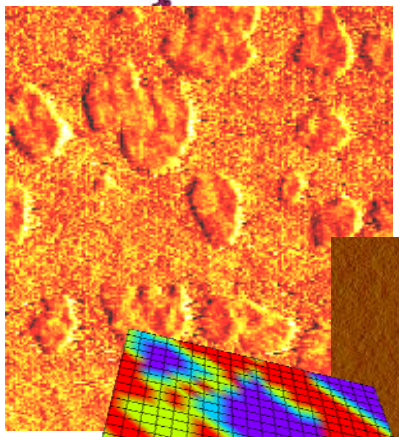


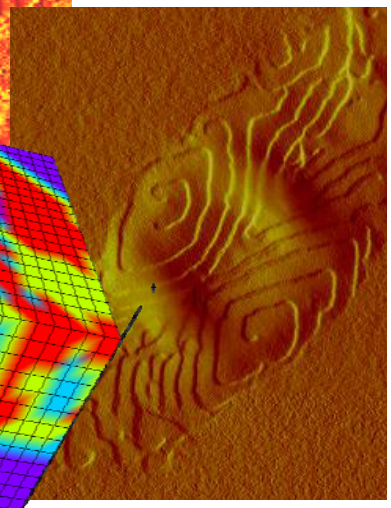
X-Ray scans

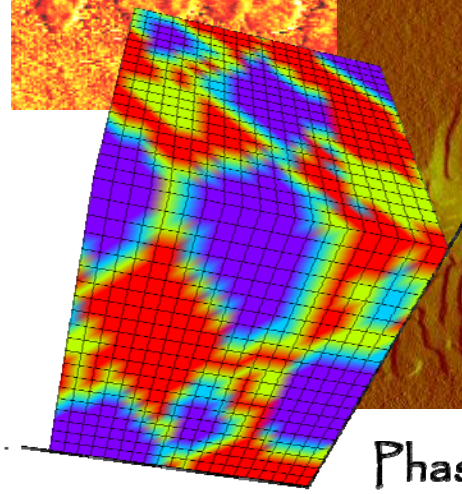


Healing of asphalt

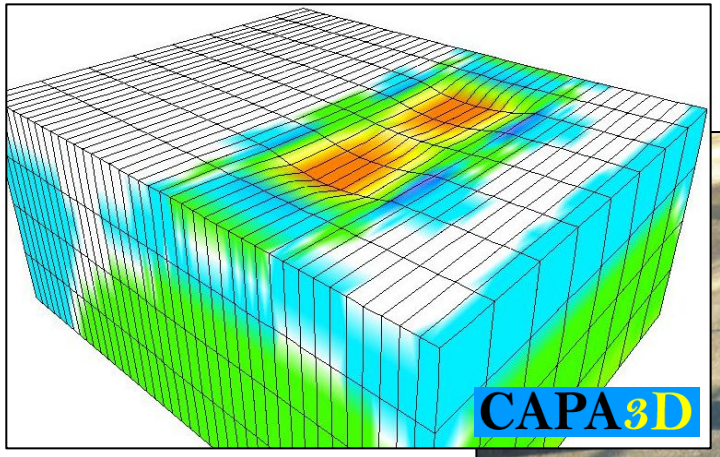
...research on all scales





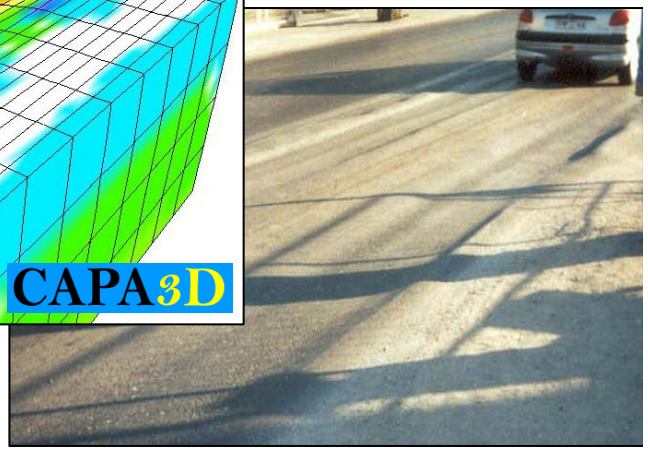


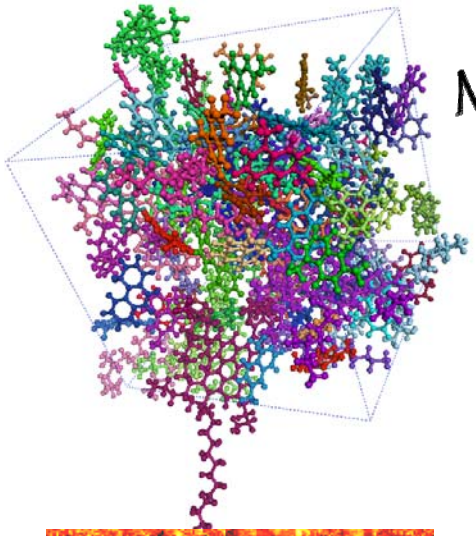
Phase behaviour



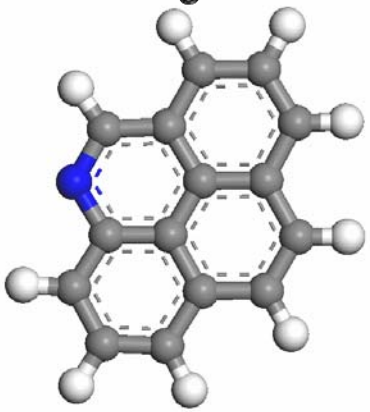
Pavement response

Finite Elements

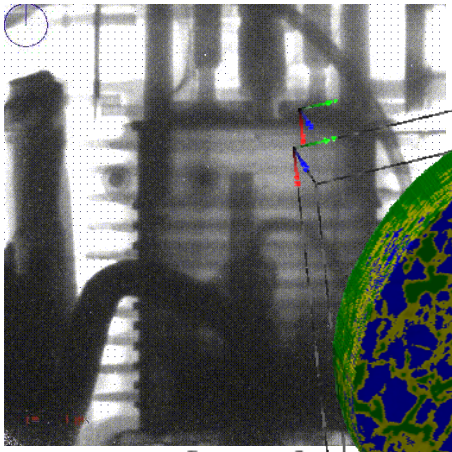




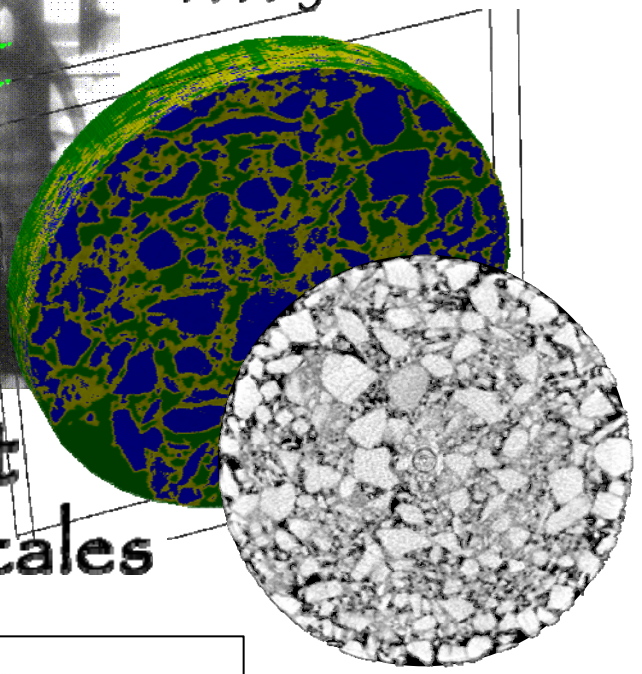
Molecular dynamics



Neutron scattering

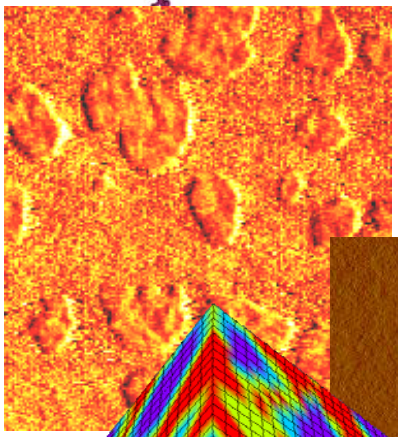


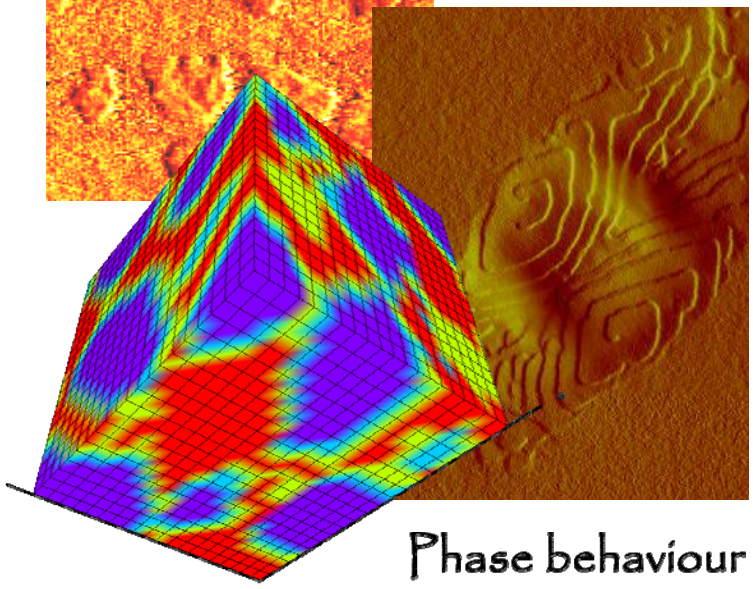
X-Ray scans



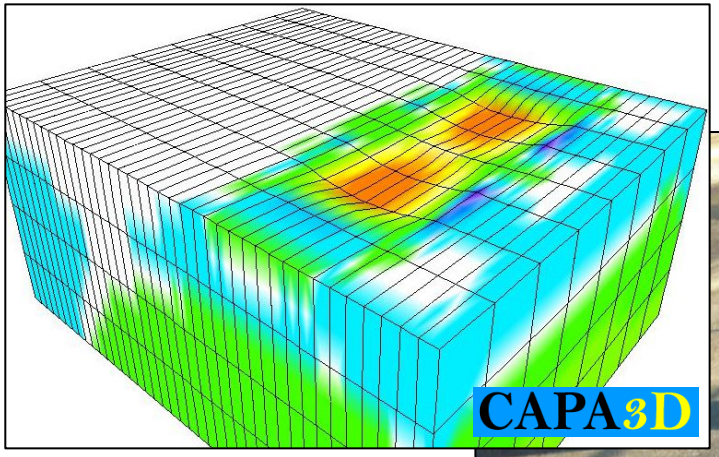
Healing of asphalt

...research on all scales



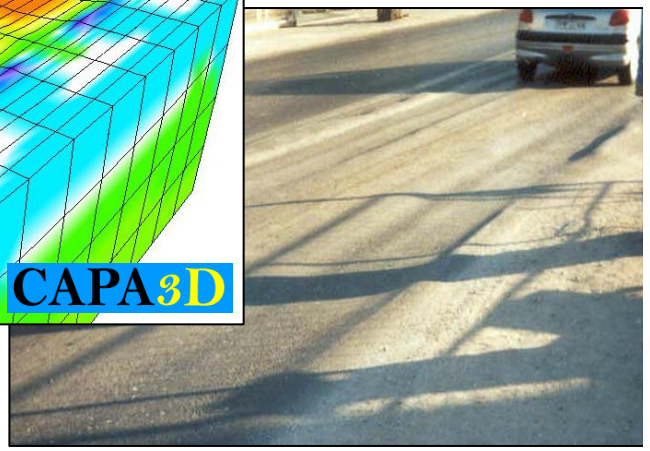


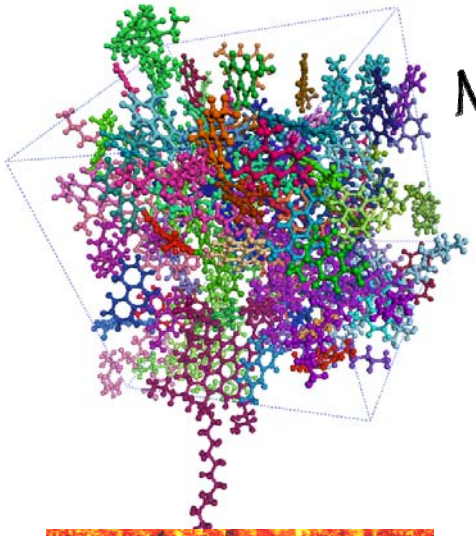
Phase behaviour



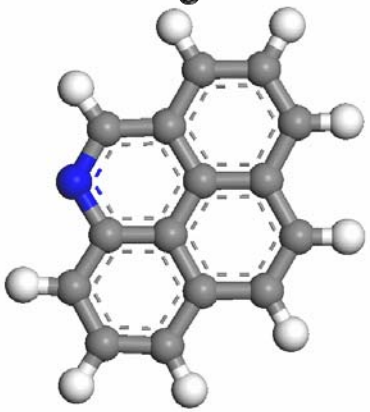
Pavement response

Finite Elements

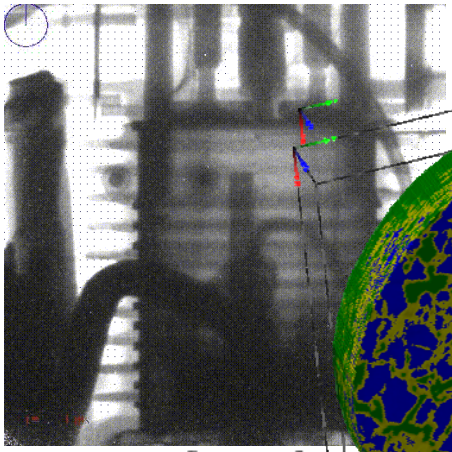




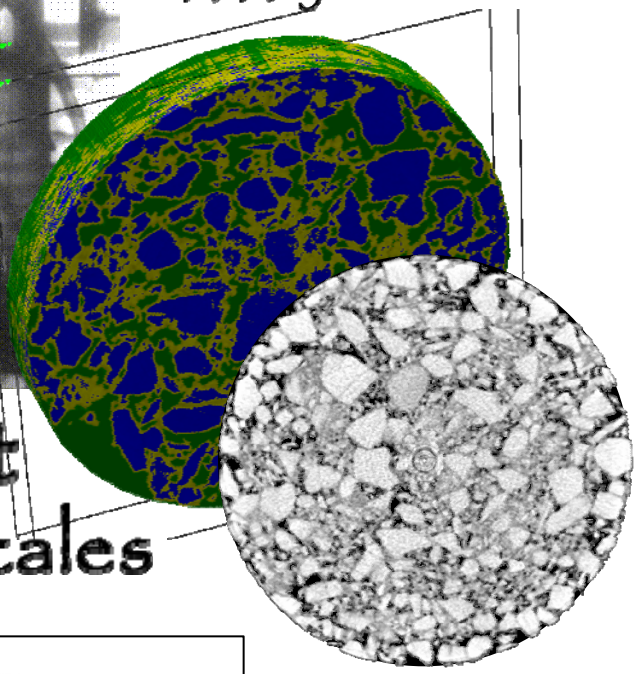
Molecular dynamics



Neutron scattering

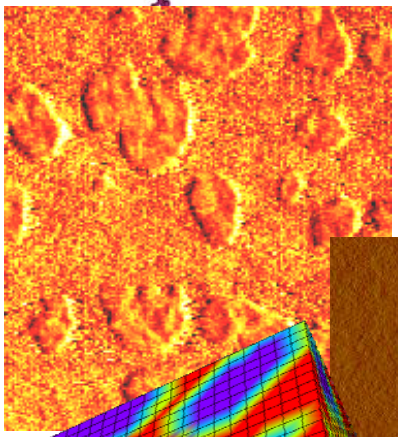


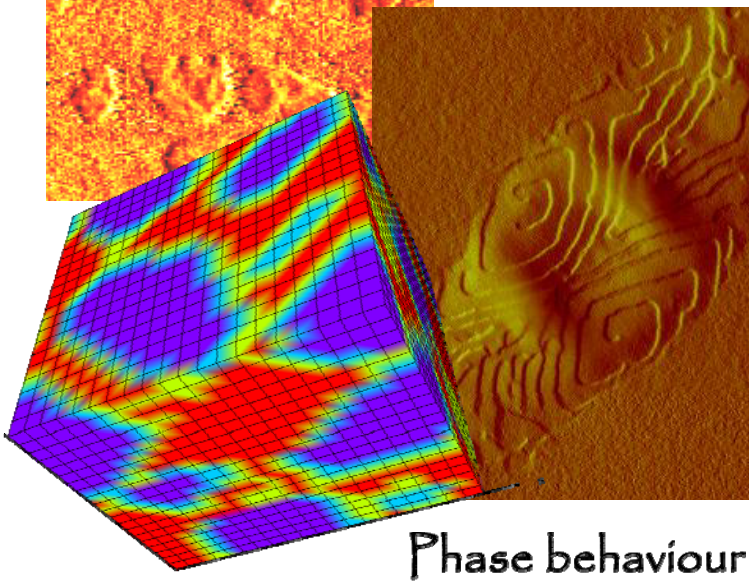
X-Ray scans



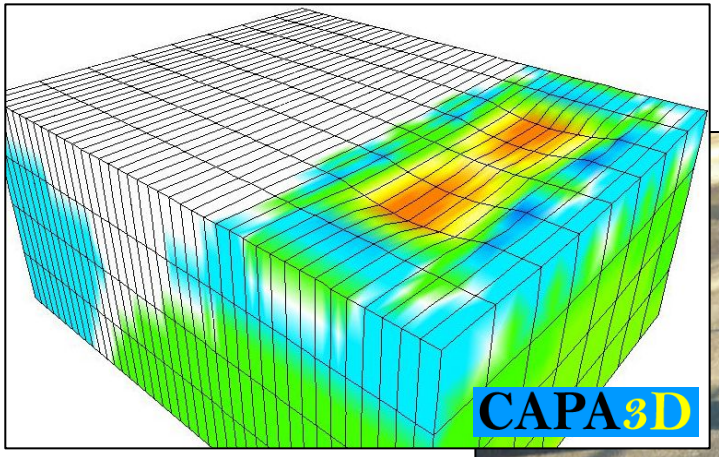
Healing of asphalt

...research on all scales



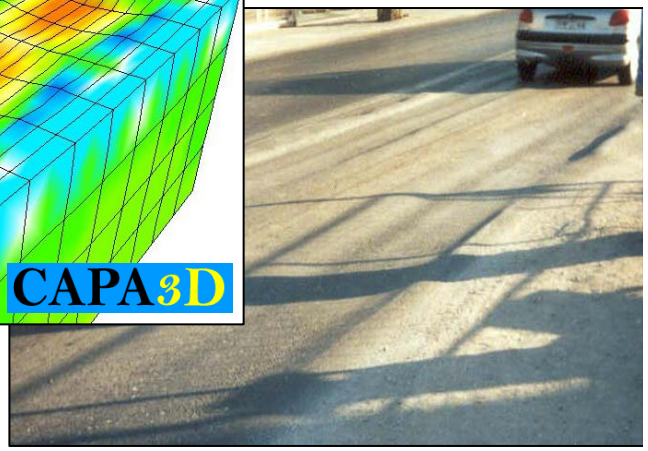


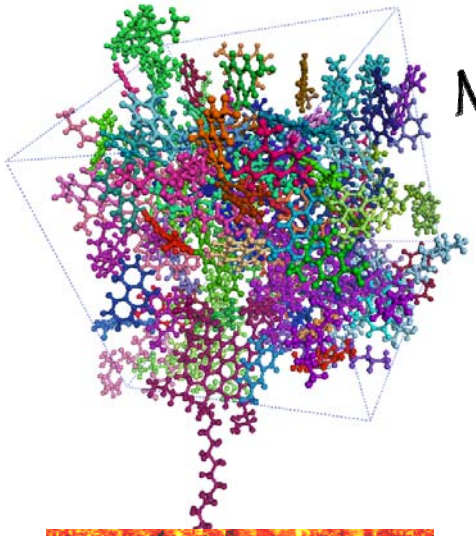
Phase behaviour



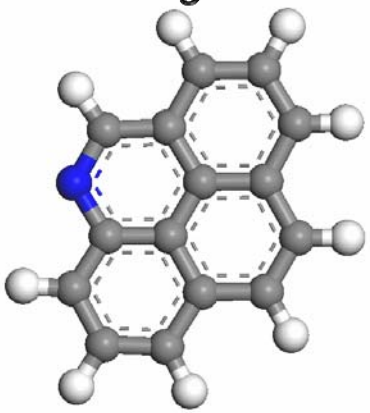
Pavement response

Finite Elements

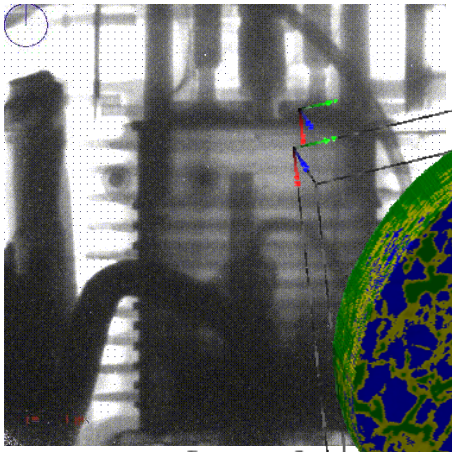




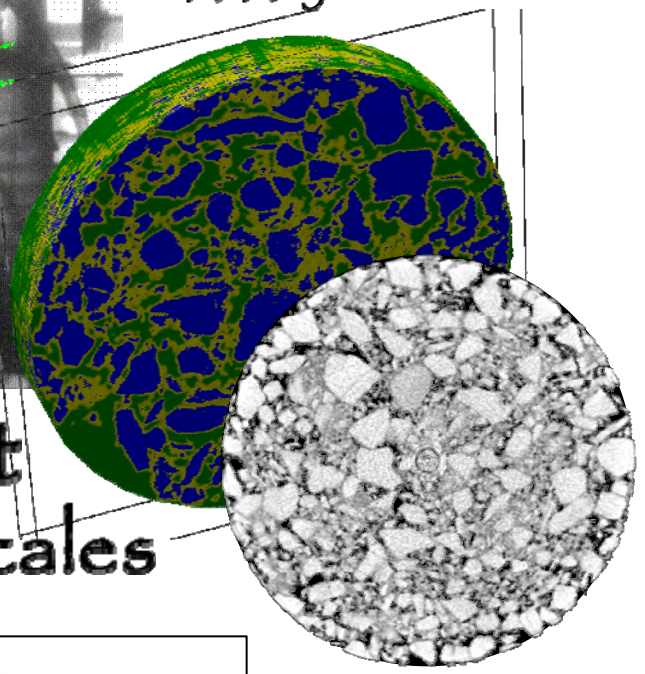
Molecular dynamics



Neutron scattering

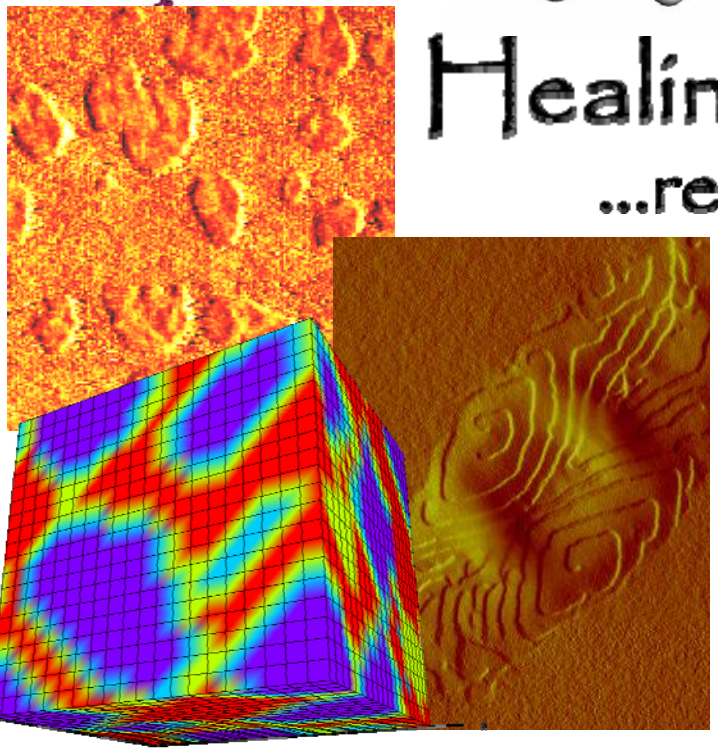


X-Ray scans

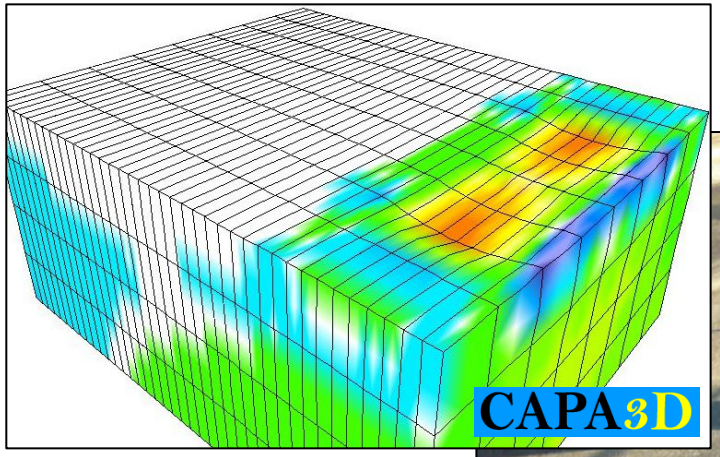


Healing of asphalt

...research on all scales

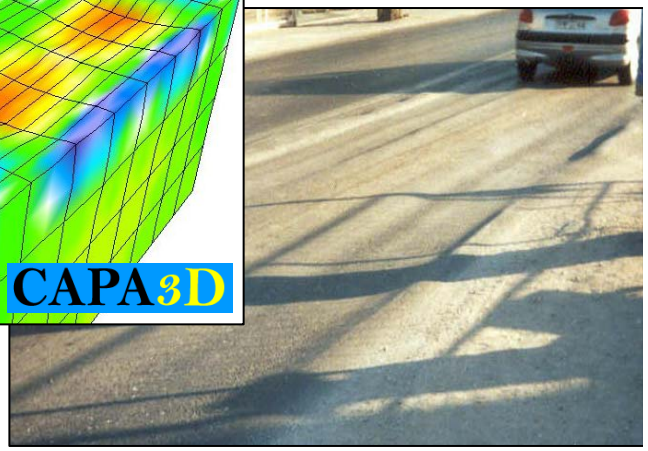


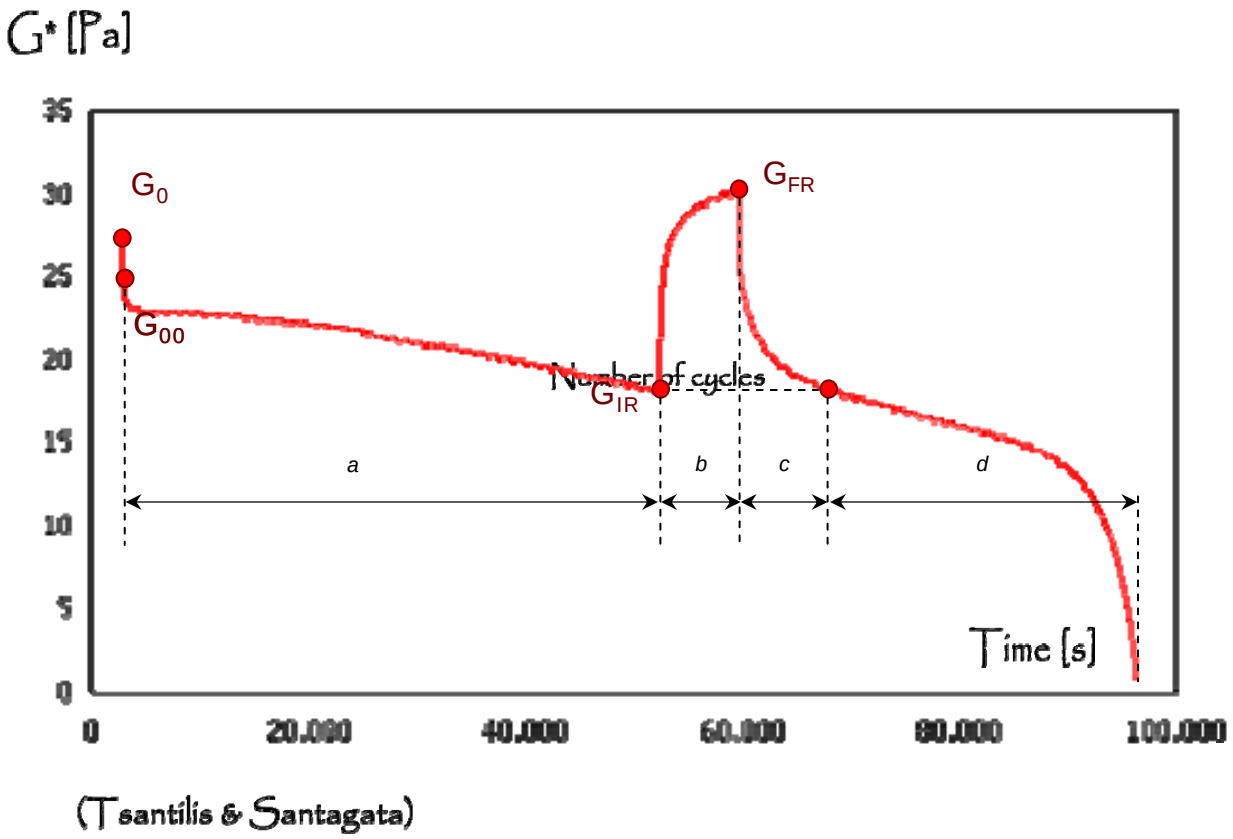
Phase behaviour



Pavement response

Finite Elements





(Tsantilis & Santagata)

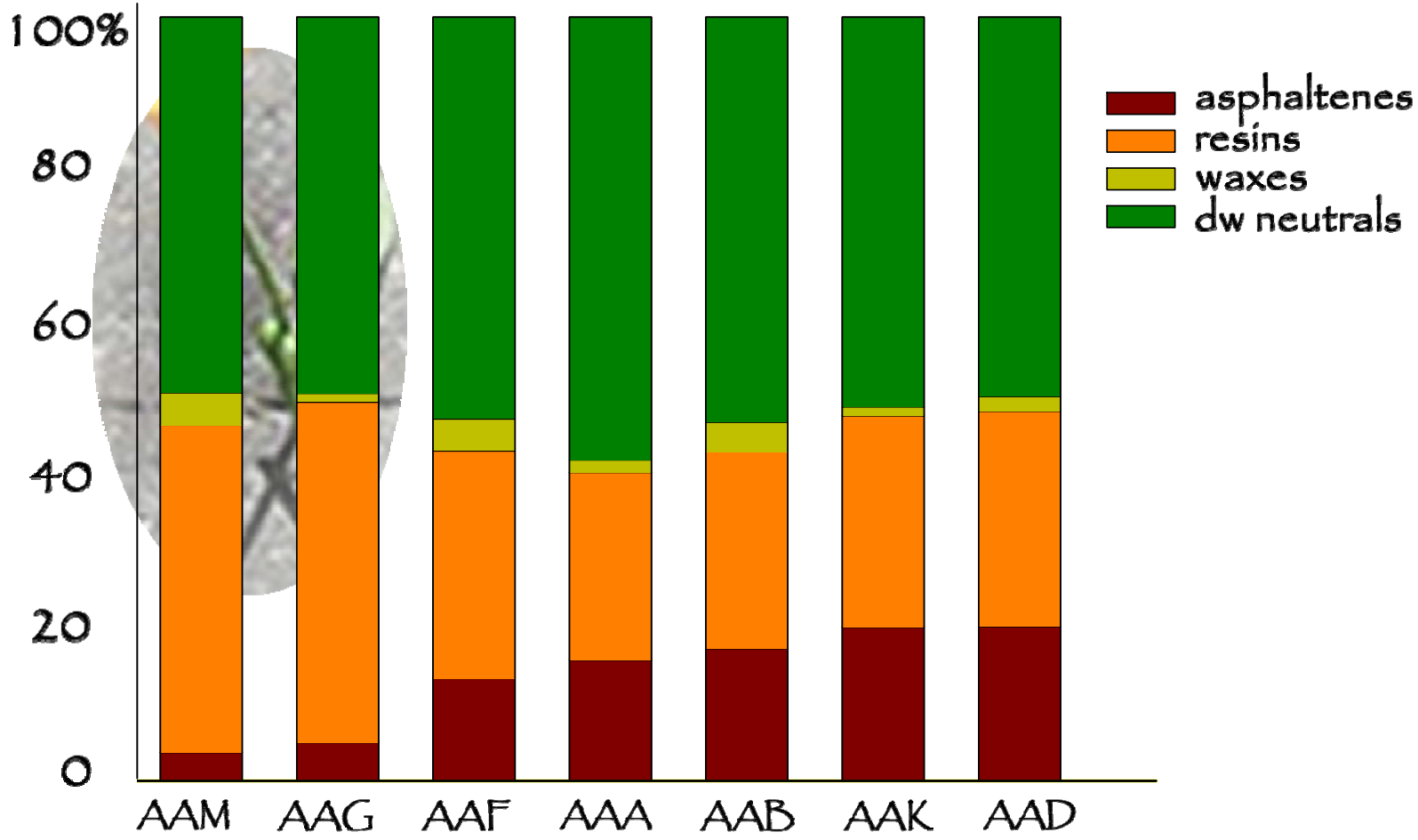
Bitumen

IS

Self Healing

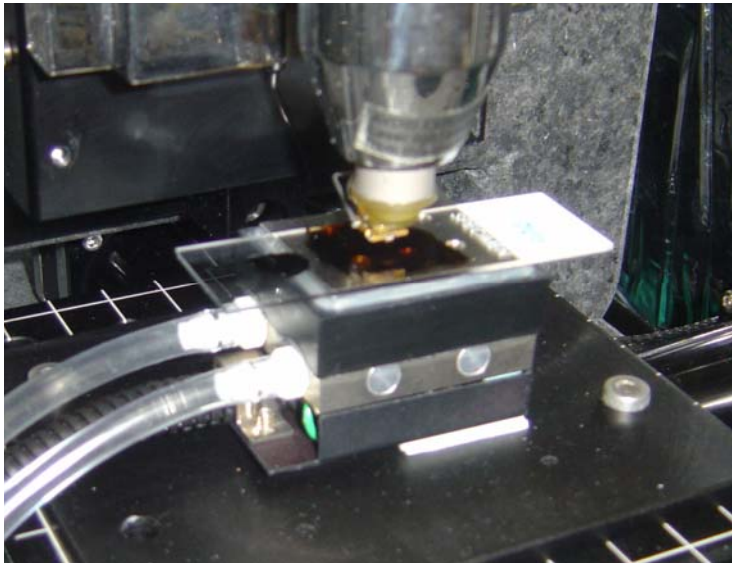
- WHY does it occur?

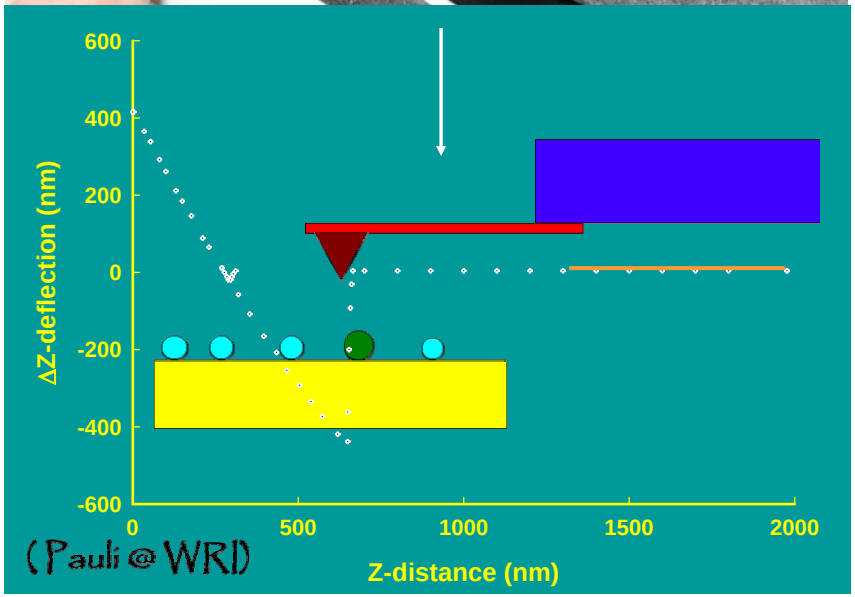
Bitumen



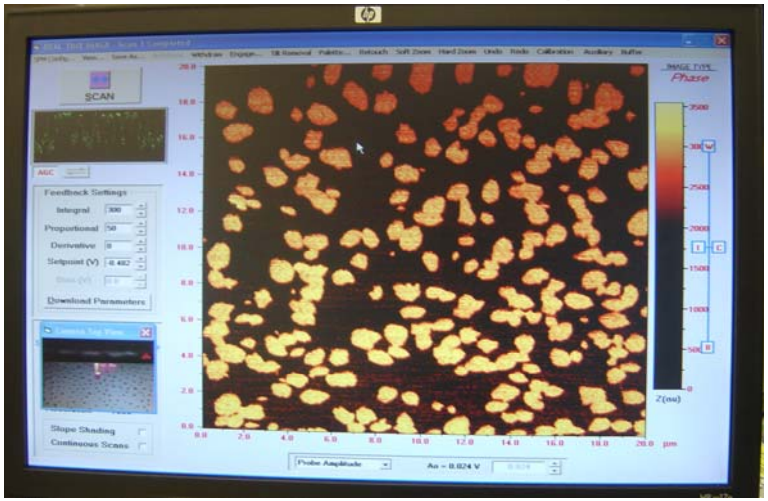
(Pauli @ WRI)

Bitumen under the AFM

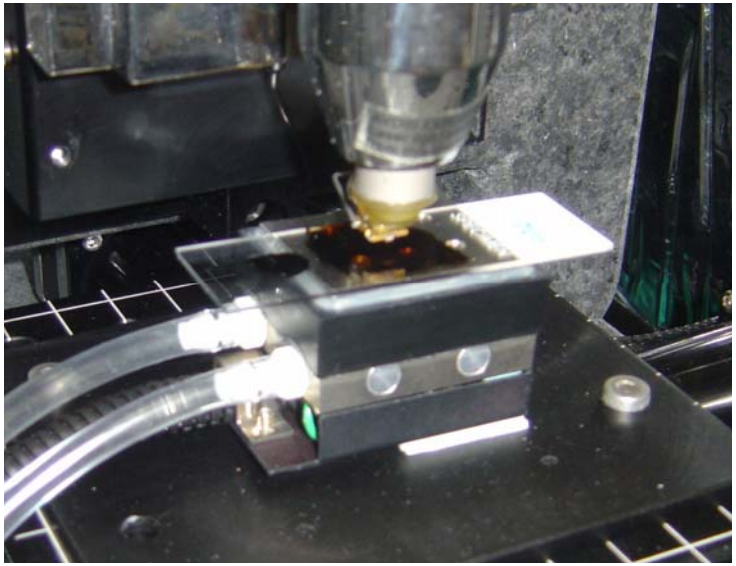


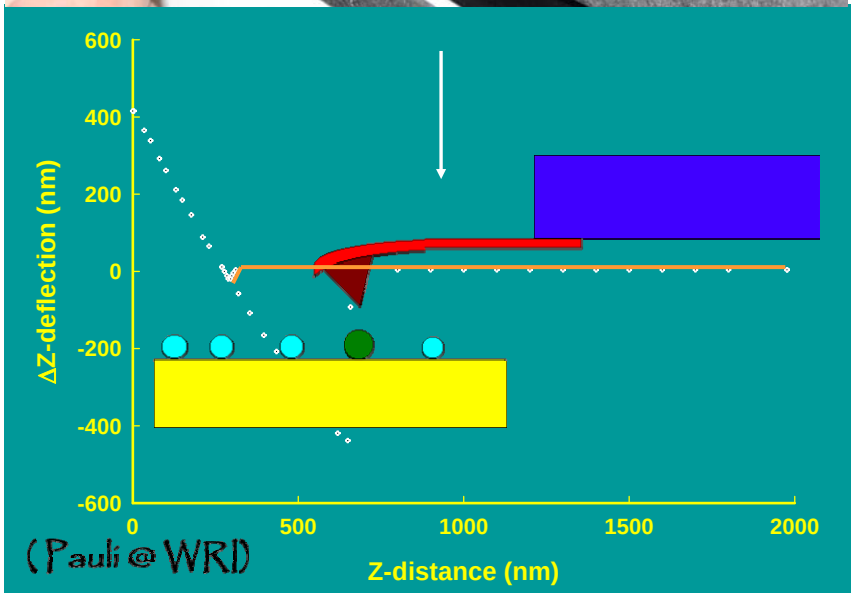


(phase image)

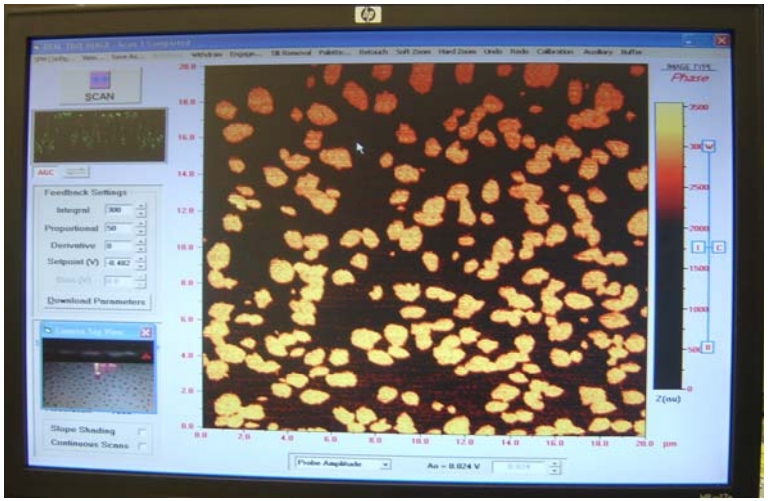


Bitumen under the AFM





(phase image)



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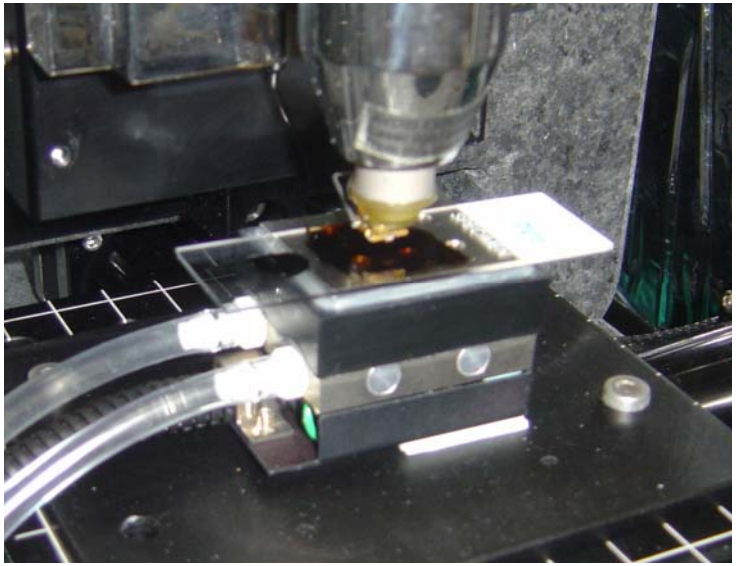

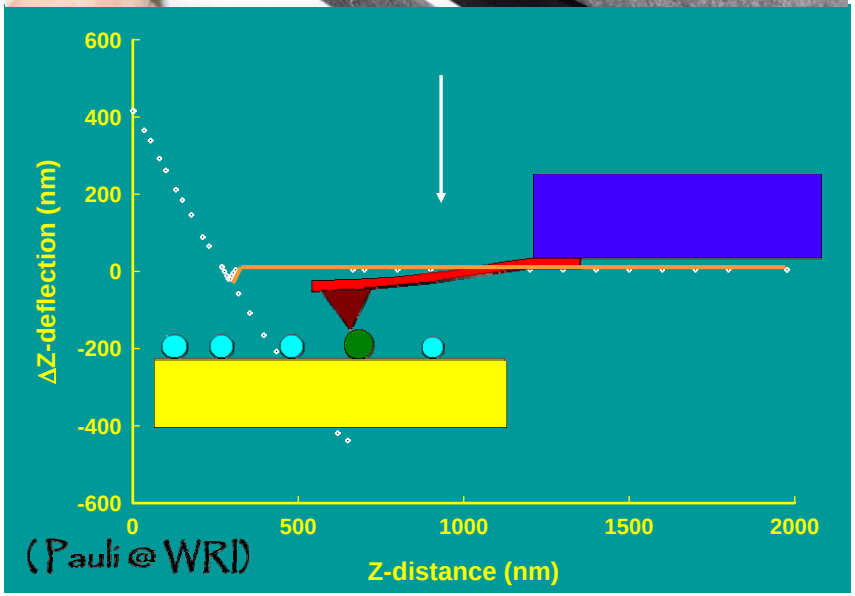

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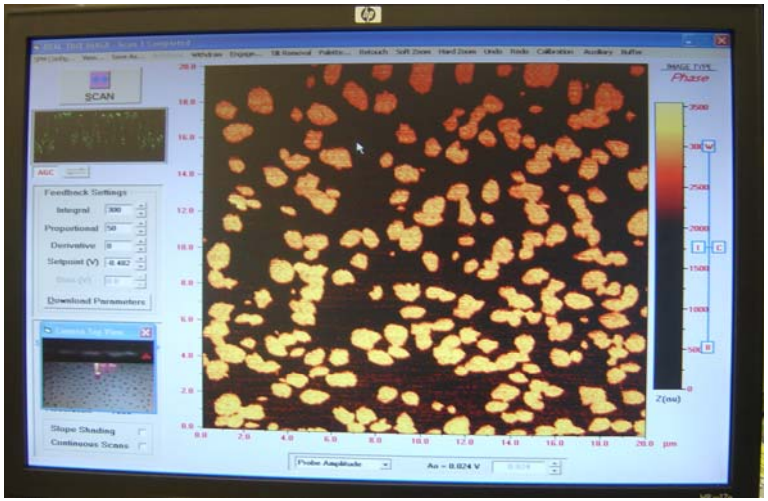

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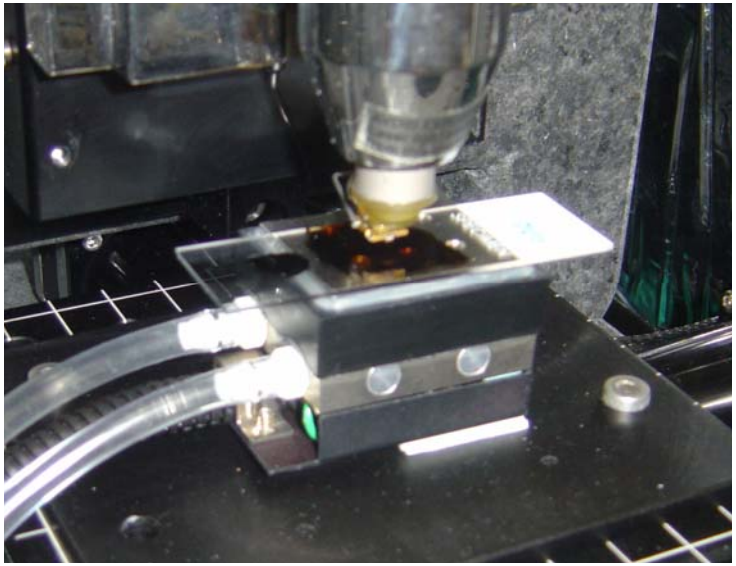

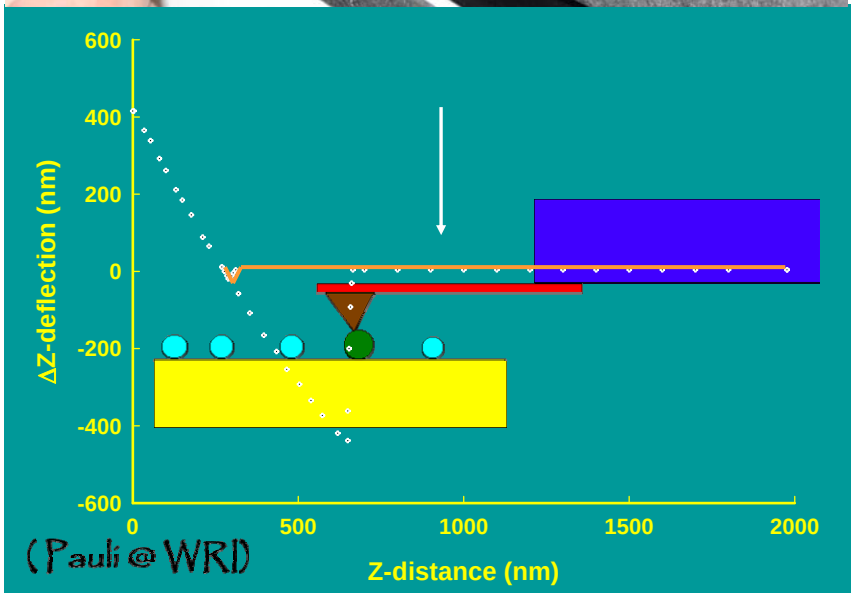

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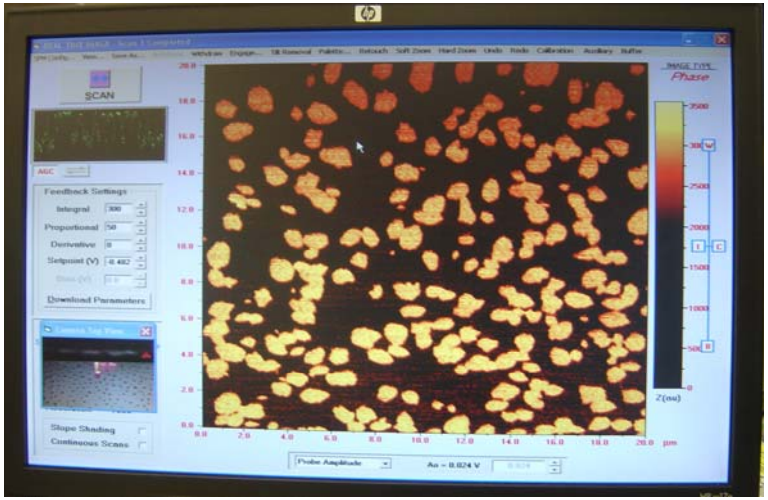

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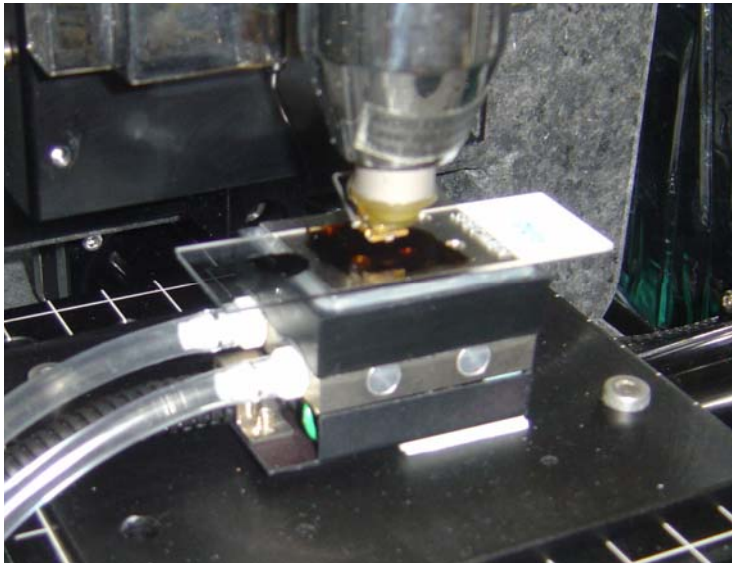

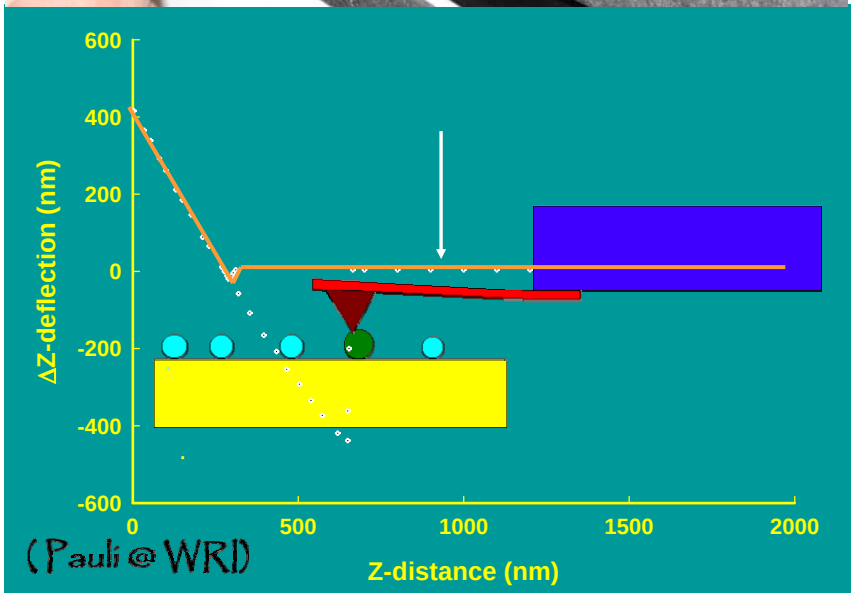

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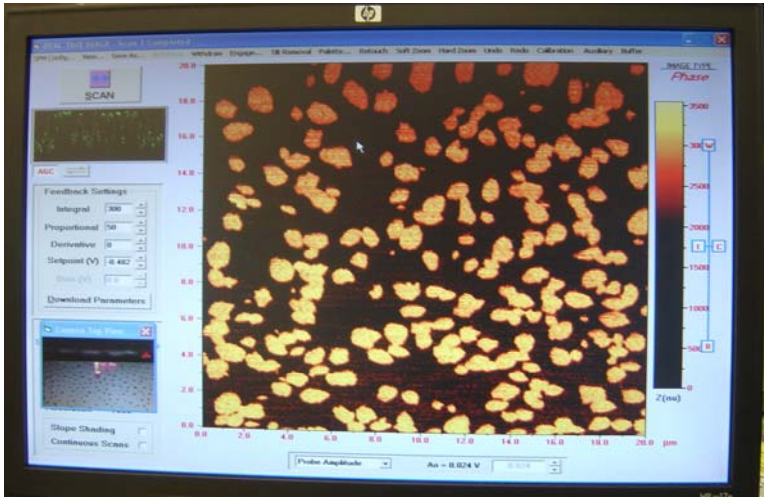

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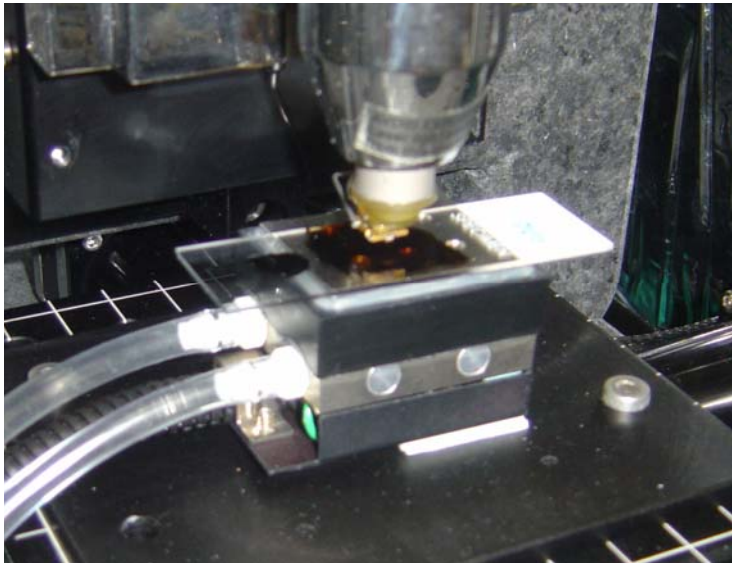

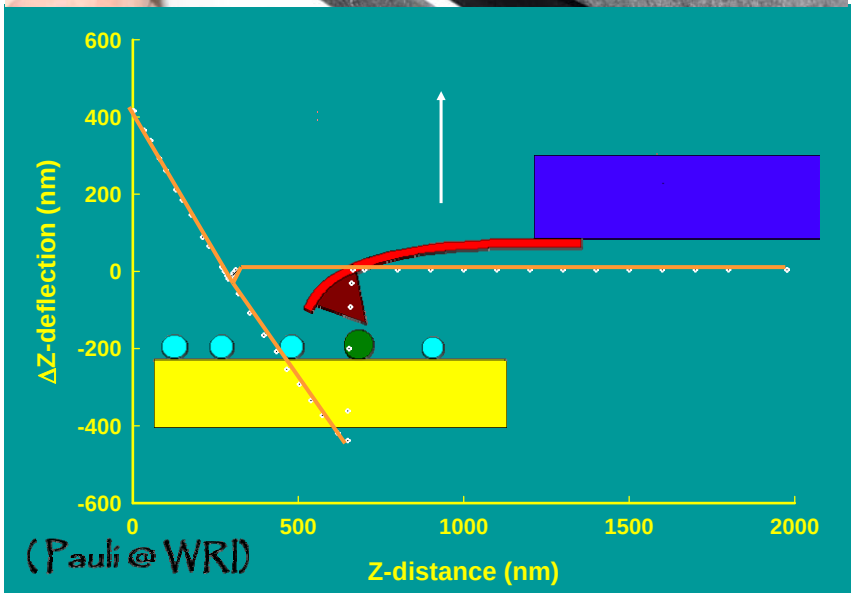

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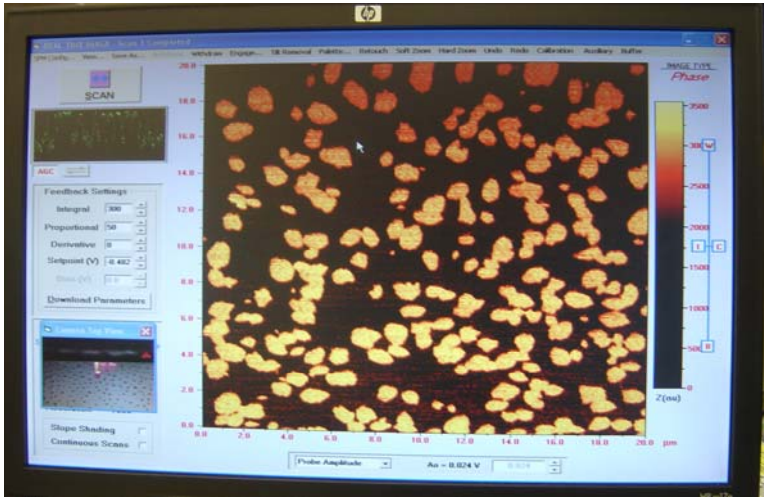

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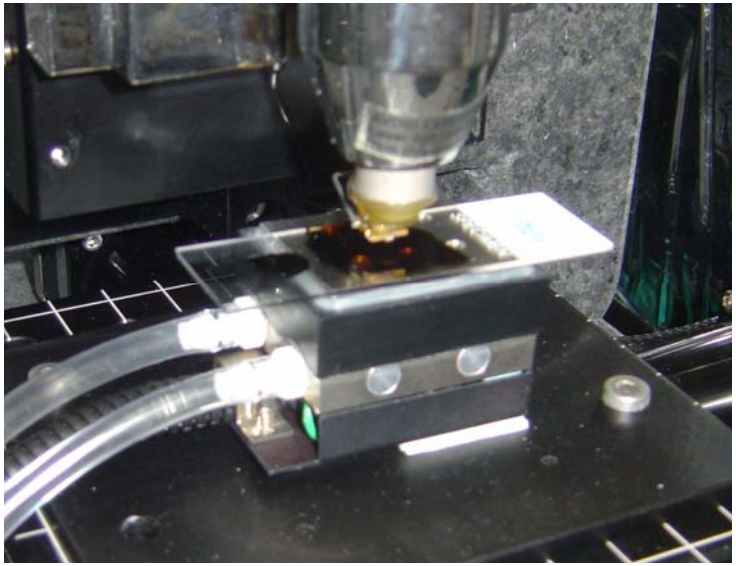

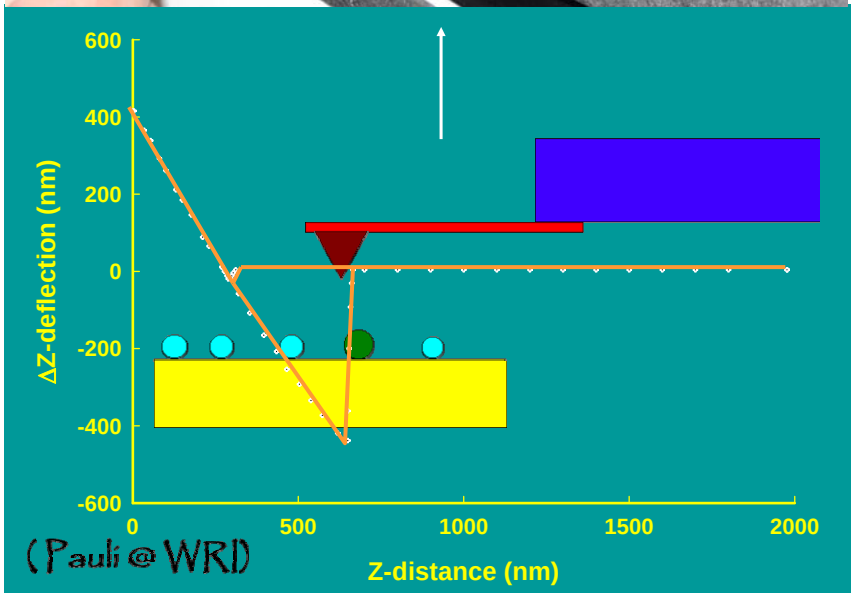

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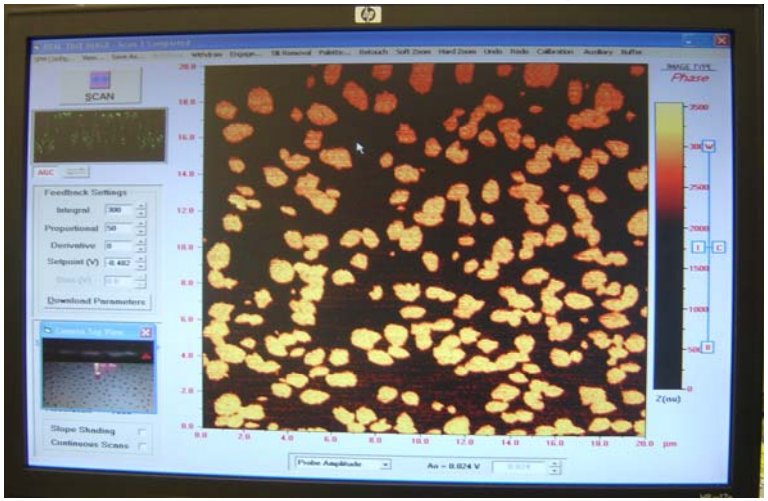

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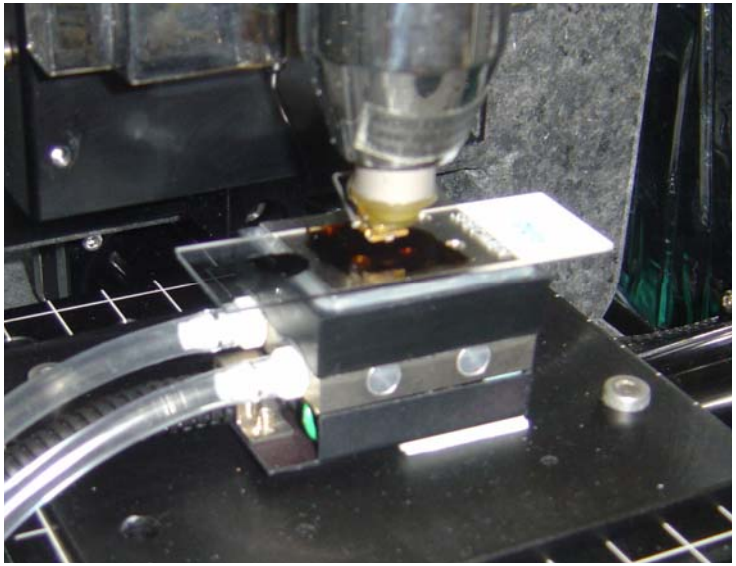

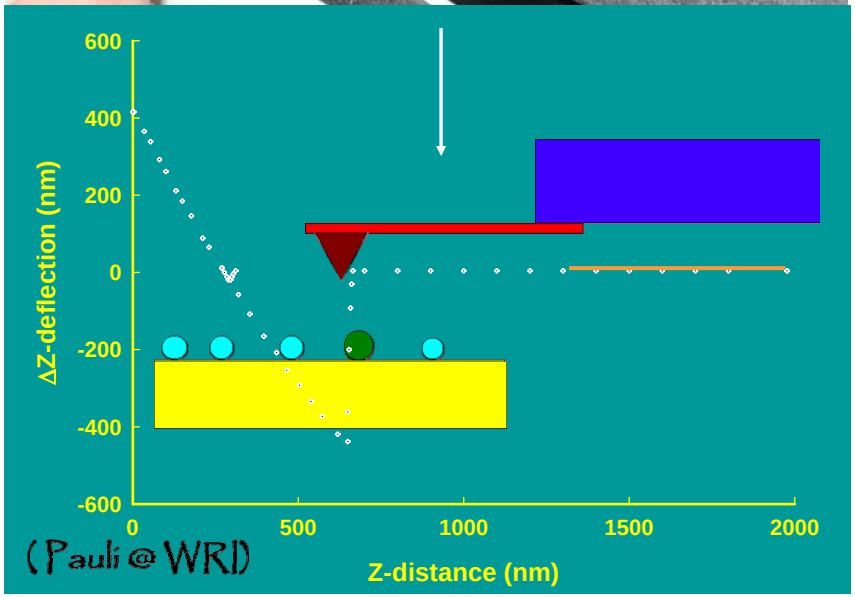

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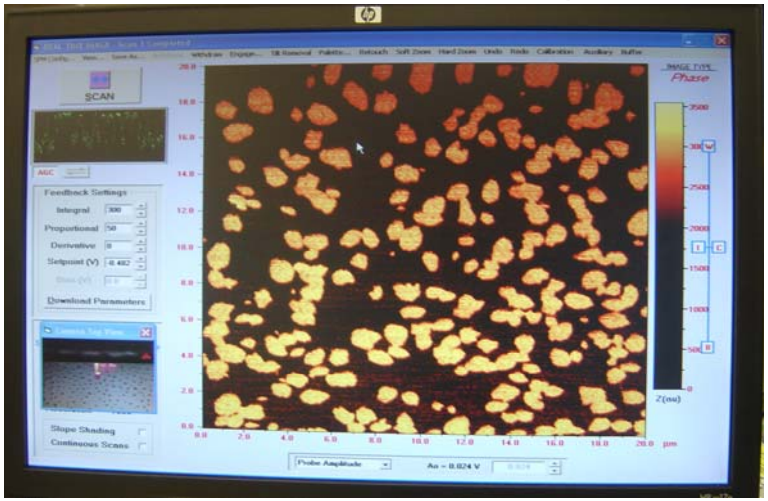

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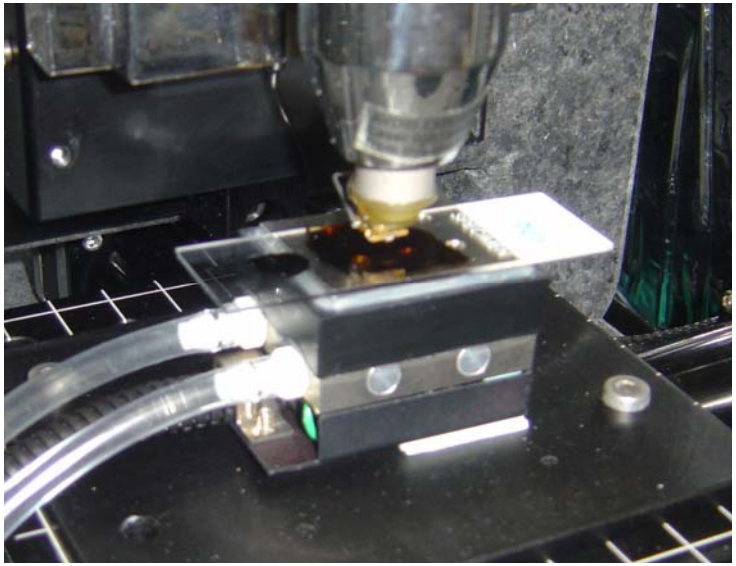

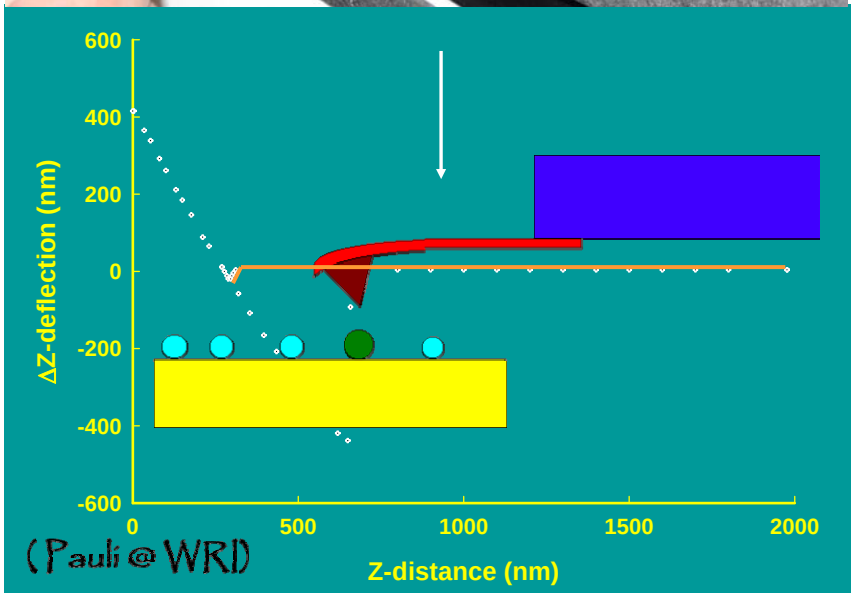

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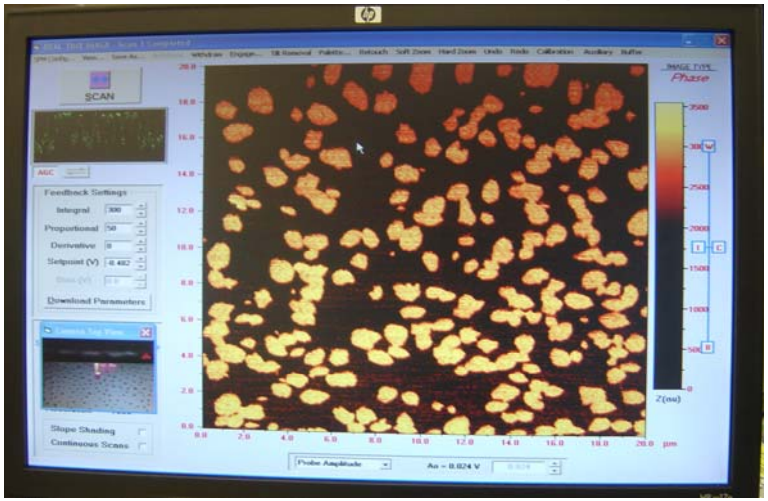

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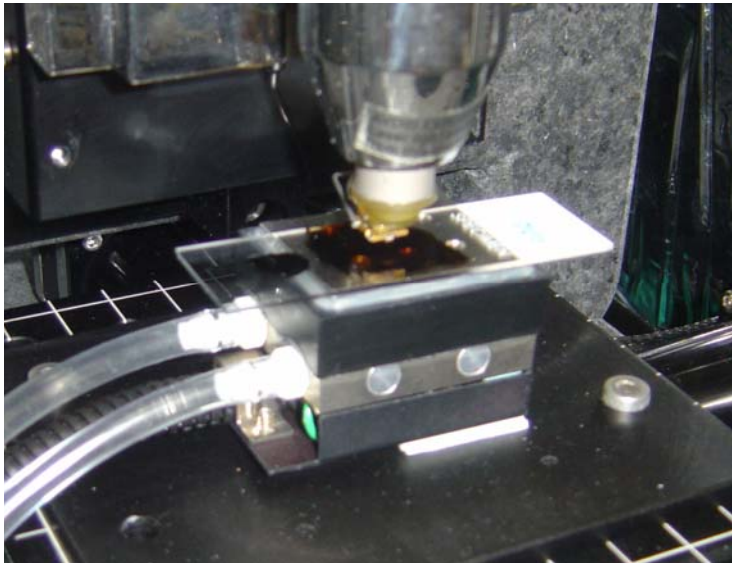

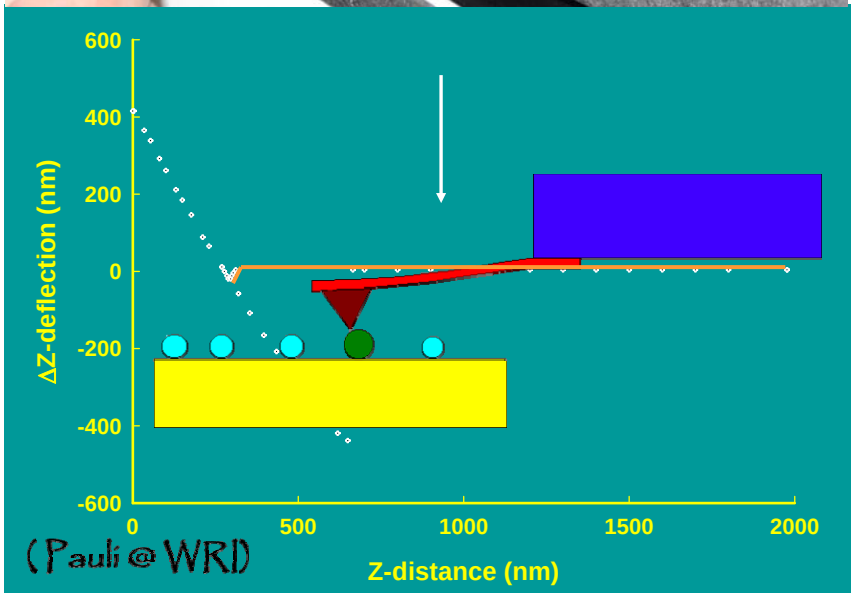

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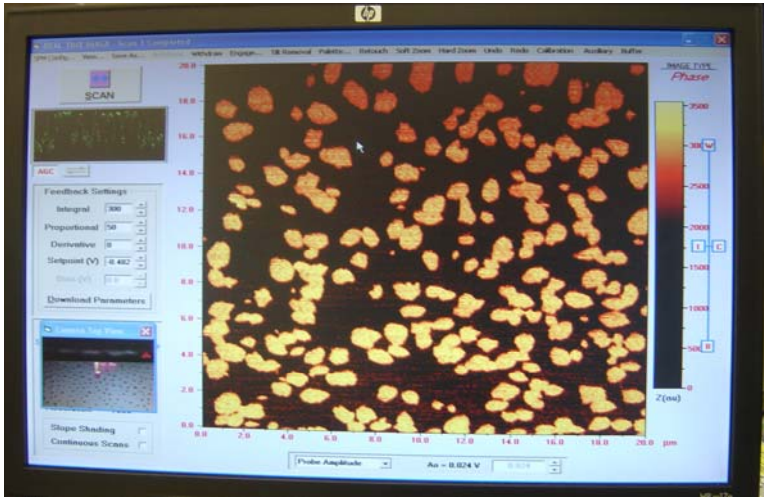

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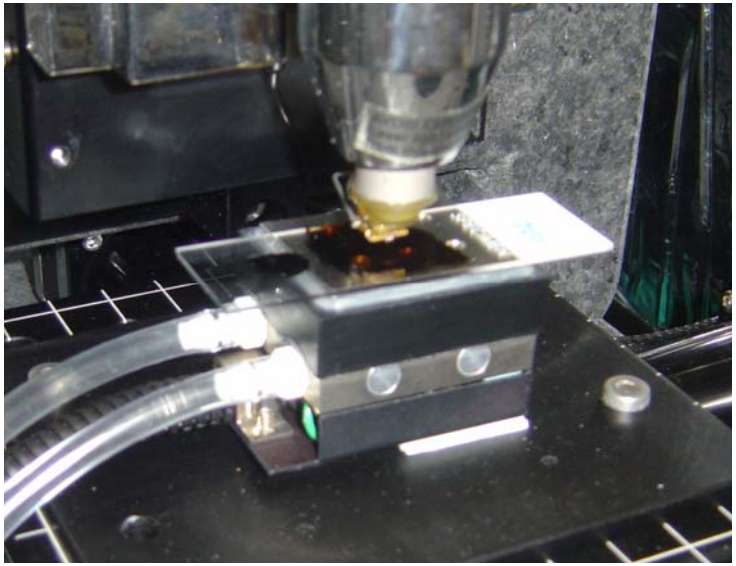

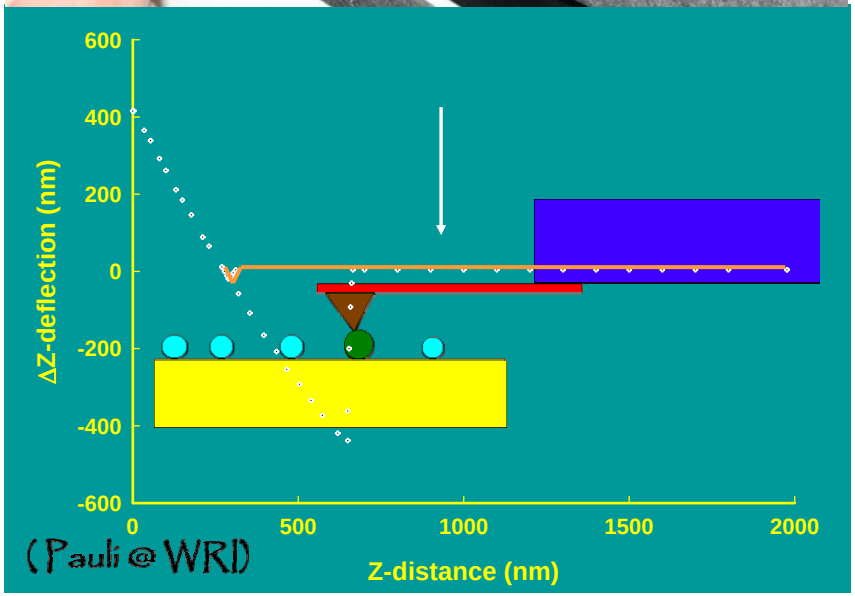

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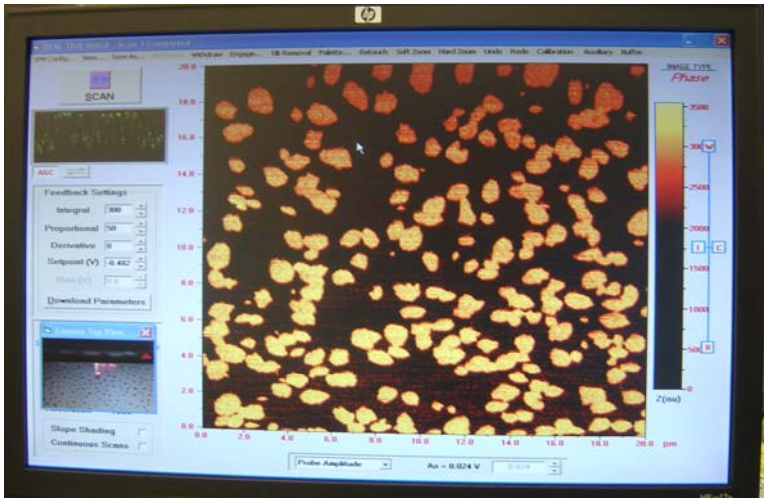

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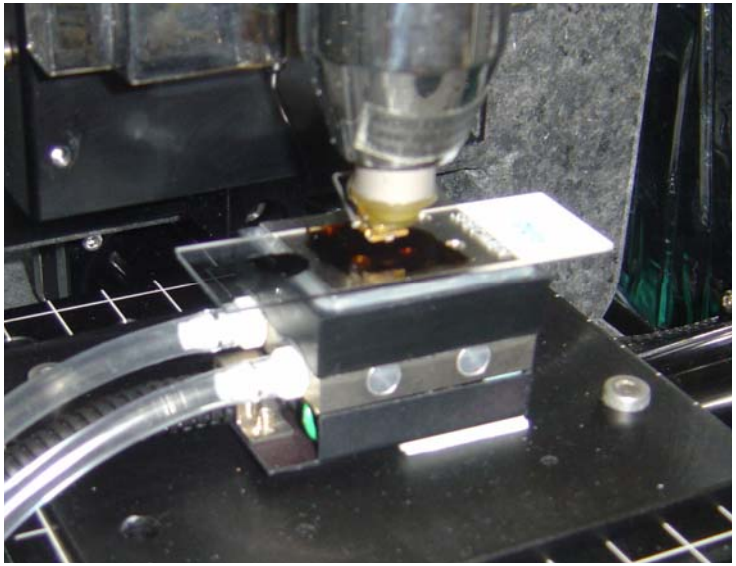

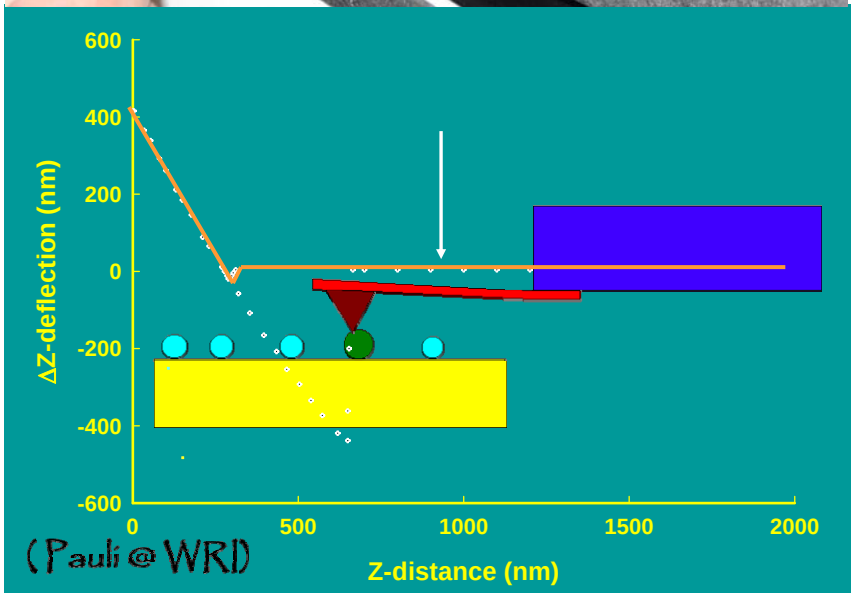

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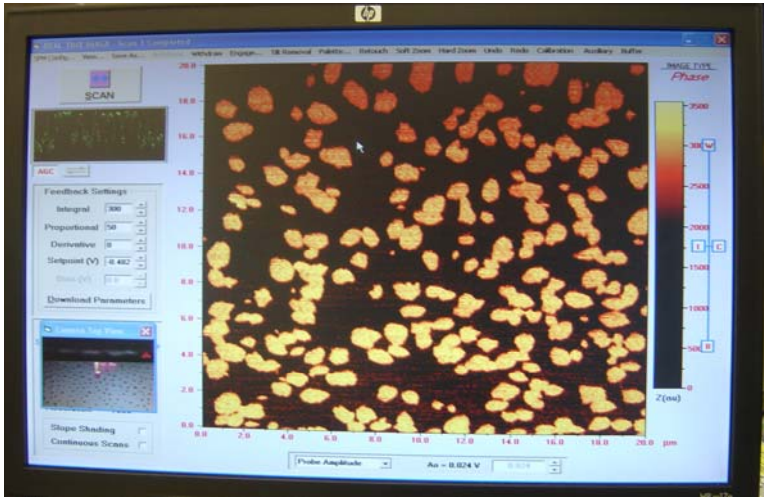

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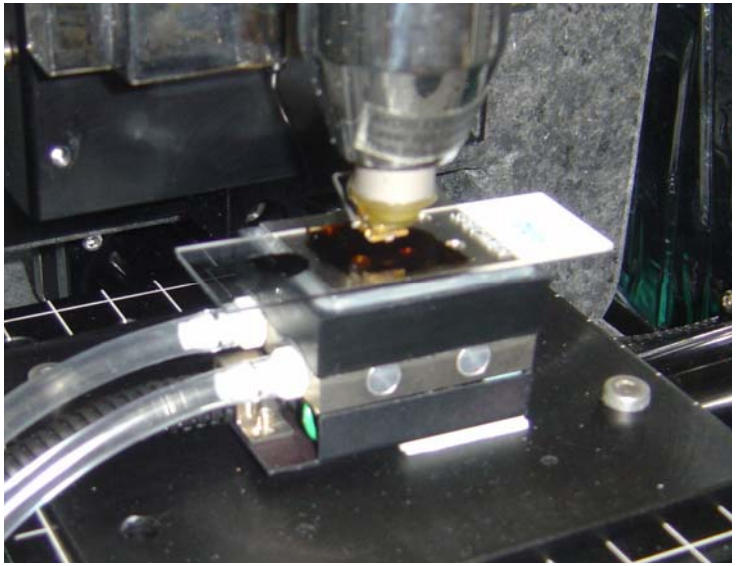

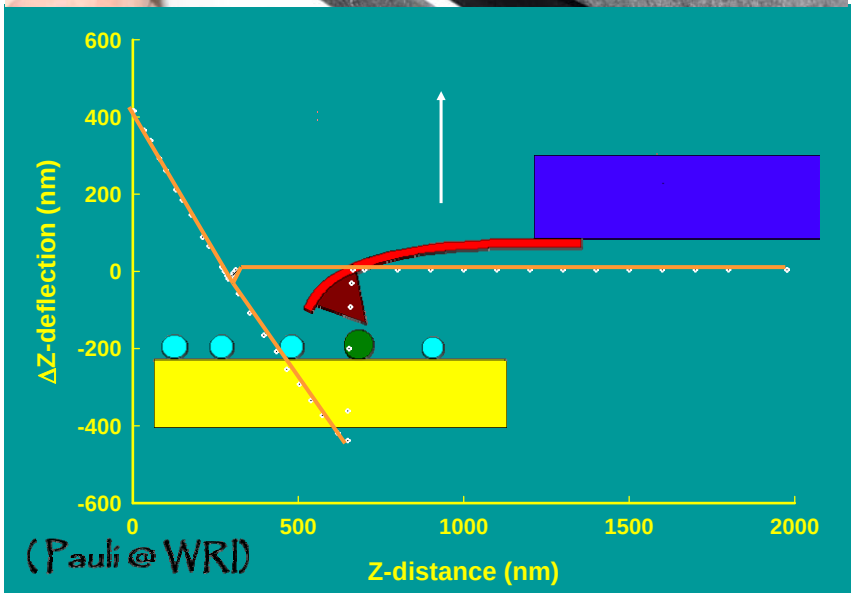

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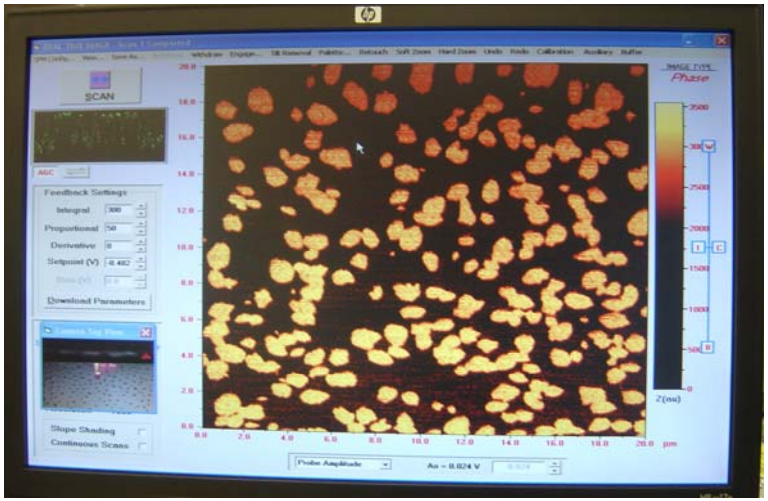

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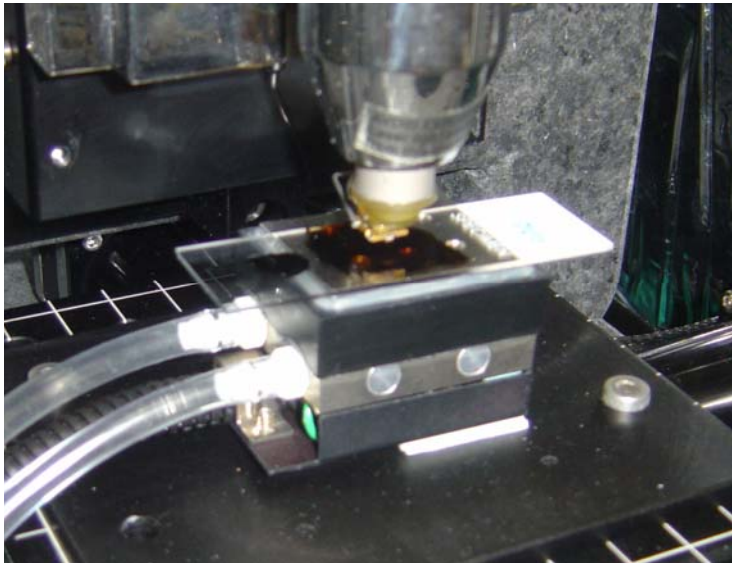

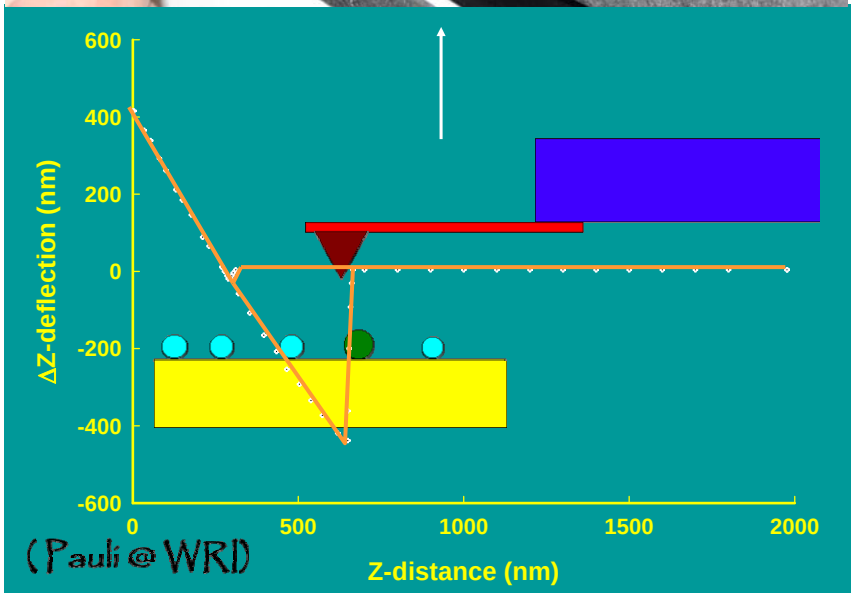

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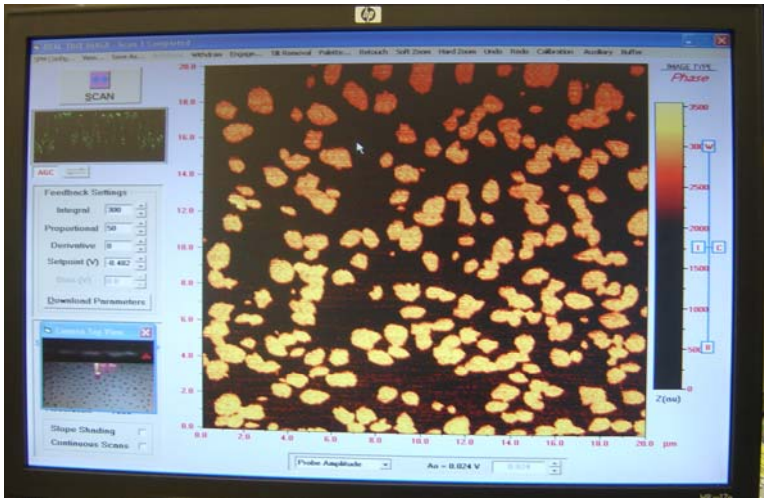

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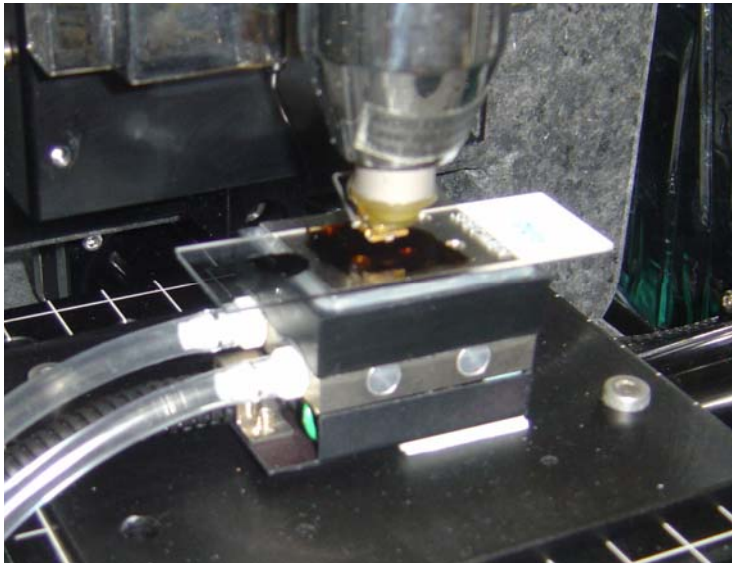

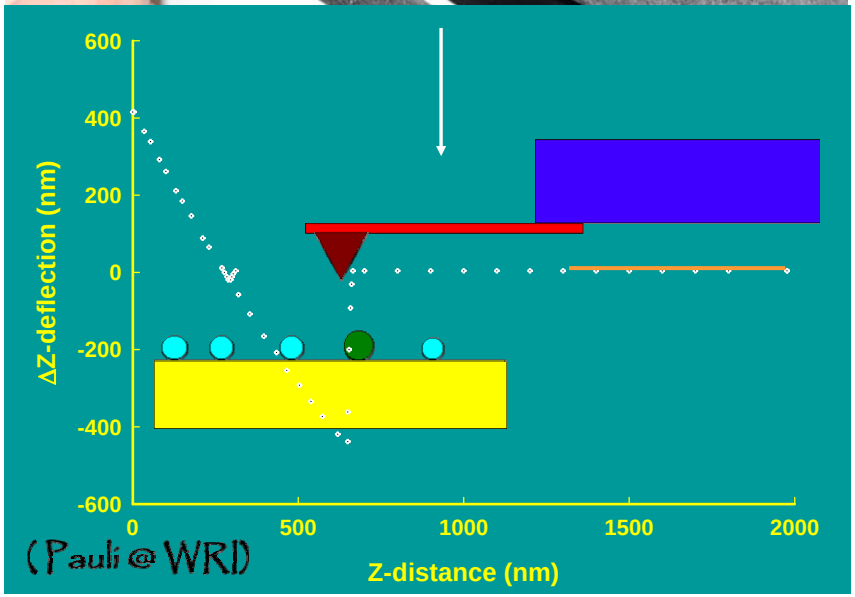

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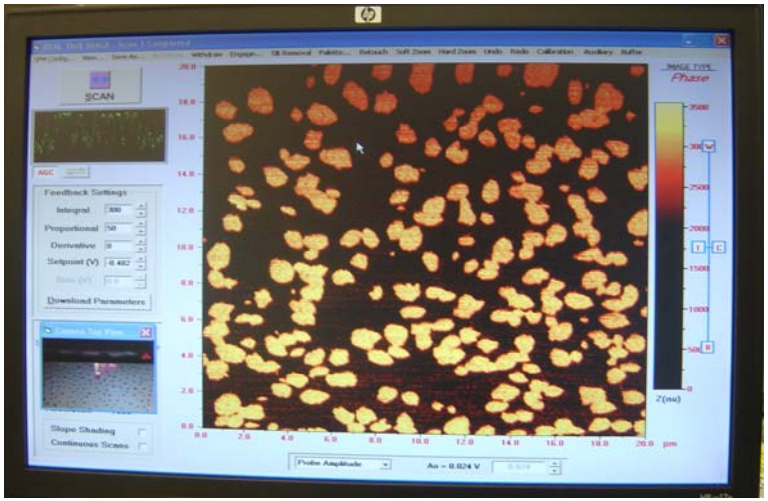

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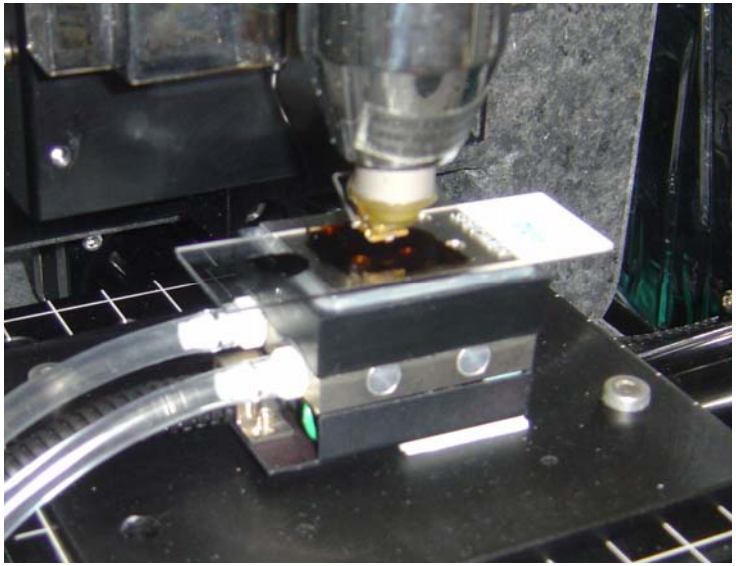

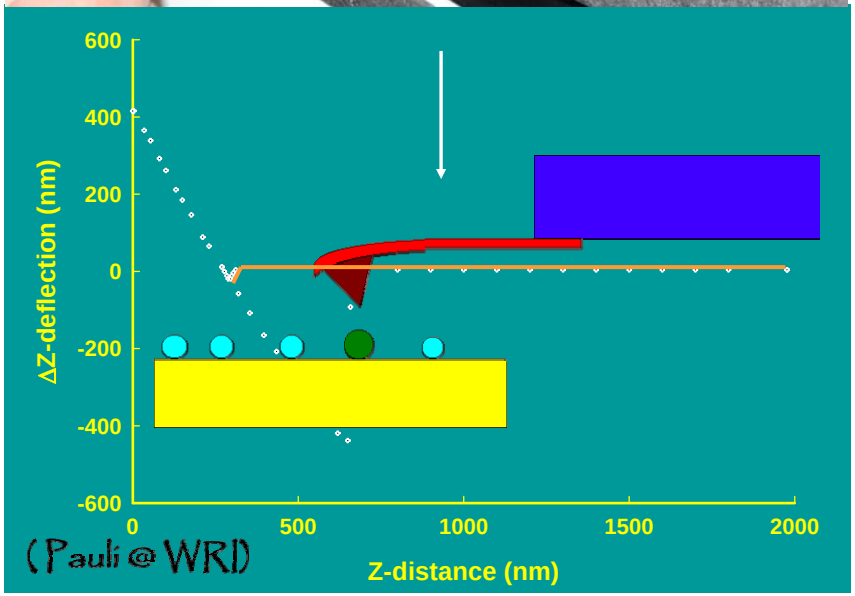

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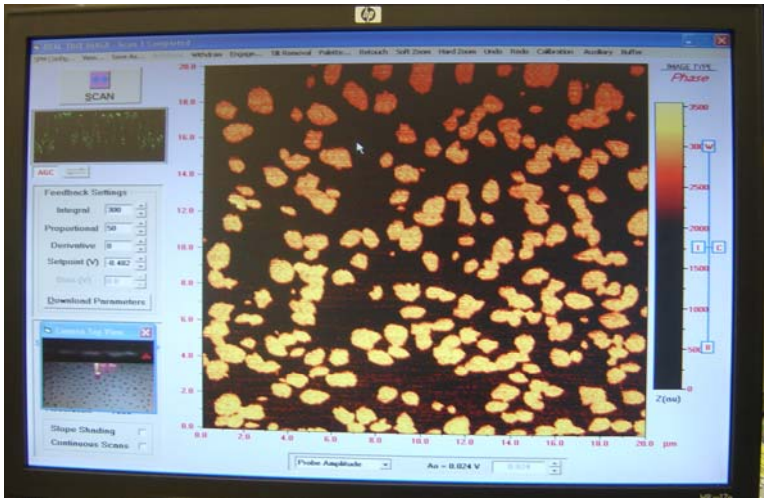

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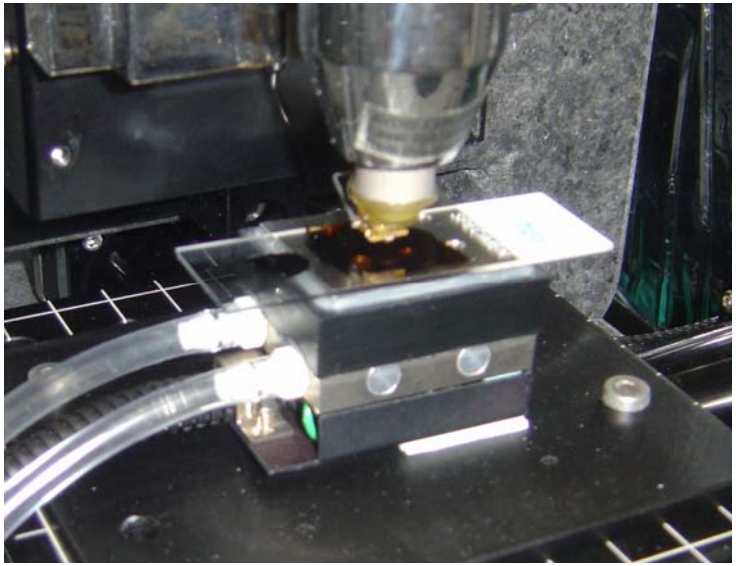

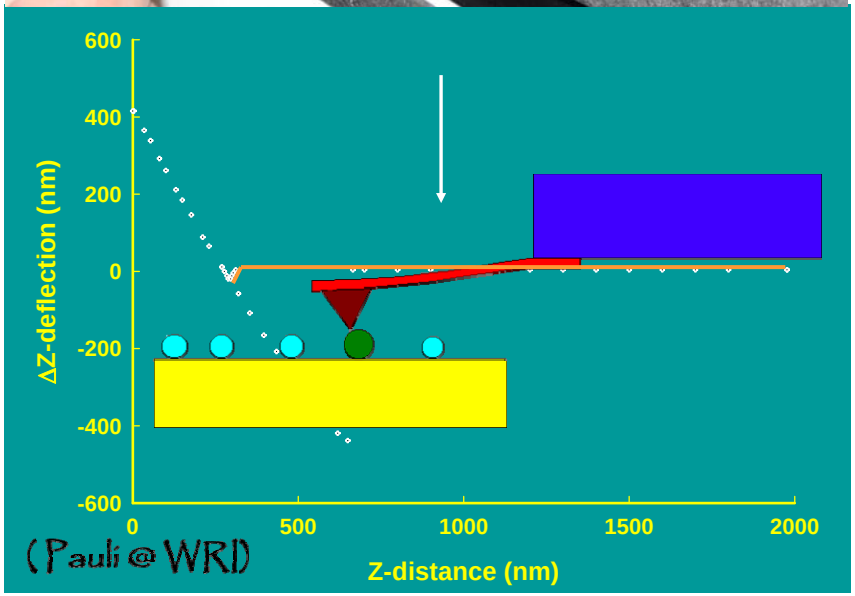

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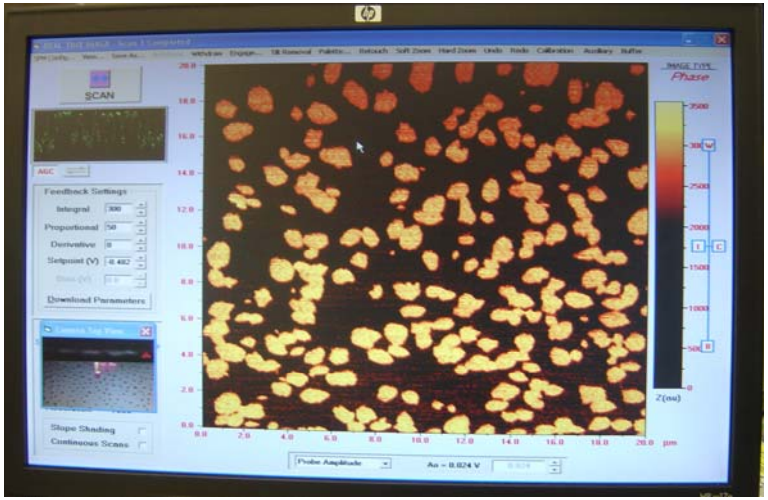

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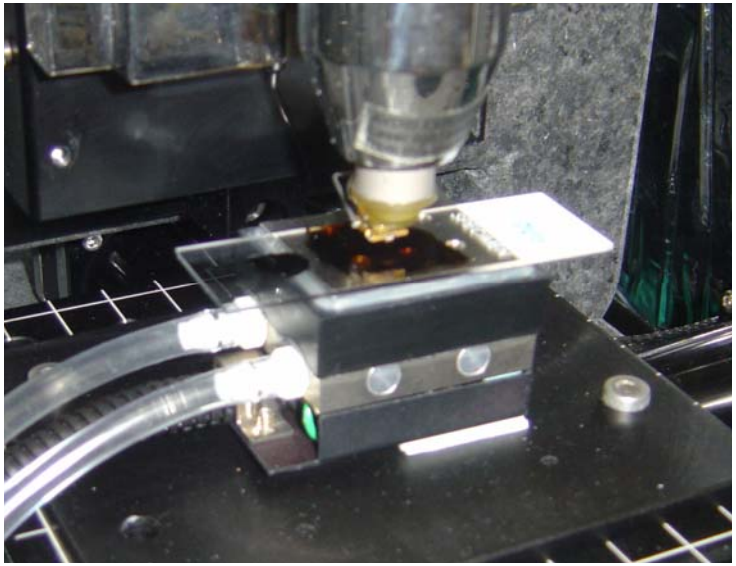

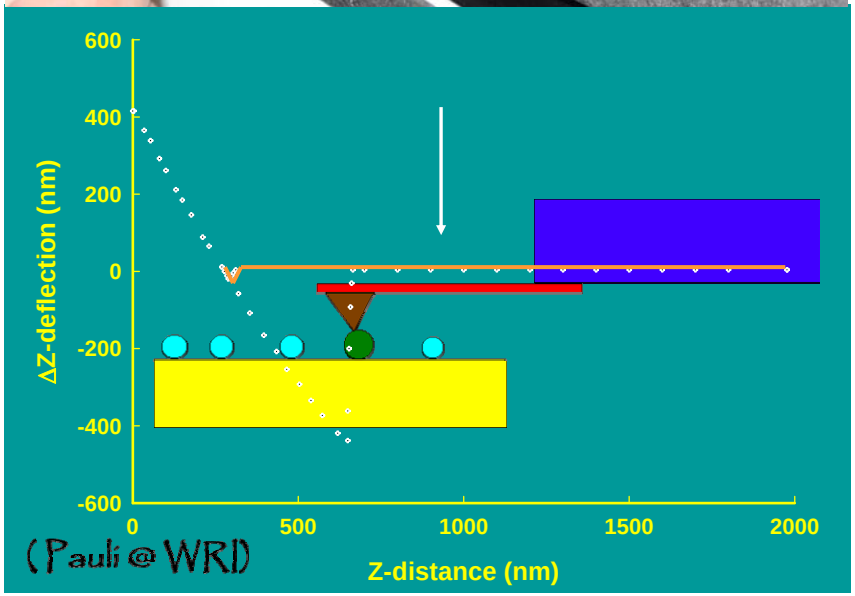

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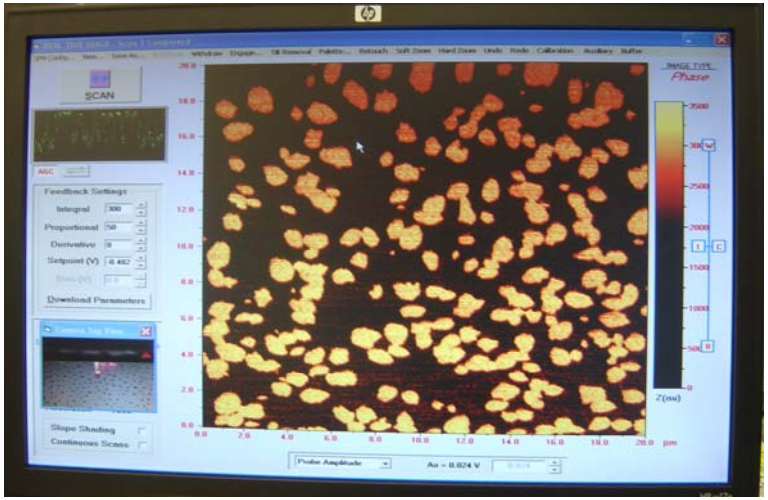

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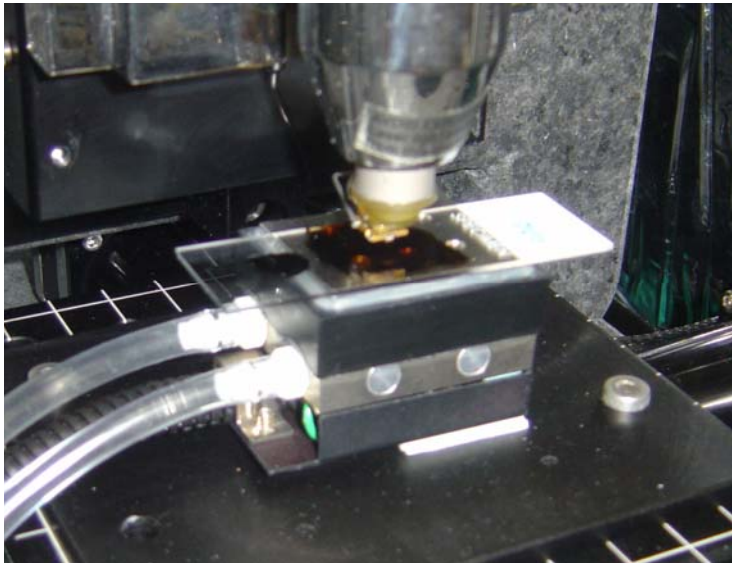

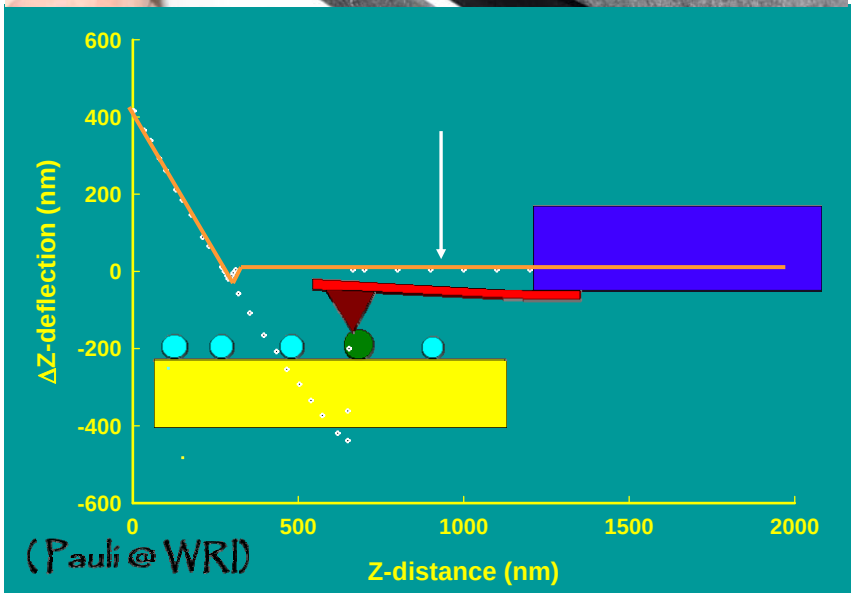

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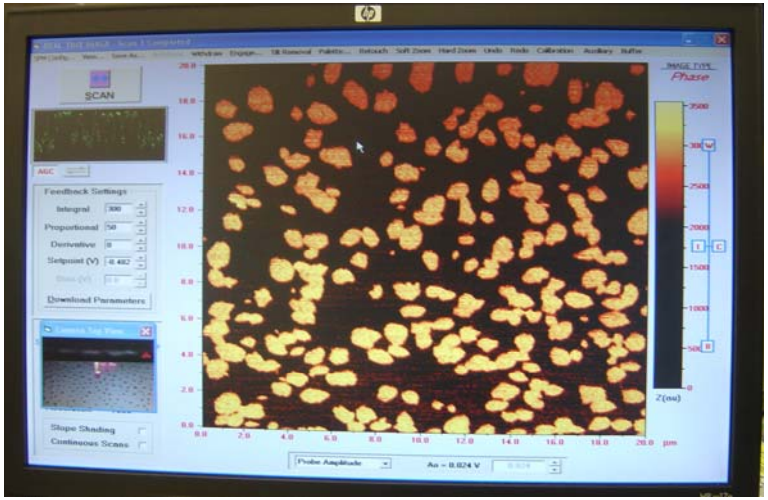

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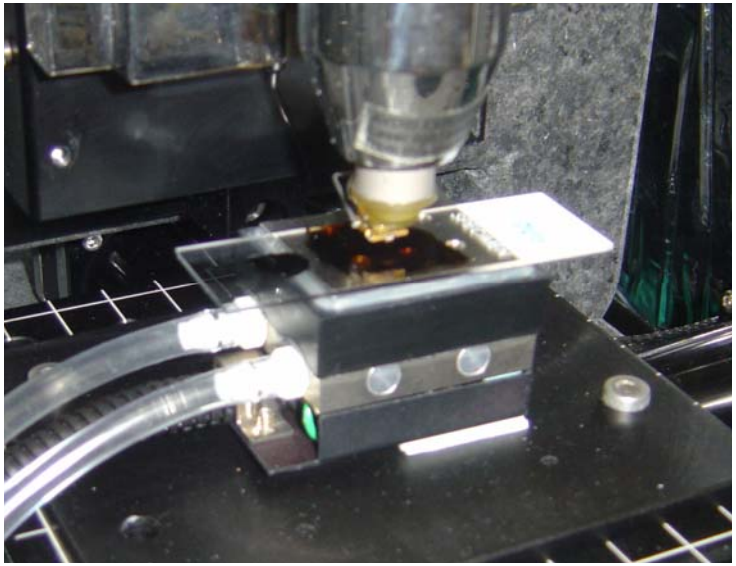

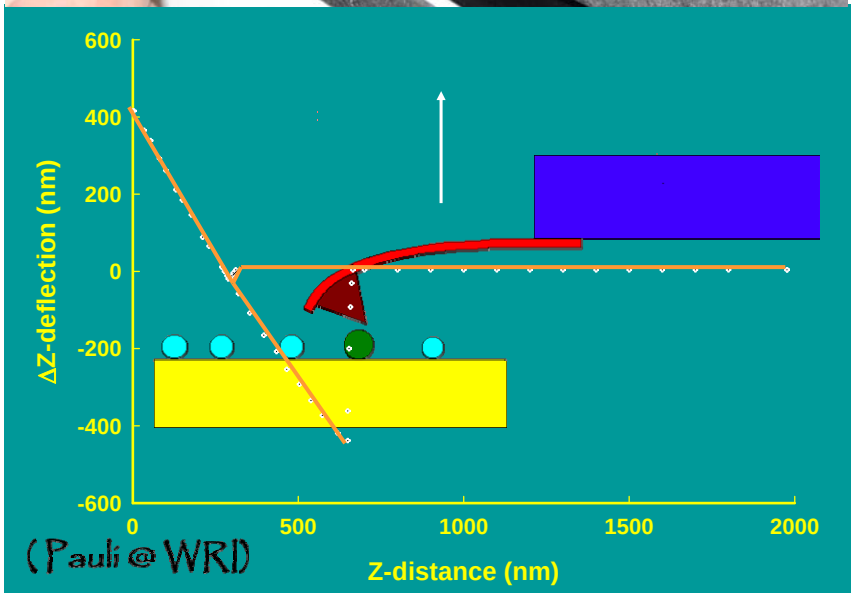

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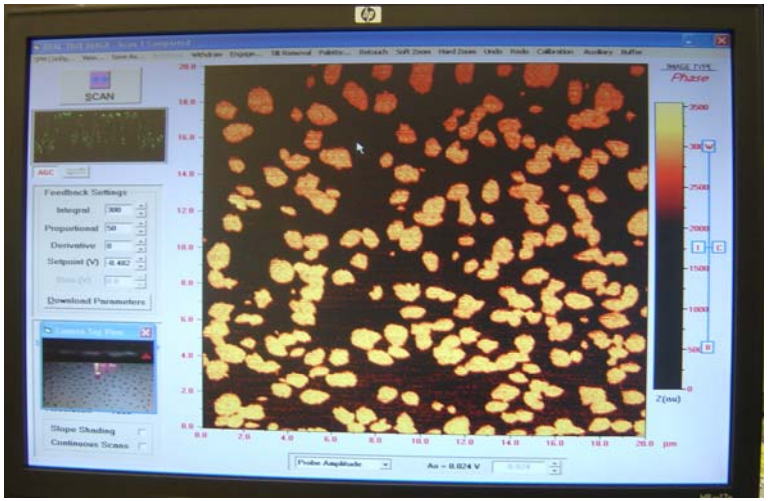
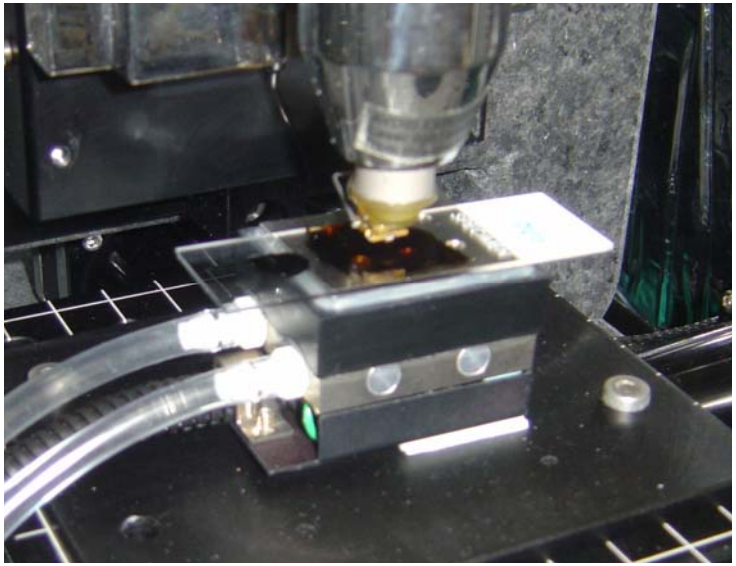
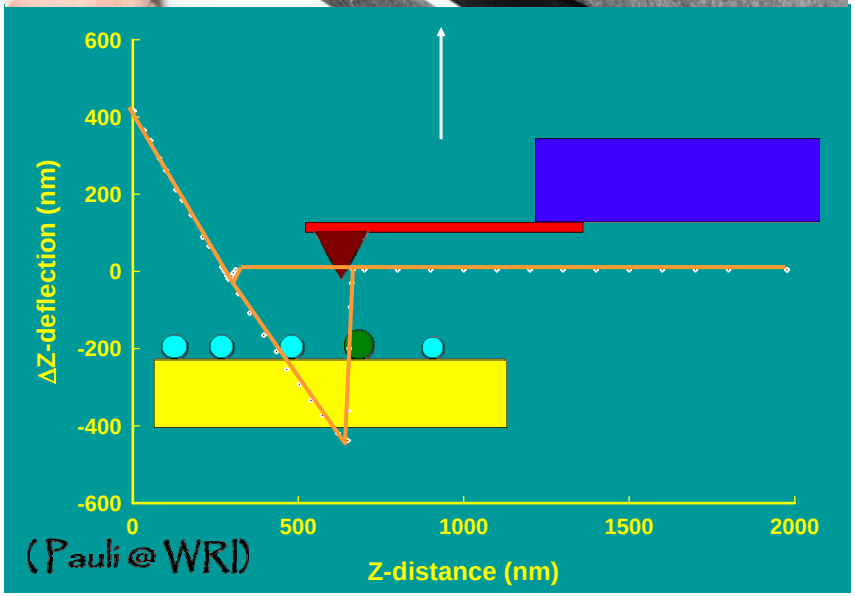


Bitumen under the AFM





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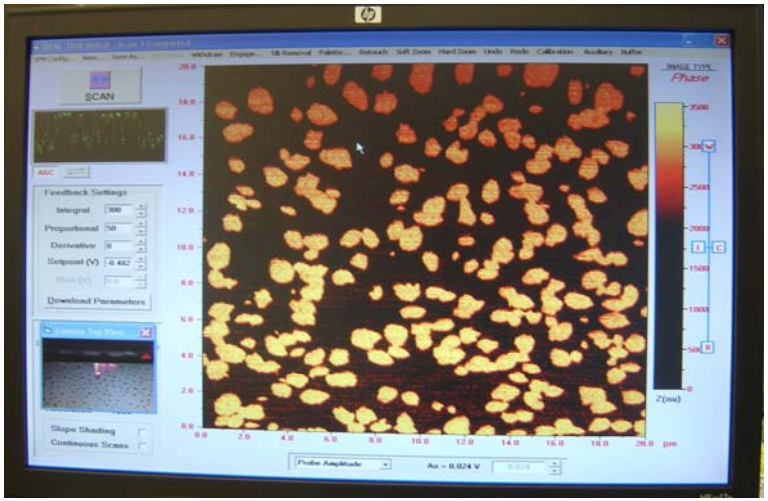

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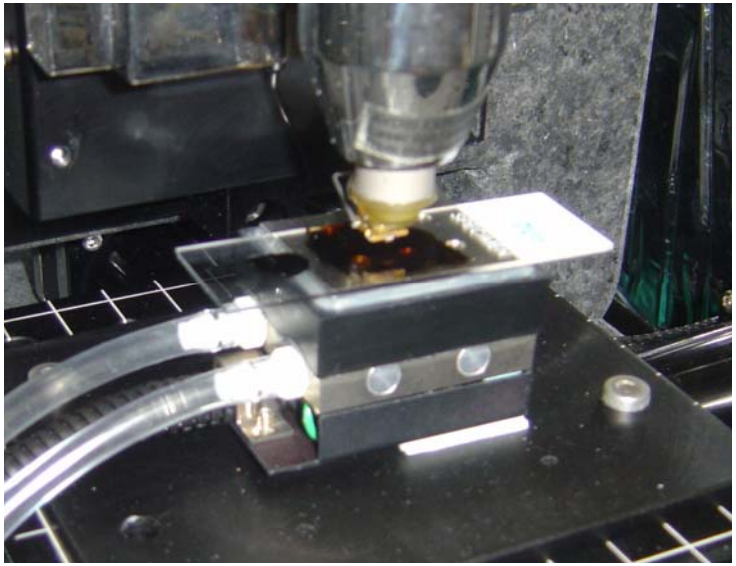

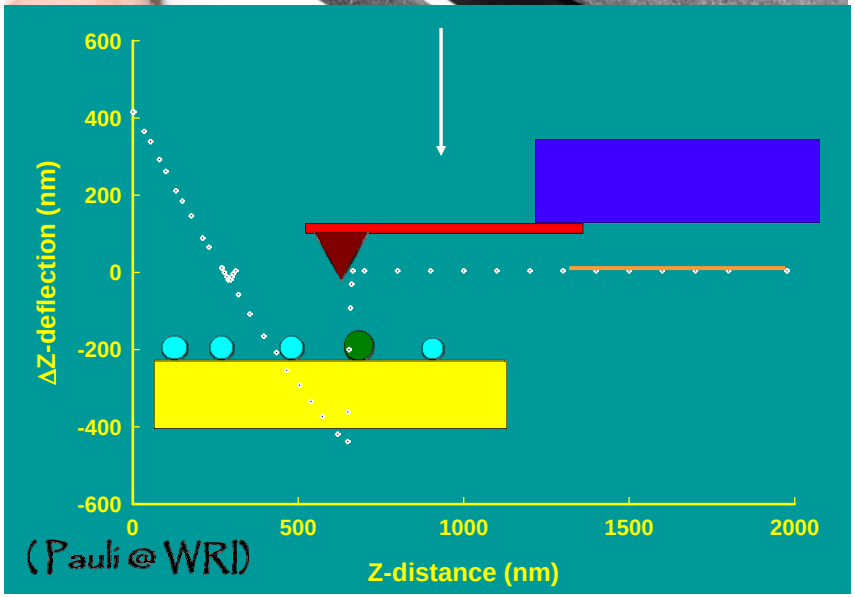

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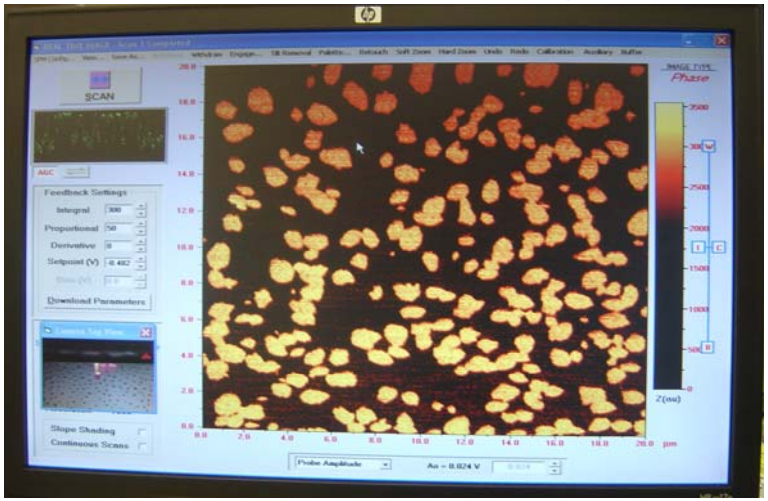

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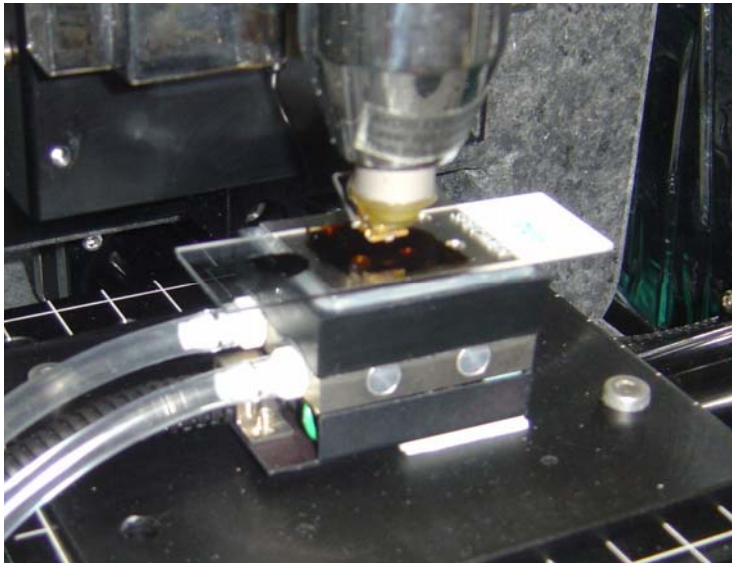

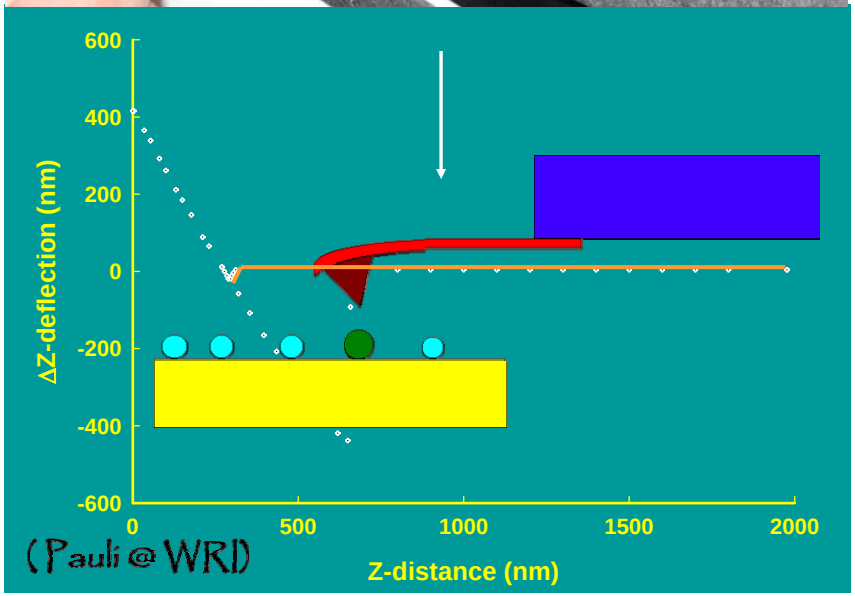

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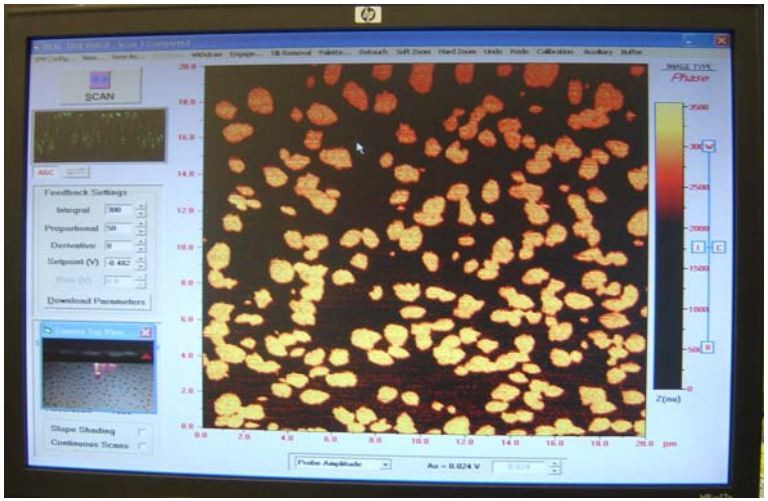

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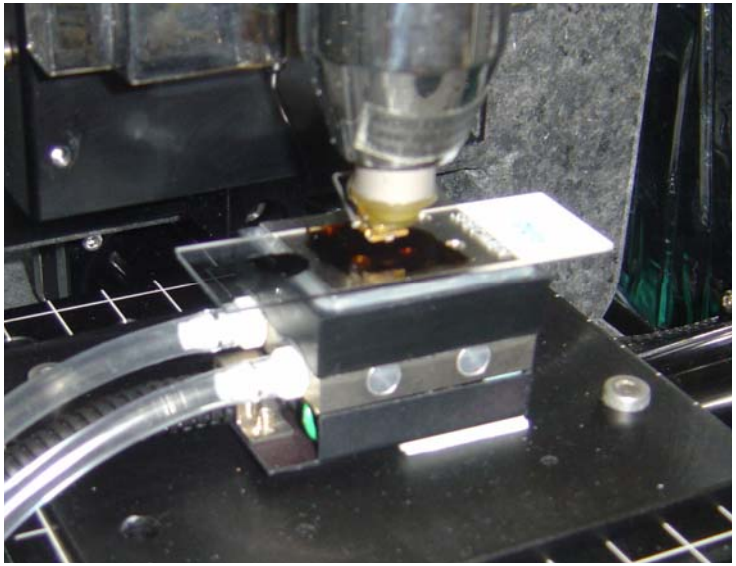

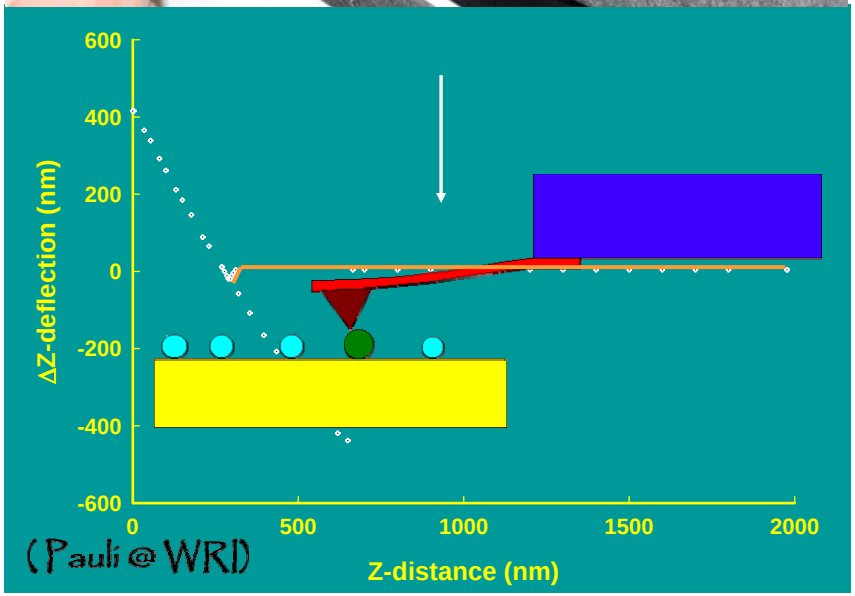

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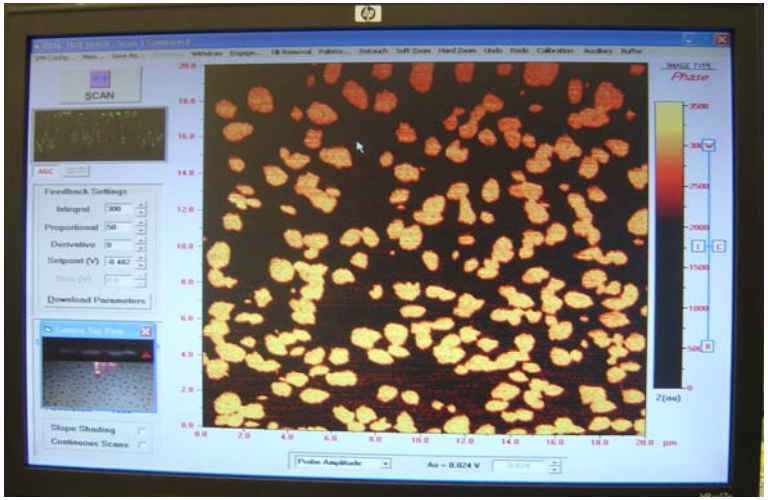

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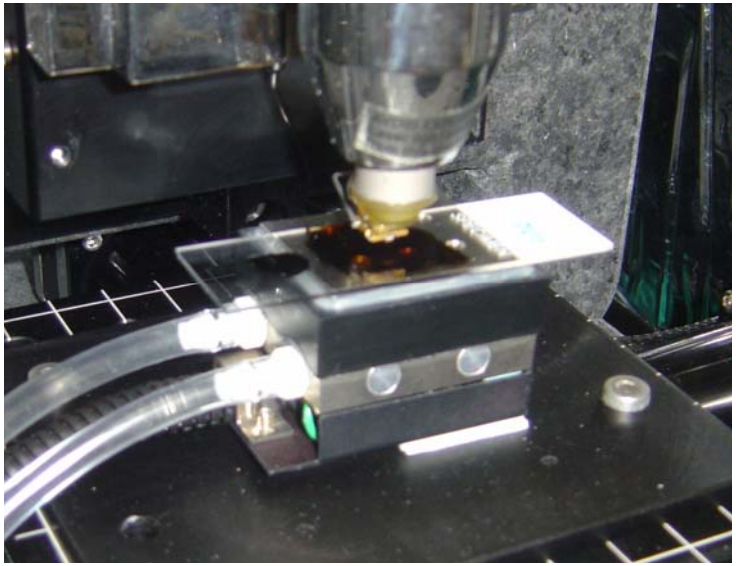

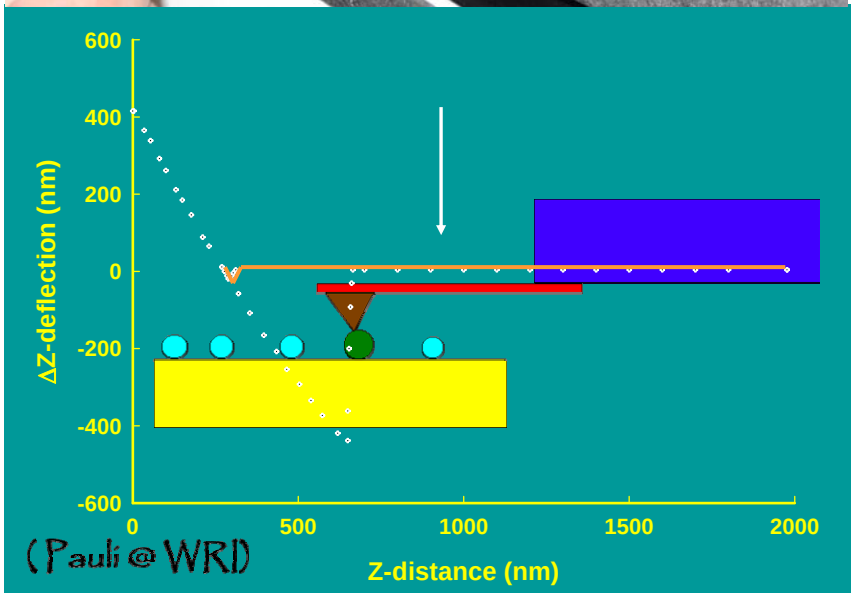

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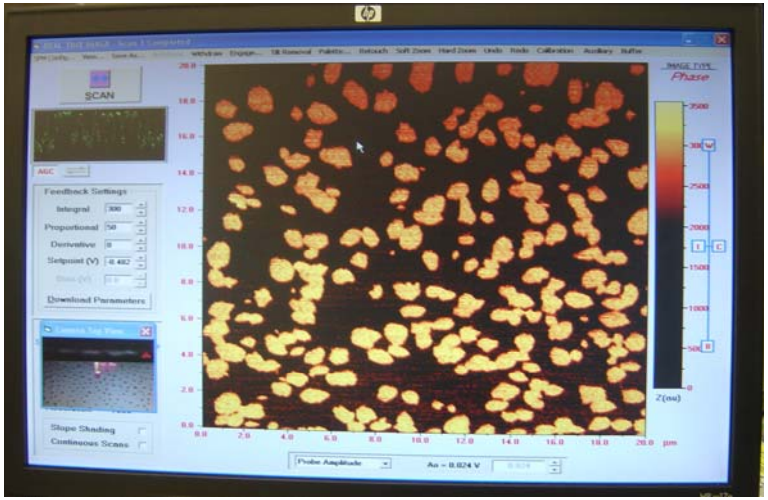

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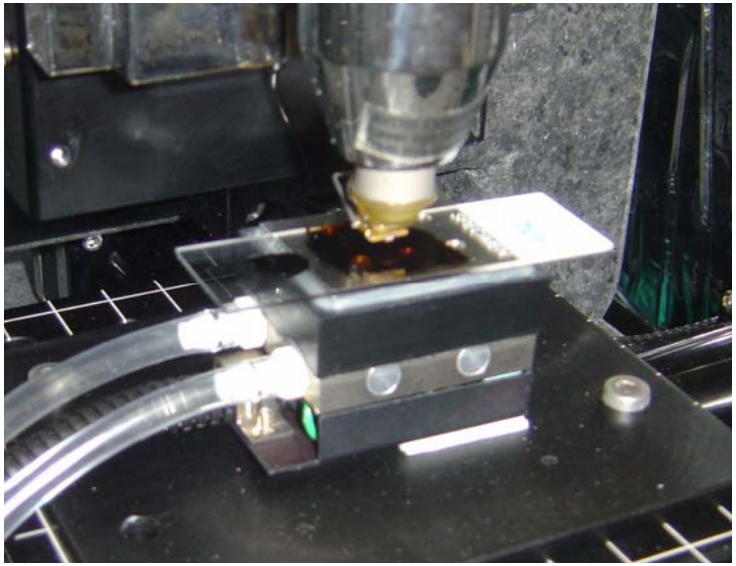

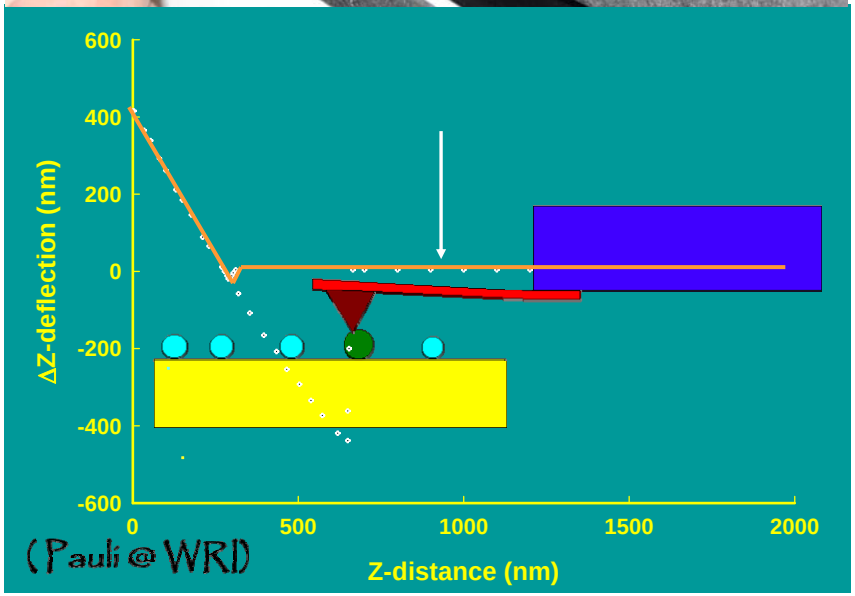

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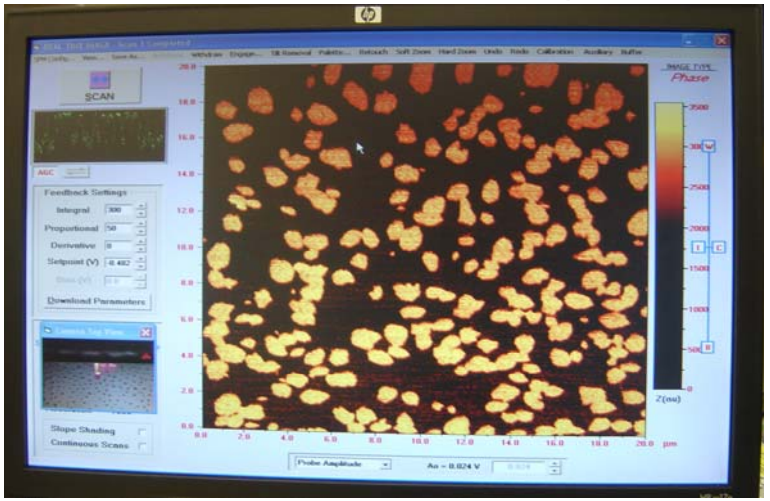
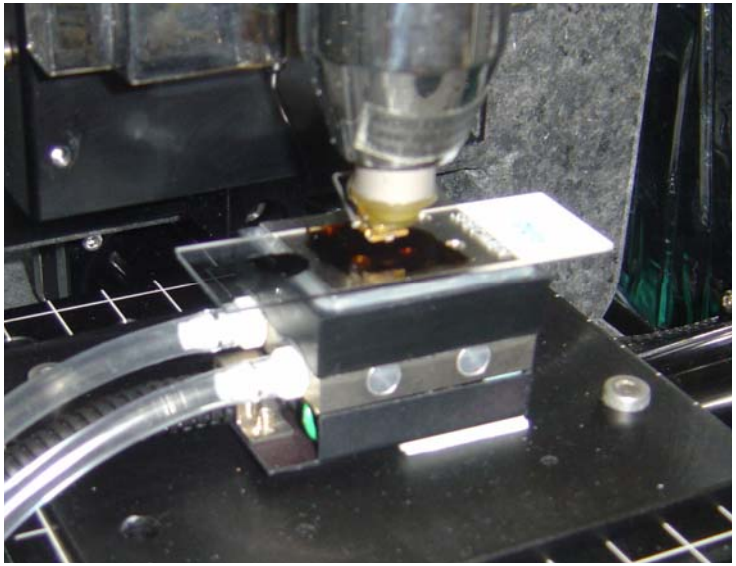
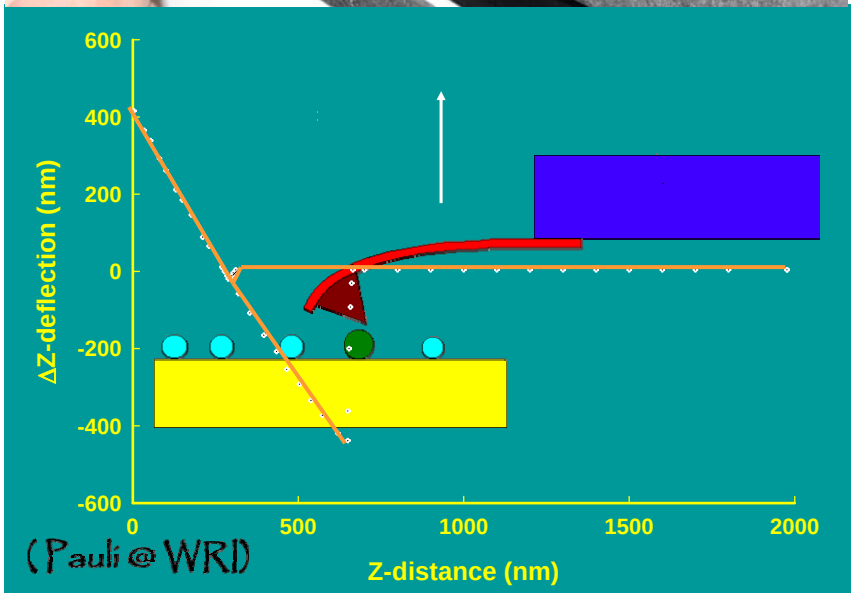


Bitumen under the AFM





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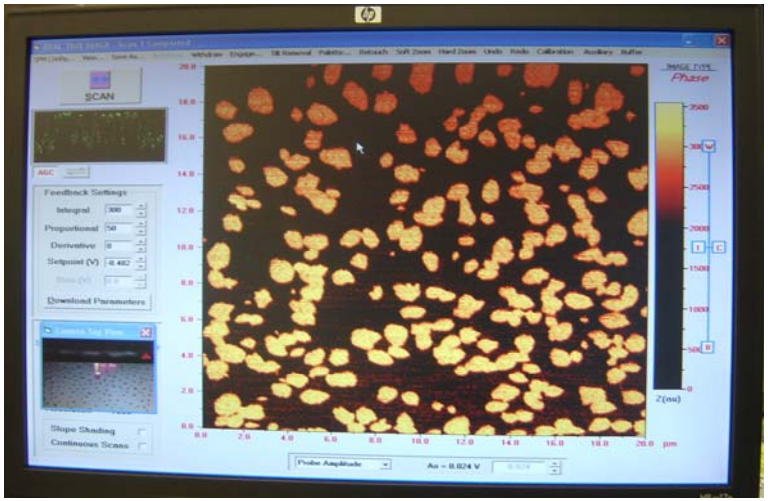
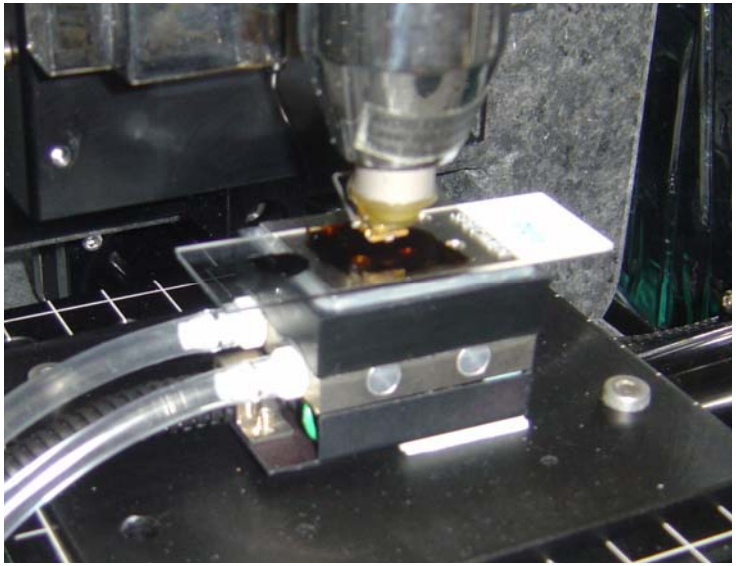
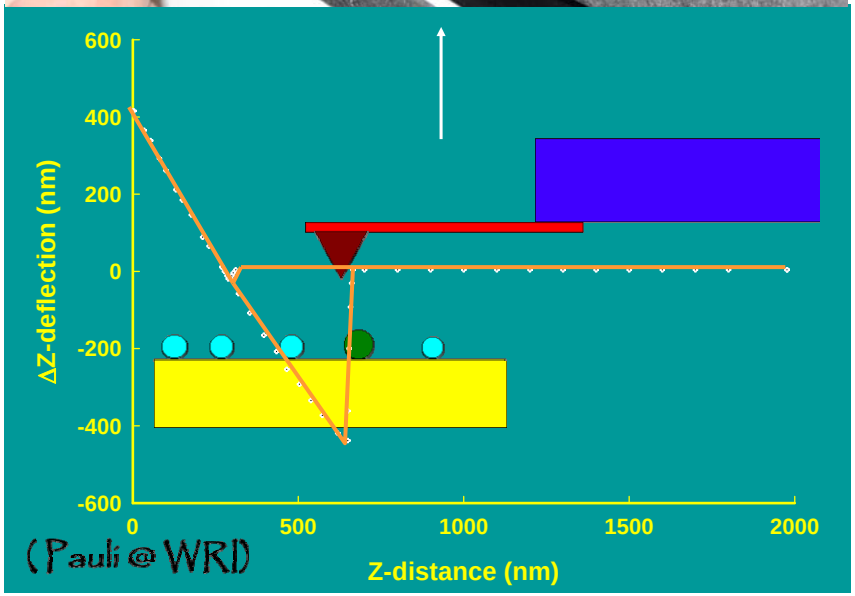


Bitumen under the AFM





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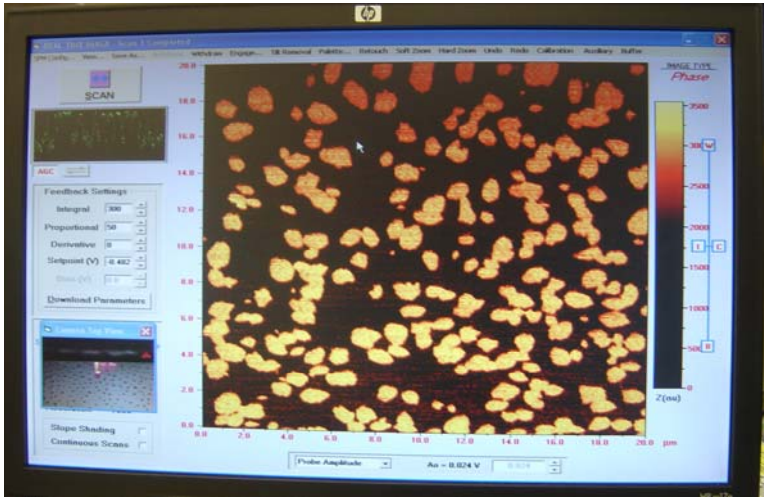
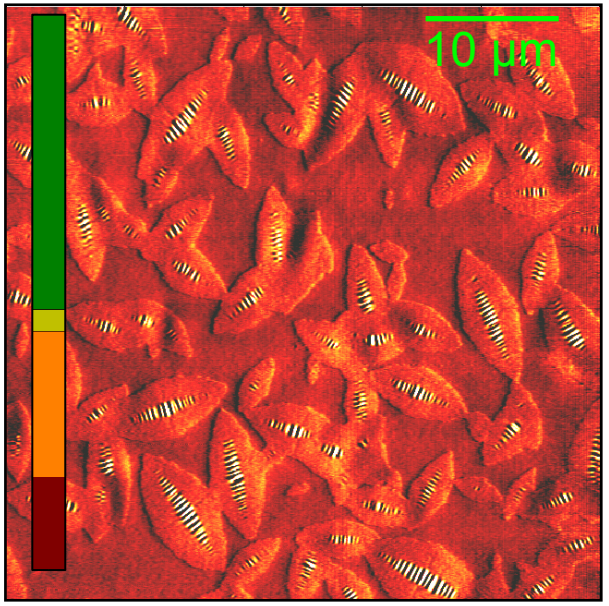
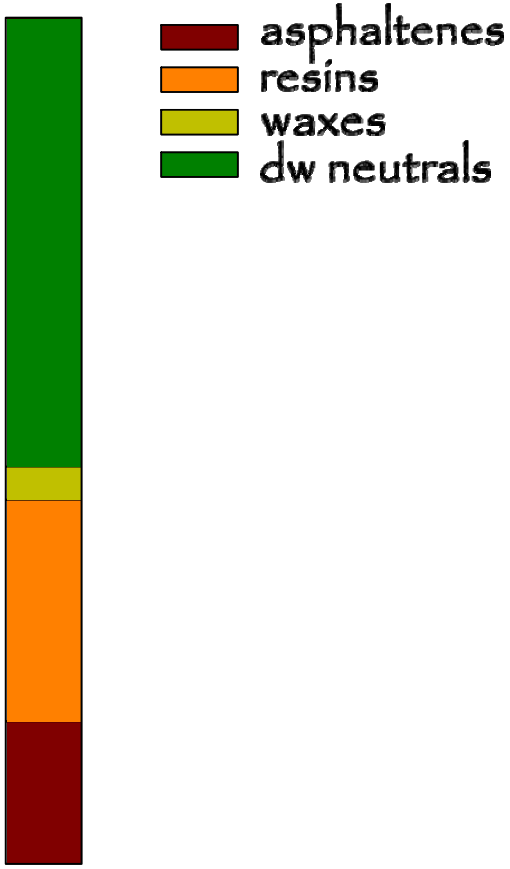


Bitumen under the AFM

TU Delft
(Pauli @ WRI)

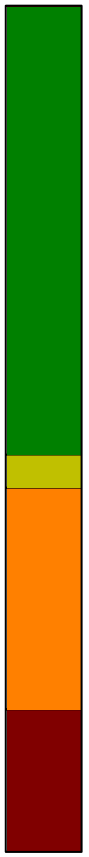




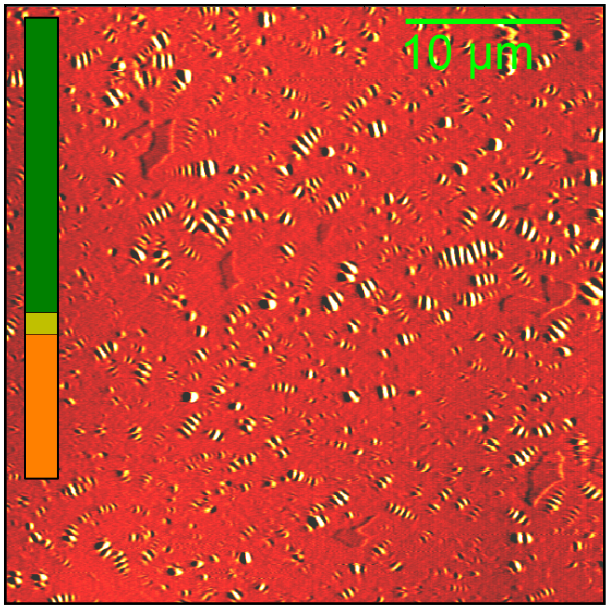
(height images)

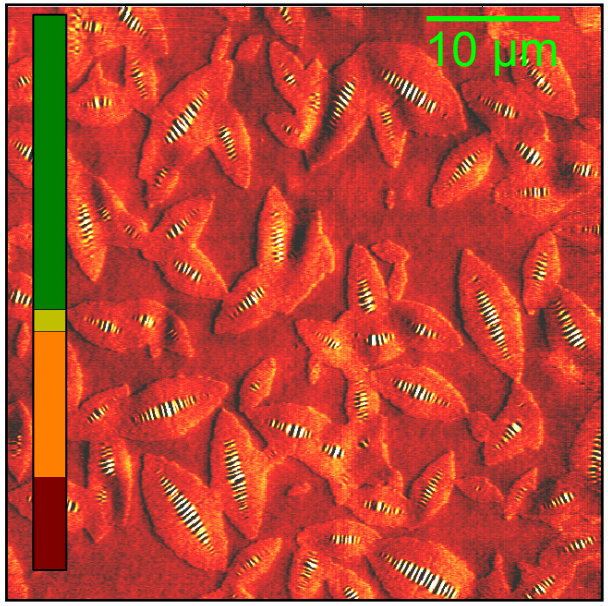
Bitumen under the AFM

TU Delft
(Pauli @ WRI)



asphaltenes
resins
waxes
dw neutrals





(height images)

Bitumen under the AFM

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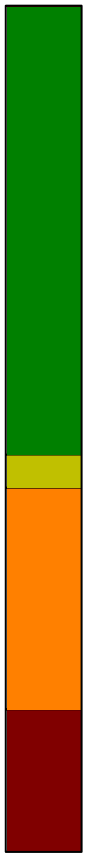
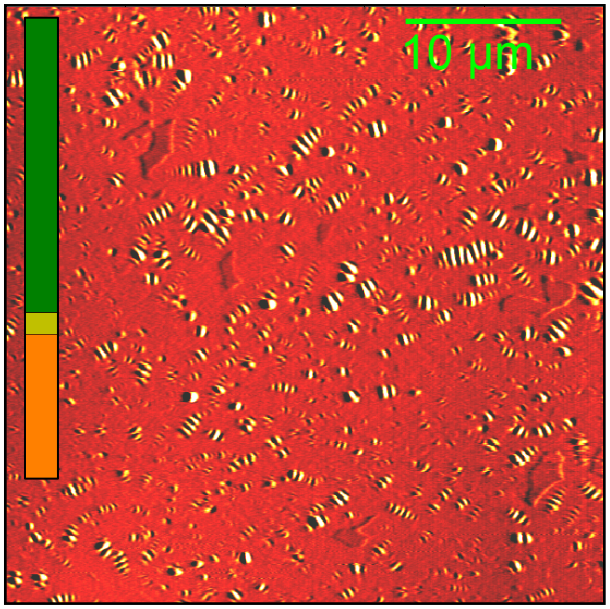
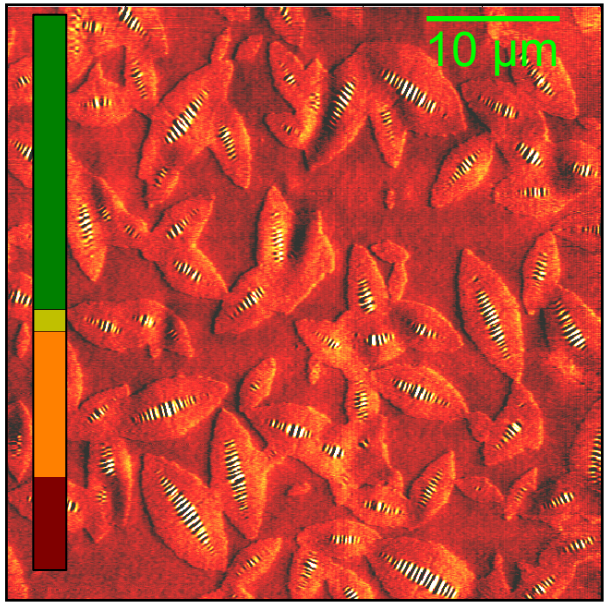
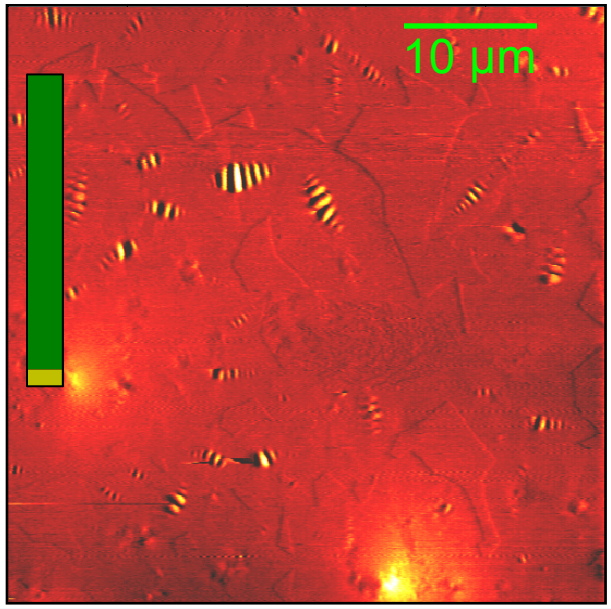


asphaltenes
resins
waxes
dw neutrals







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Bitumen under the AFM

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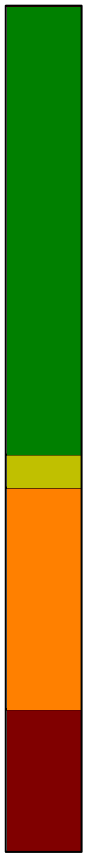

asphaltenes
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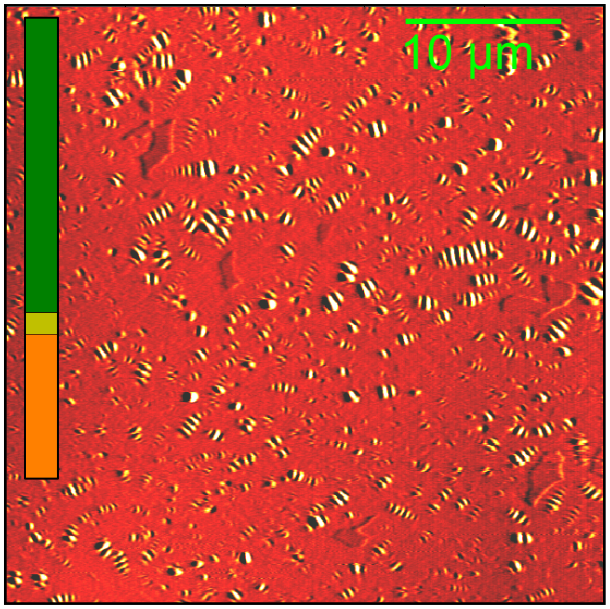
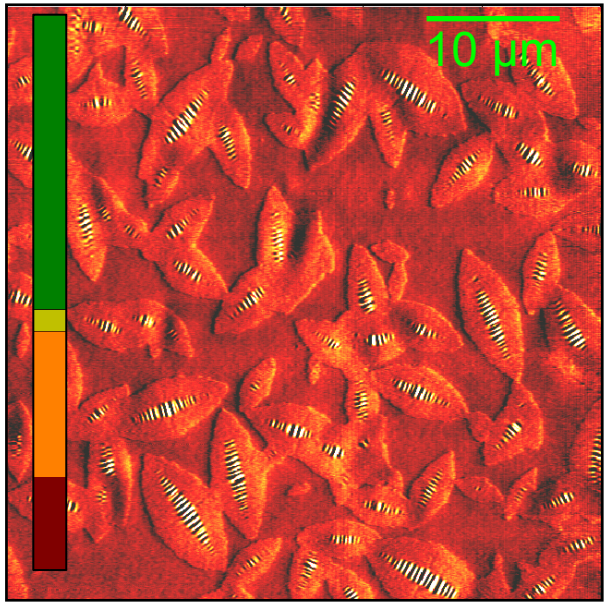
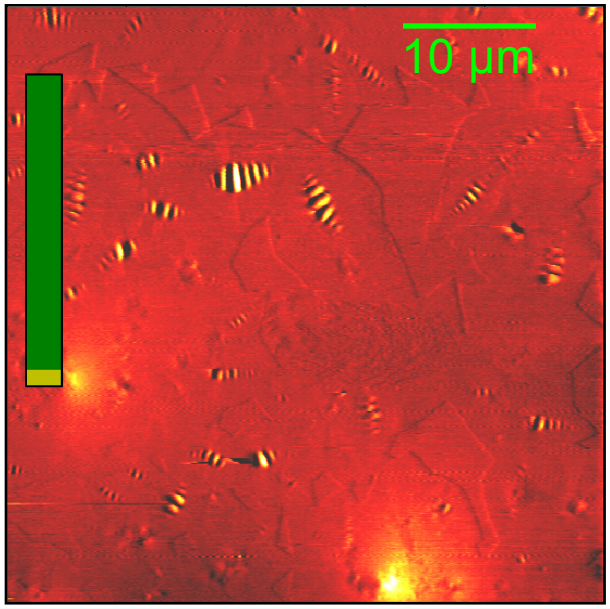
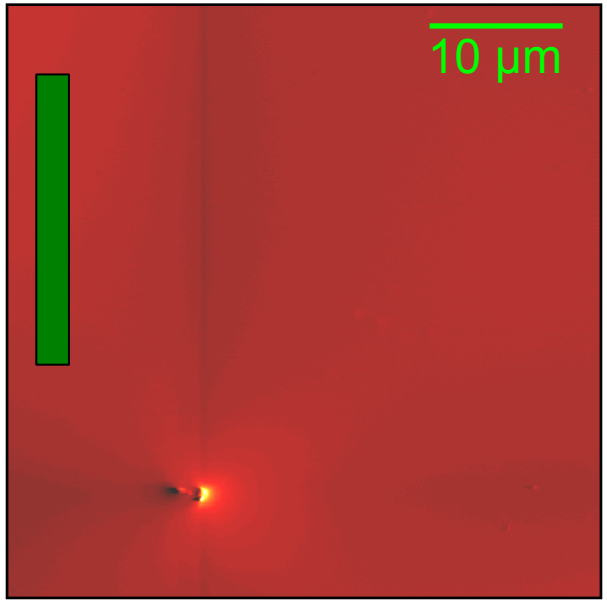
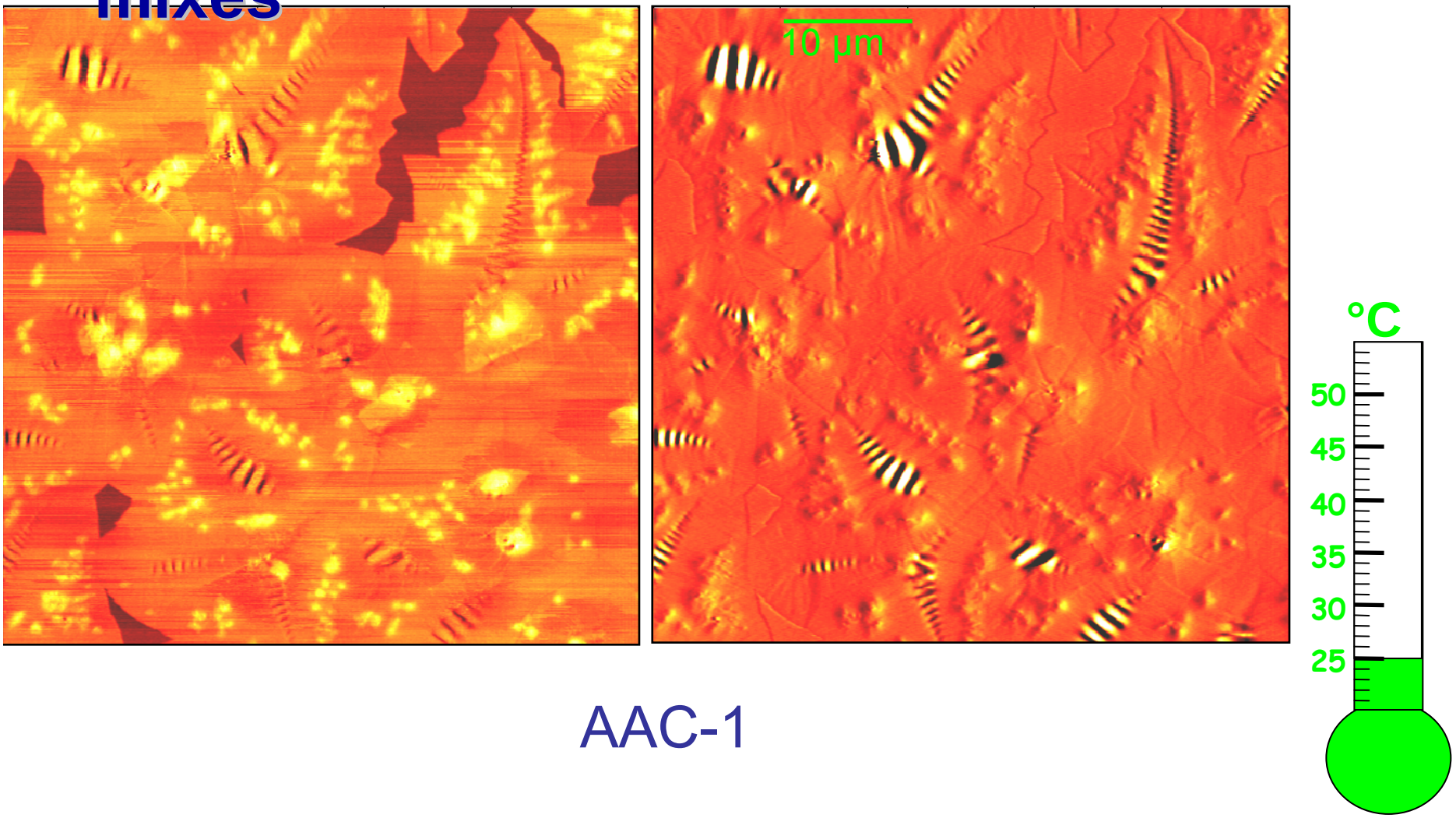






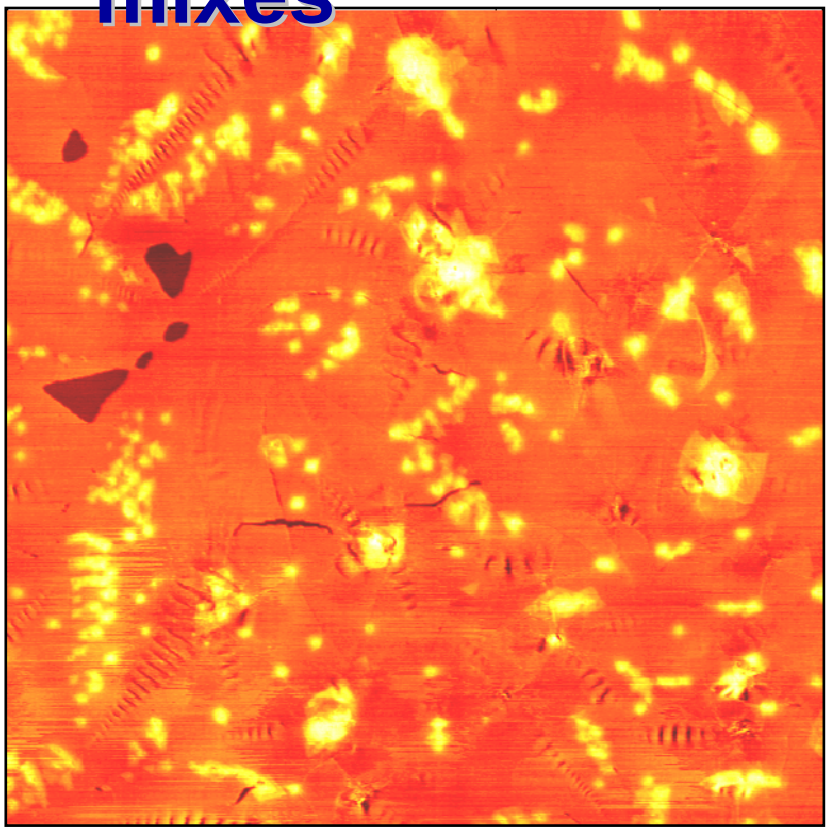


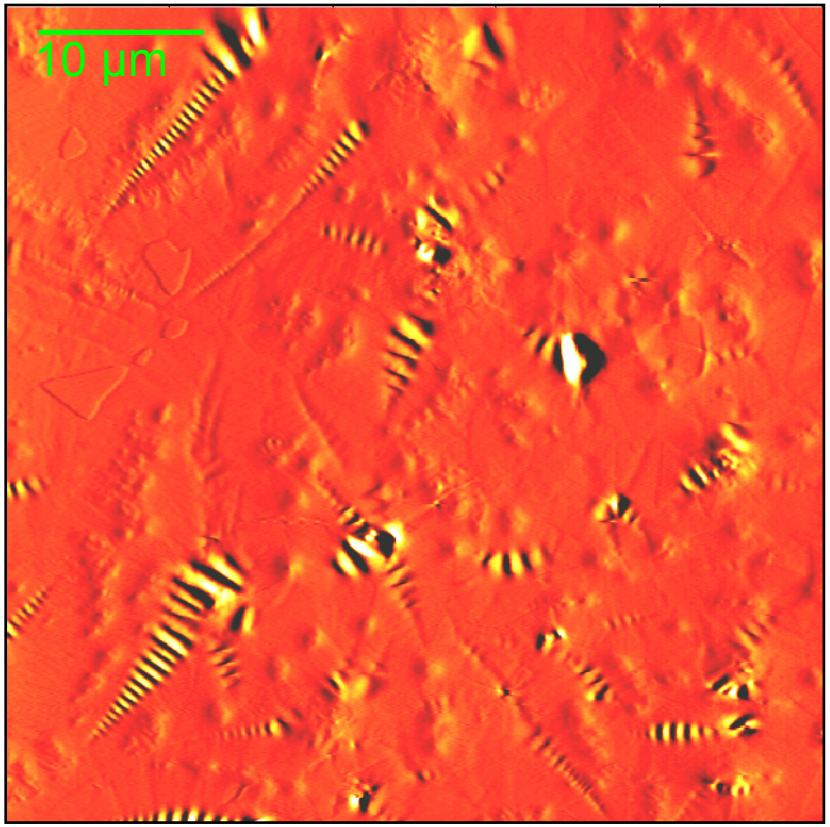
- **Microstructure evolution in asphalt mixes**

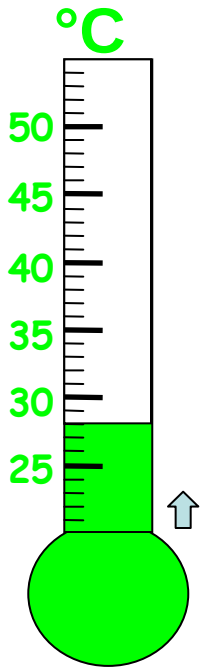


AAC-1

- **Microstructure evolution in asphalt mixes**

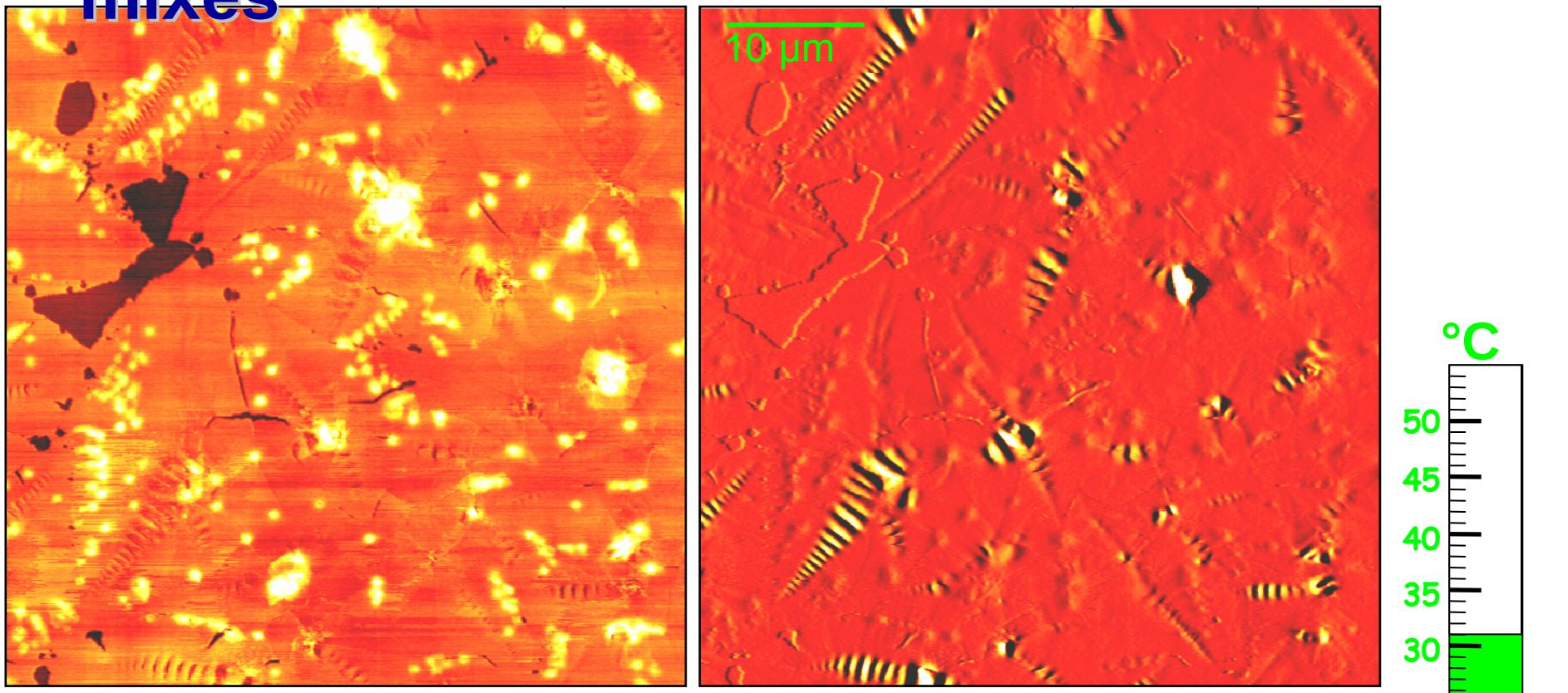






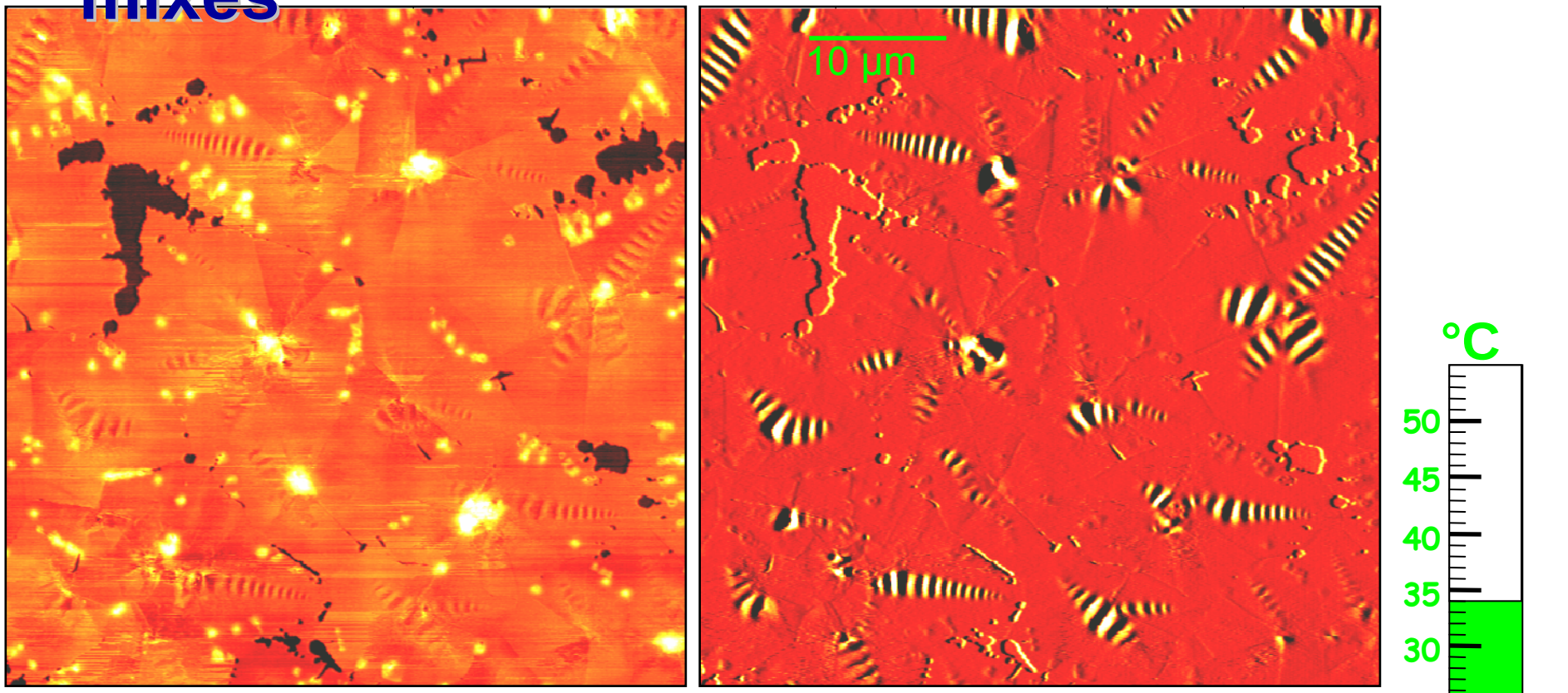
AAC-1

- **Microstructure evolution in asphalt mixes**



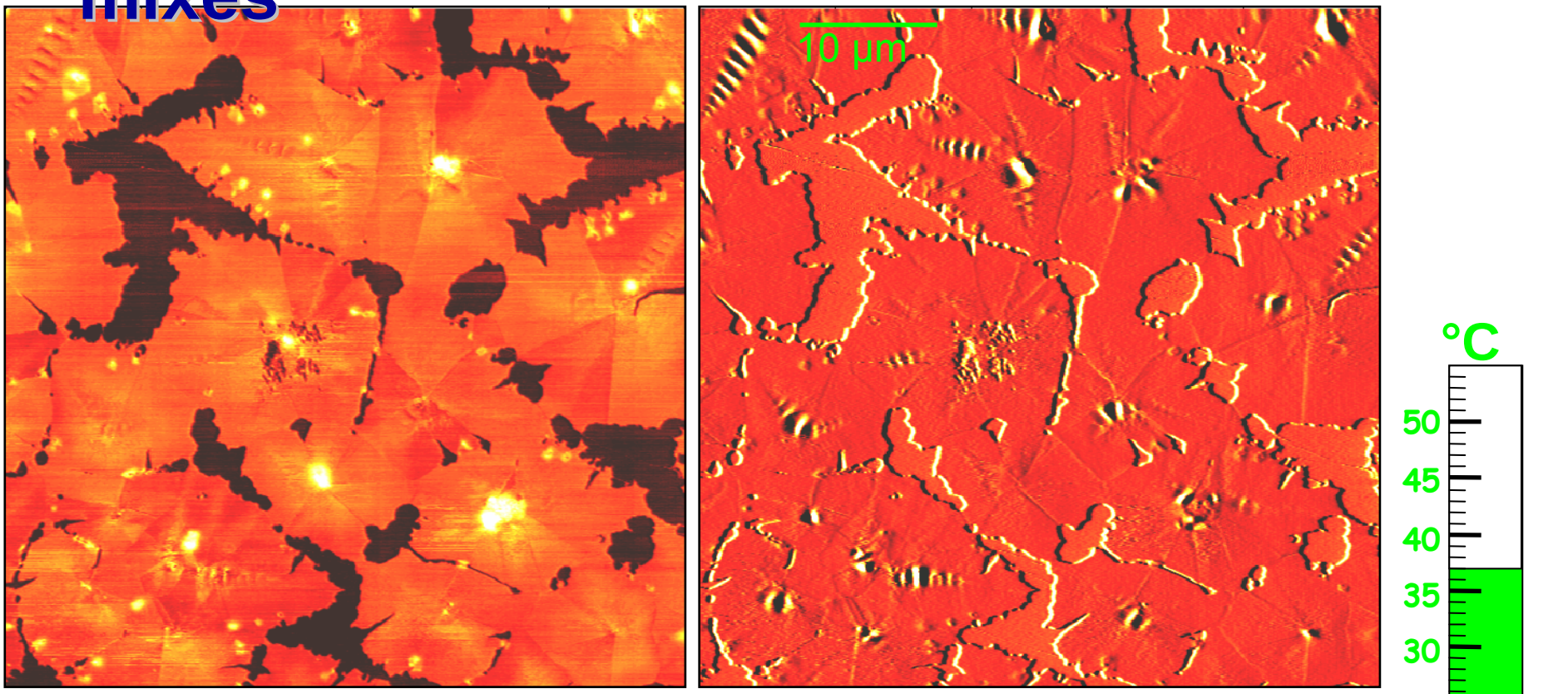
AAC-1

- **Microstructure evolution in asphalt mixes**



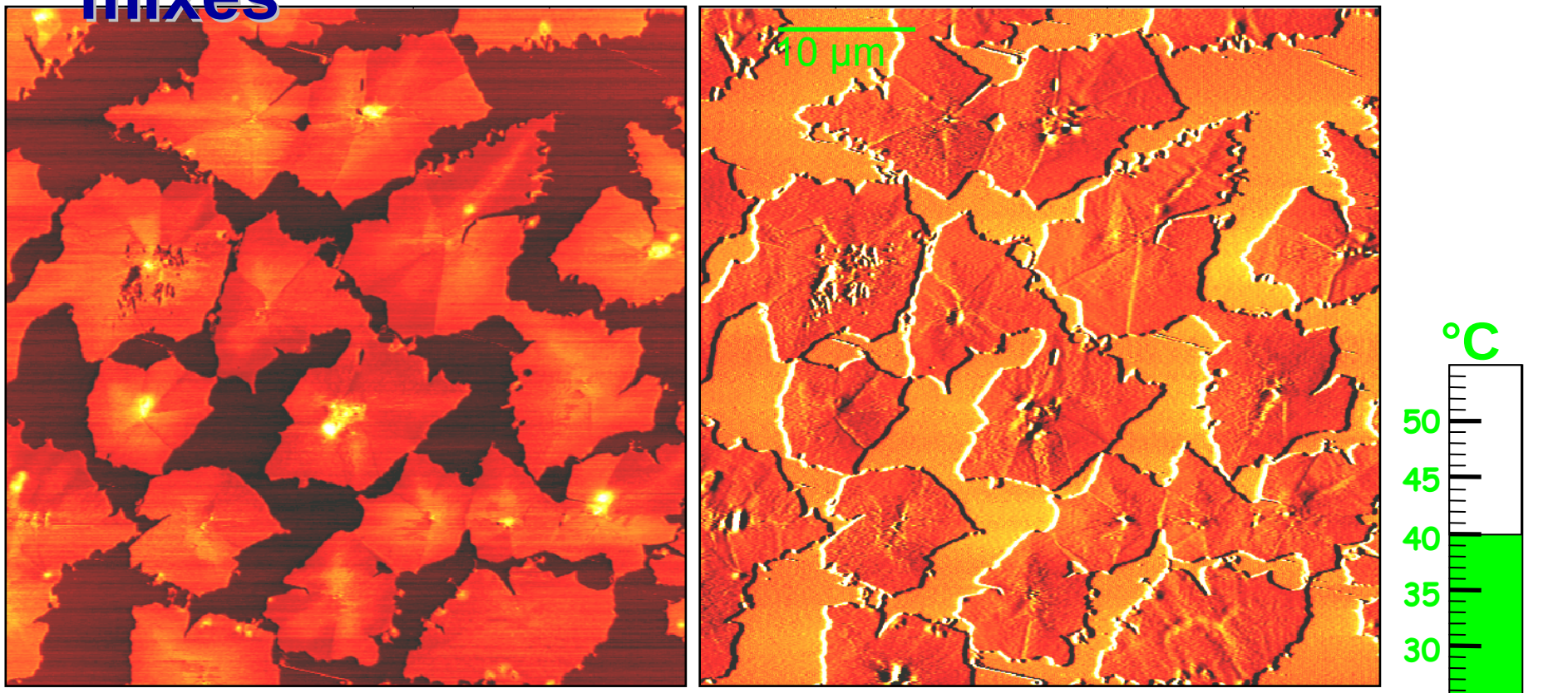
AAC-1

- **Microstructure evolution in asphalt mixes**



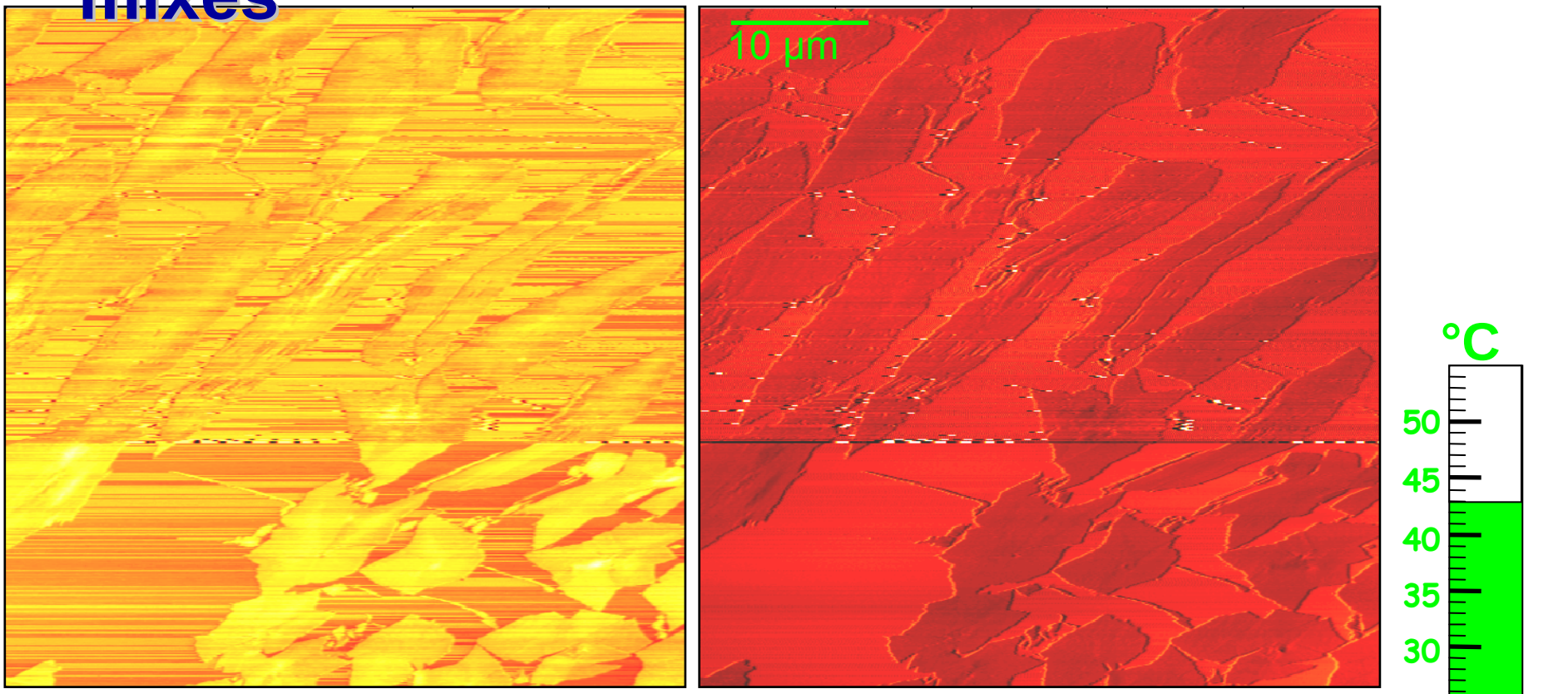
AAC-1

- **Microstructure evolution in asphalt mixes**



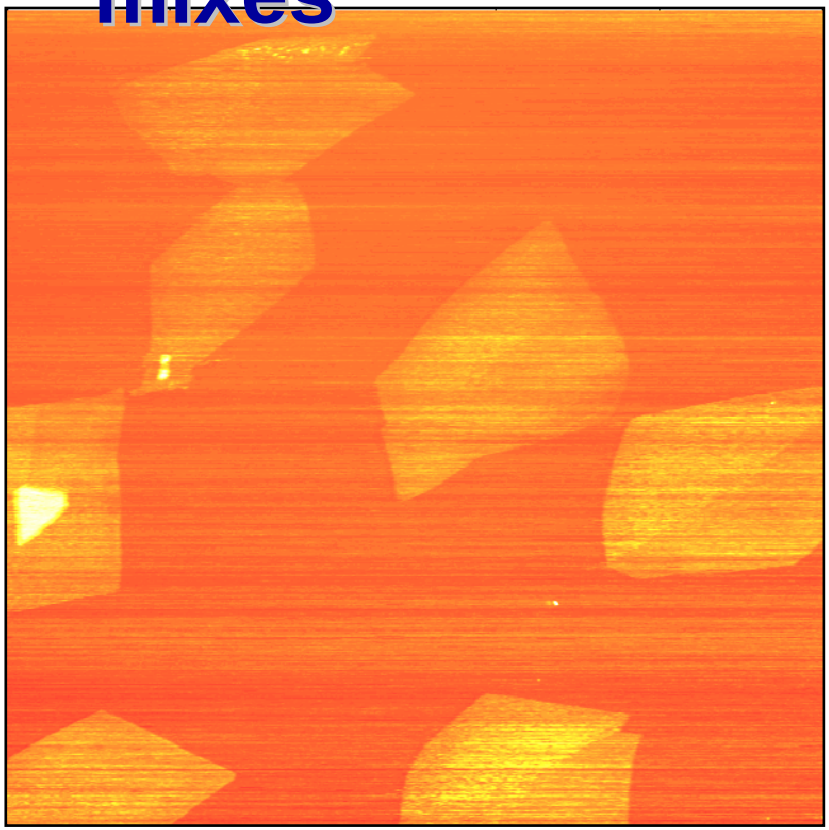
AAC-1

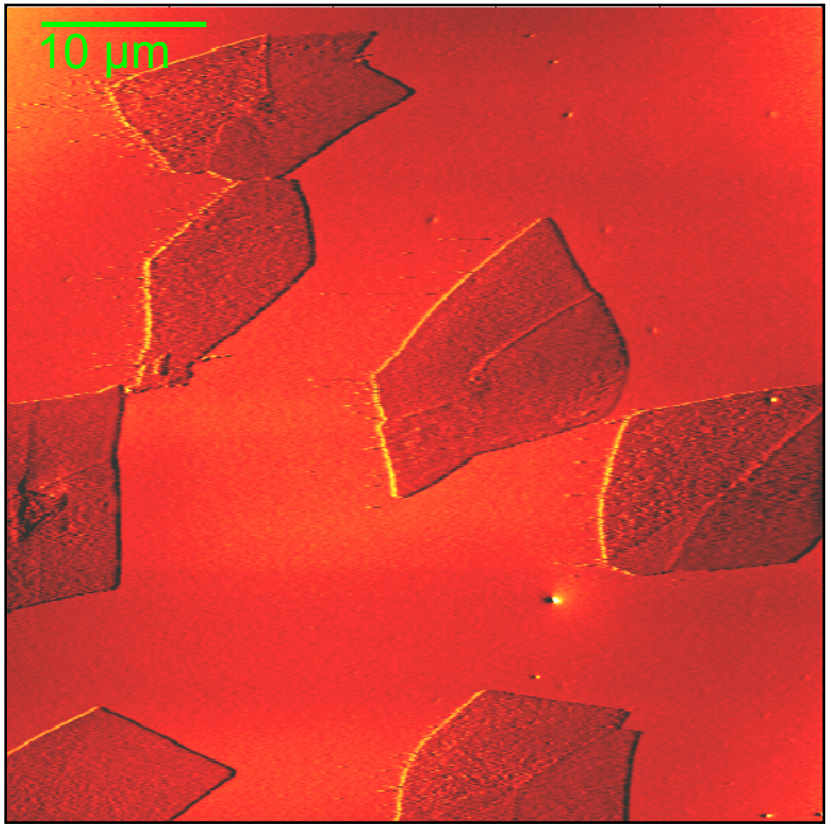
- **Microstructure evolution in asphalt mixes**

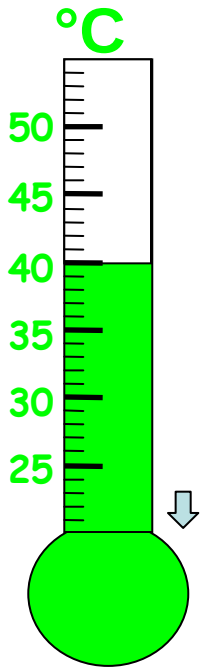


AAC-1

- **Microstructure evolution in asphalt mixes**







AAC-1

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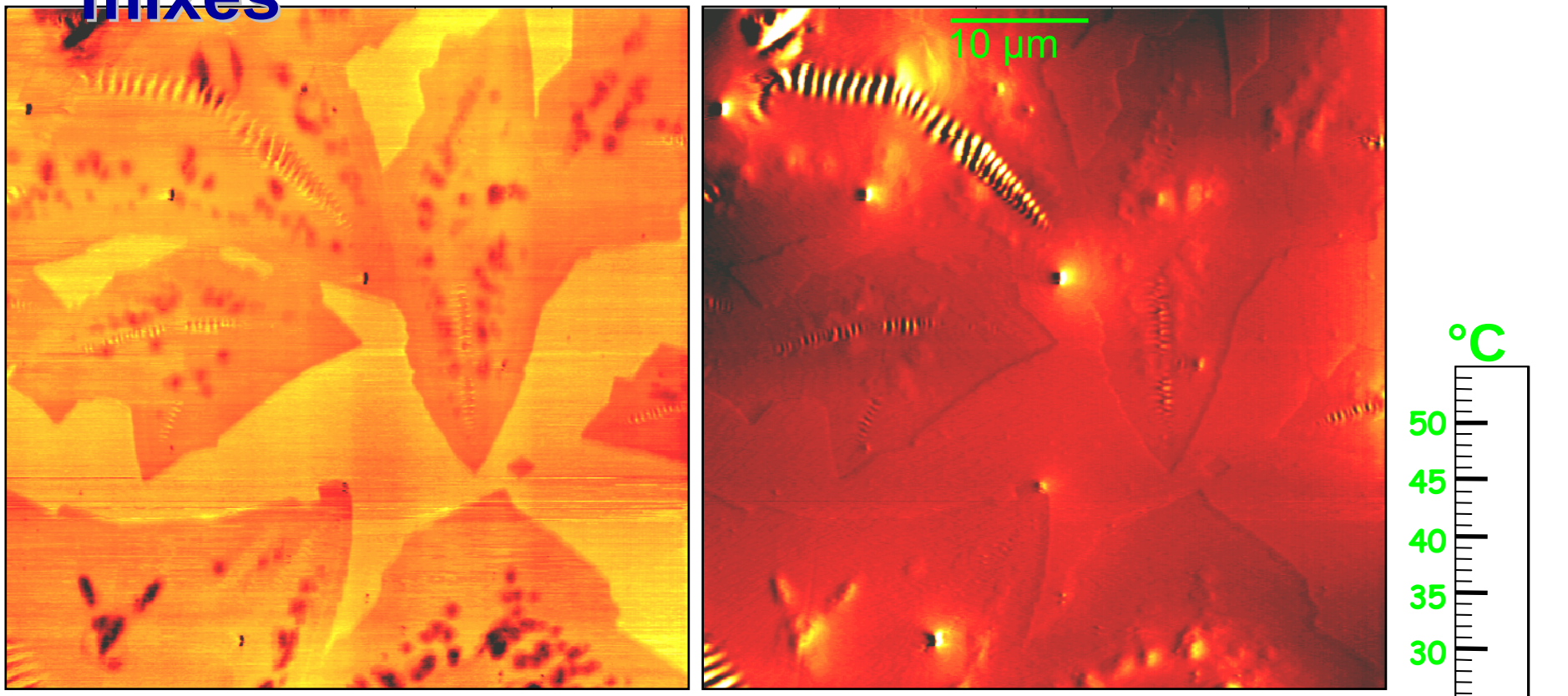
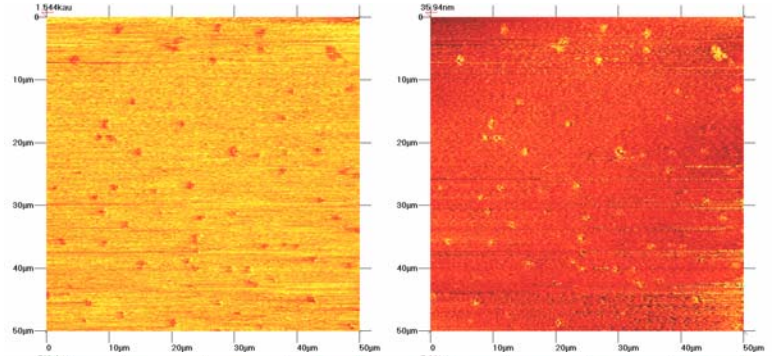


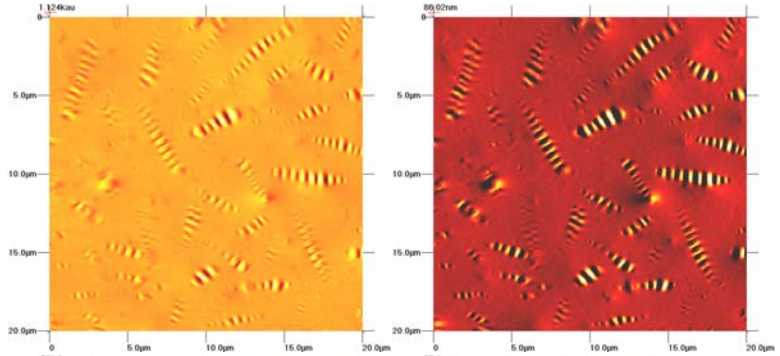
AAC-1

Asphalts

AAA-1



AAF-1



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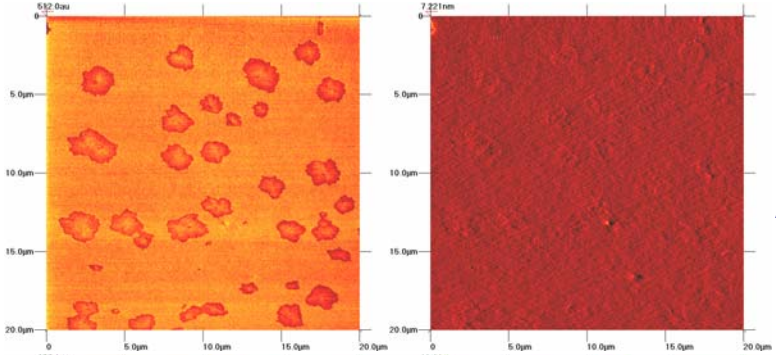

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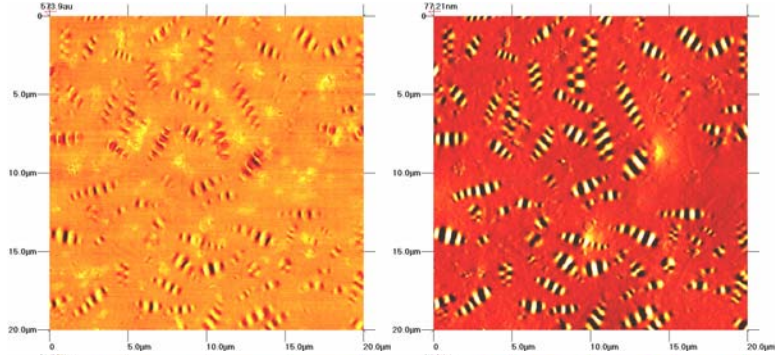

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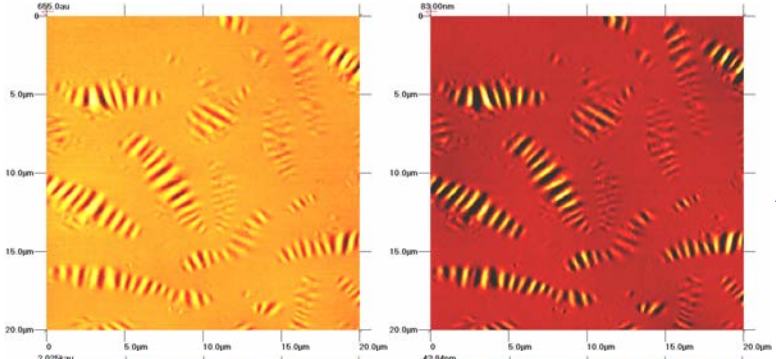

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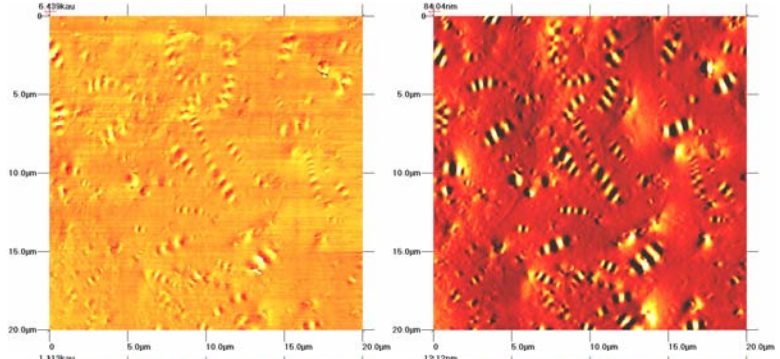

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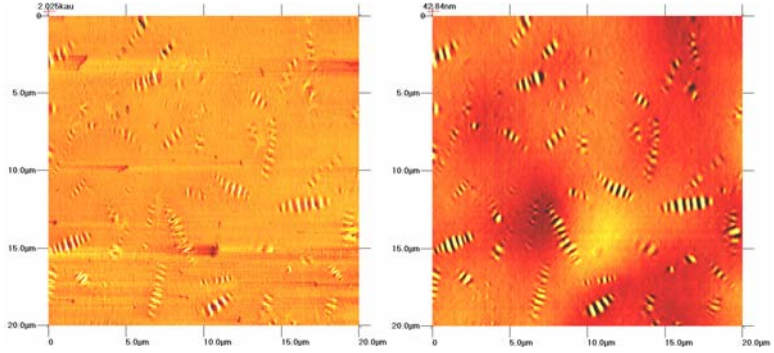

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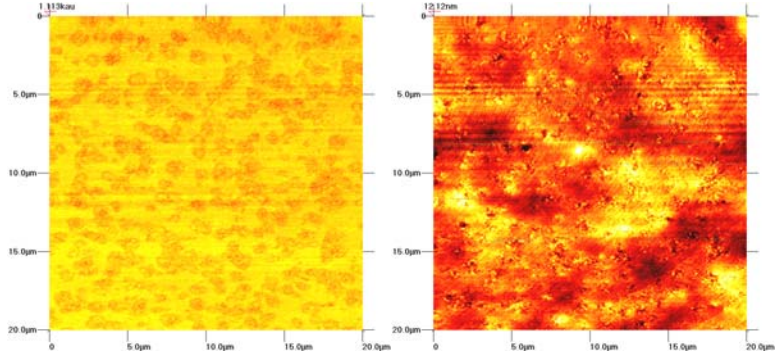
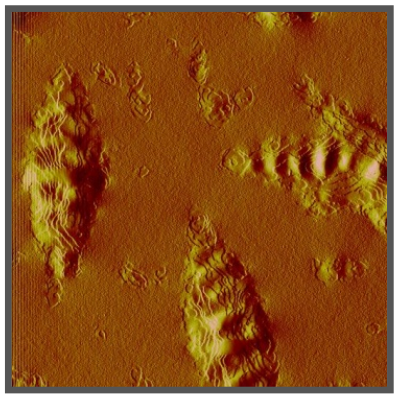


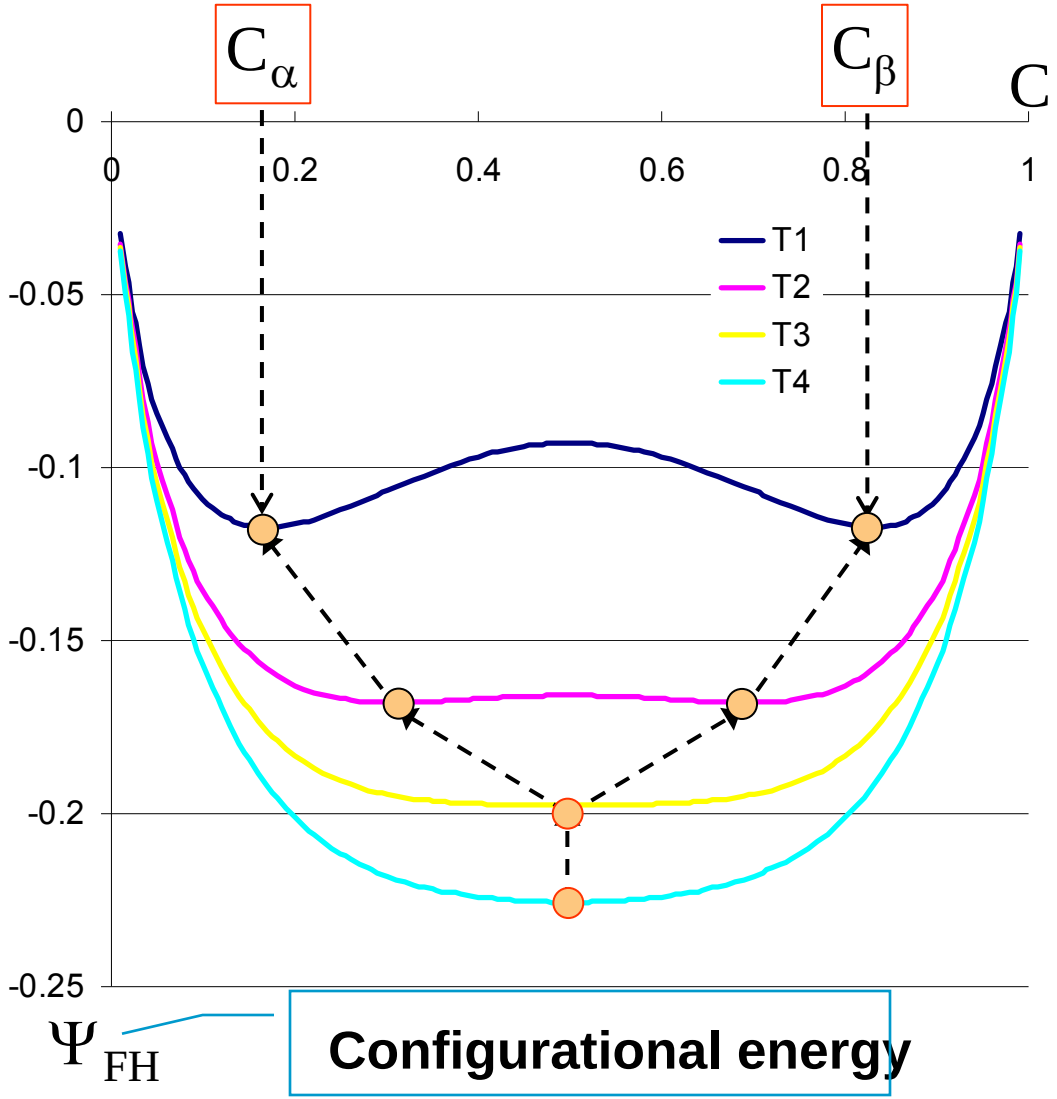
• Mixing theory



T = 22 °C

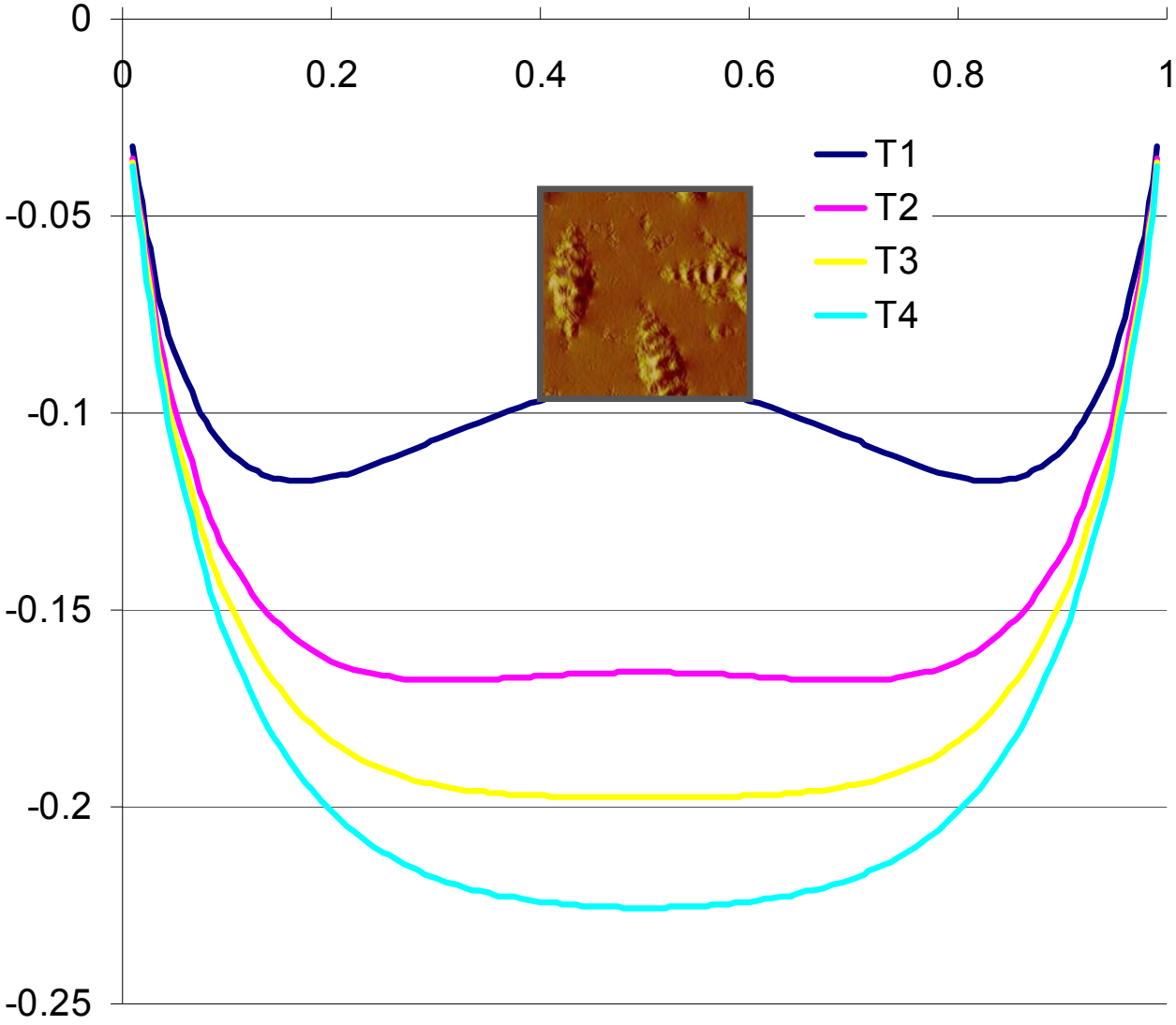
-2 °C/min

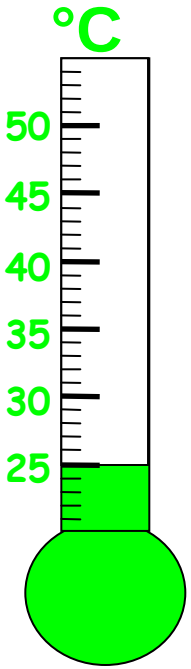
T = 40 °C



70/100 pen bitumen, AFM with heating element:

• Mixing theory





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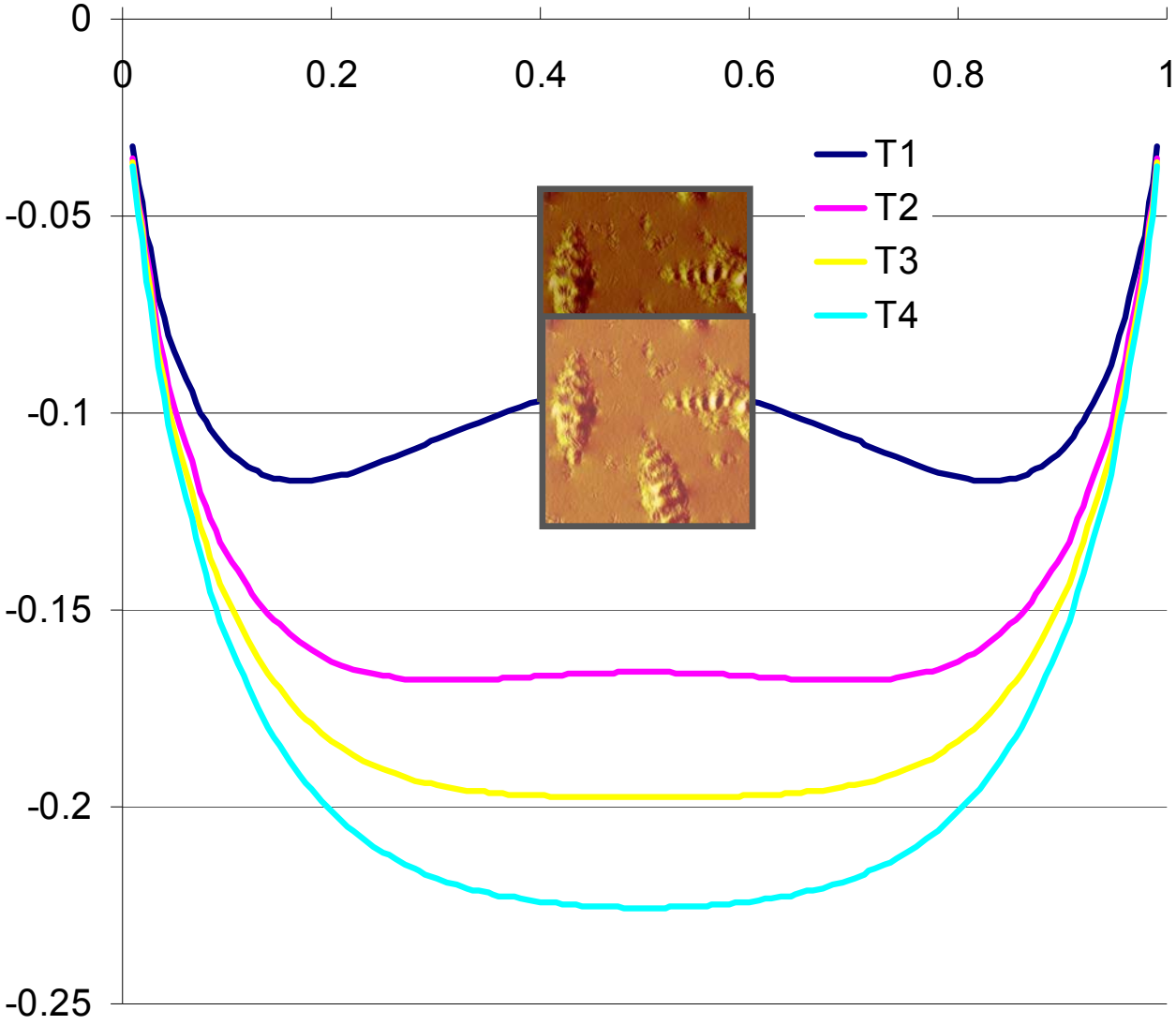

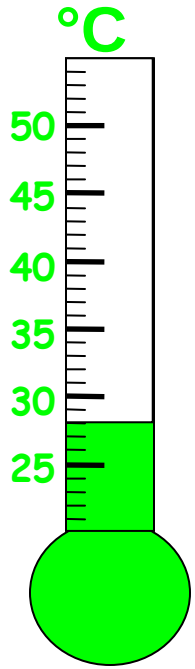

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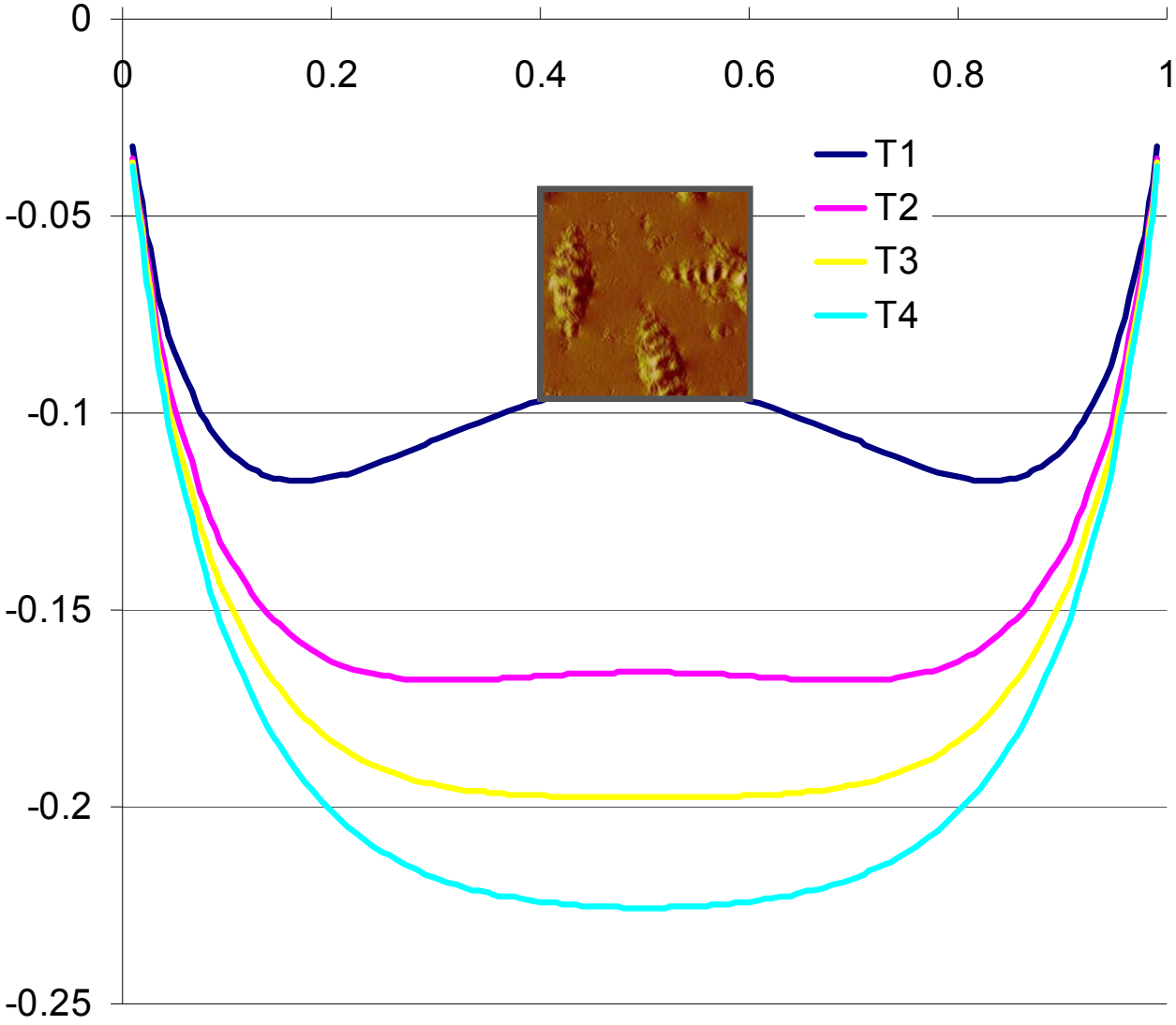

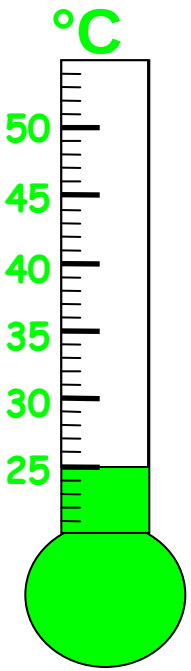

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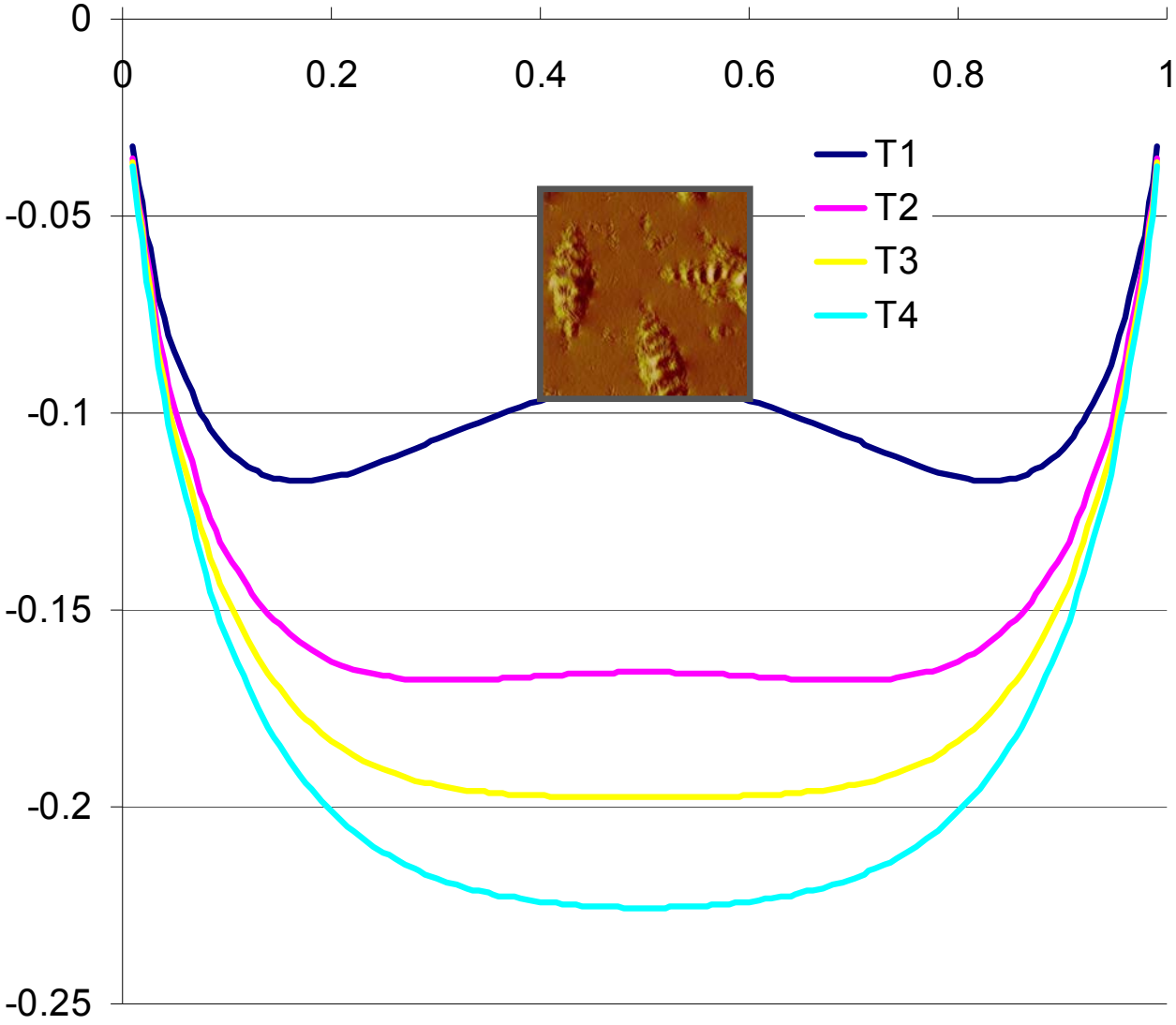

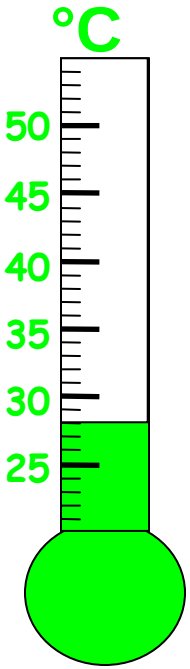

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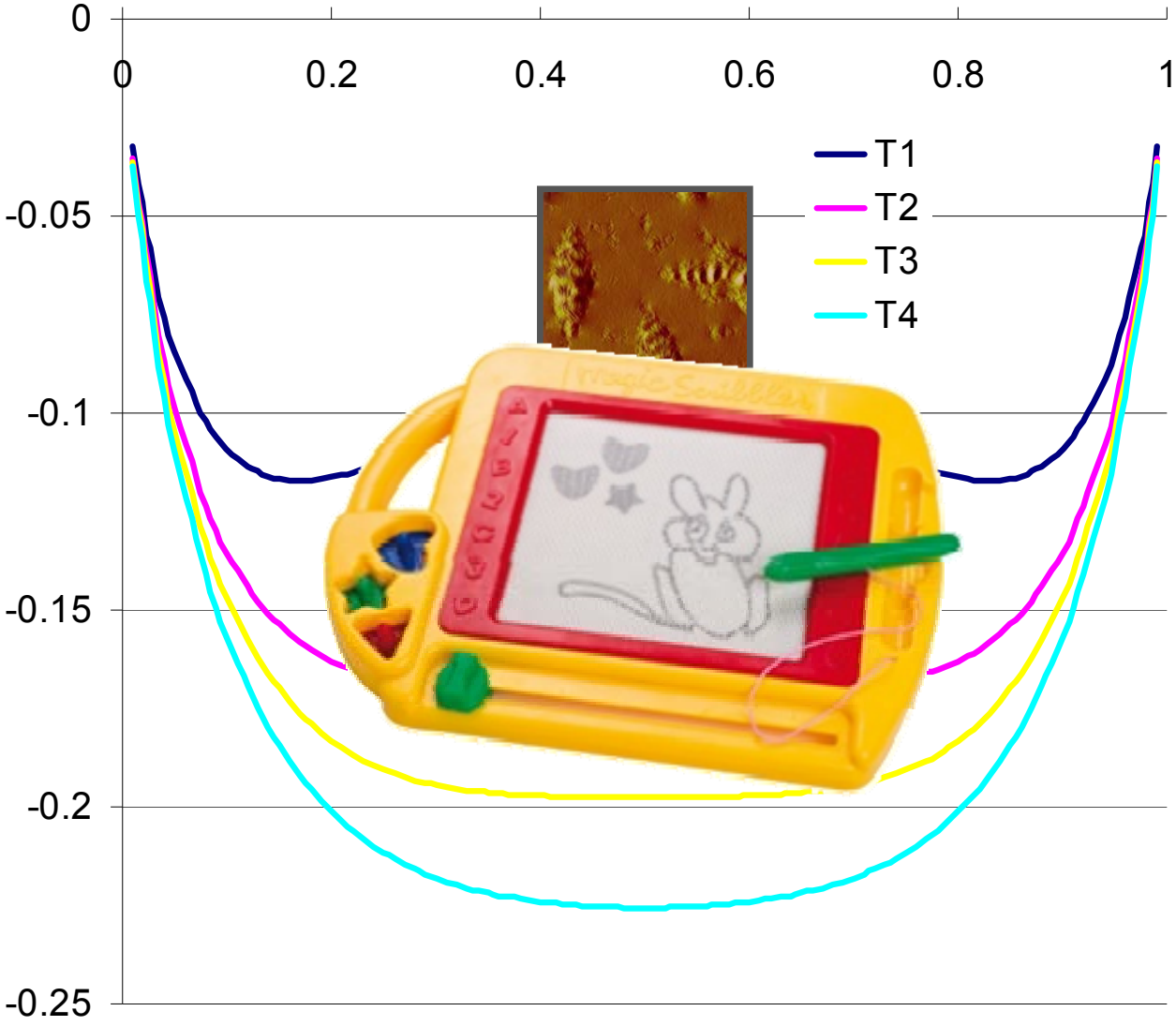

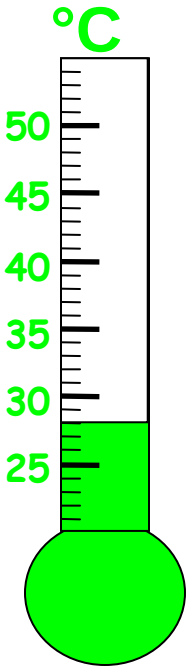

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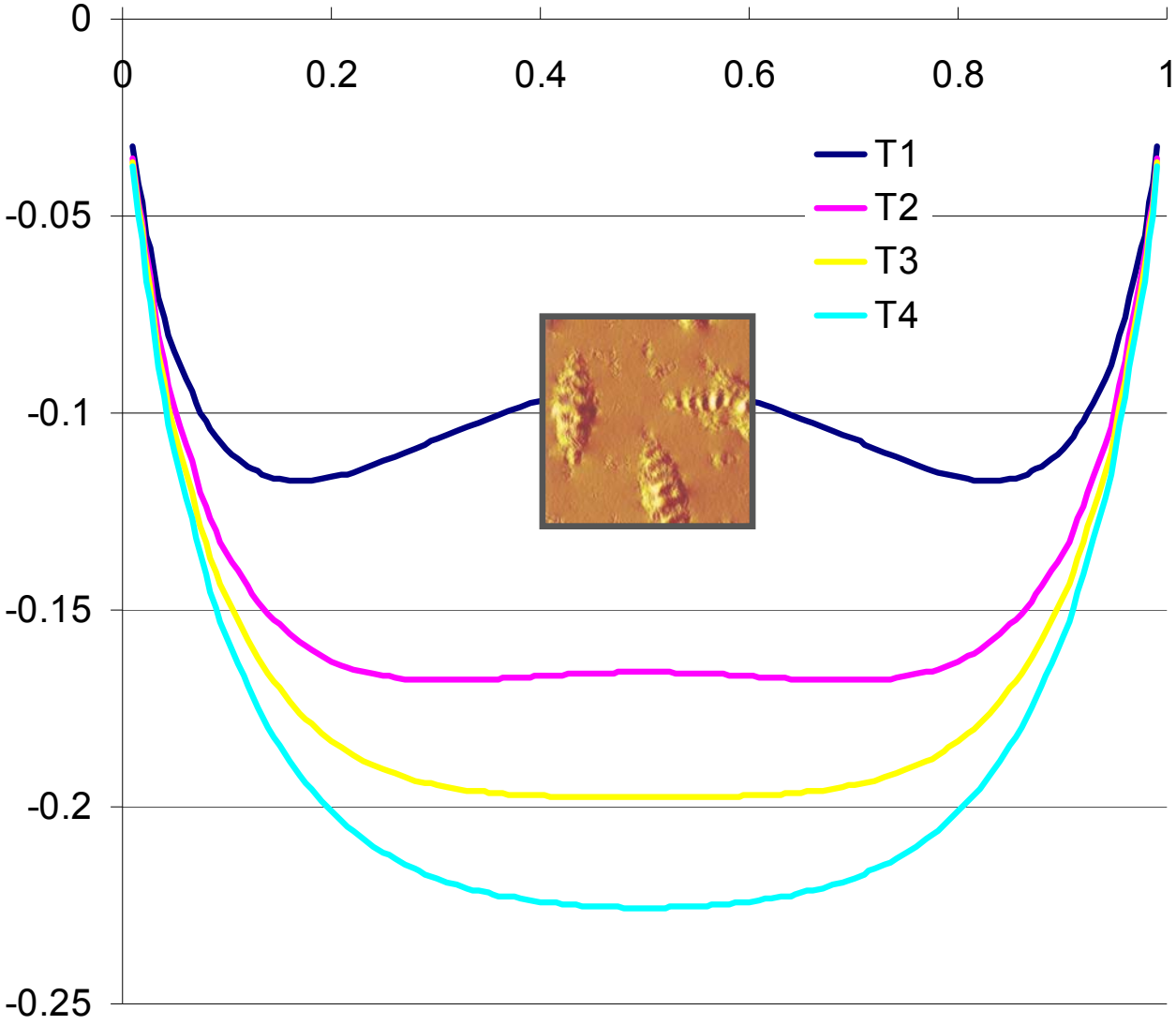

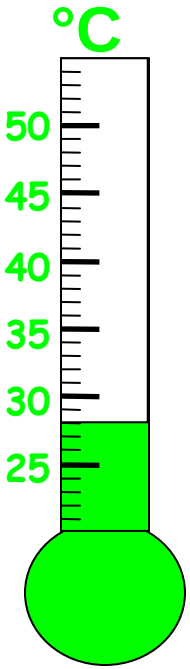

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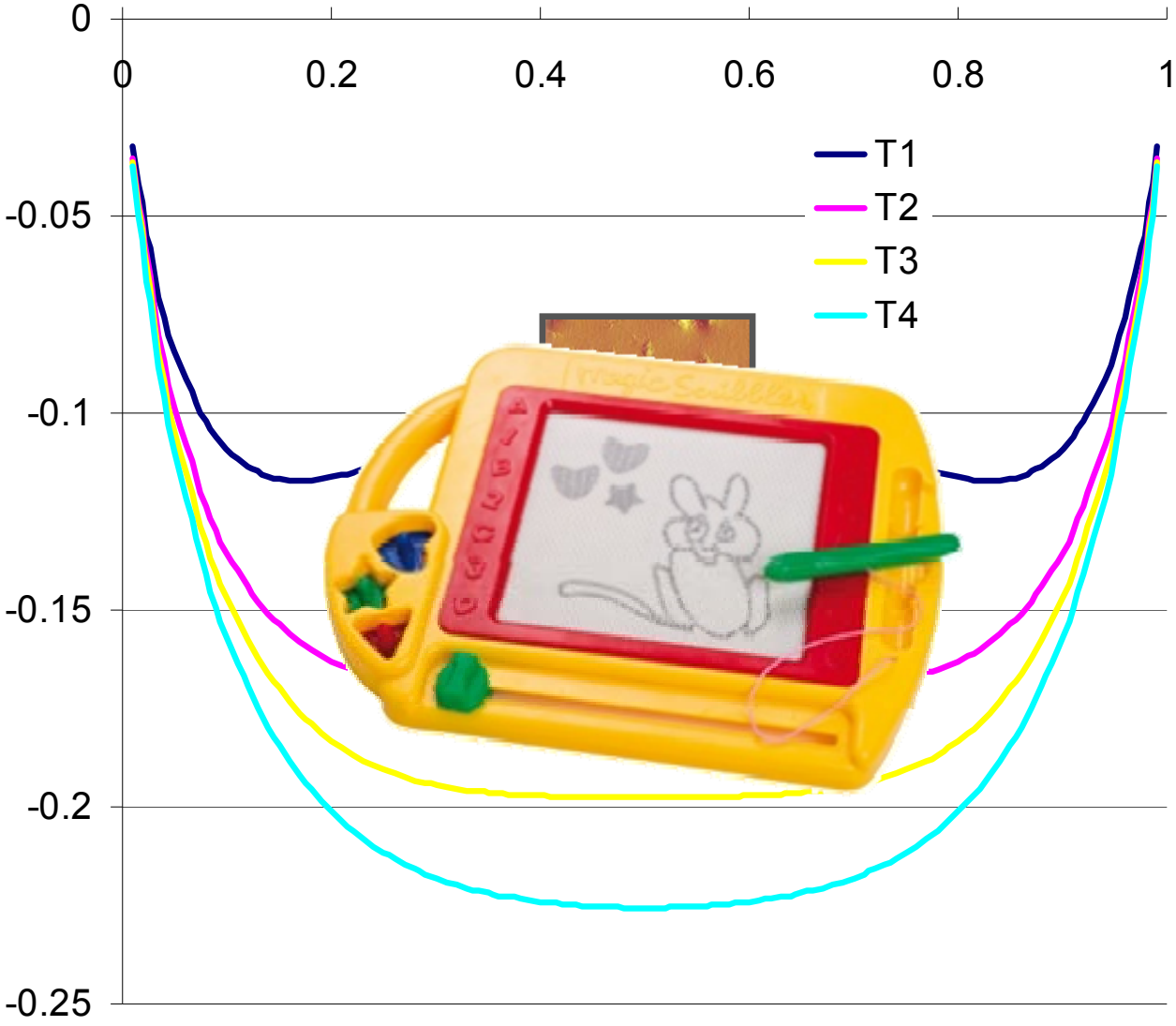

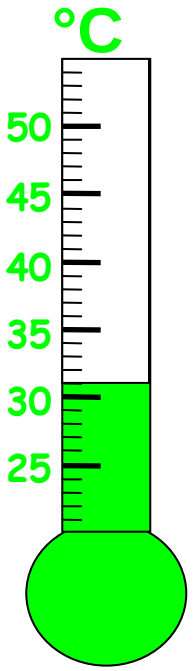

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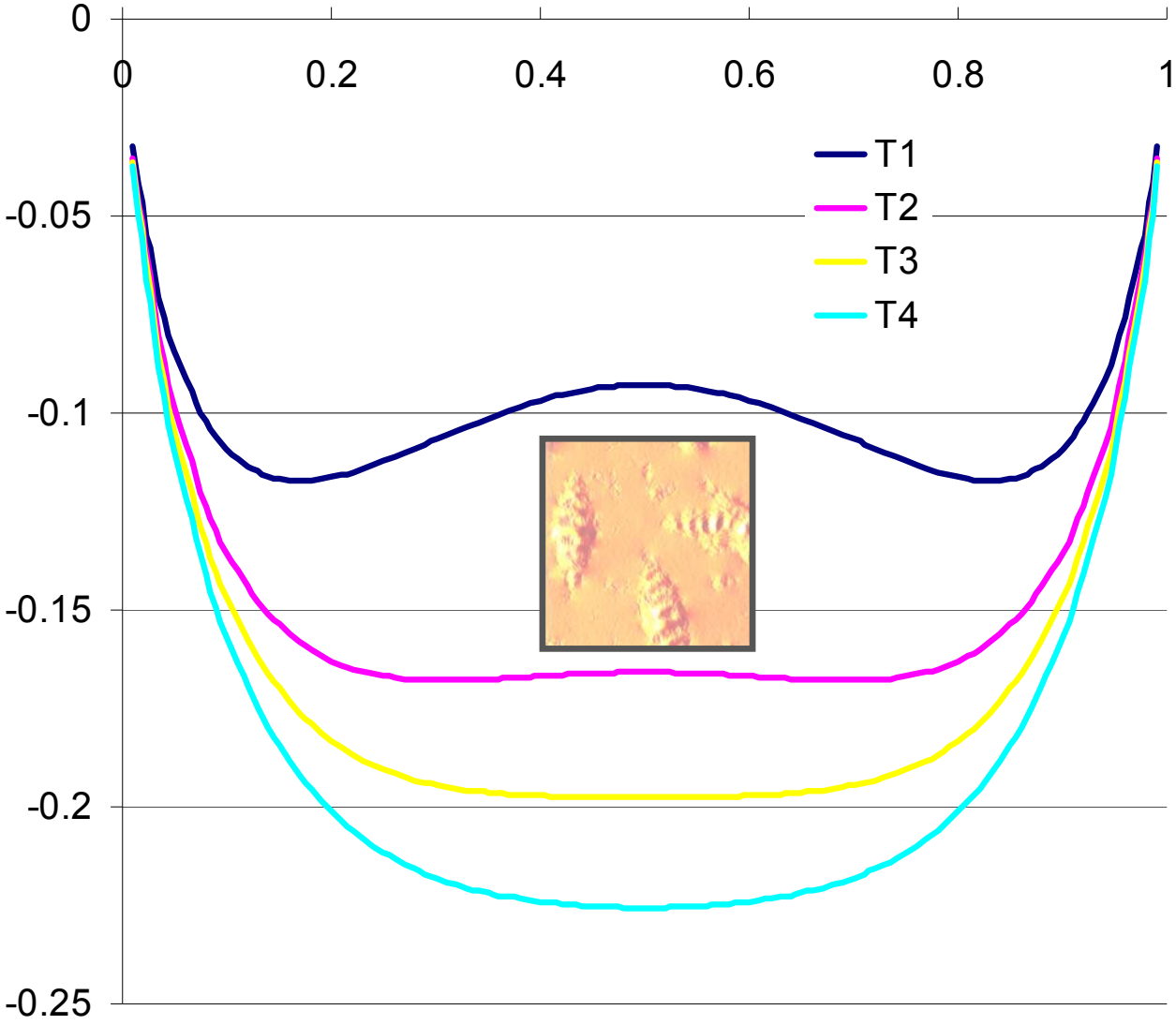

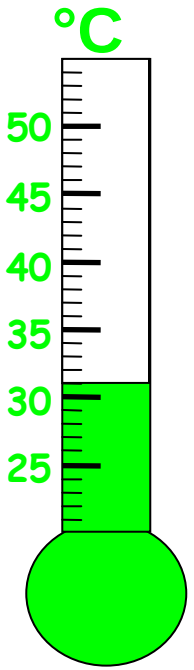

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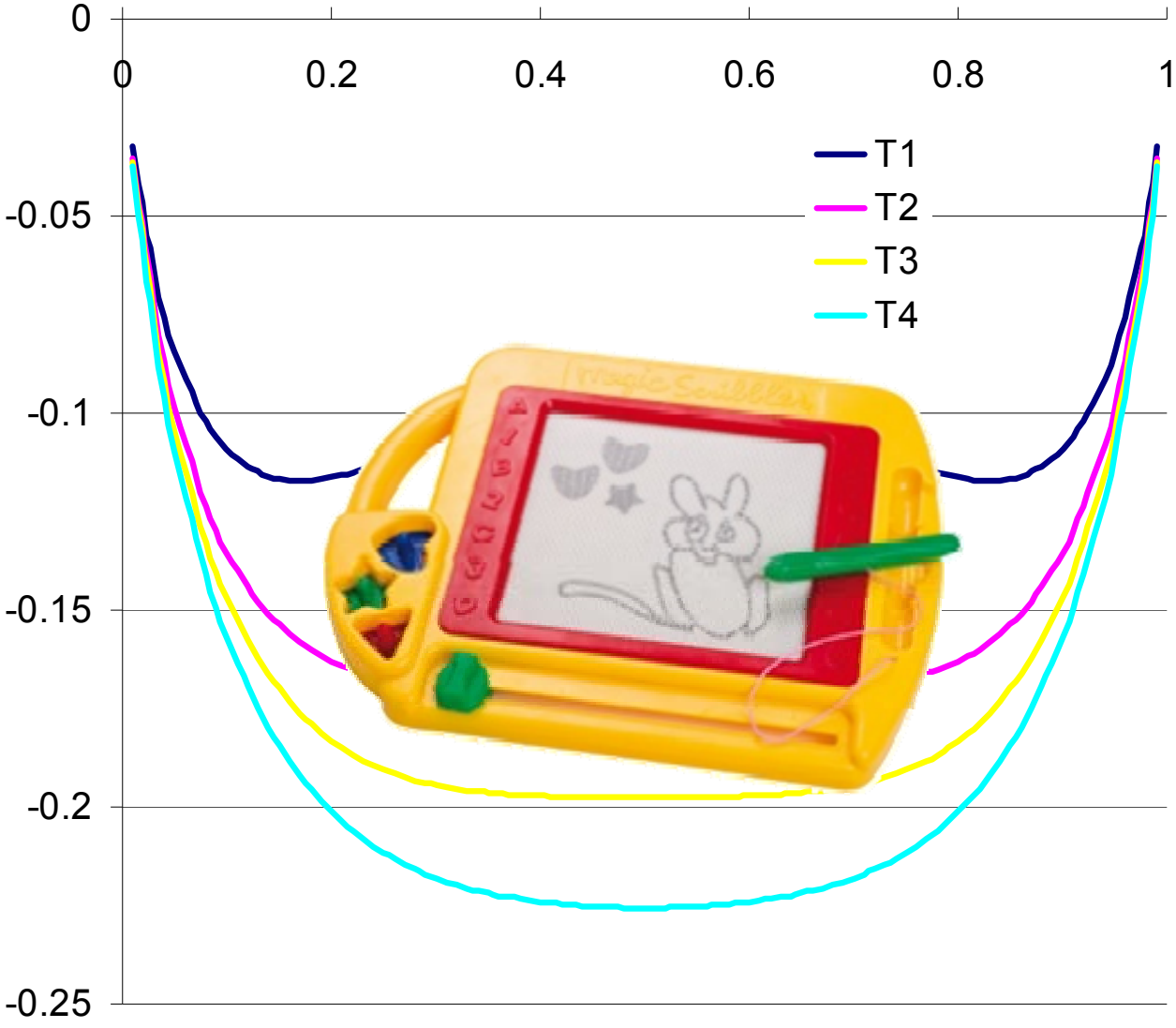

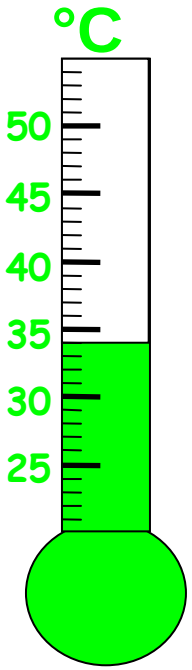

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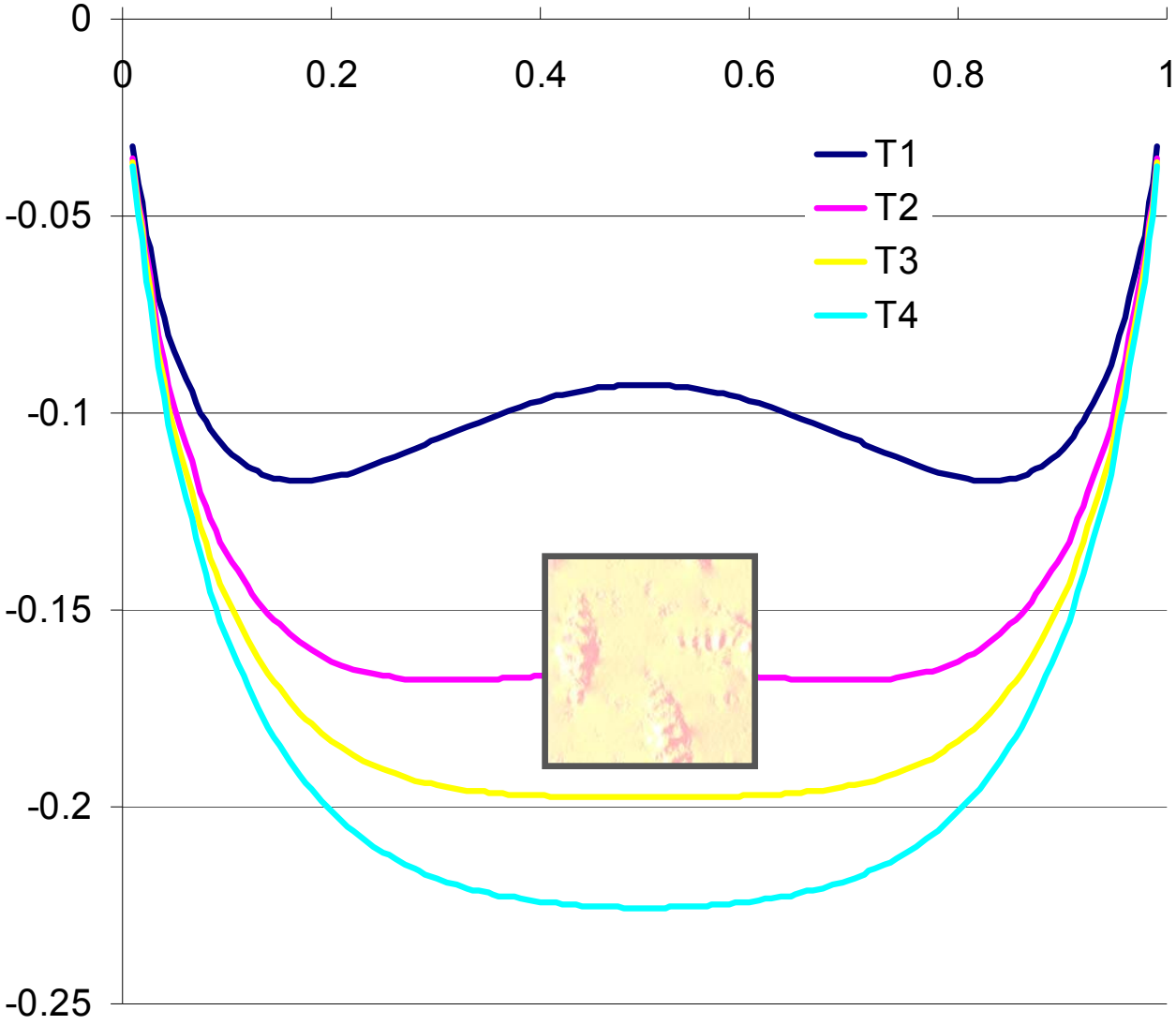

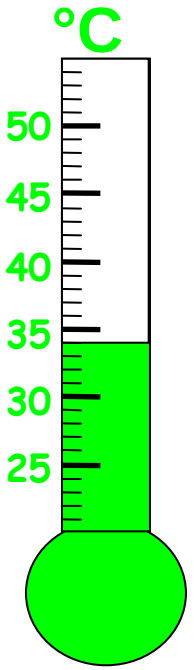

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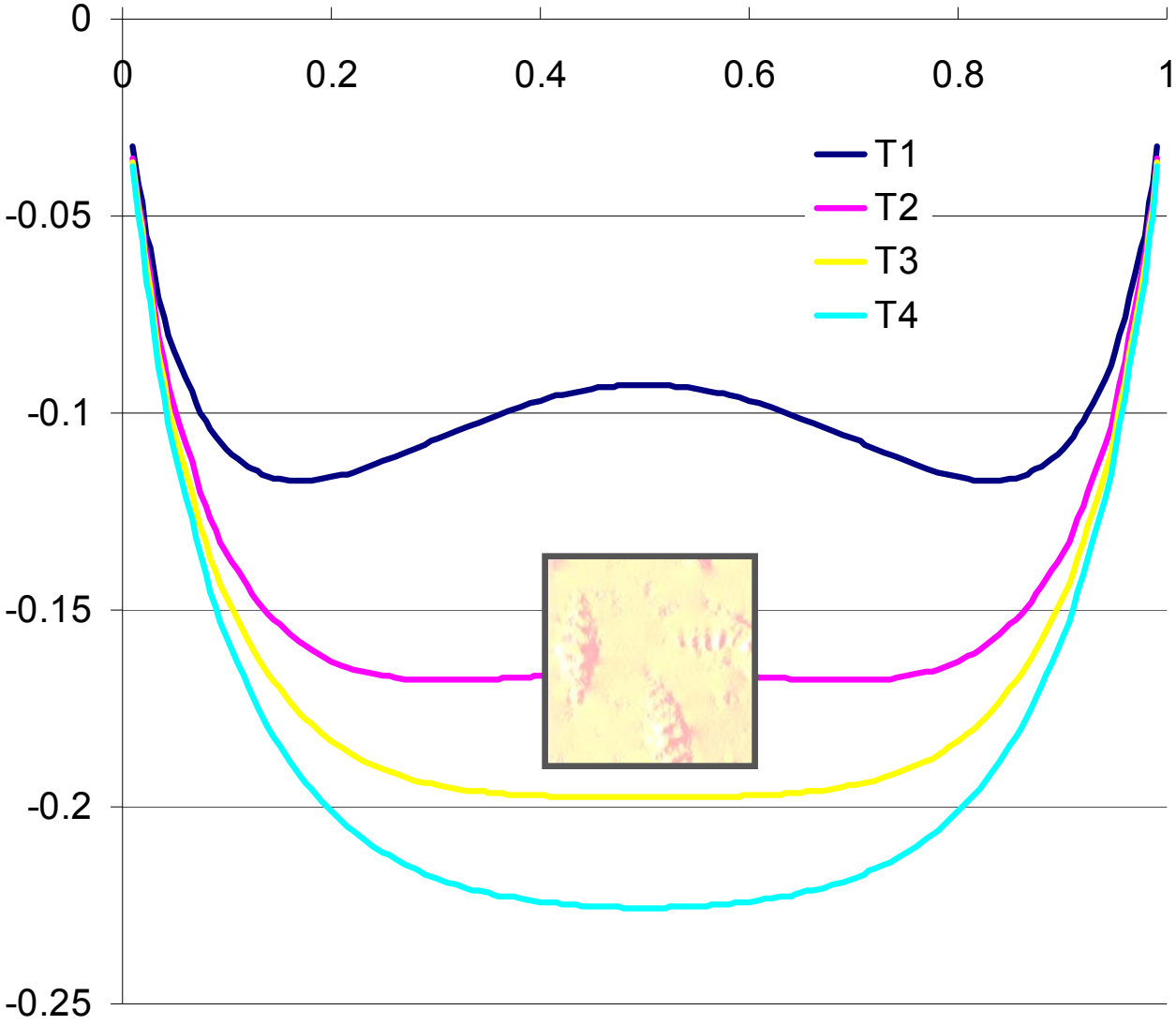

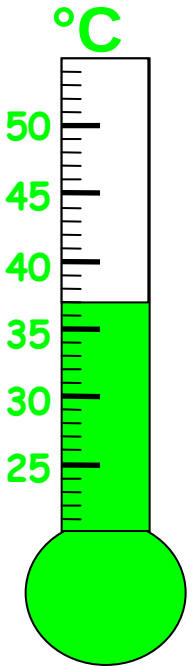

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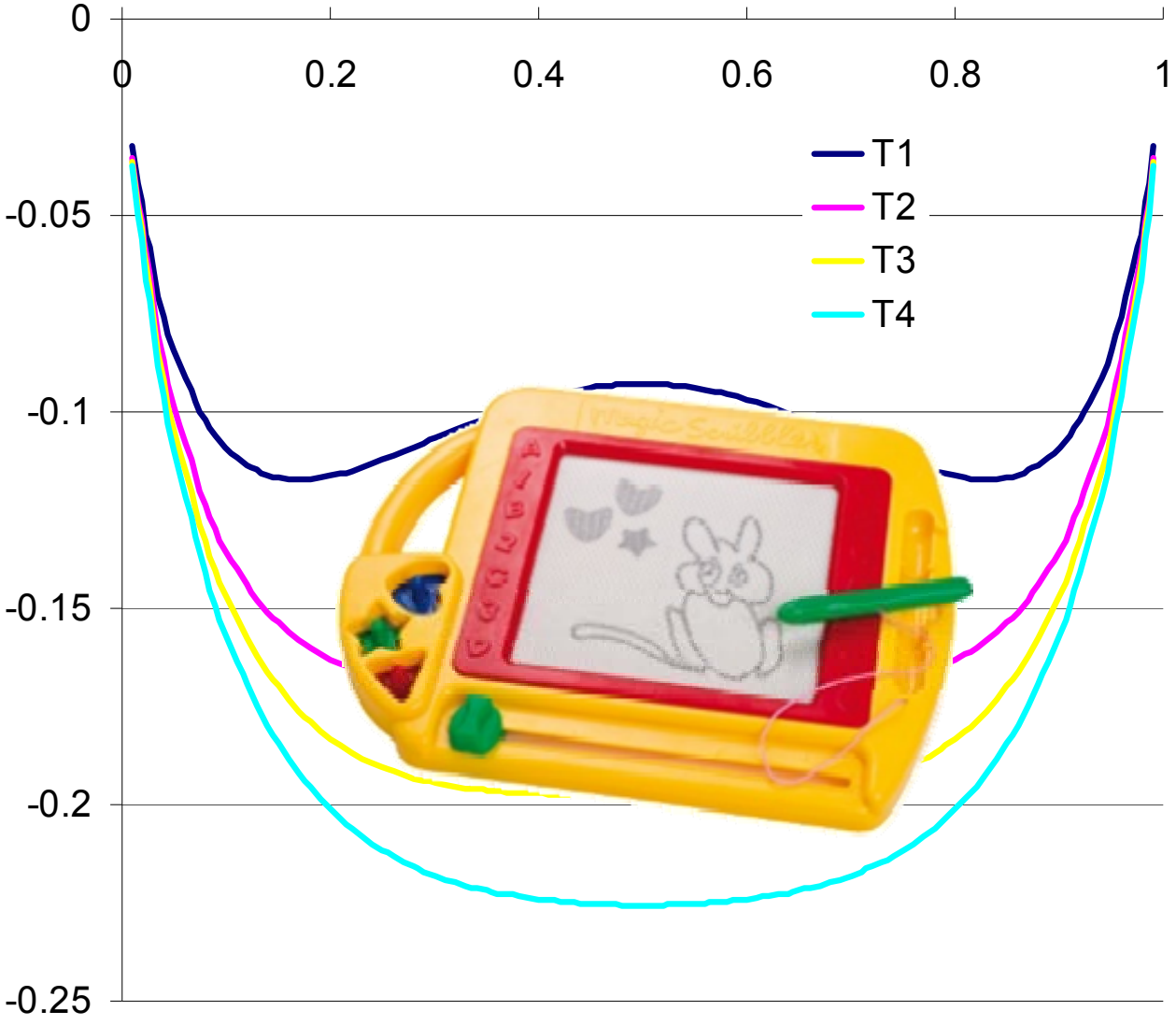

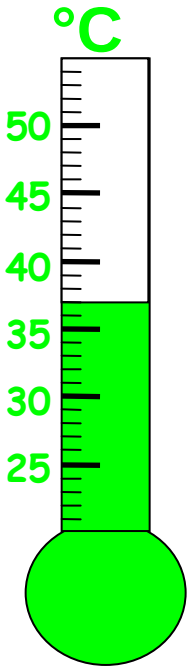

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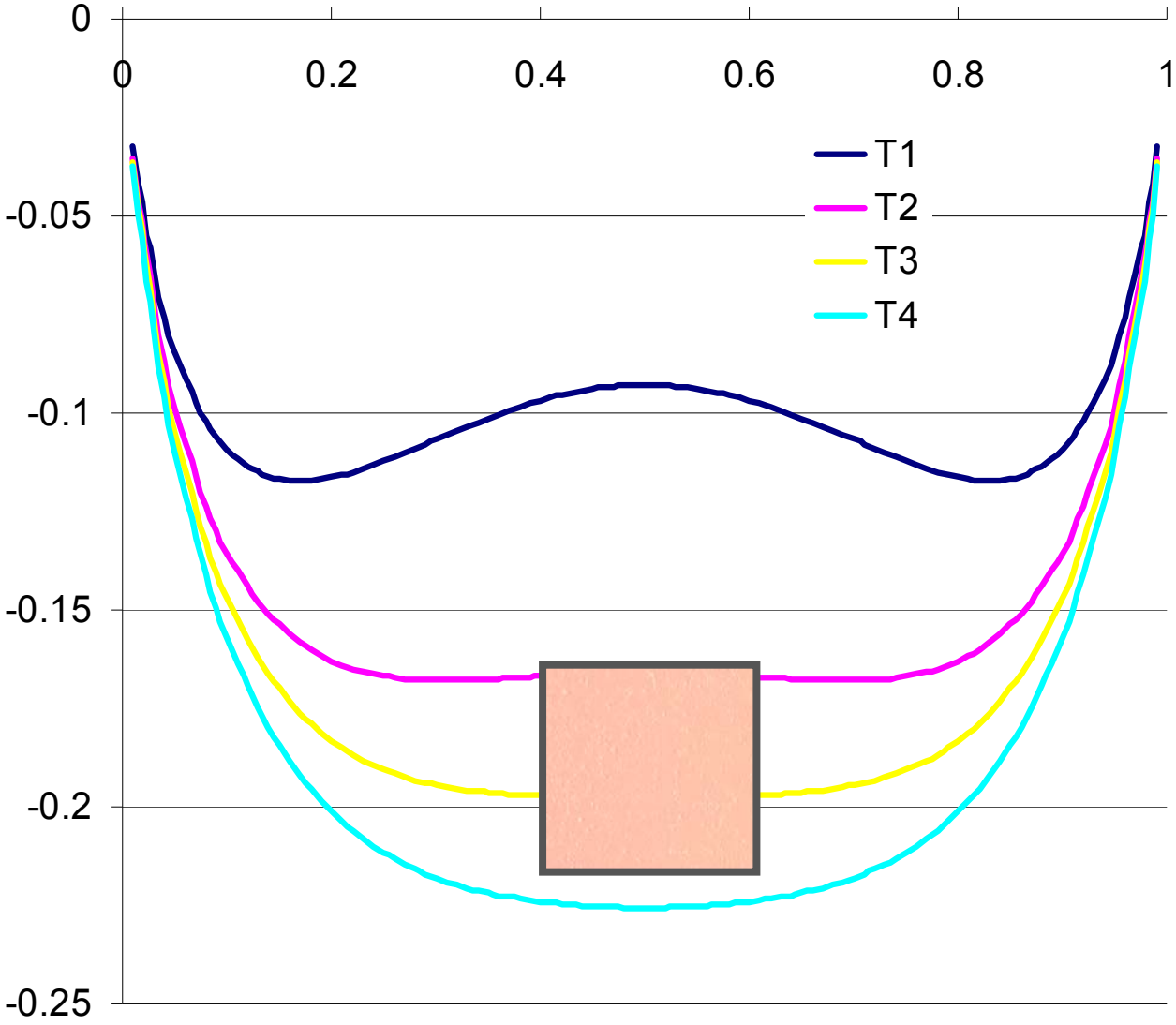
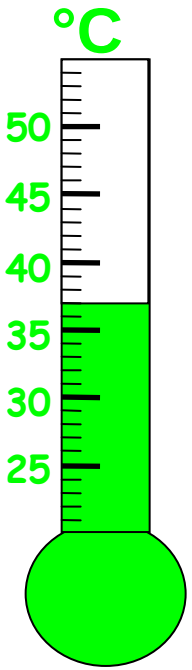
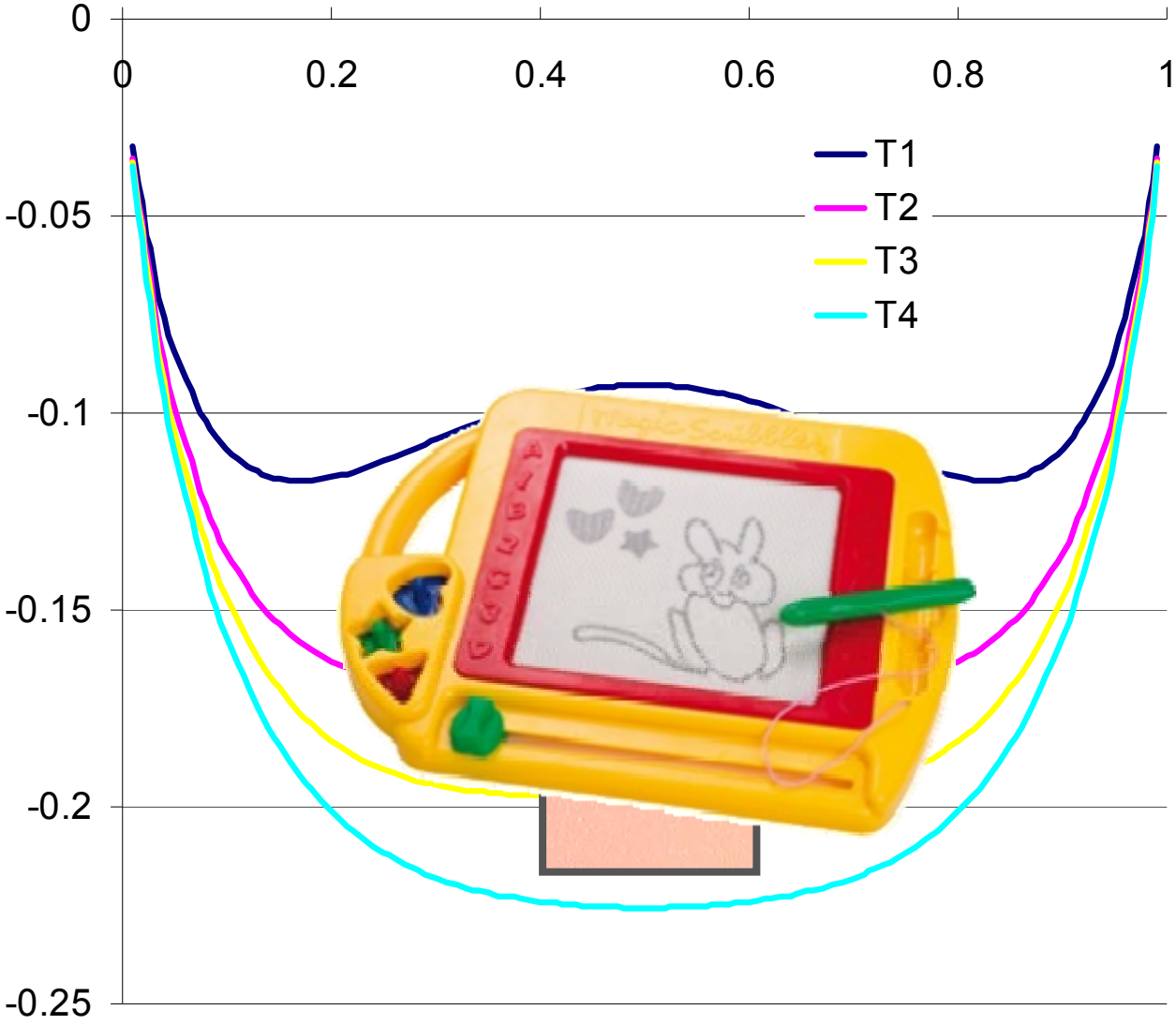
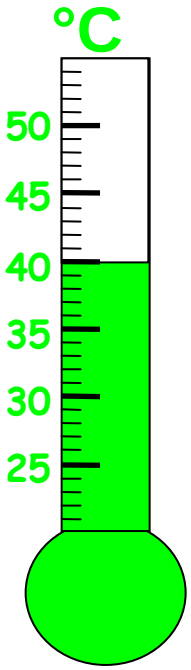




• Mixing theory





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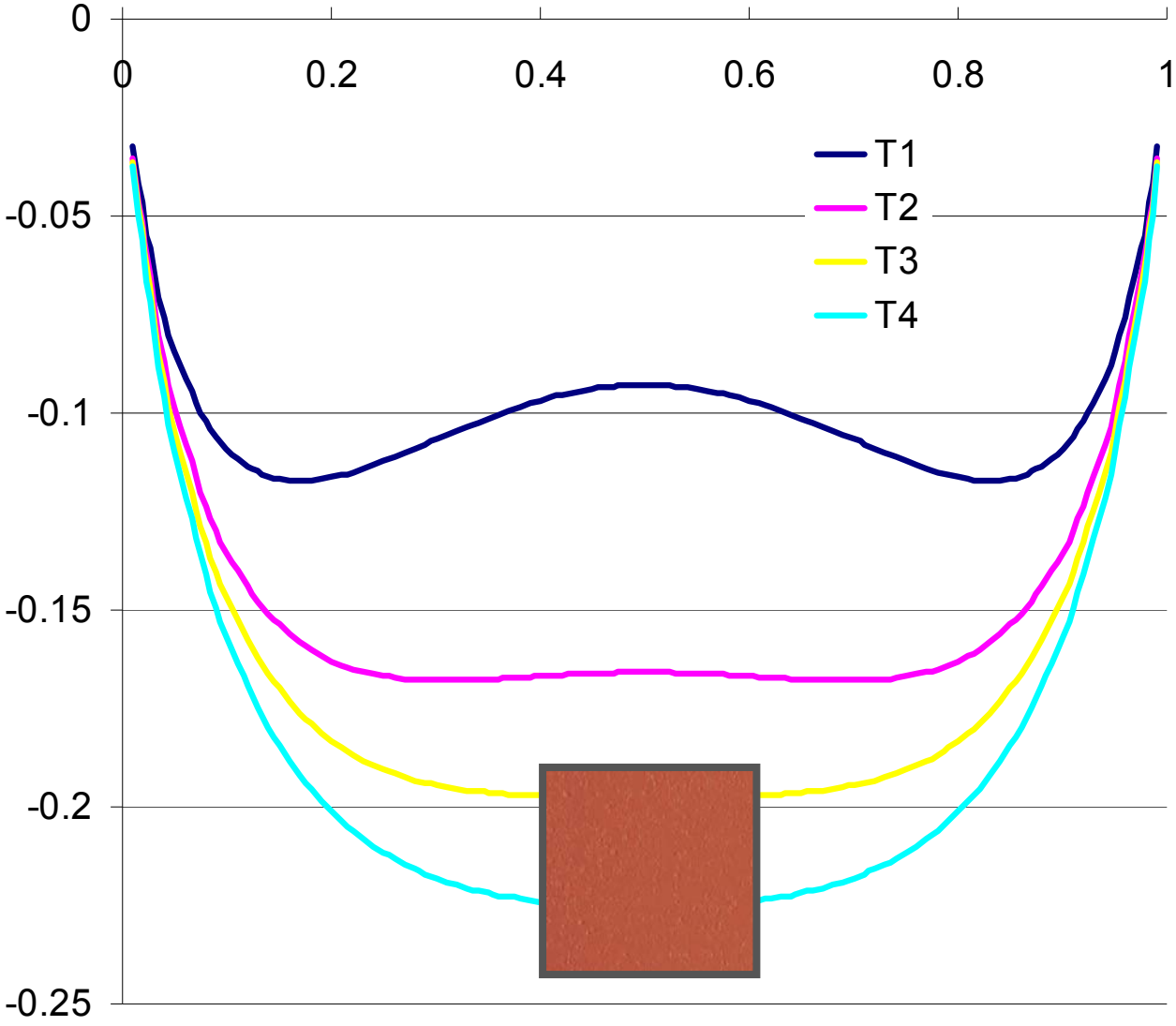

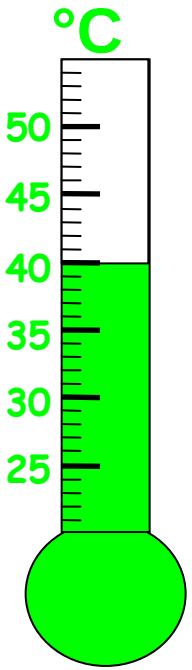

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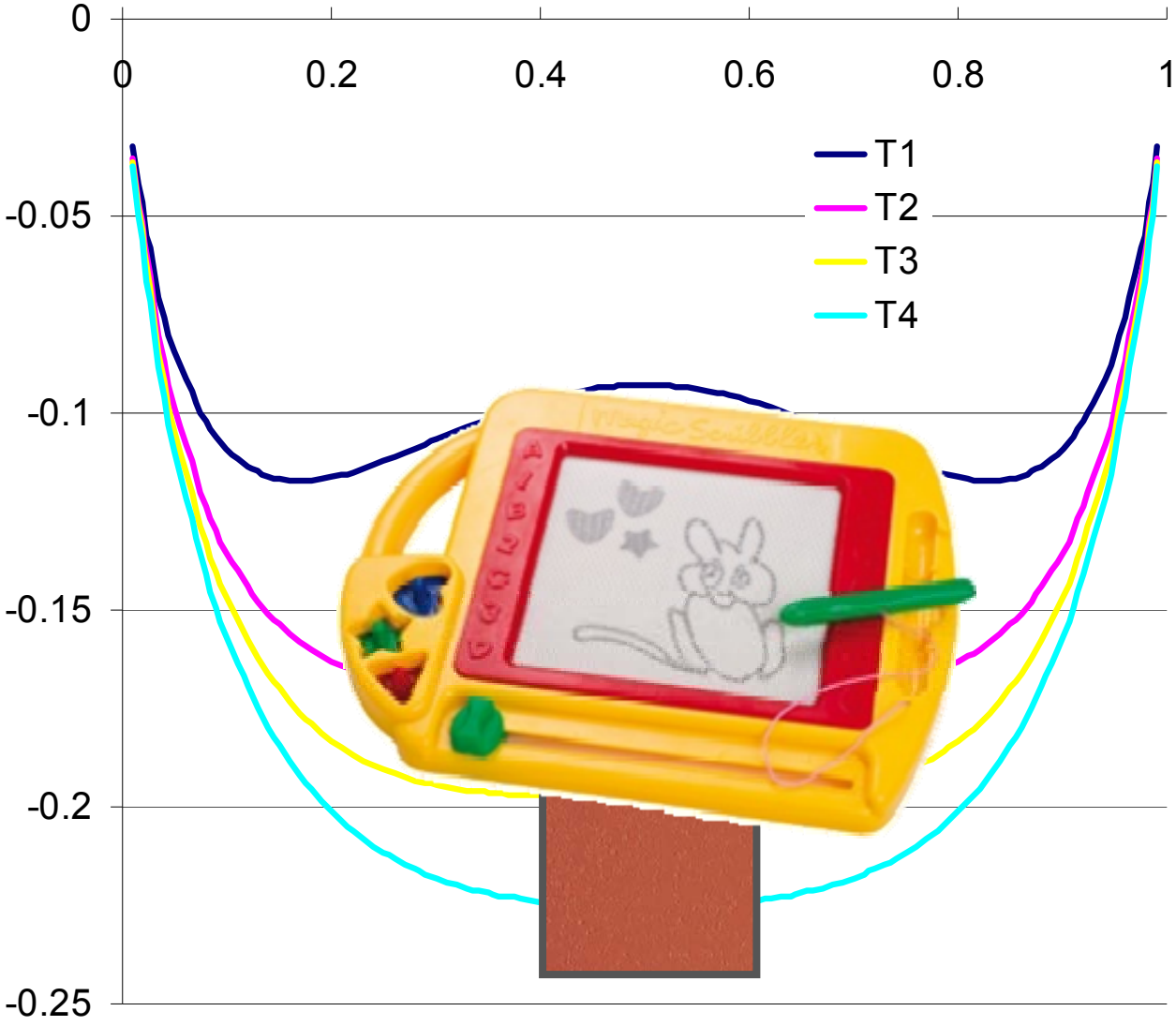

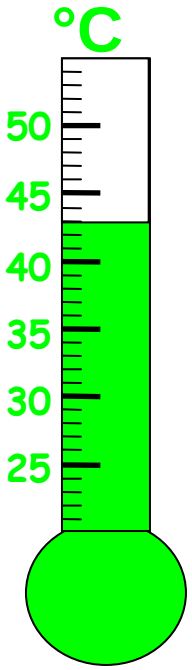

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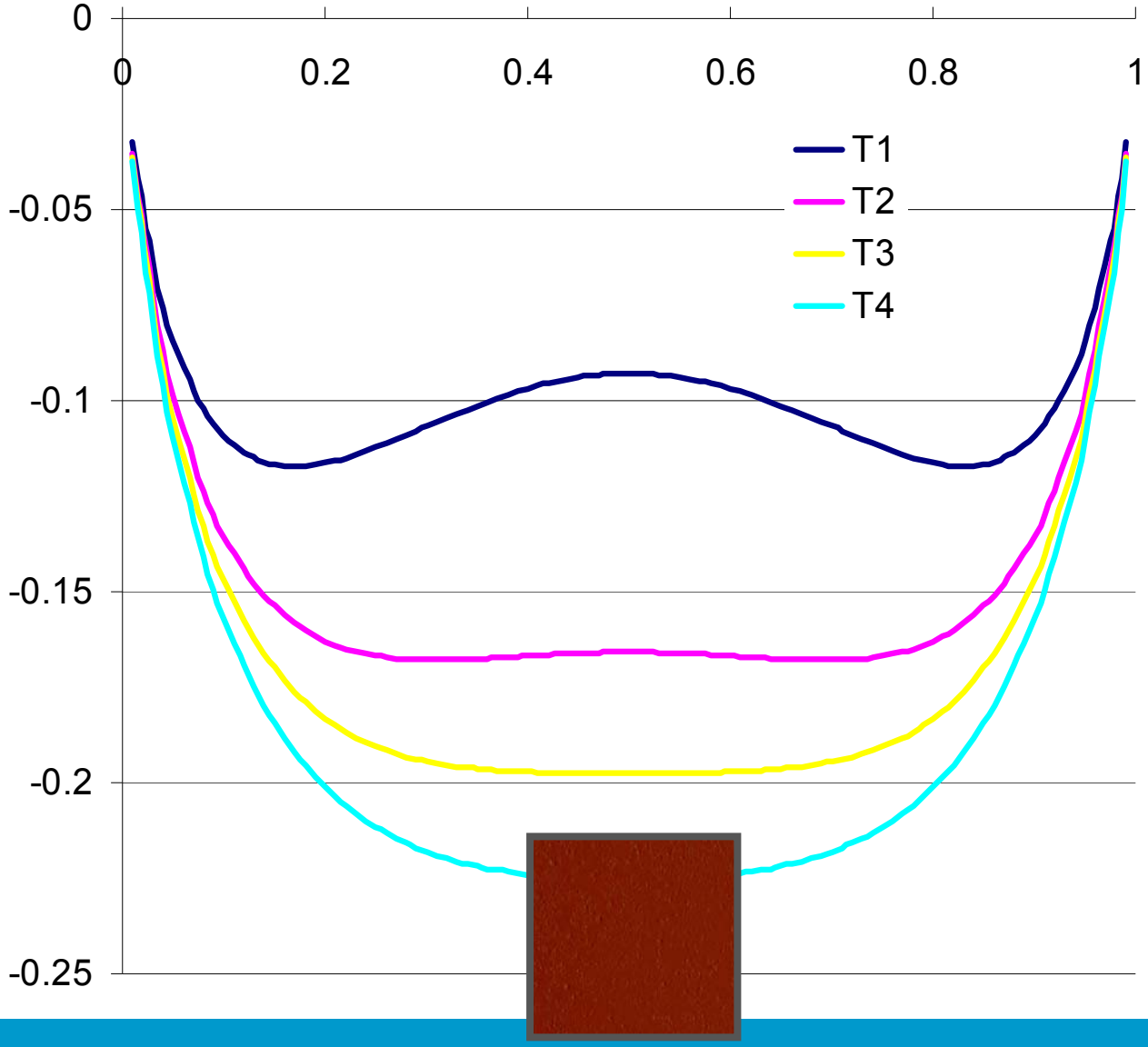
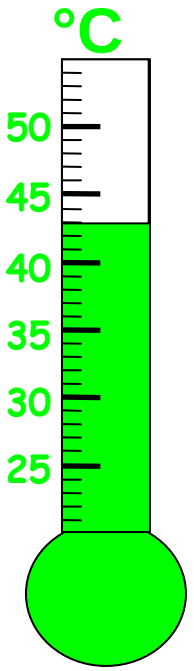




• Mixing theory

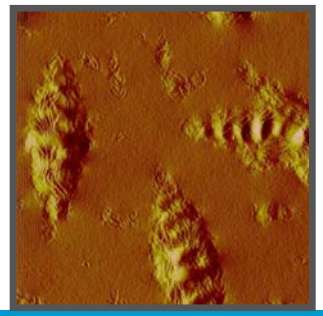
Governing equation:

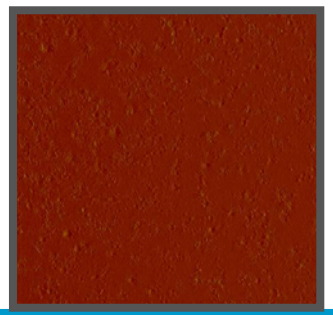
$$\rho_\alpha \frac{DC_\alpha}{Dt} - \mathrm{div}\left(\rho_\alpha \underset{\sim}{M} \cdot \nabla\mu_\alpha\right) = 0$$

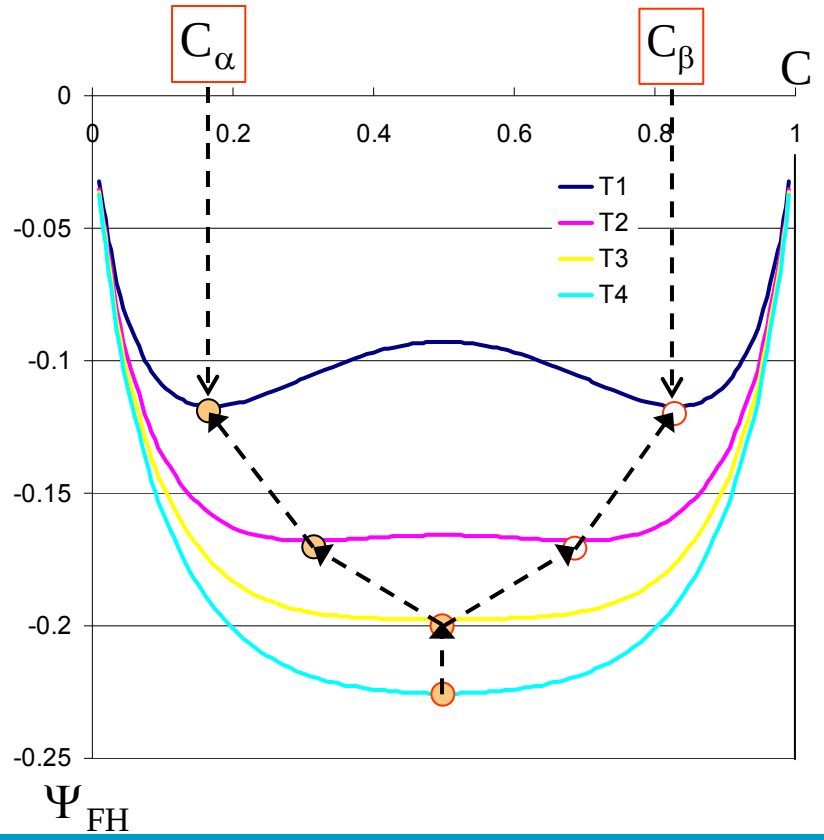
$$\underset{\sim}{M} = \sum_{i,j} M_{ij} e_i \otimes e_j$$

mobility tensor

$$\nabla\mu_\alpha = \nabla\left(\frac{\delta\Psi_{FH}}{\delta C_\alpha}\right)$$







• Mixing theory

Governing equation:

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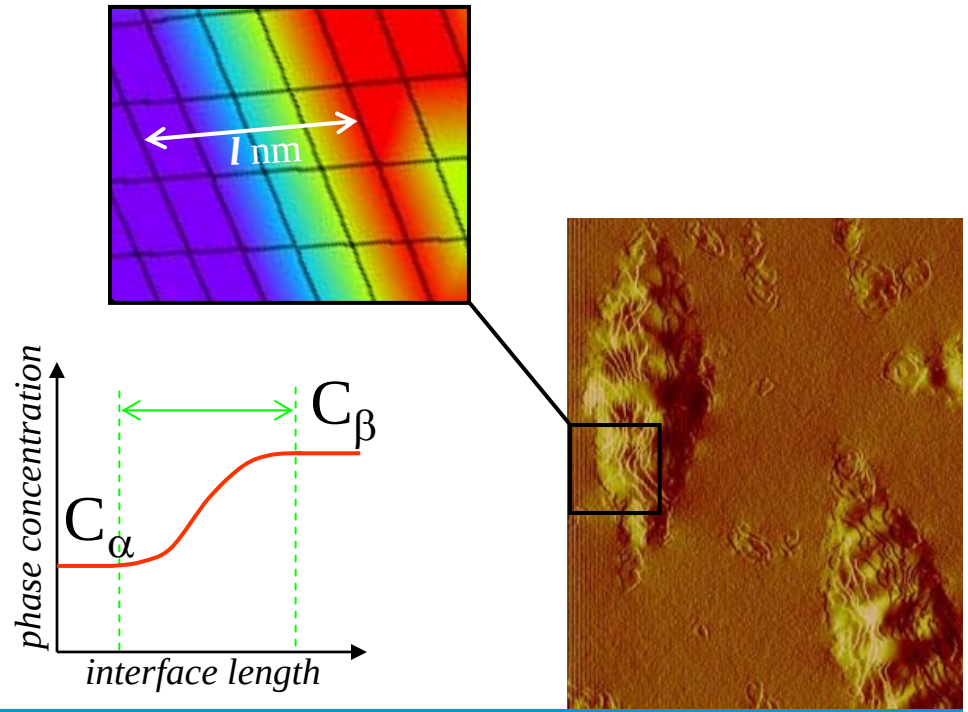
$$\rho_\alpha \frac{DC_\alpha}{Dt} - \mathrm{div}\left(\rho_\alpha \underset{\sim}{M} \cdot \nabla \mu_\alpha\right) = 0$$

$$\nabla \mu_\alpha = \nabla\left(\frac{\delta \Psi}{\delta C_\alpha}\right)$$

$$\Psi = \Psi_{FH} + \Psi_\gamma + \Psi_\varepsilon + \ldots$$

surface

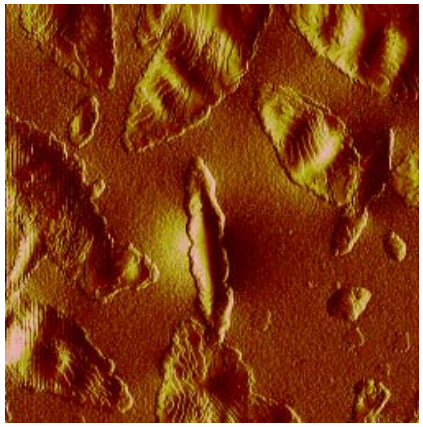
mechanical

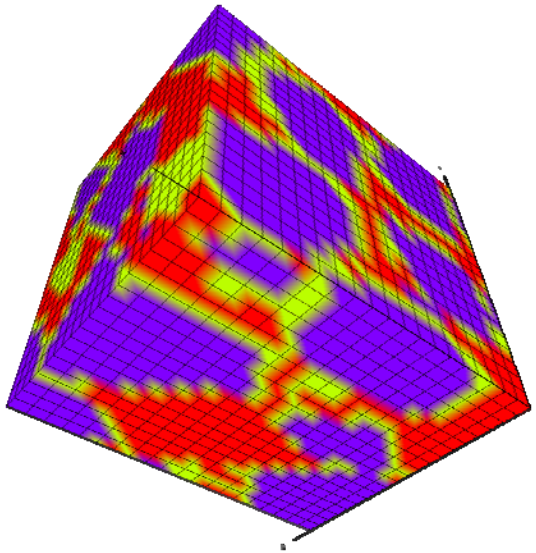


• Mixing theory

Finite element formulation:

$$\int_V w_i \rho_\alpha \frac{DC_\alpha}{Dt} dV + \int_V \nabla w_i \rho_\alpha \underset{\sim}{M} \left(\frac{\partial^2 \Psi}{\partial C_\alpha^2} + \kappa \right) \nabla C_\alpha \, dV - \int_V \nabla w_i \rho_\alpha \underset{\sim}{M} \, \kappa \nabla \bar{C}_\alpha \, dV = 0$$

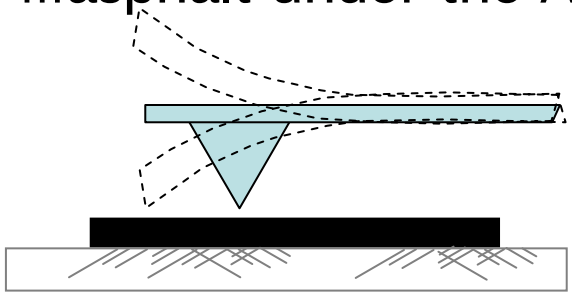


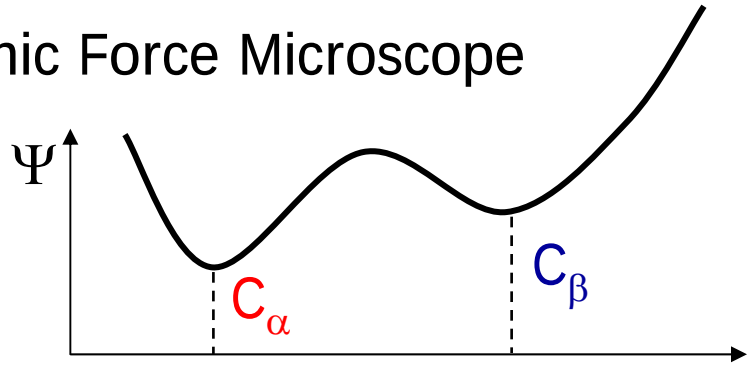


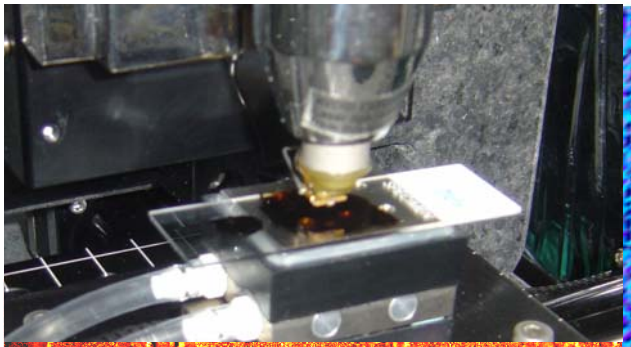
• Mixing theory

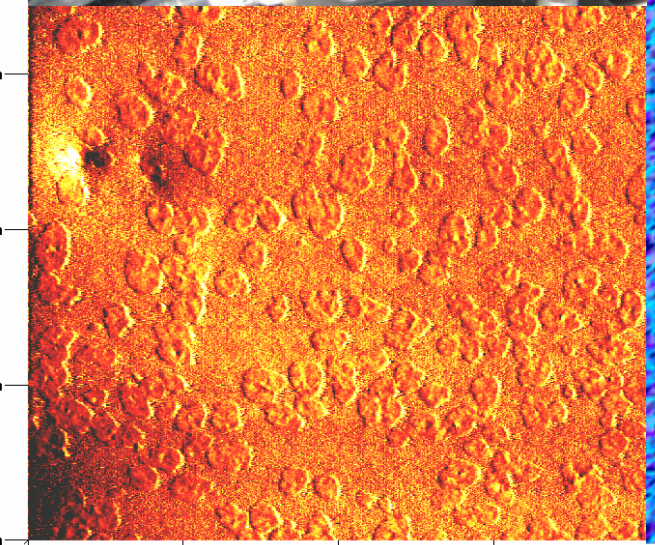
INPUT PARAMETER	Value
Gas constant R	$8.314472\ \mathrm{J/K \cdot mol}$
Temperature T	$273.14 + \mathrm{T}\left(^{\circ}\mathrm{C}\right)$
Molecular volume V_α	e.g. 636 ml/mol
Solubility of δ_α and δ_β of two phases to compute the interaction parameter $X = \frac{V_\alpha}{RT}\left(\delta_\beta - \delta_\alpha\right)^2$	e.g. $\delta_\alpha = 14$ and $\delta = 17$
M_{ij}	e.g. $M_{ij}\delta_{ij}$ and $M_{11} = M_{22} = M_{33}$
λ from $\overline{c} = c + \lambda^2 \nabla \cdot \nabla c$	From calibration
κ_2 from which $\kappa = -\frac{\kappa_2}{\lambda^2}$	From calibration

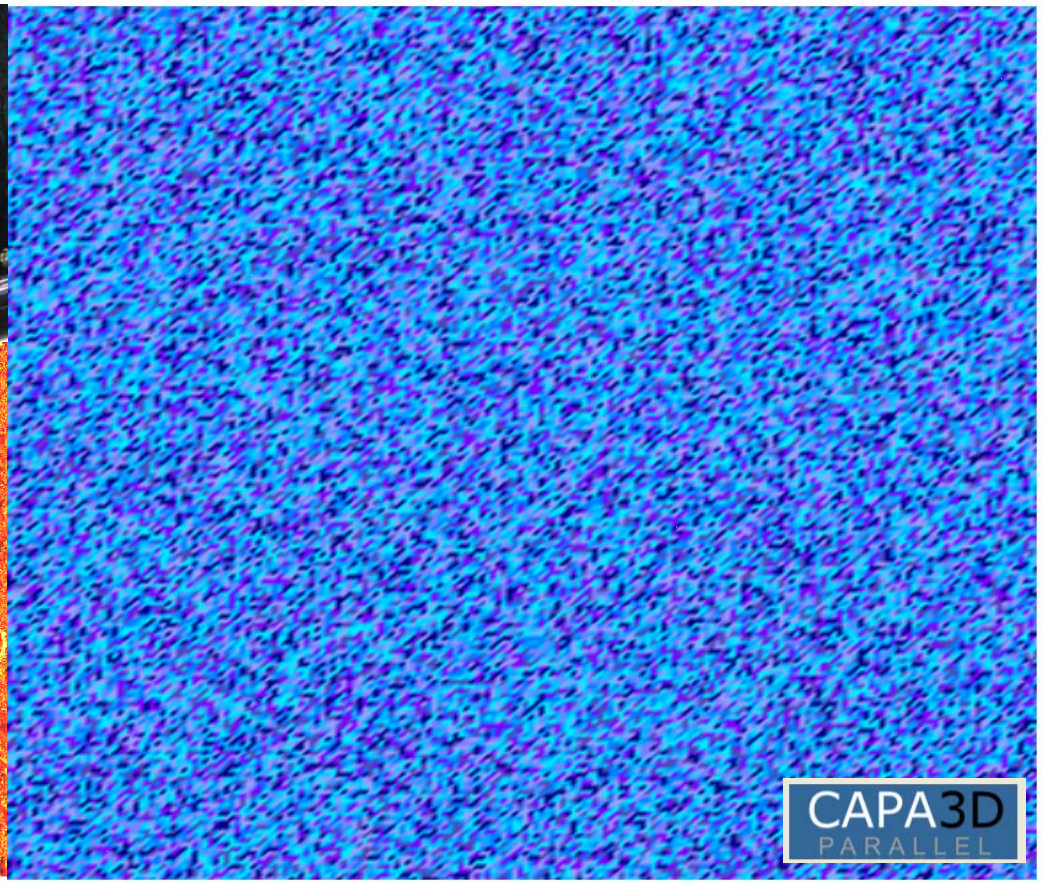
...asphalt under the Atomic Force Microscope



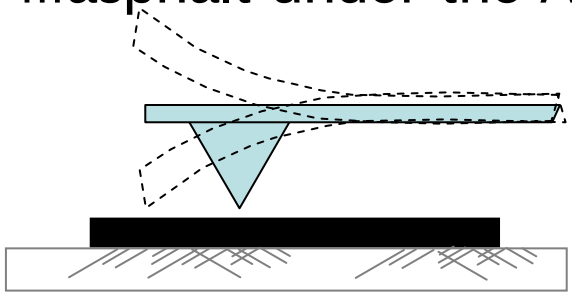


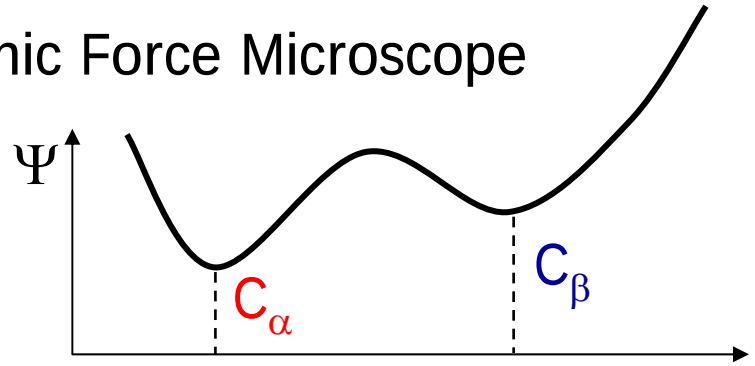


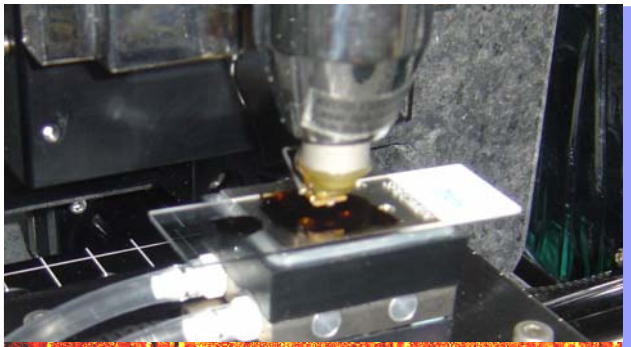


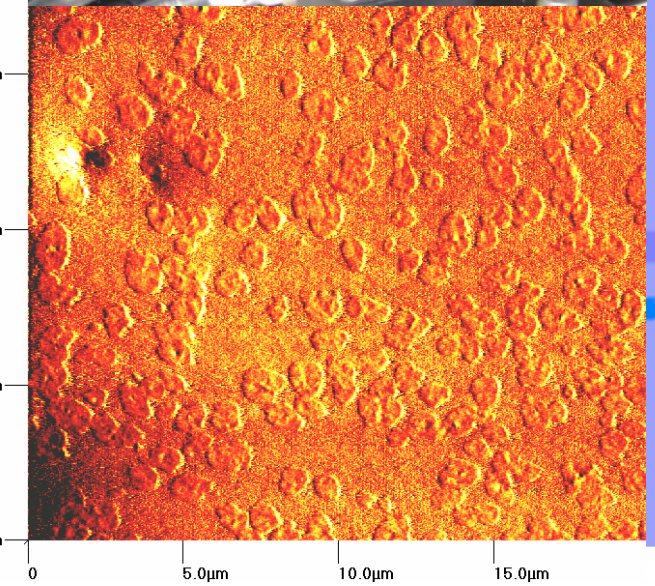


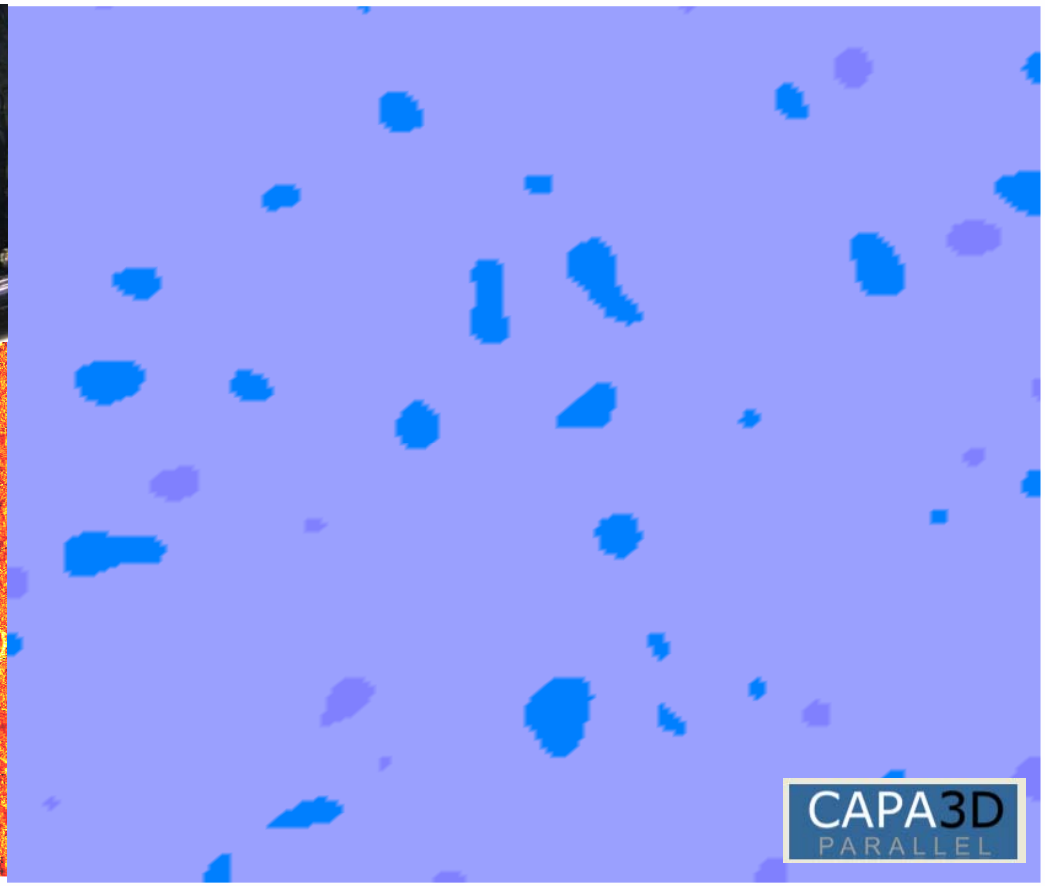
...asphalt under the Atomic Force Microscope











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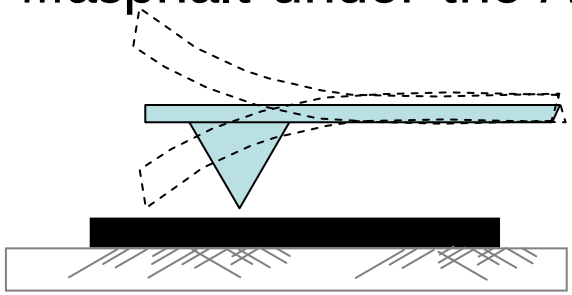
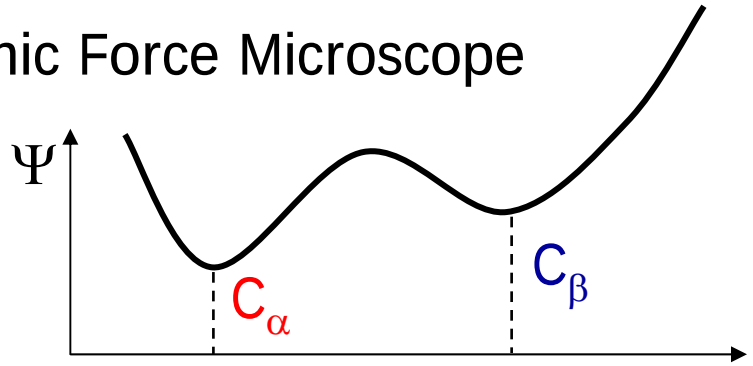
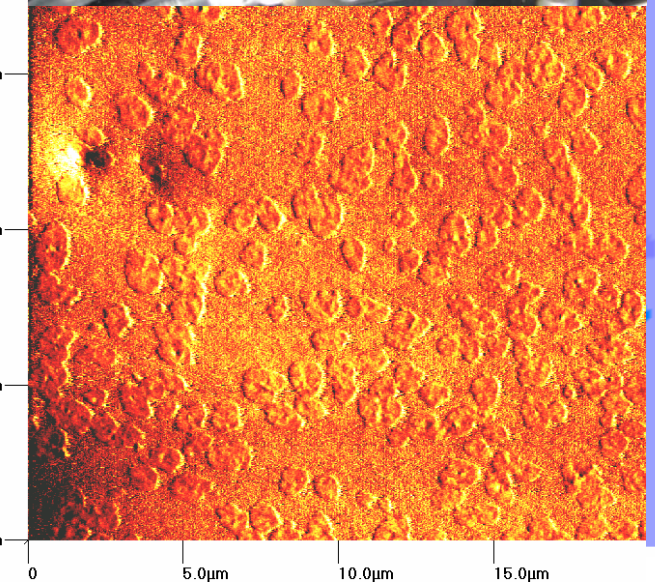
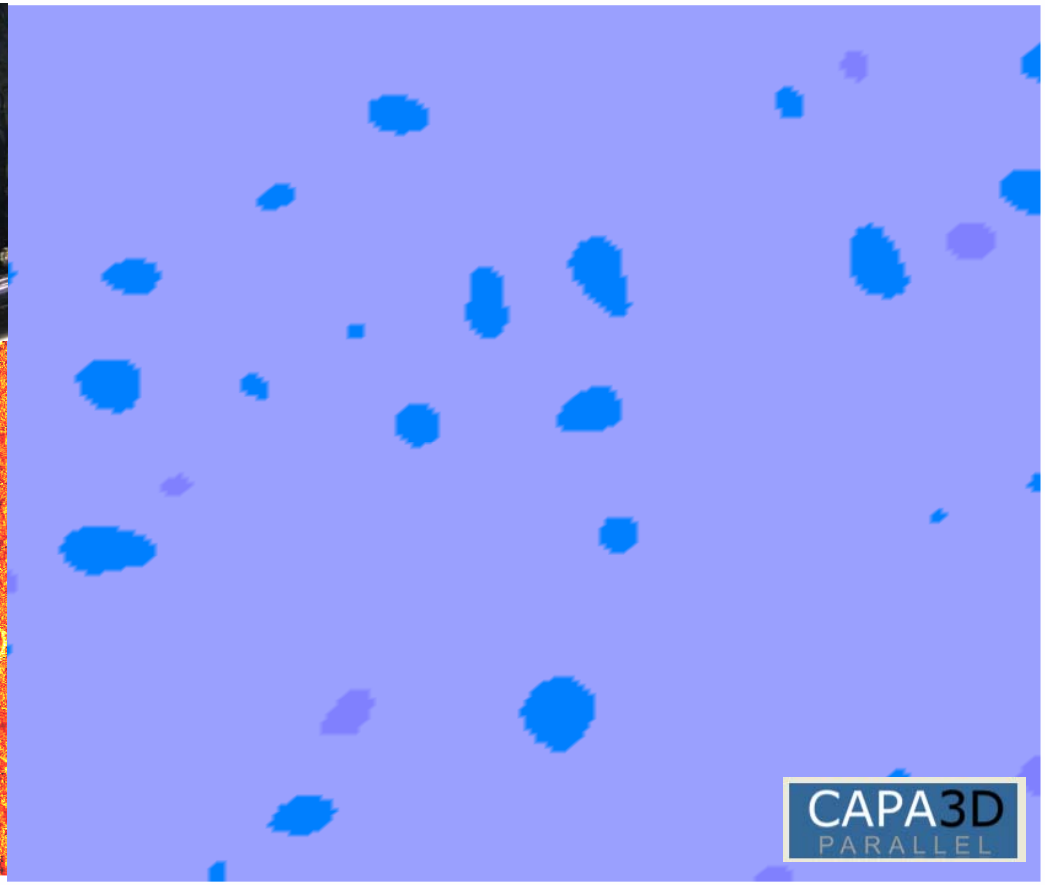
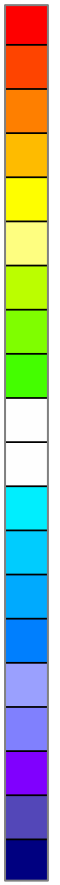


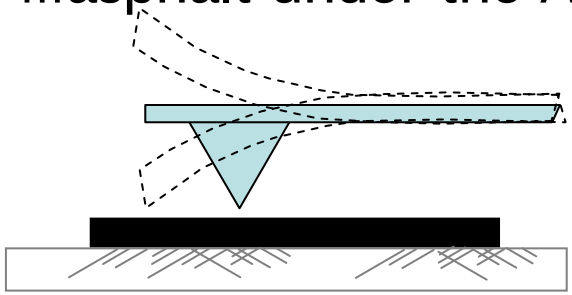


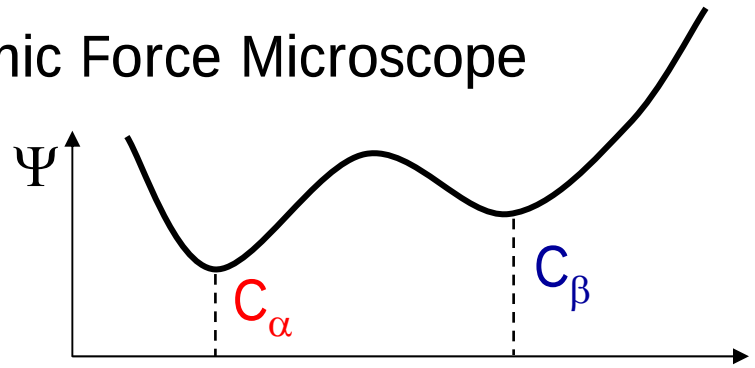


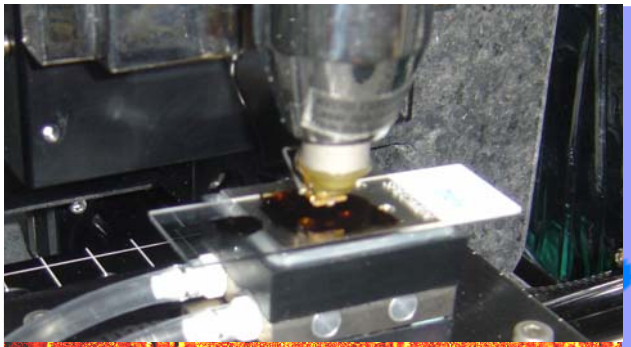


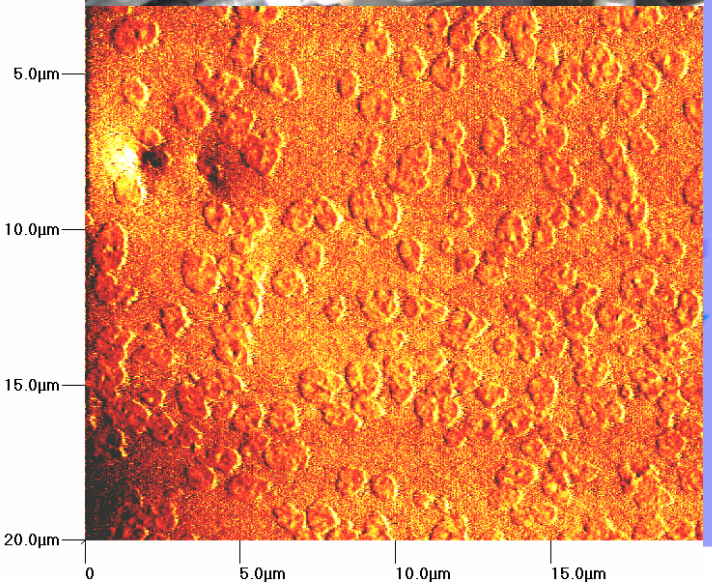


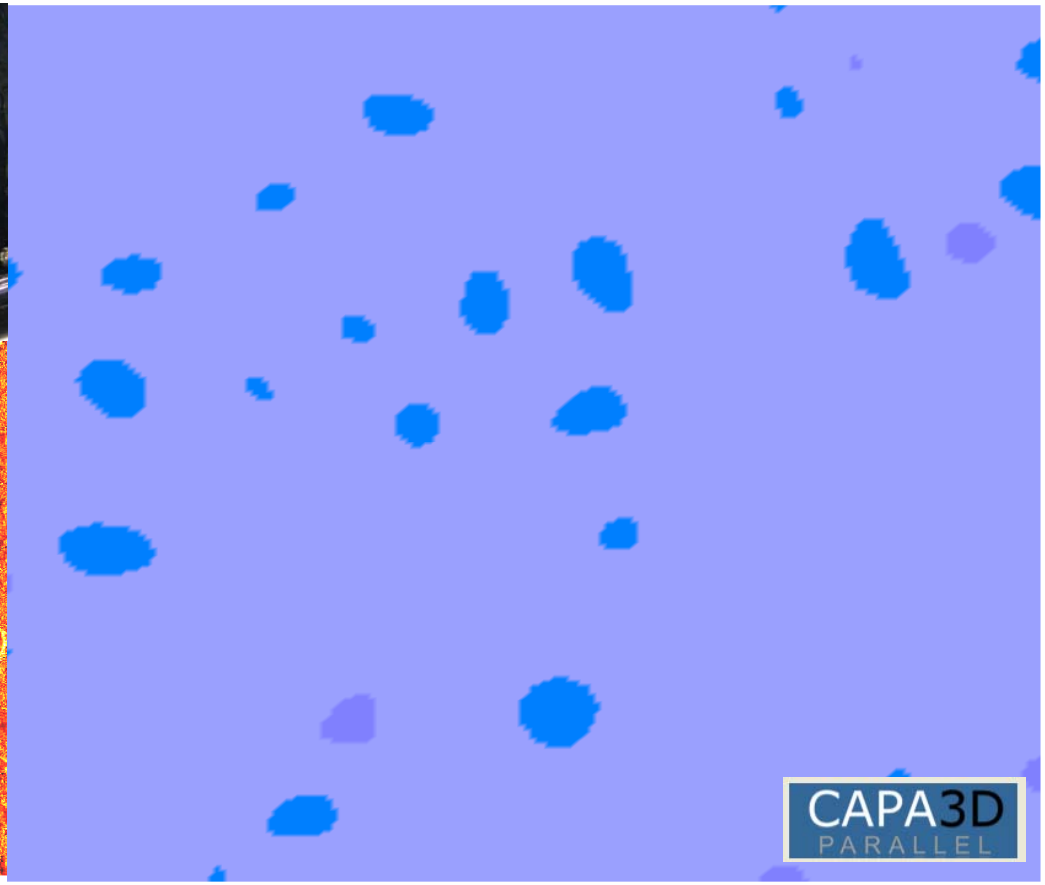
...asphalt under the Atomic Force Microscope



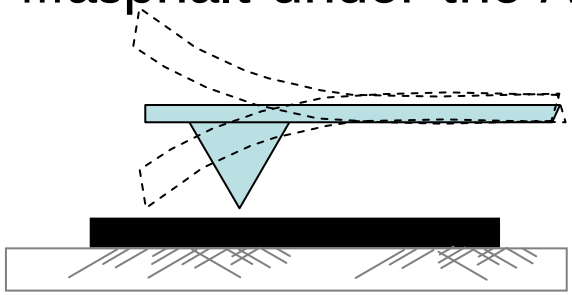


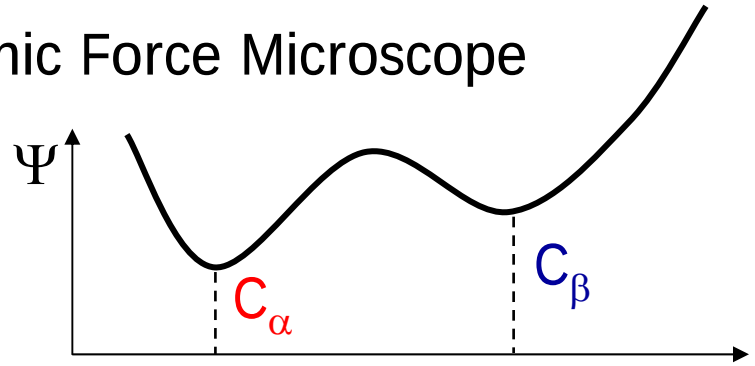


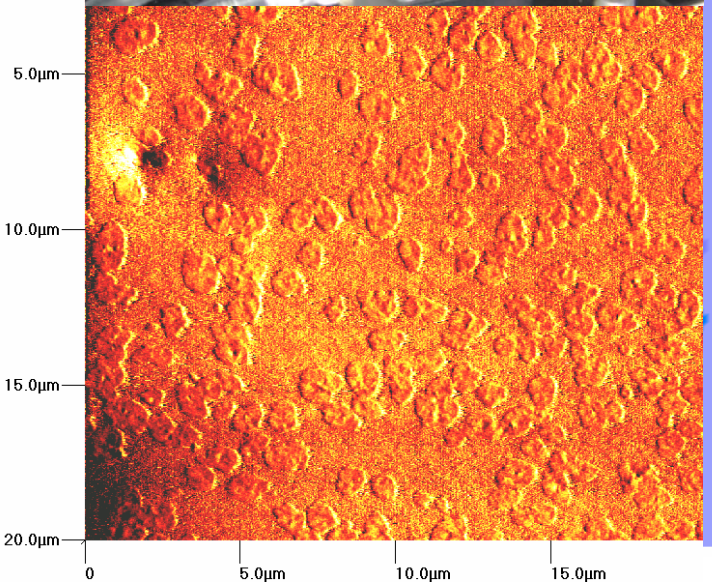


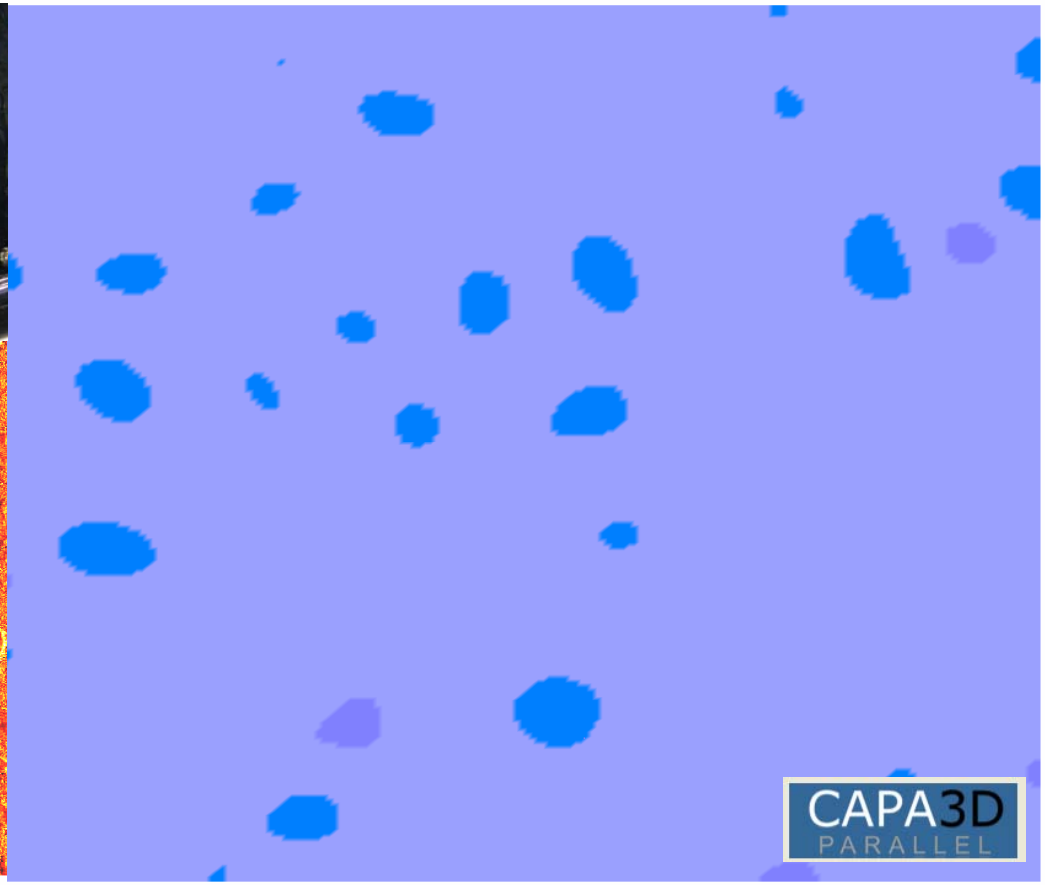


...asphalt under the Atomic Force Microscope









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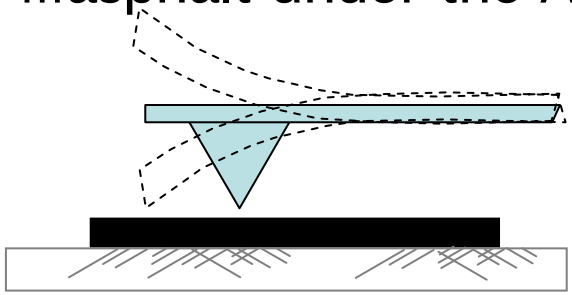
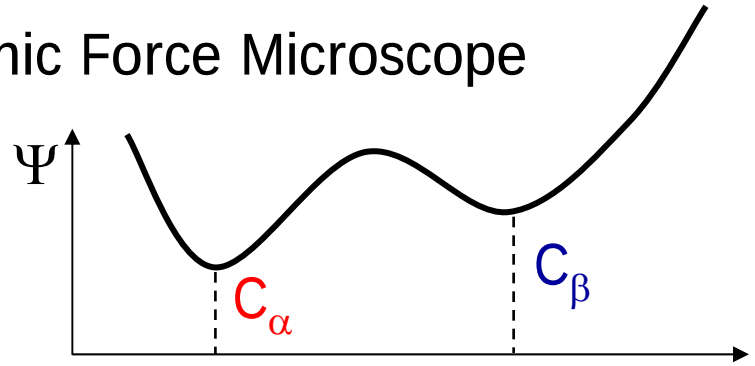
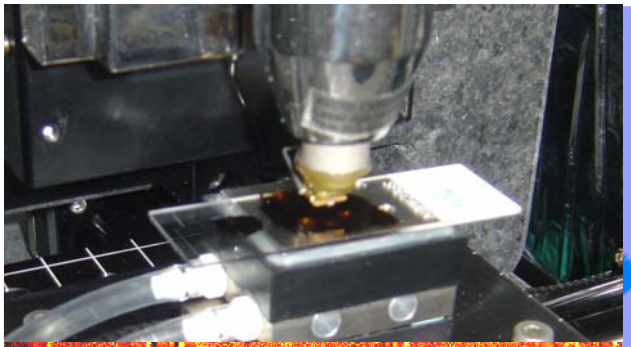
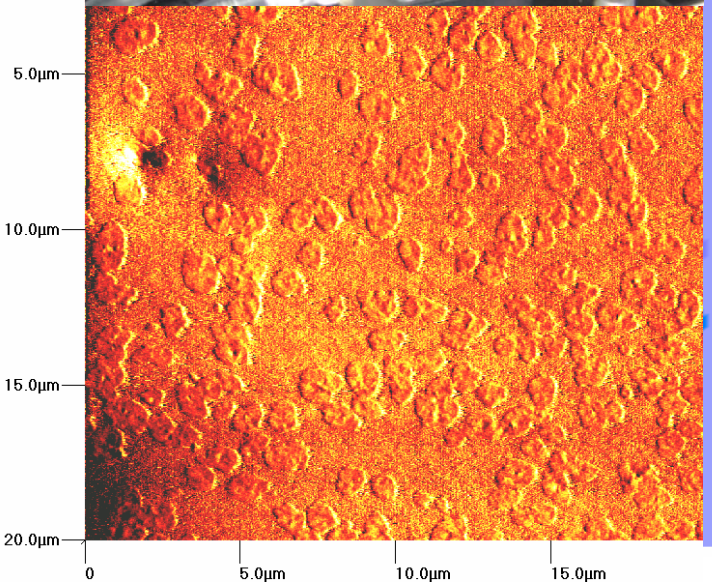
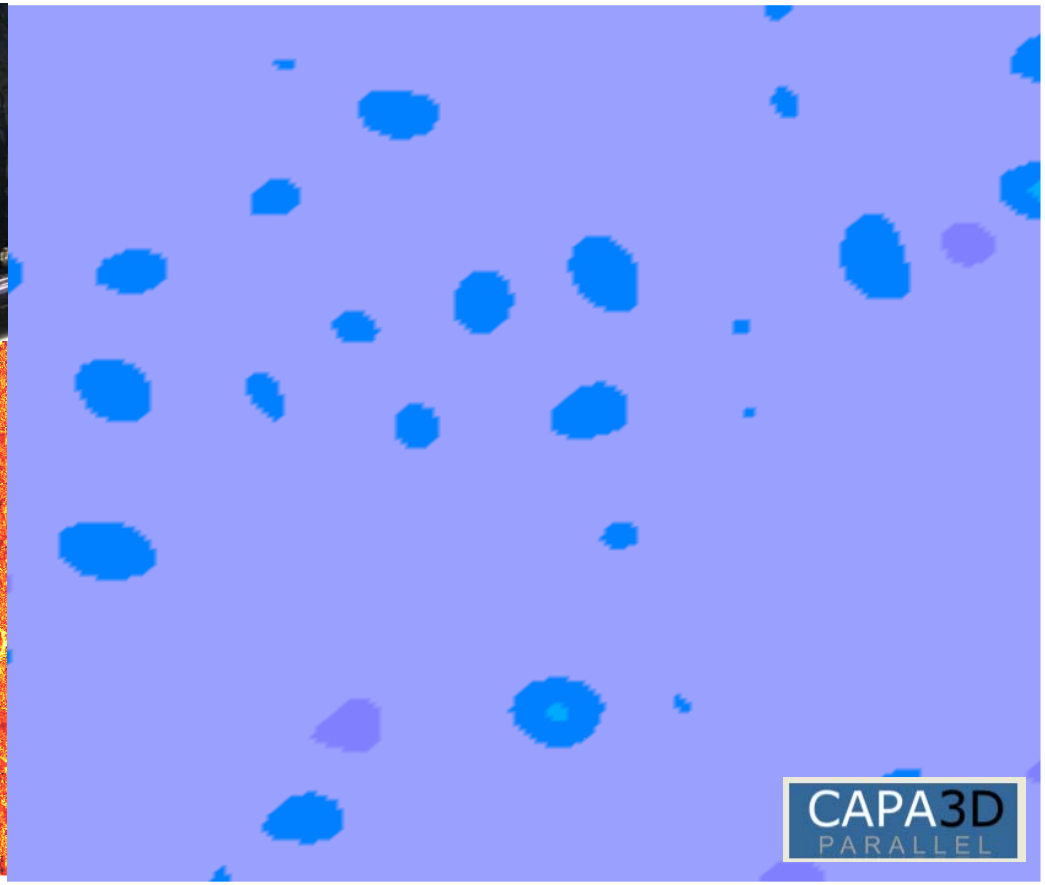


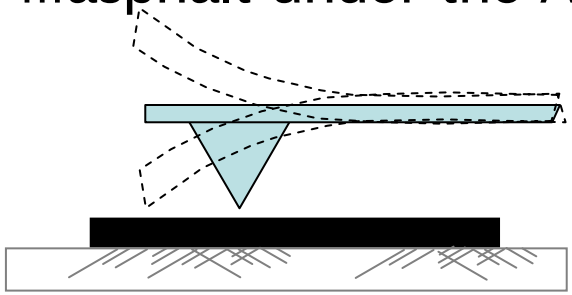


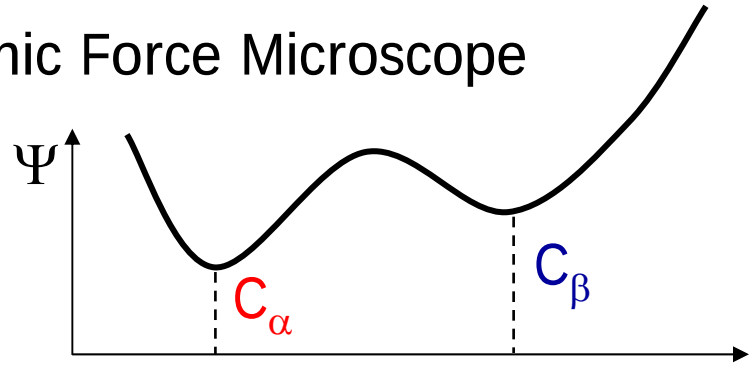


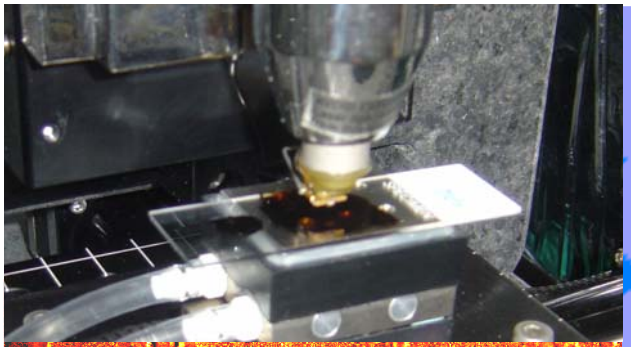


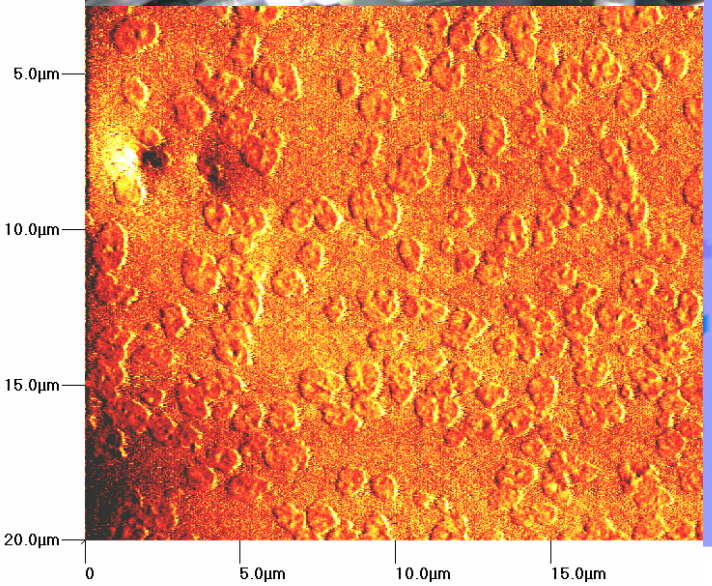


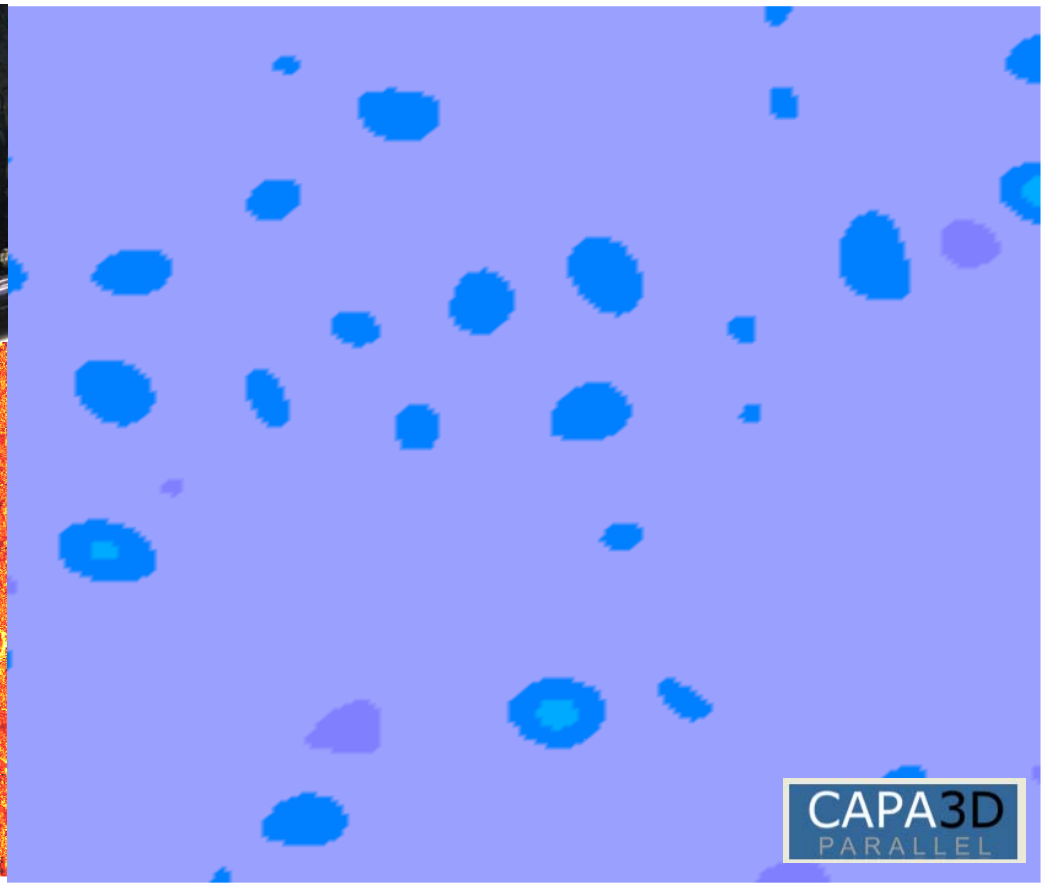
...asphalt under the Atomic Force Microscope



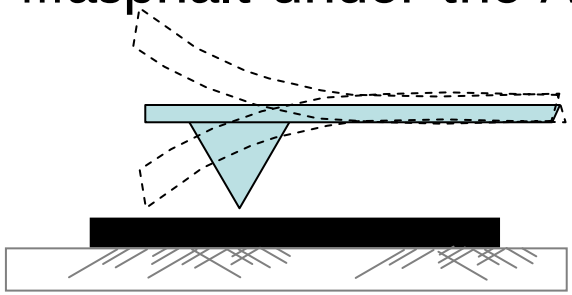


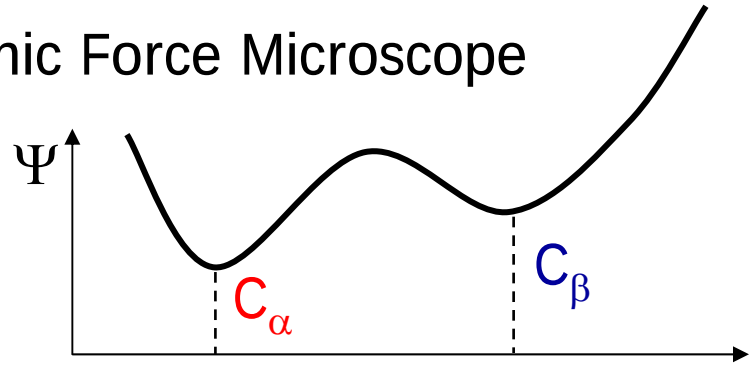


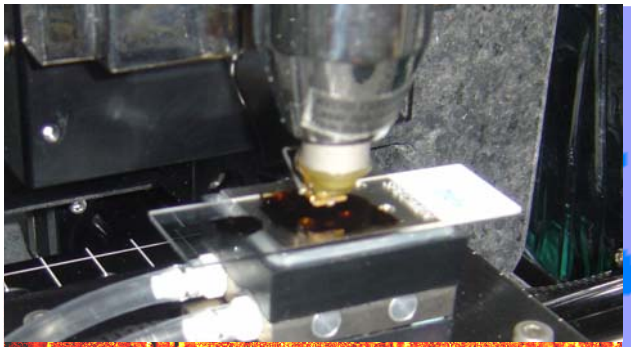


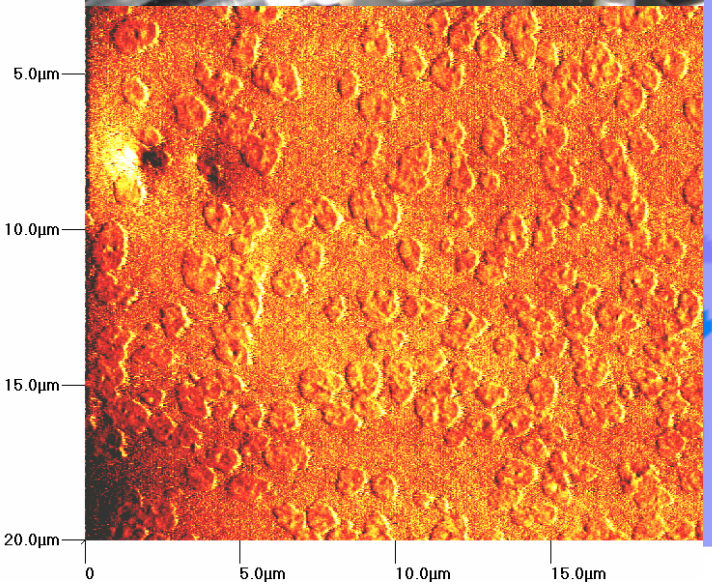


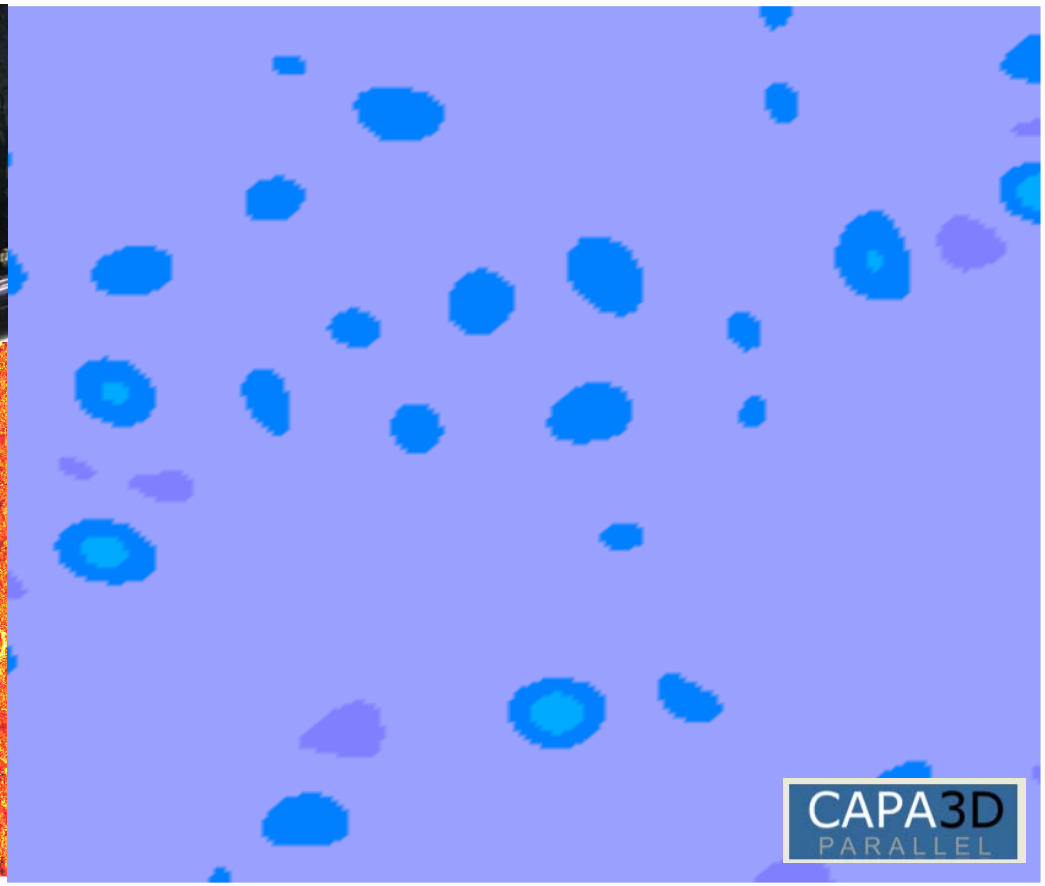
...asphalt under the Atomic Force Microscope



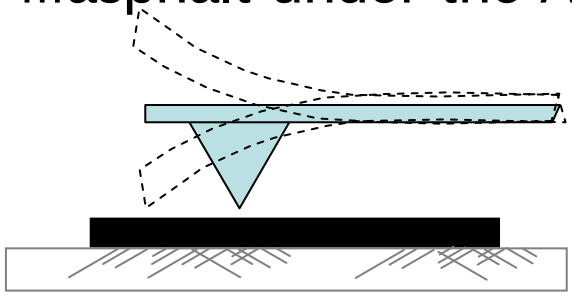


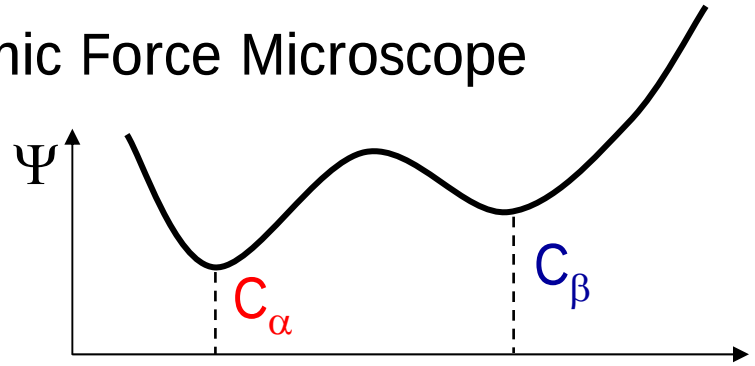


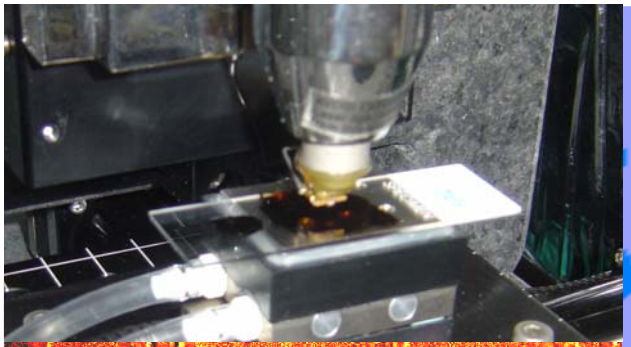


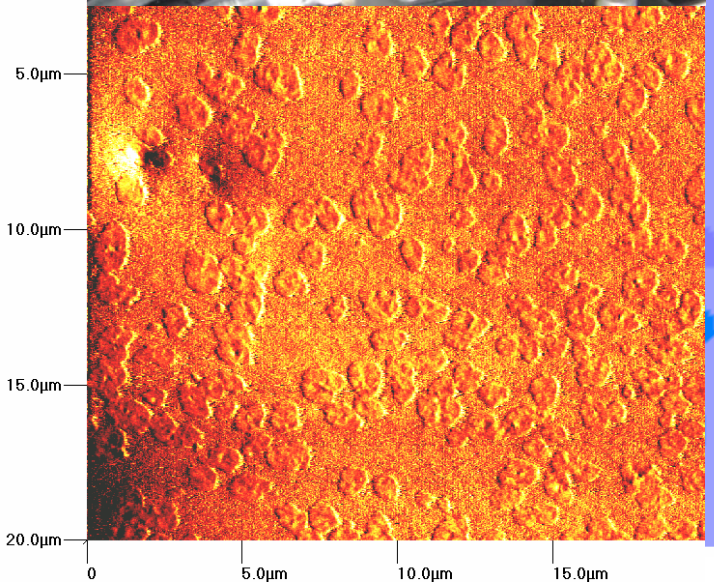


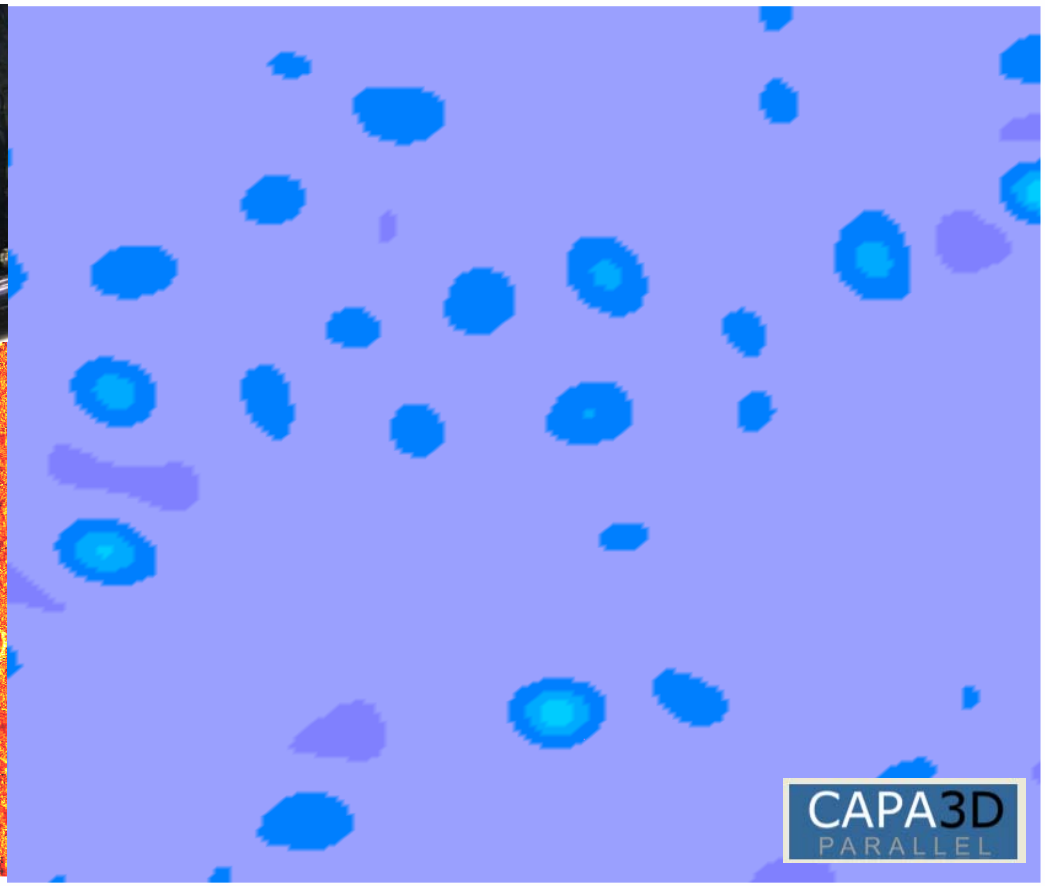
...asphalt under the Atomic Force Microscope



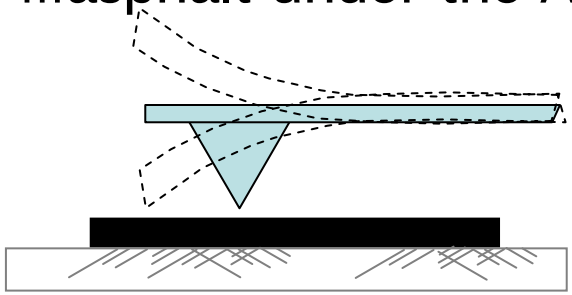


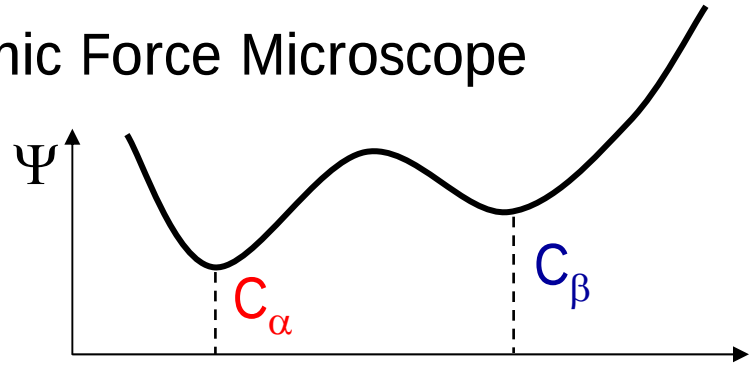


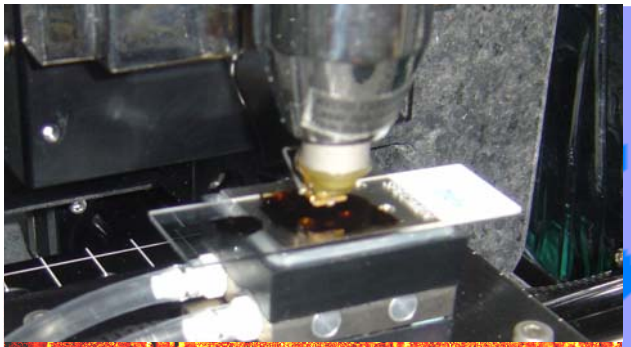


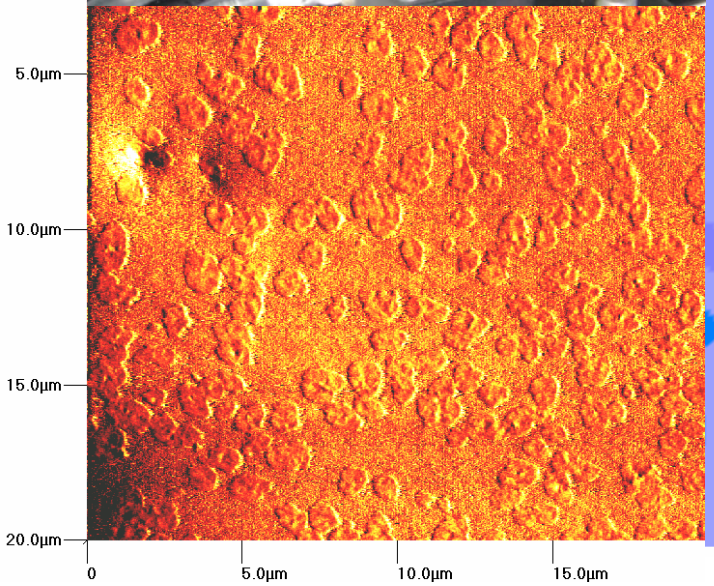


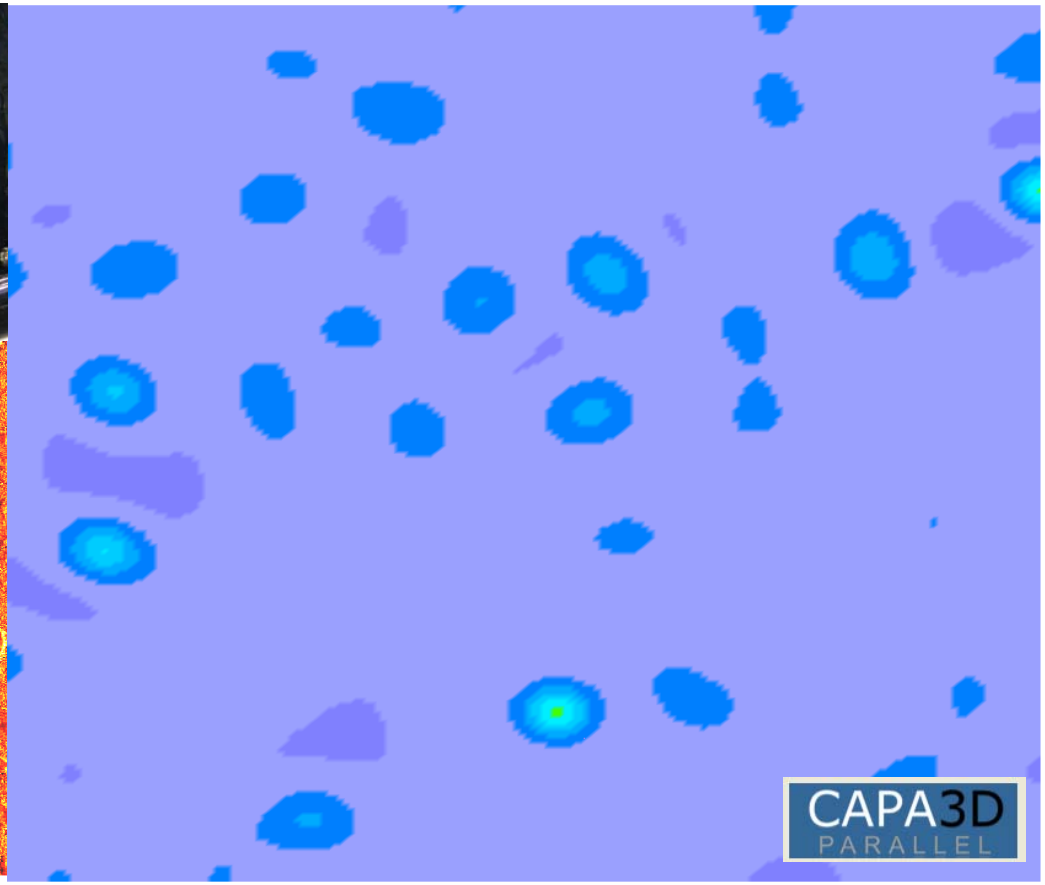
...asphalt under the Atomic Force Microscope



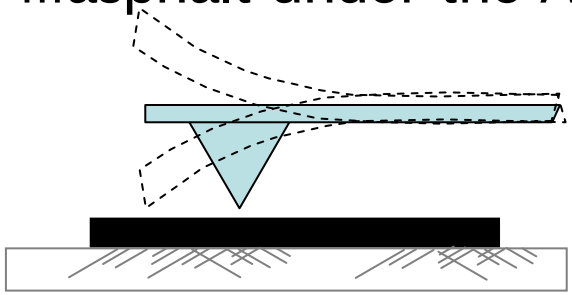


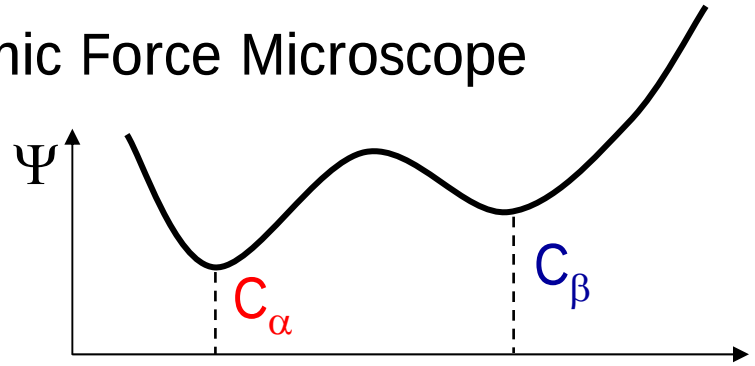


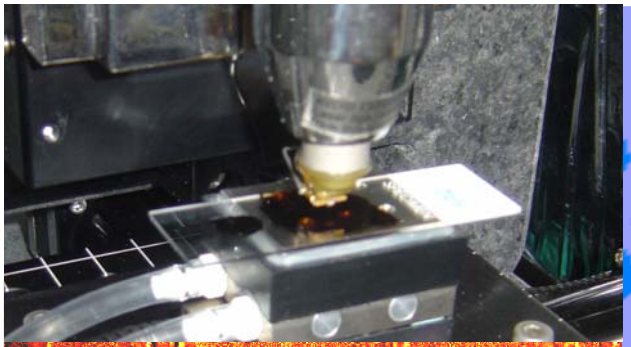


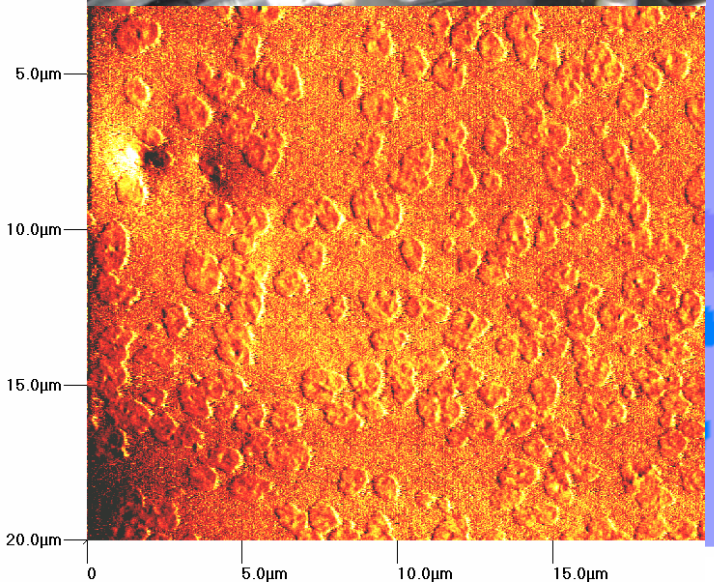


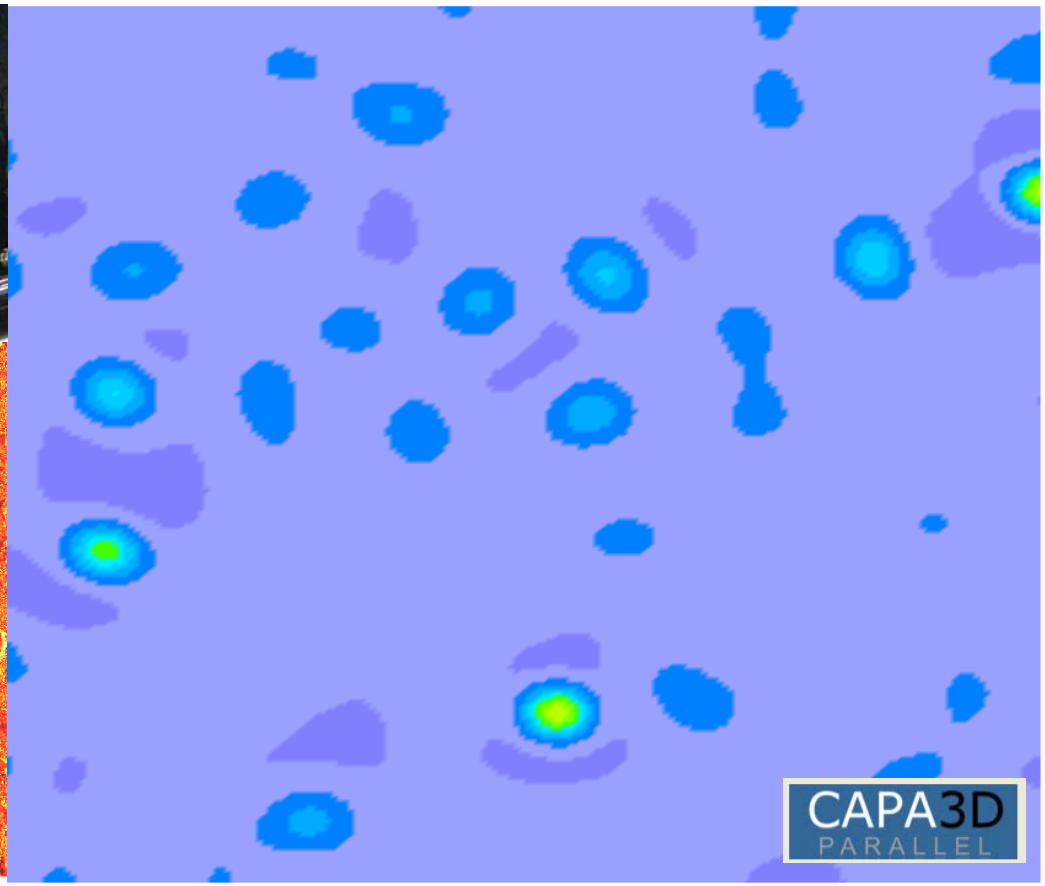
...asphalt under the Atomic Force Microscope



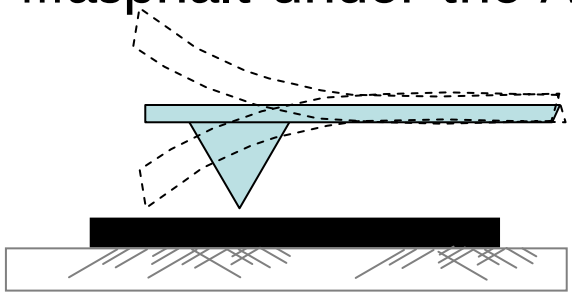


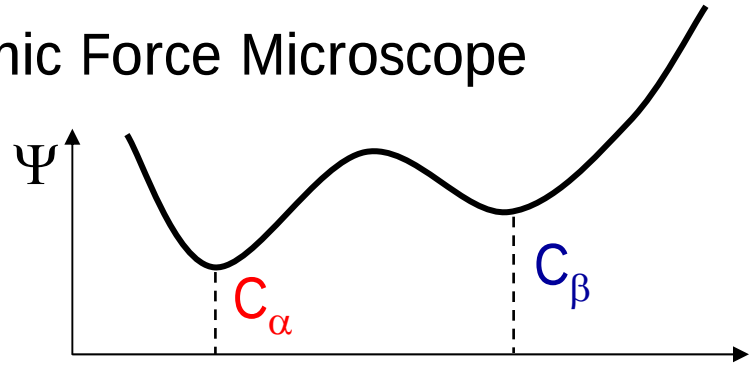


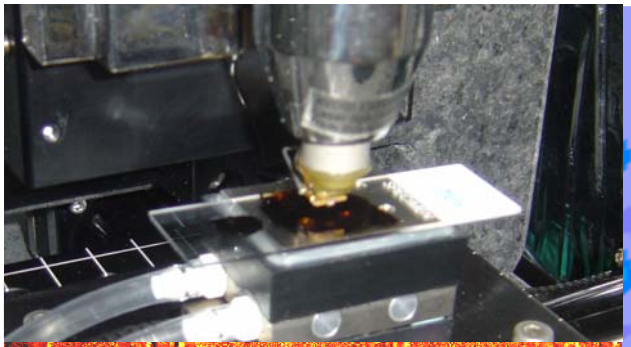


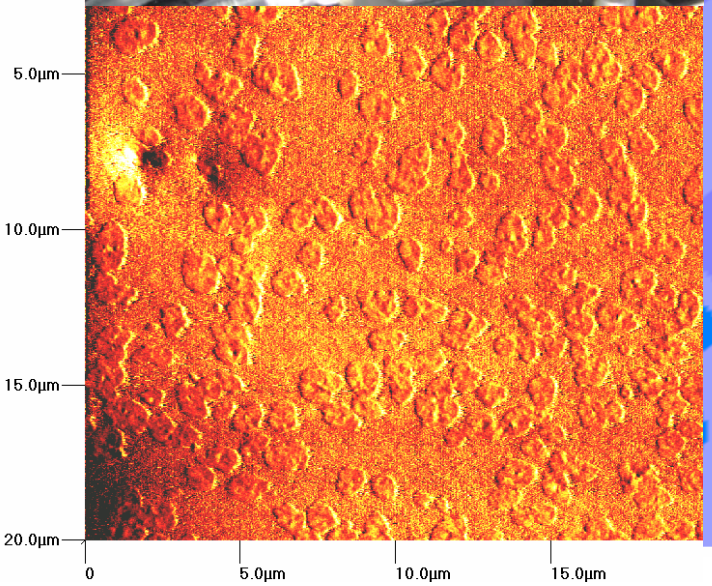


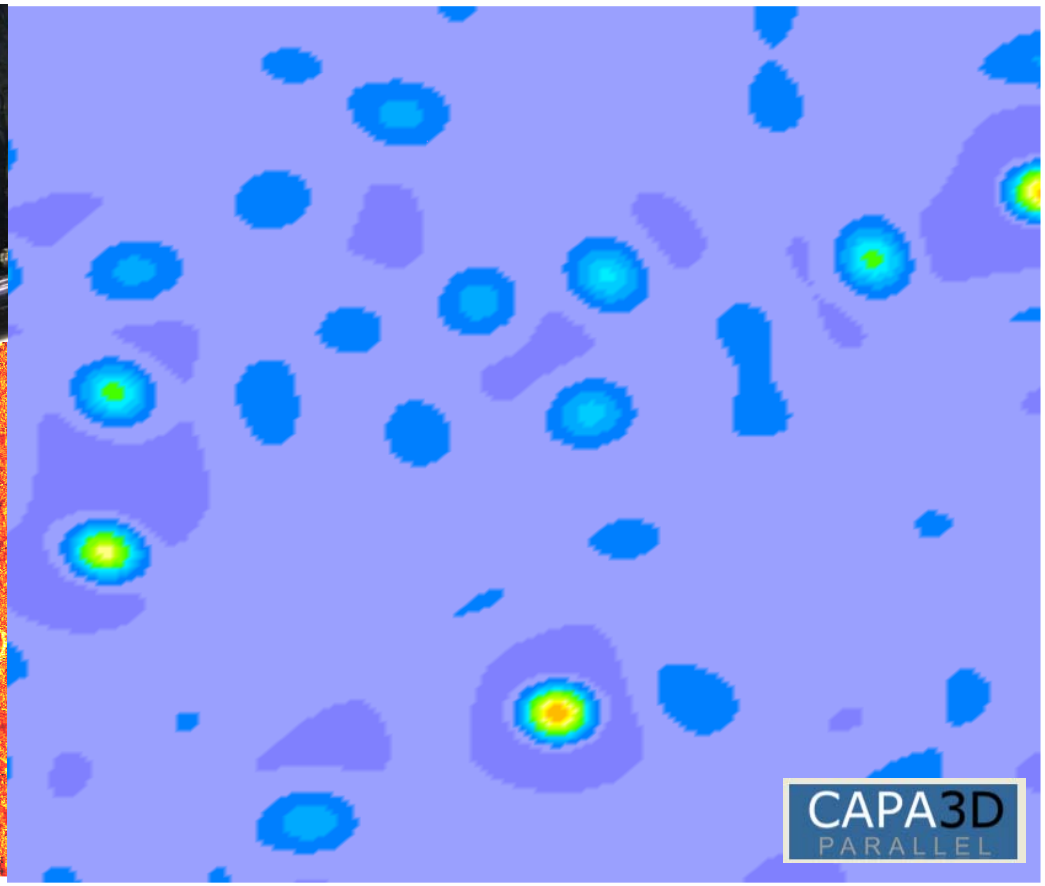
...asphalt under the Atomic Force Microscope



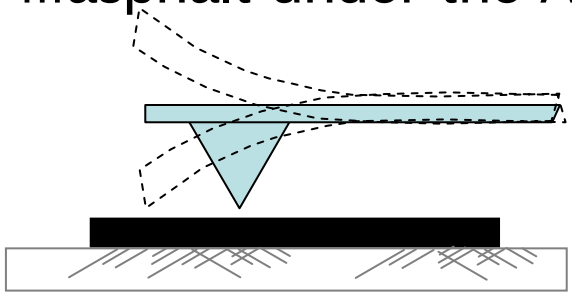


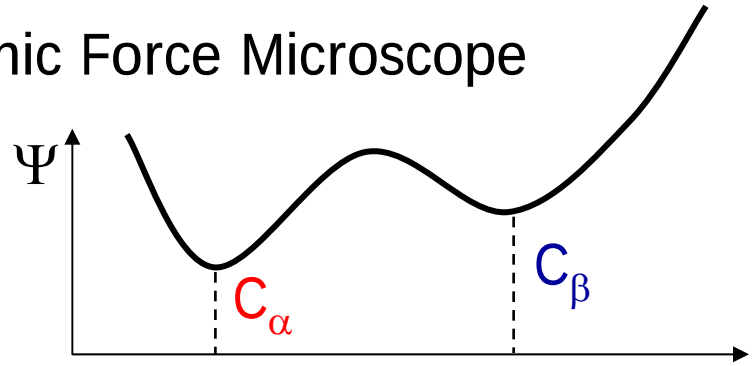


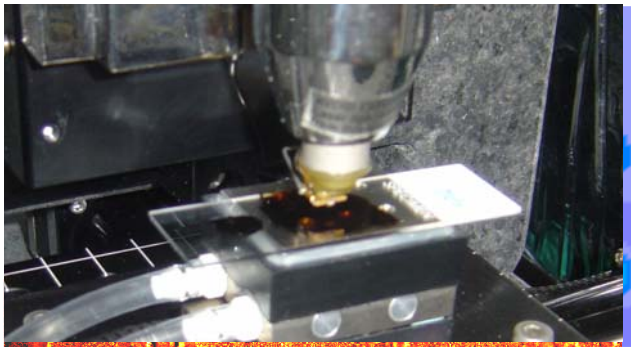


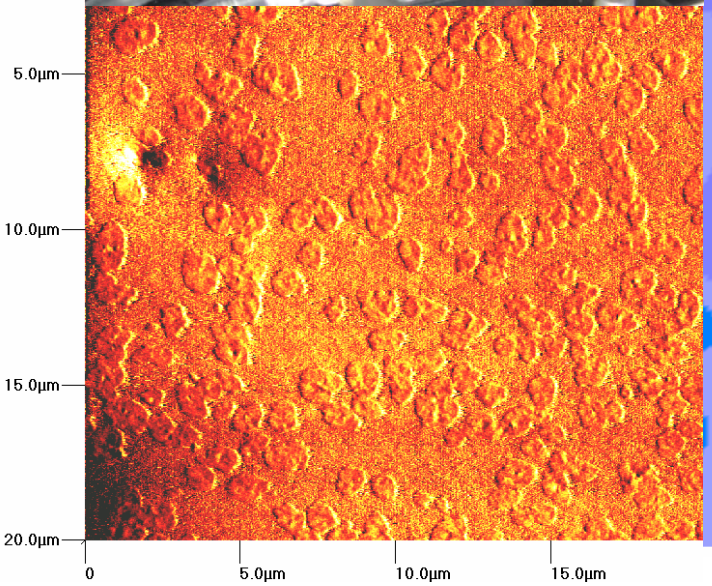


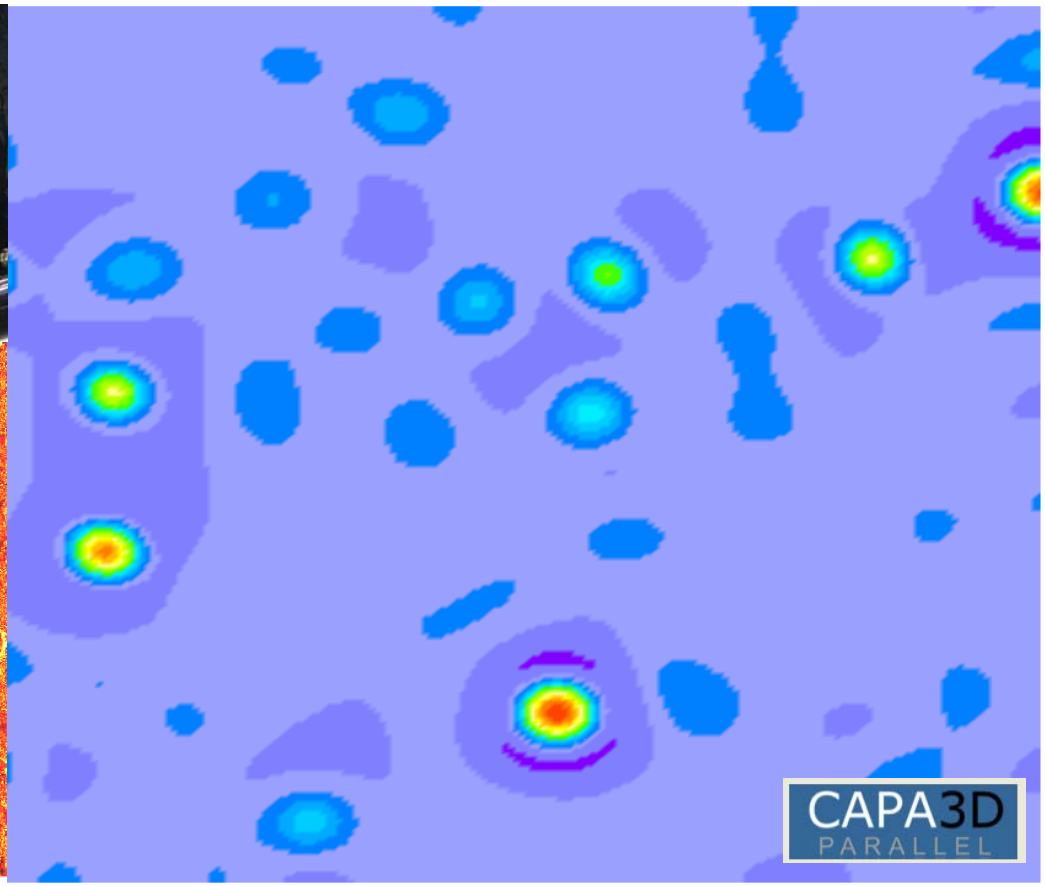
...asphalt under the Atomic Force Microscope



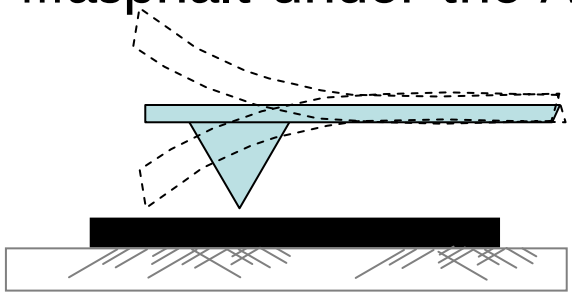


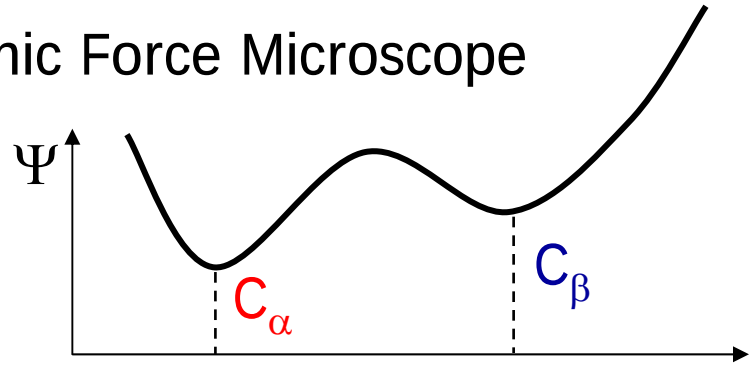


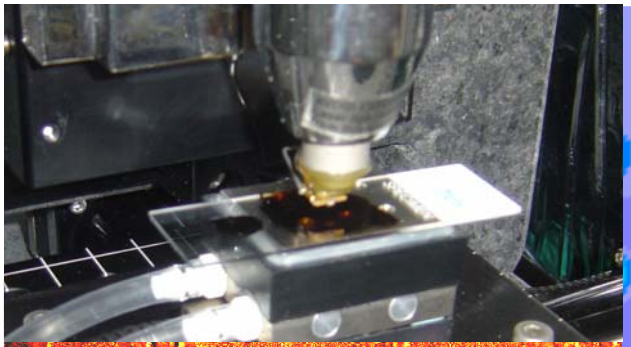


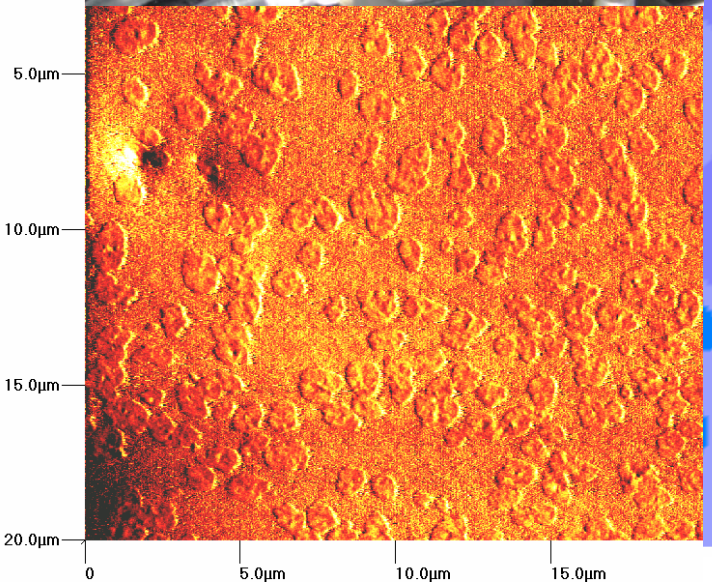


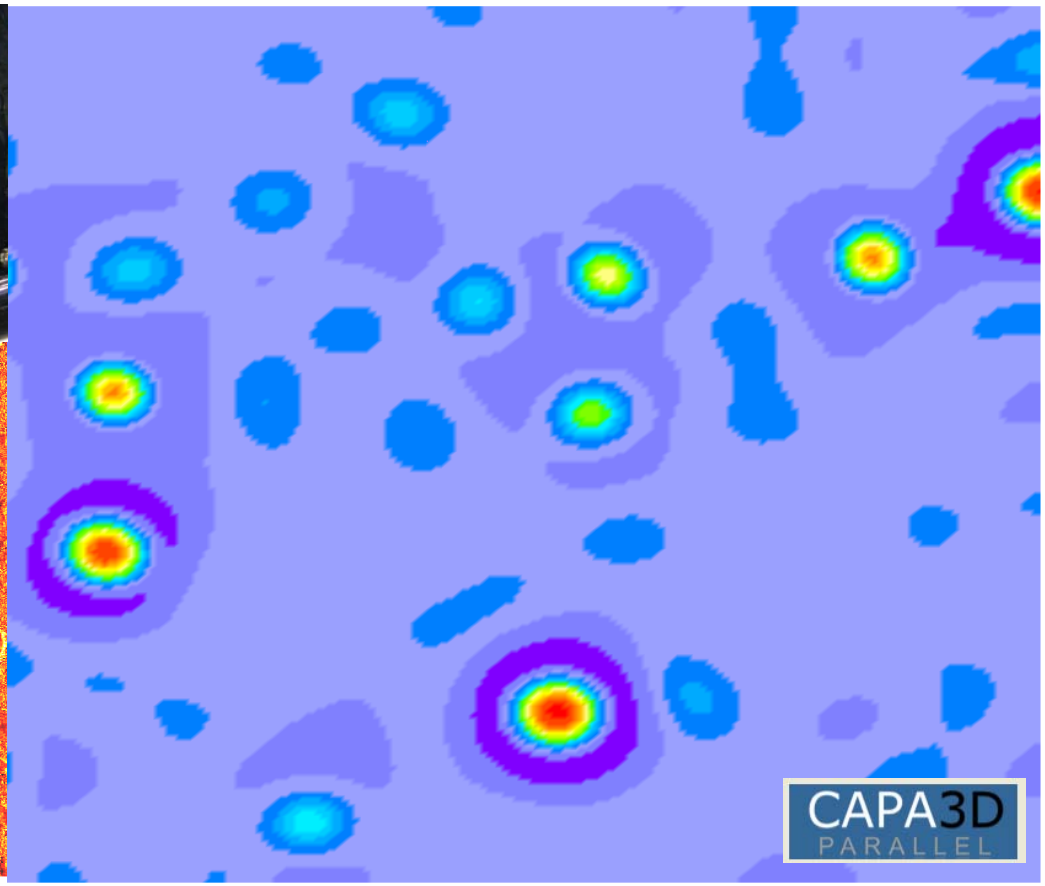
...asphalt under the Atomic Force Microscope



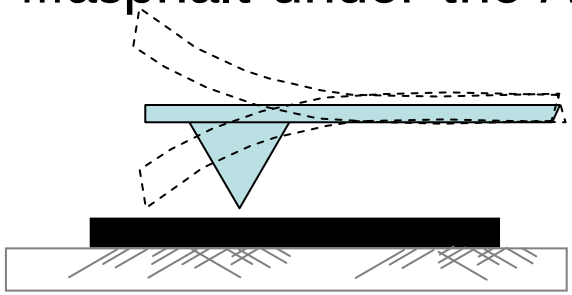


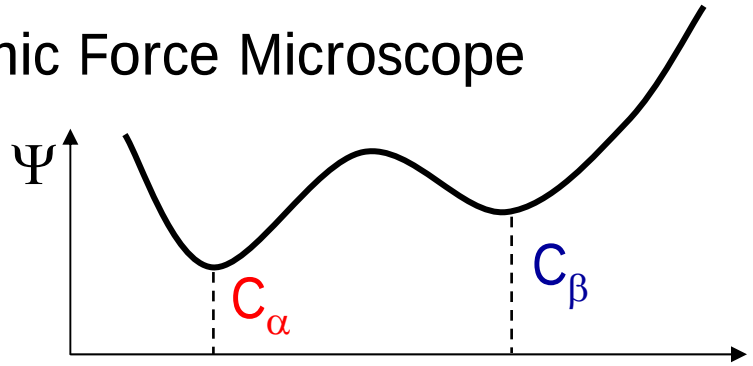


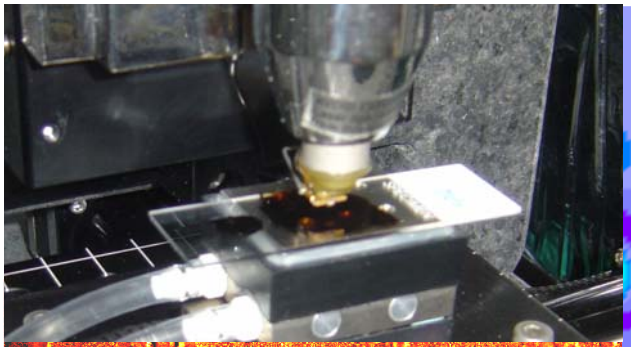


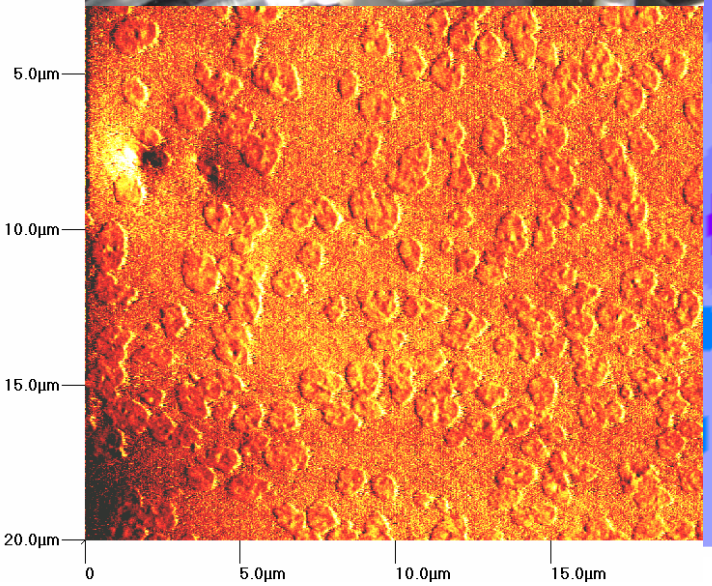


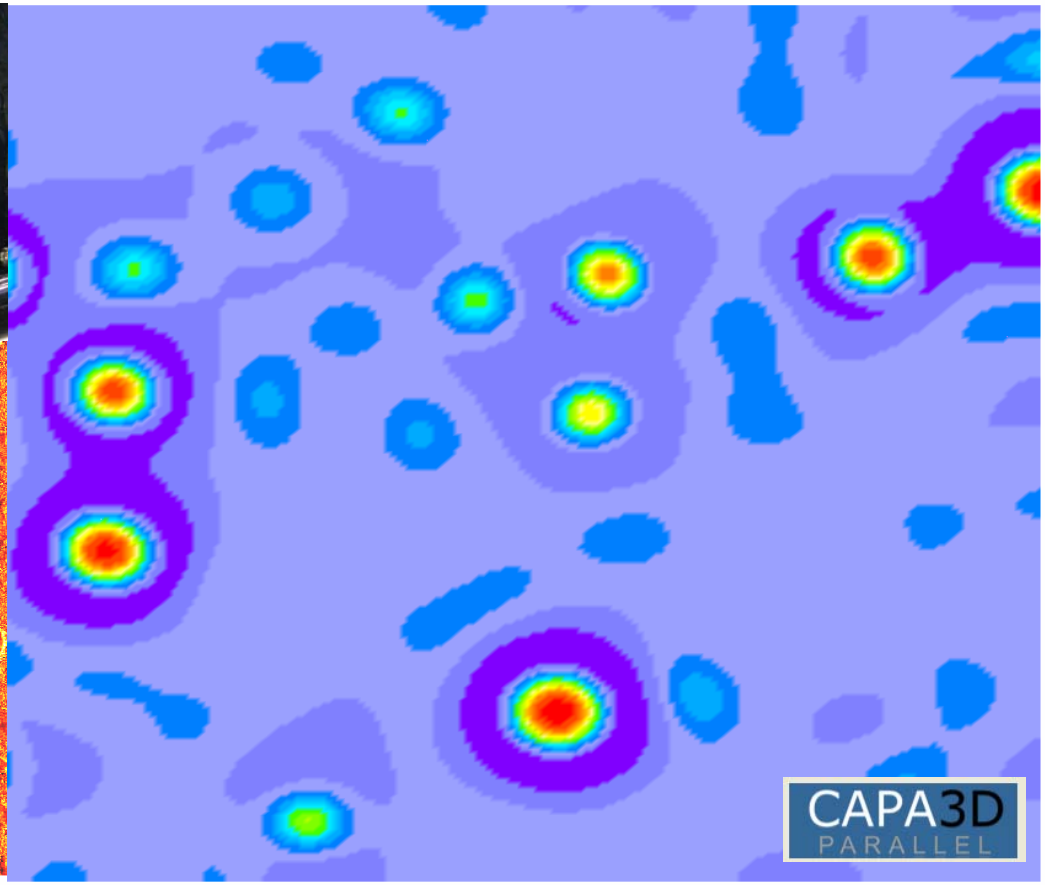
...asphalt under the Atomic Force Microscope



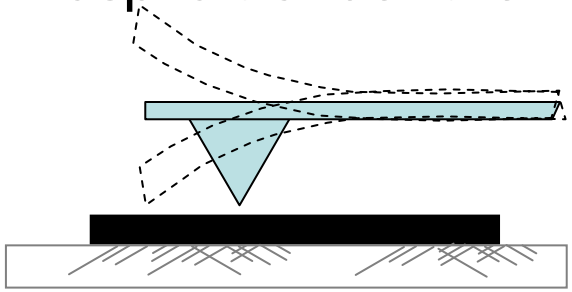


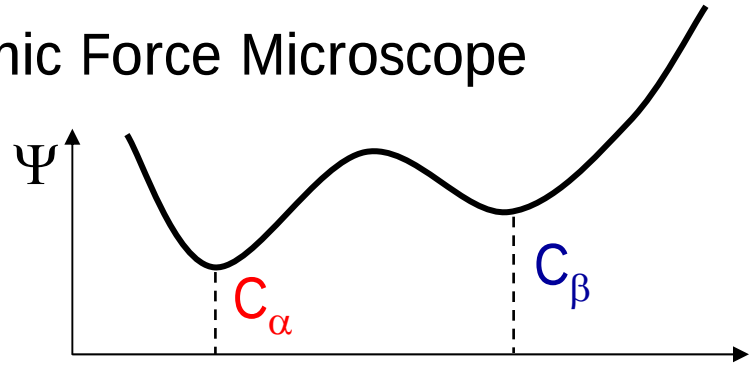


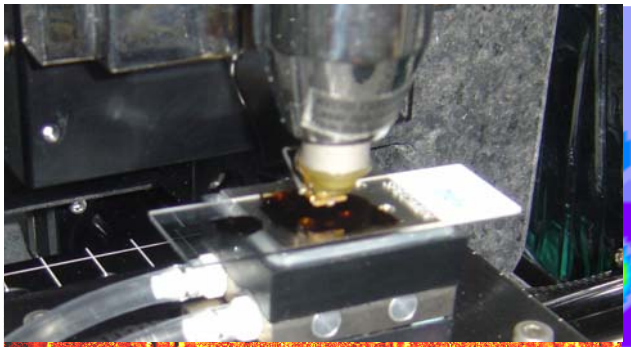


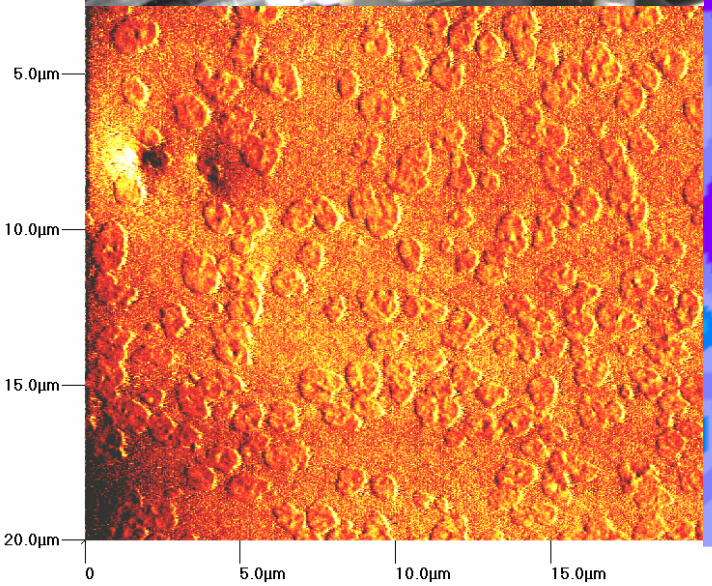


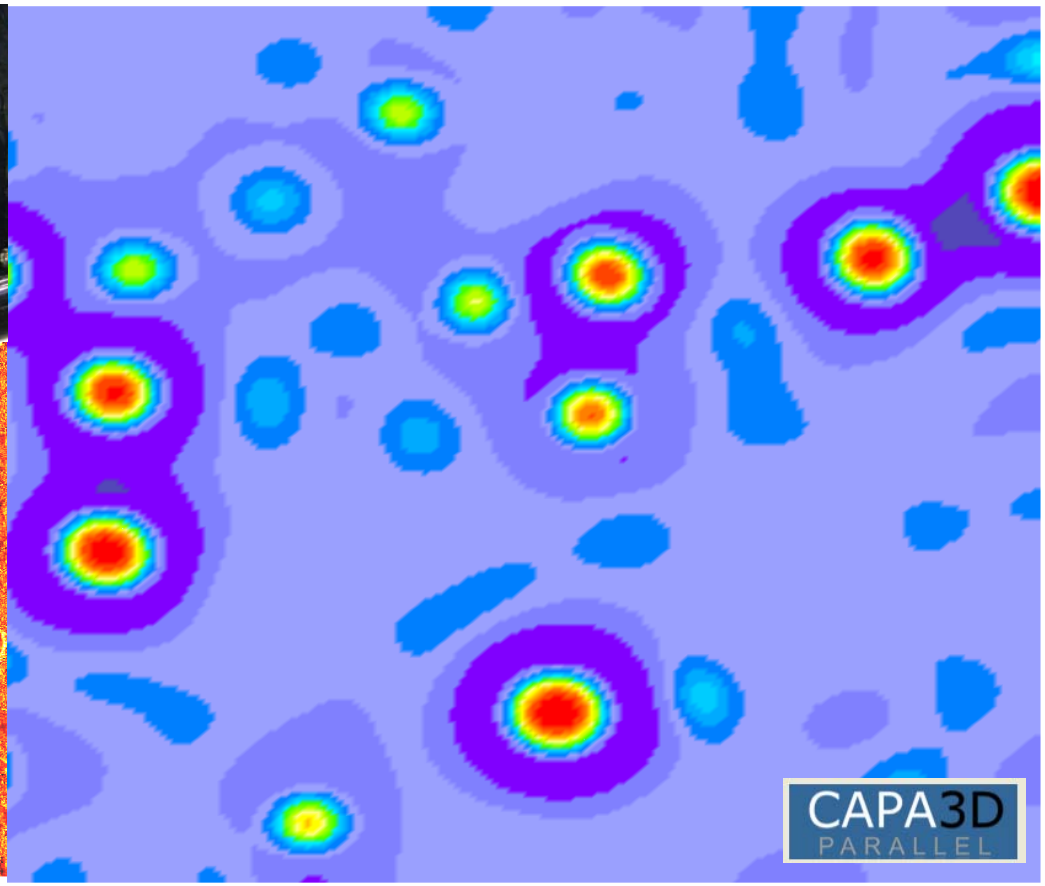
...asphalt under the Atomic Force Microscope



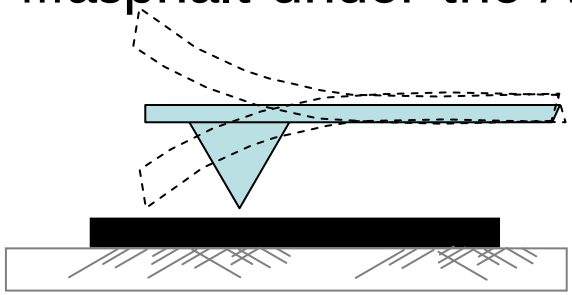


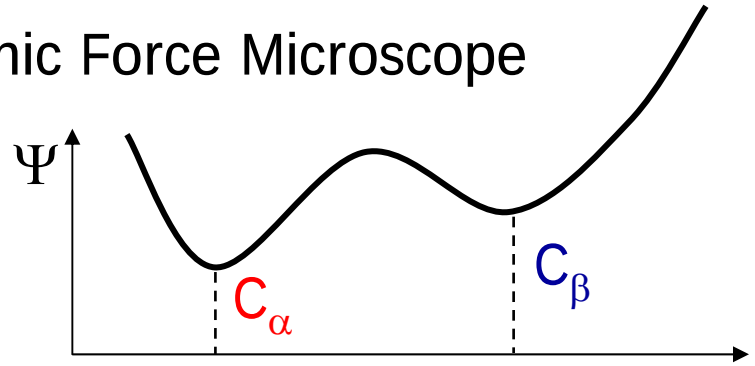


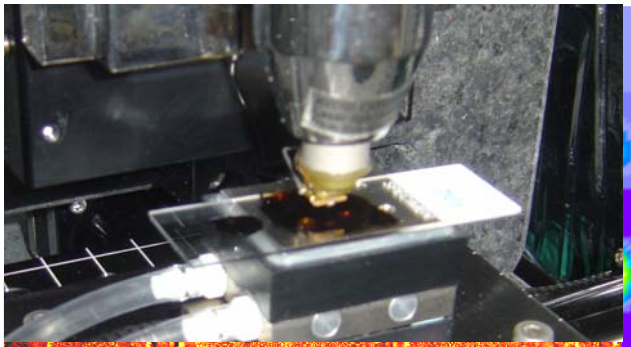


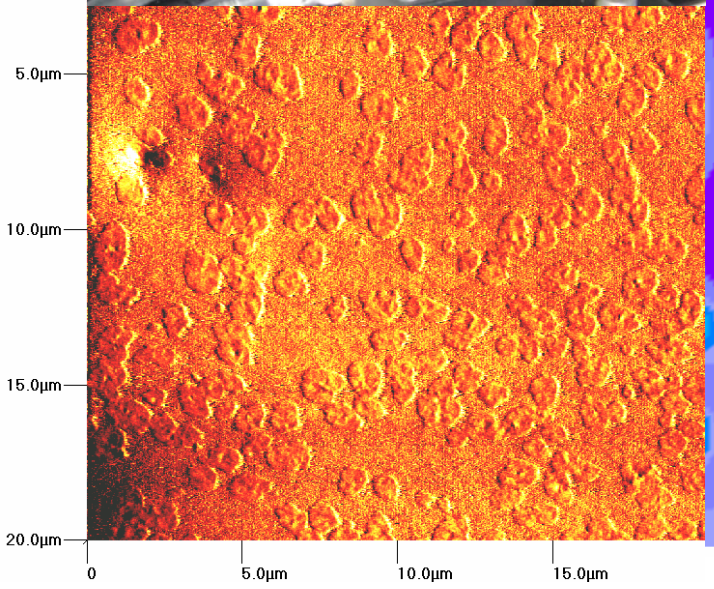


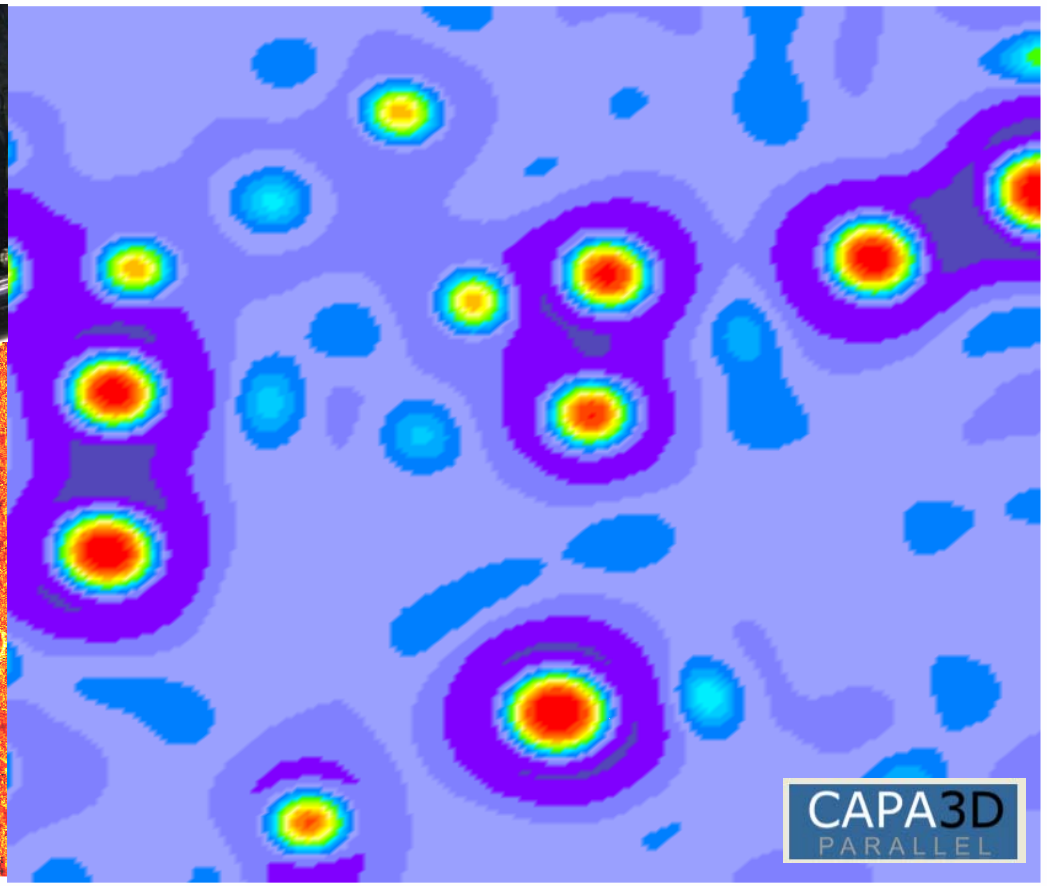
...asphalt under the Atomic Force Microscope

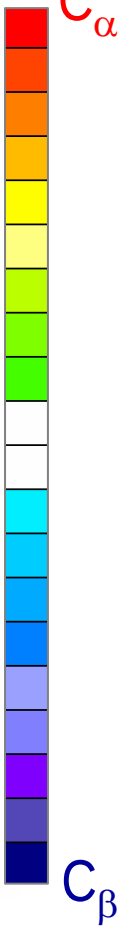












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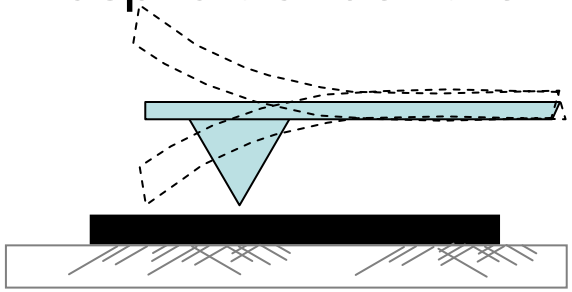
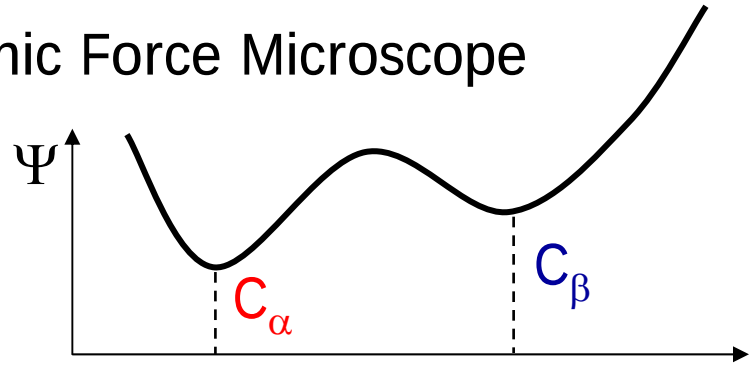
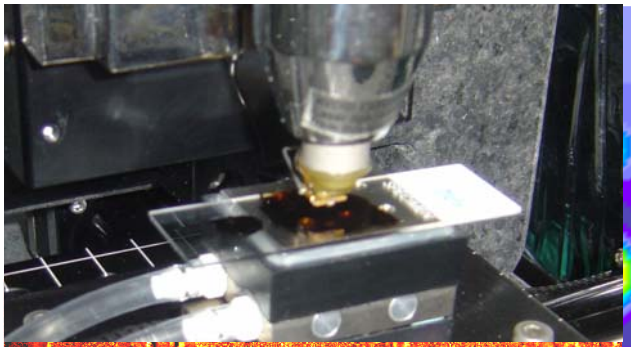
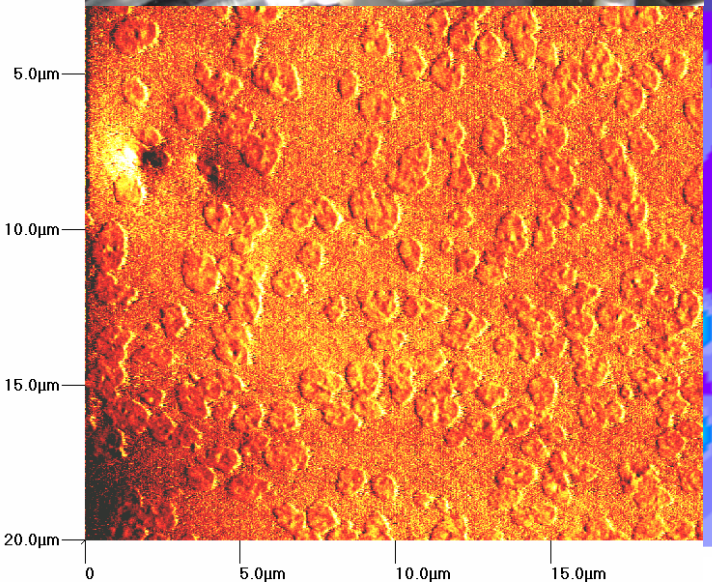
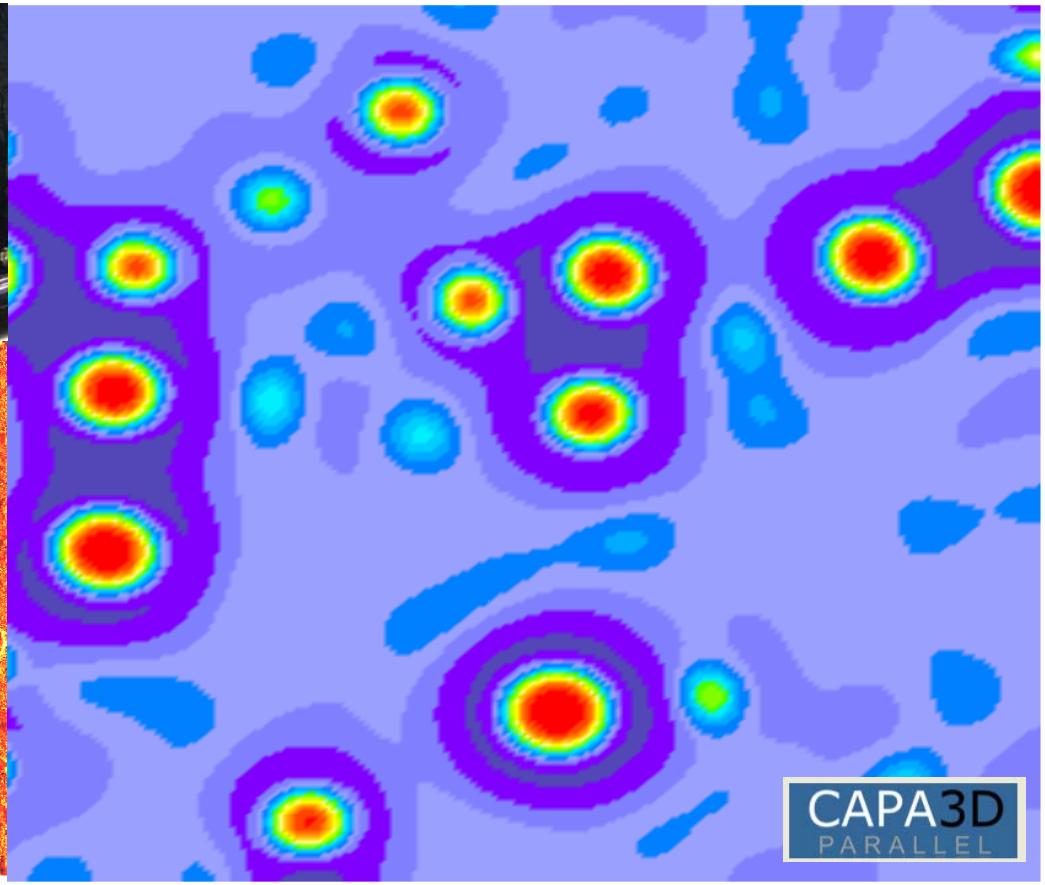


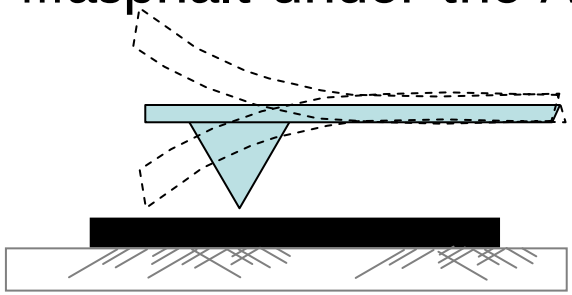


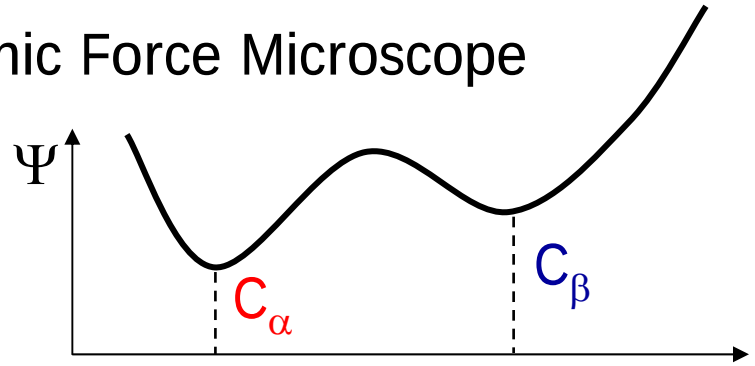


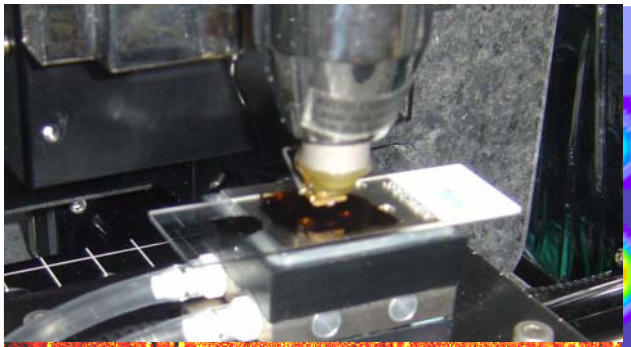


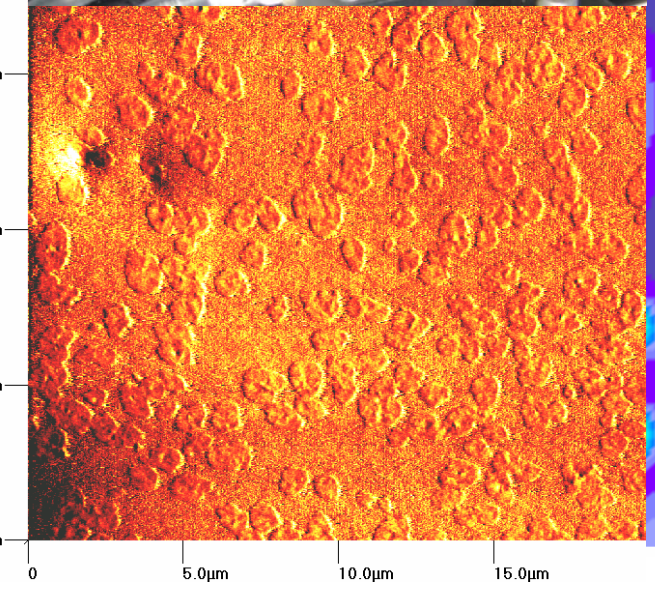


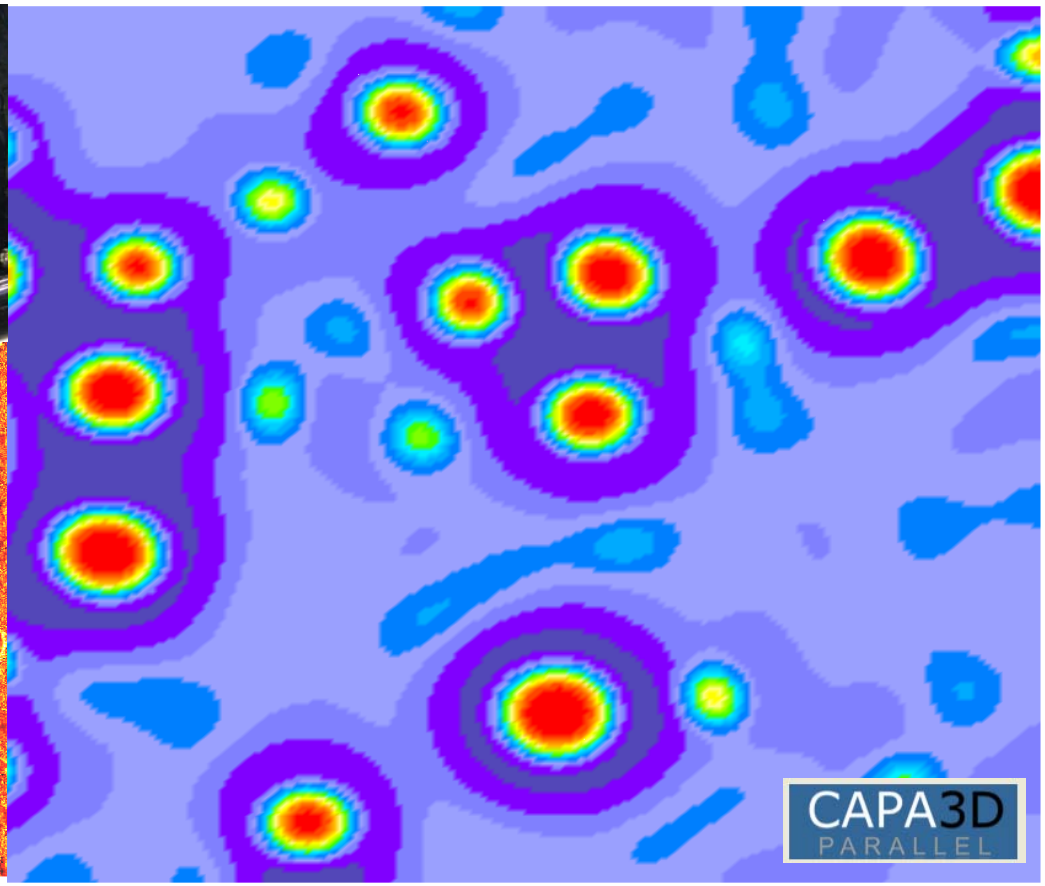
...asphalt under the Atomic Force Microscope



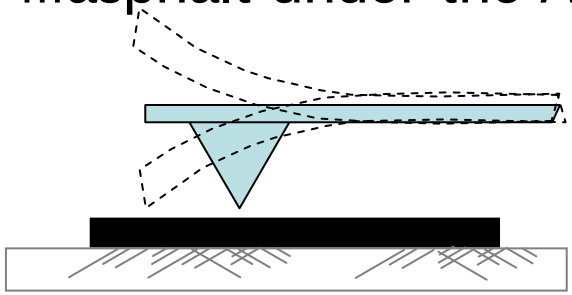


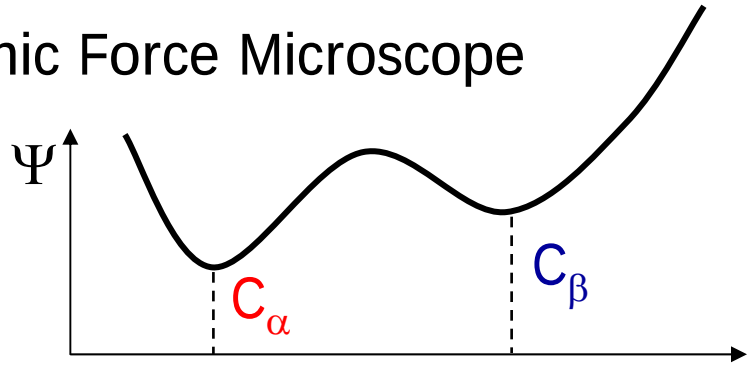


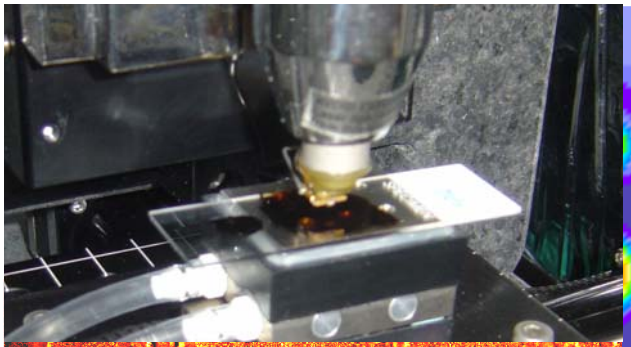


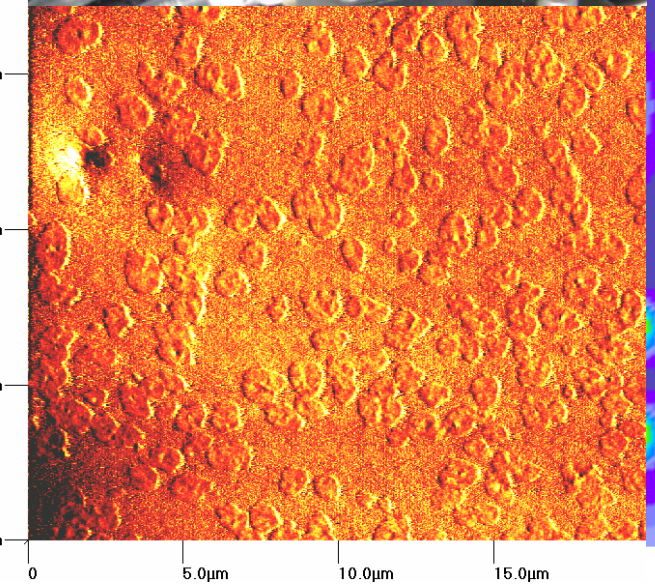


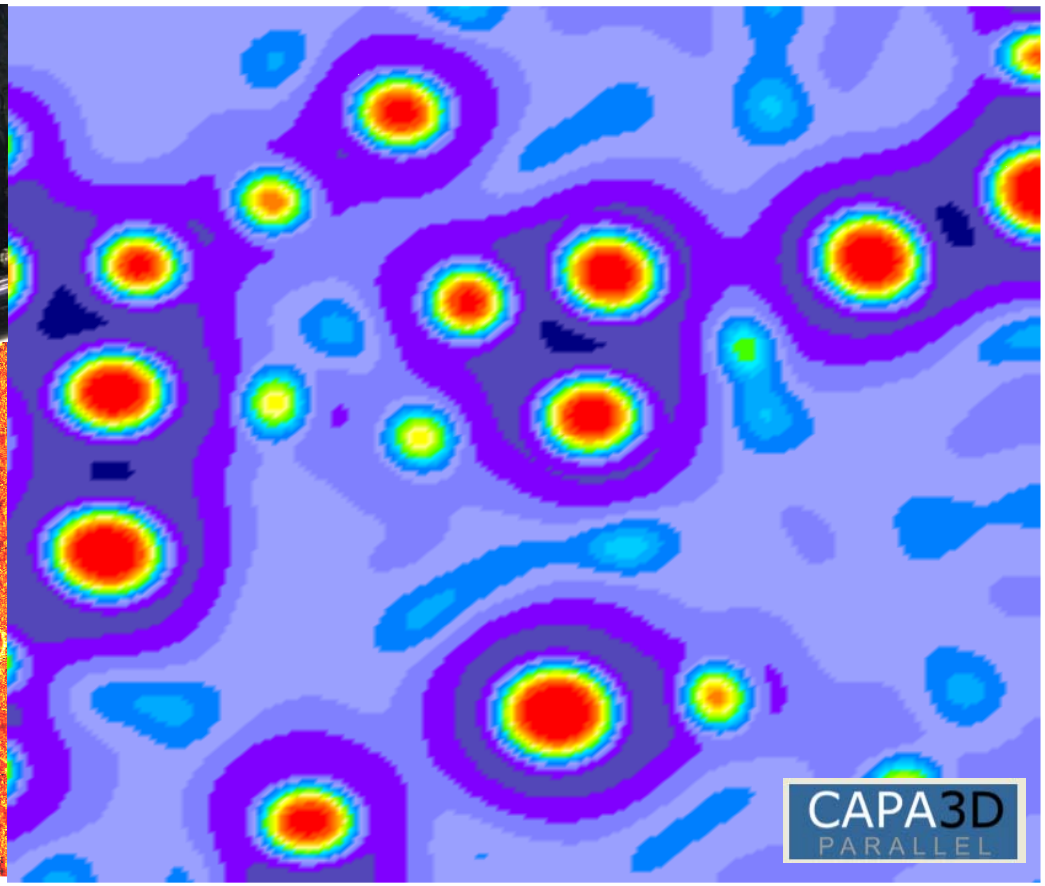
...asphalt under the Atomic Force Microscope



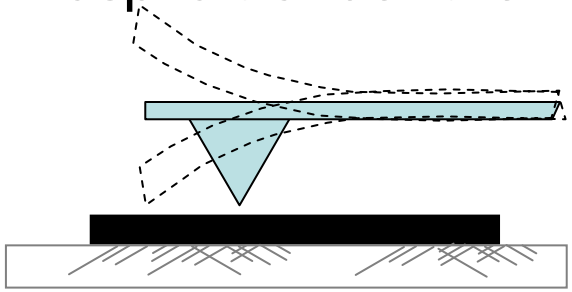


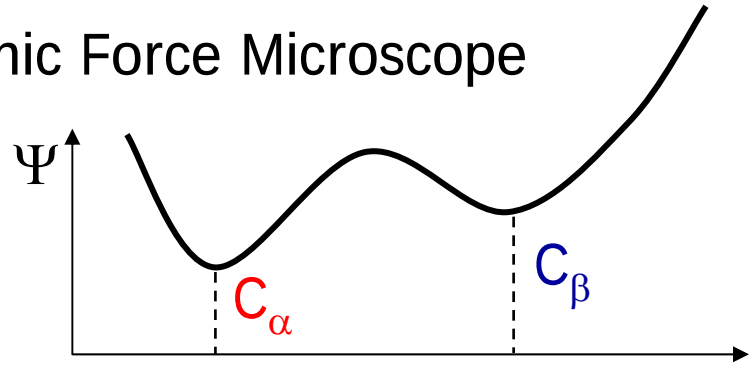


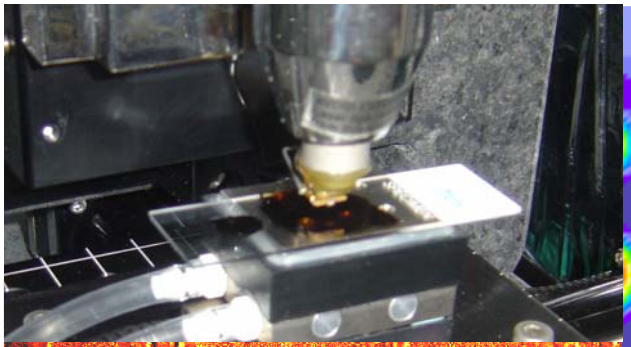


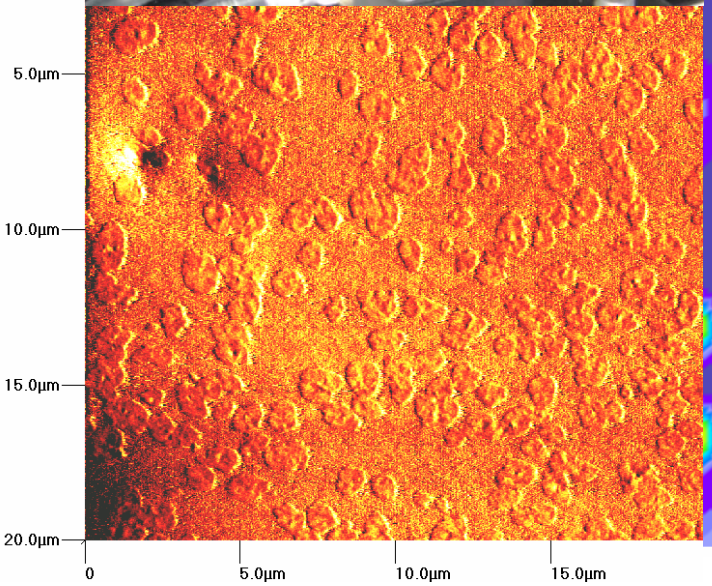


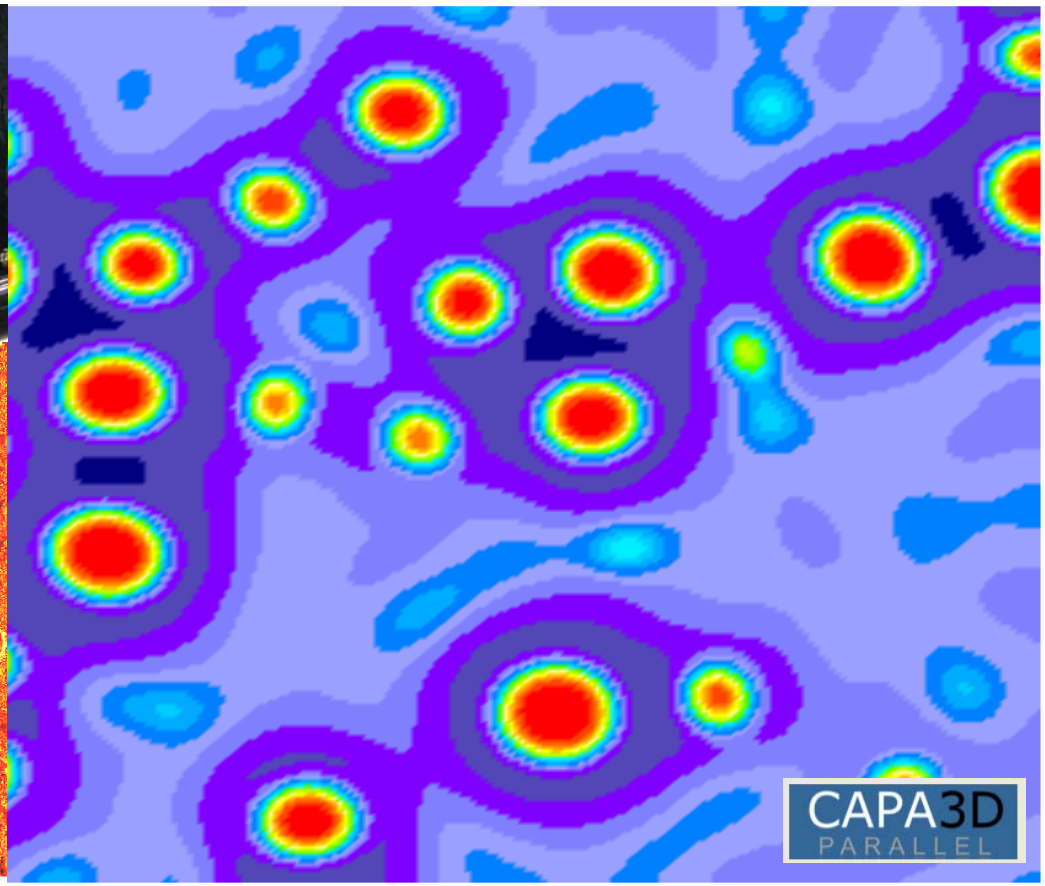
...asphalt under the Atomic Force Microscope



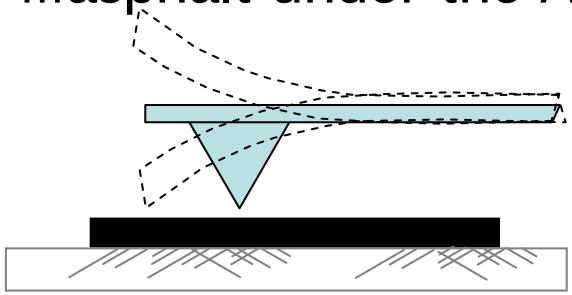


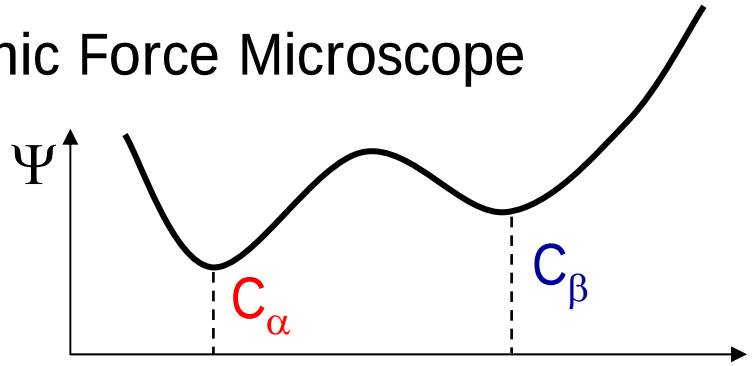


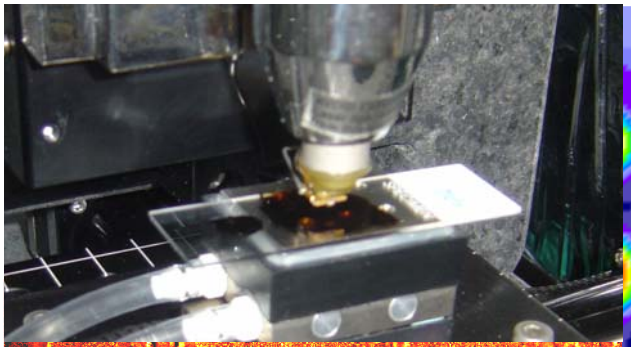


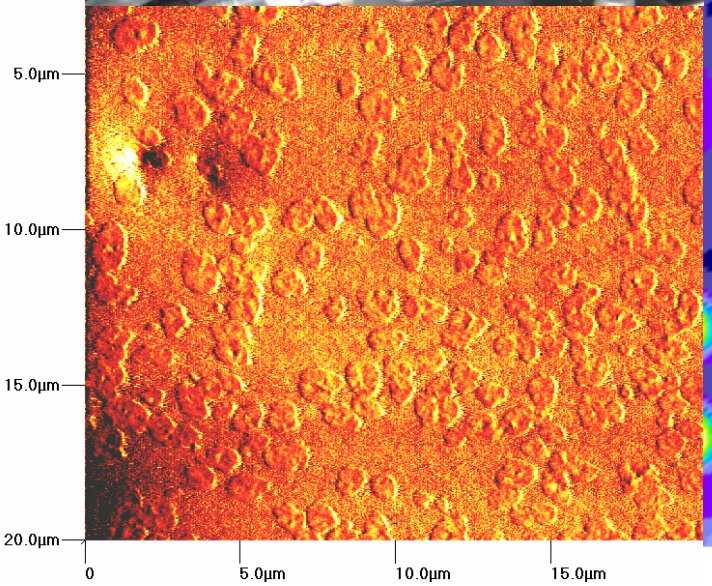


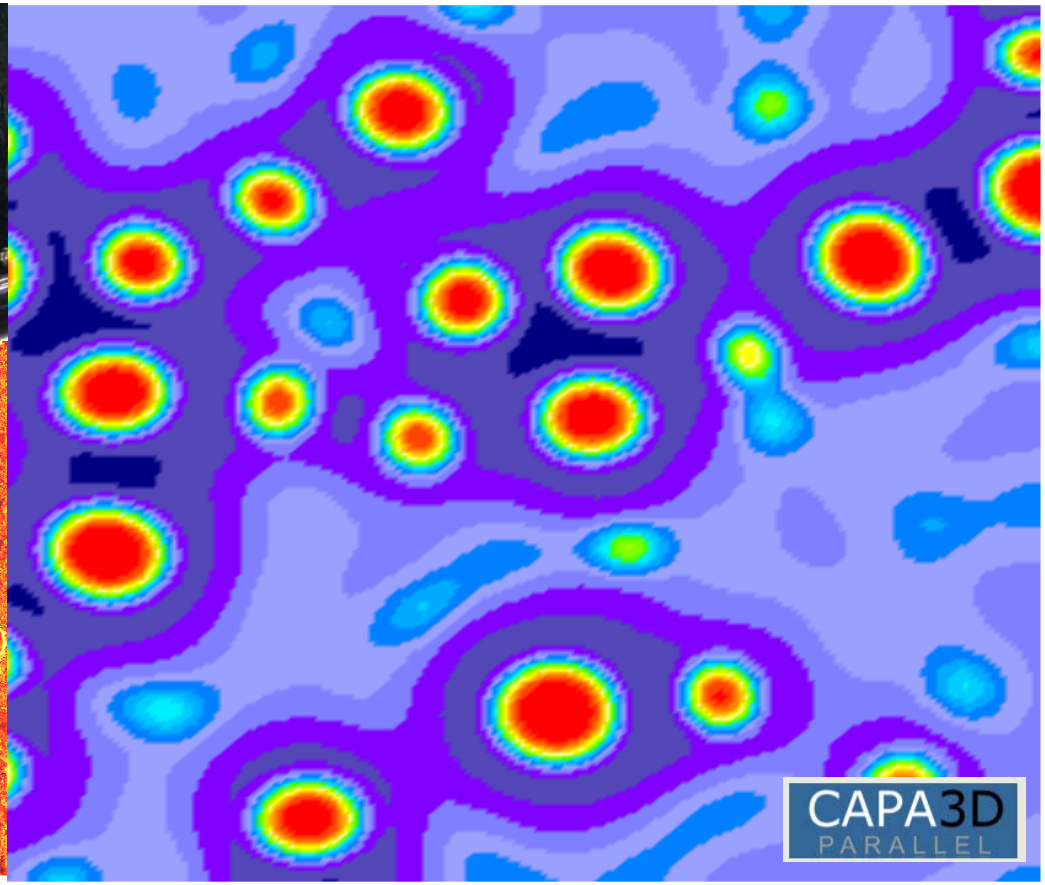
...asphalt under the Atomic Force Microscope



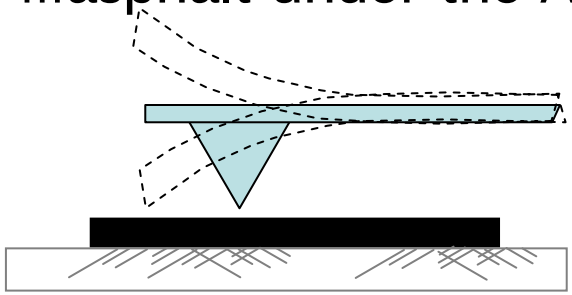


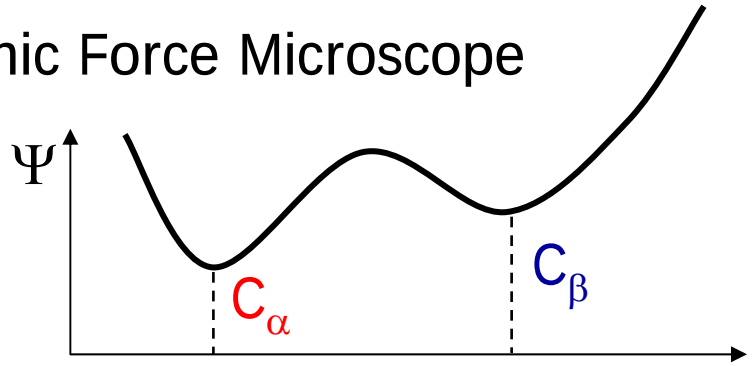


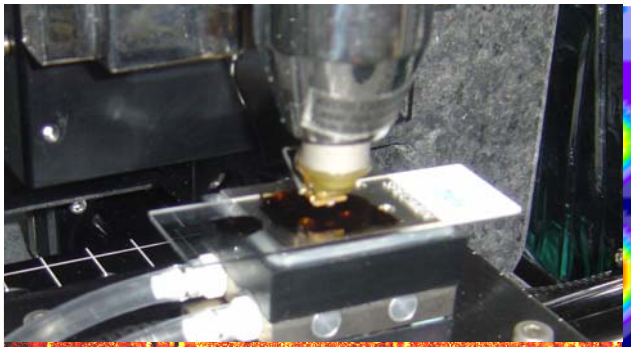


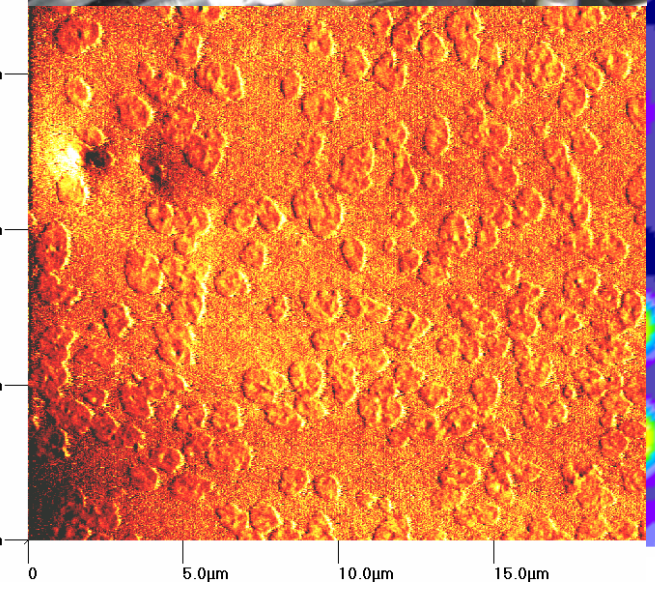


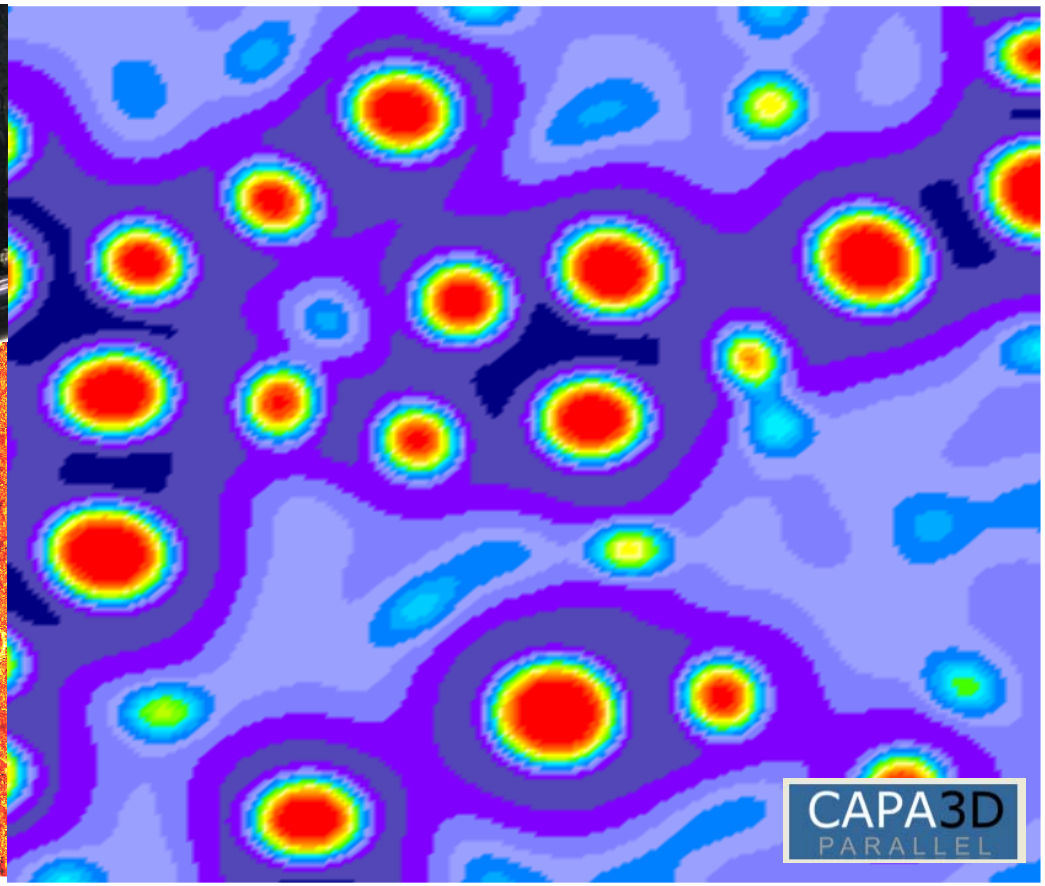
...asphalt under the Atomic Force Microscope











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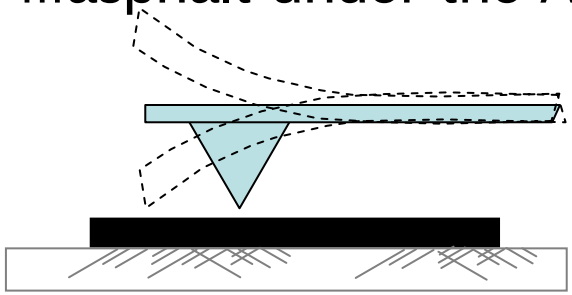

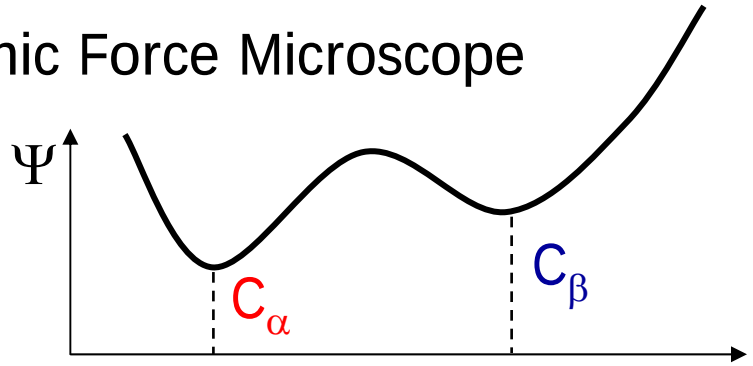

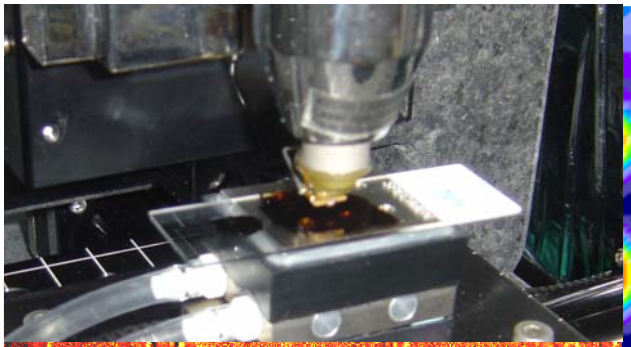

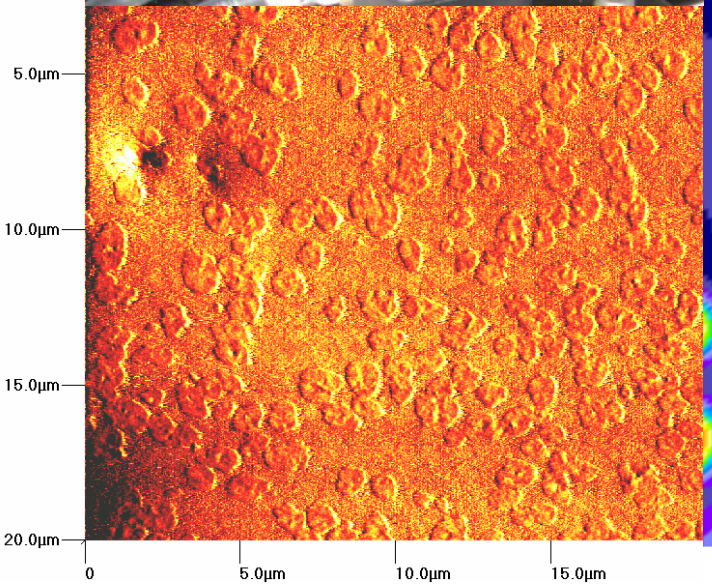

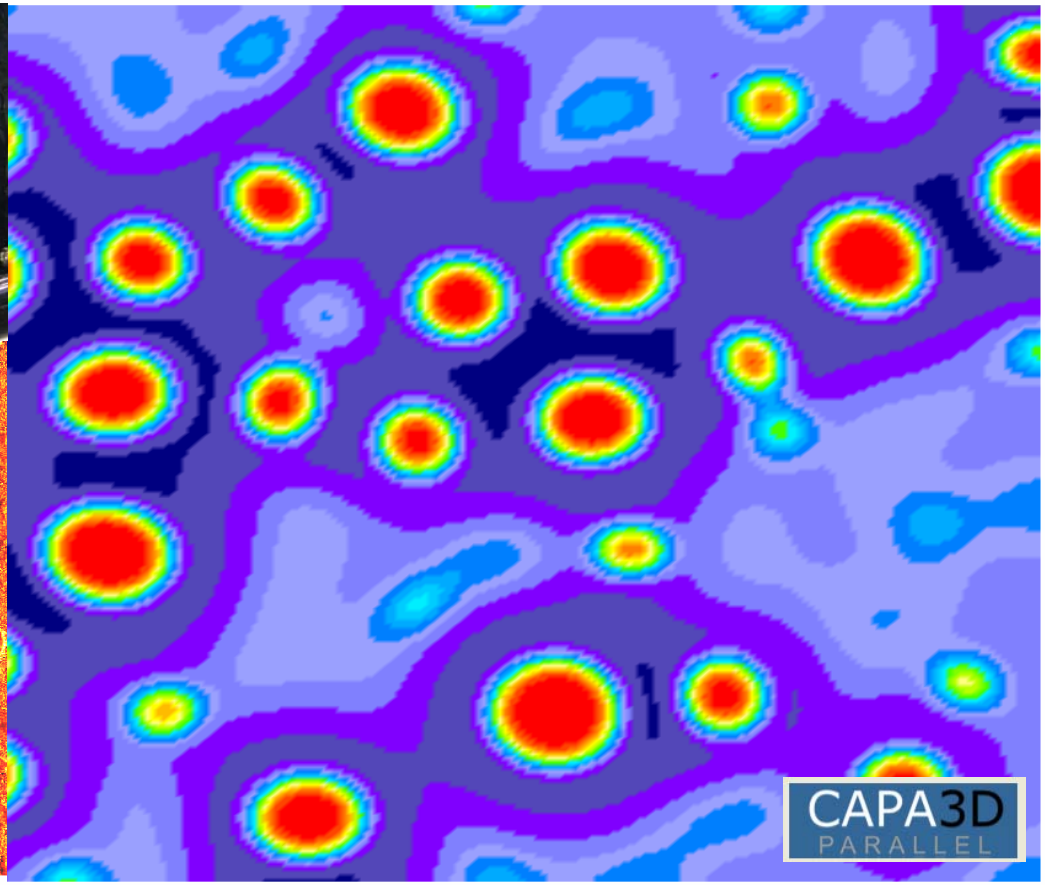

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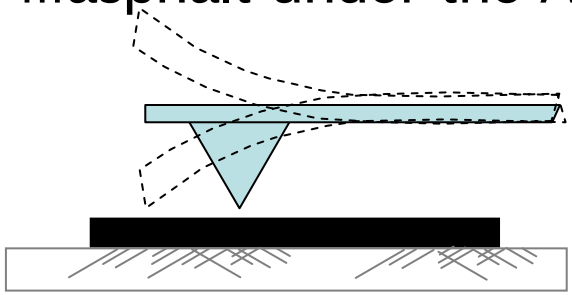

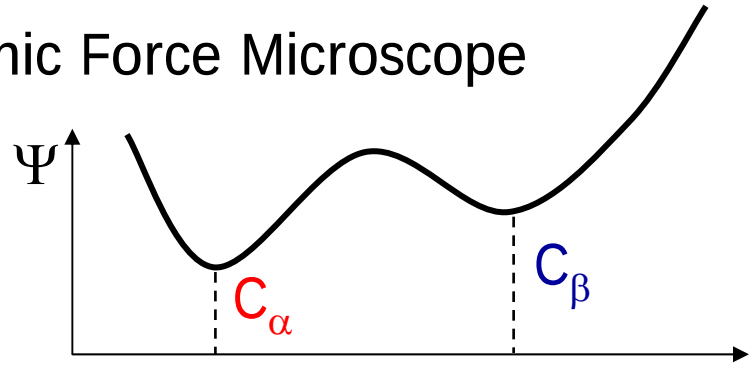

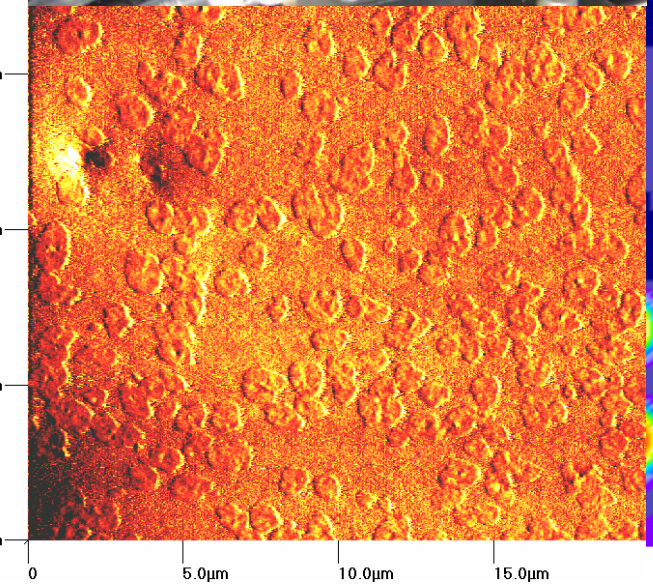

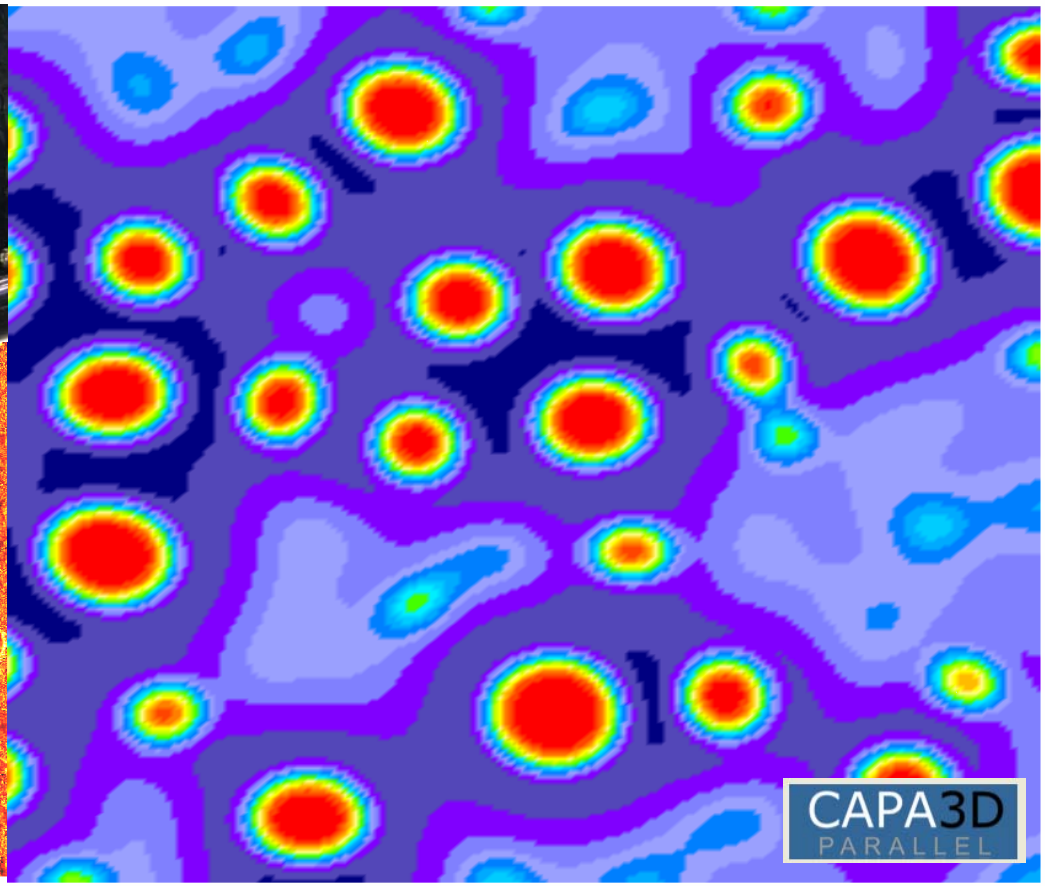

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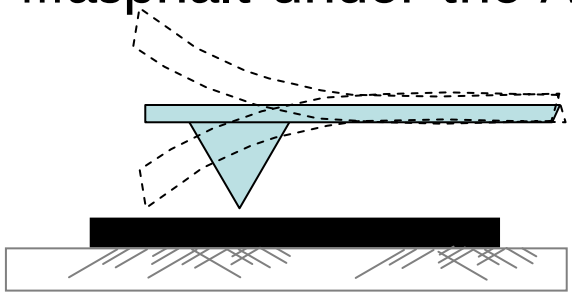

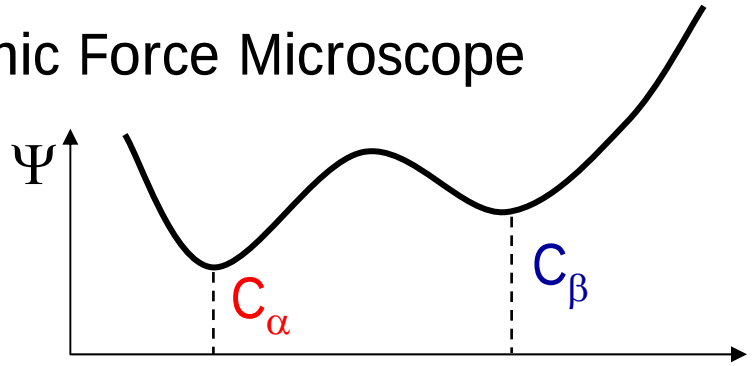

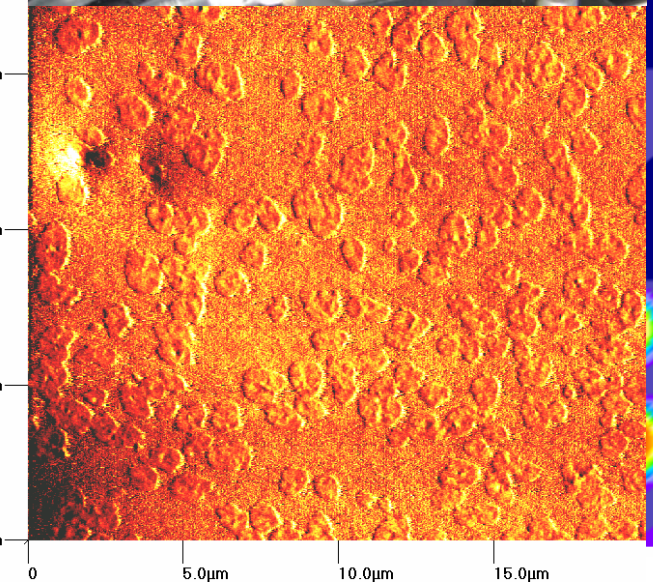

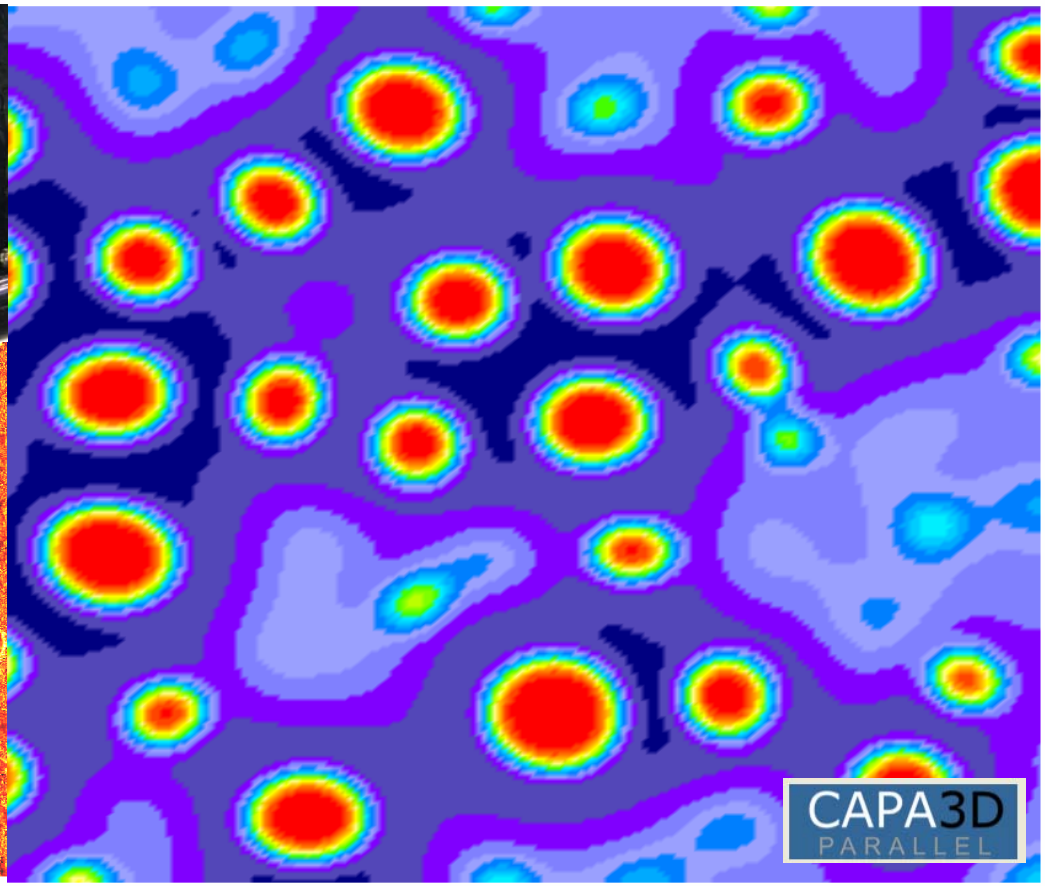

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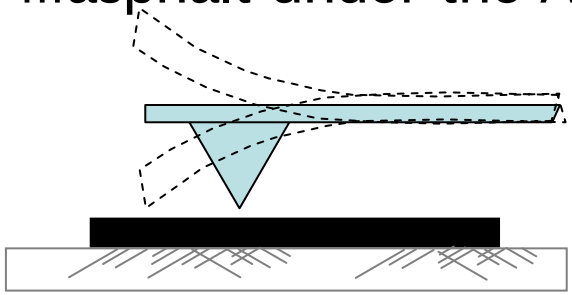

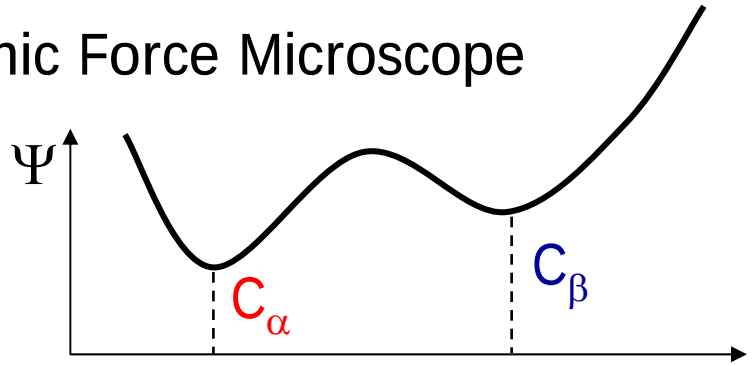

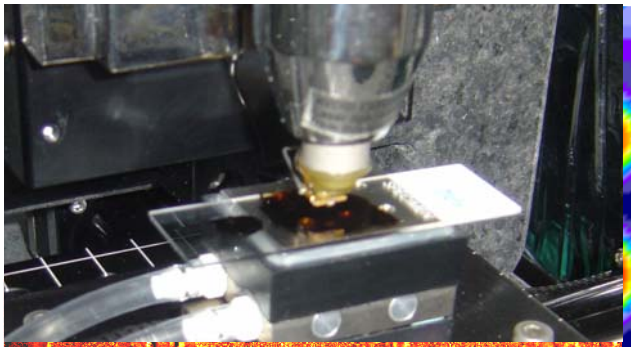

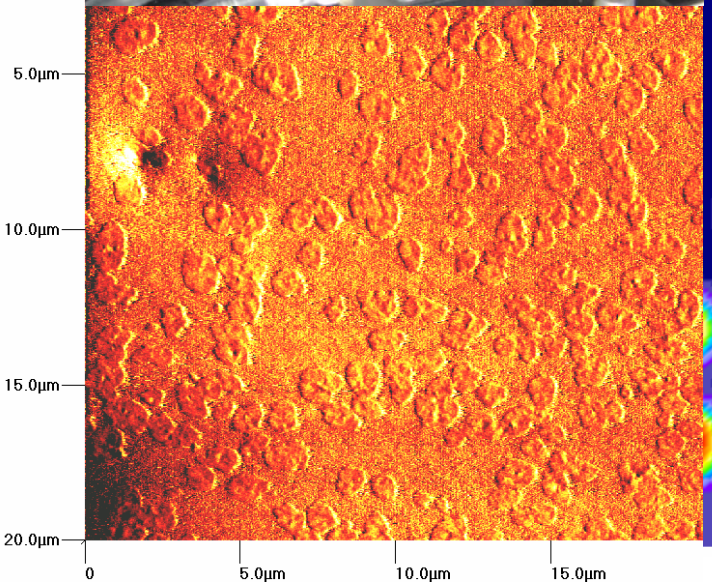

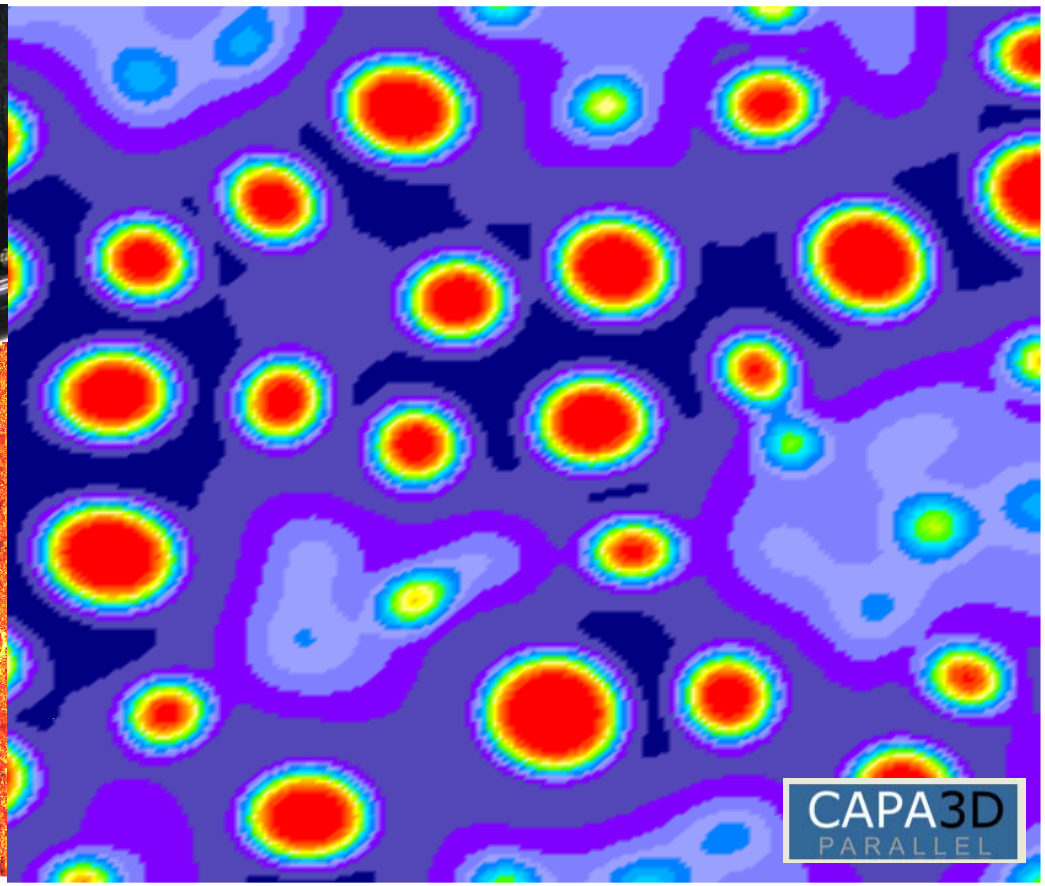

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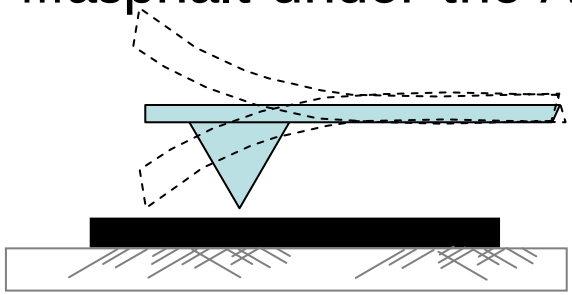

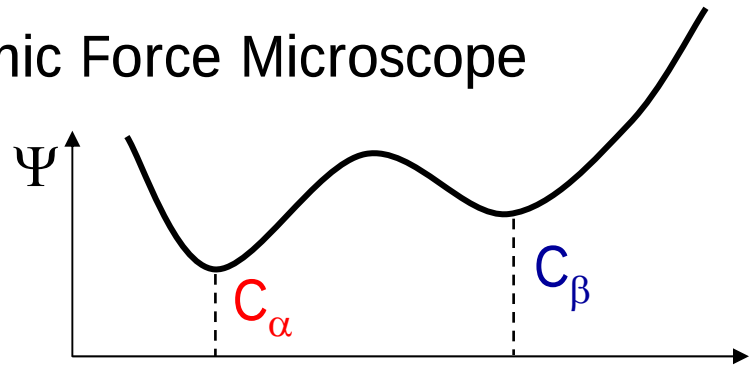

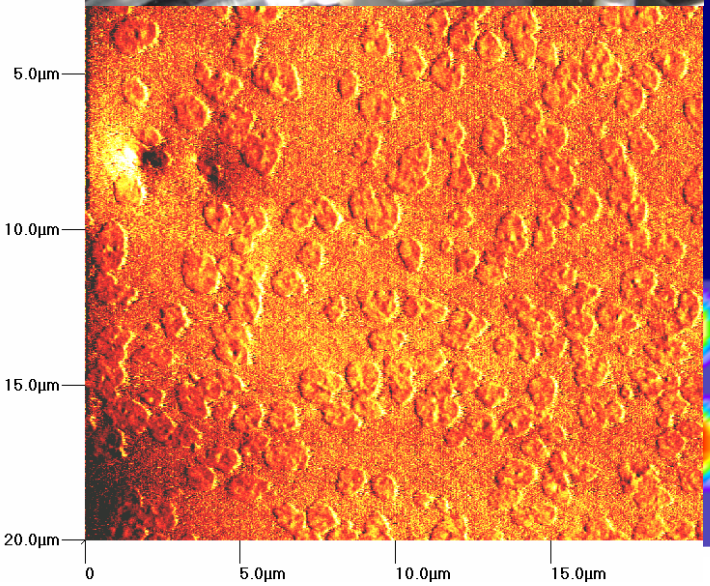

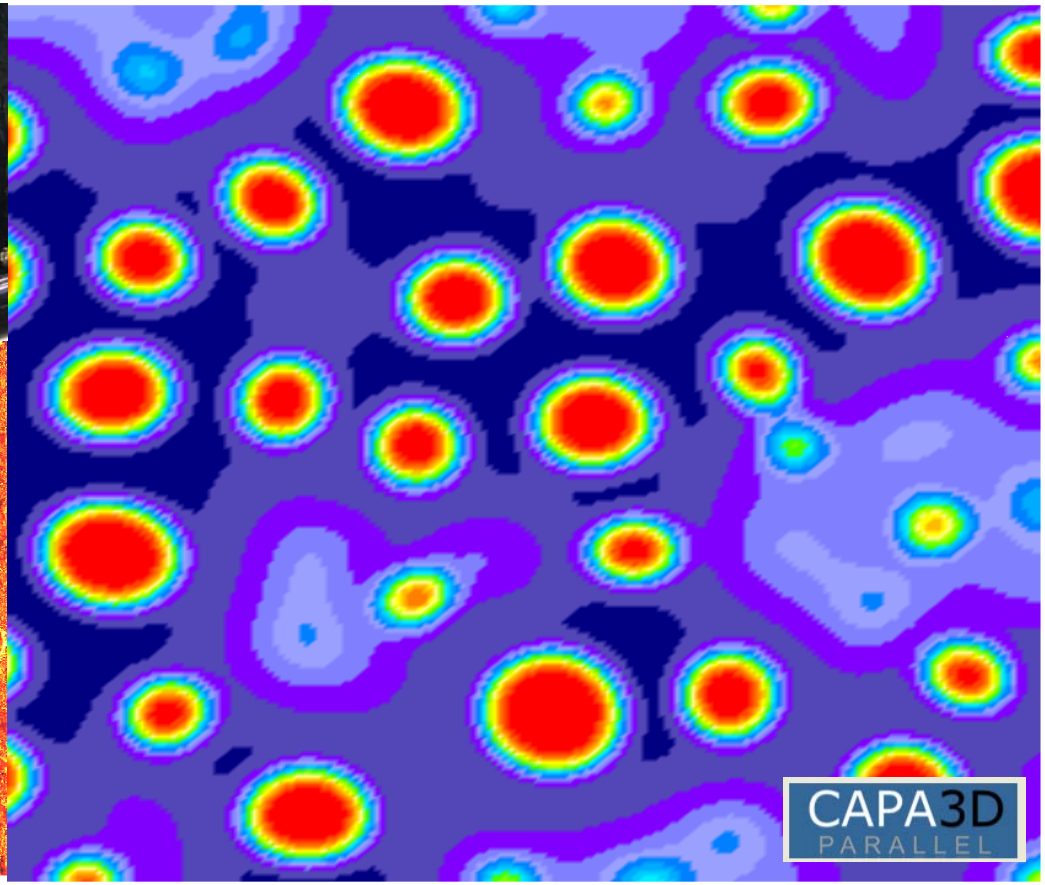

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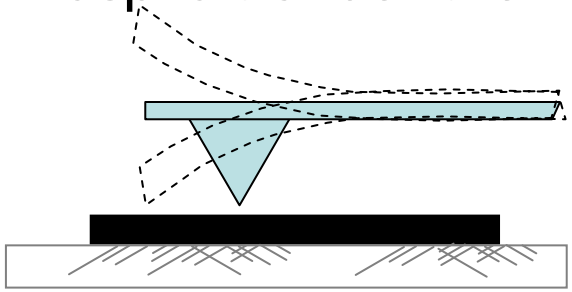

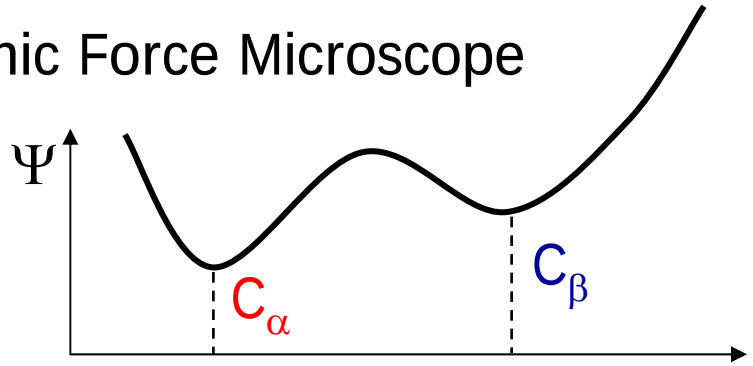

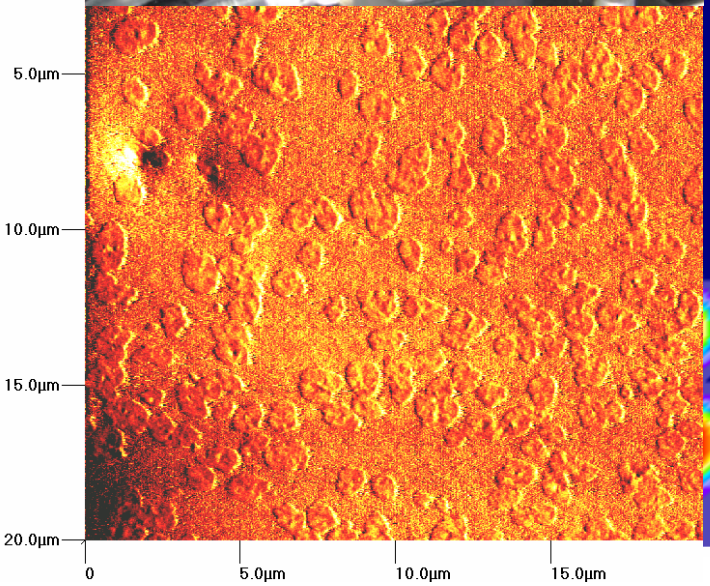

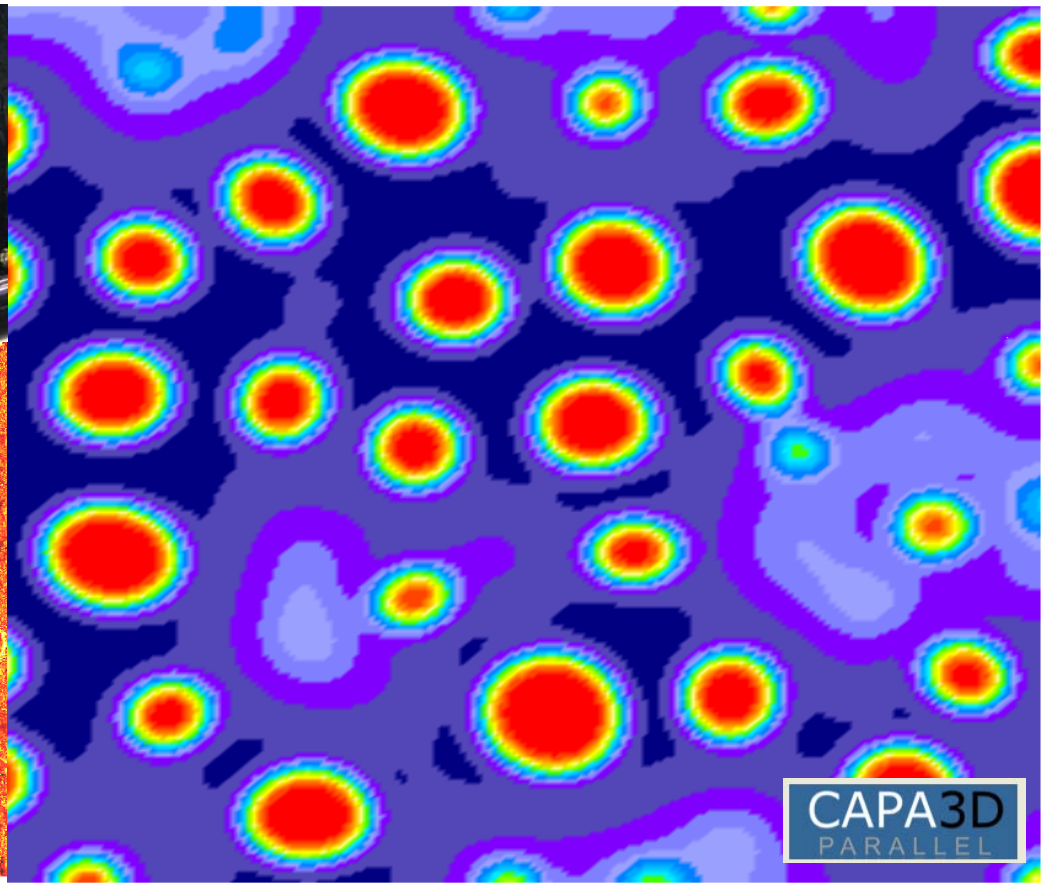

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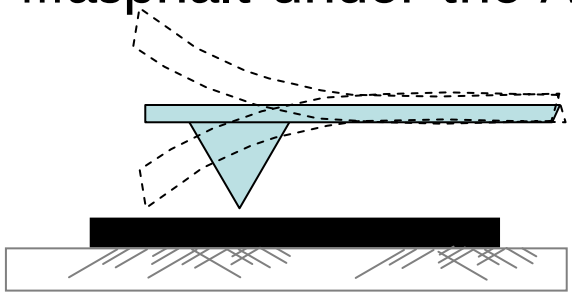

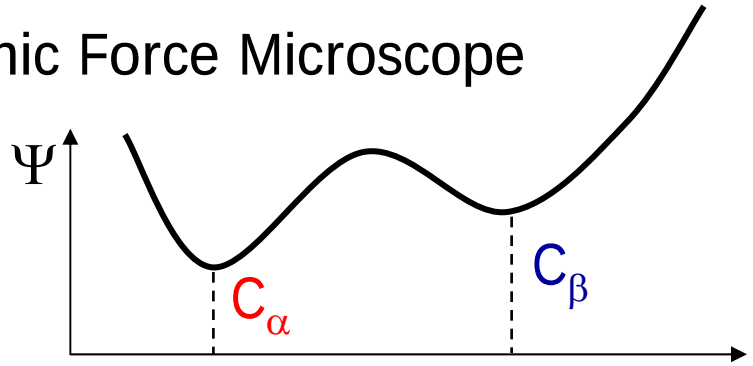

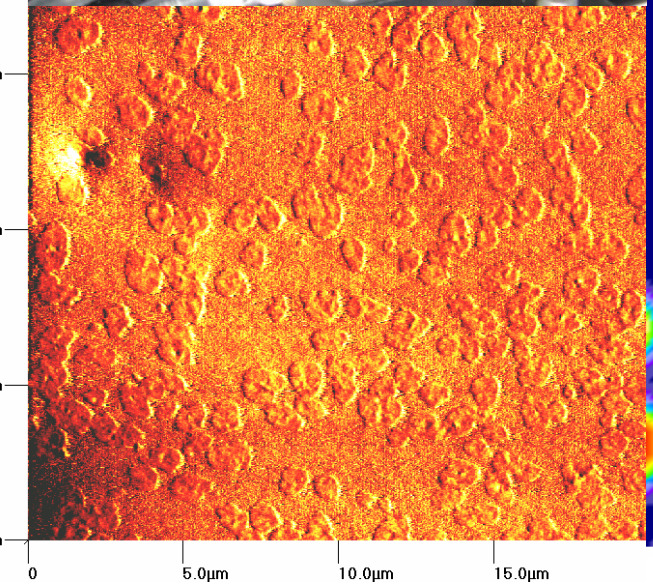

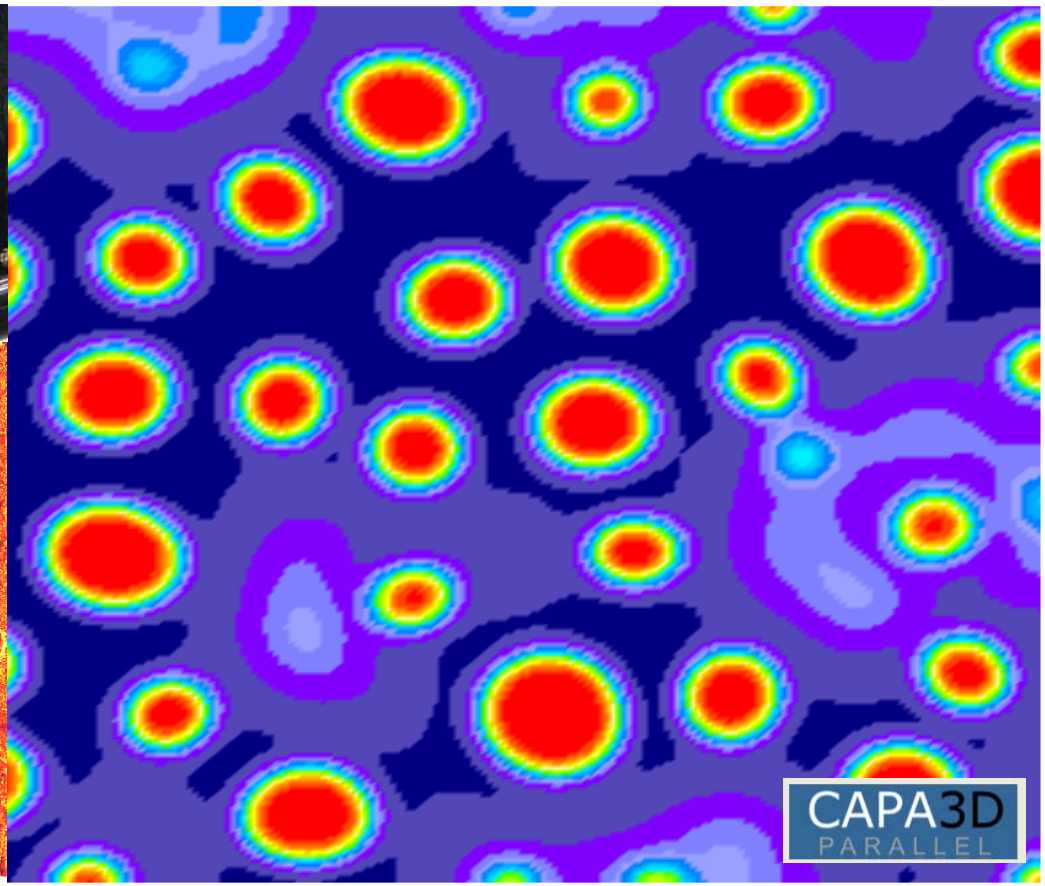

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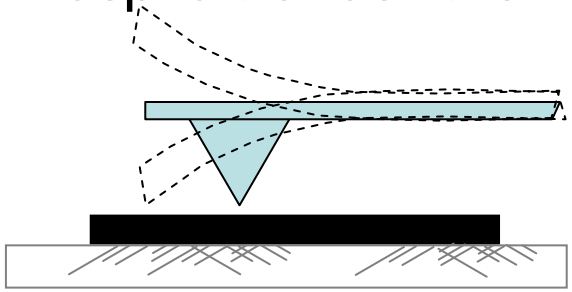

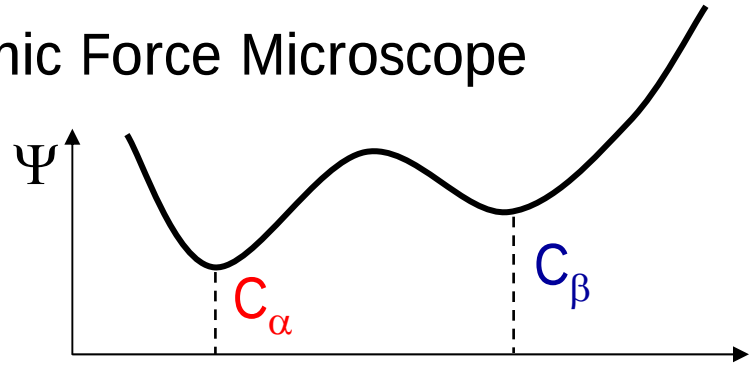

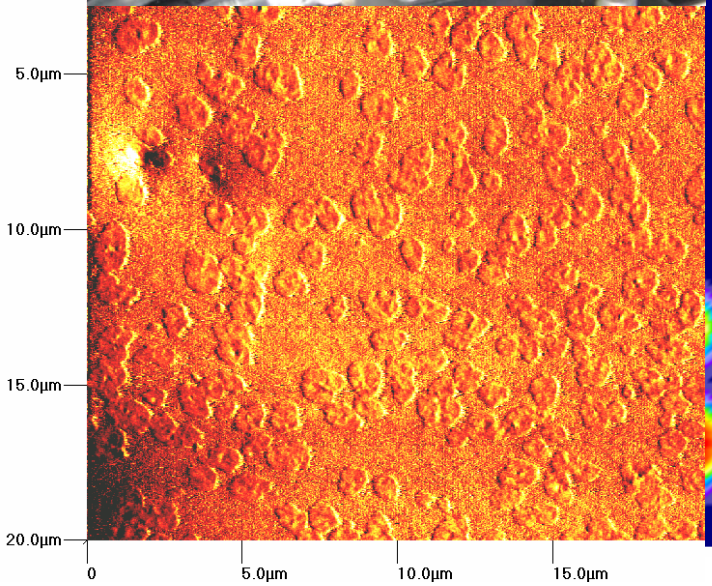

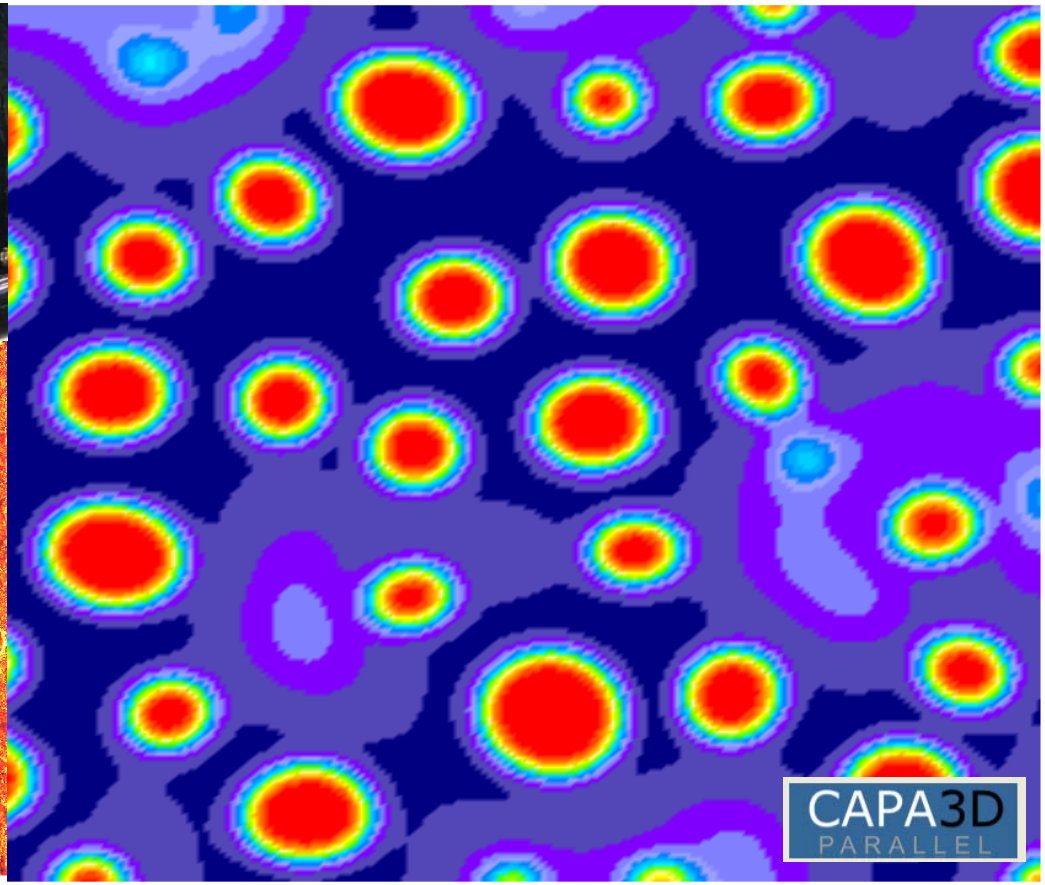

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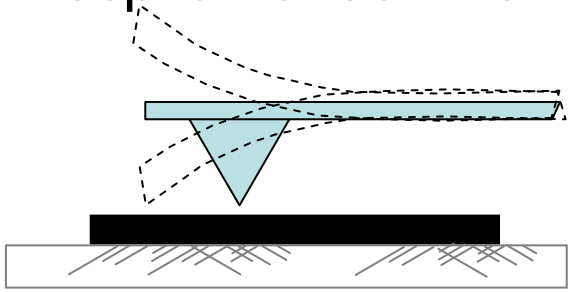

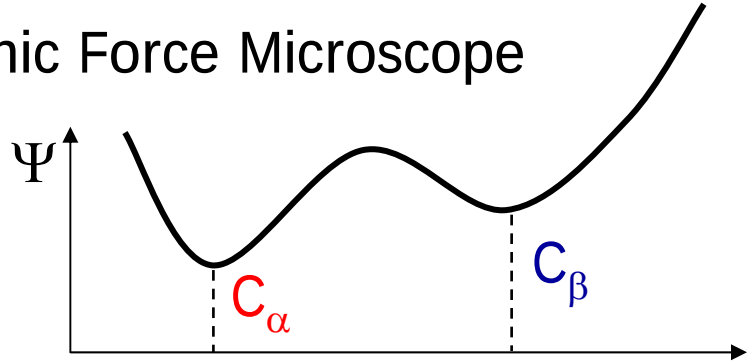

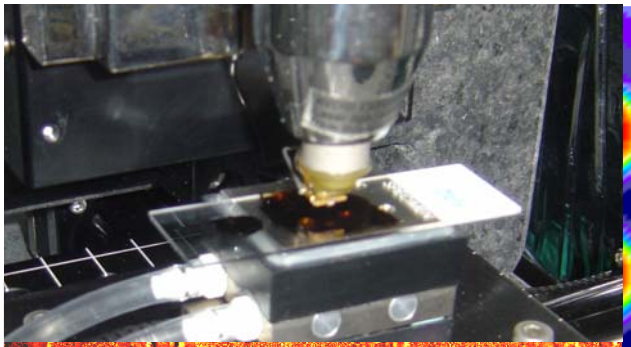

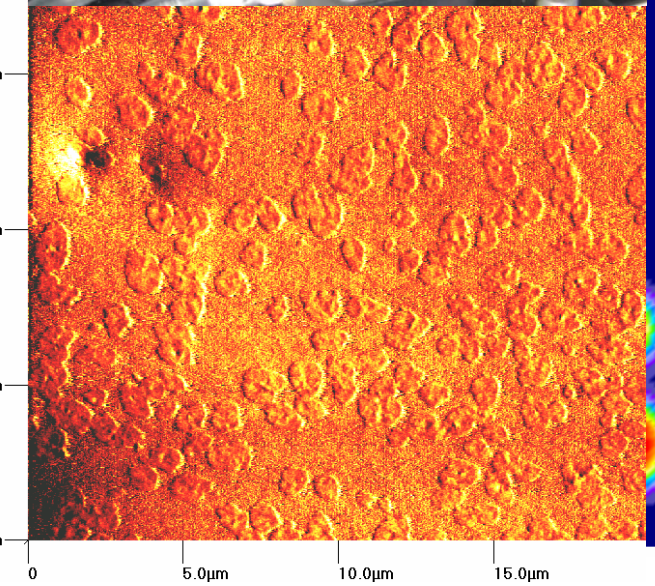

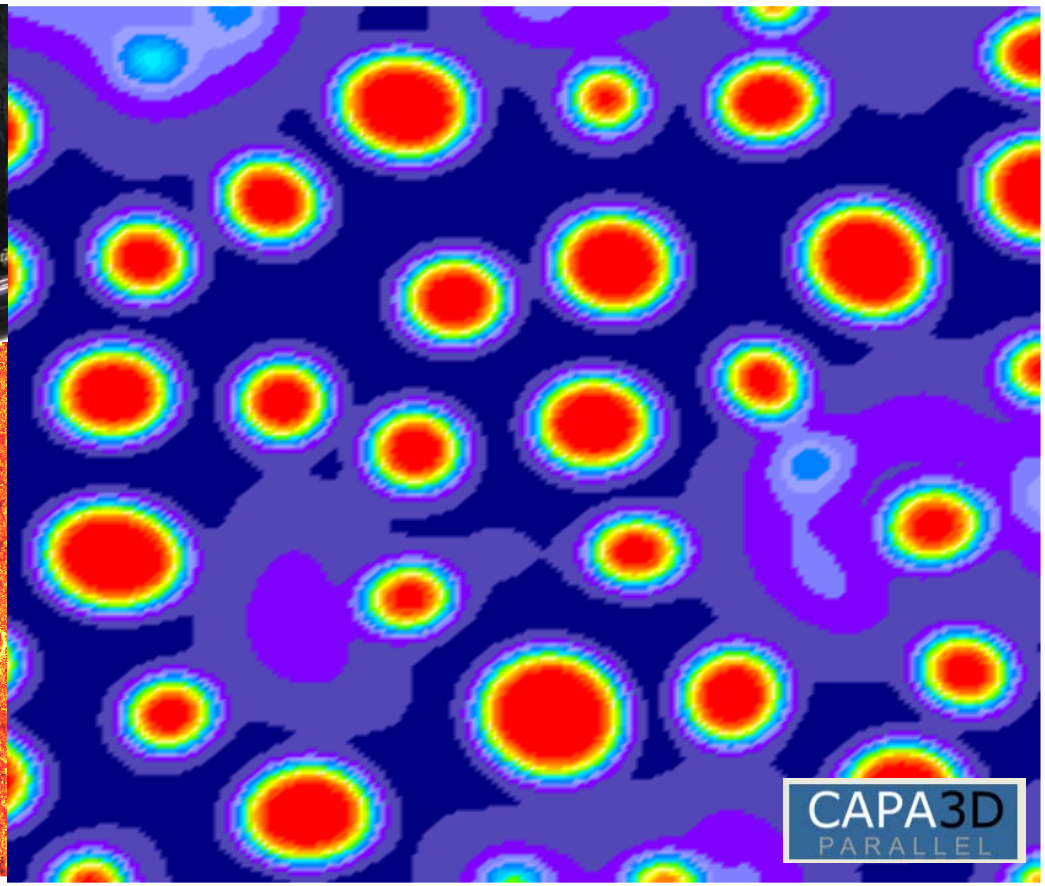

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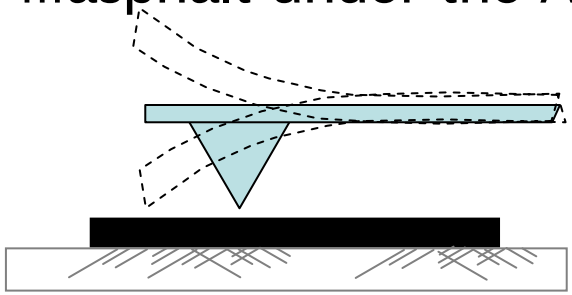

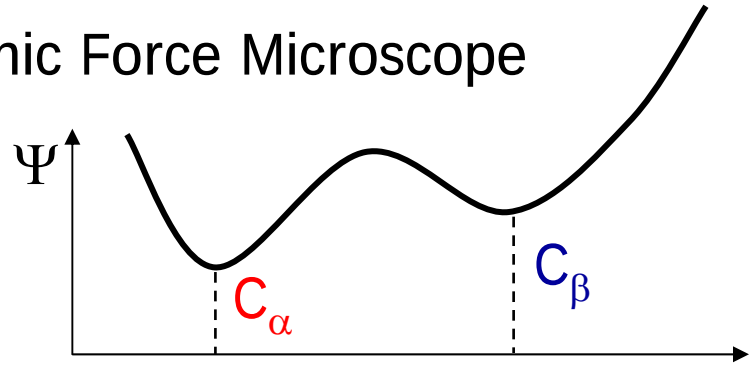

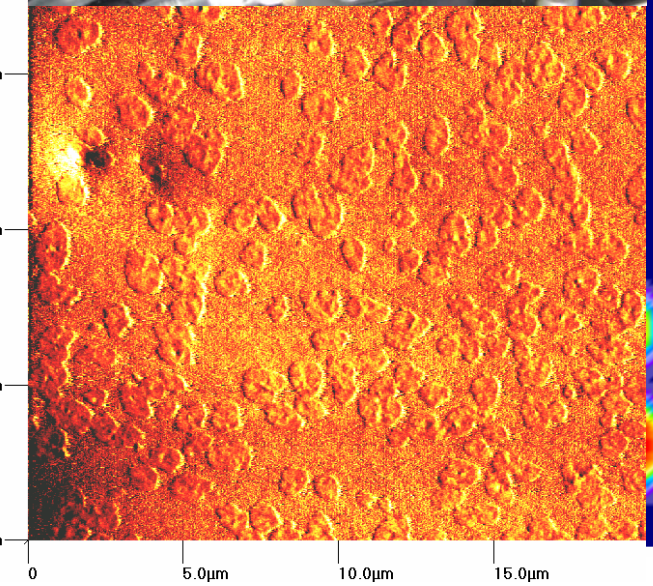

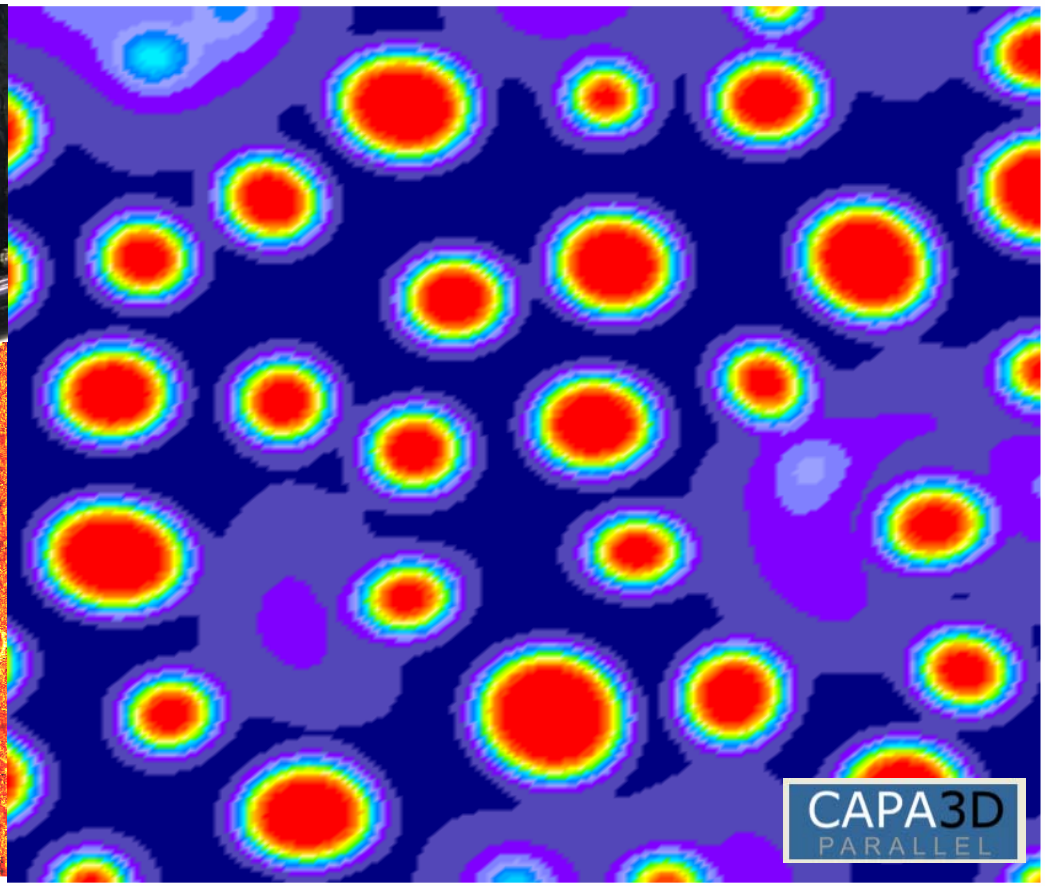

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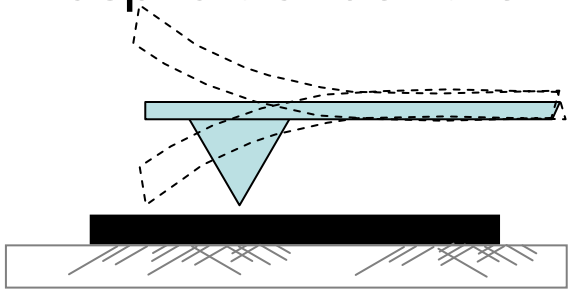

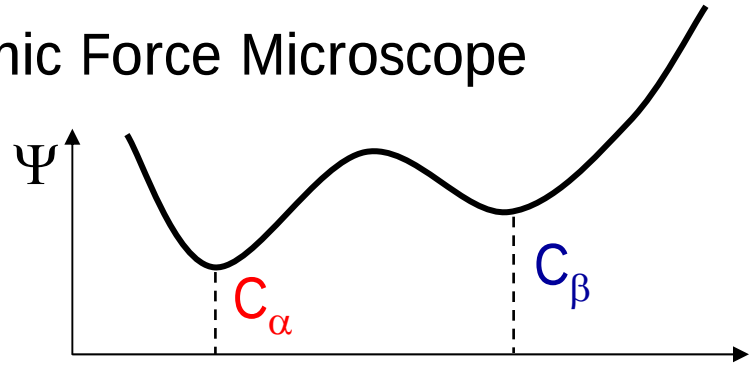

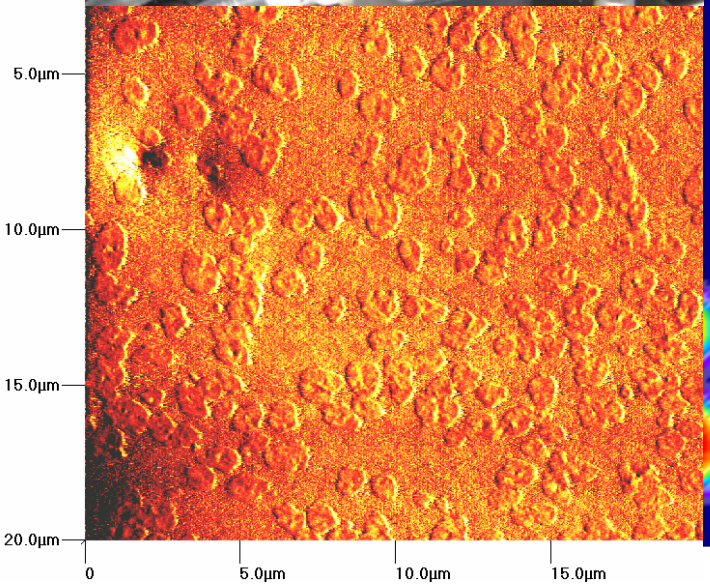

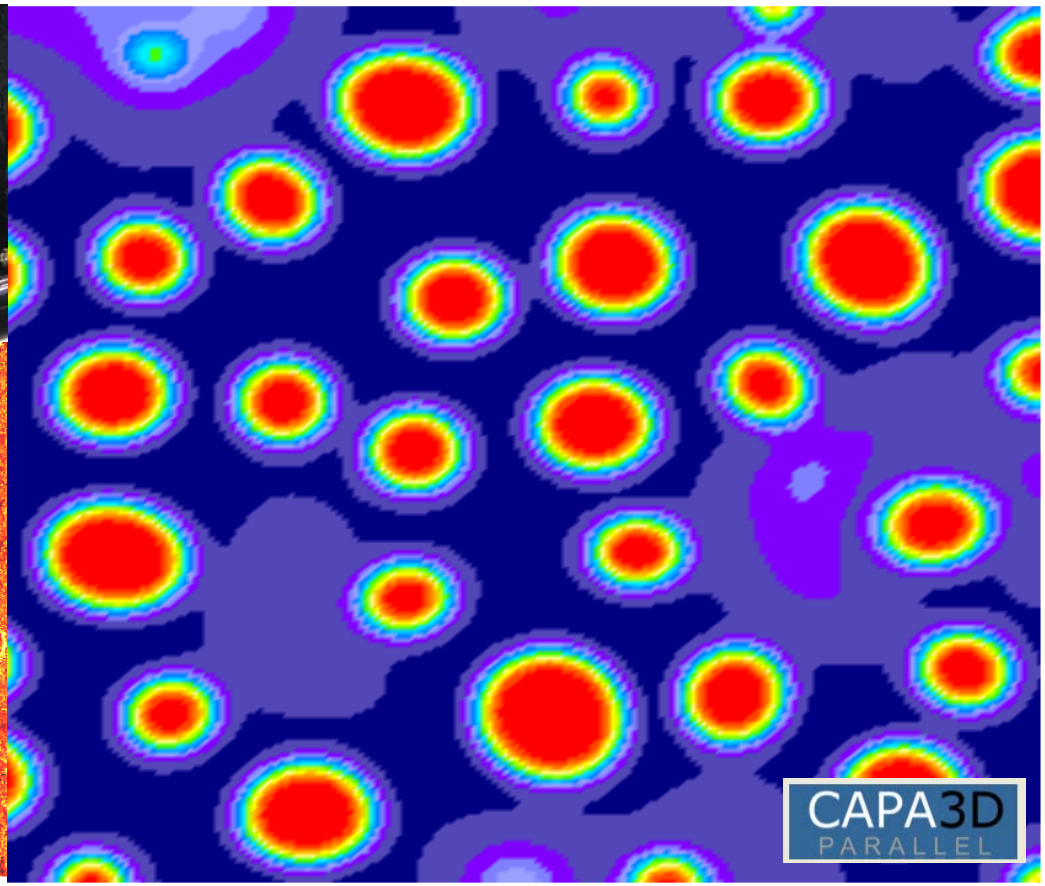

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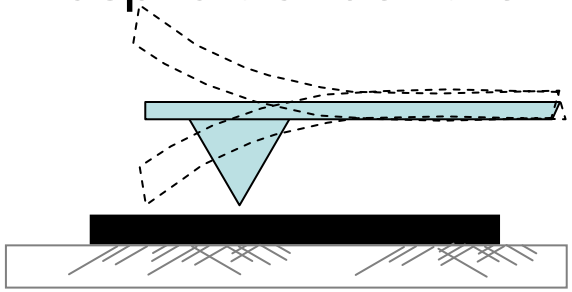

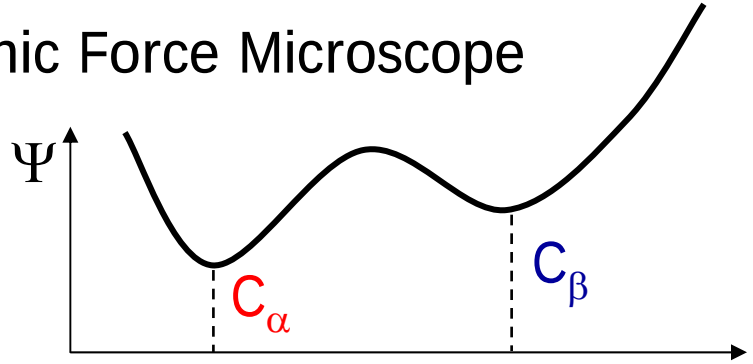

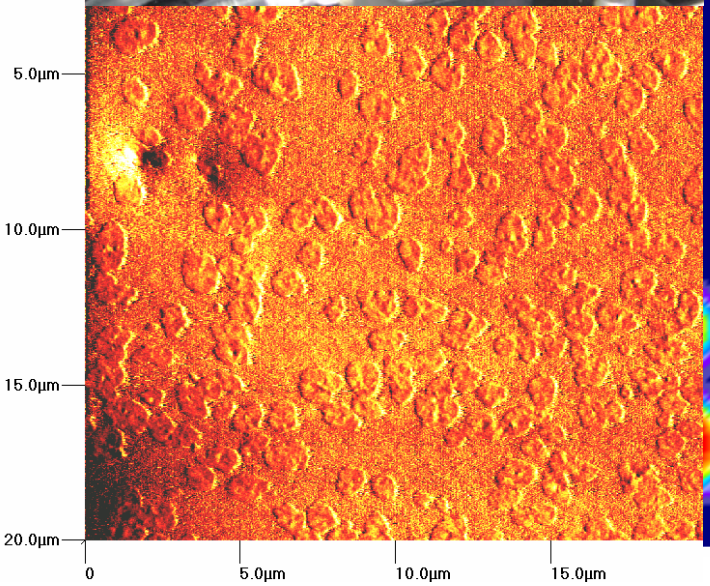

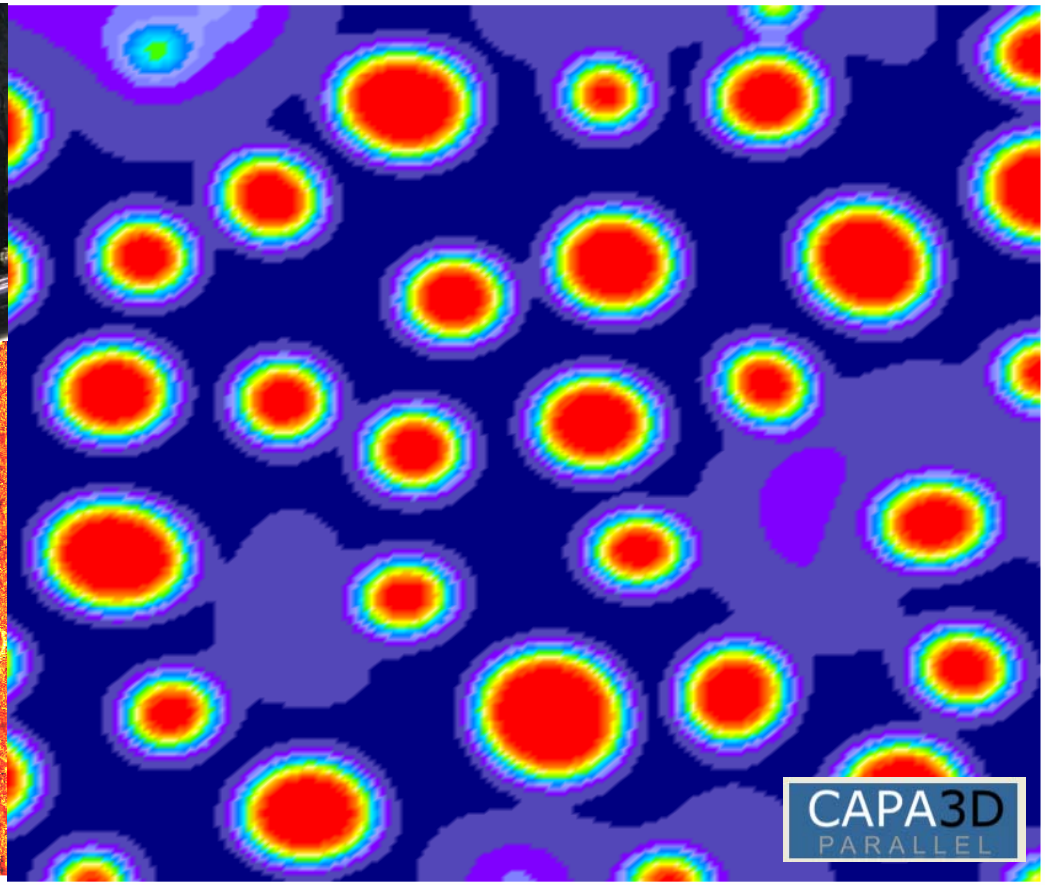

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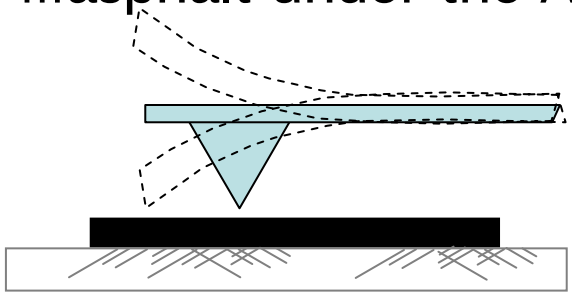

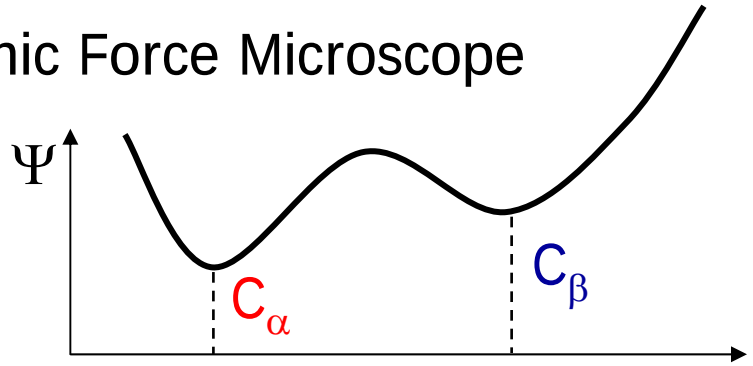

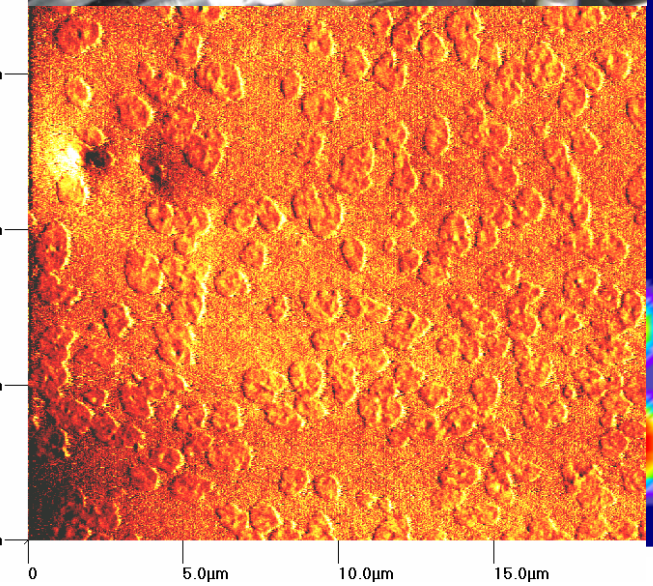

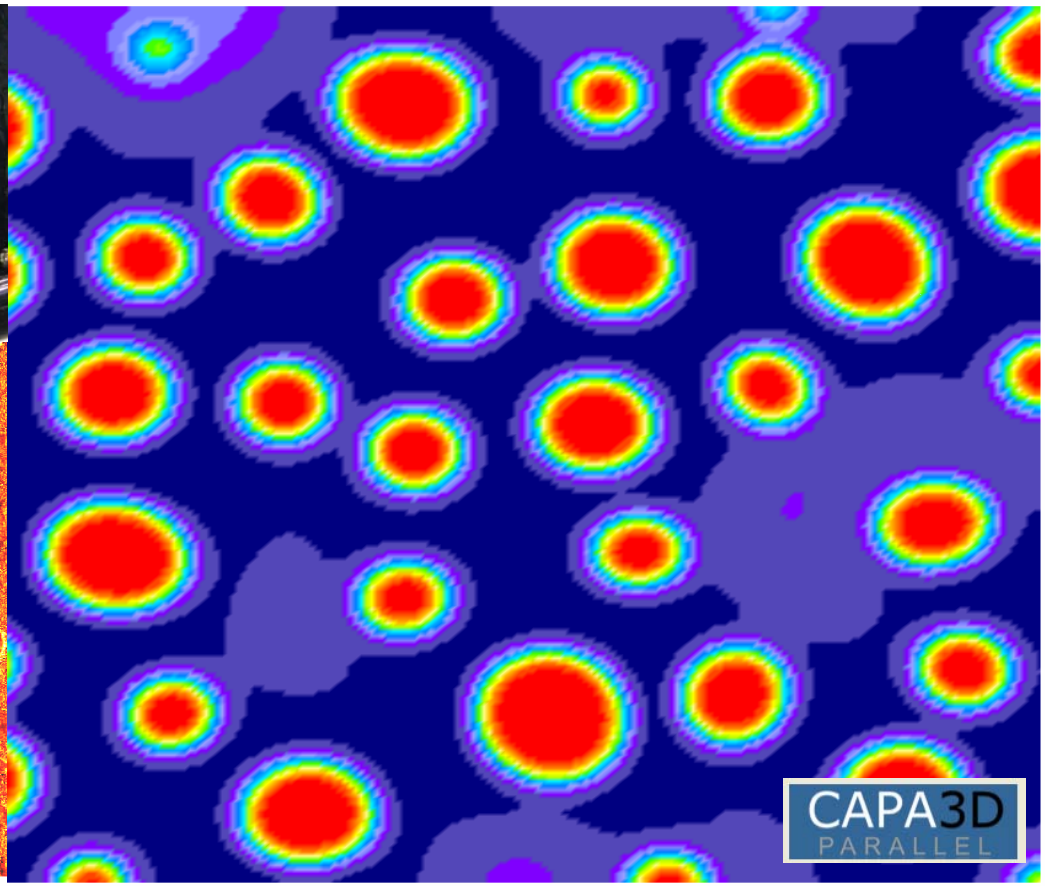

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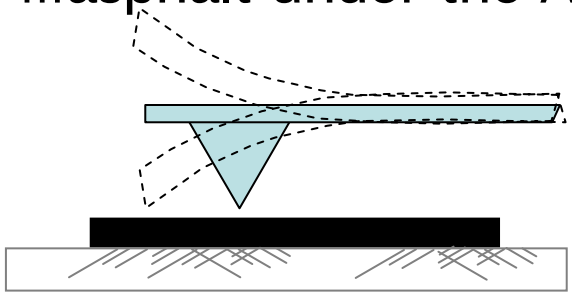

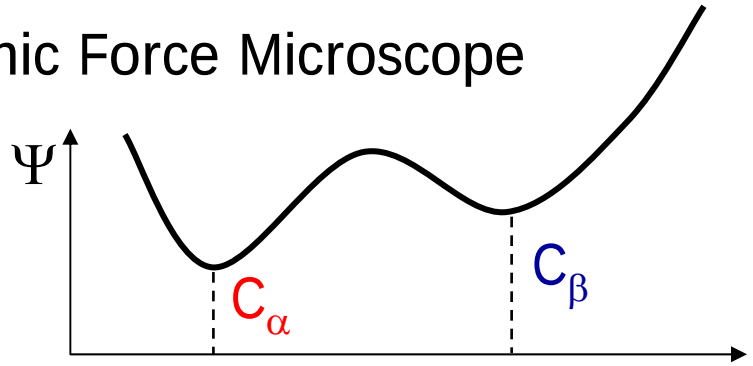

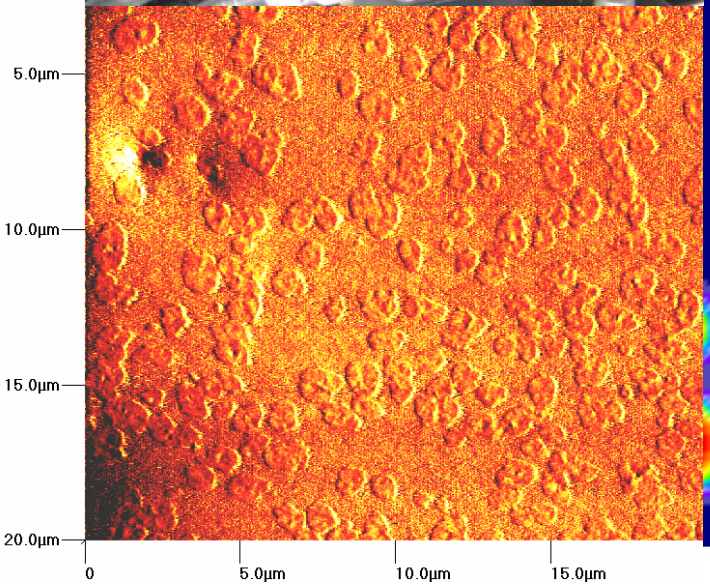

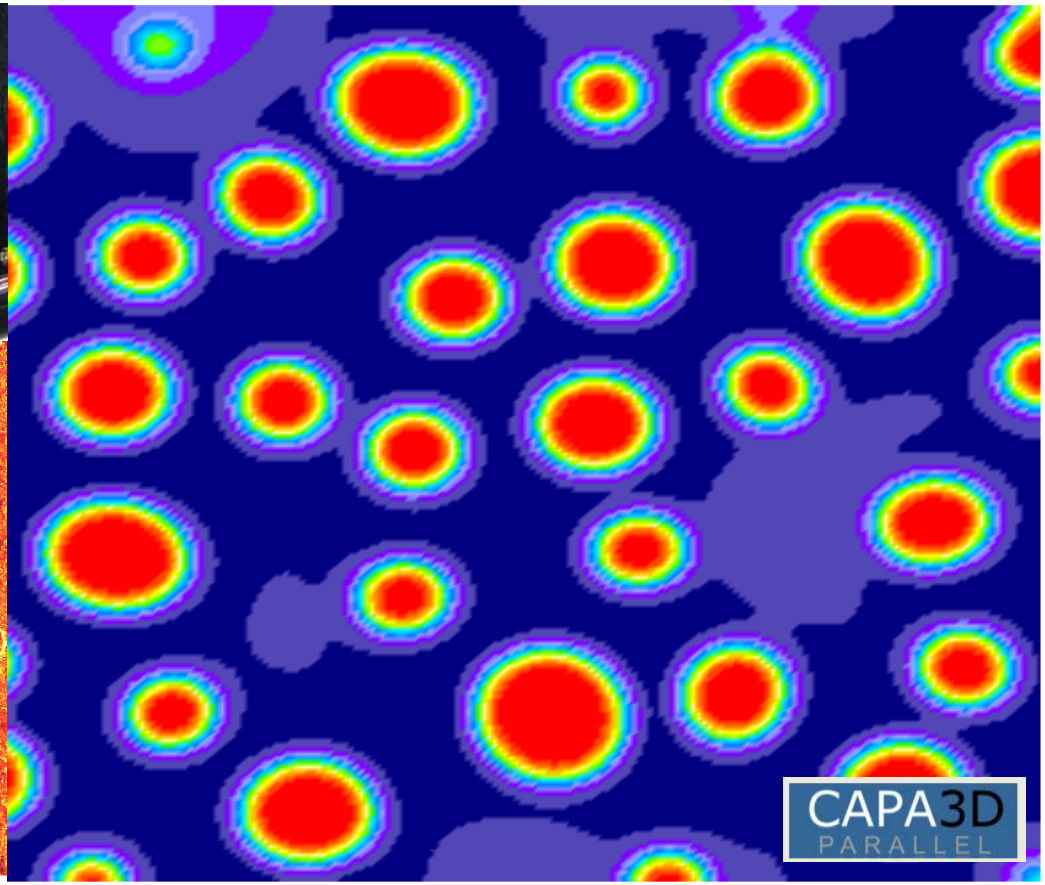

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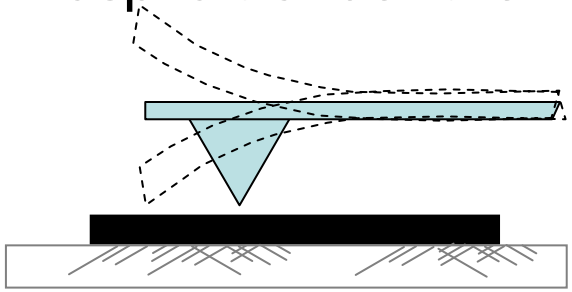

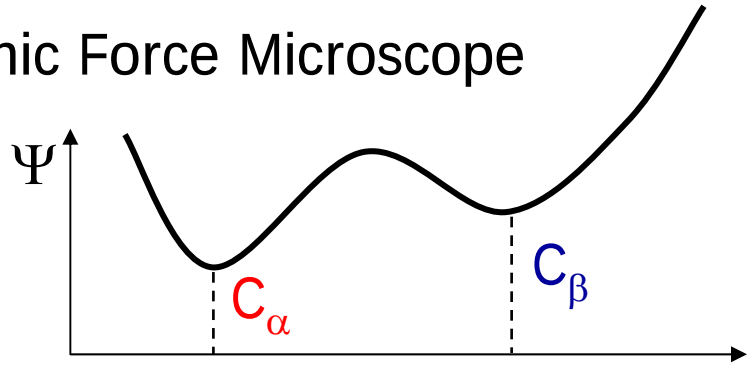

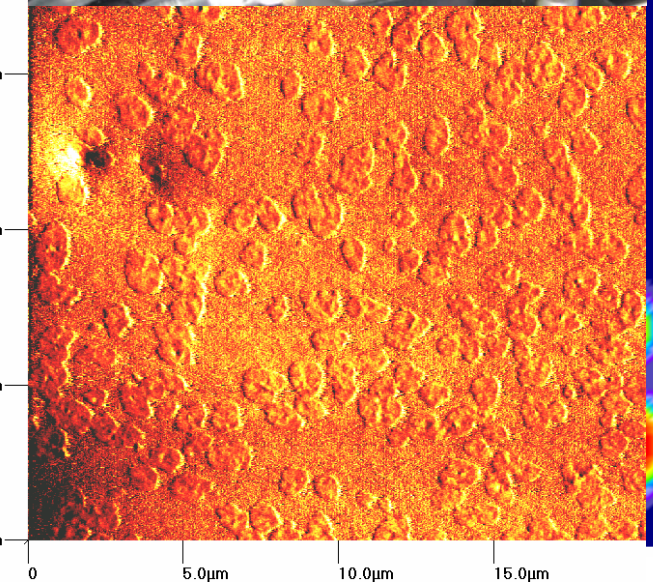

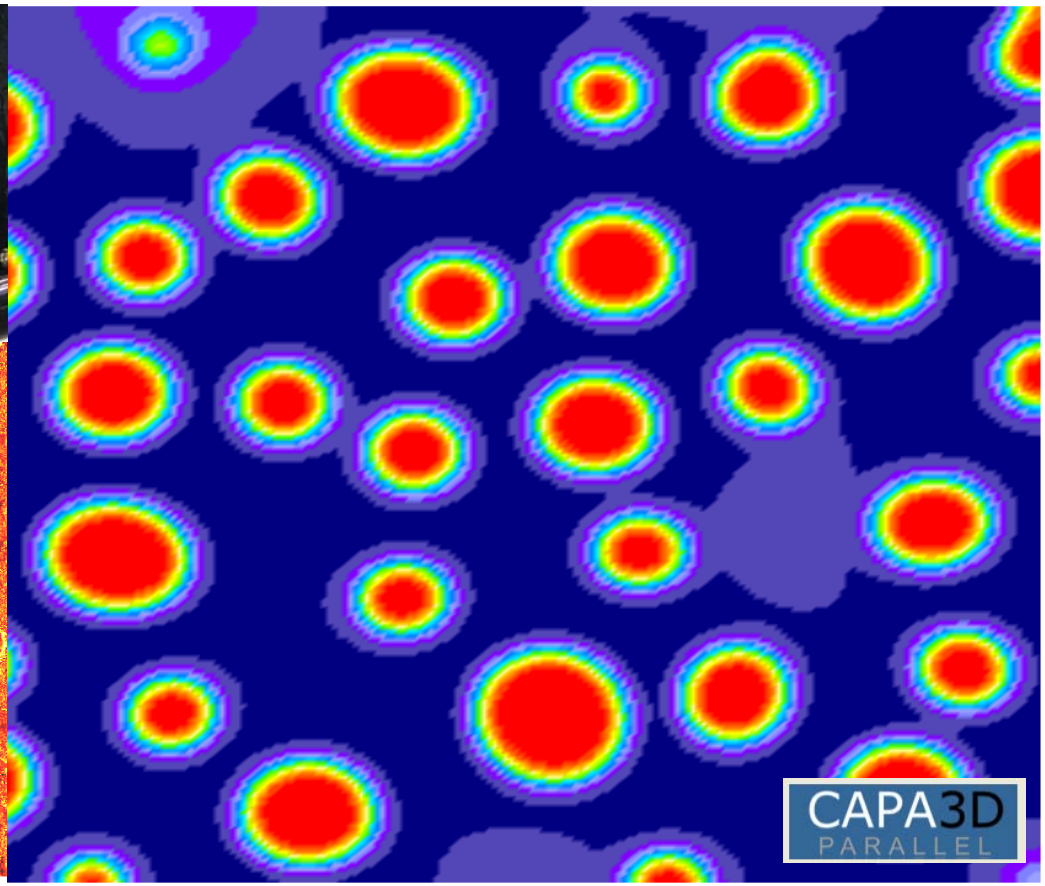

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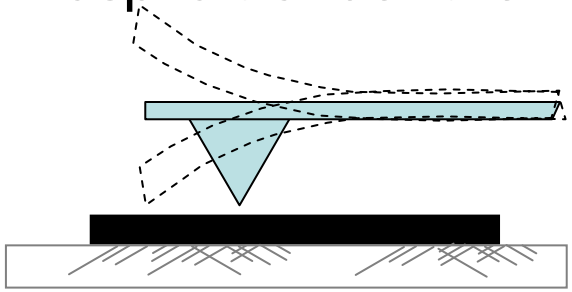

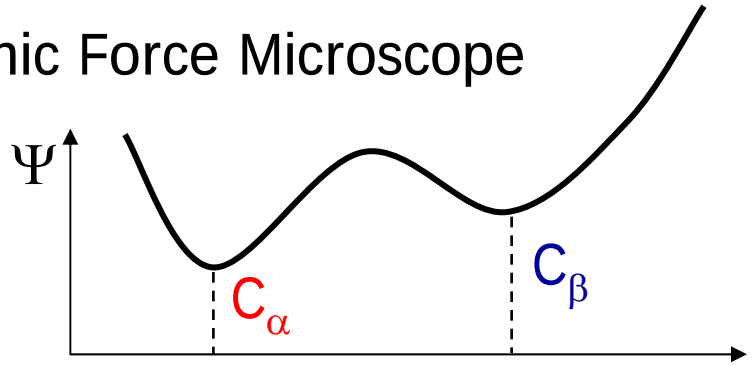

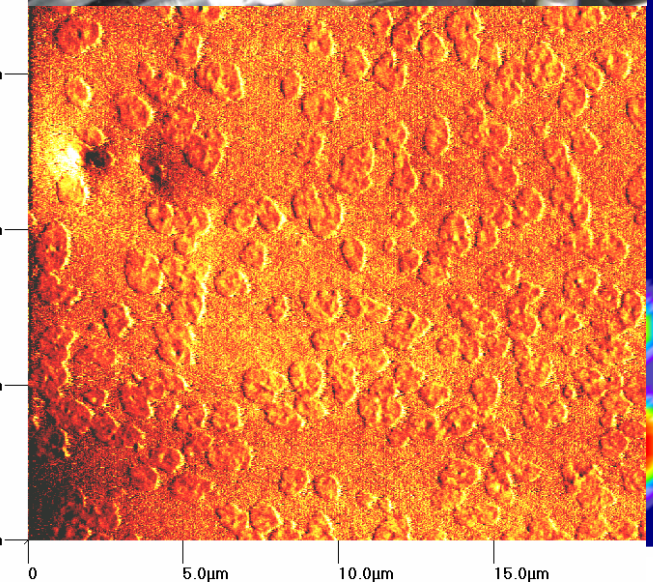

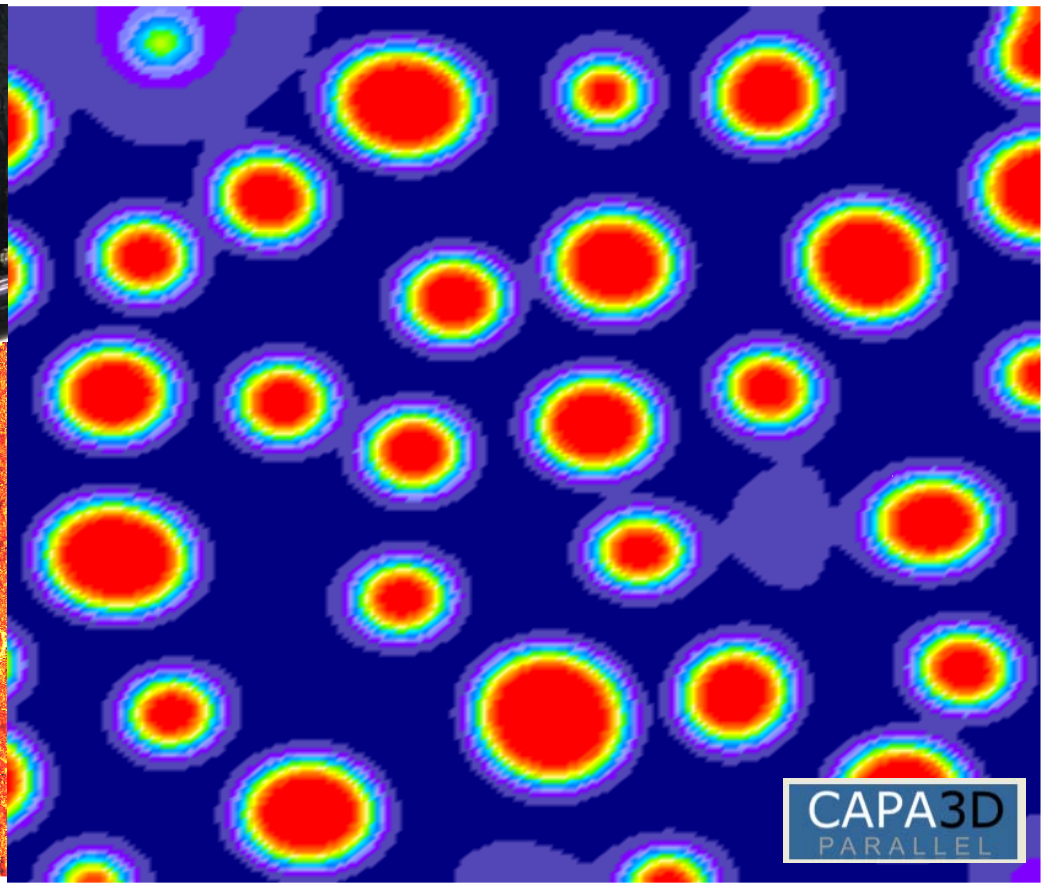

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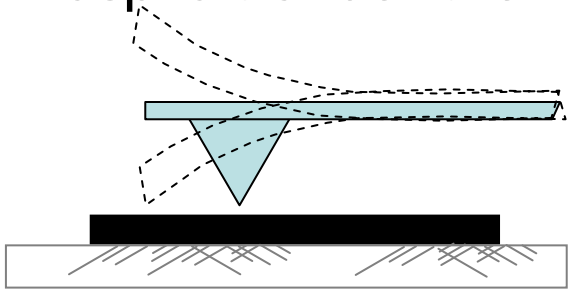

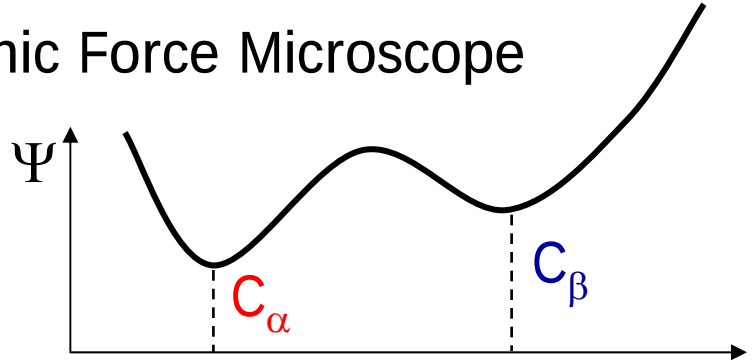

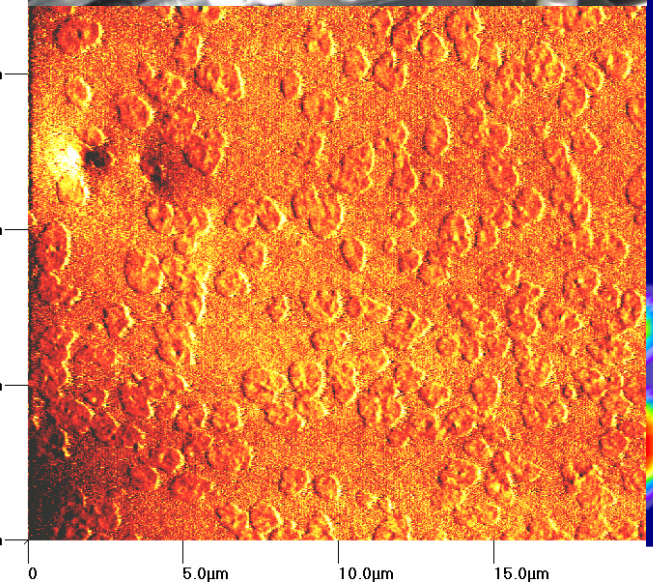

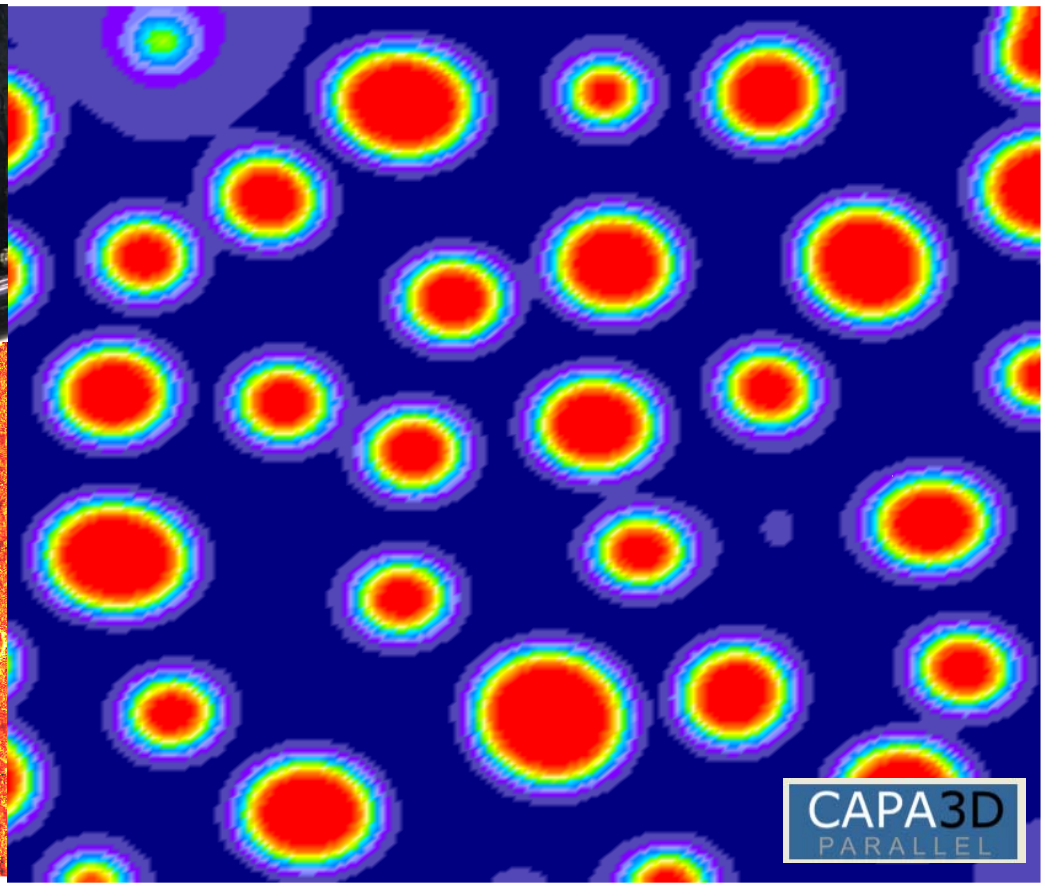

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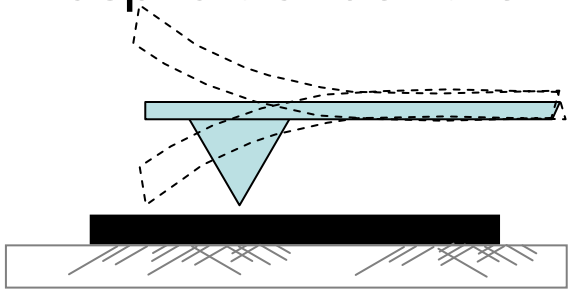

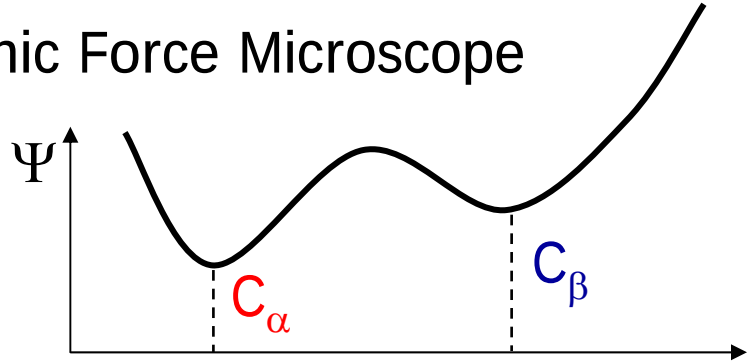

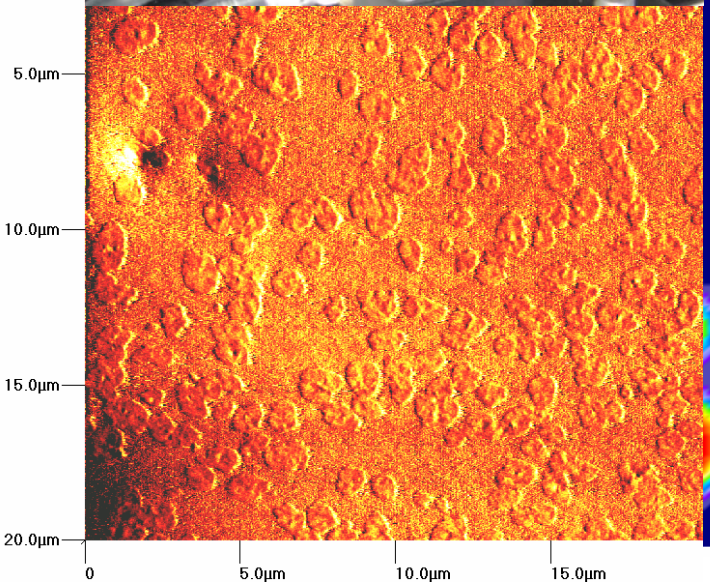

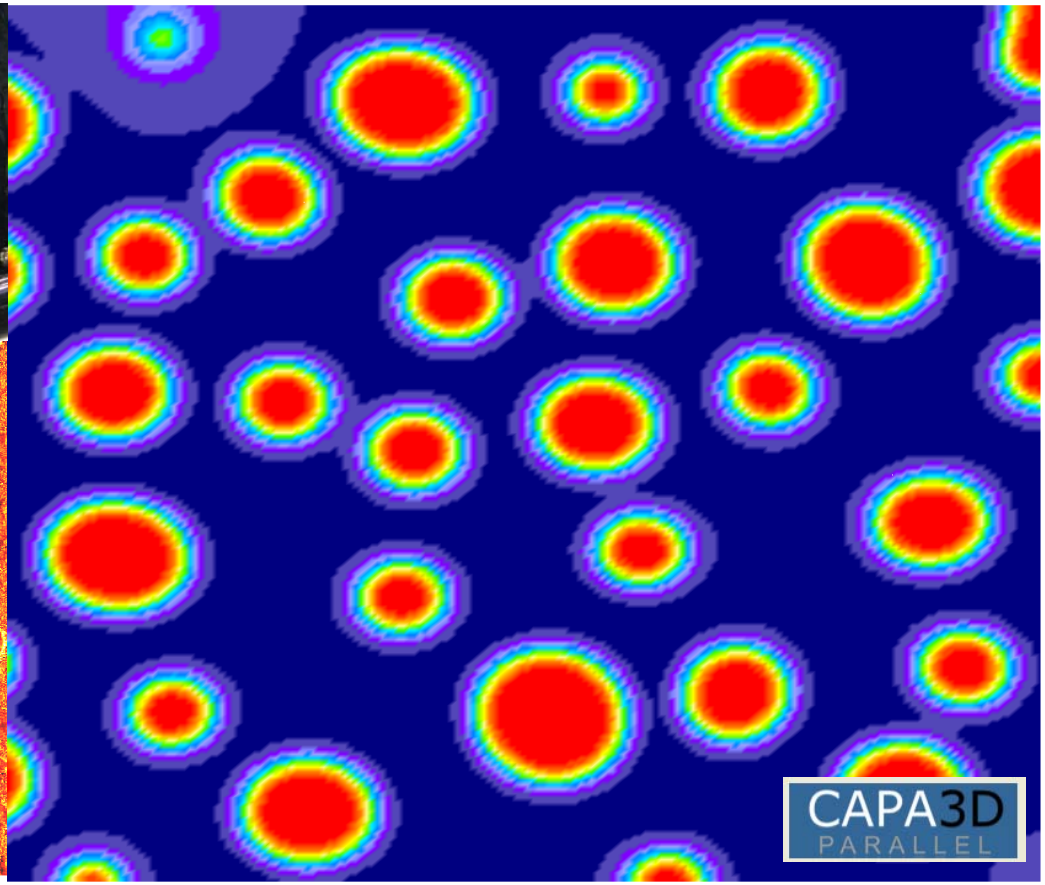

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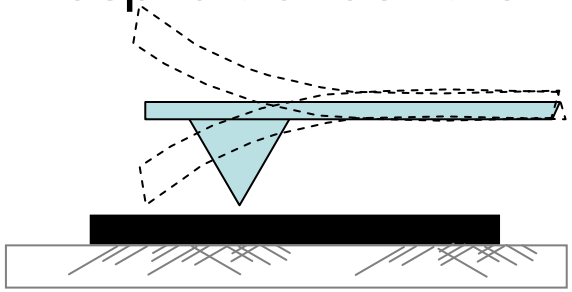

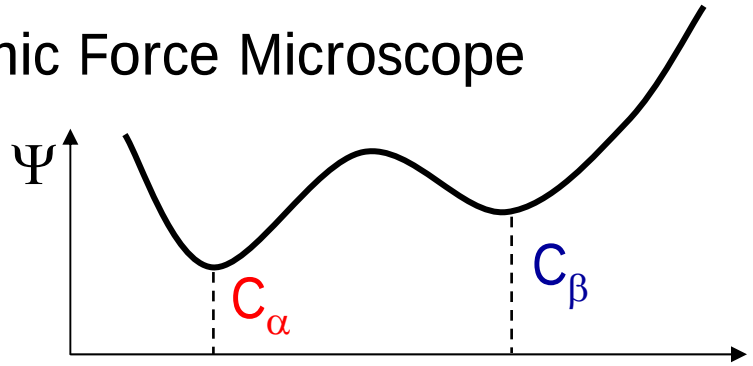

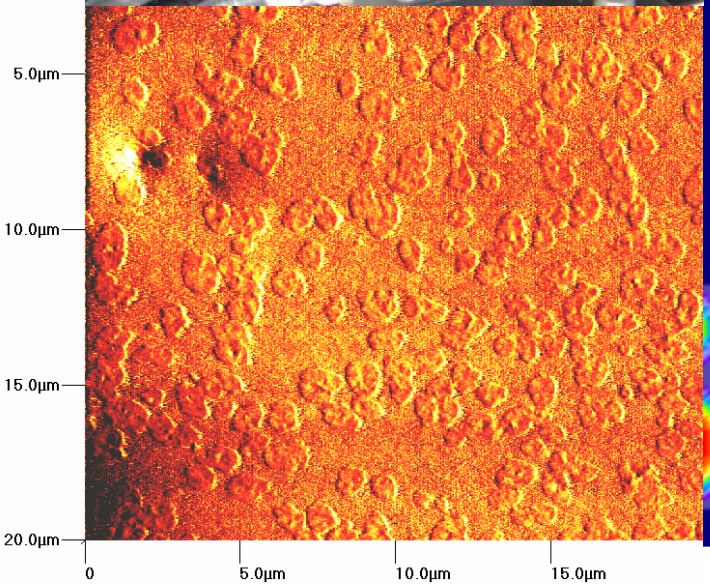

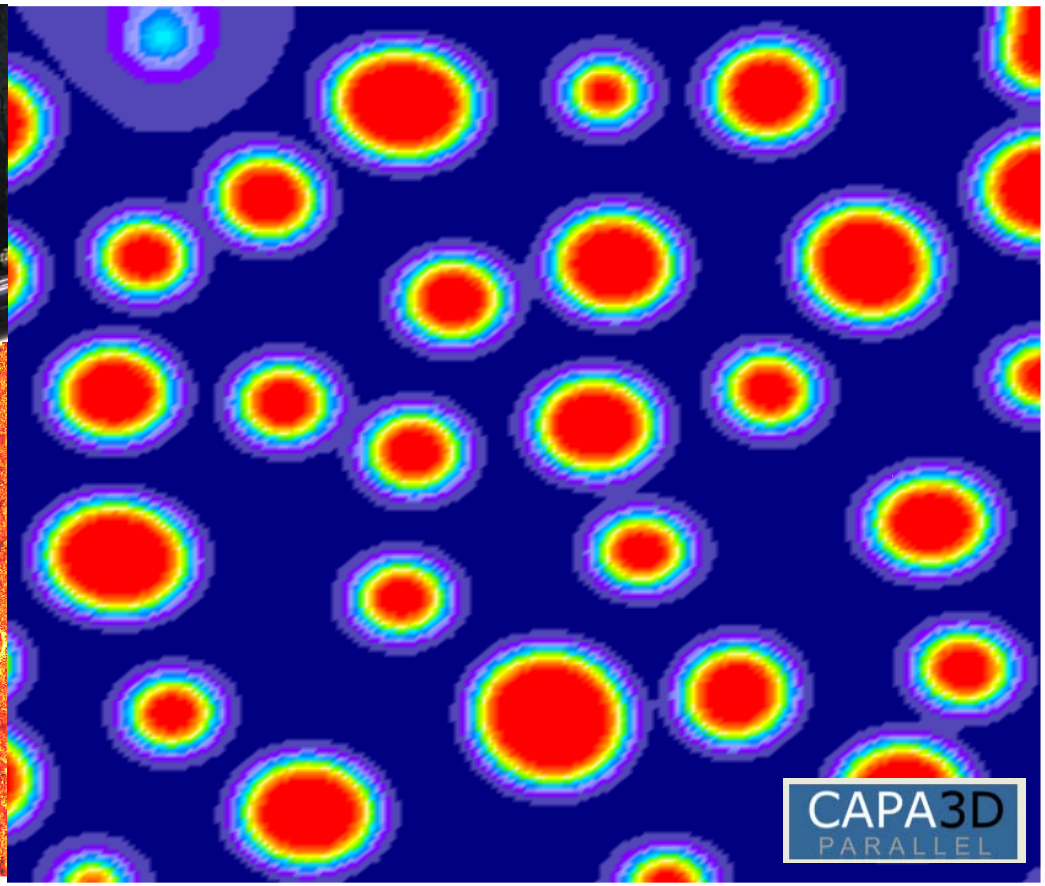

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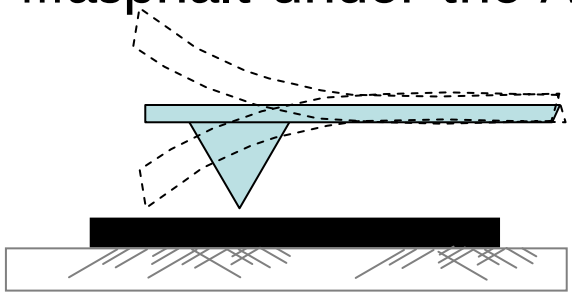

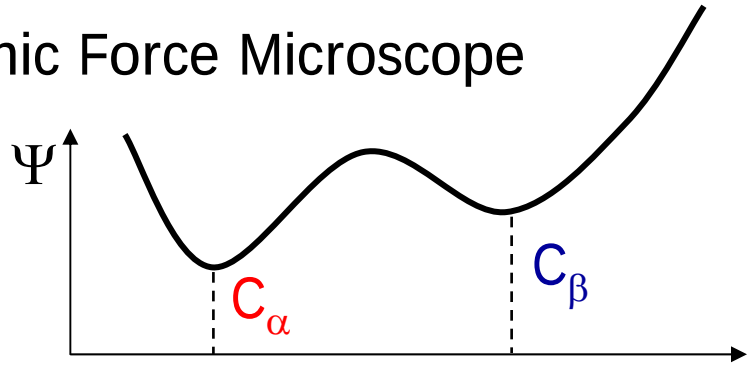

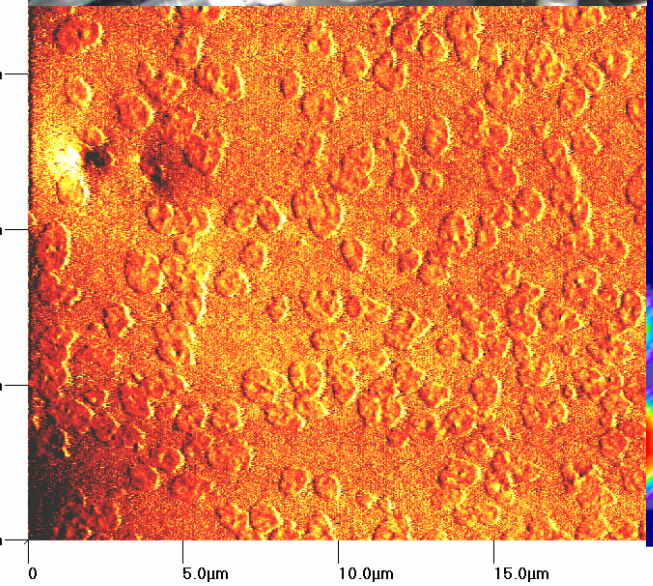

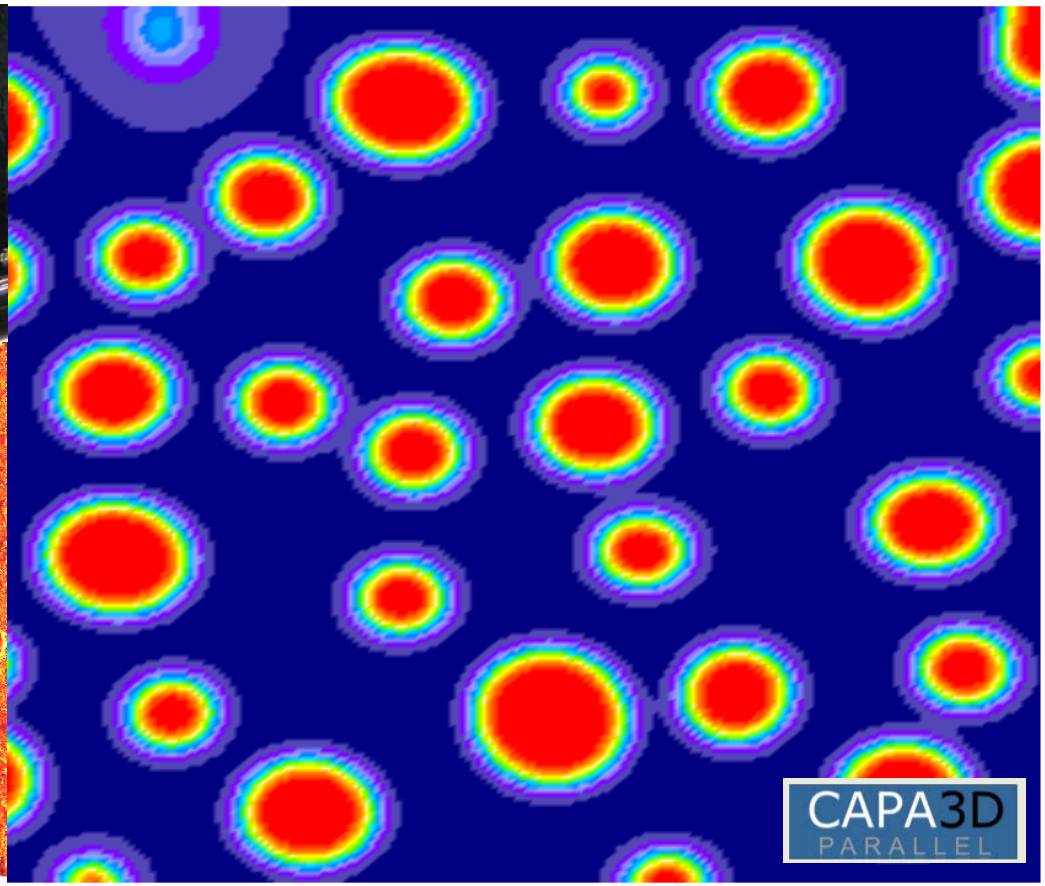

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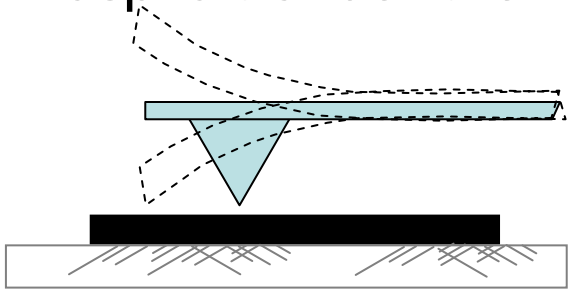

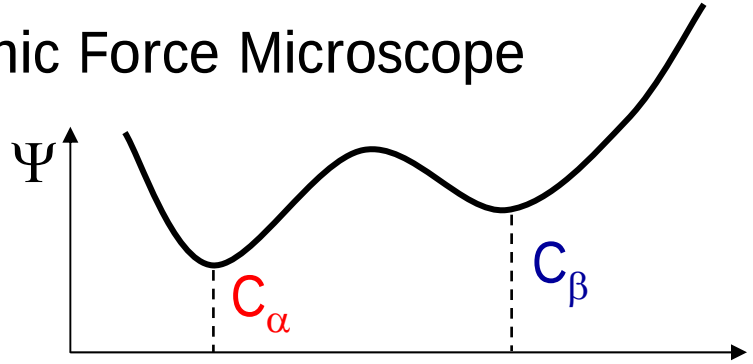

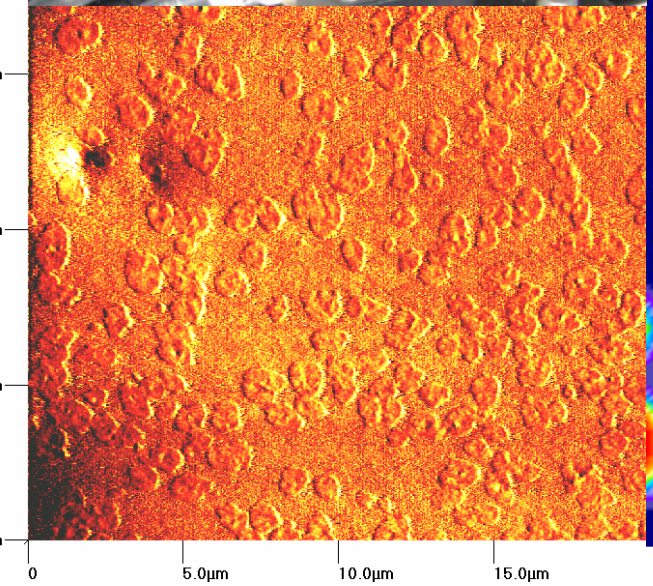

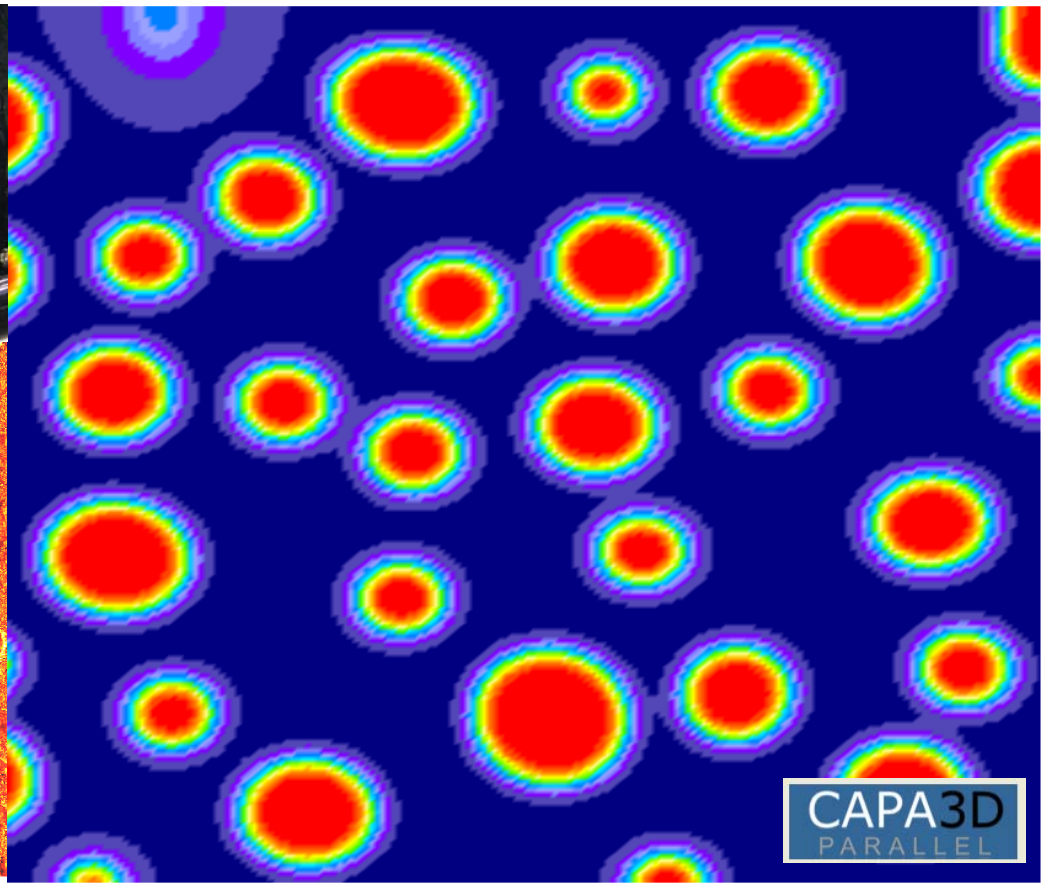

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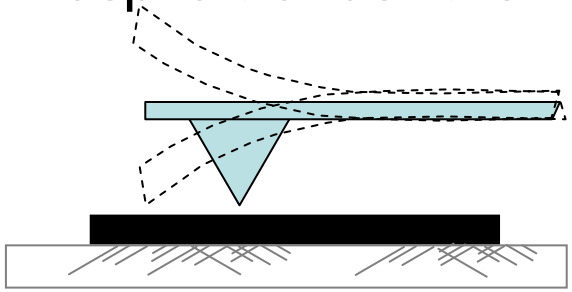

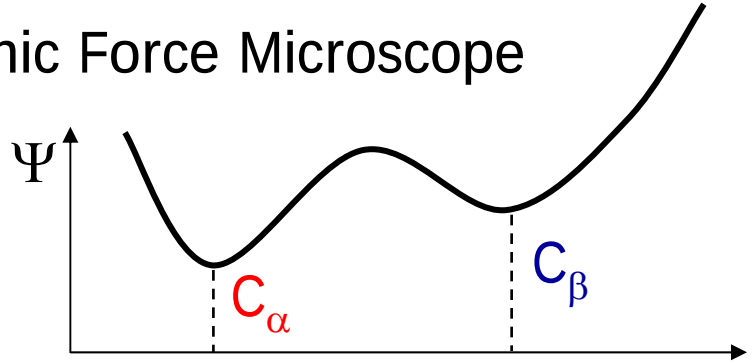

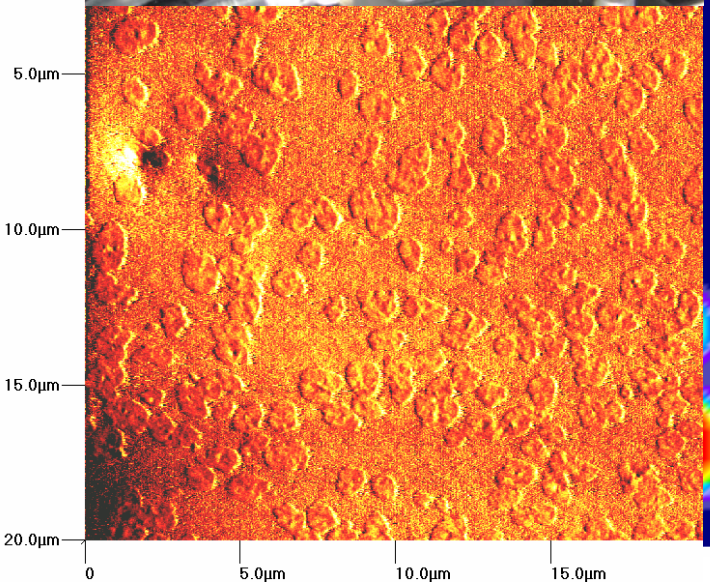

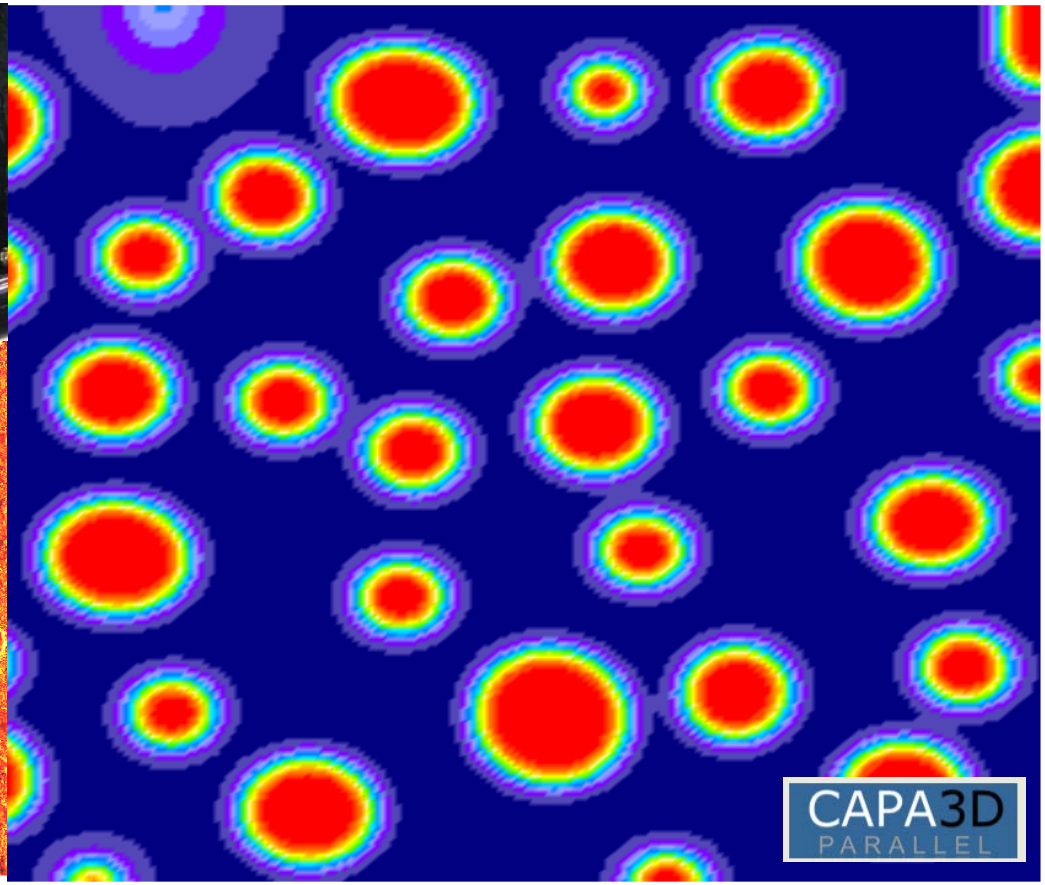

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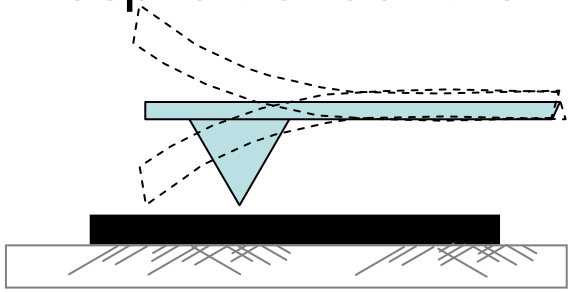

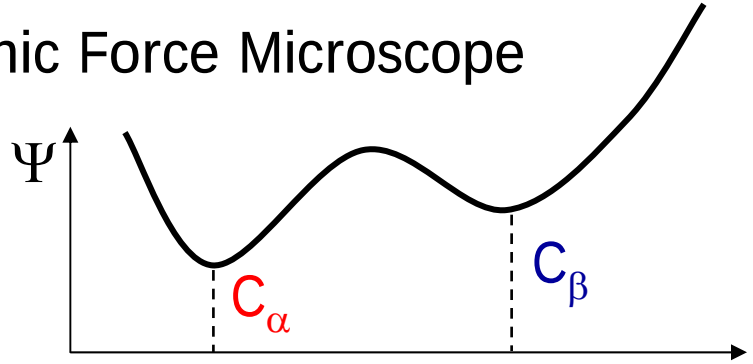

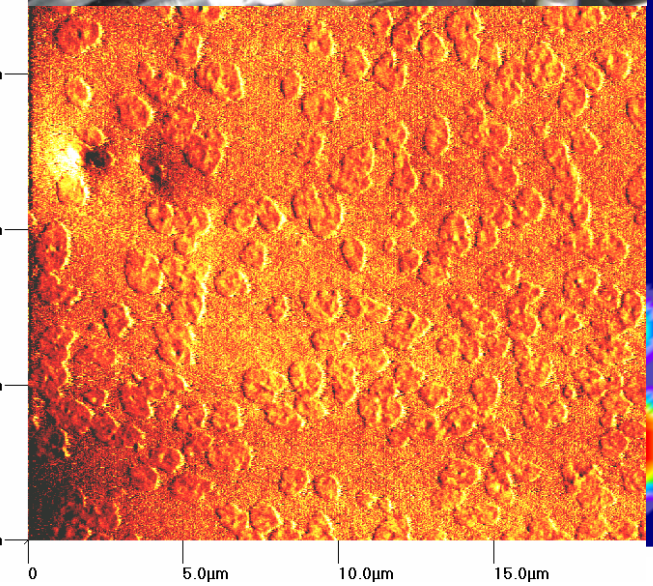

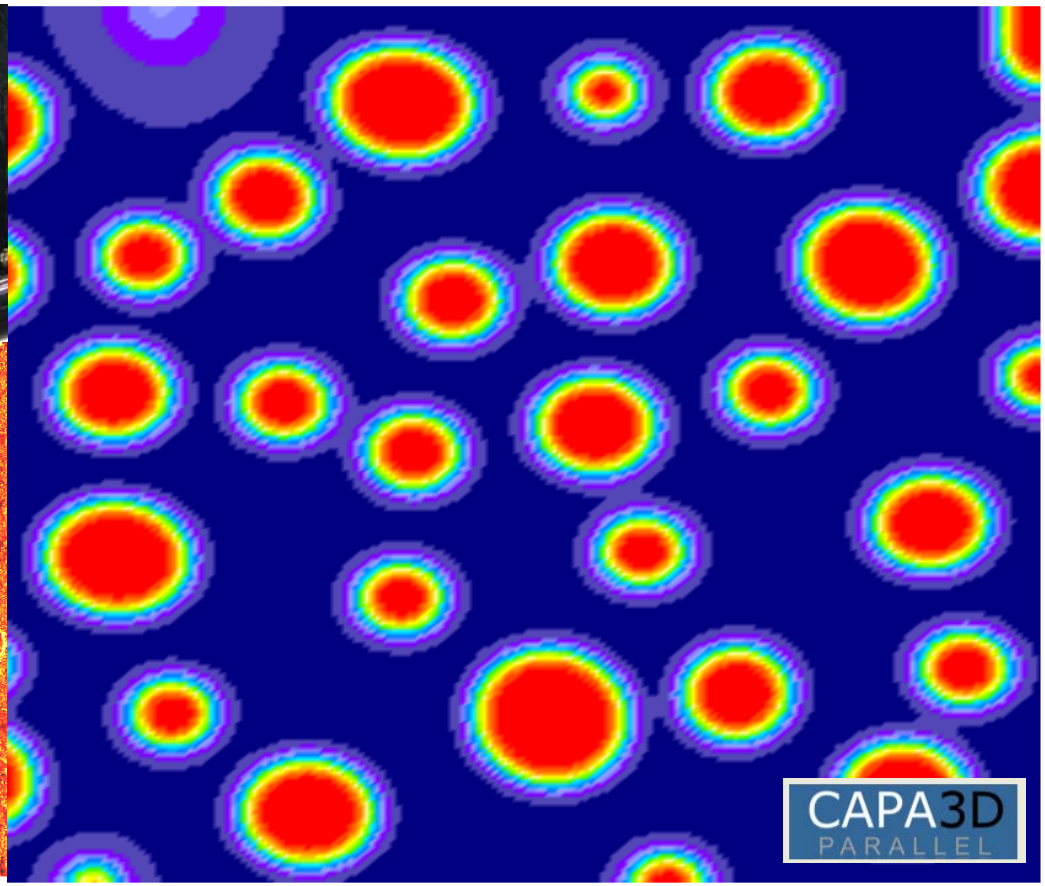

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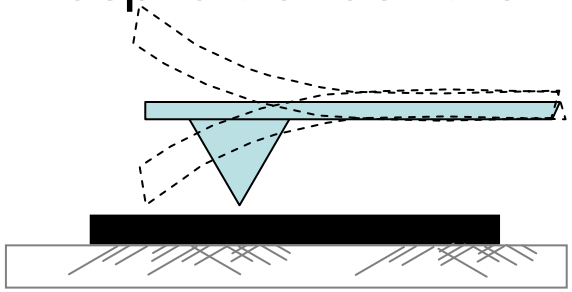

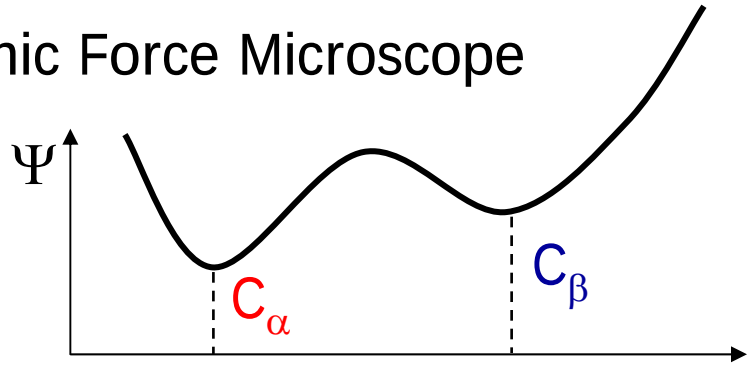

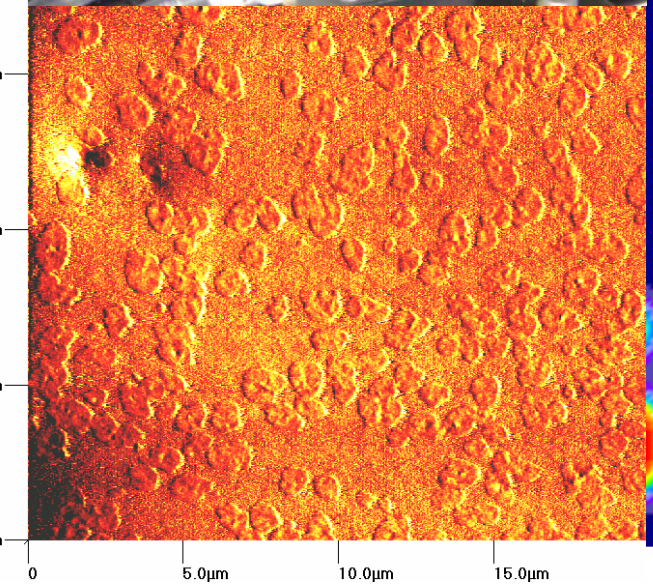

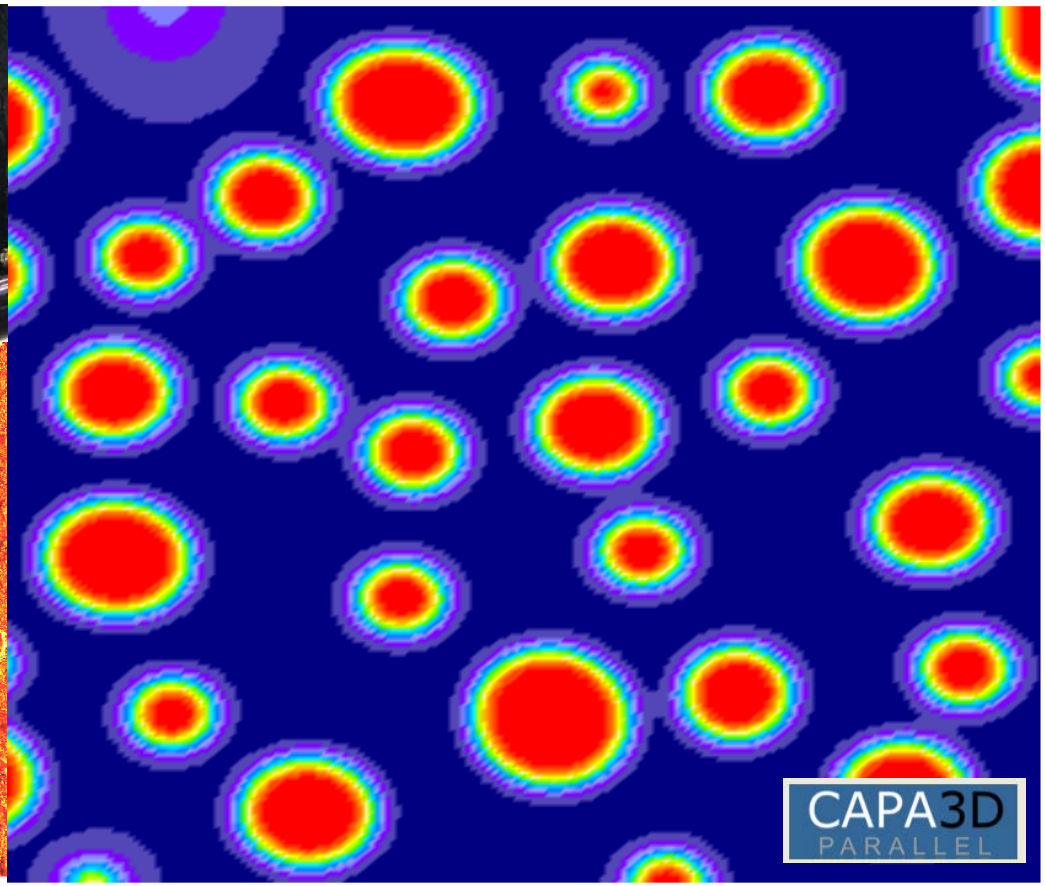

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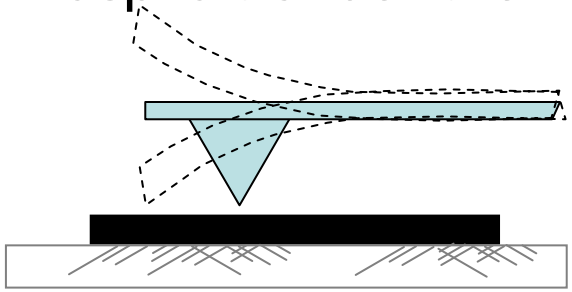

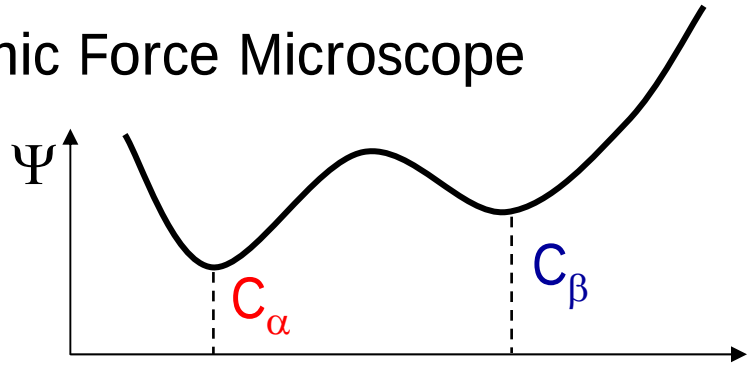

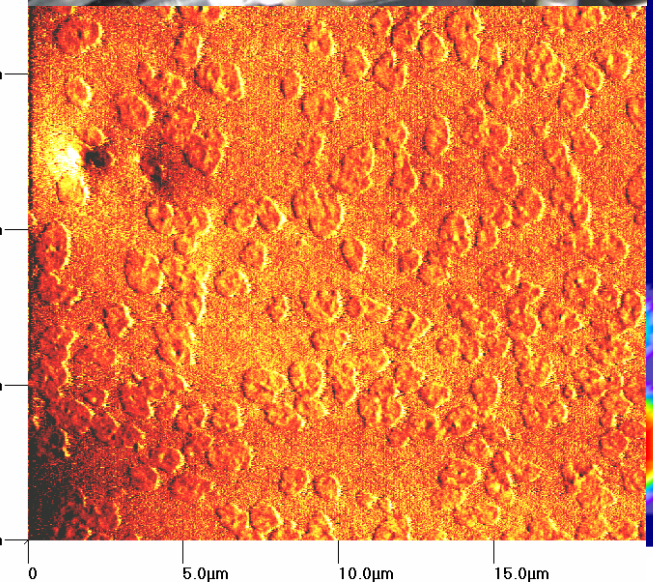

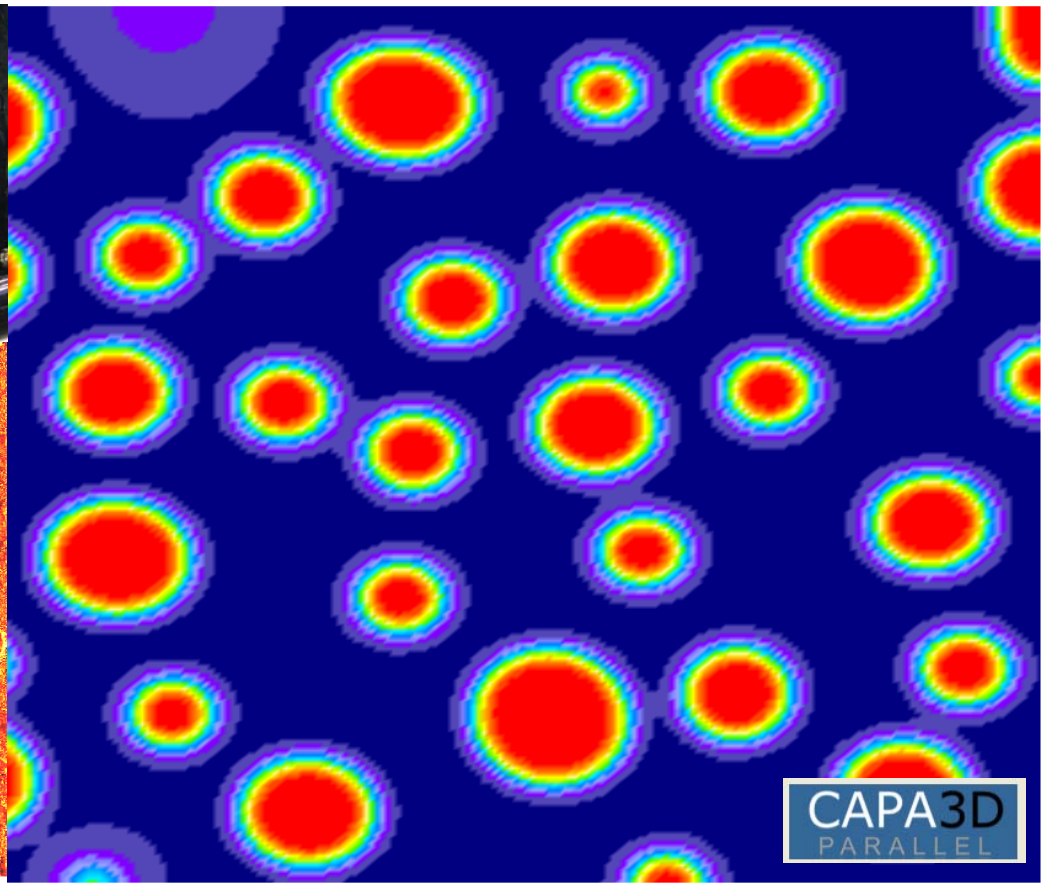

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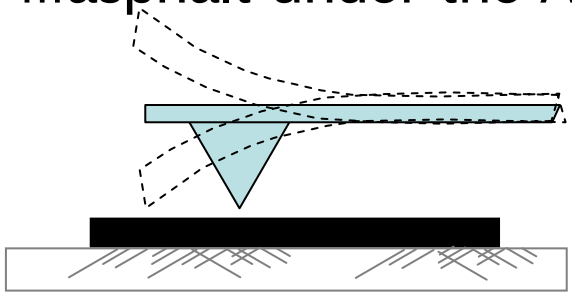

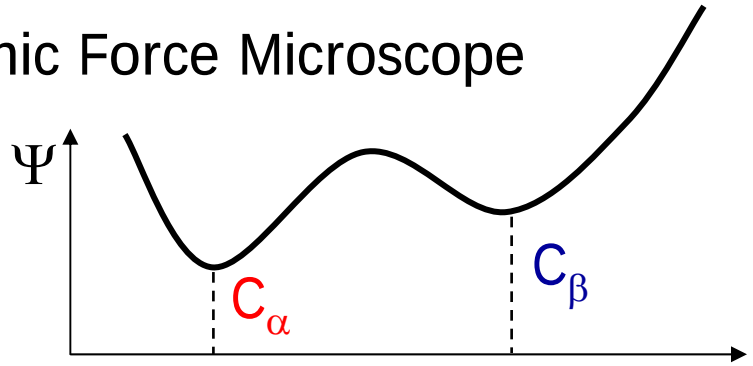

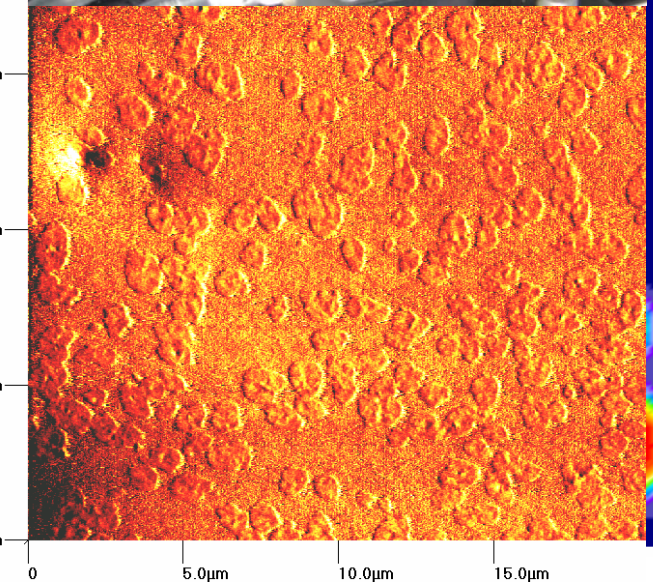

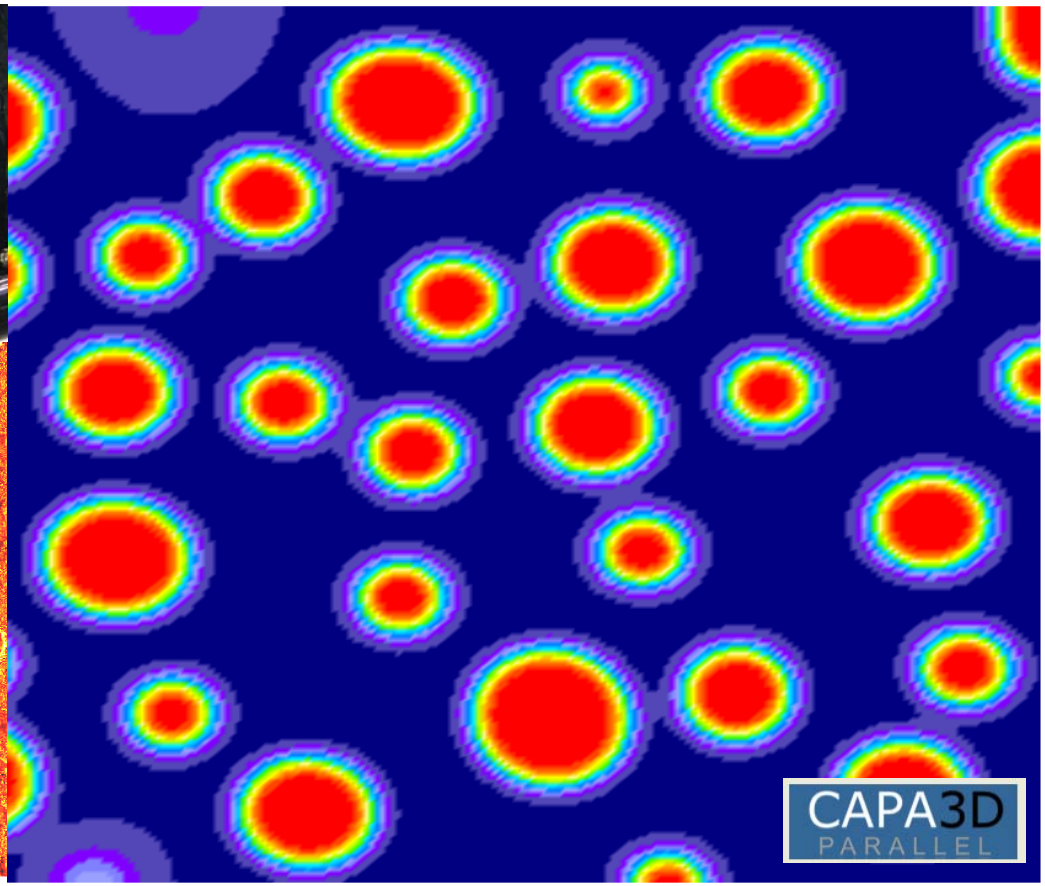

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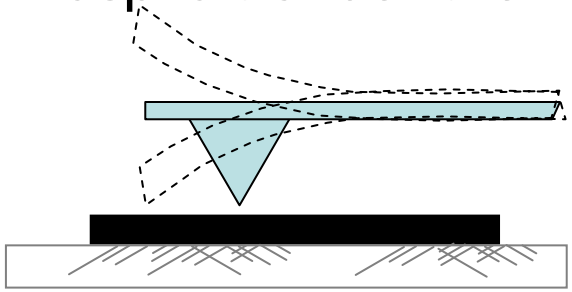

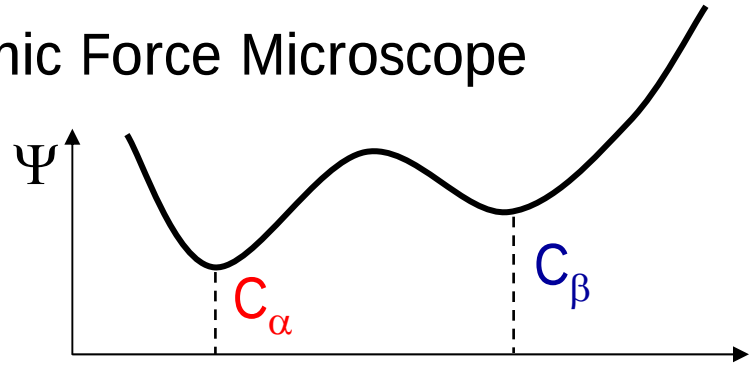

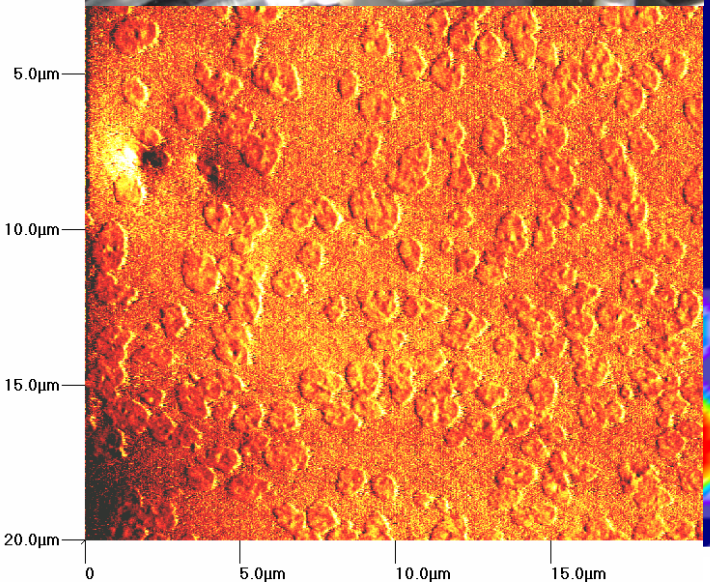

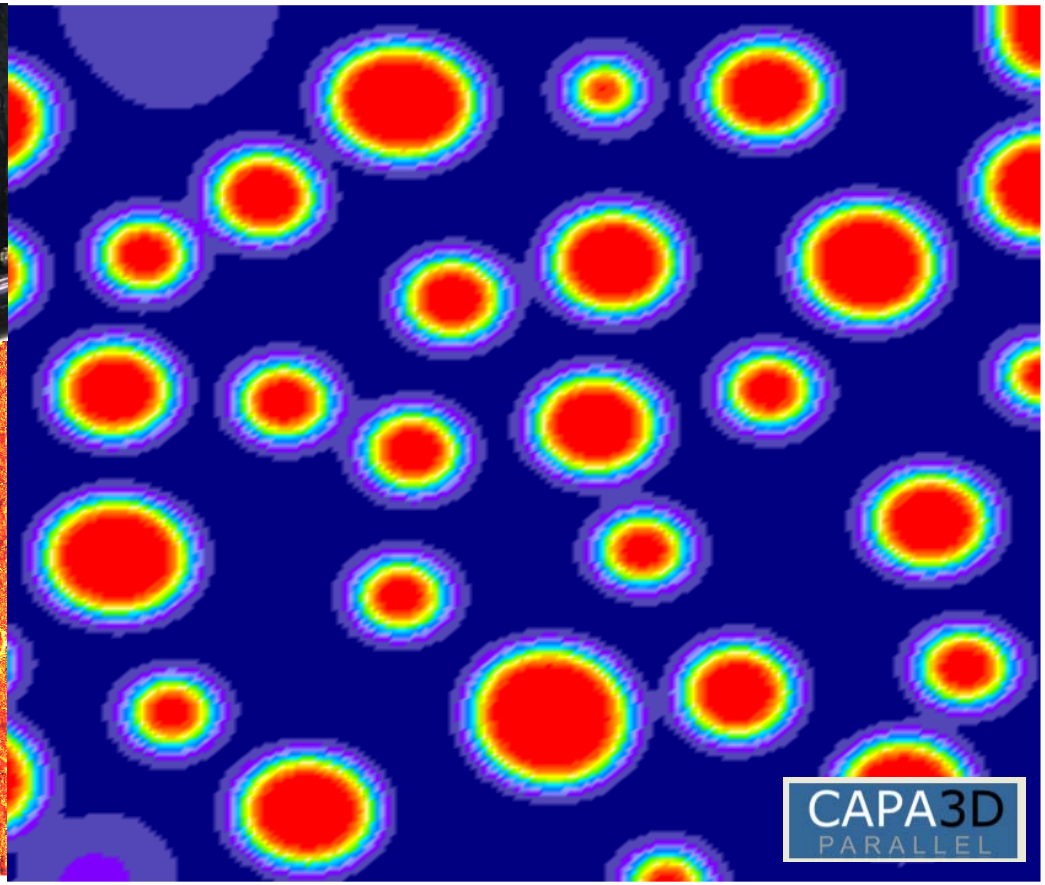

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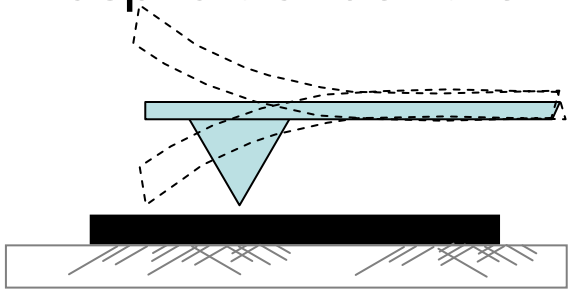

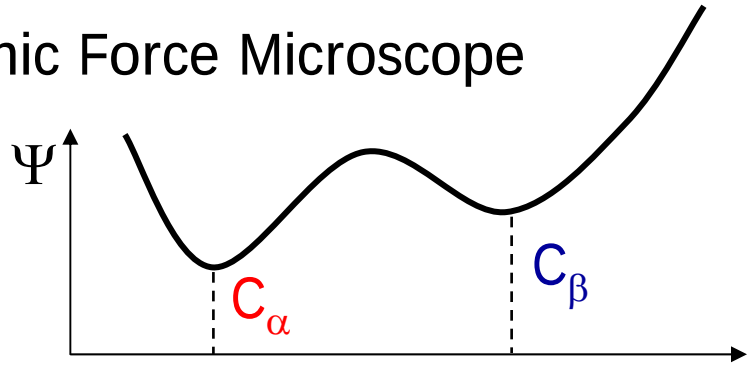

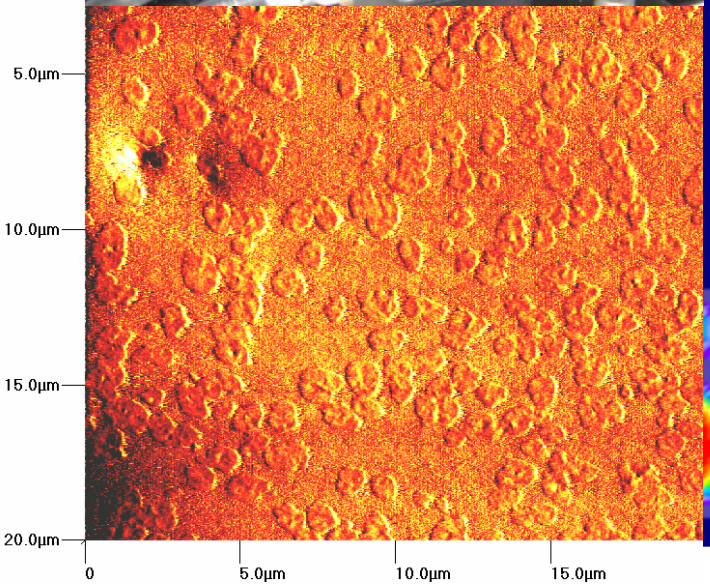

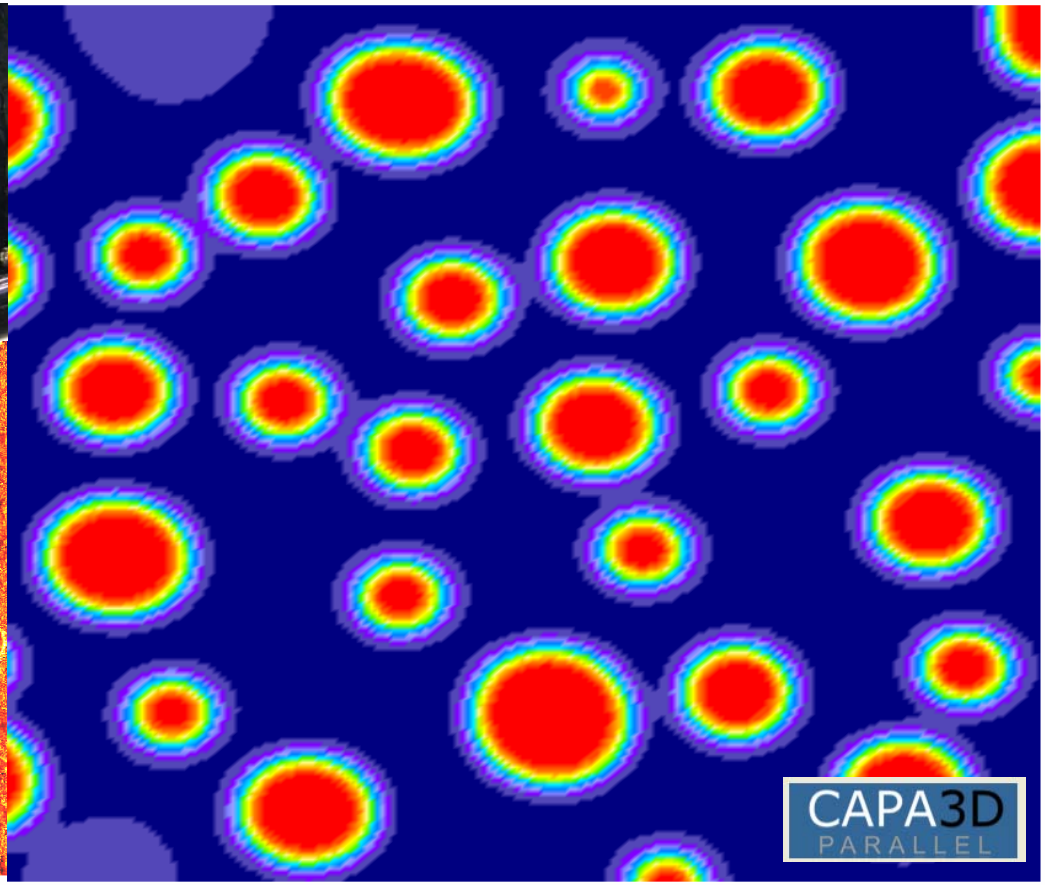

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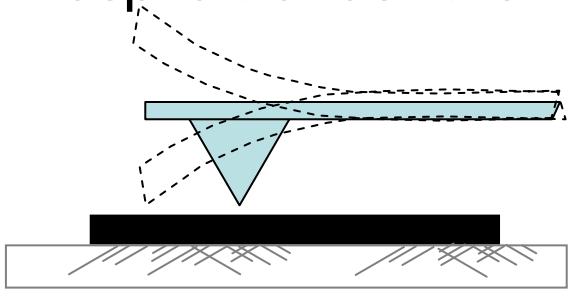

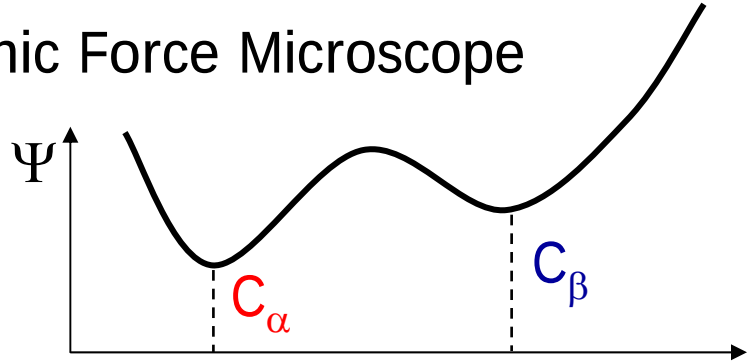

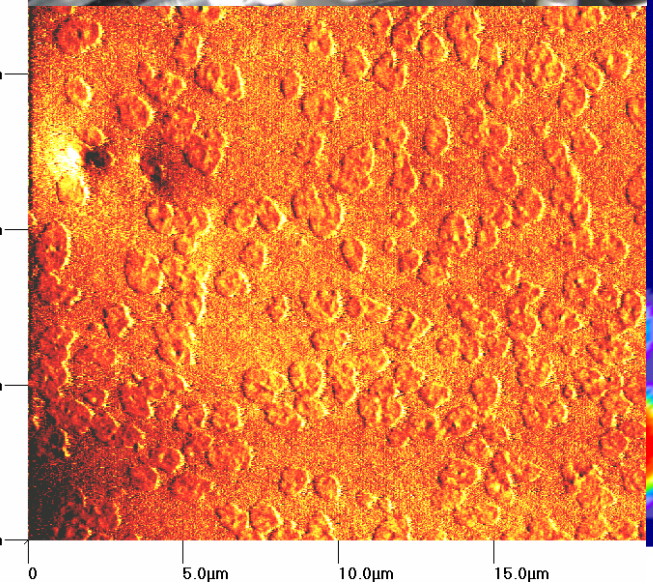

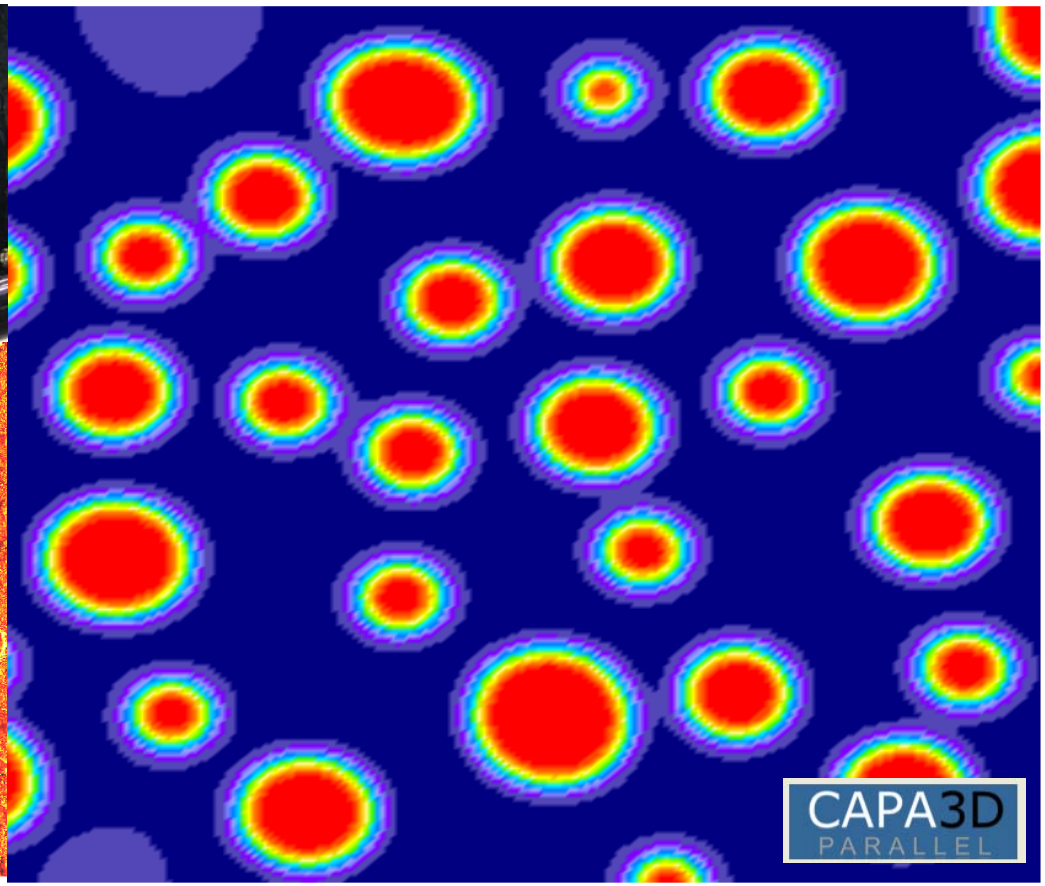

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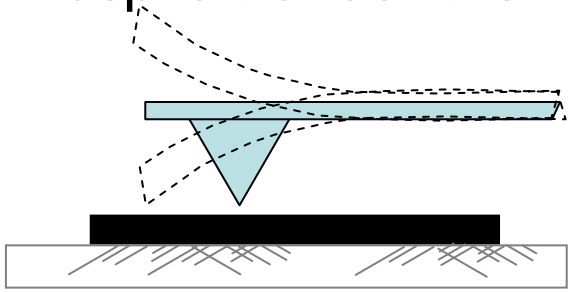

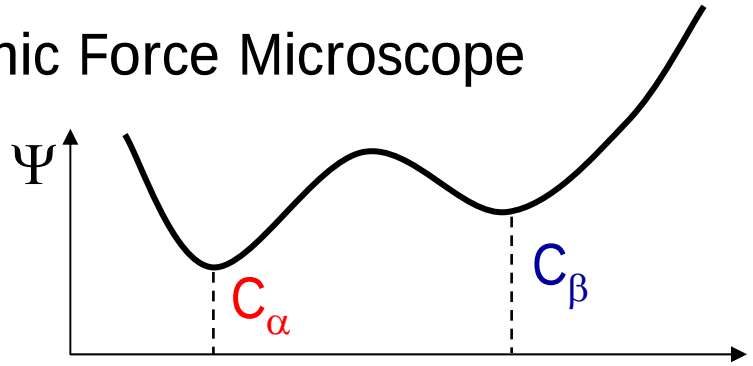

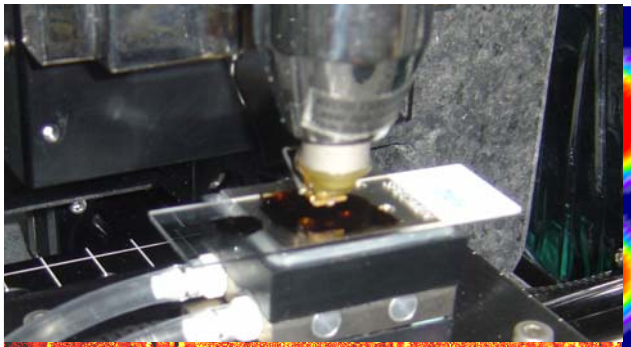

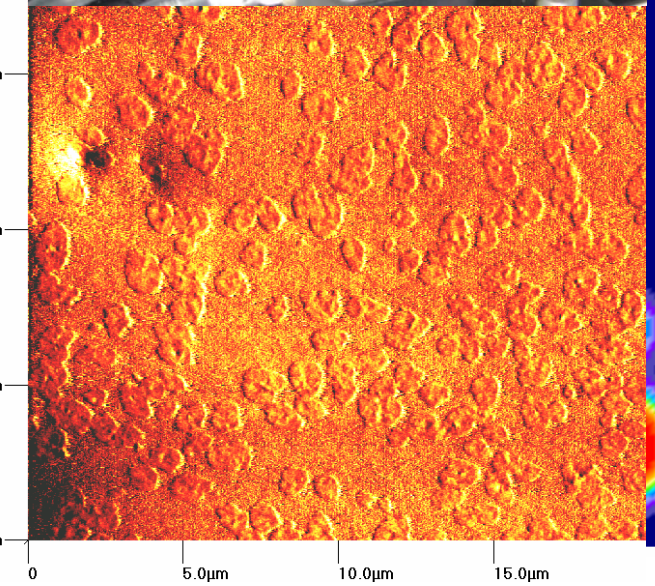

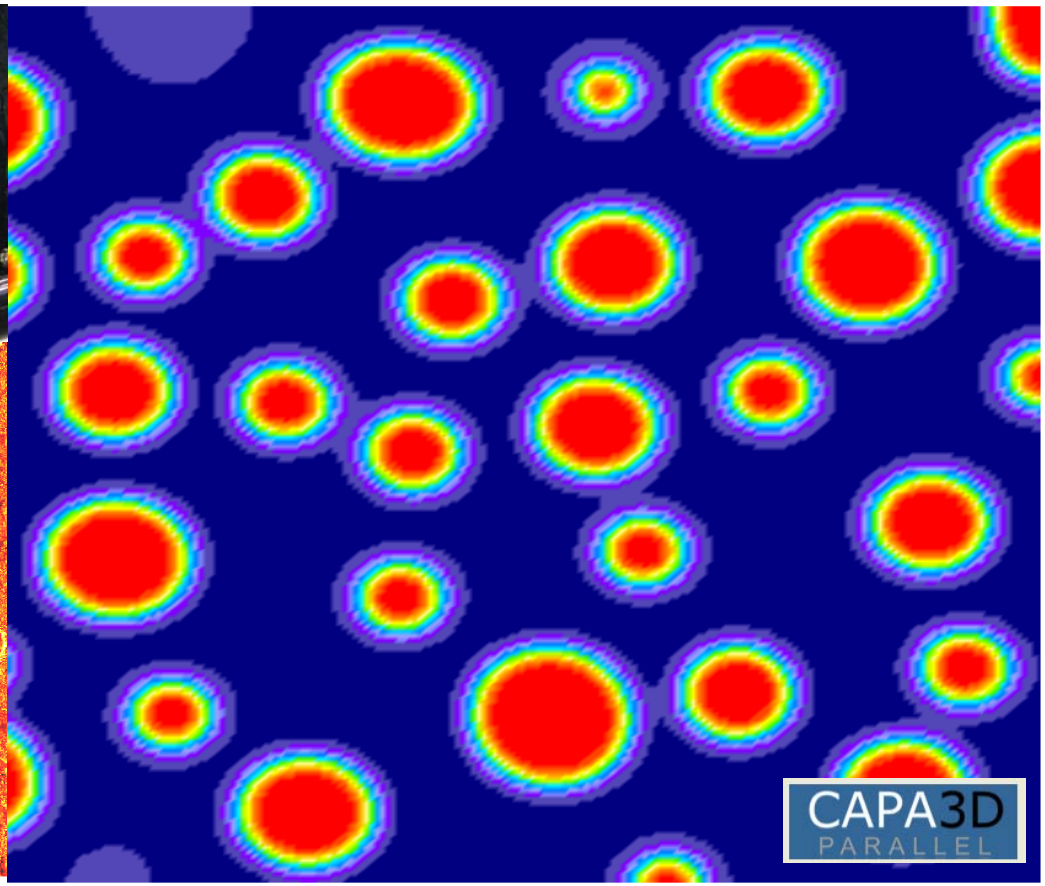

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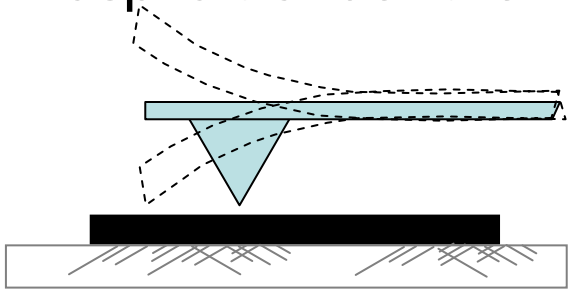

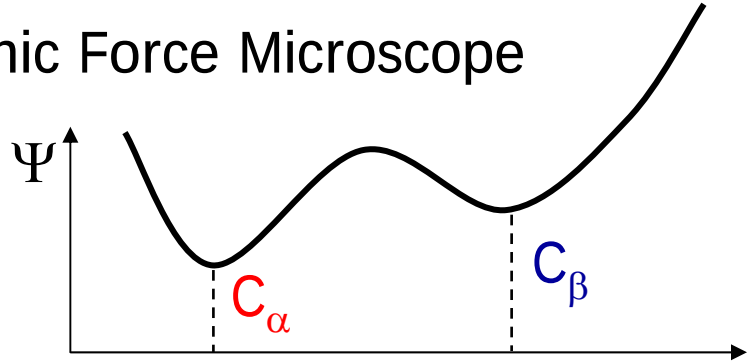

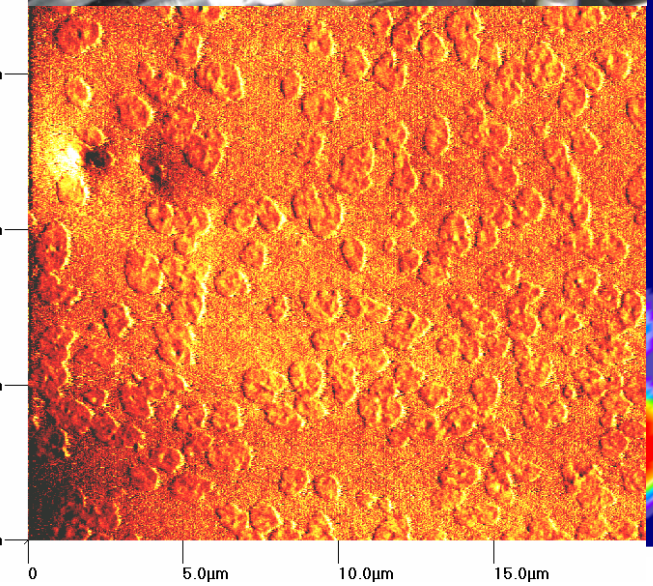

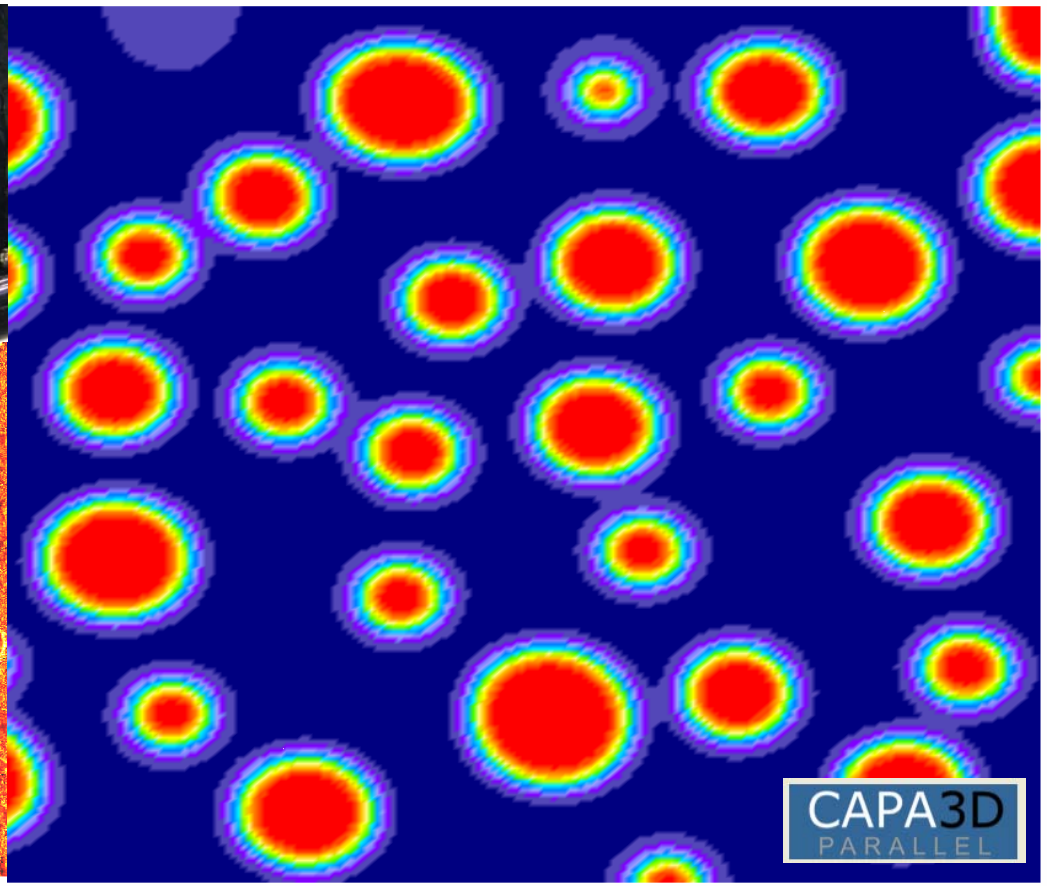

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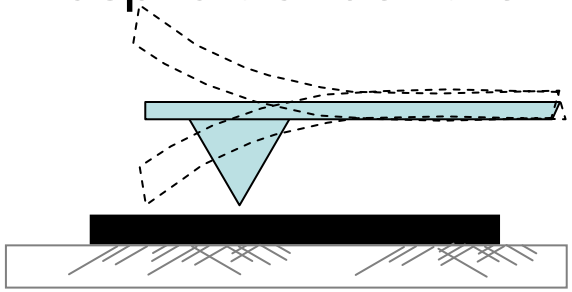

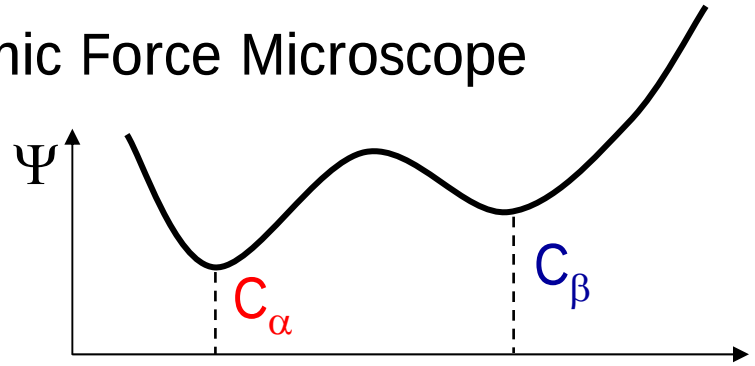

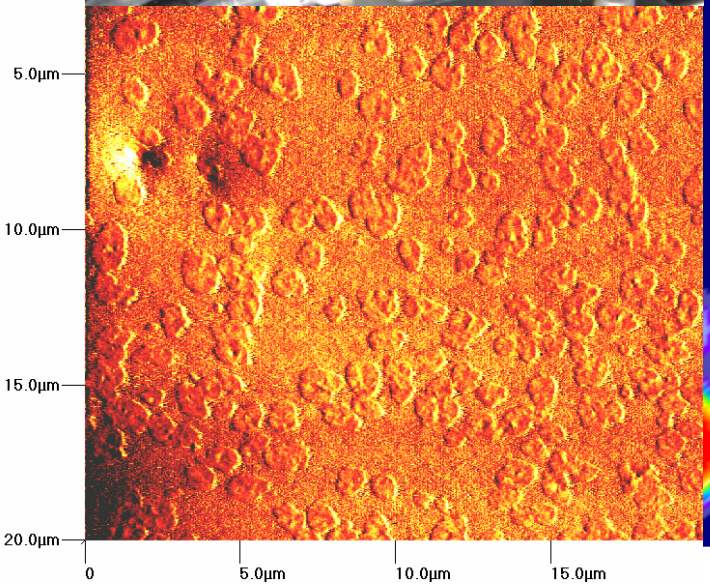

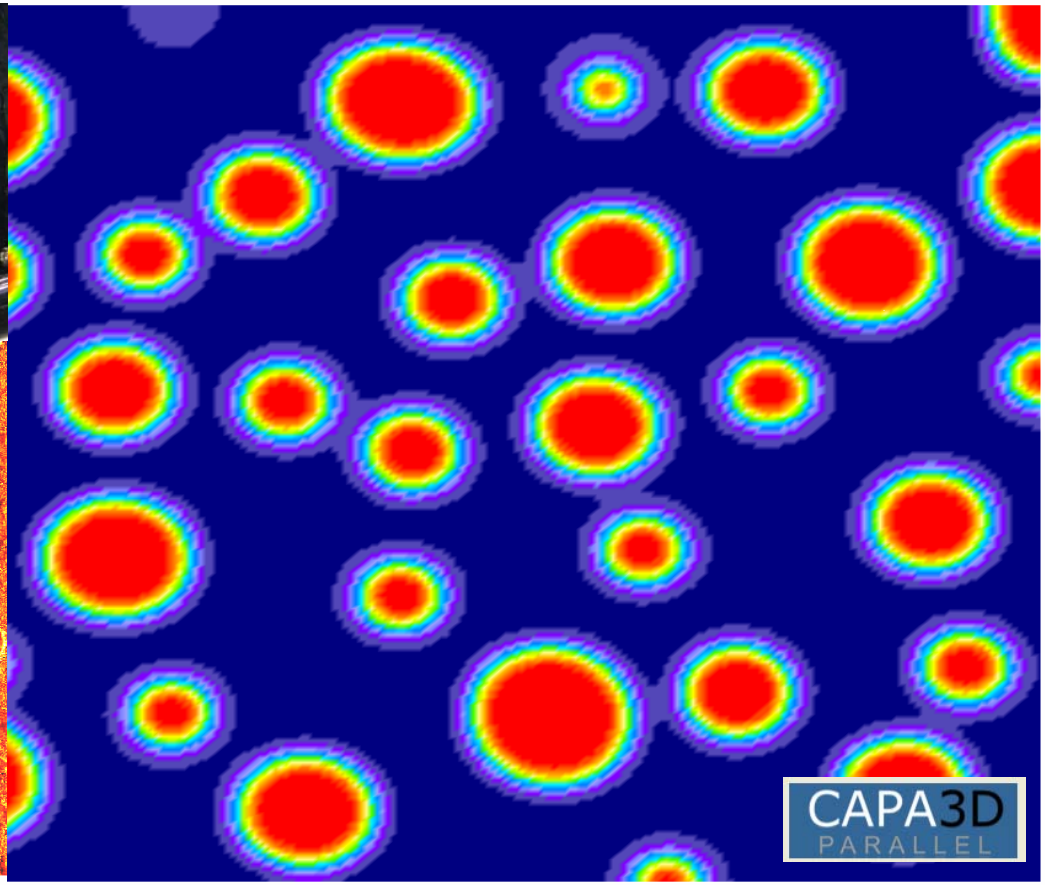

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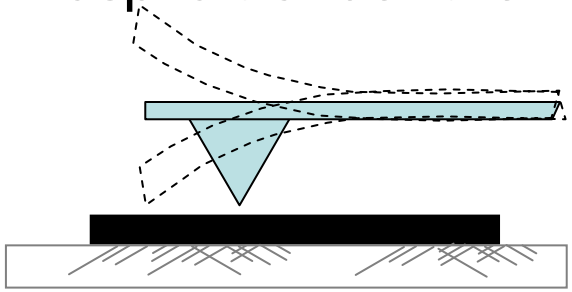

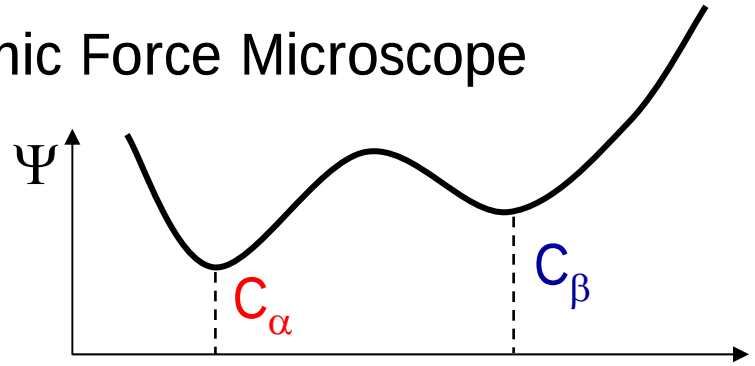

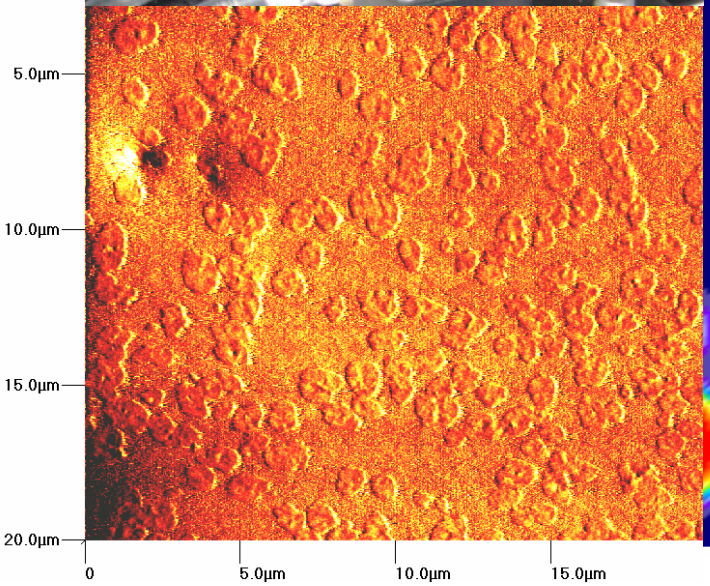

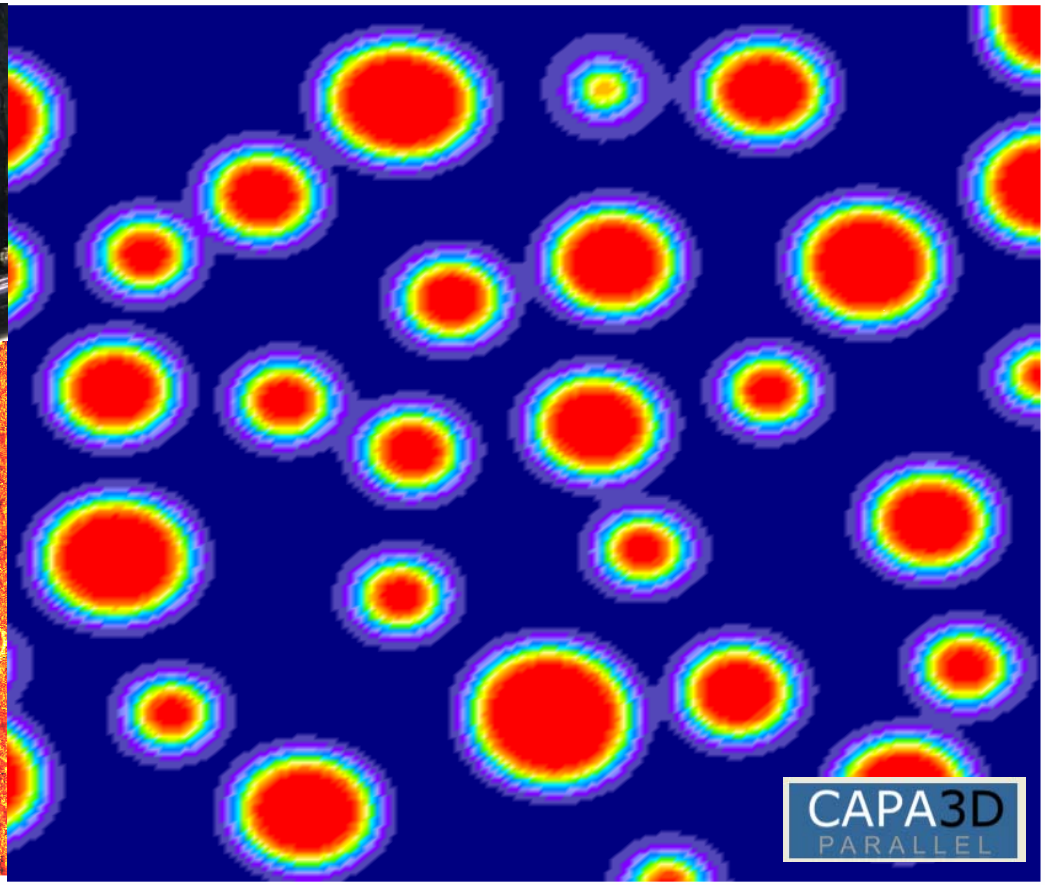

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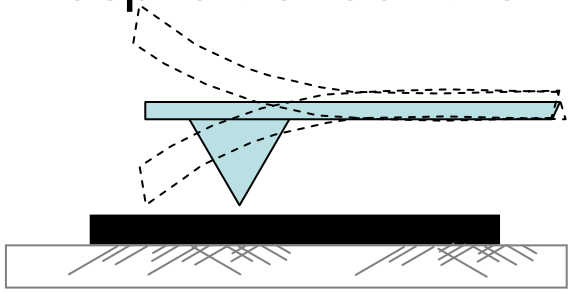

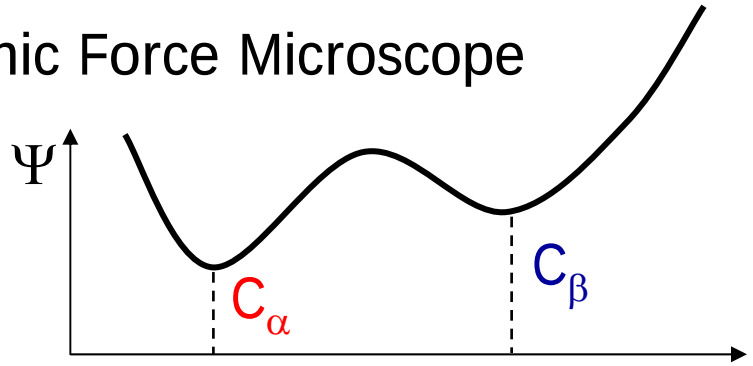

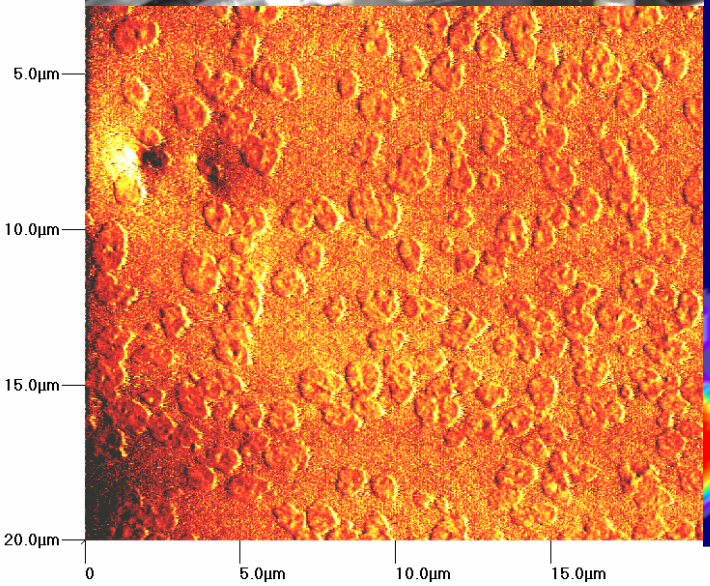

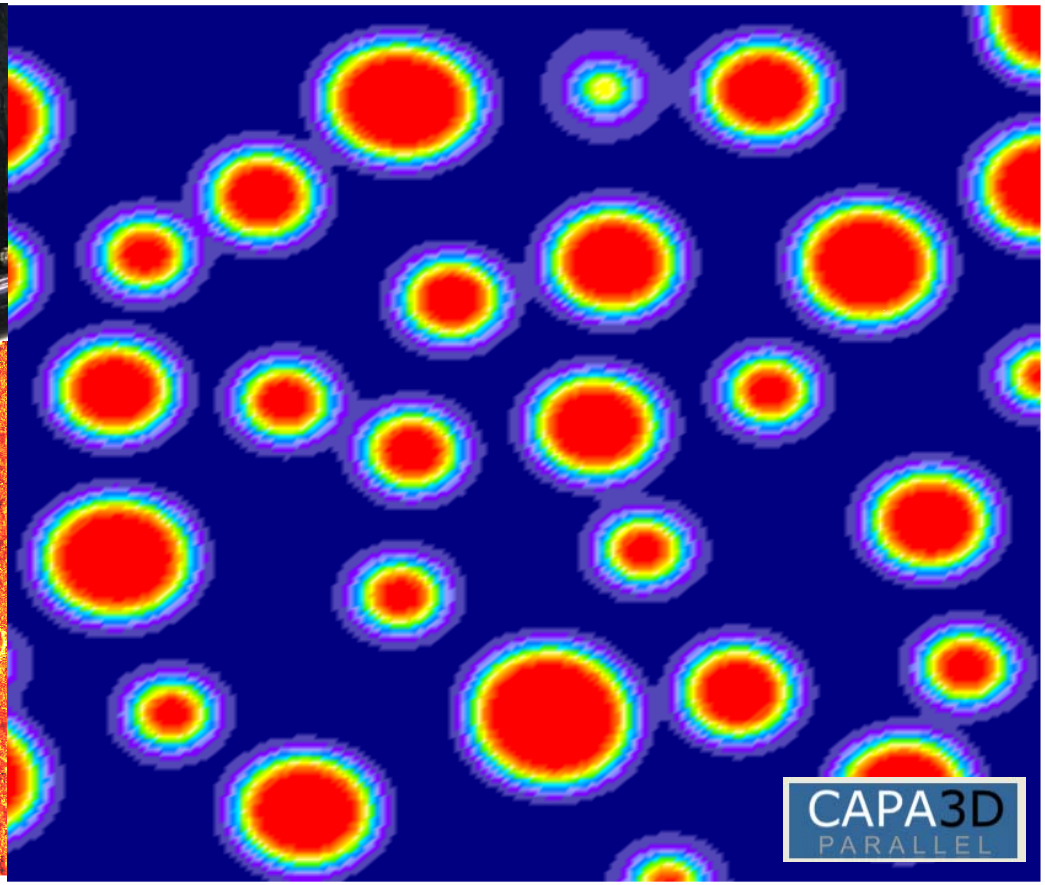

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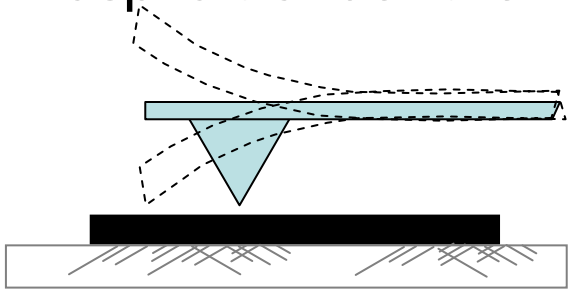

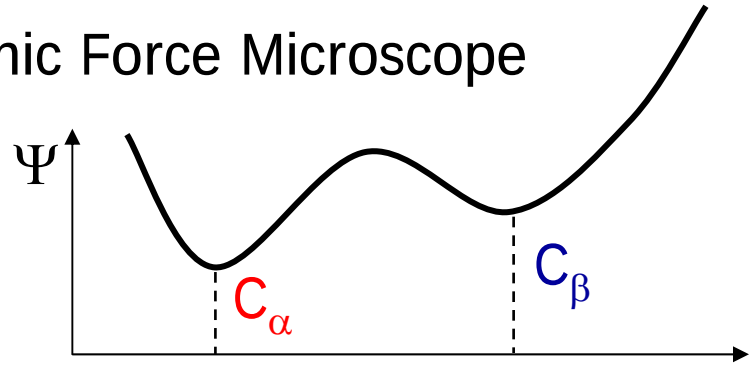

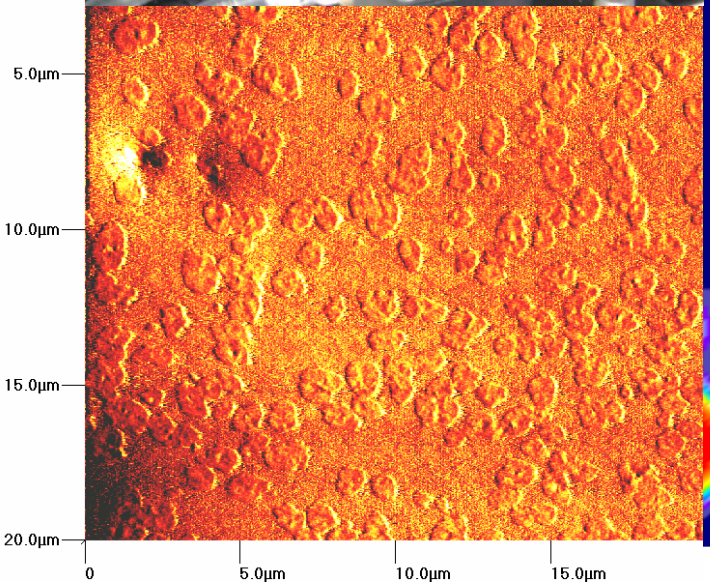

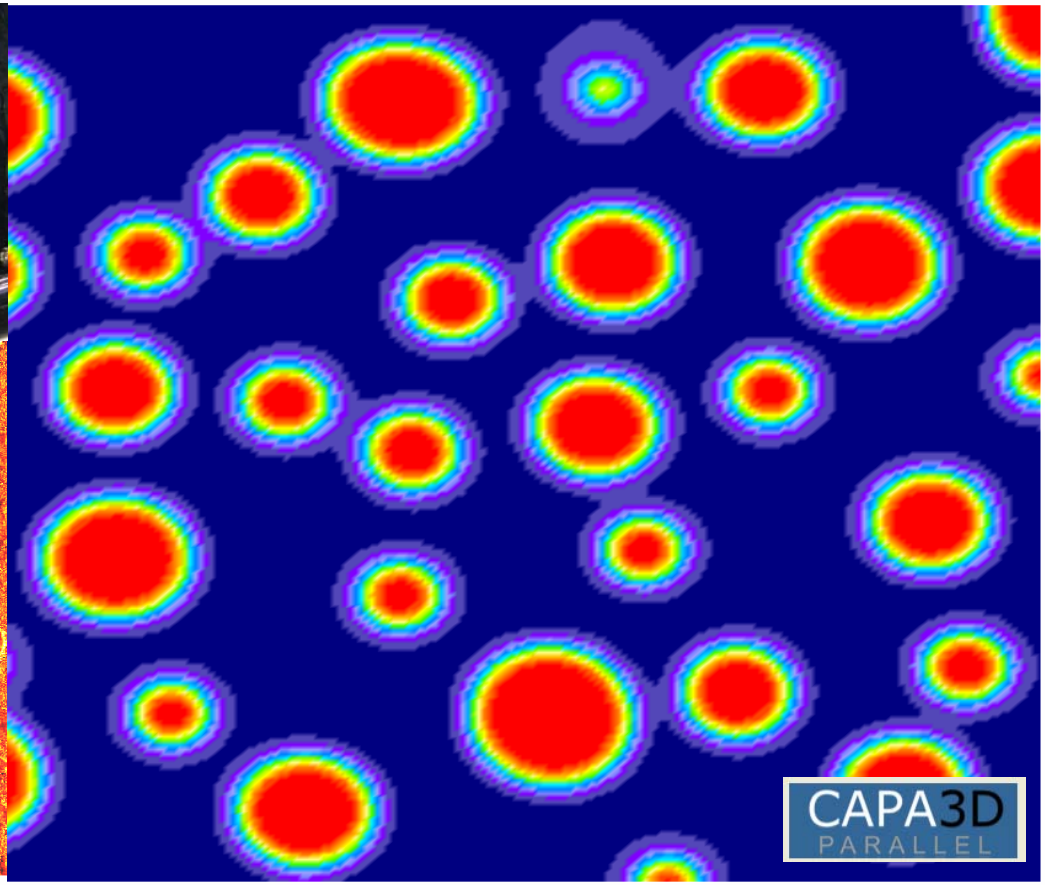

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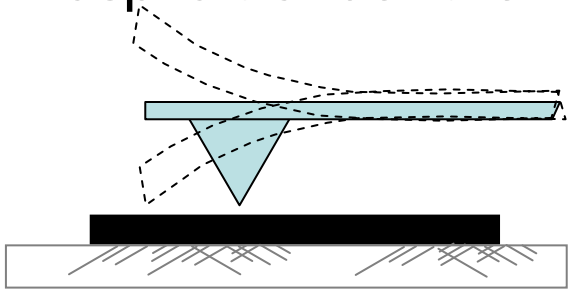

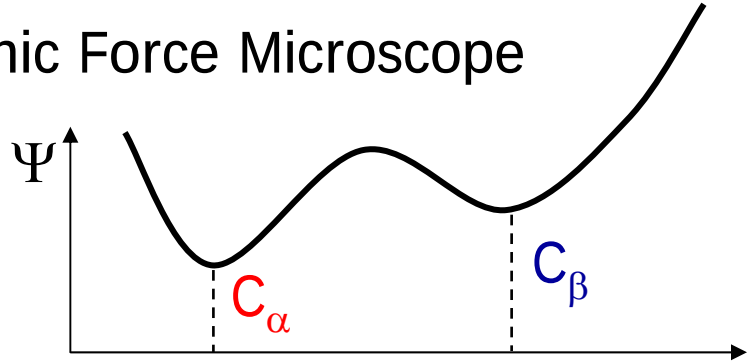

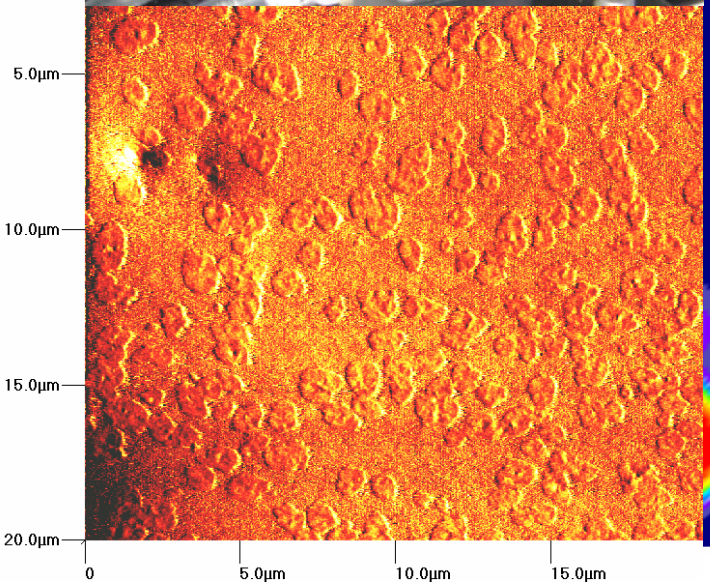

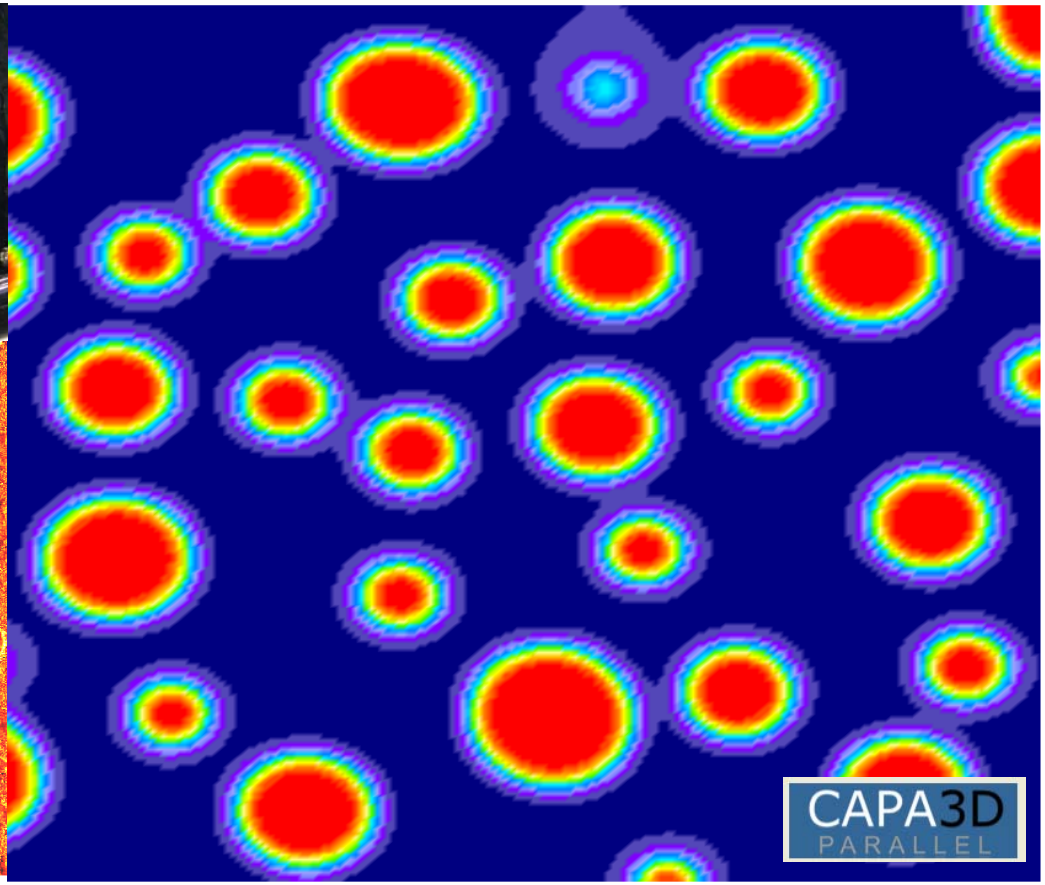

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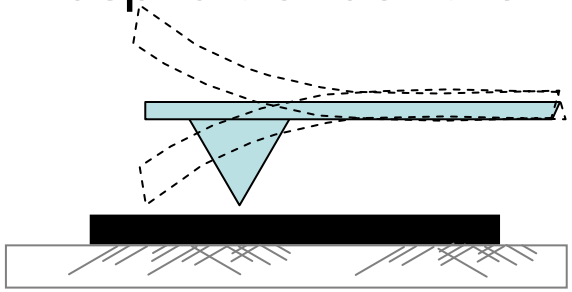

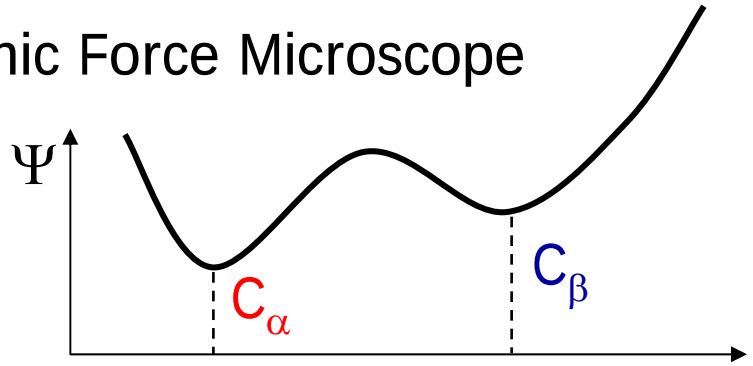

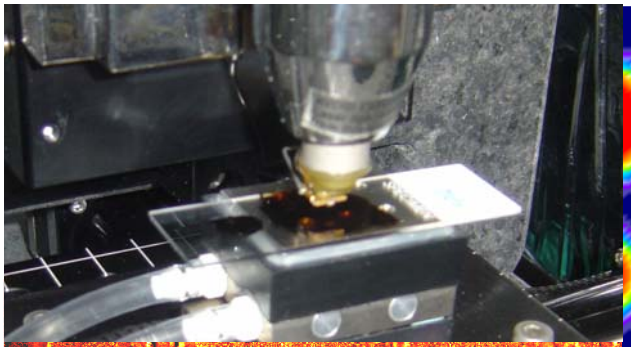

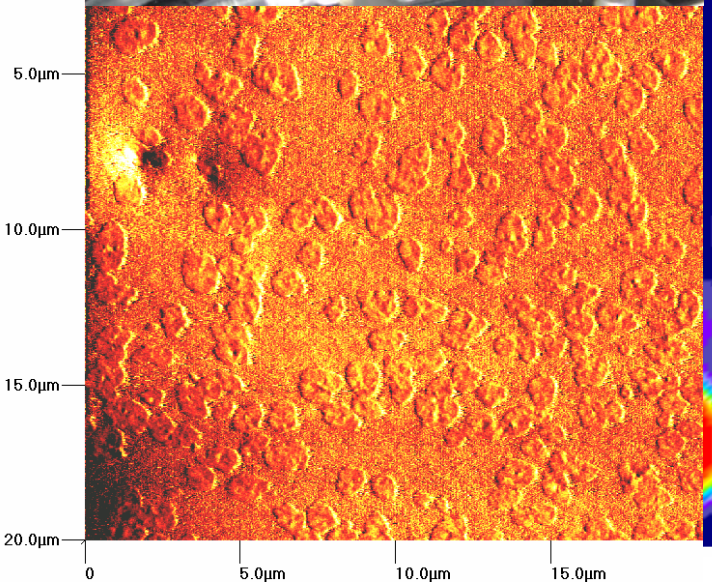

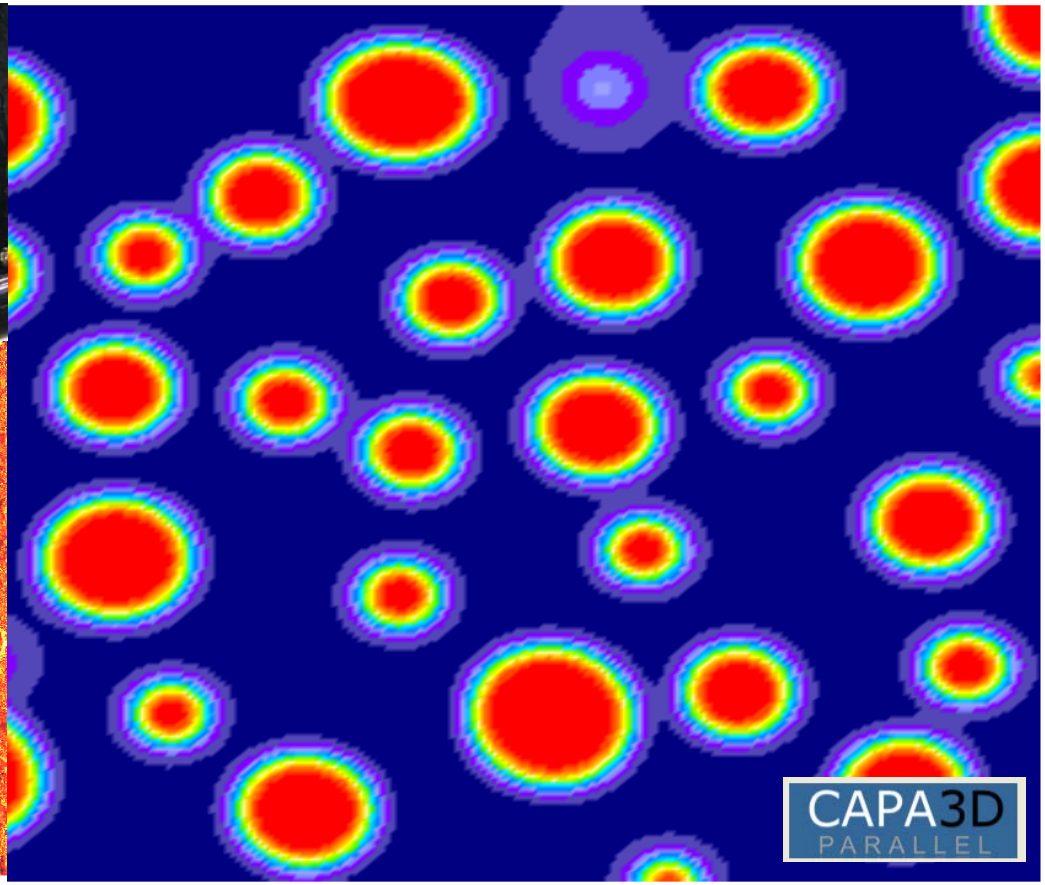

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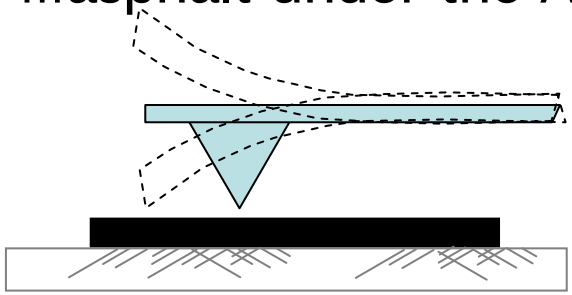

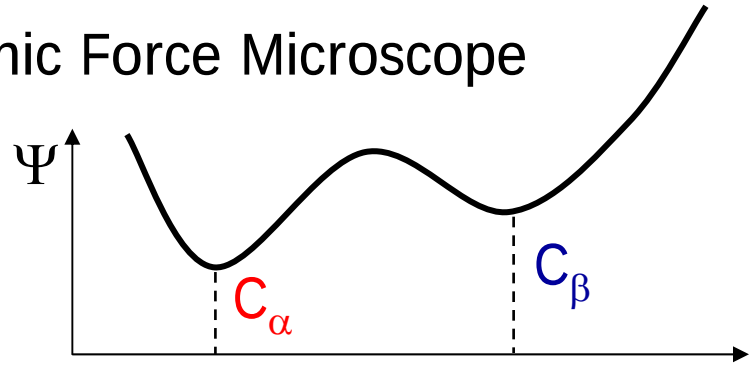

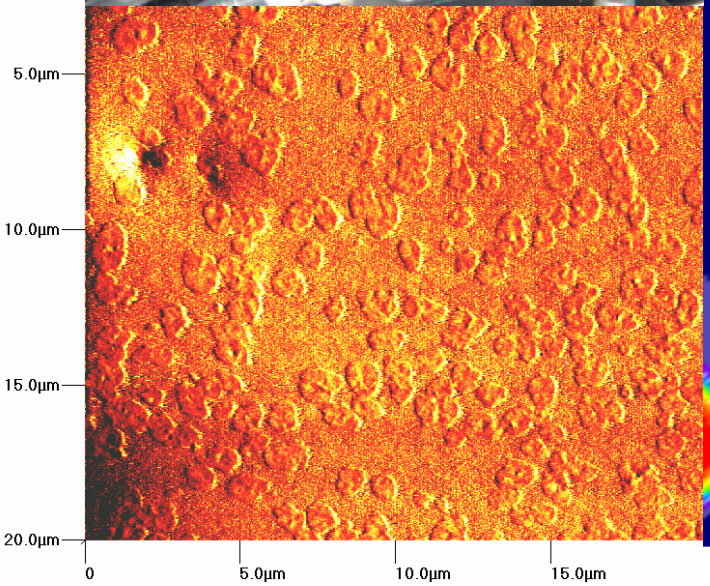

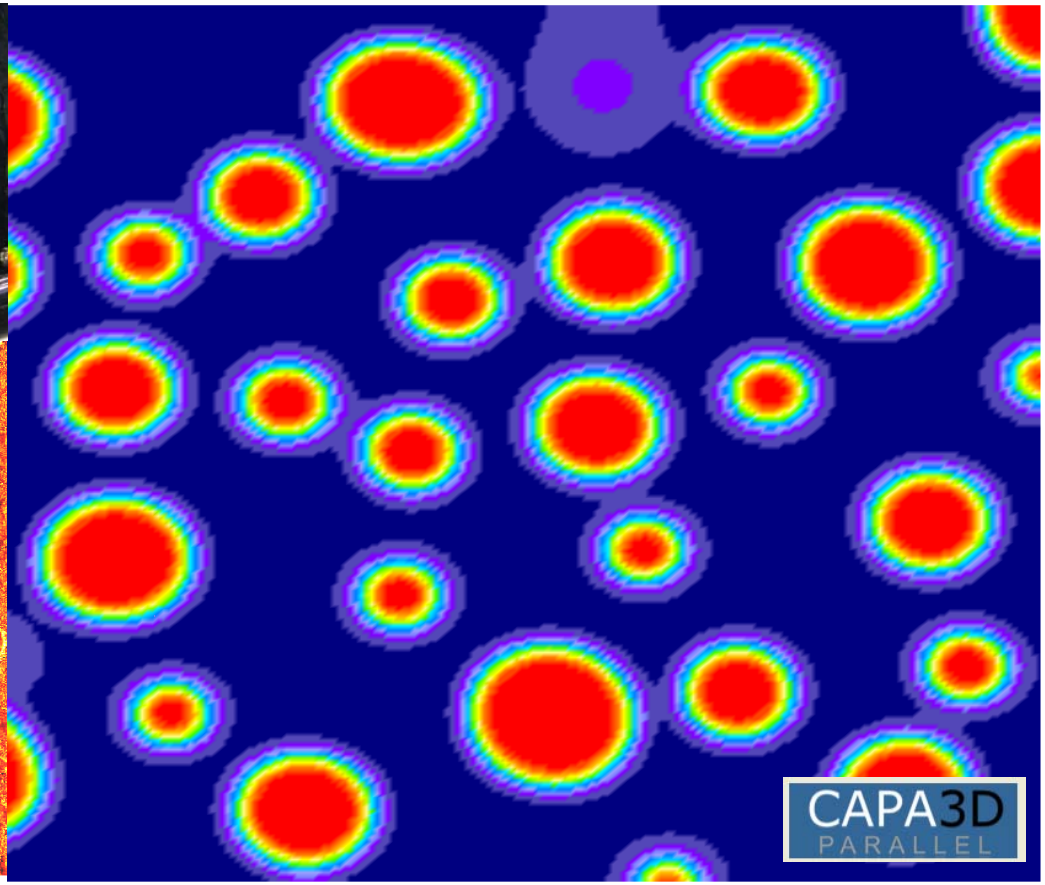

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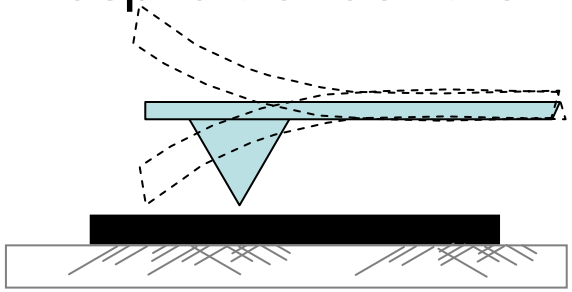

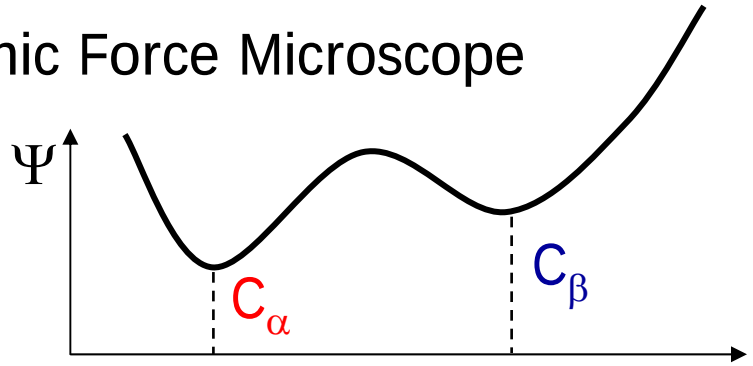

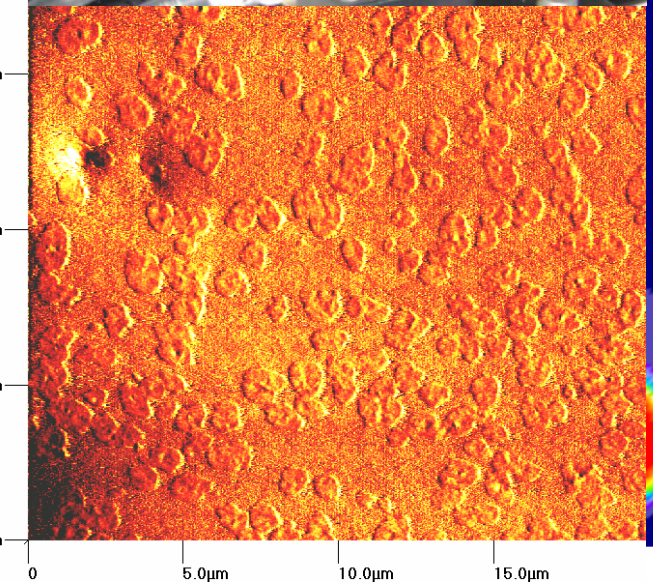

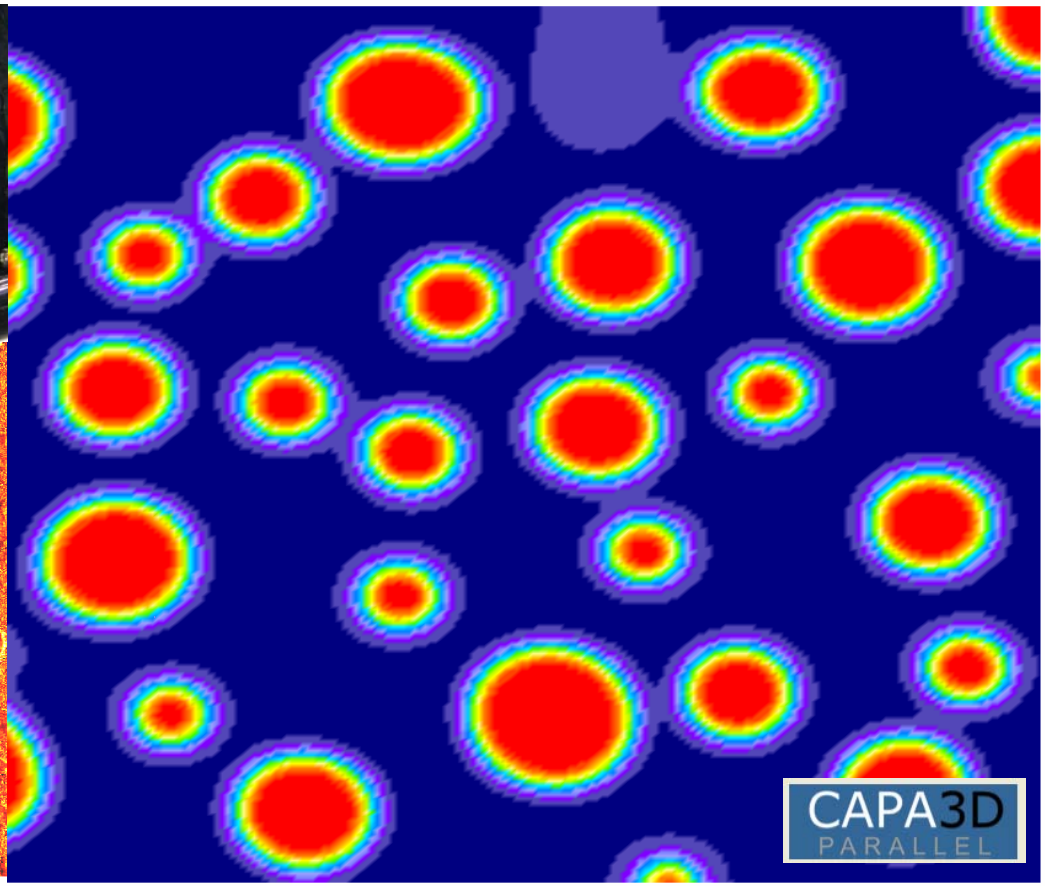

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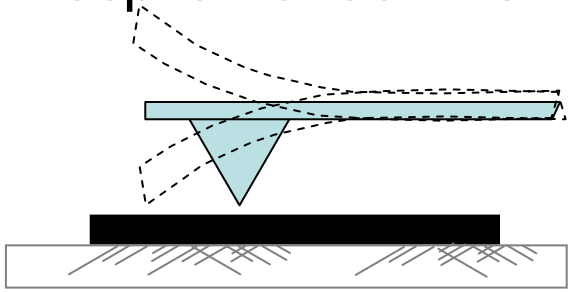

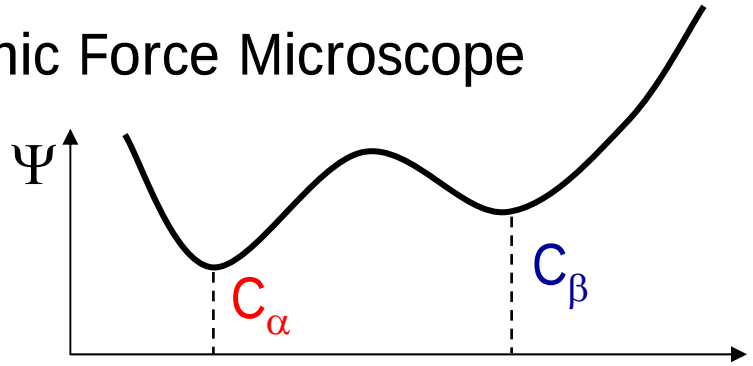

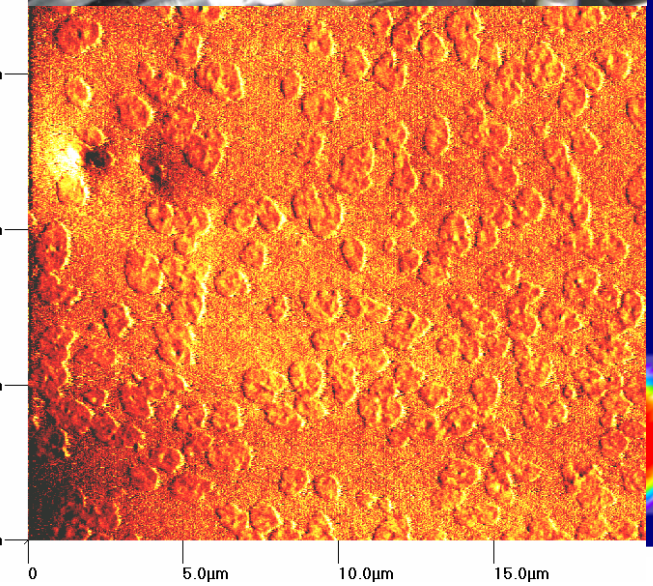

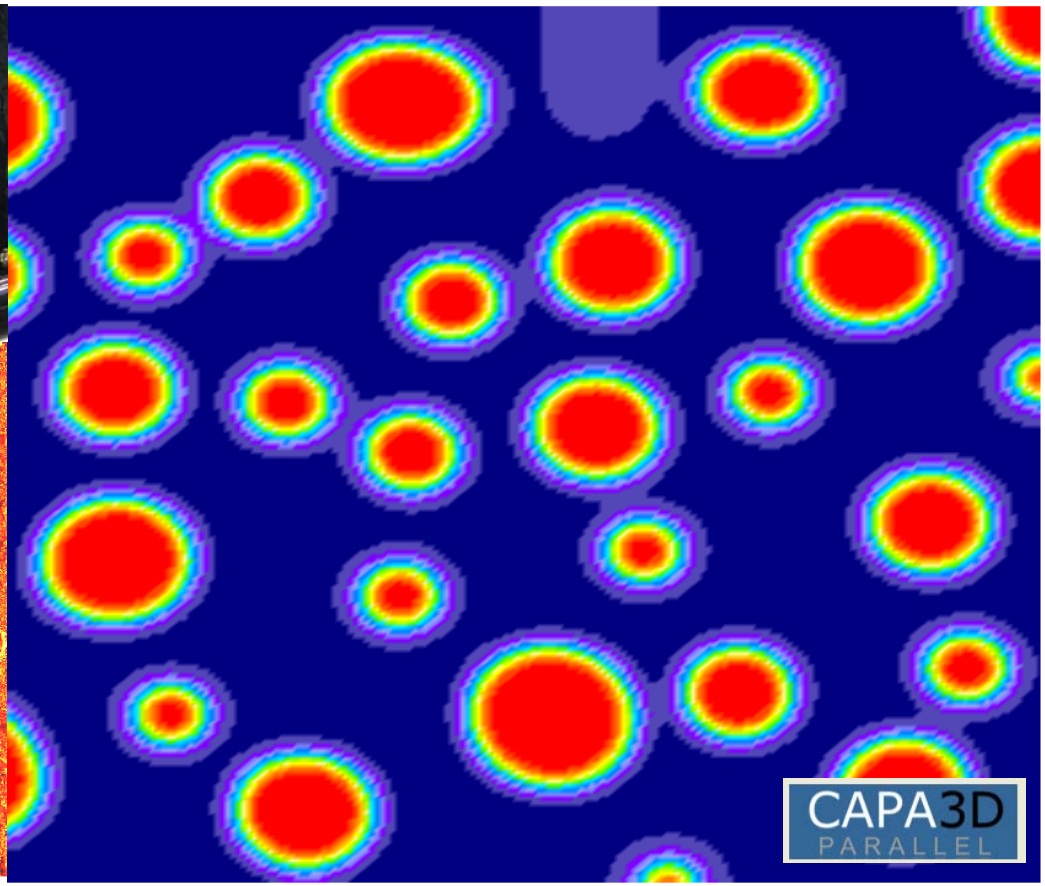

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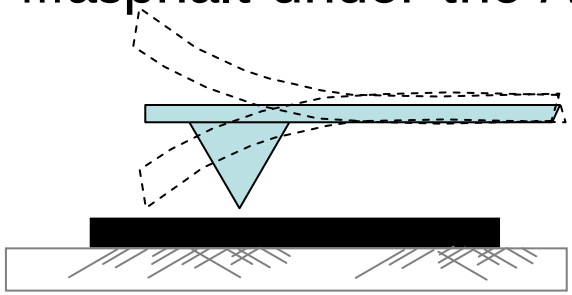

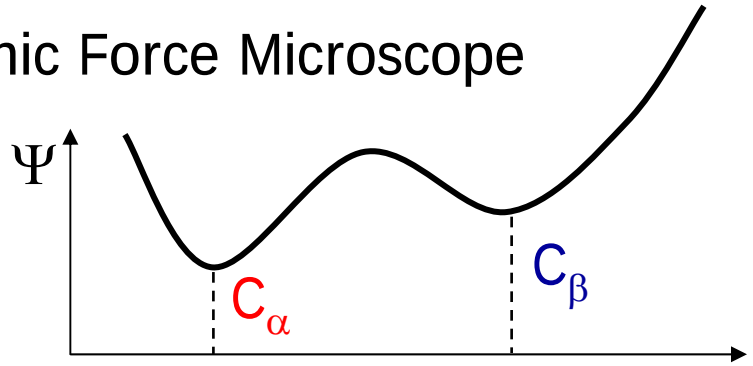

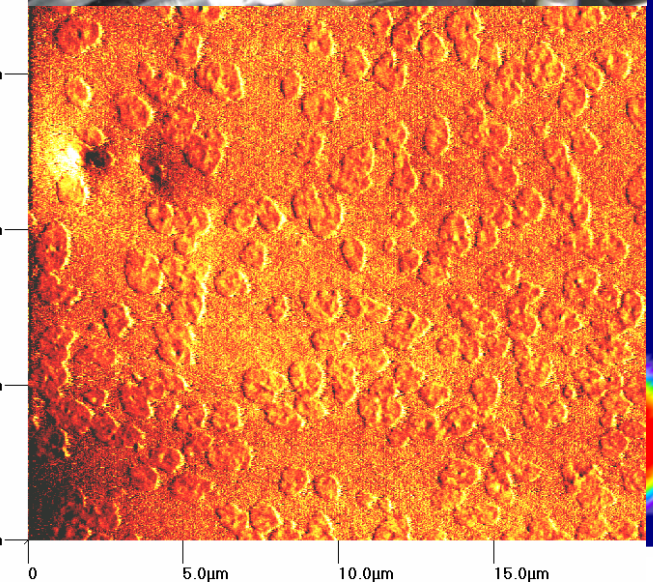

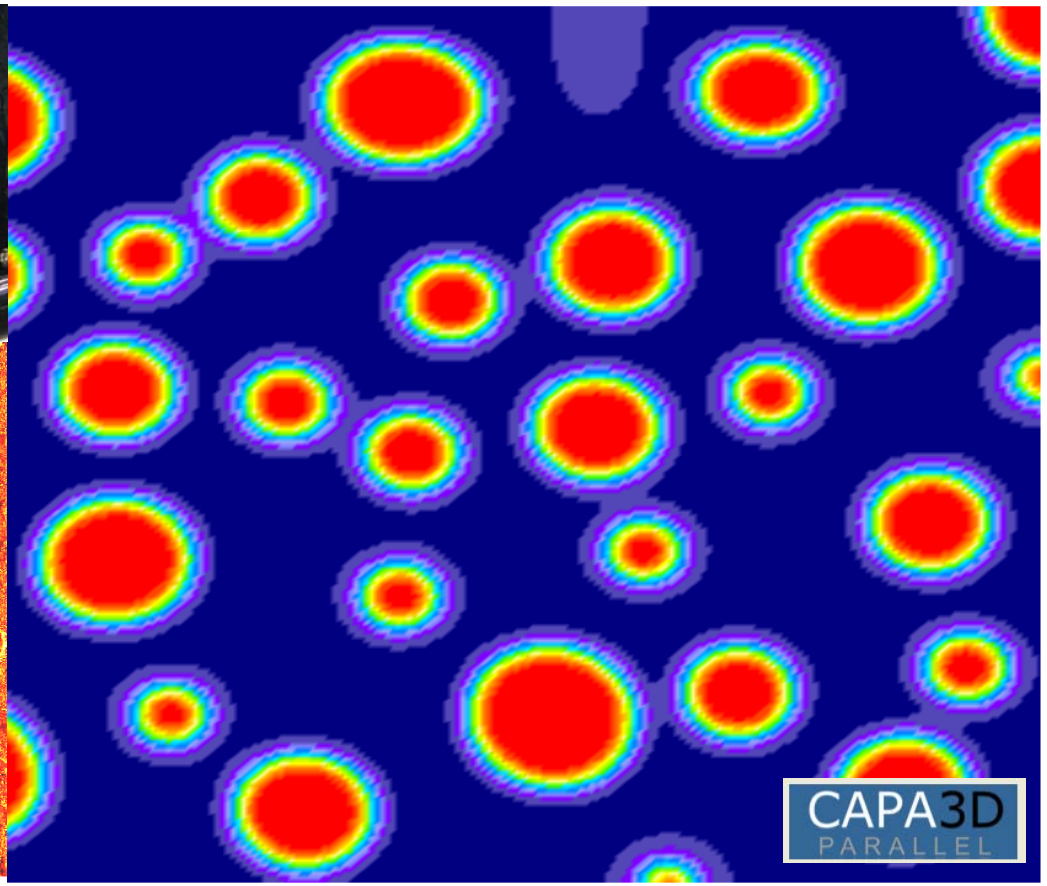

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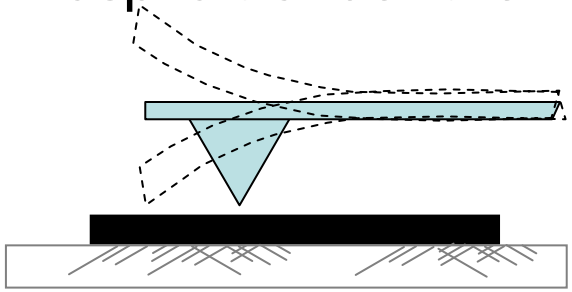

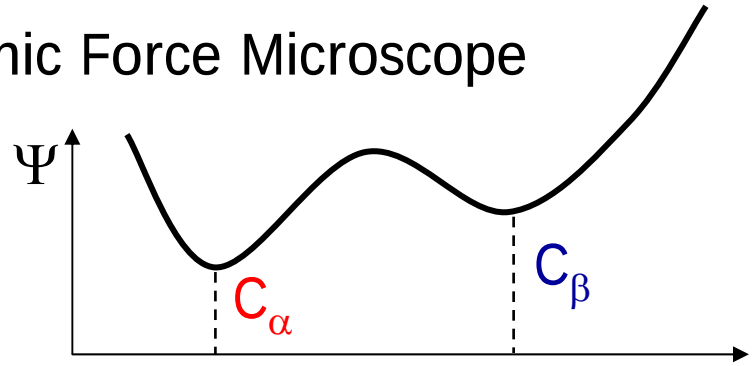

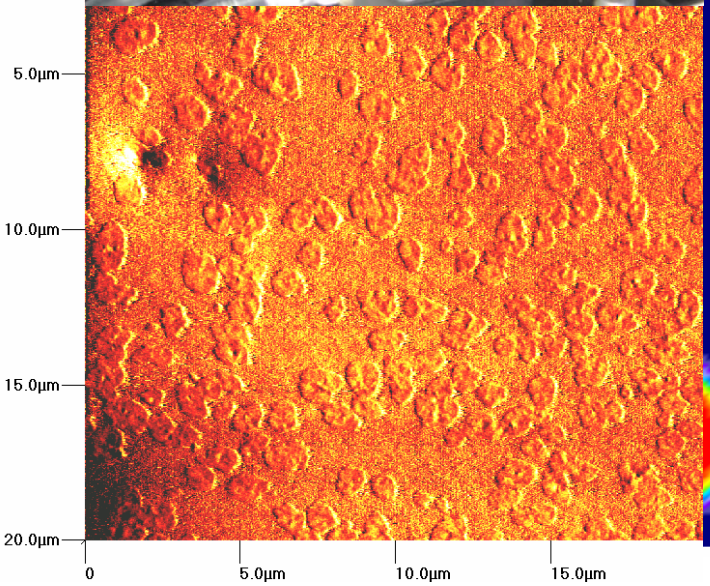

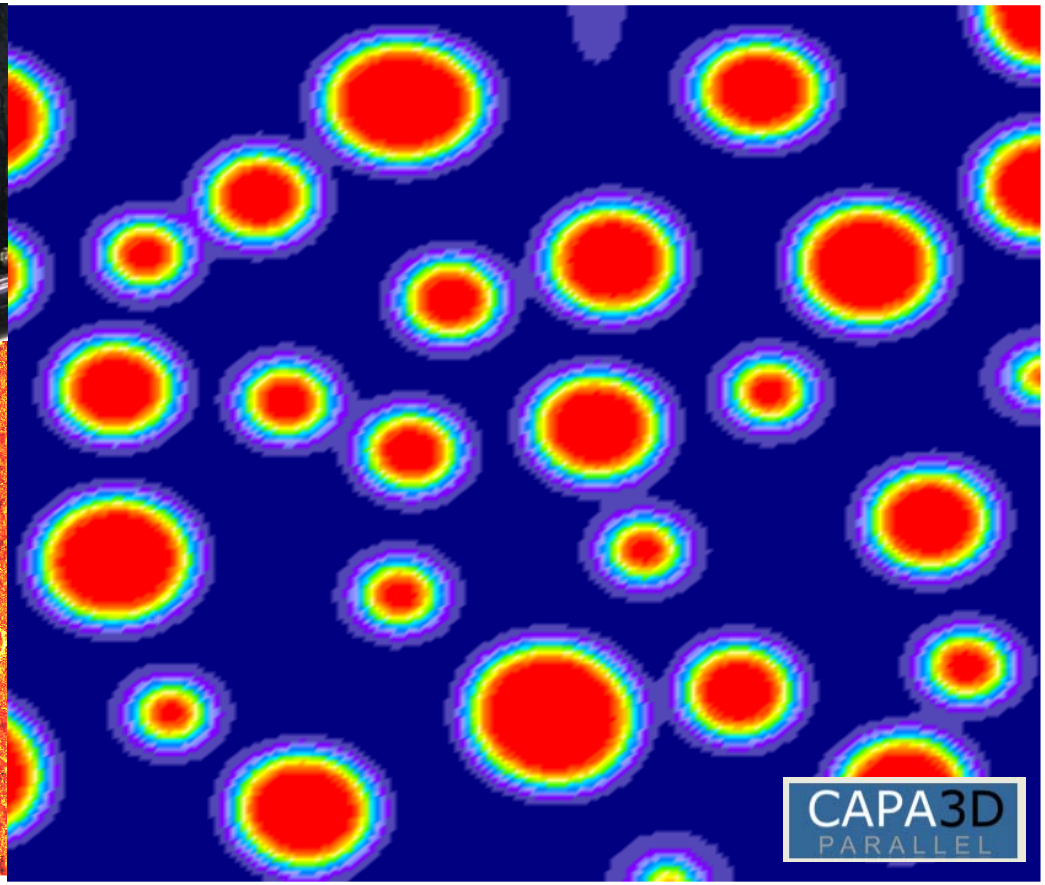

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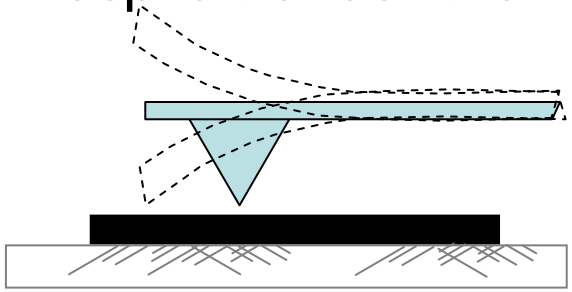

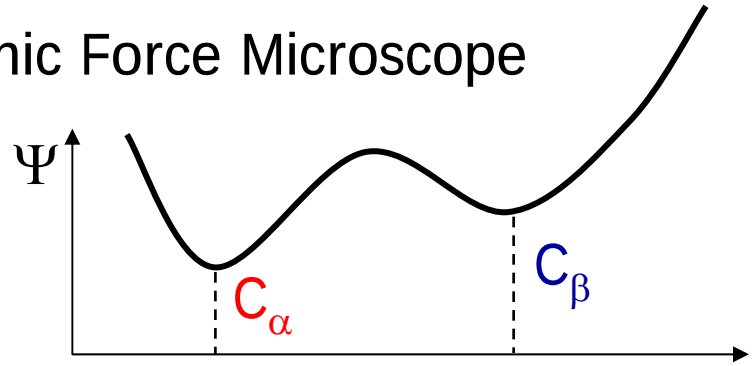

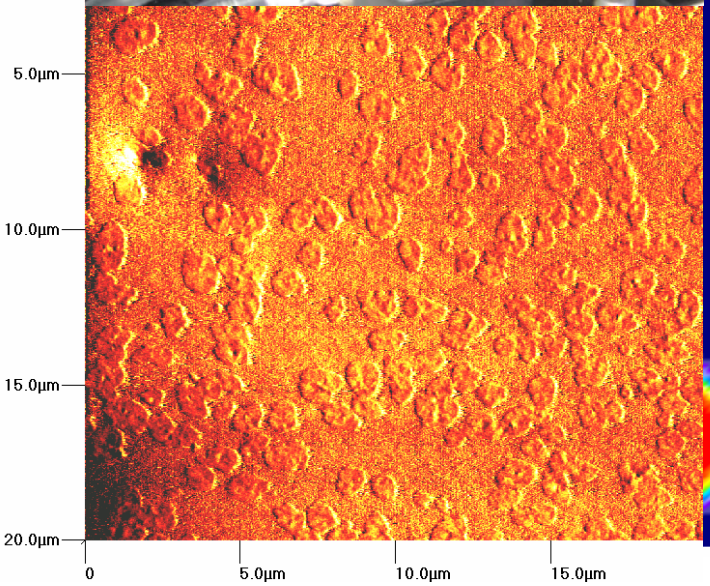

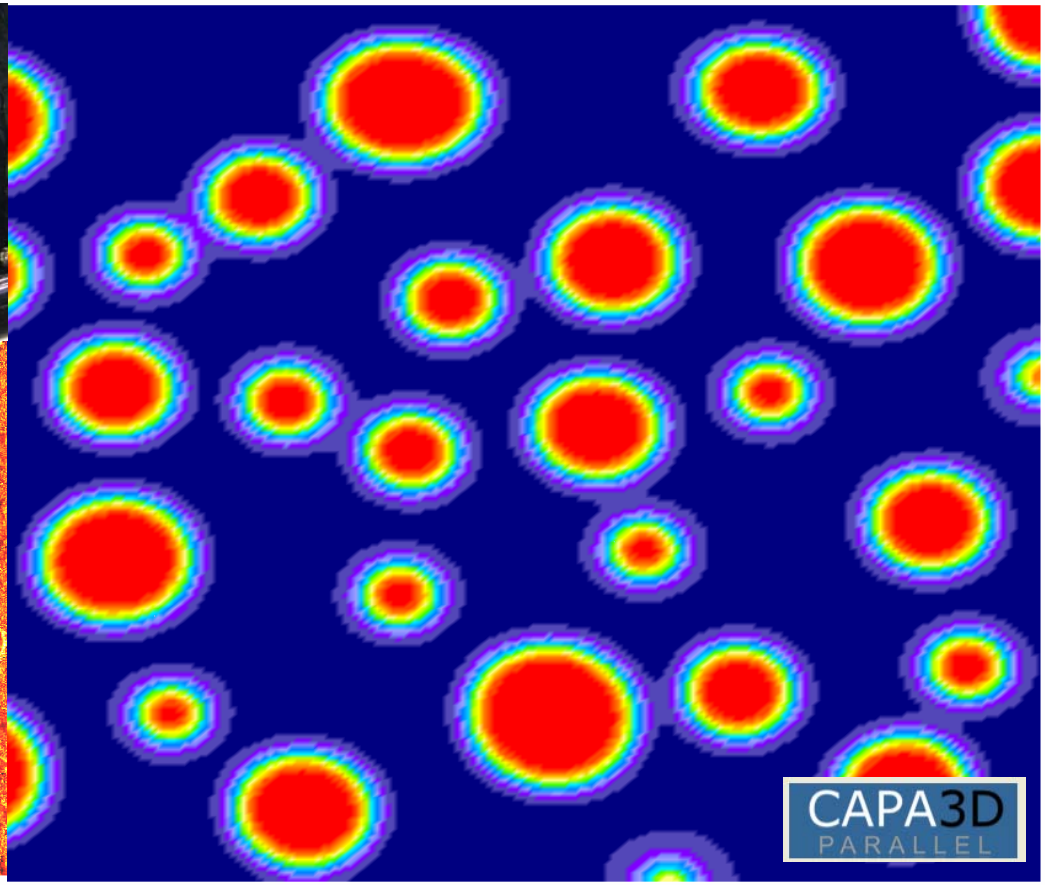

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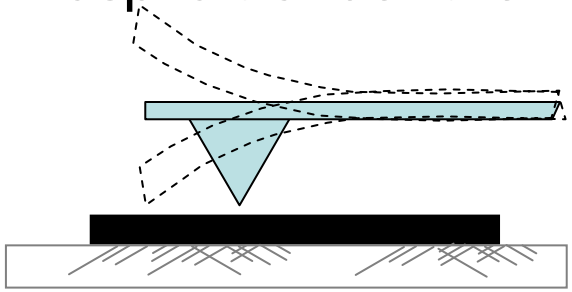

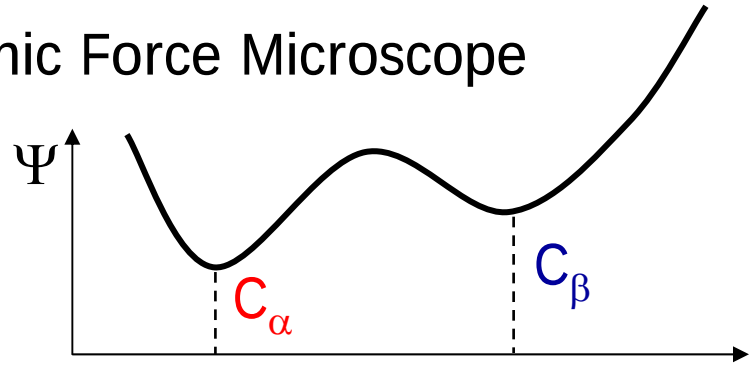

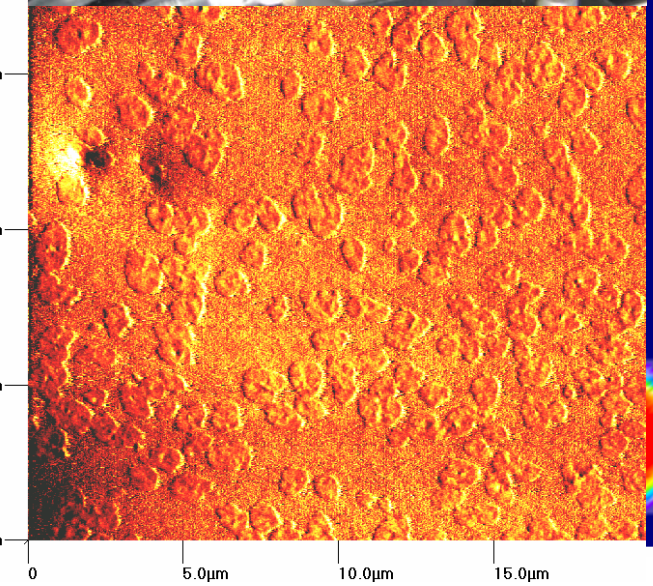

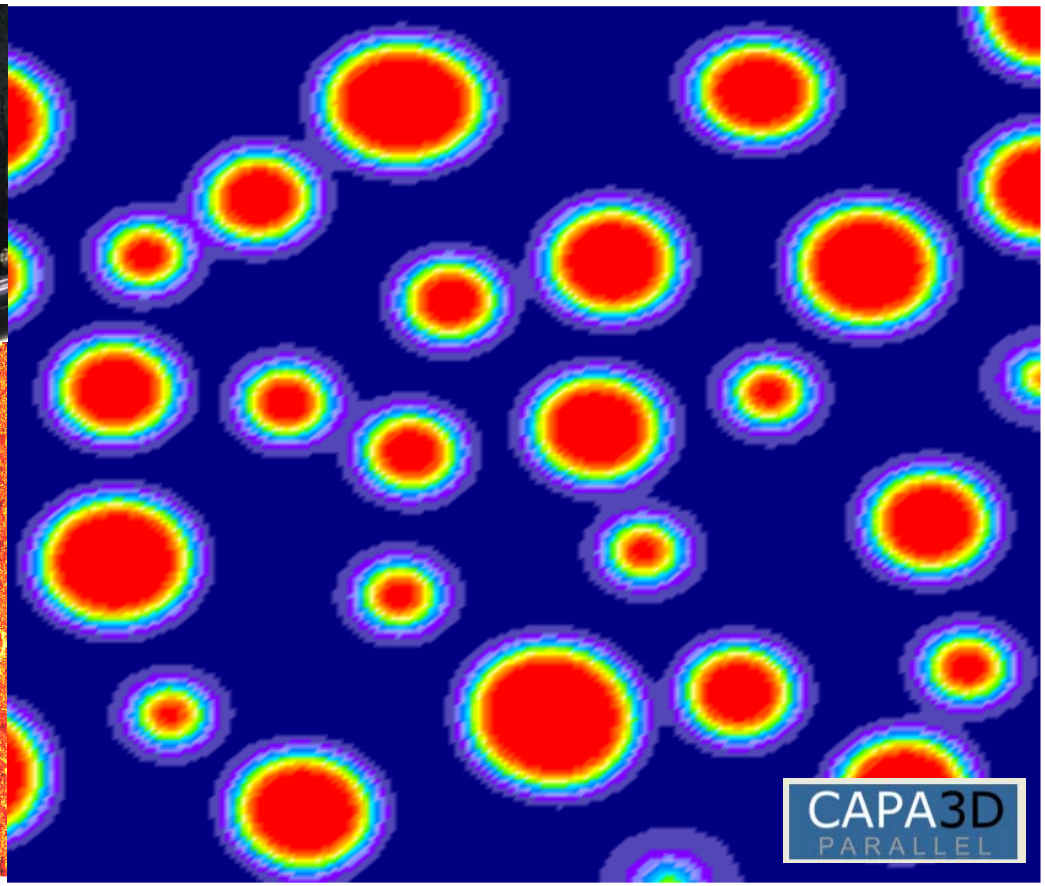

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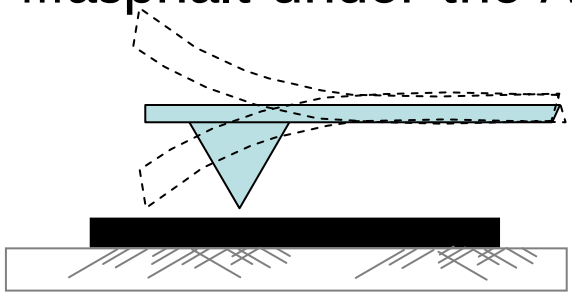

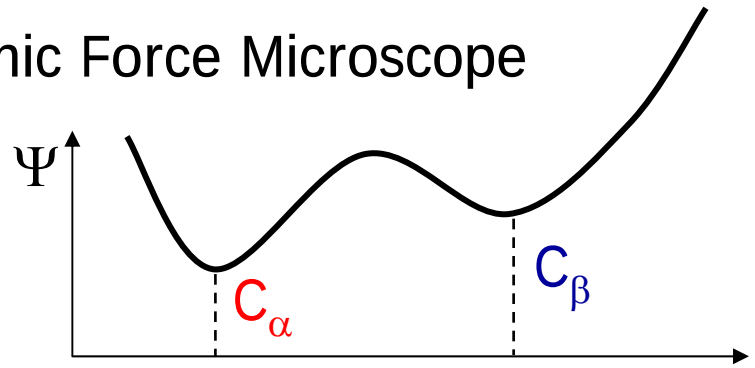

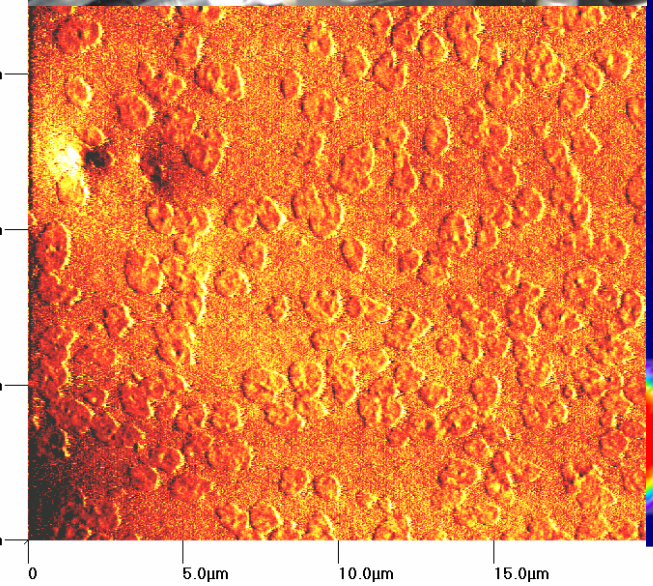

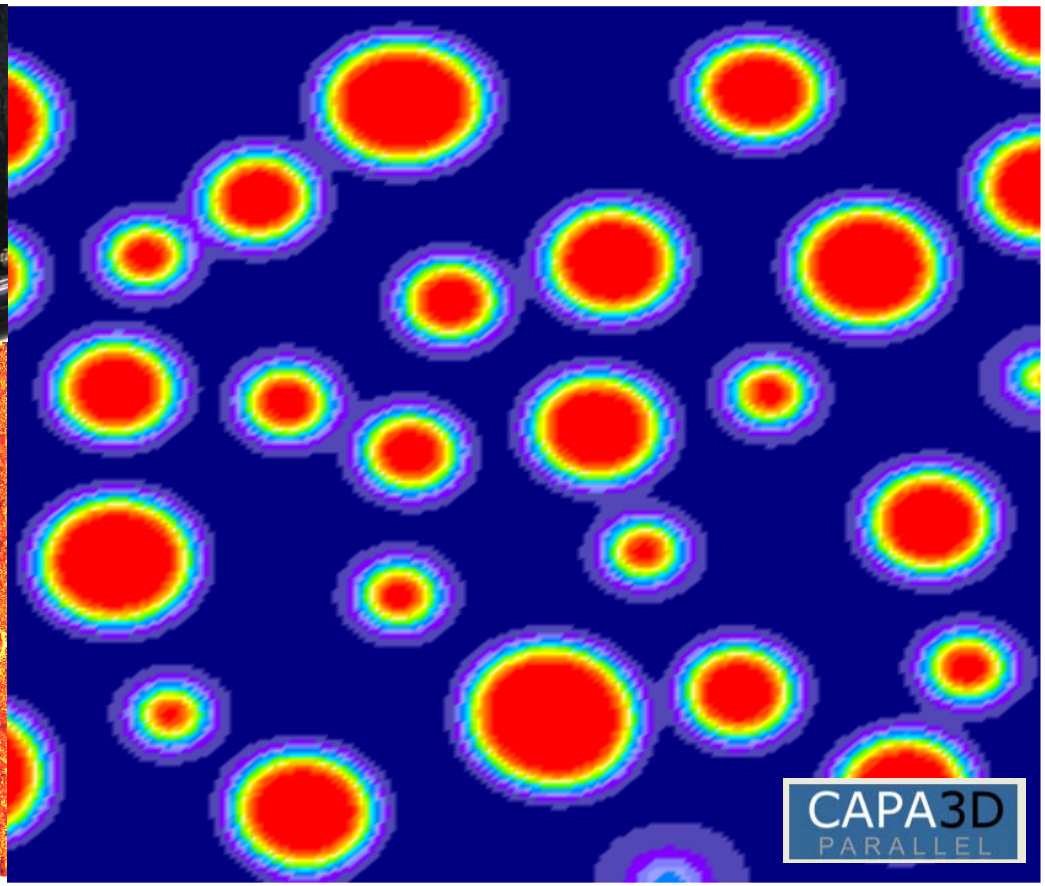

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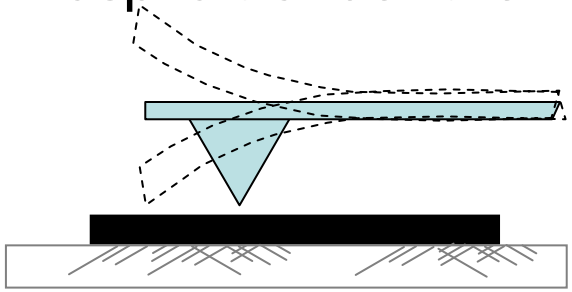

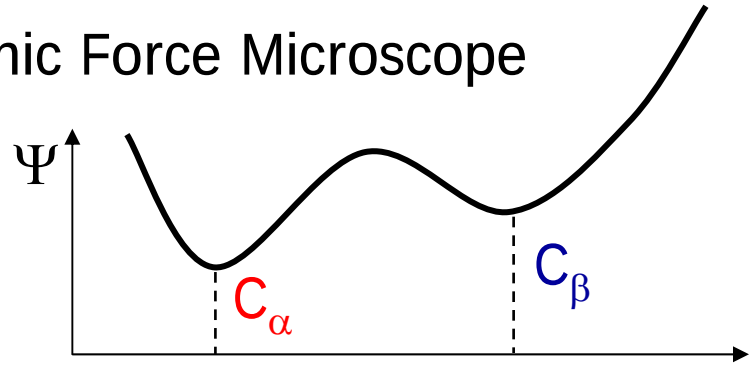

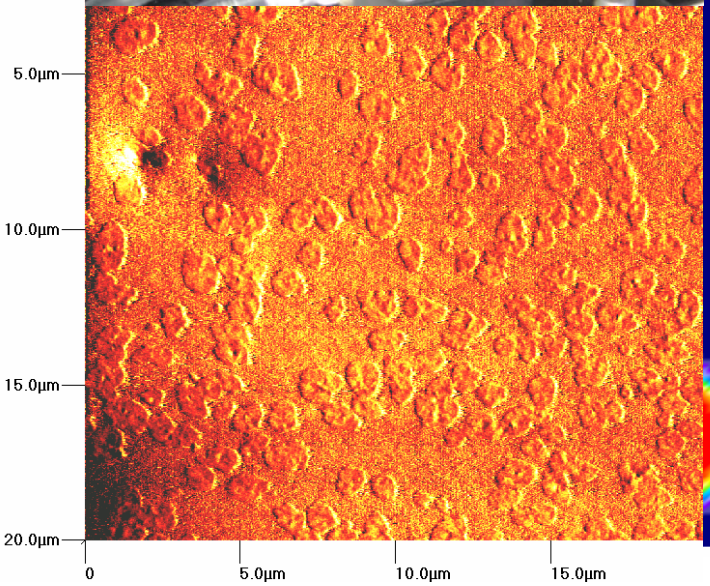

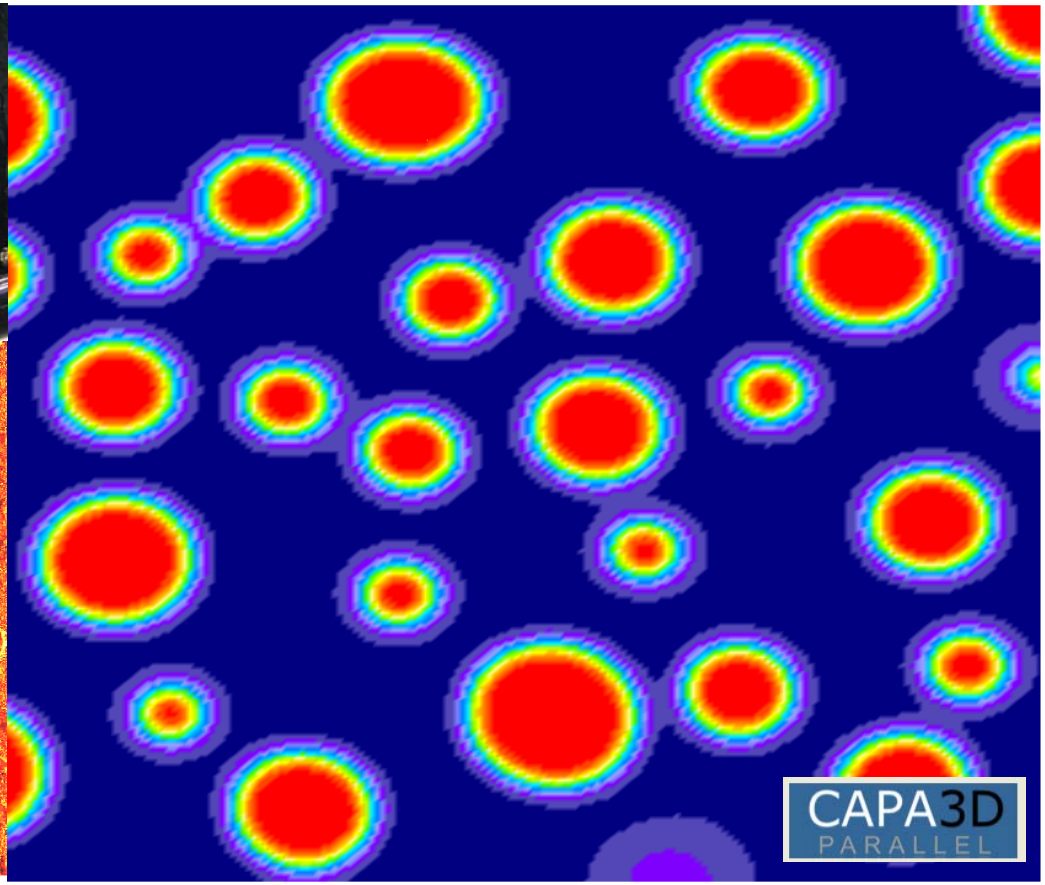

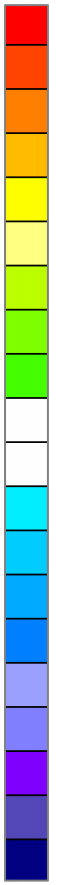

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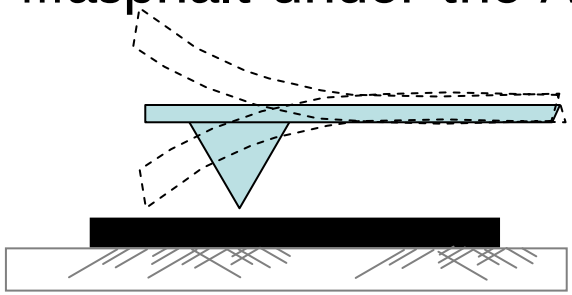

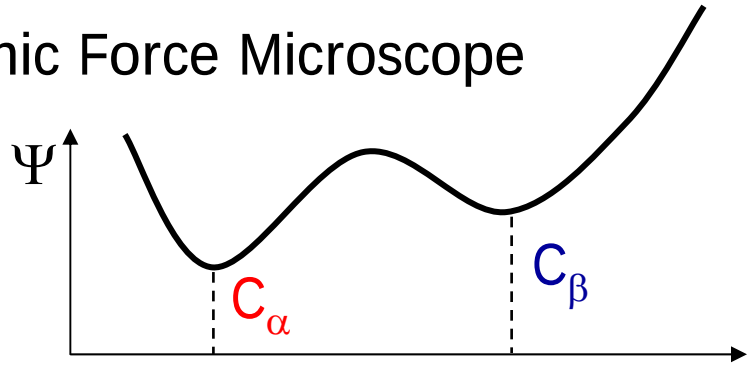

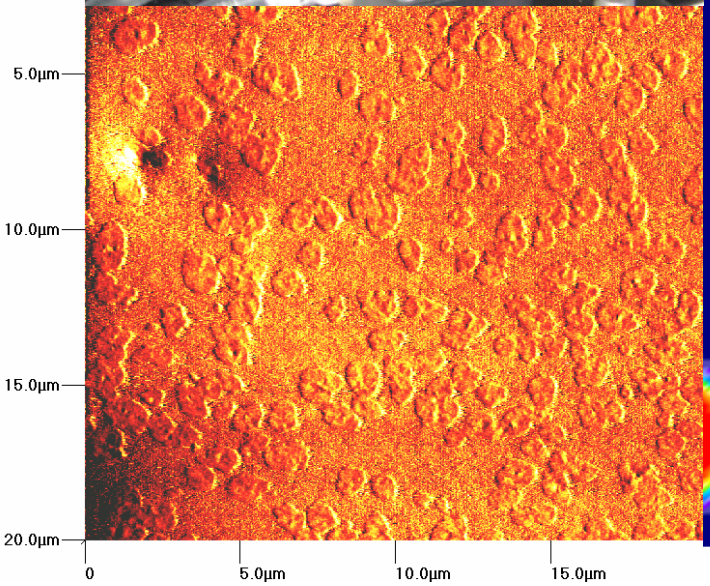

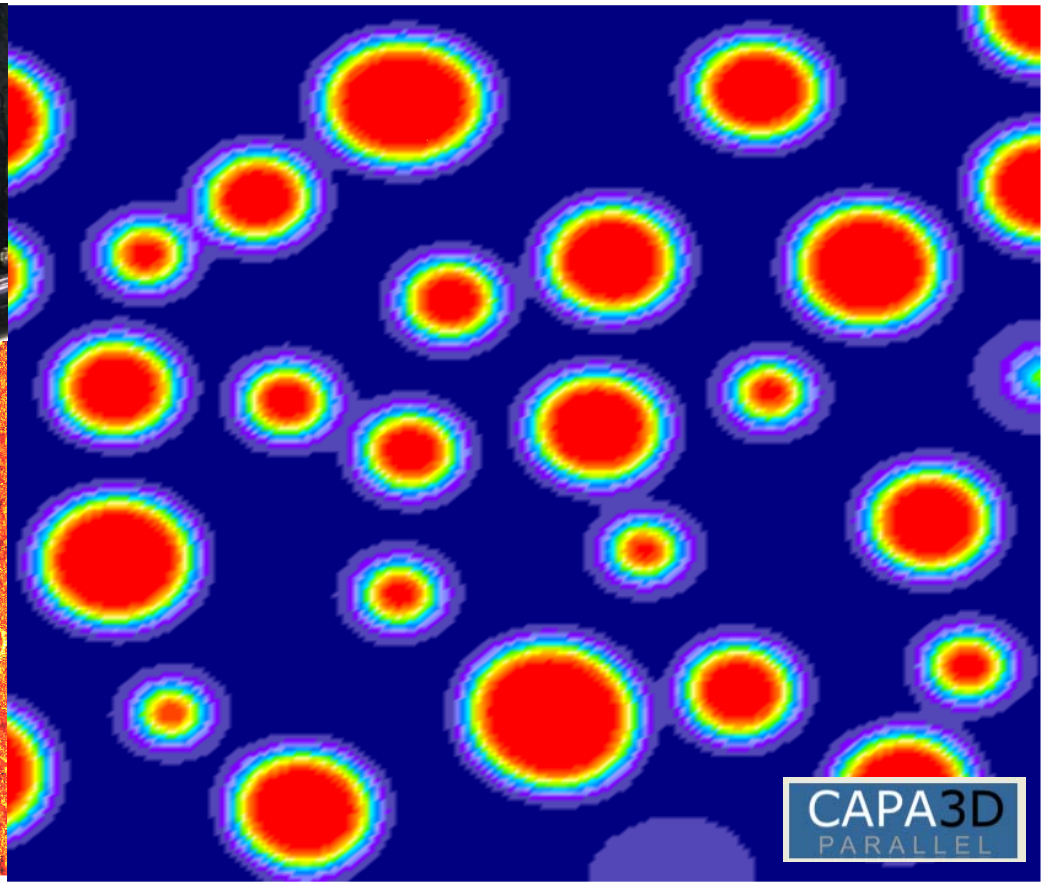

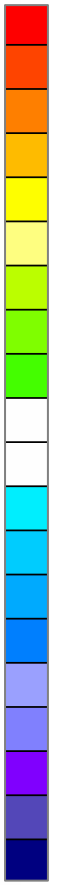

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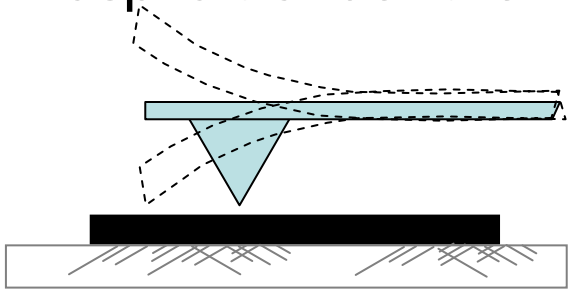

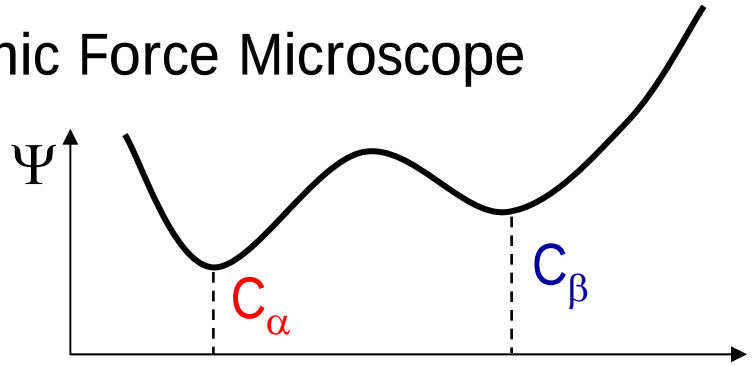

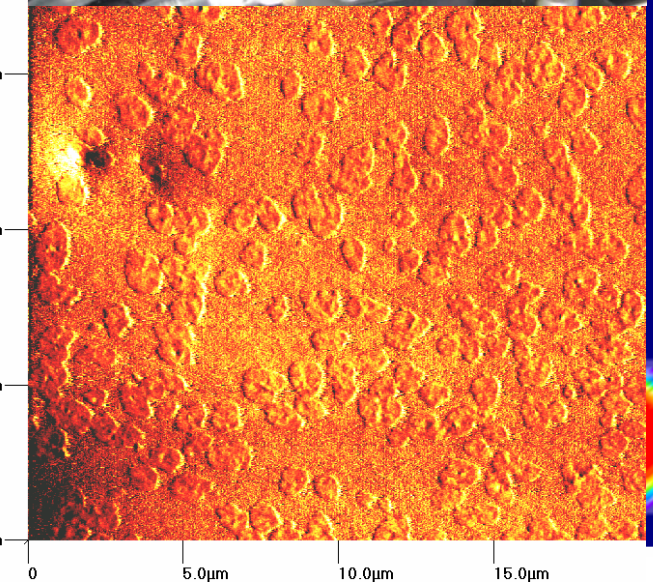

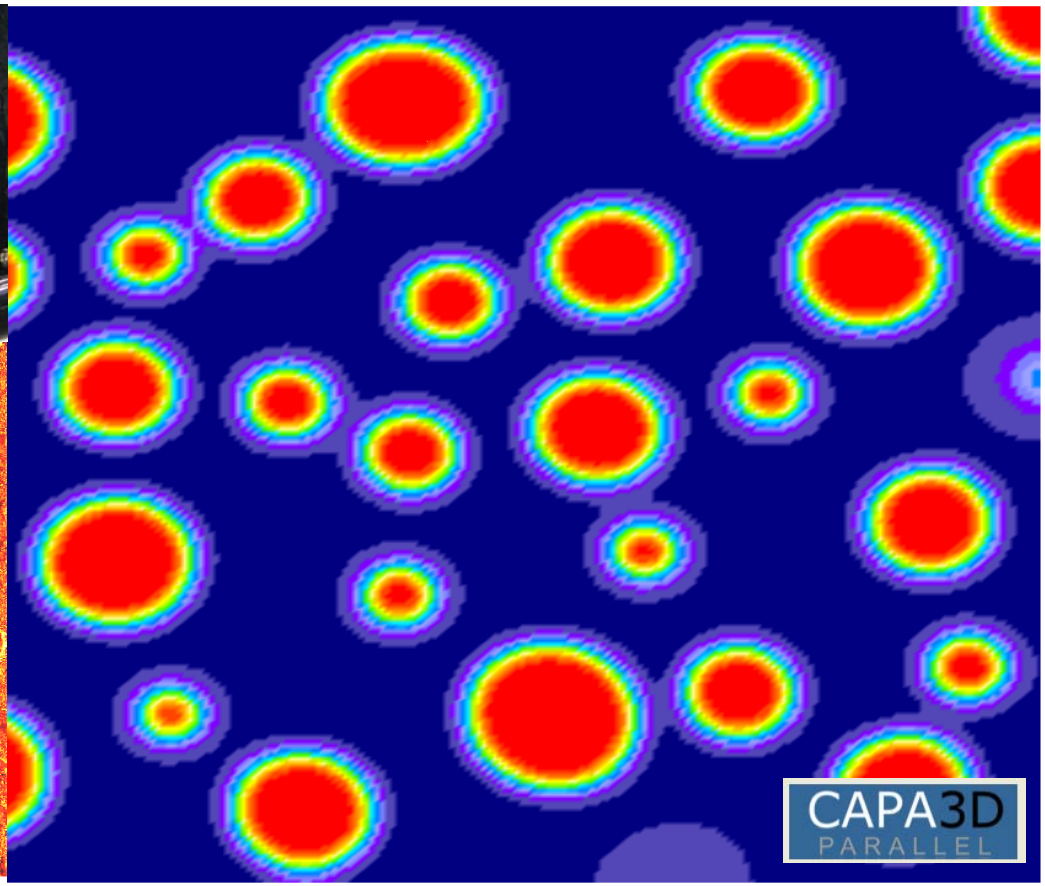

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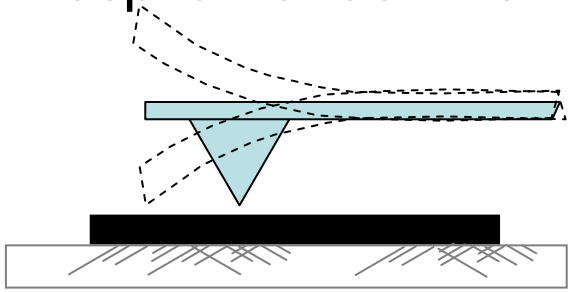

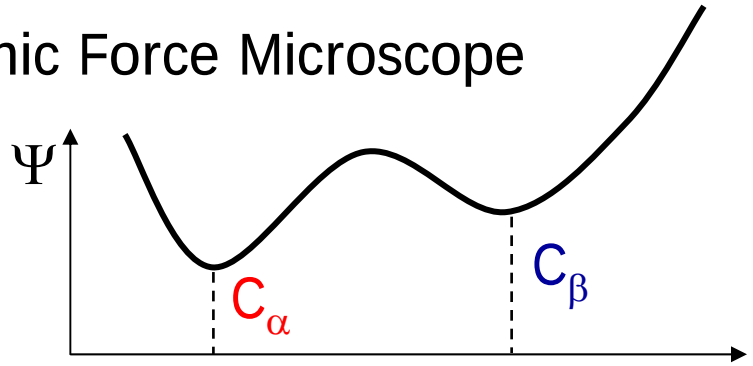

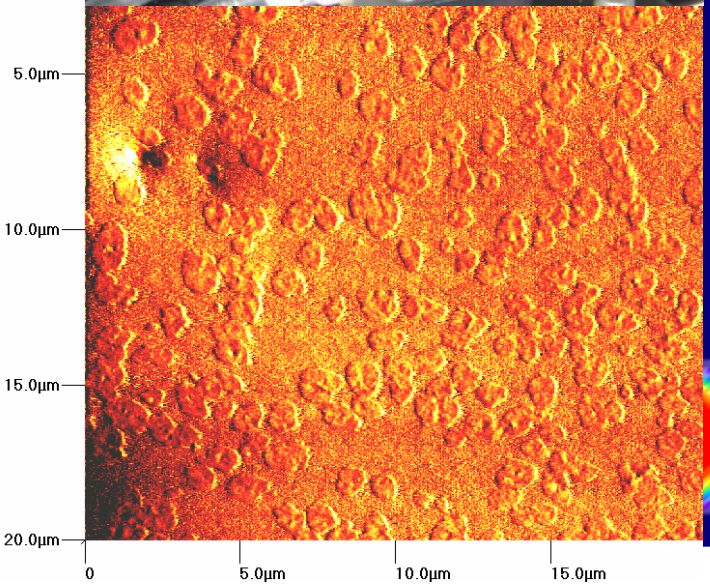

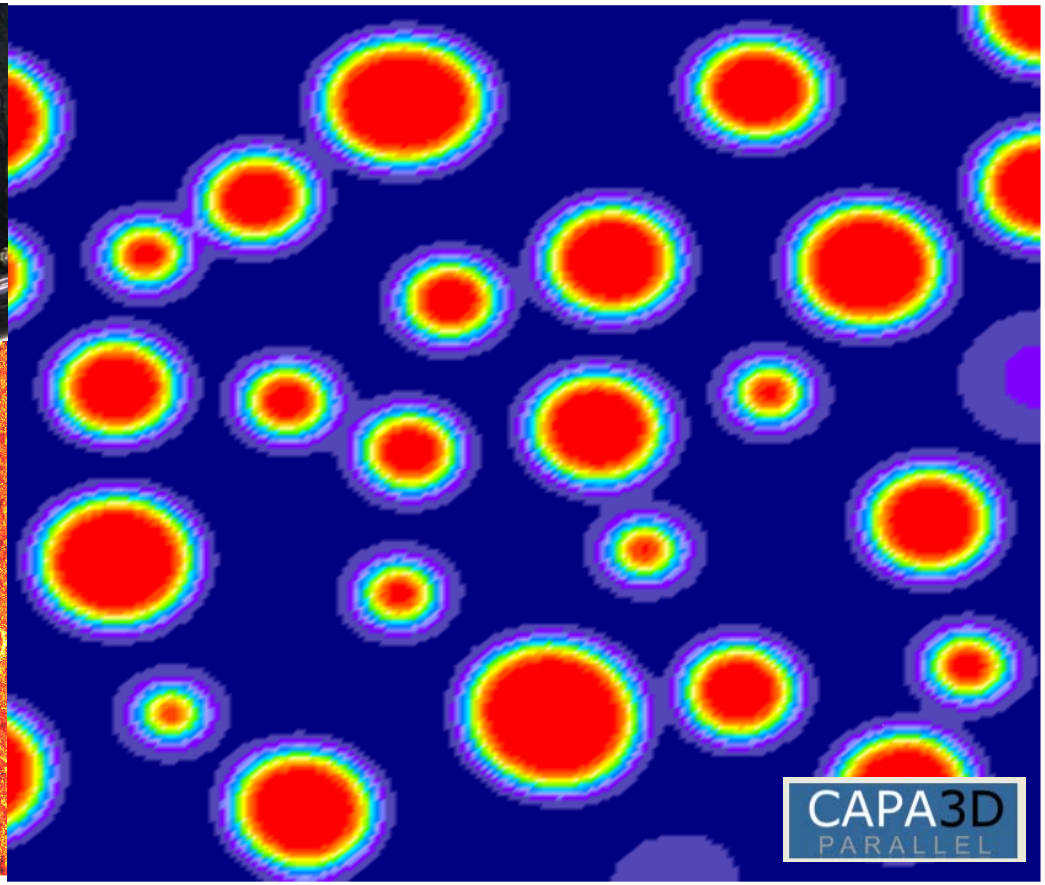

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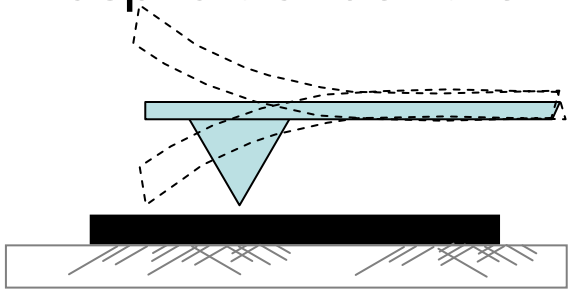

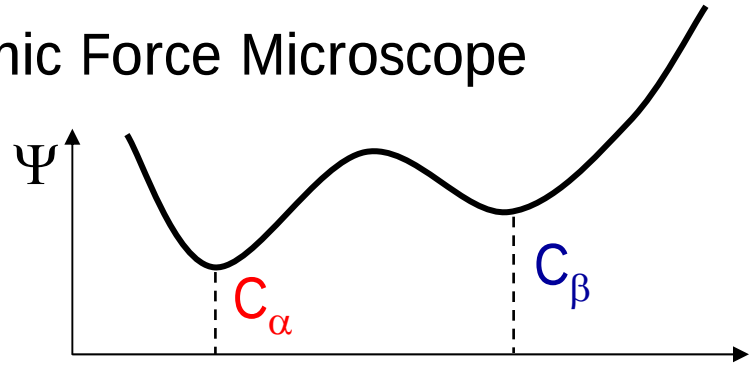

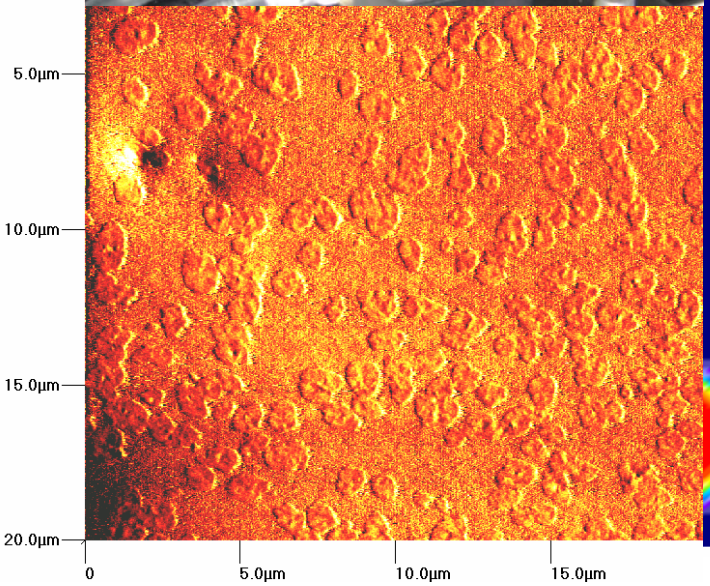

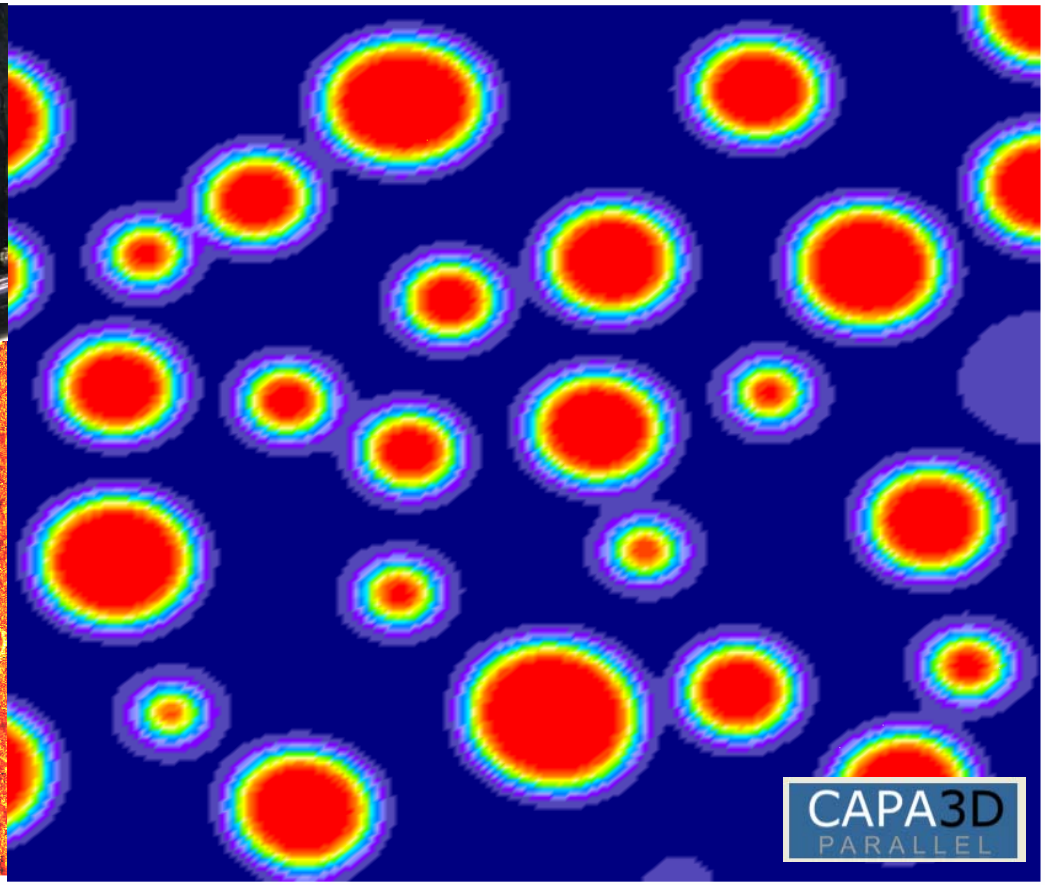

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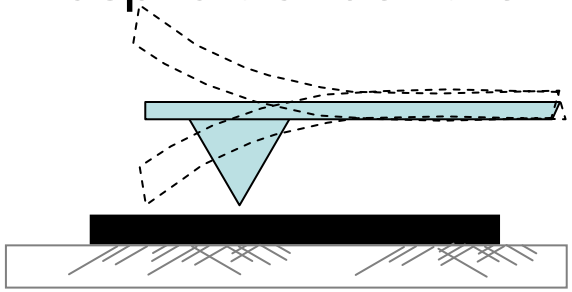

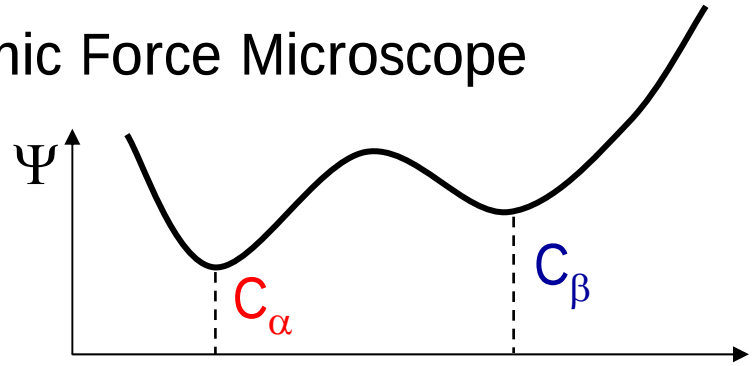

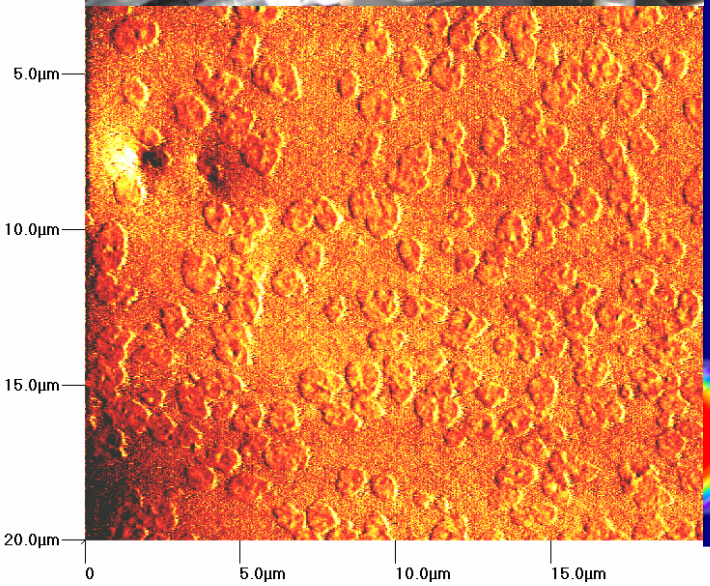

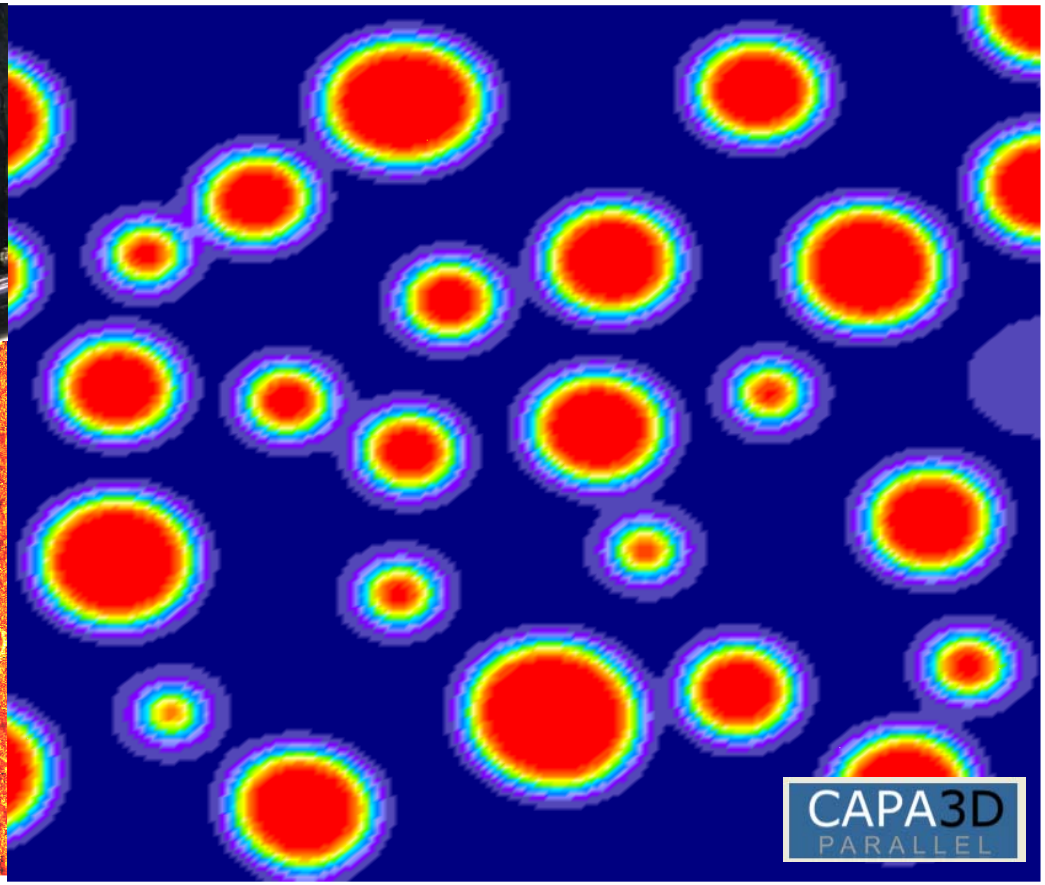

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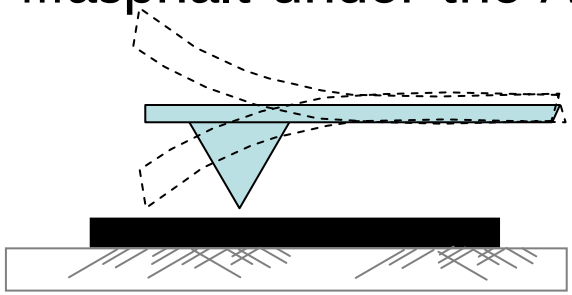

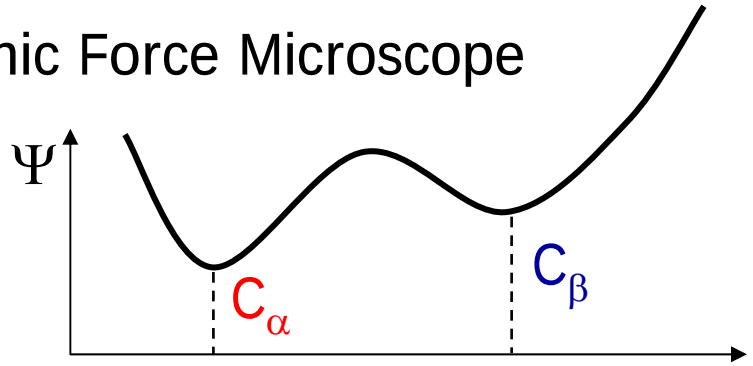

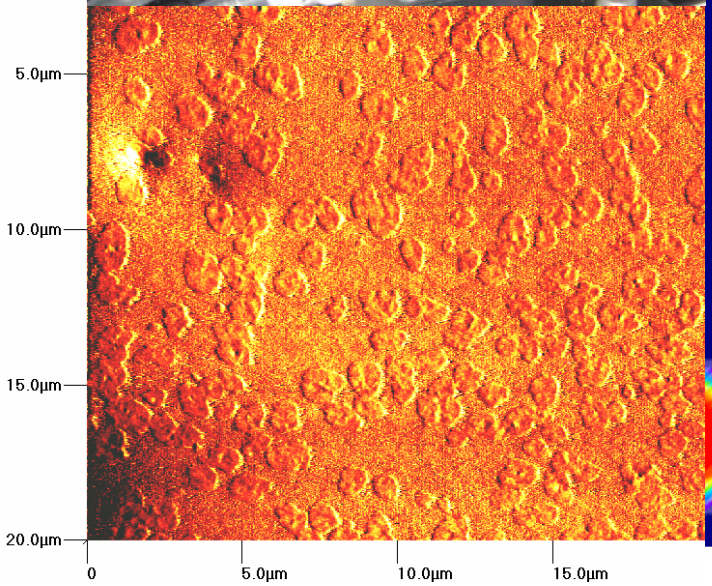

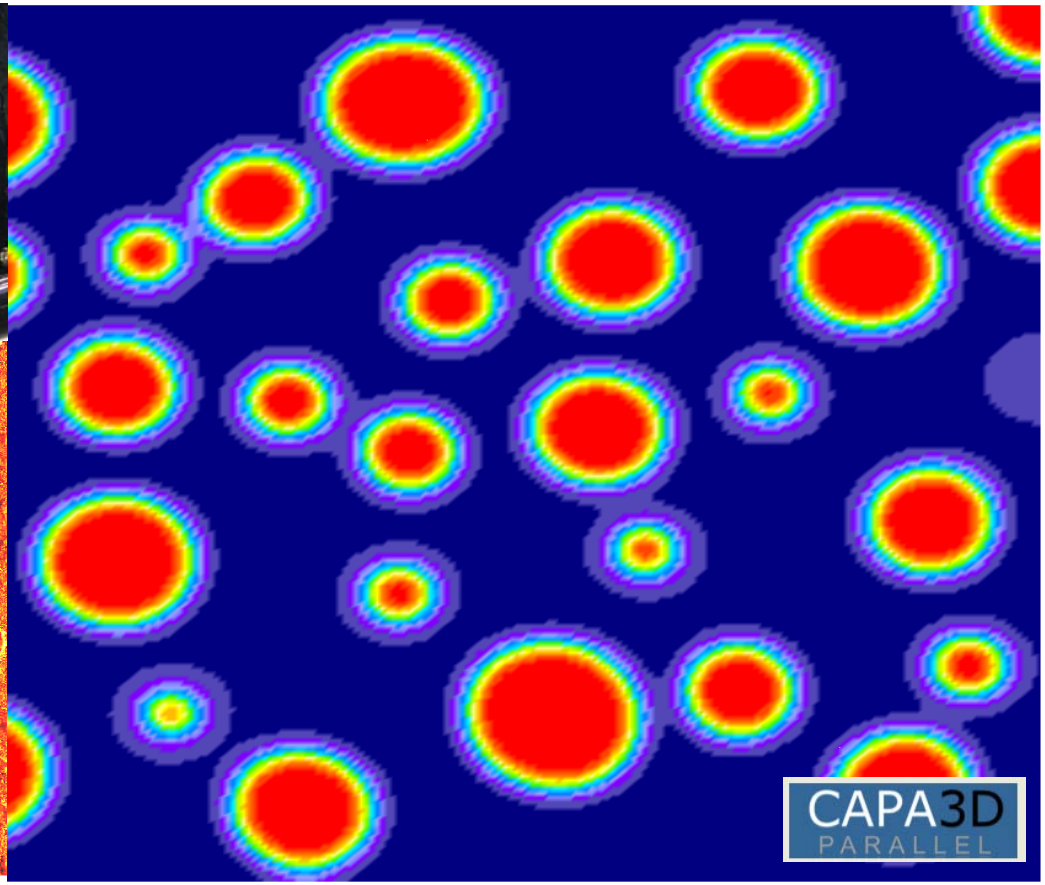

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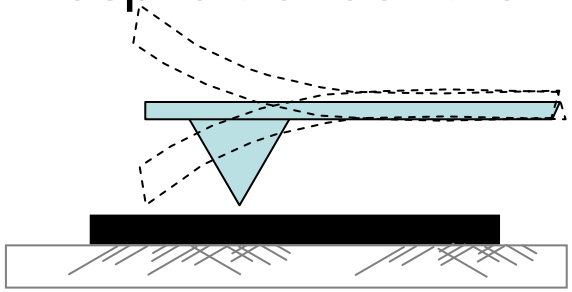

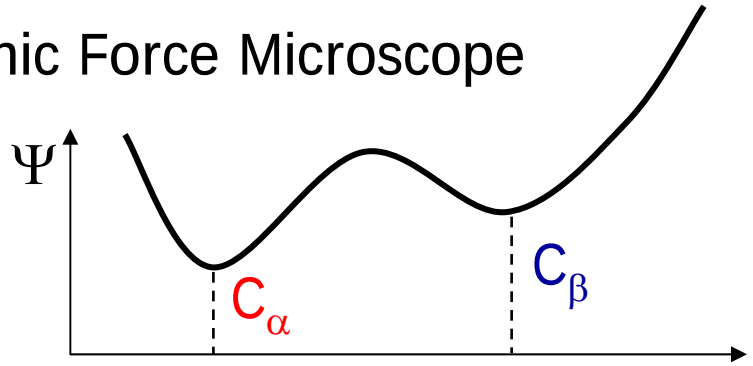

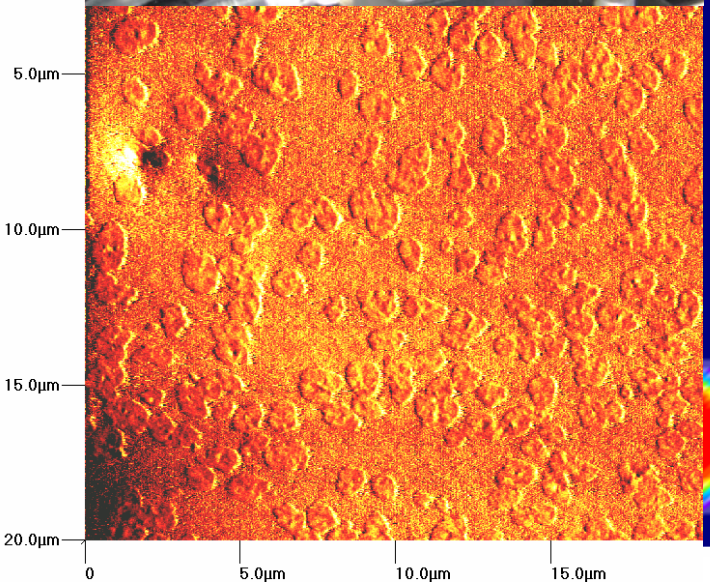

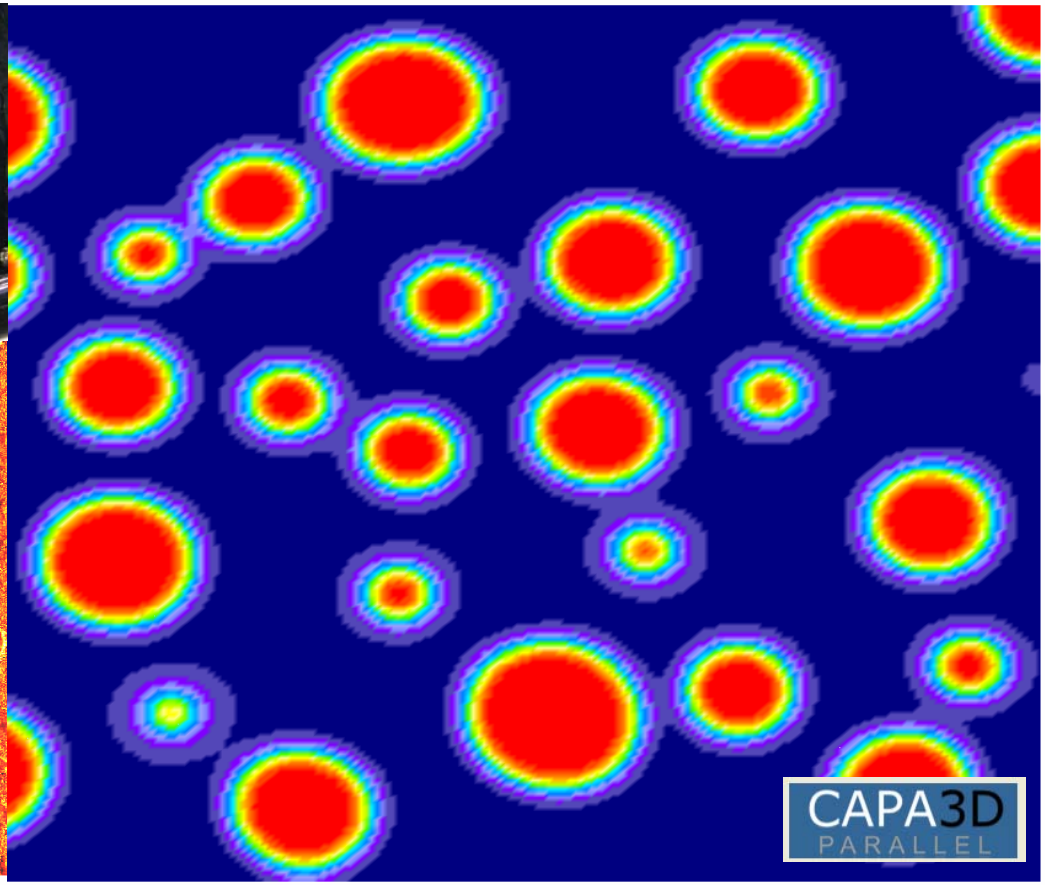

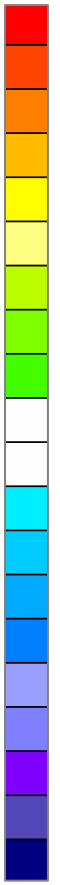

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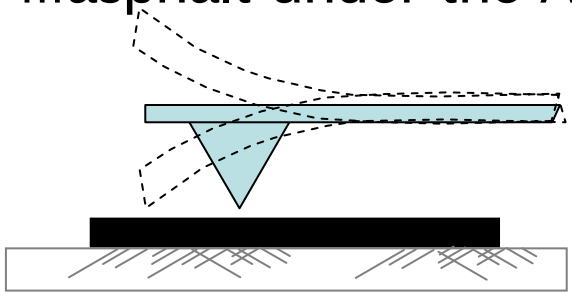

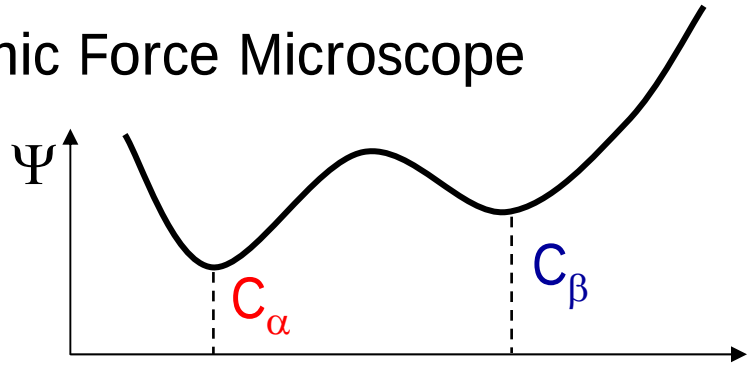

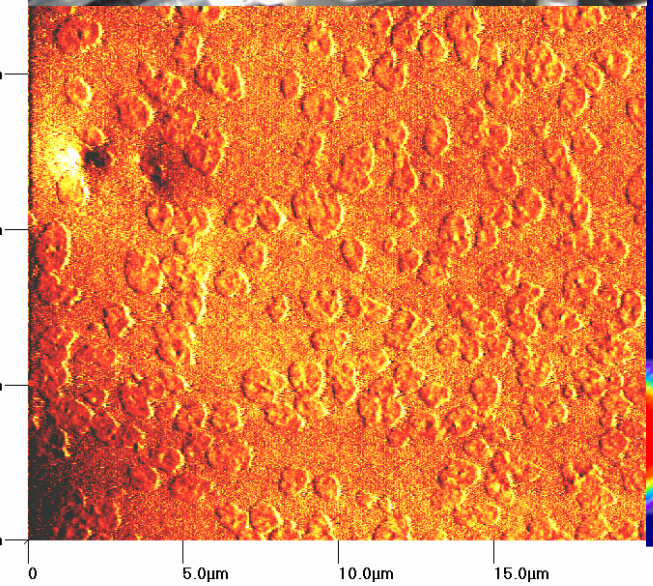

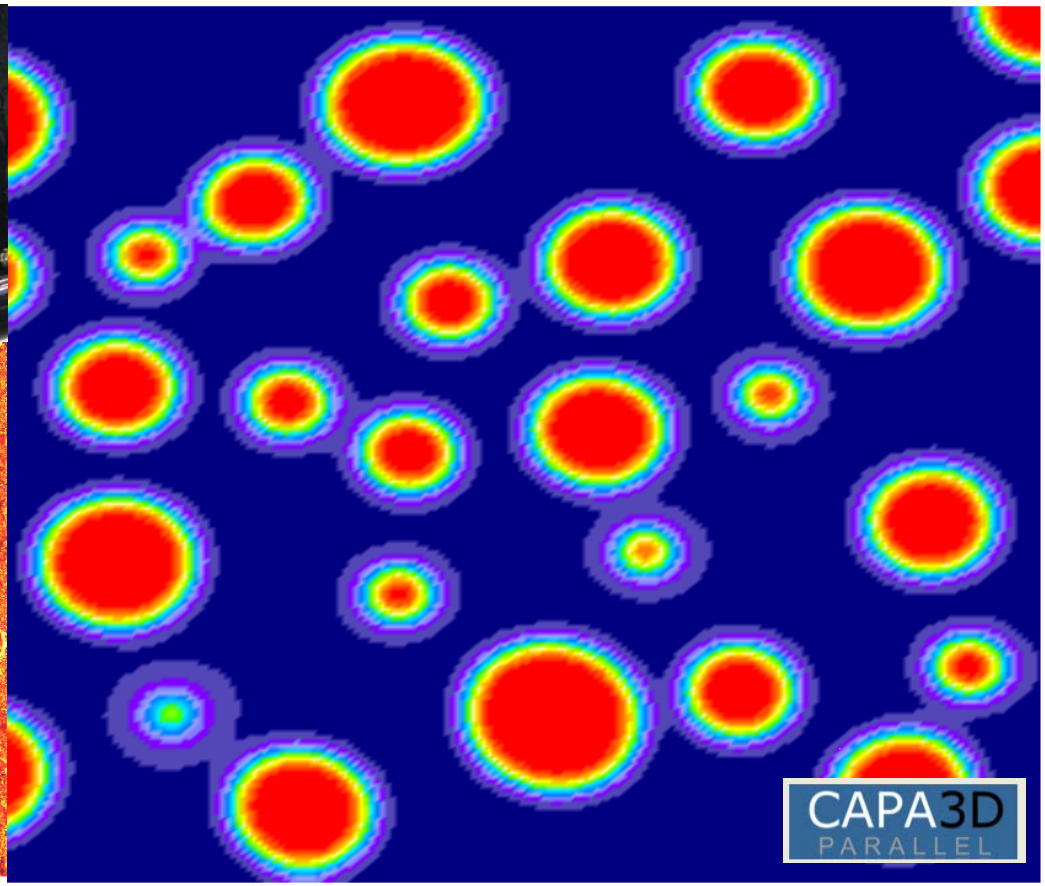

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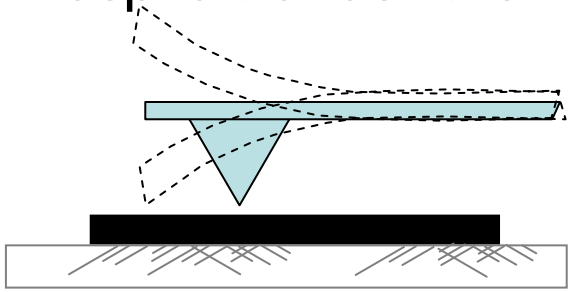

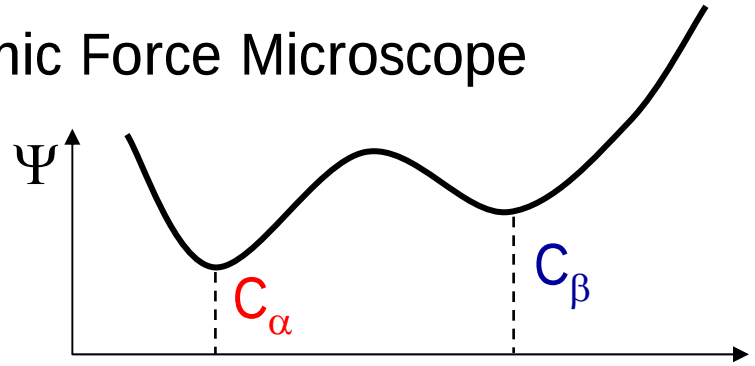

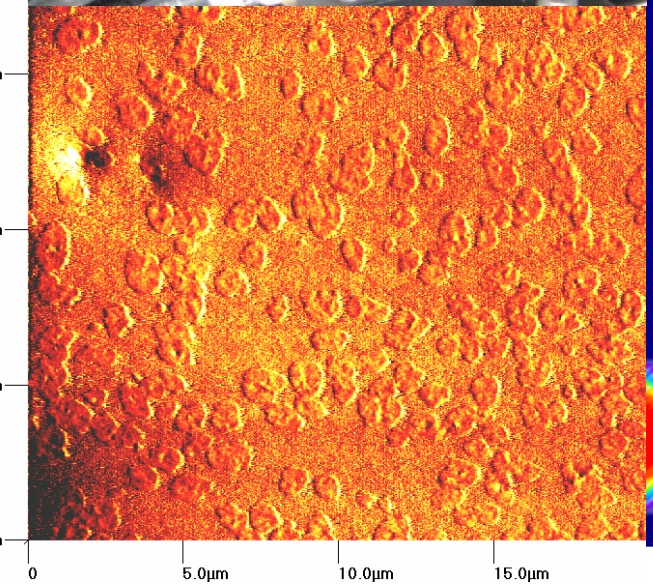

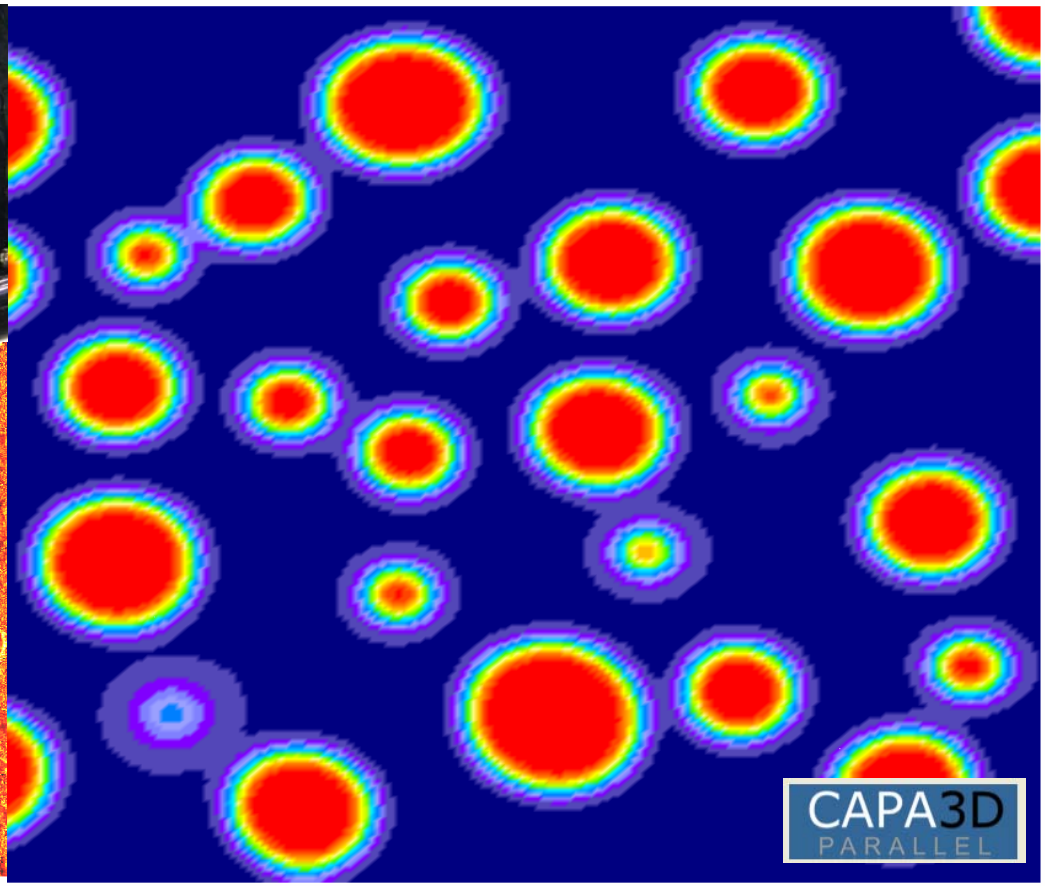

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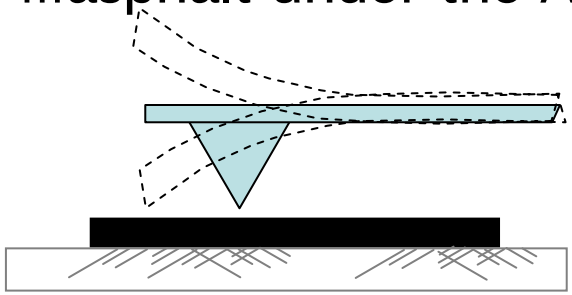

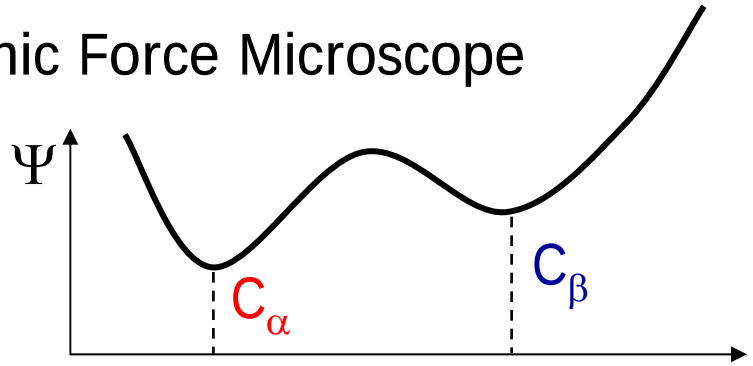

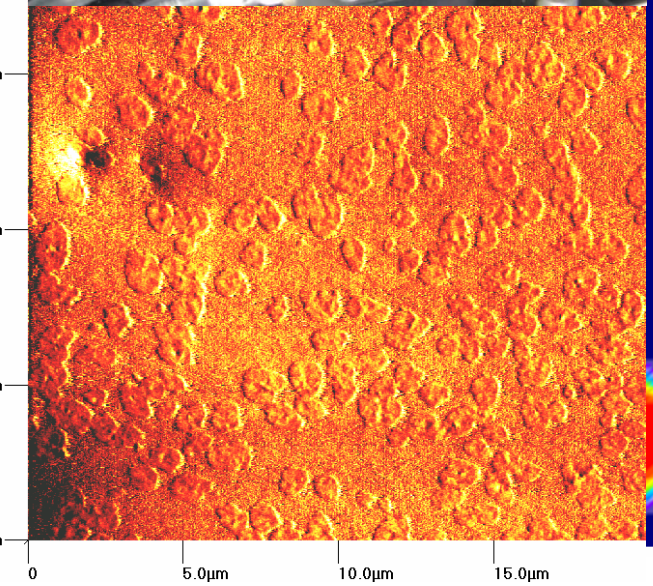

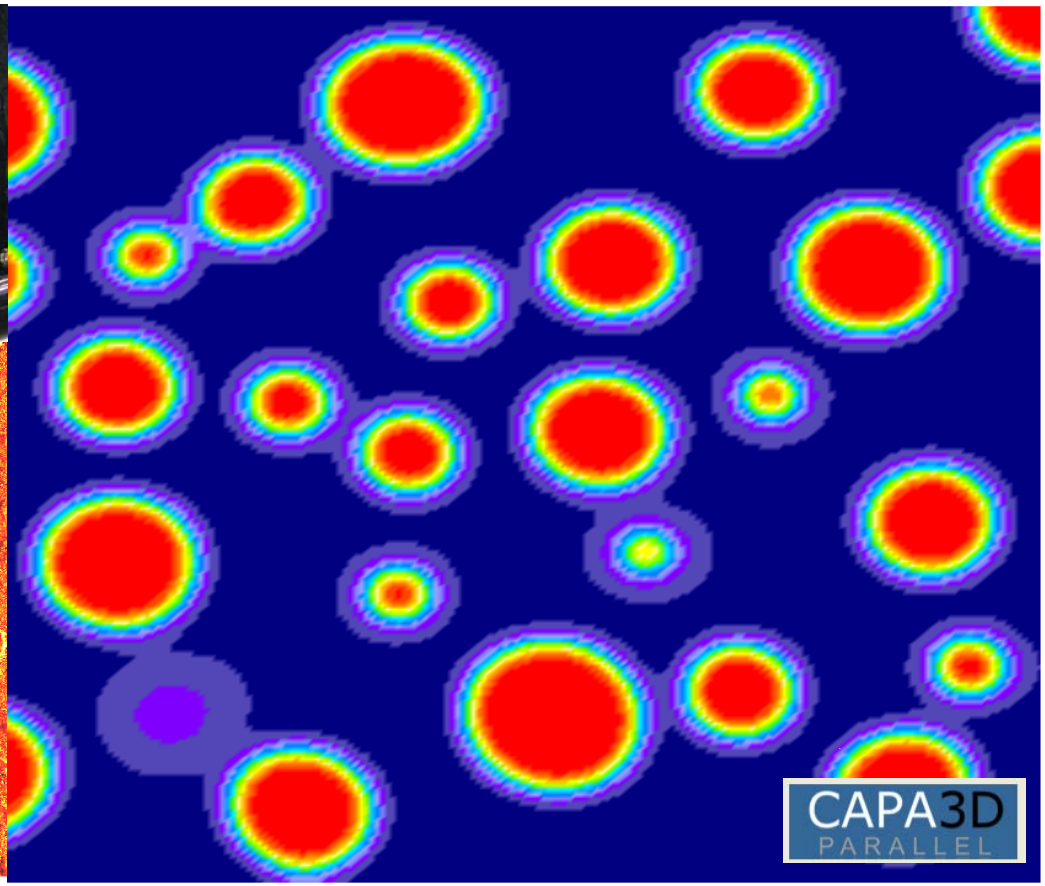

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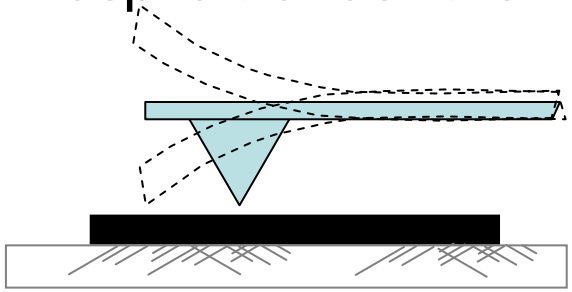

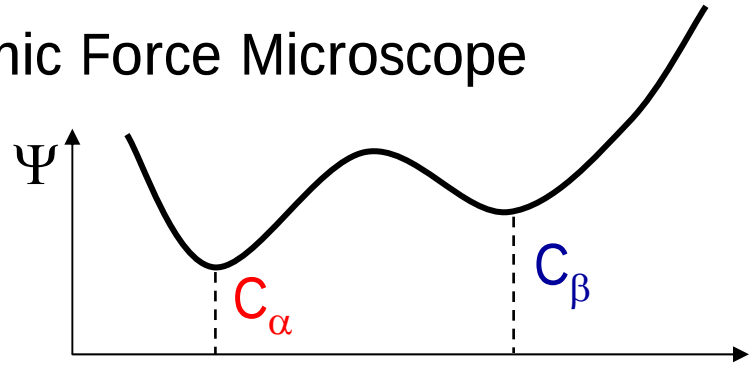

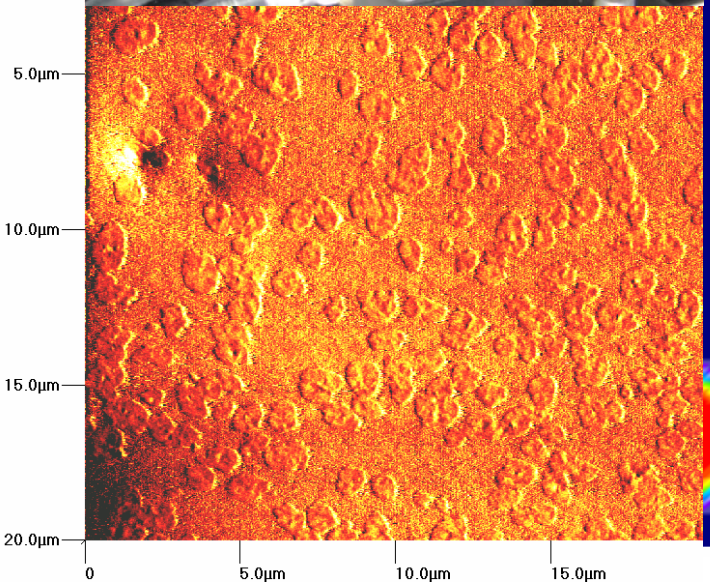

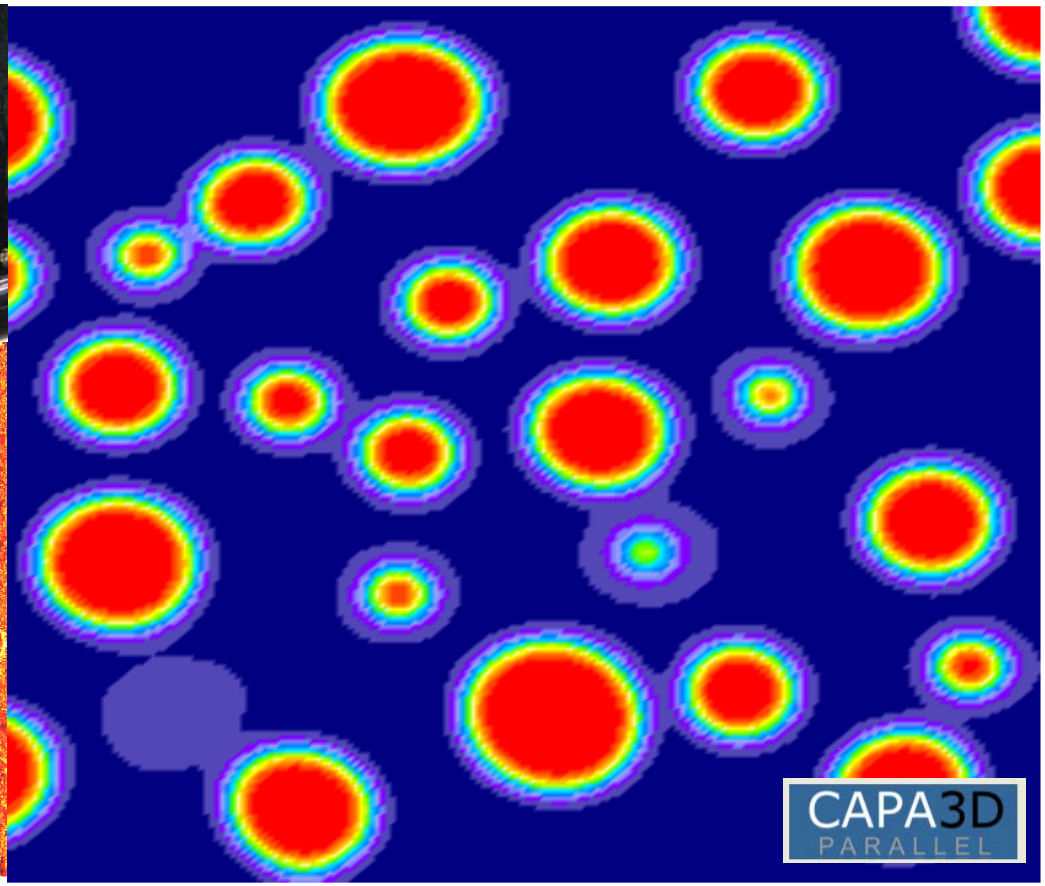

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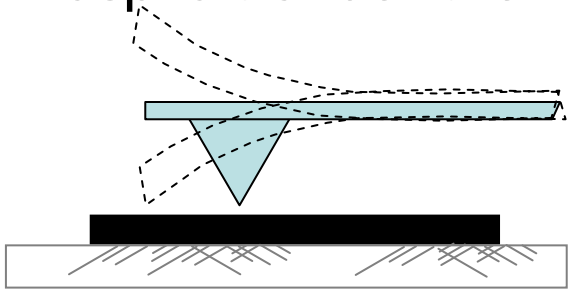

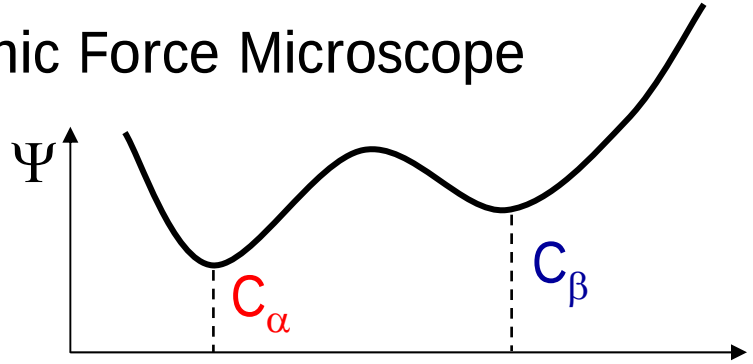

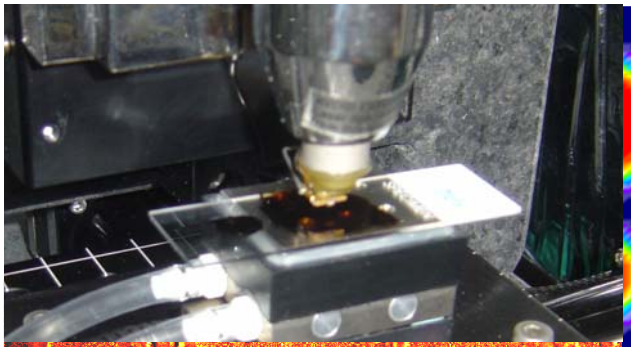

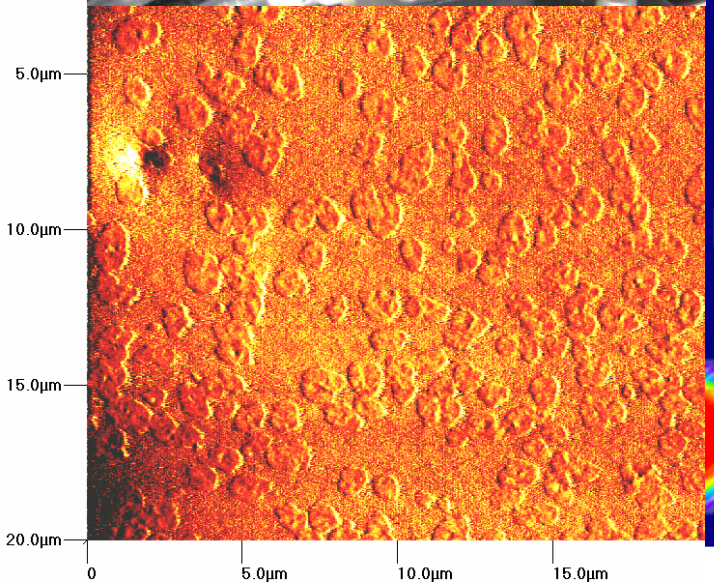

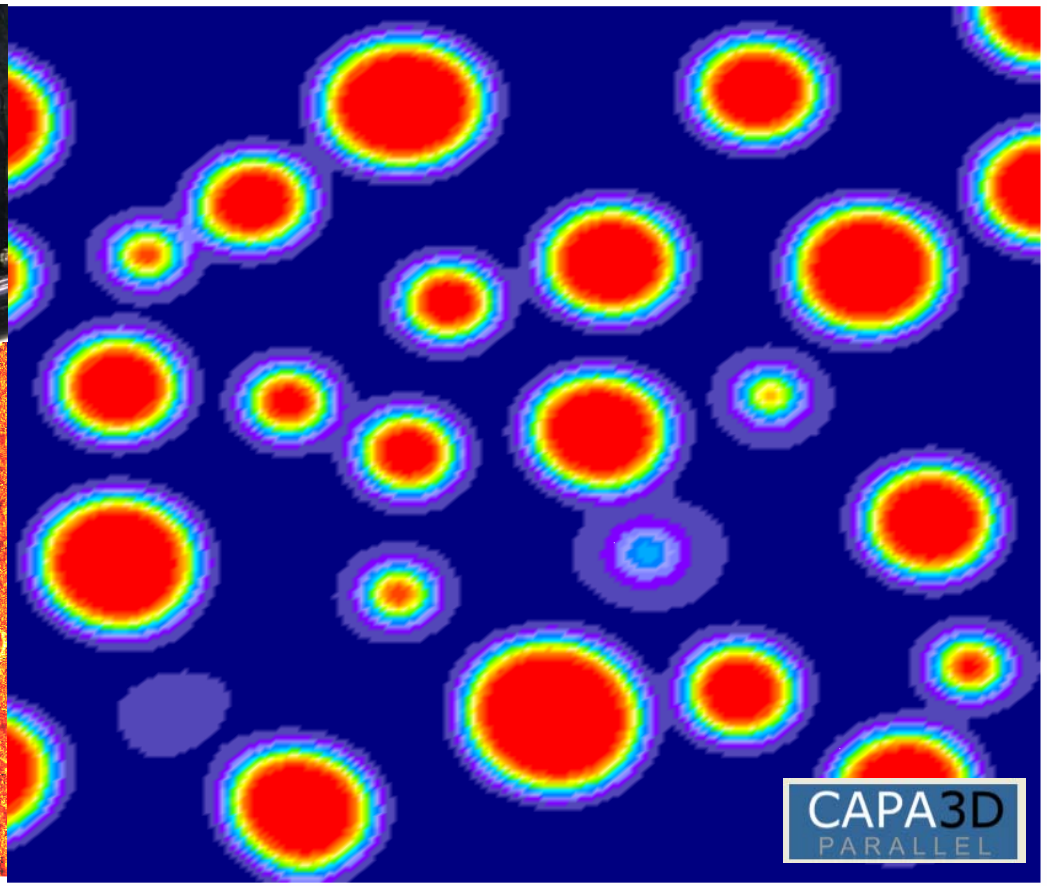

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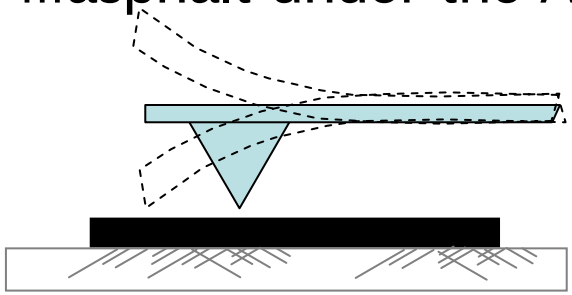

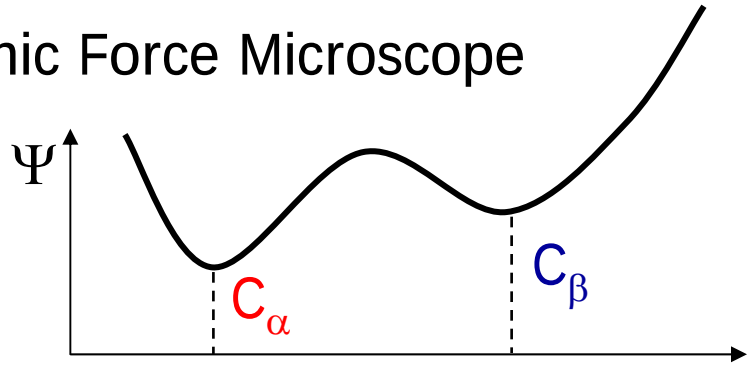

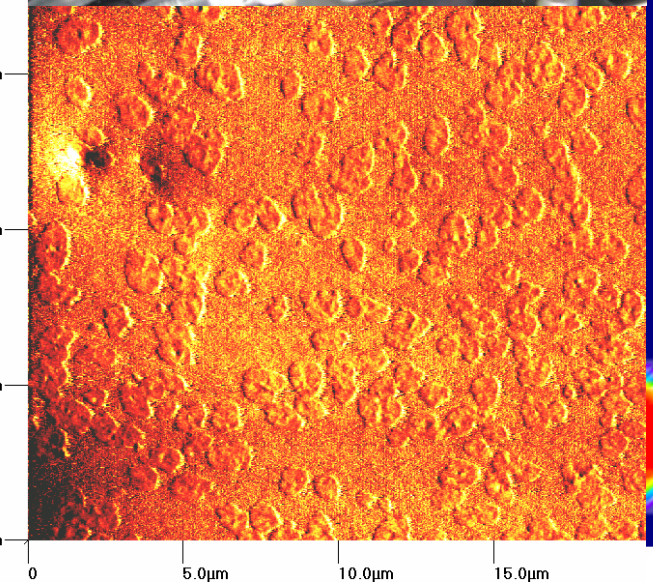

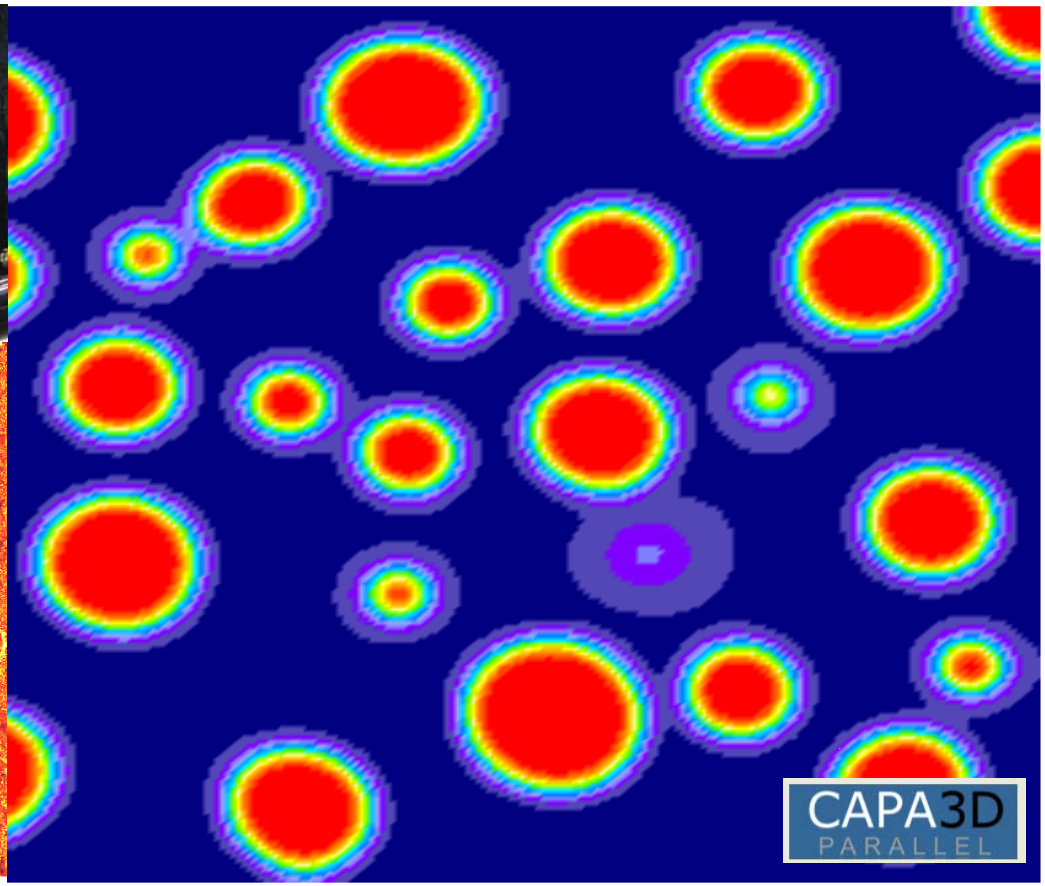

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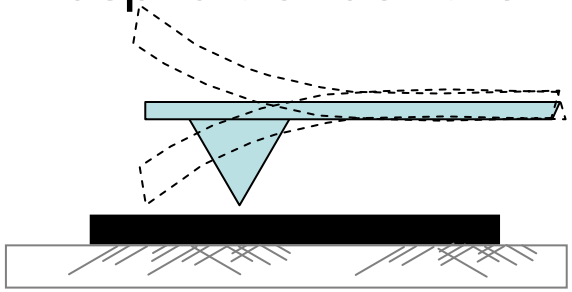
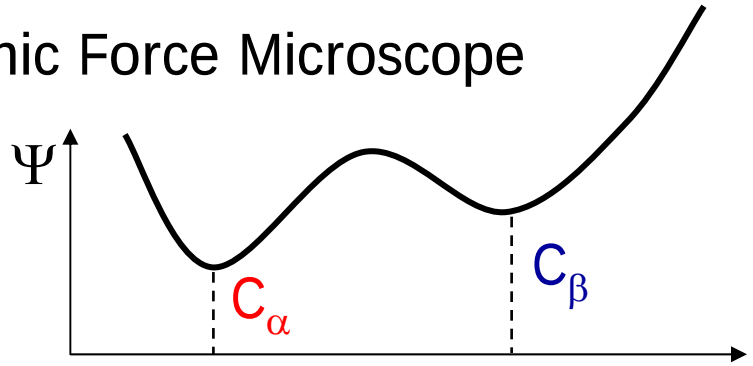
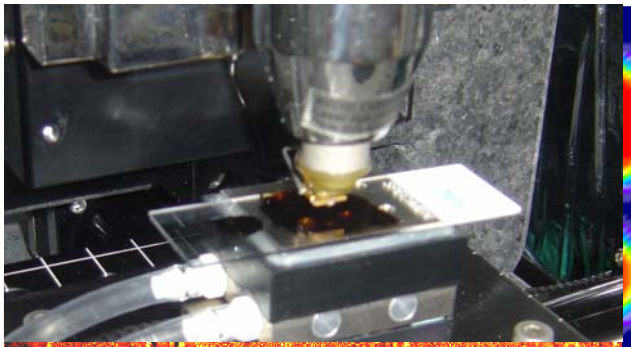
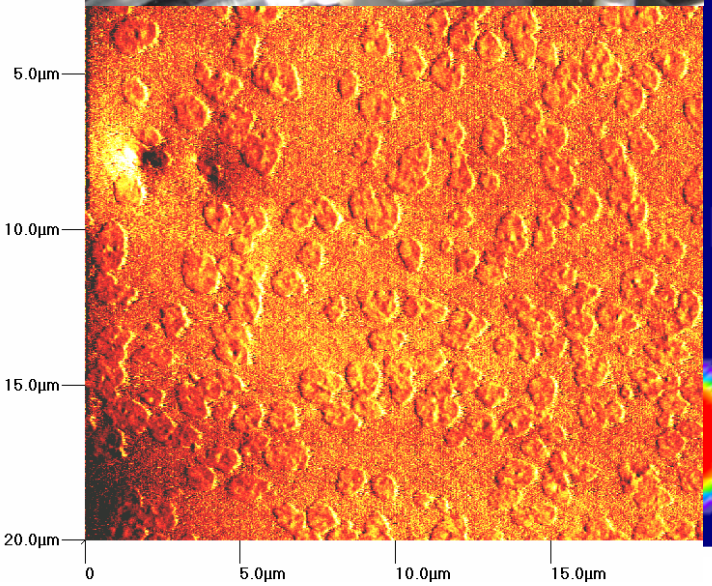
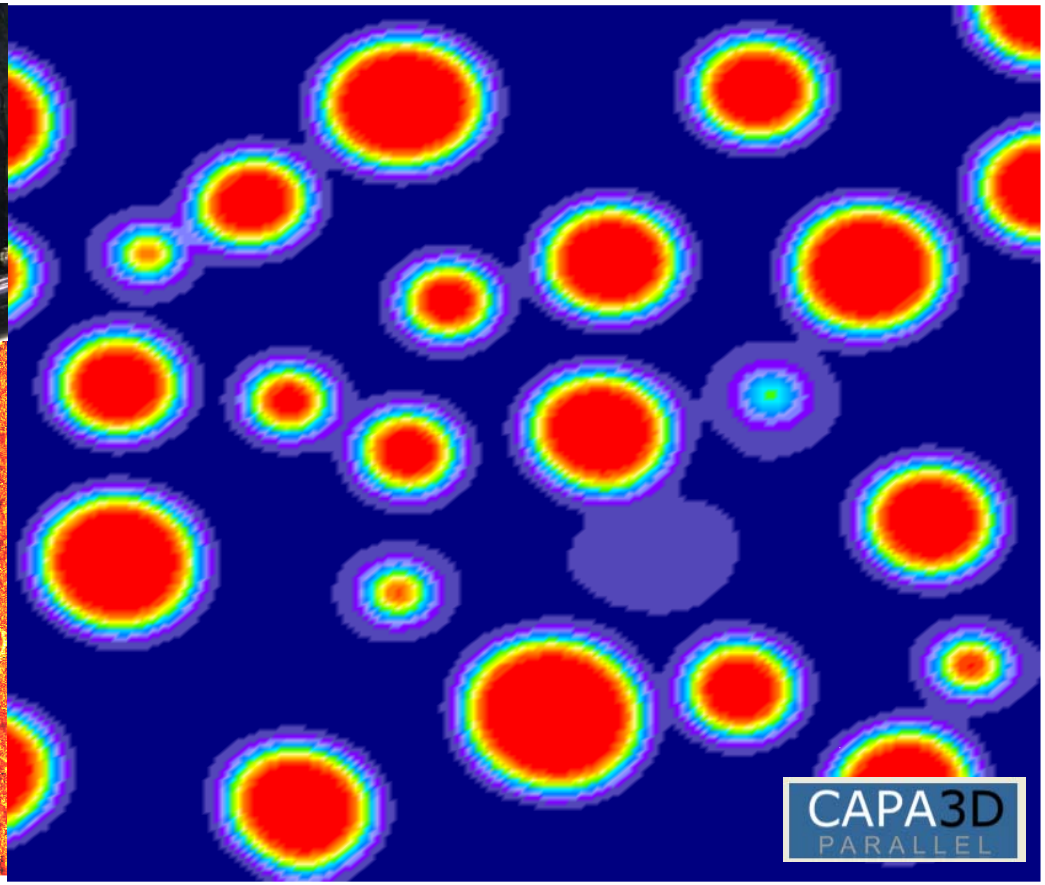


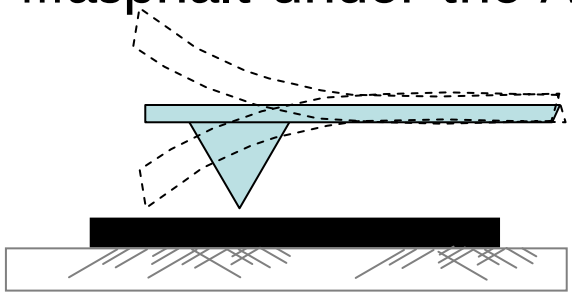


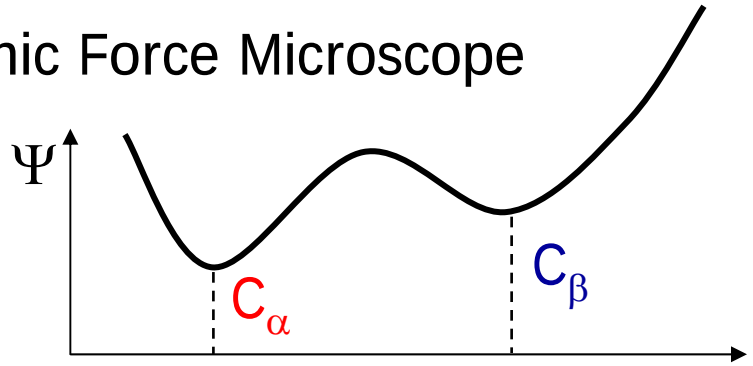


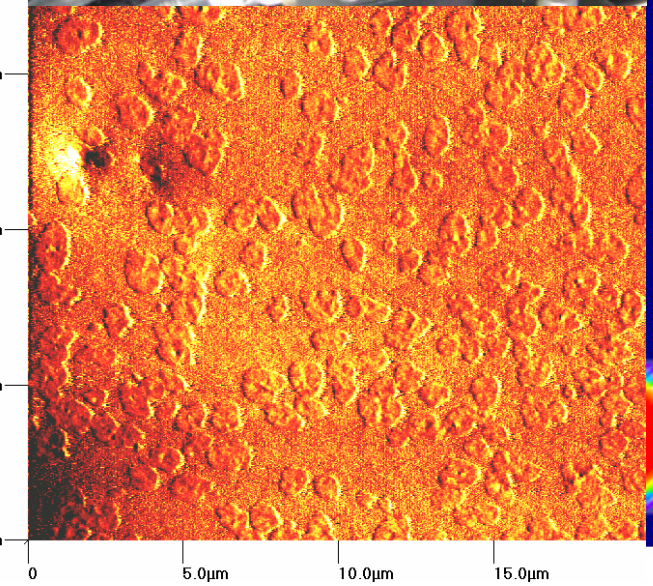


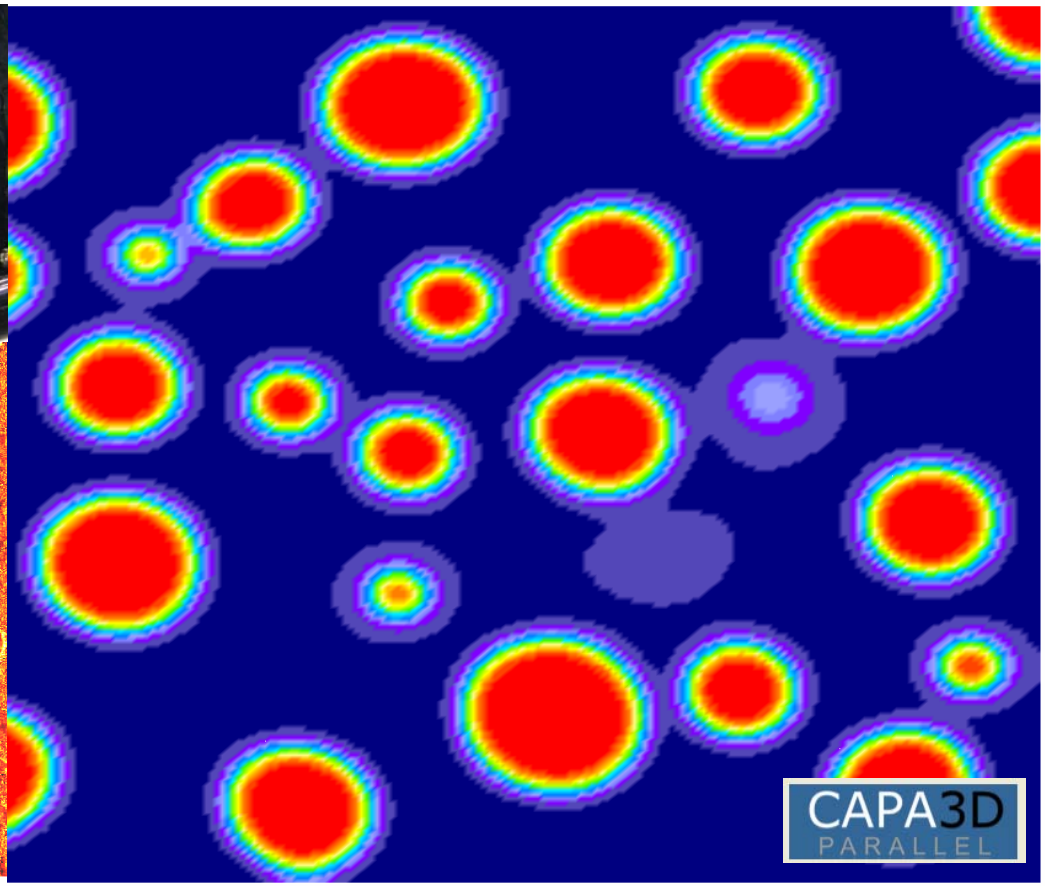


...asphalt under the Atomic Force Microscope









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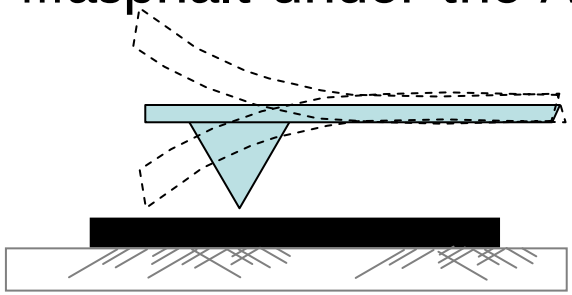

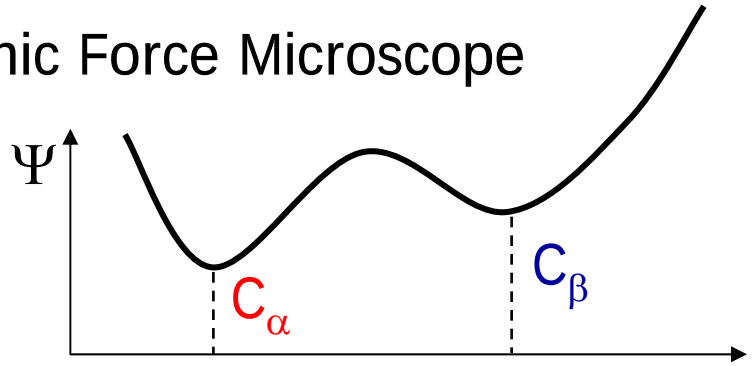

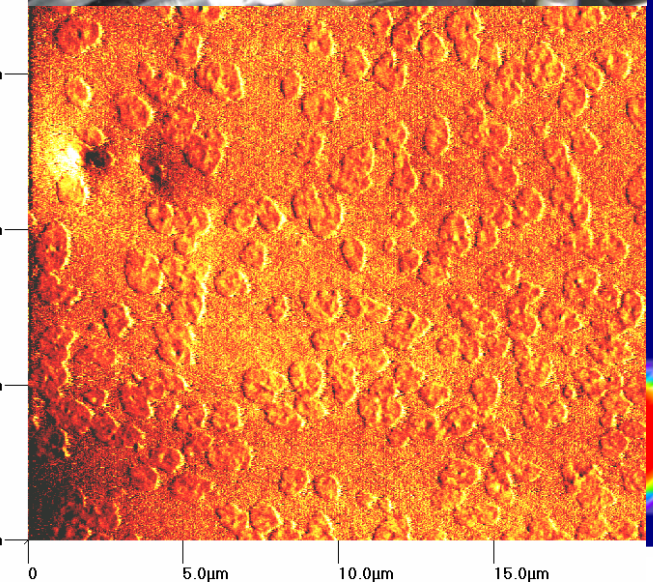

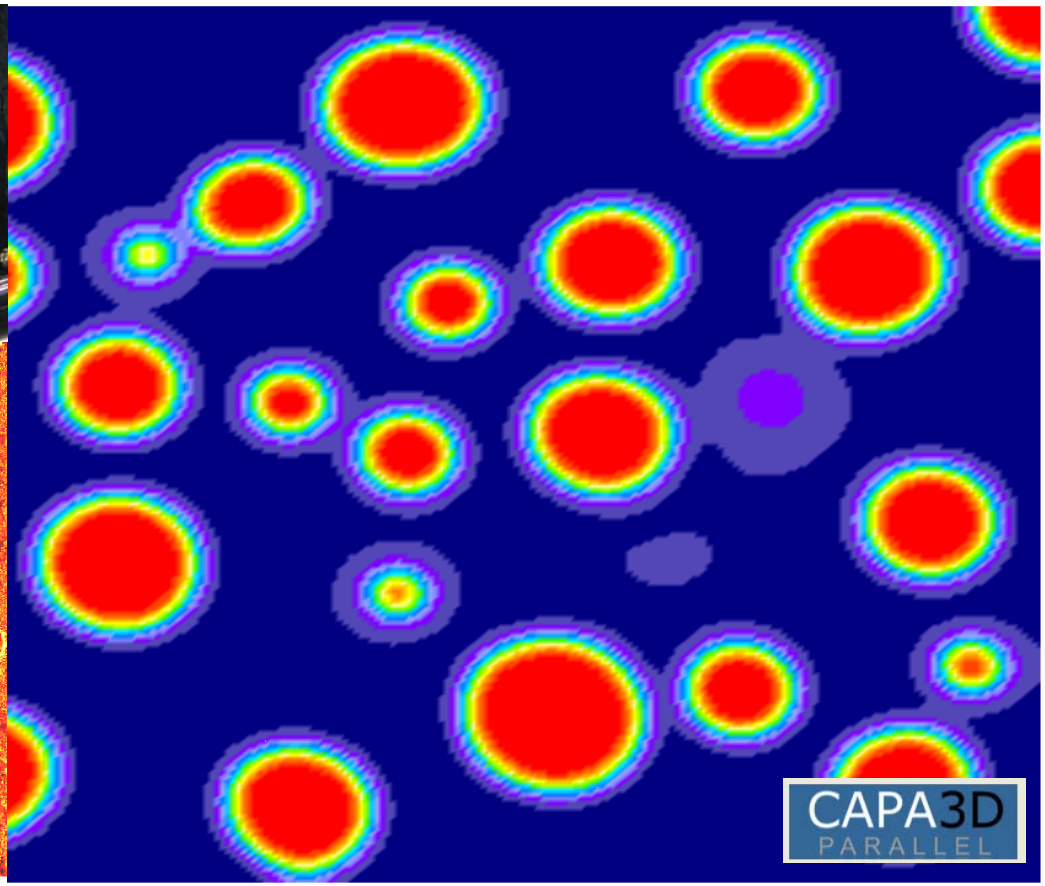

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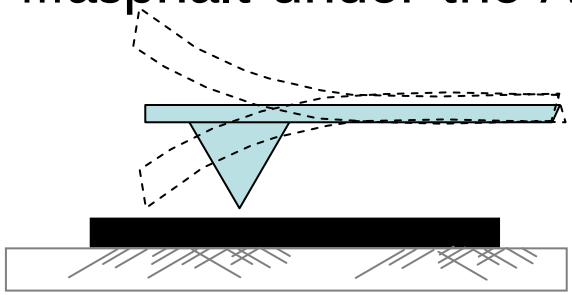

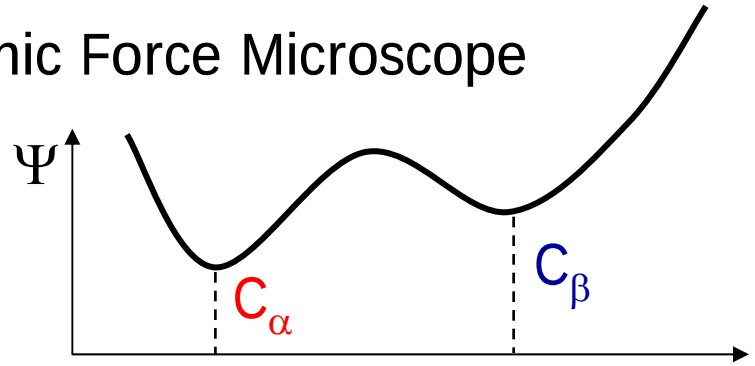

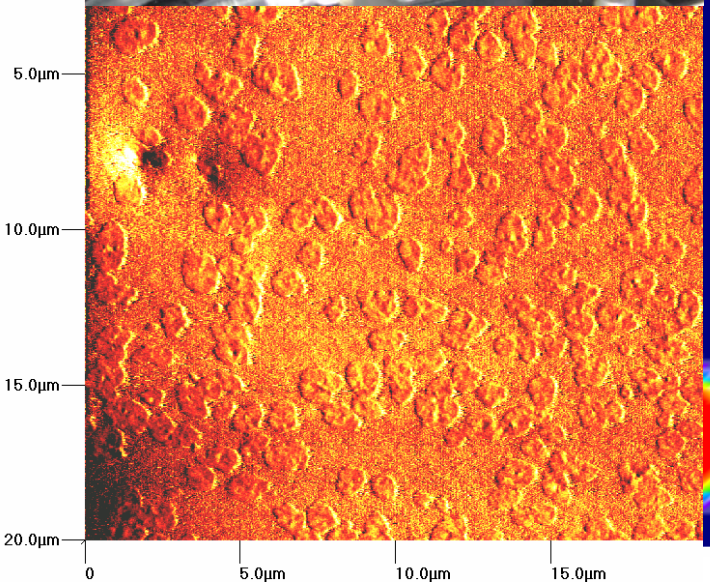

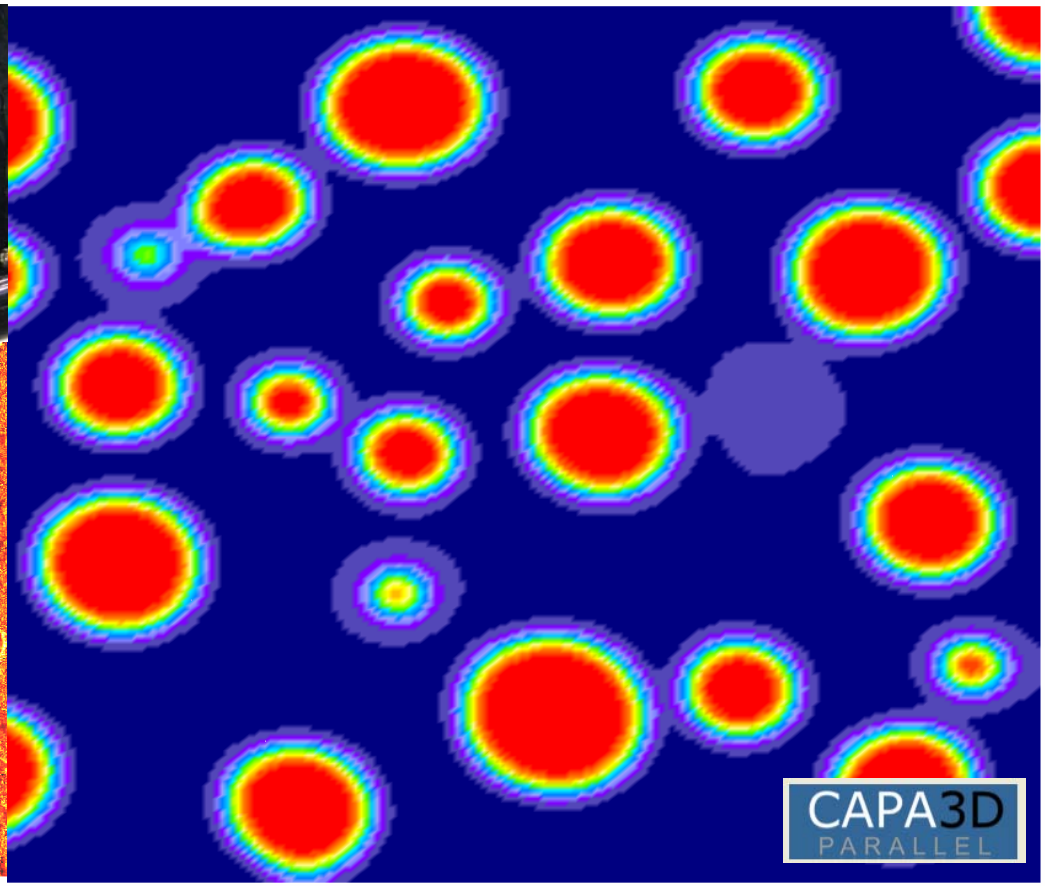

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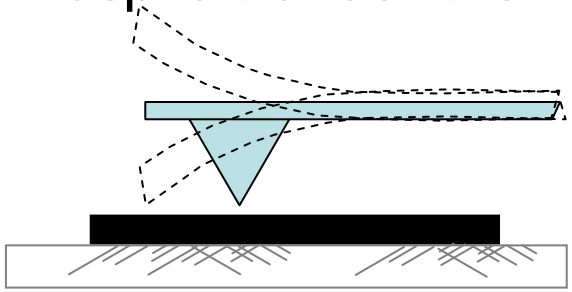

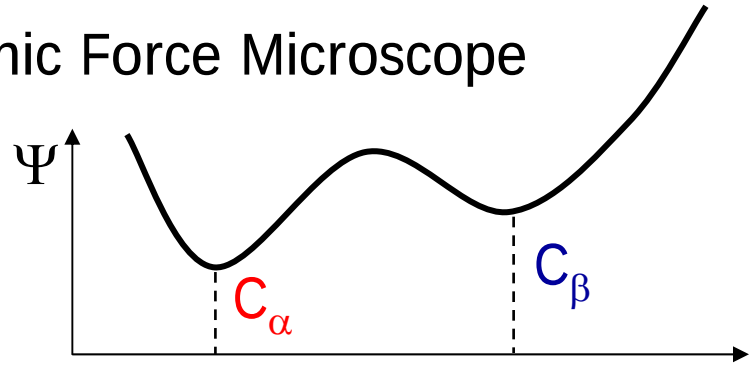

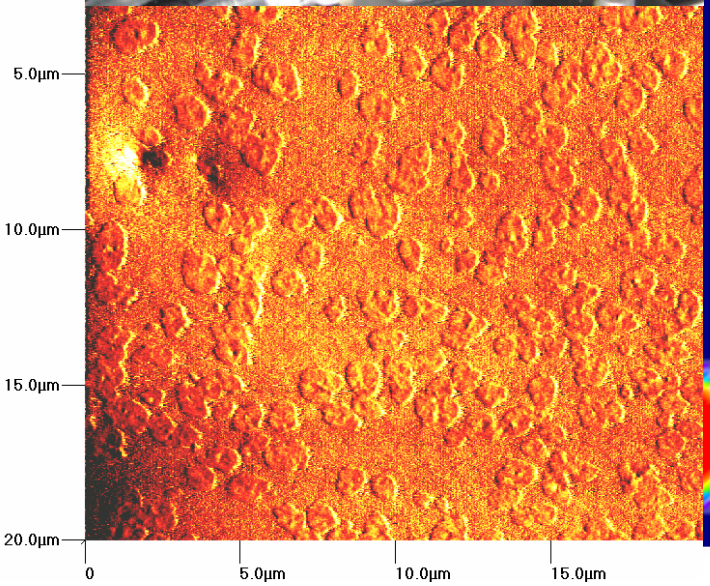

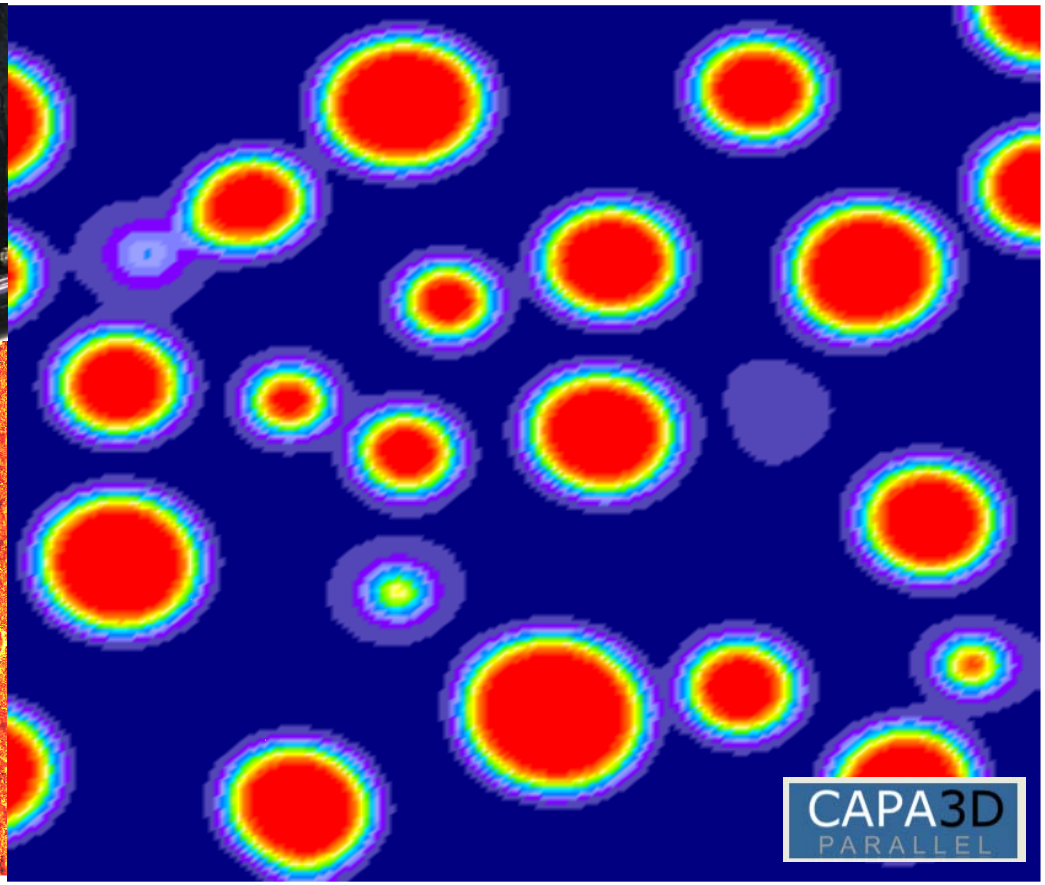

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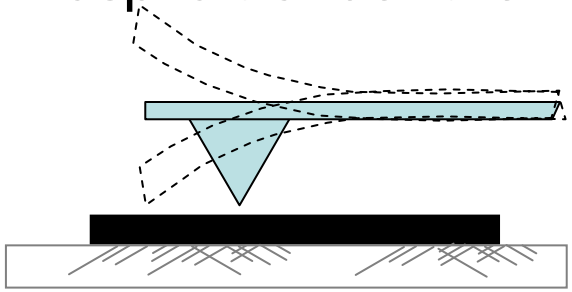

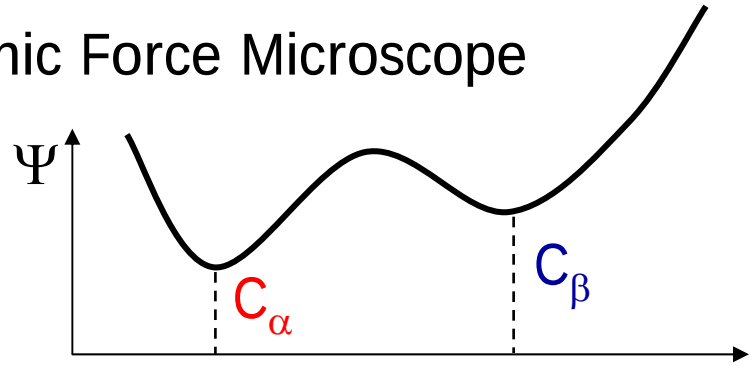

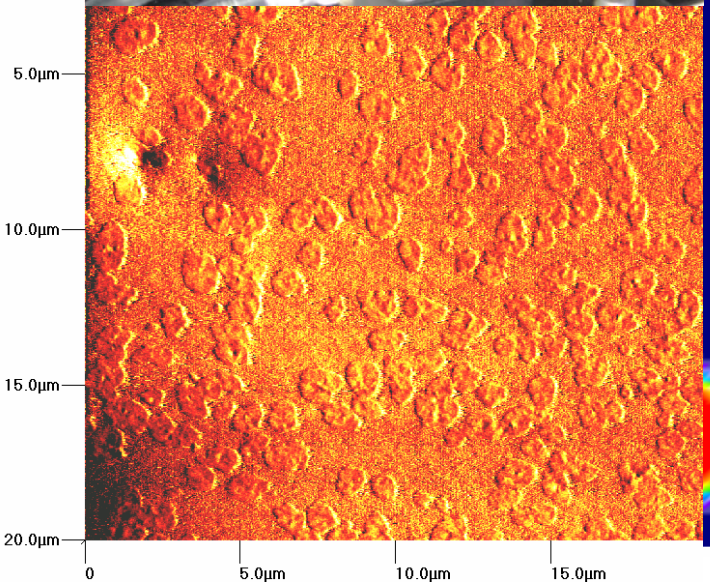

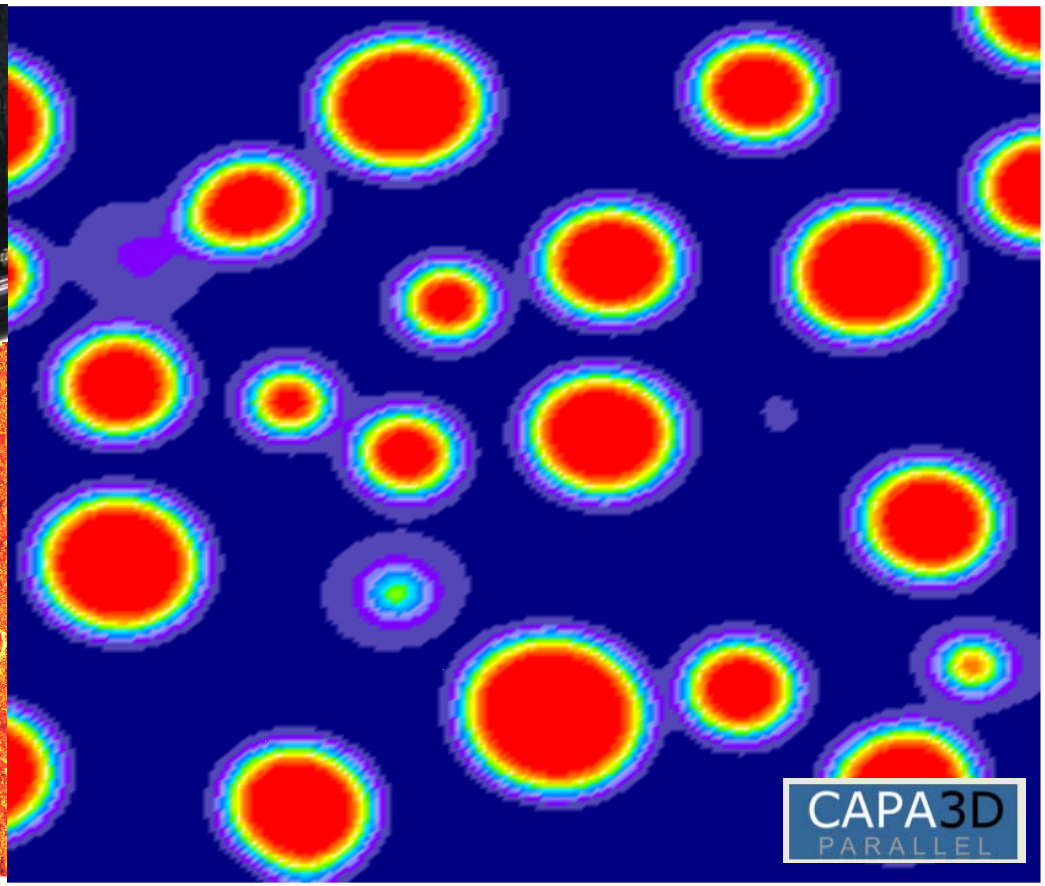

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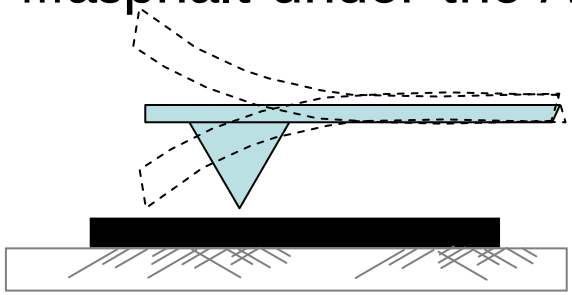

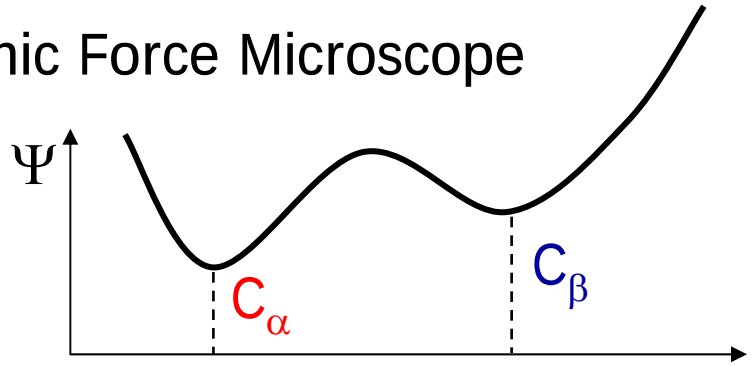

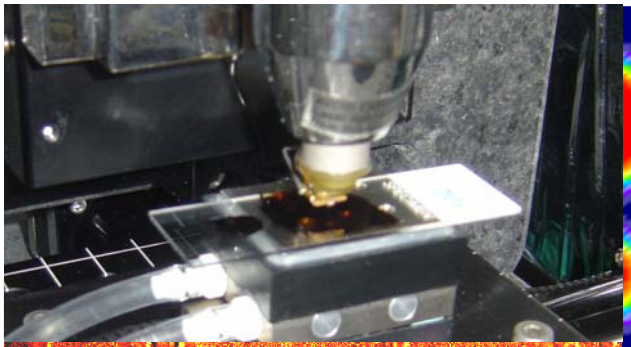

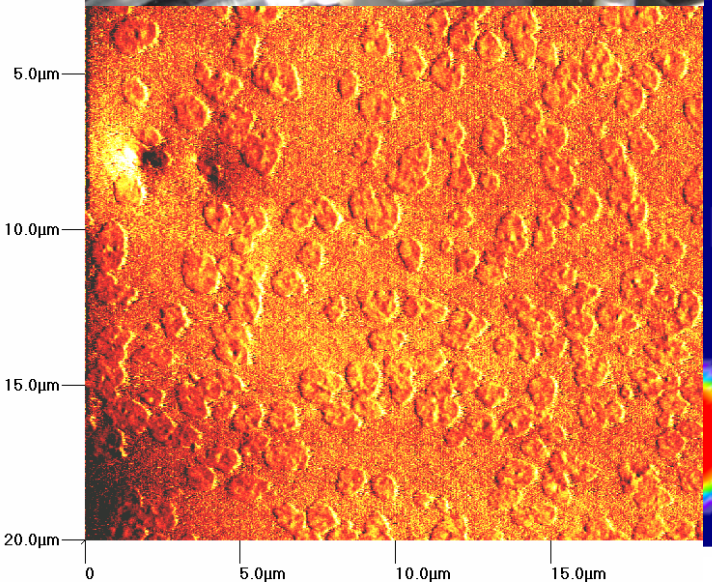

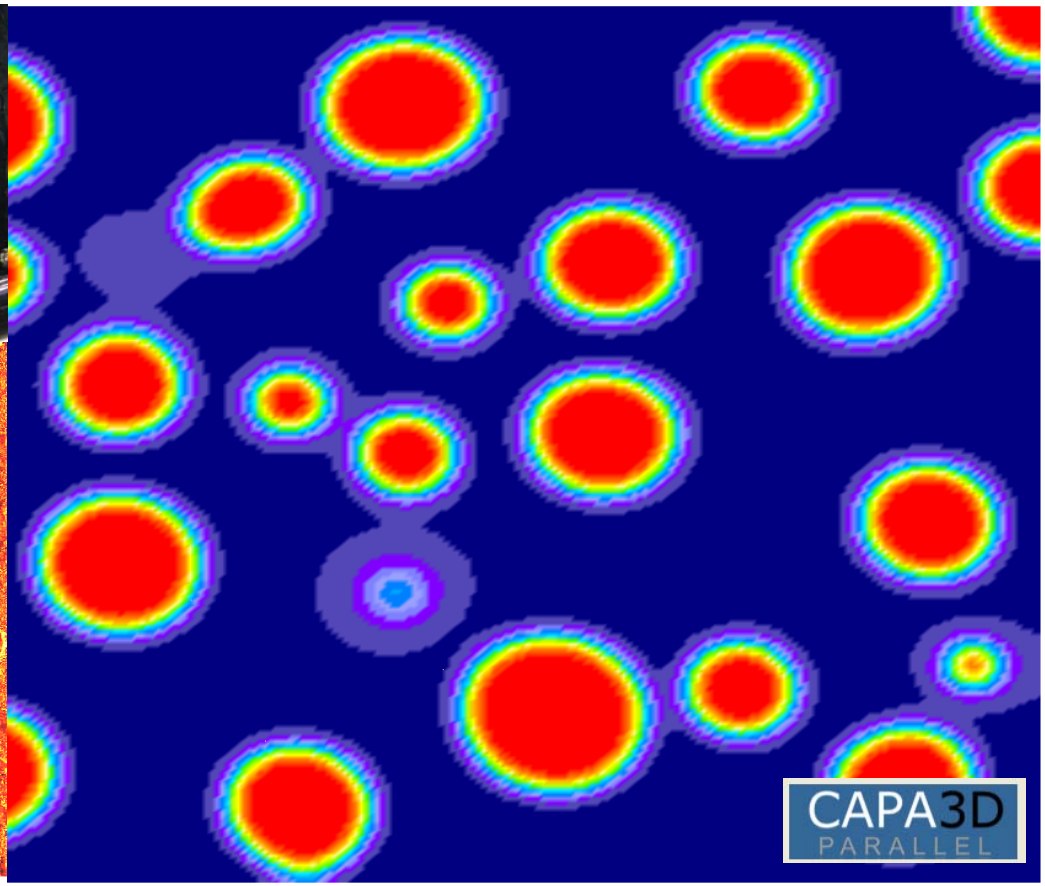

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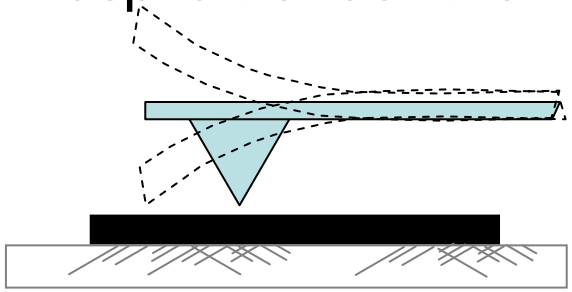

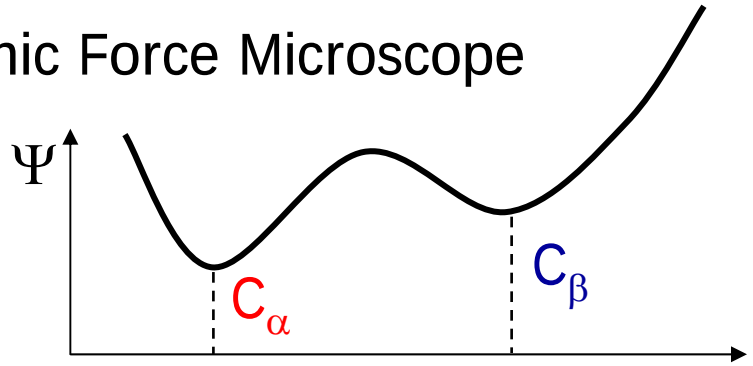

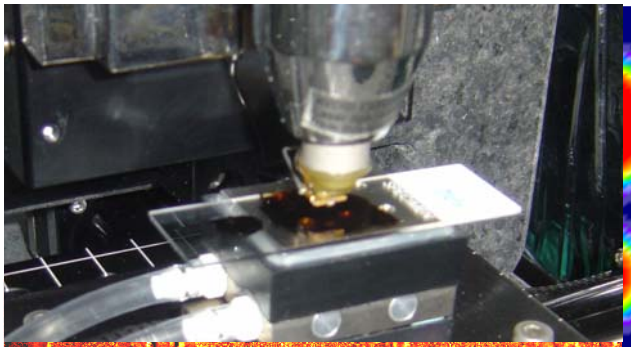

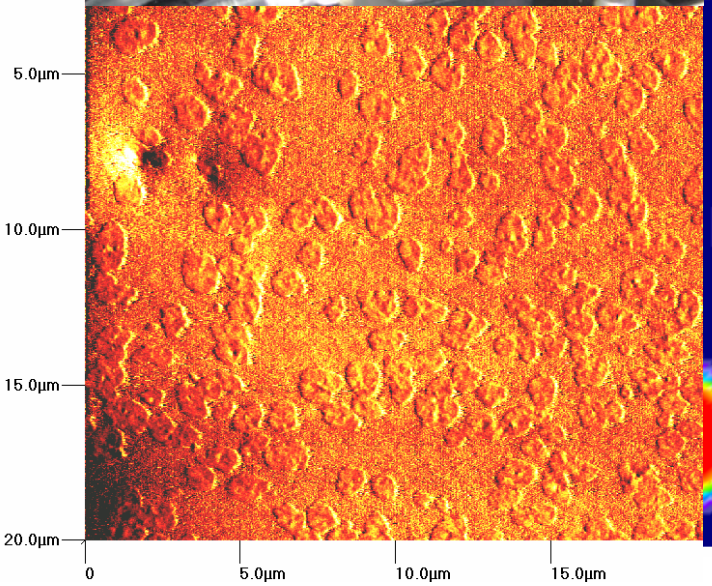

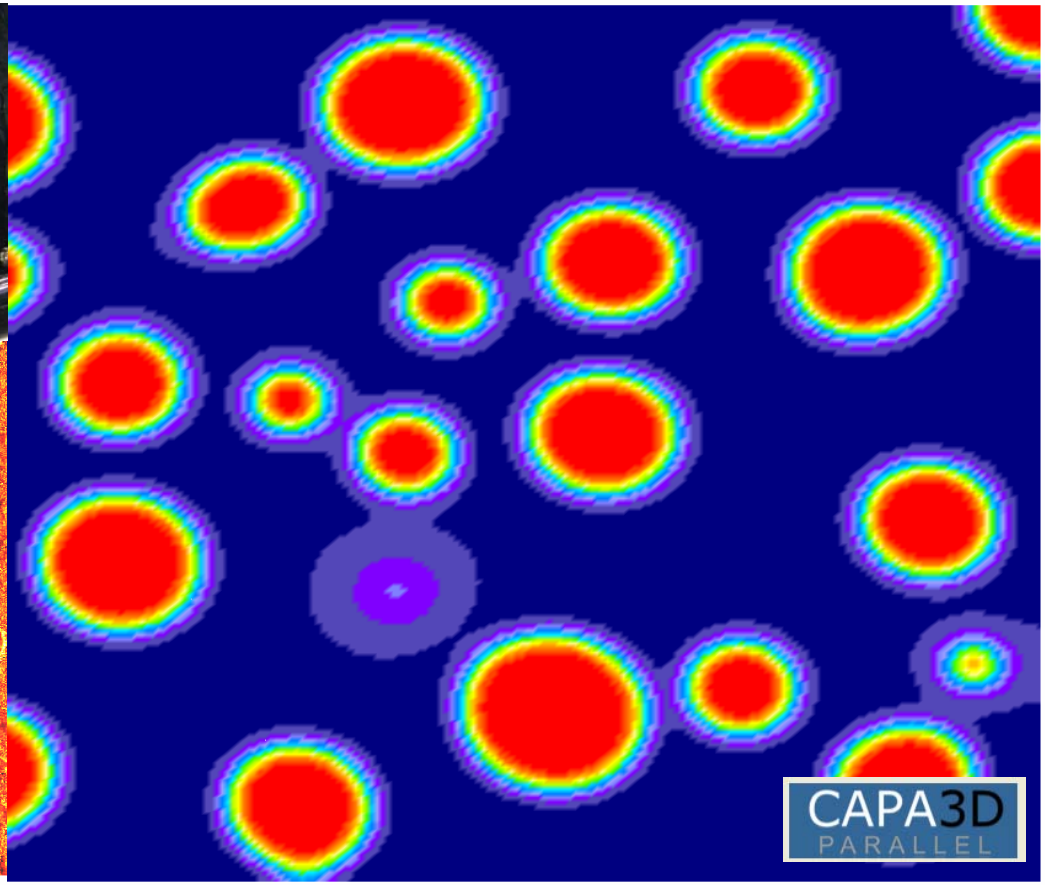

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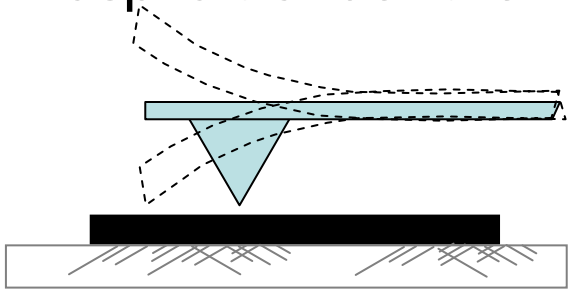
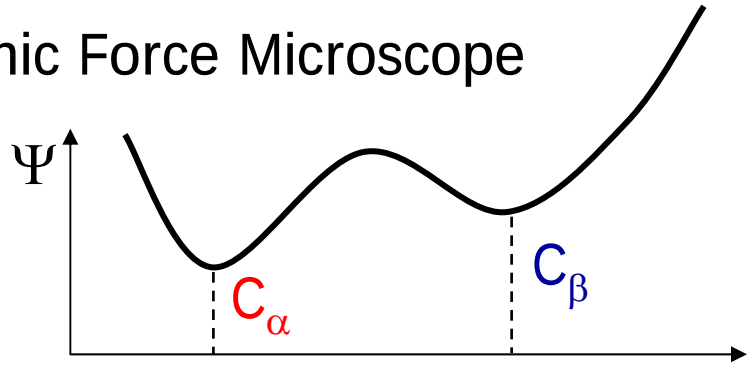
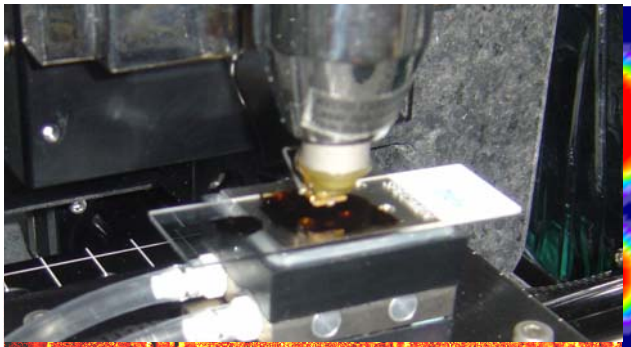
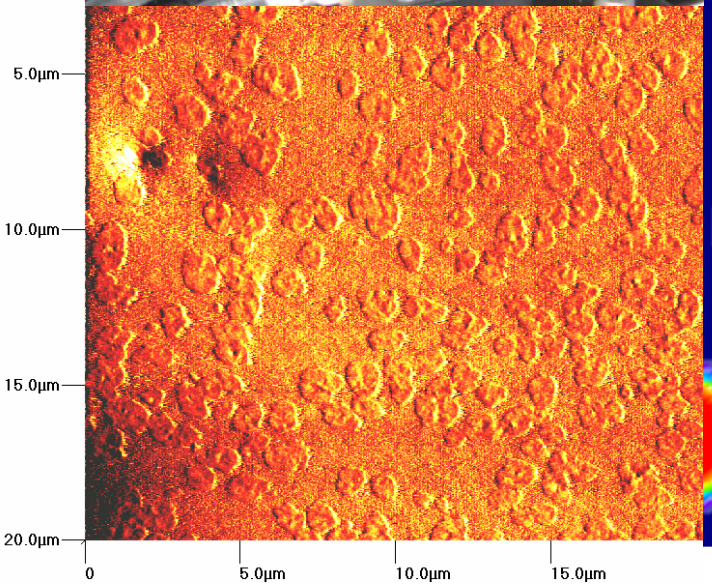
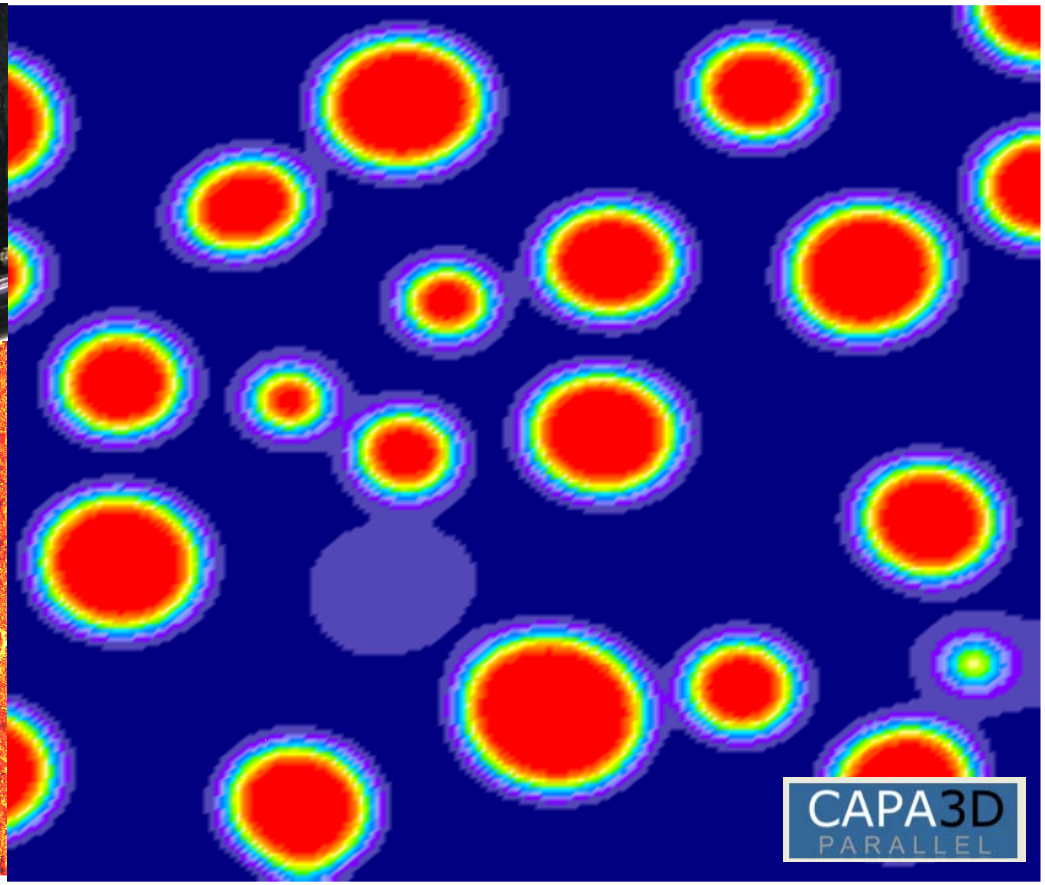


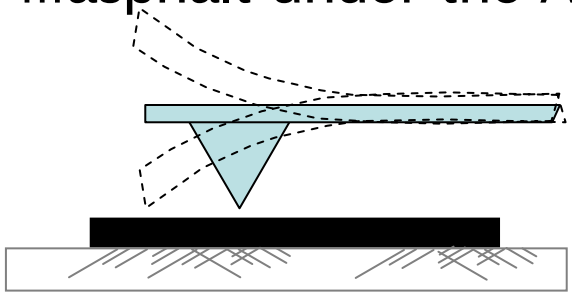


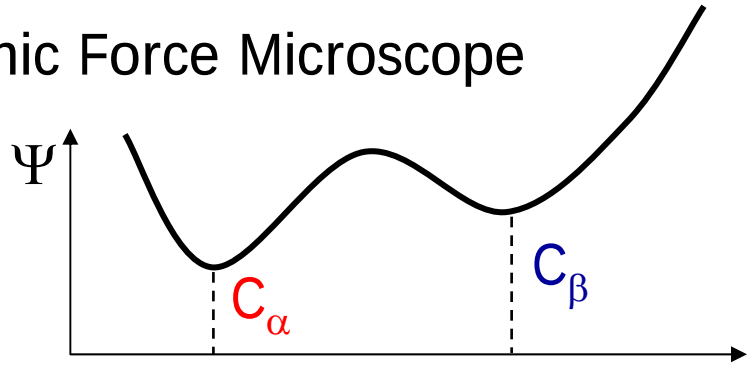


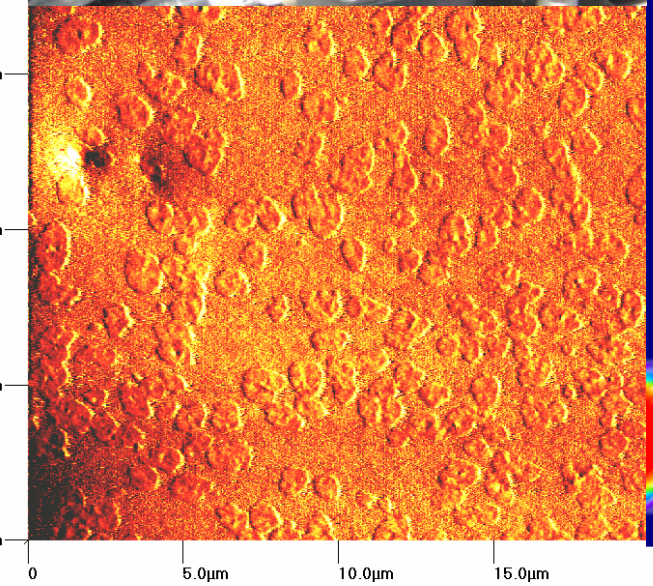


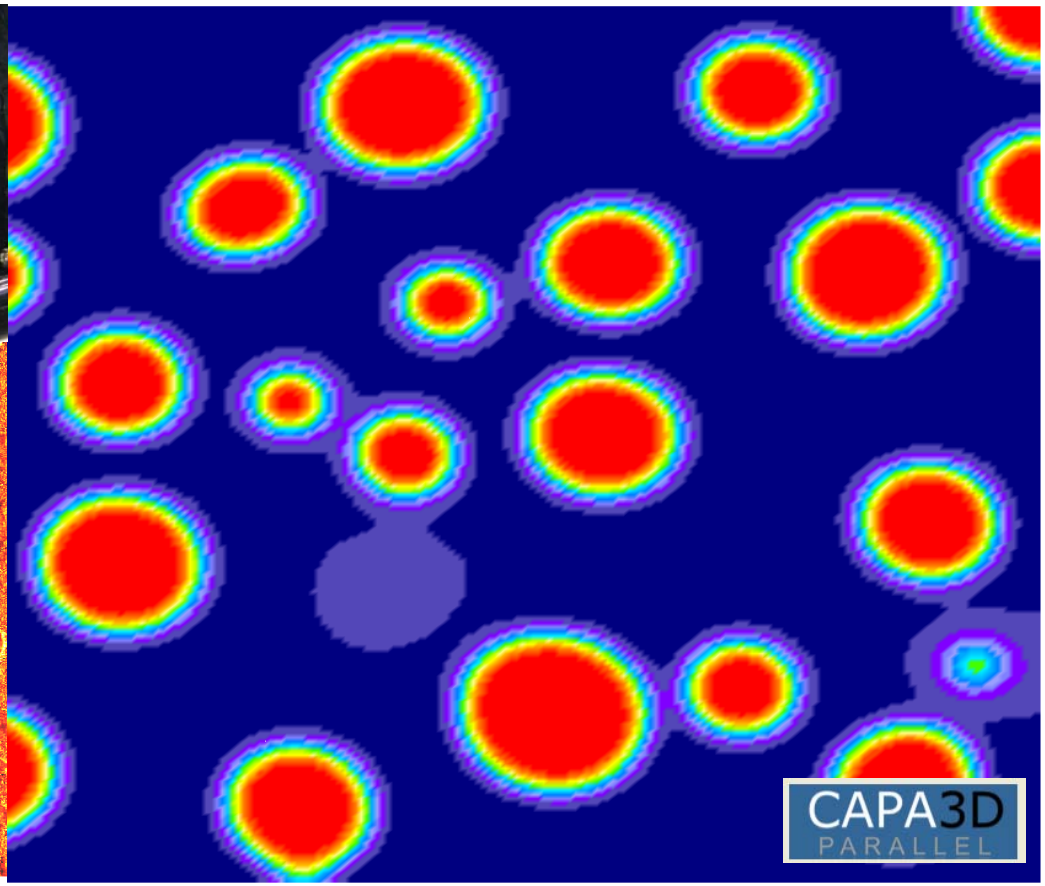


...asphalt under the Atomic Force Microscope









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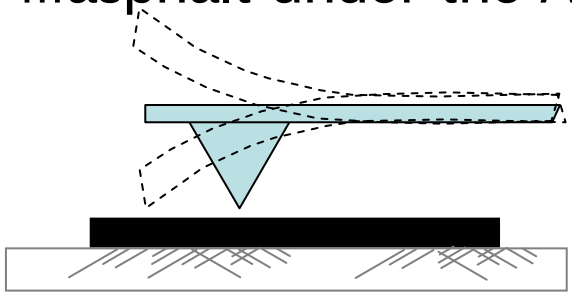

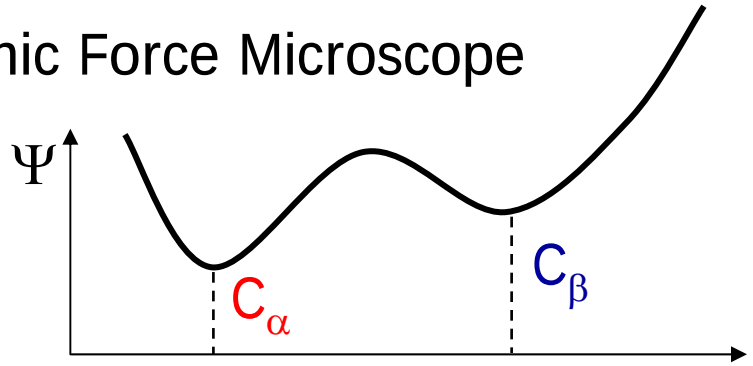

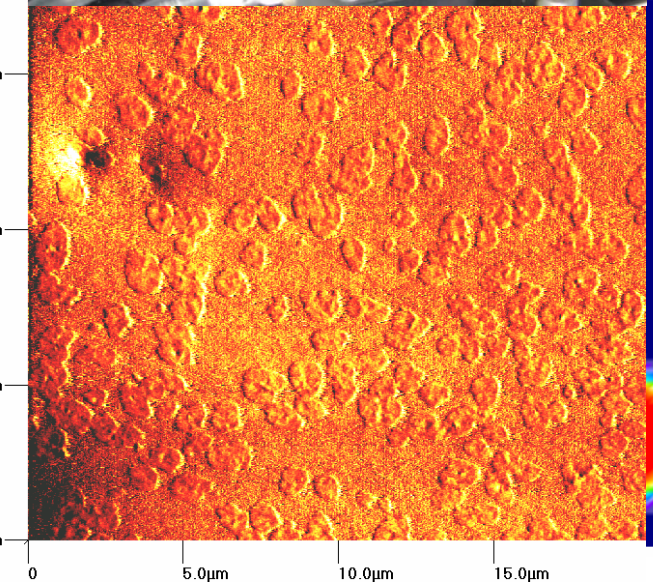

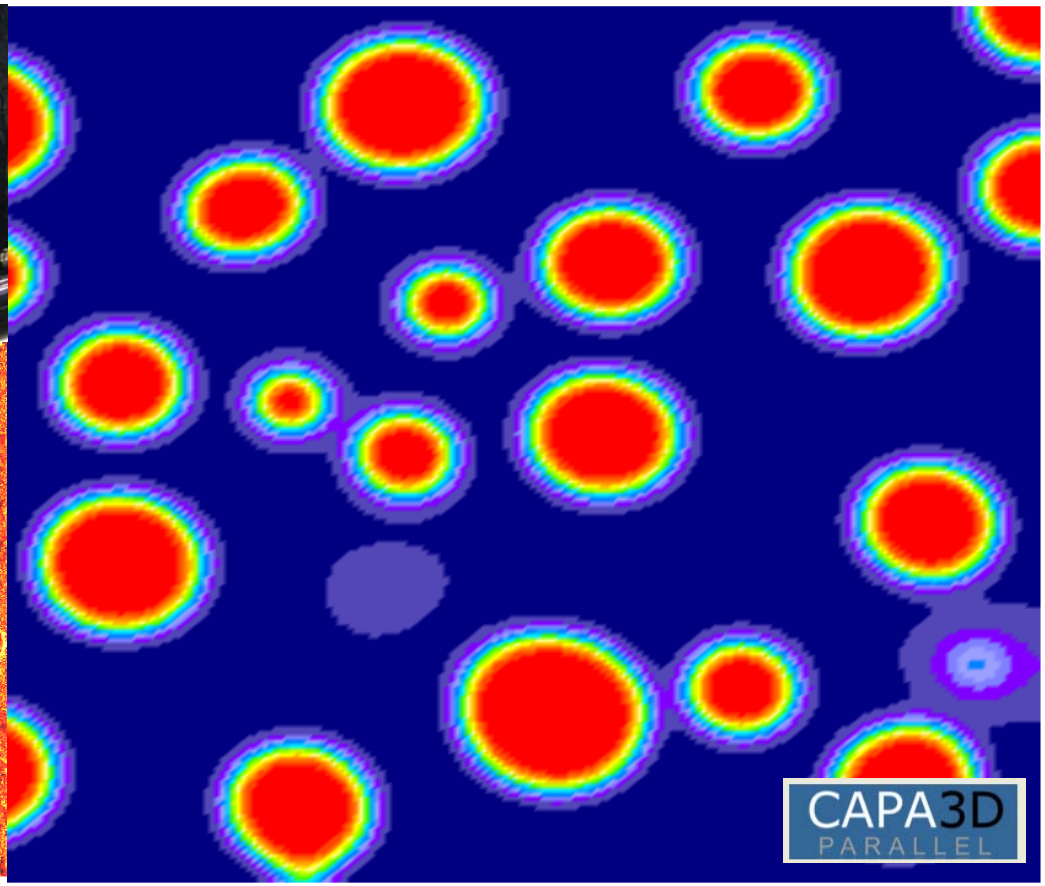

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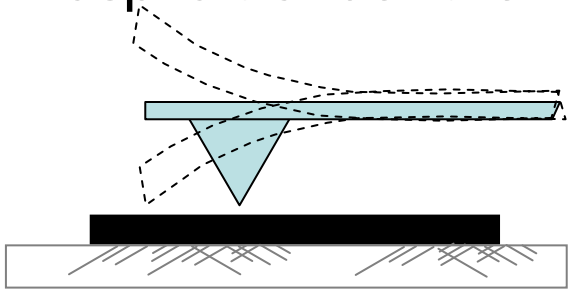

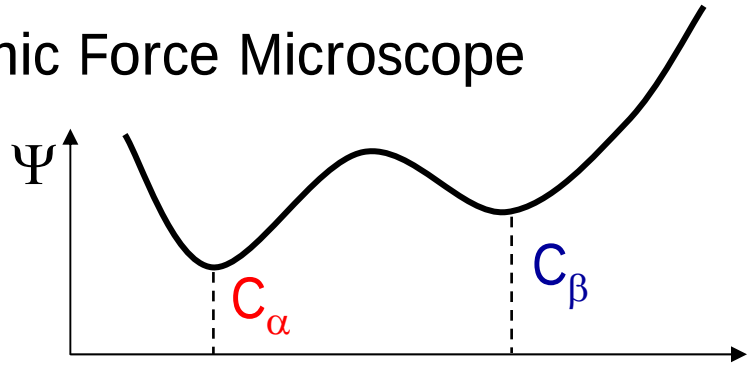

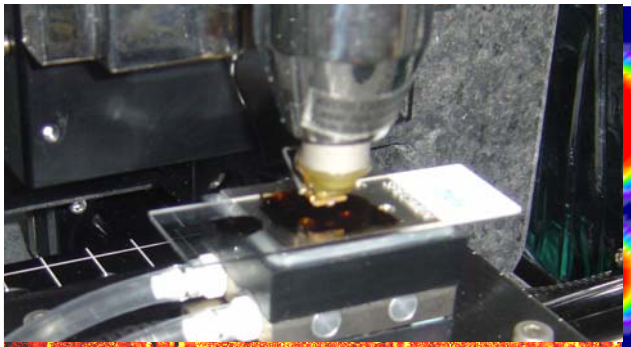

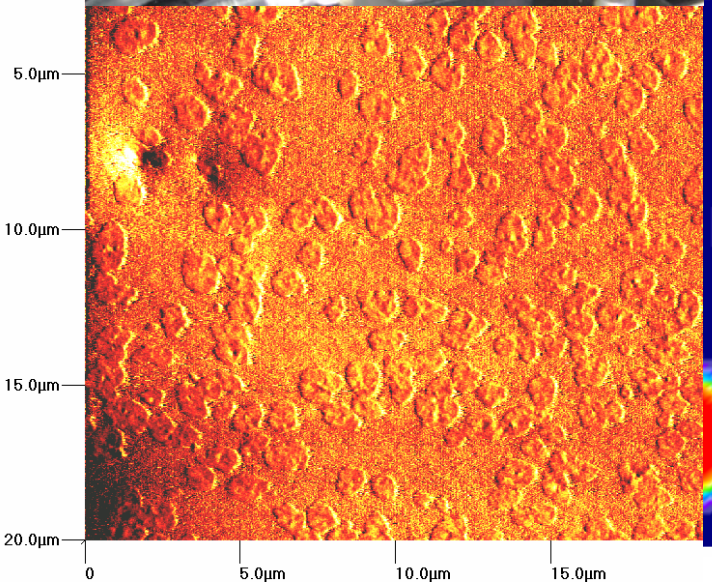

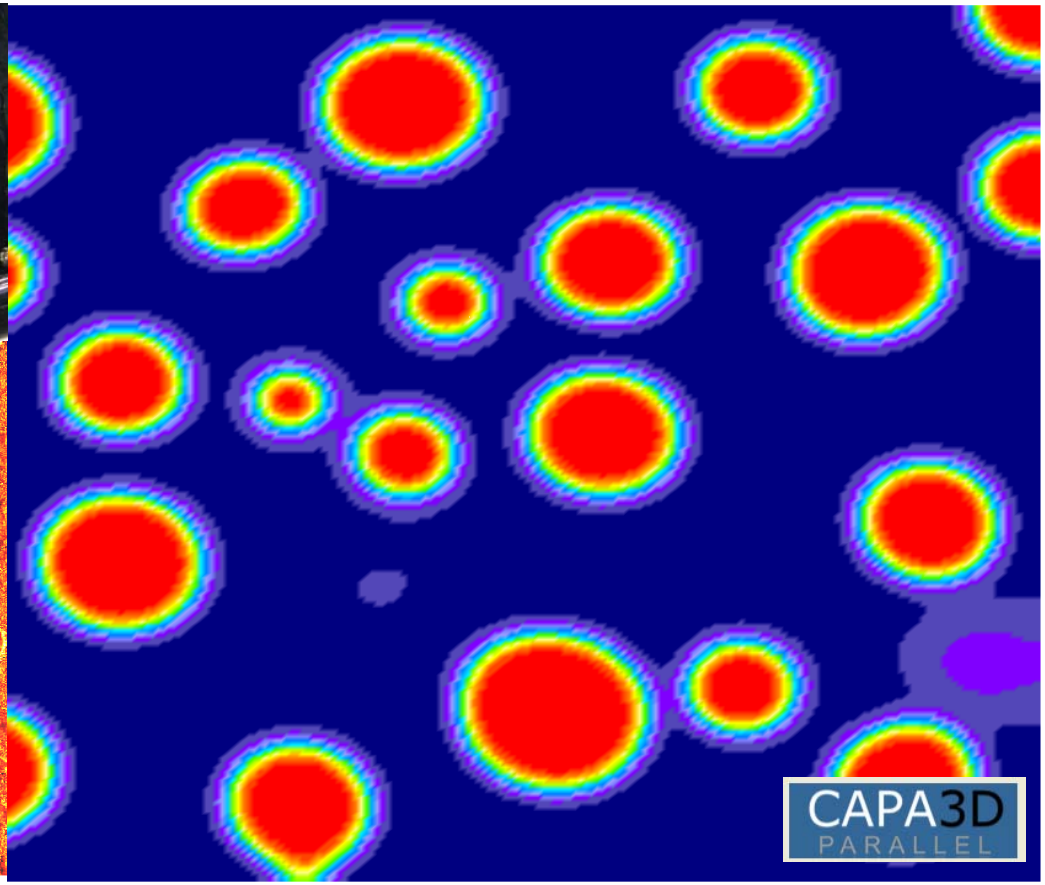

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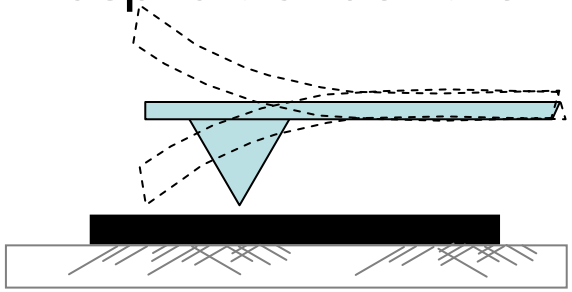
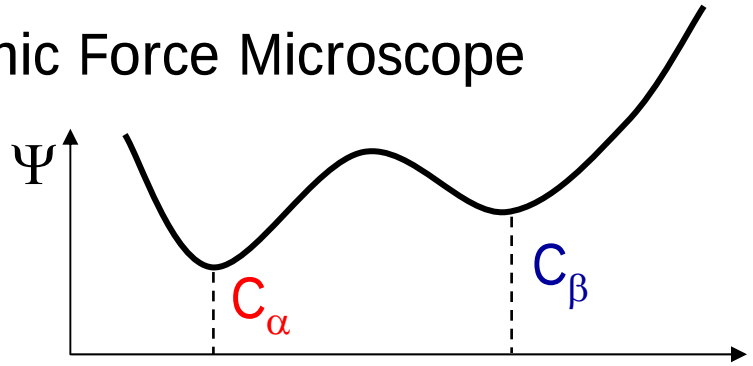
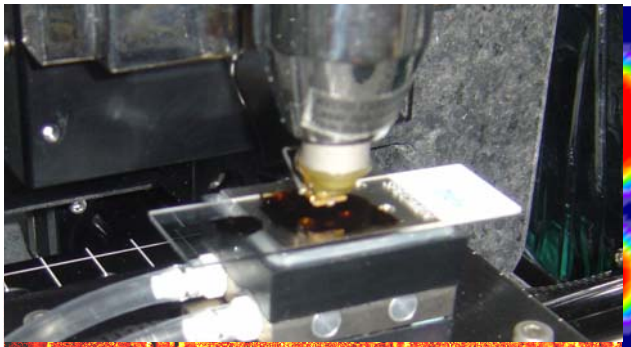
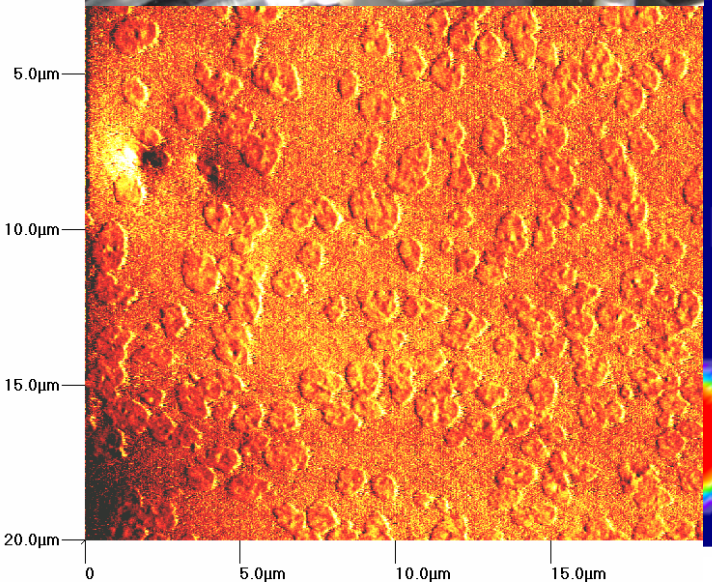
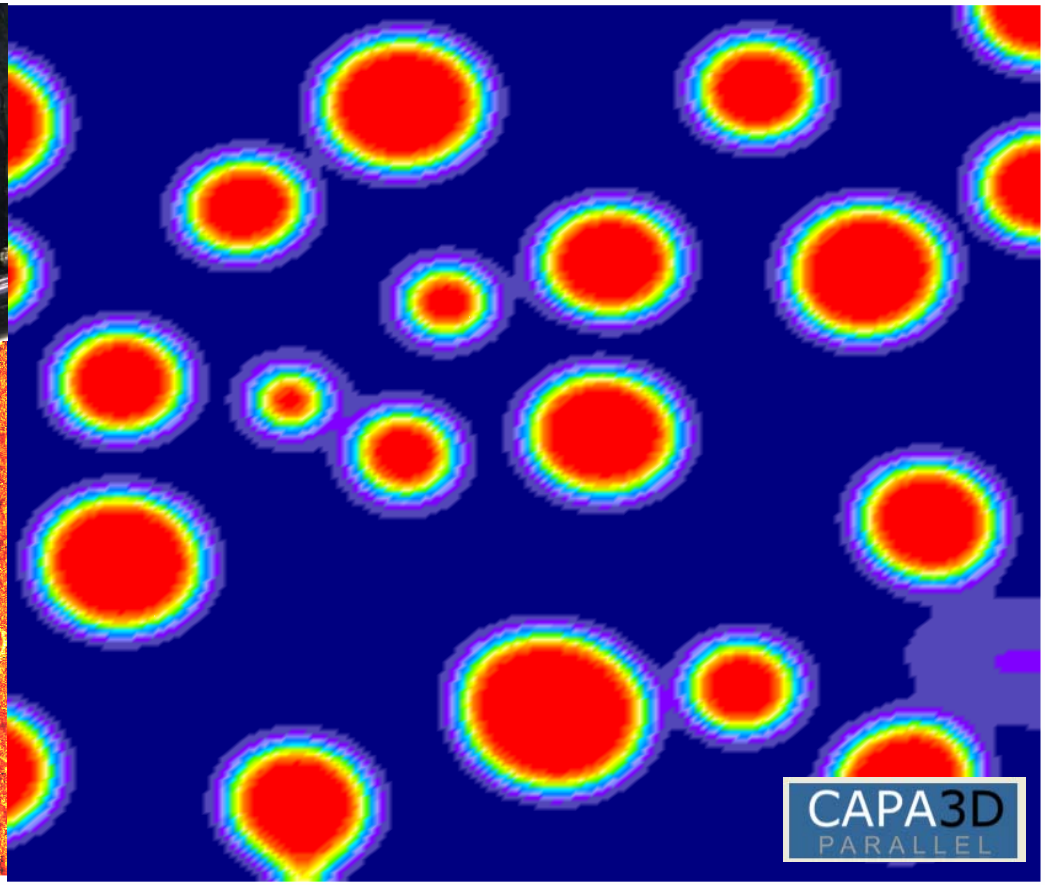


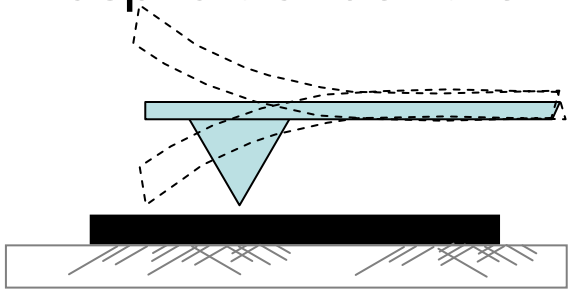


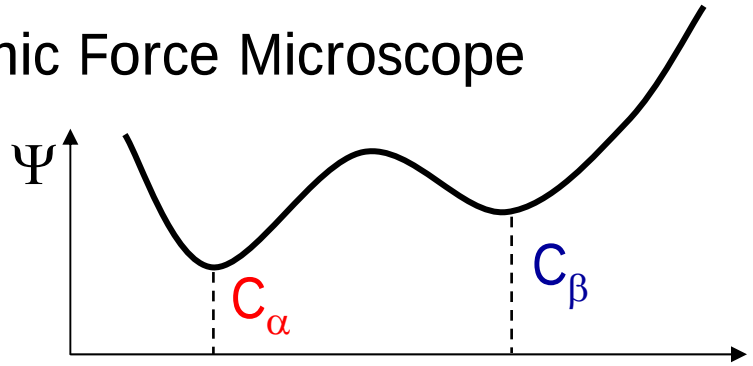


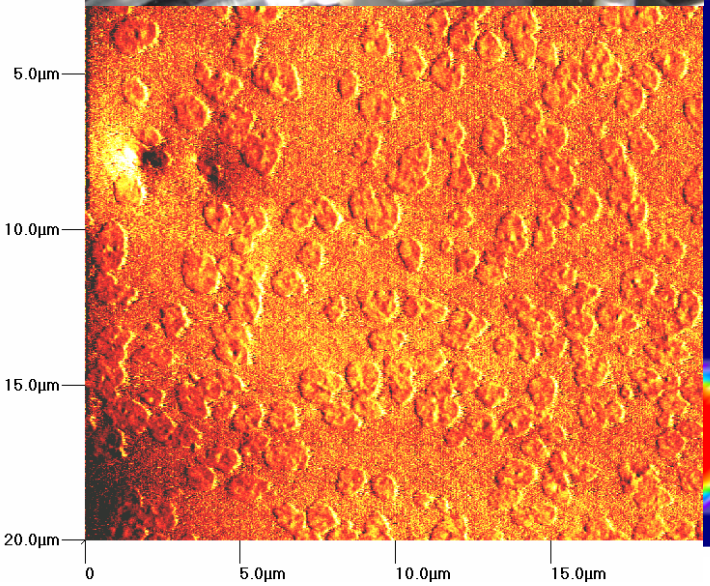


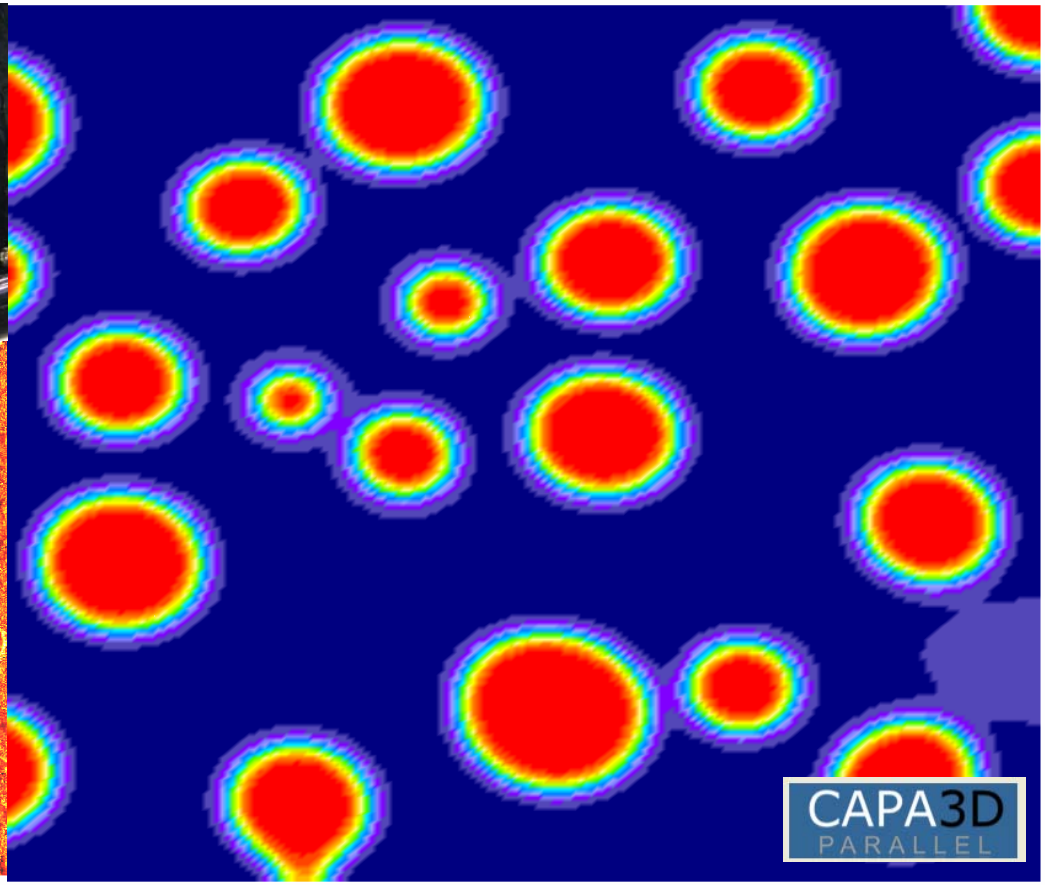


...asphalt under the Atomic Force Microscope









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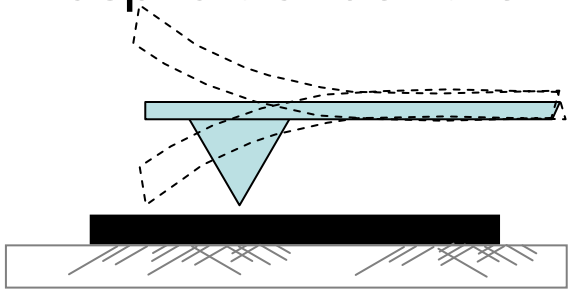

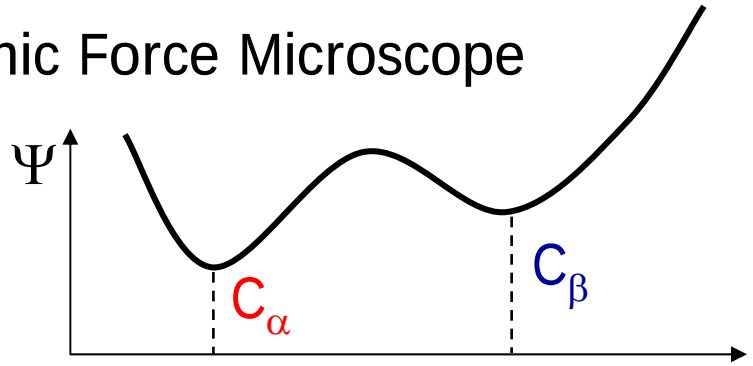

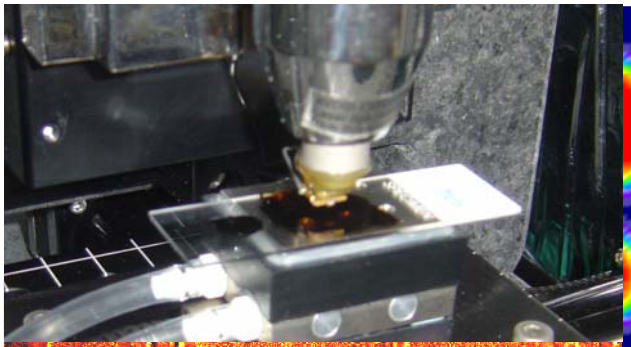

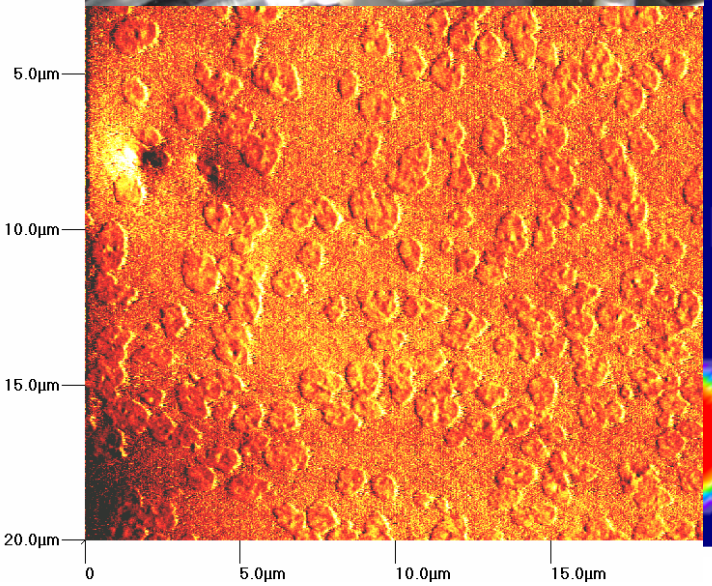

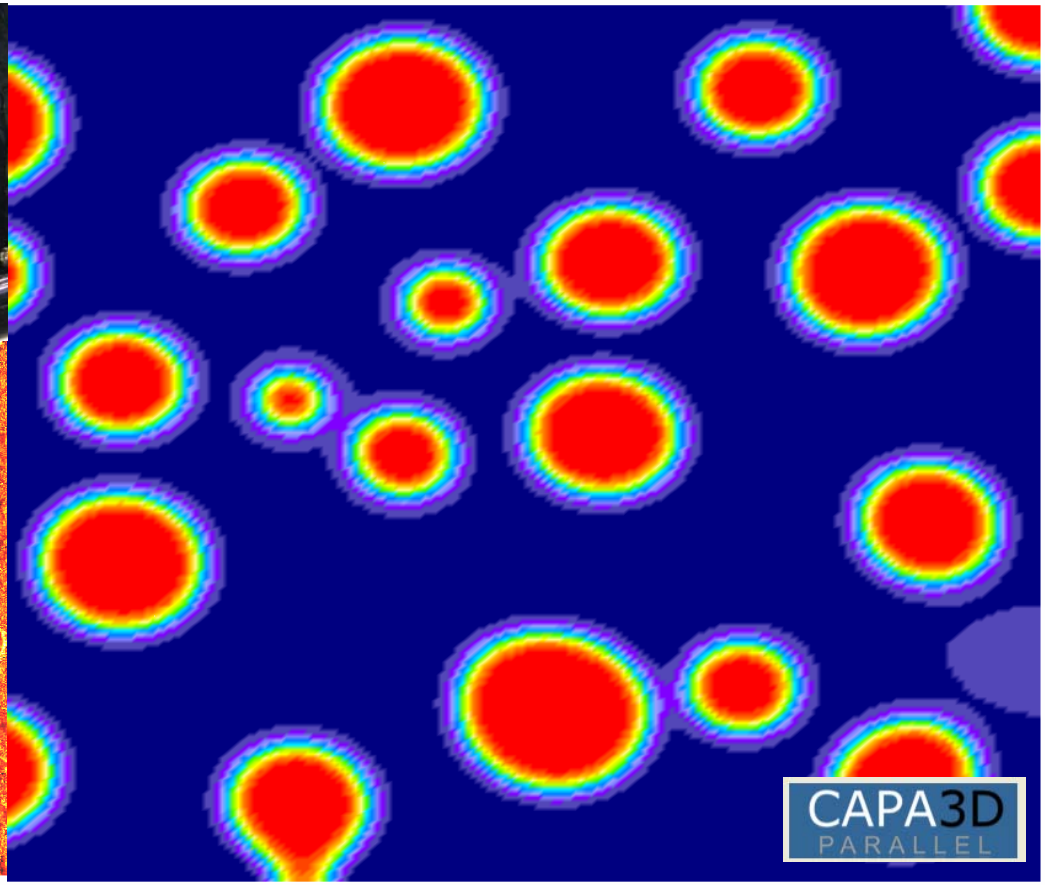

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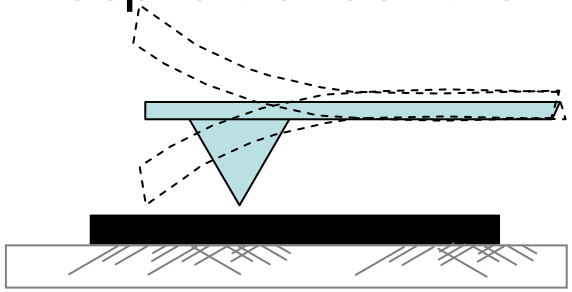
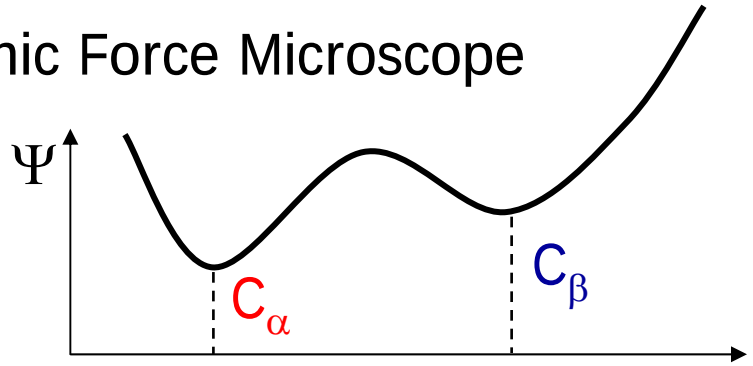
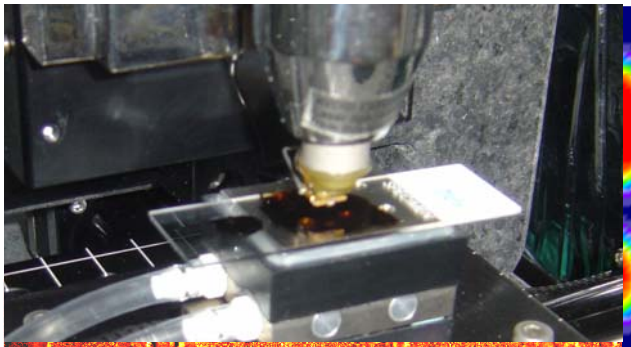
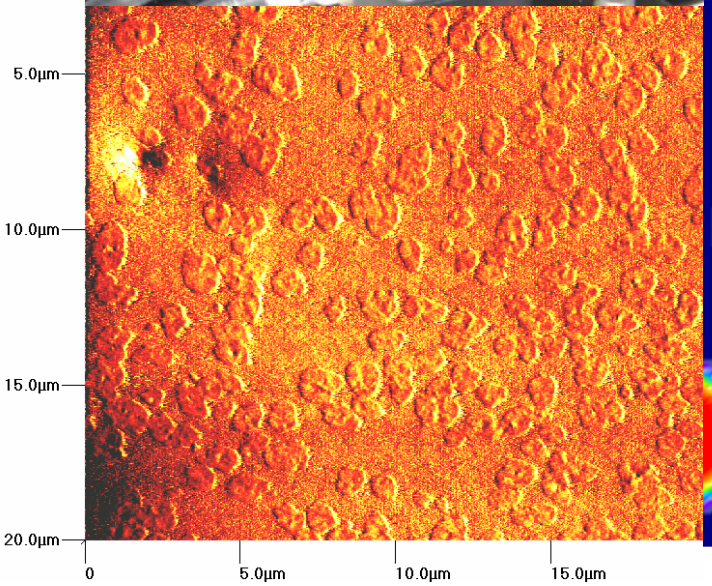
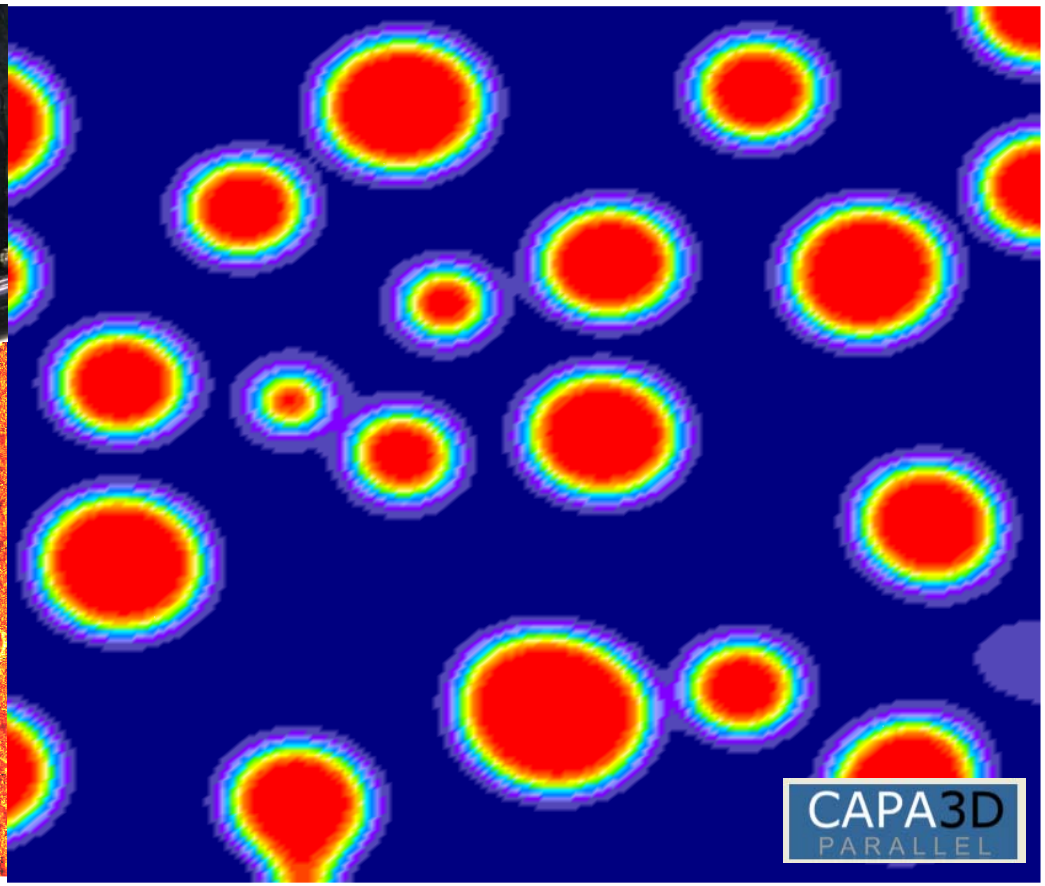


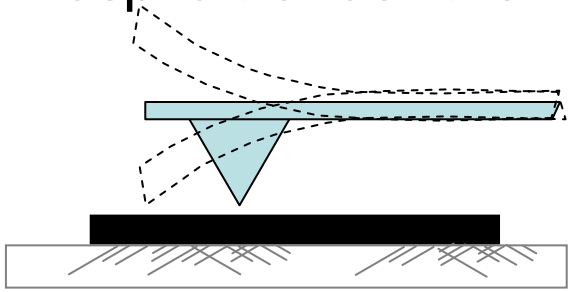


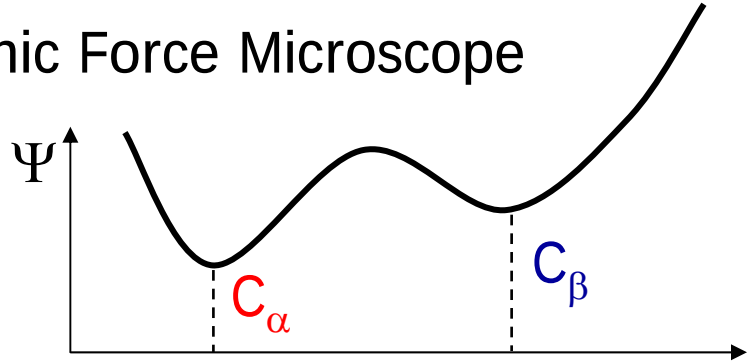


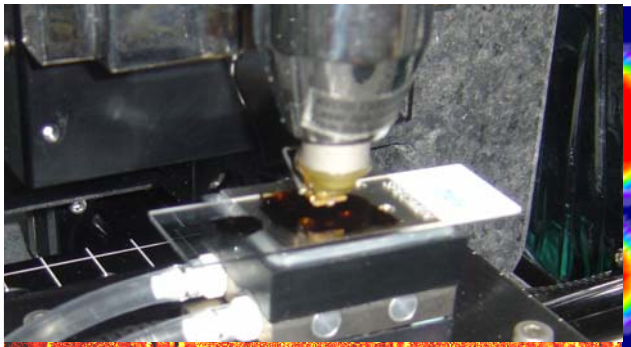


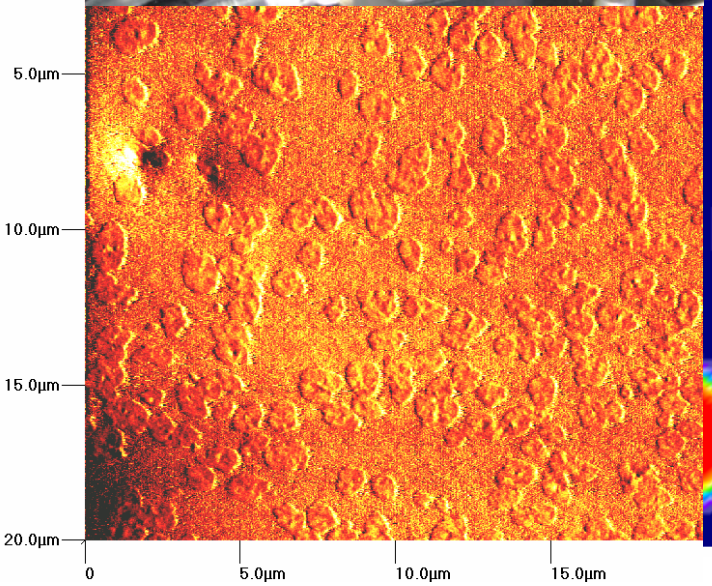


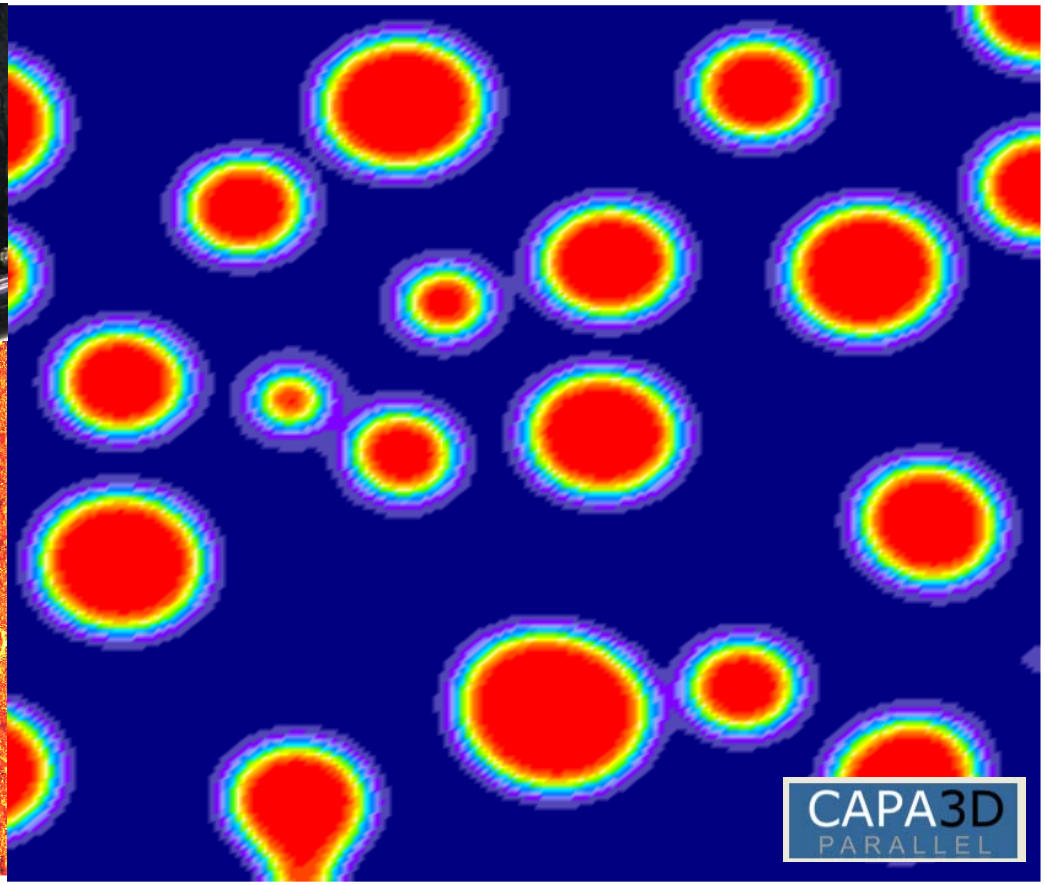
...asphalt under the Atomic Force Microscope



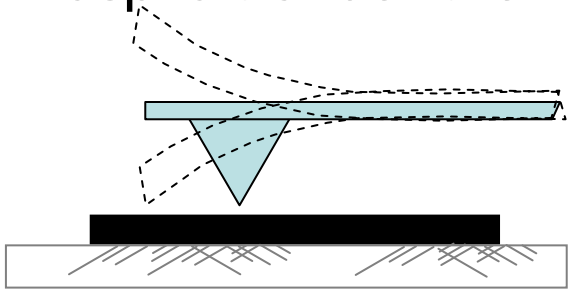


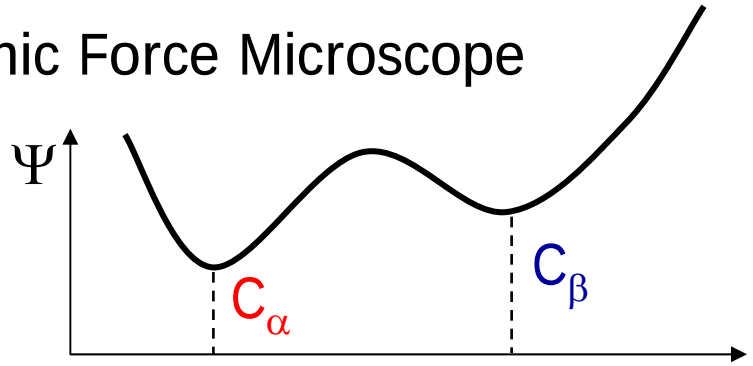


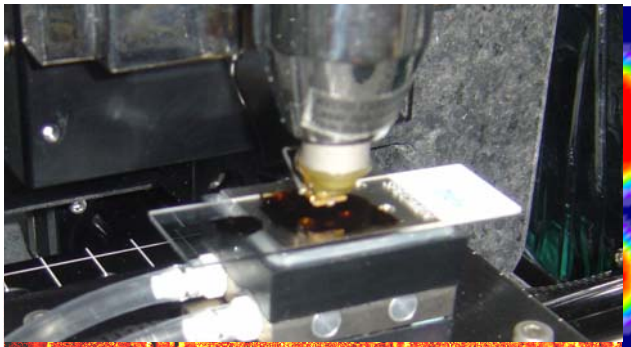


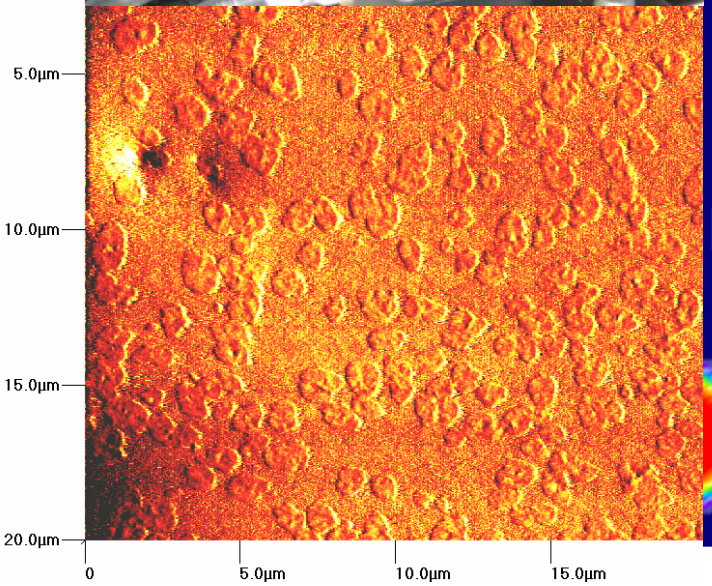


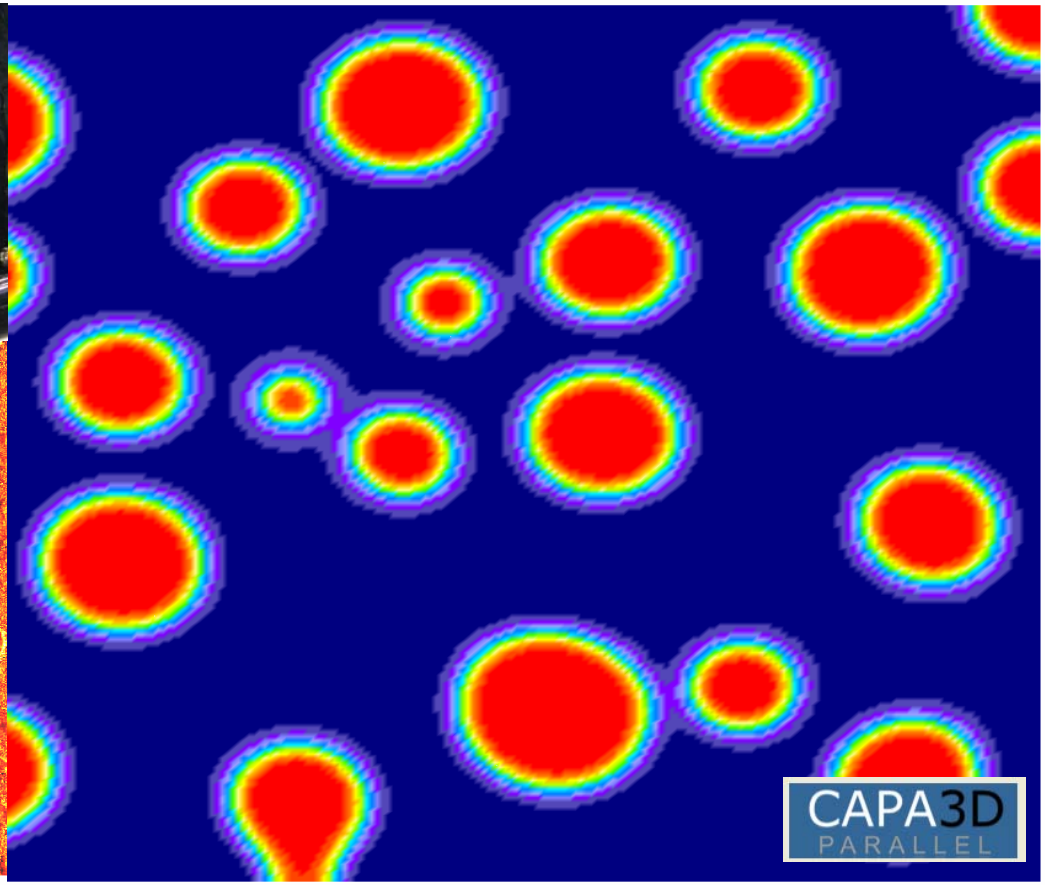
...asphalt under the Atomic Force Microscope



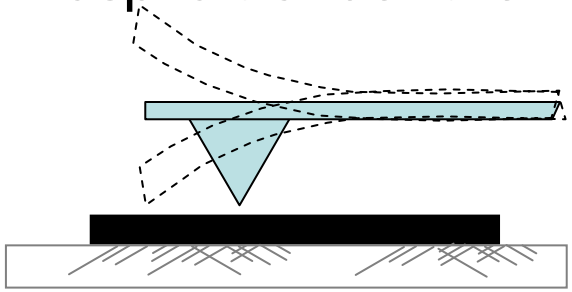


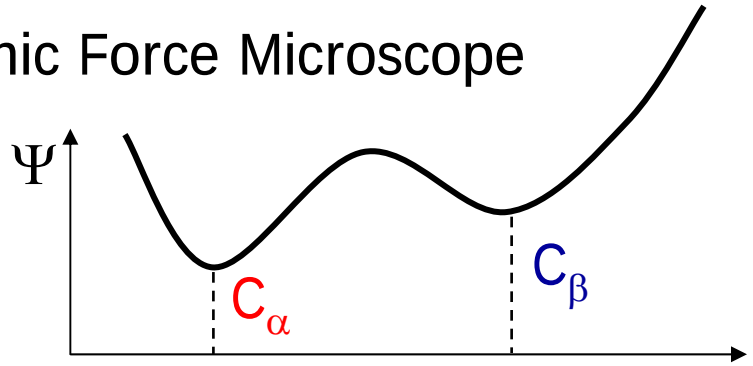


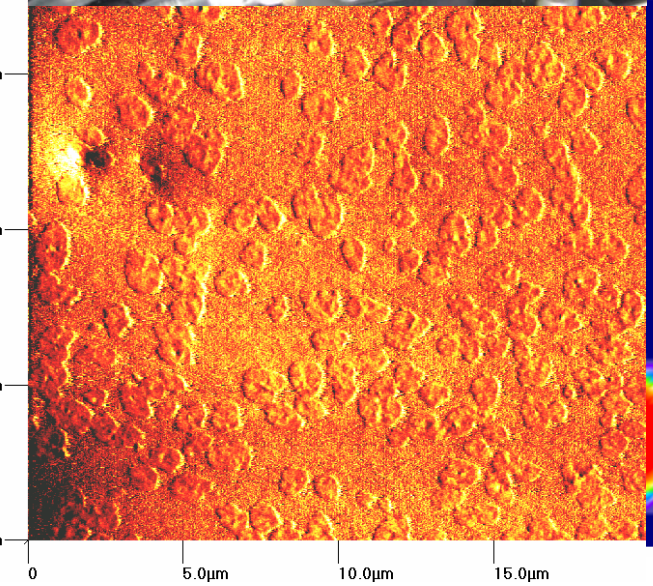


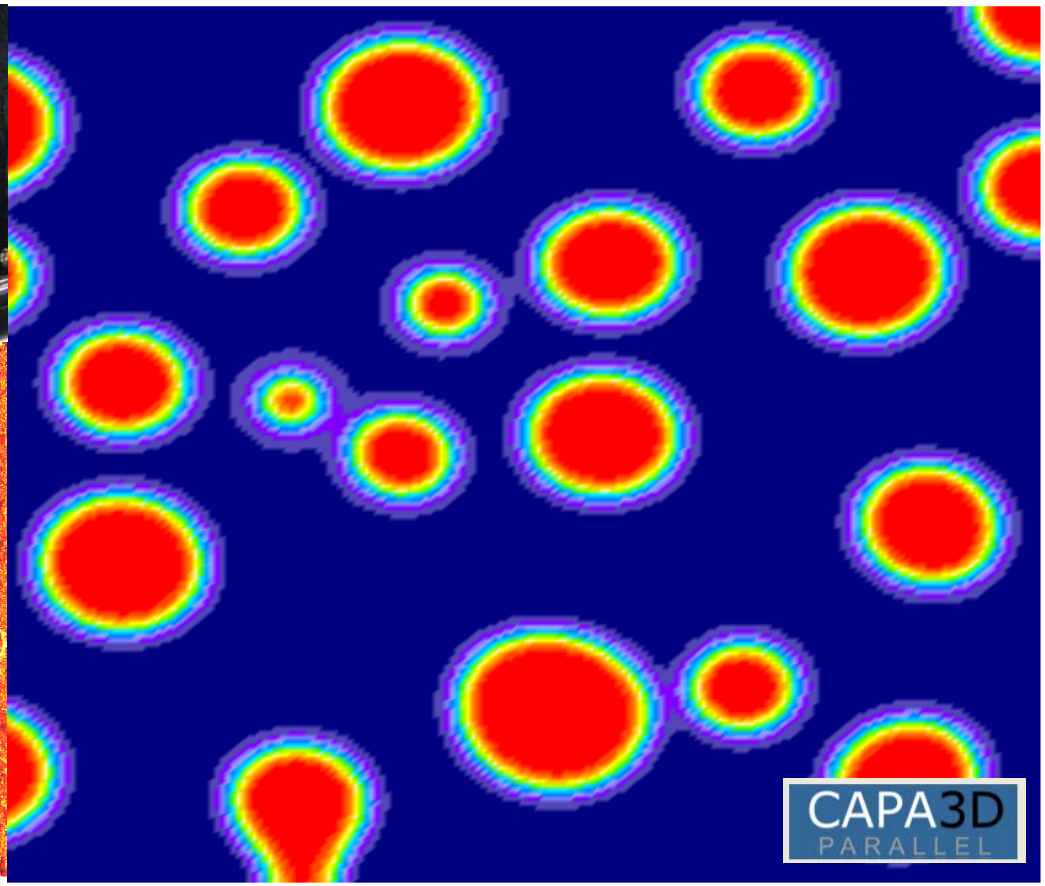


...asphalt under the Atomic Force Microscope









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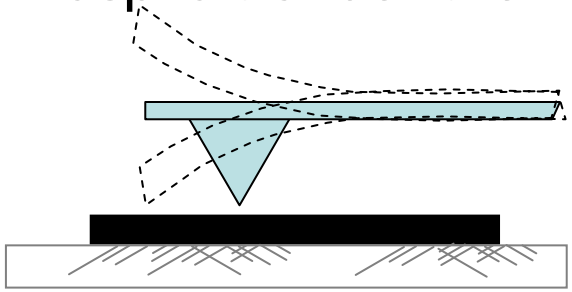

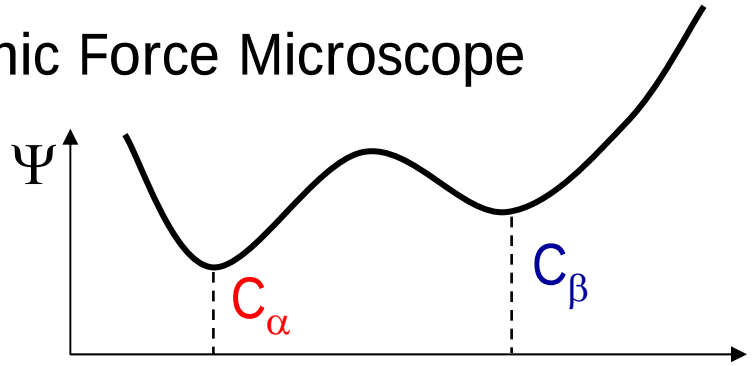

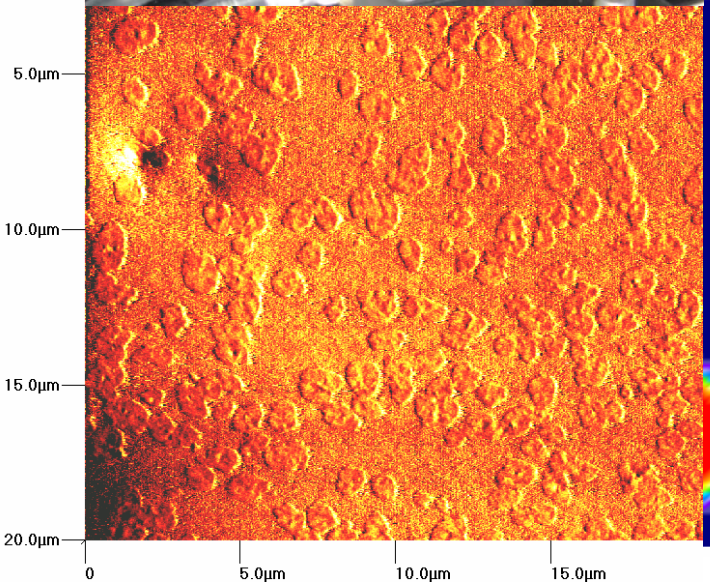

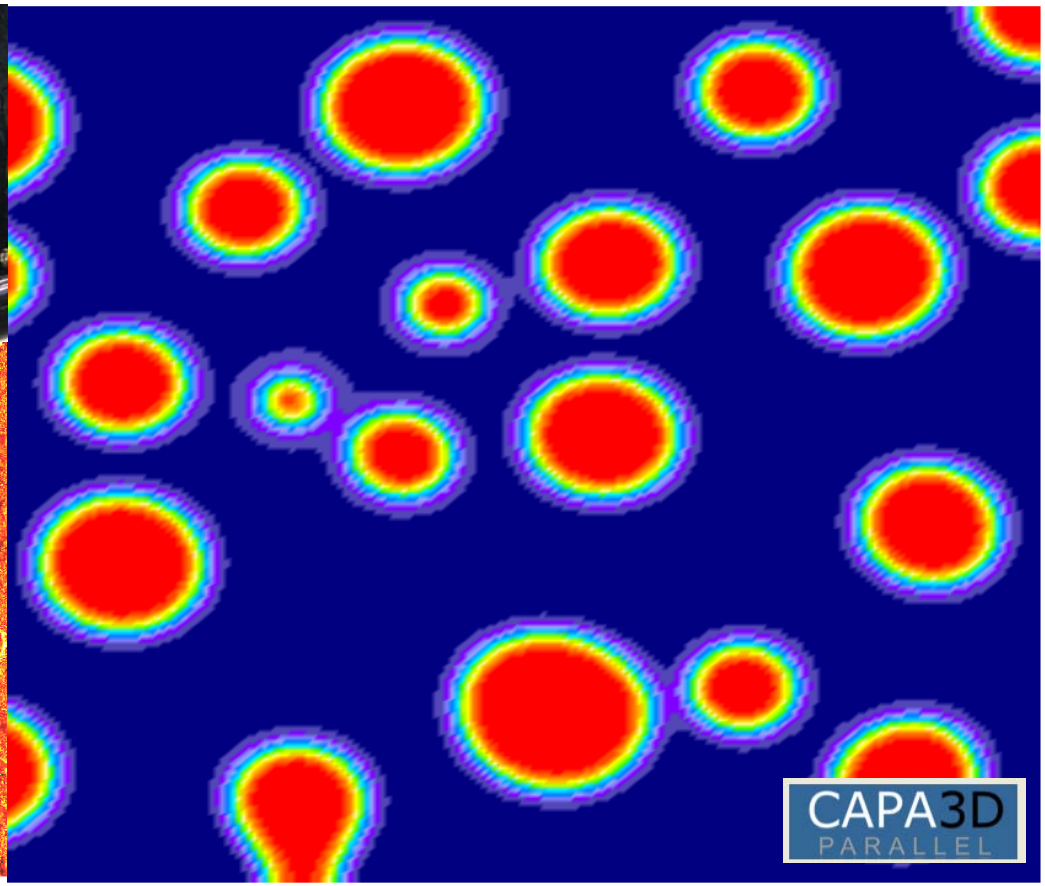

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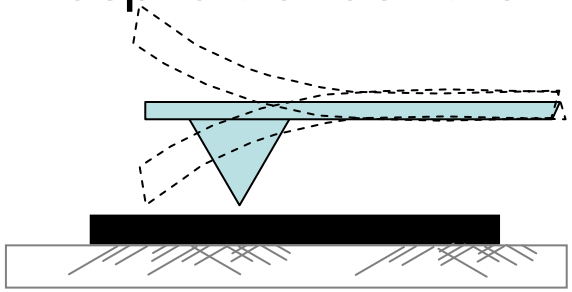

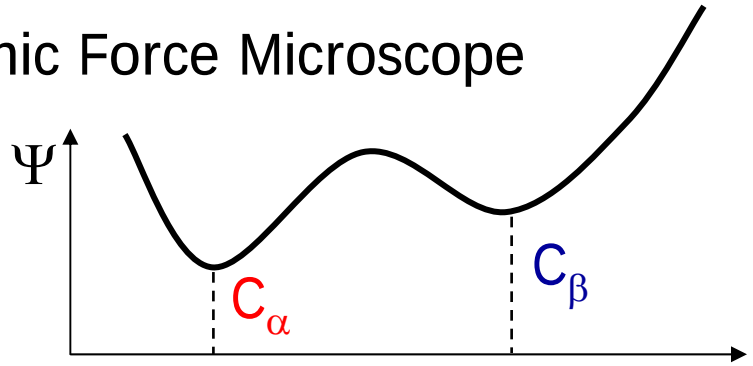

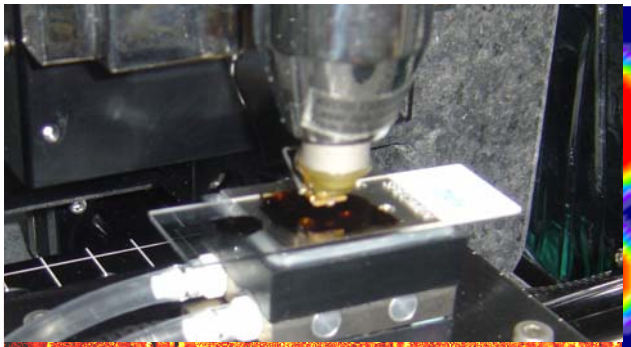

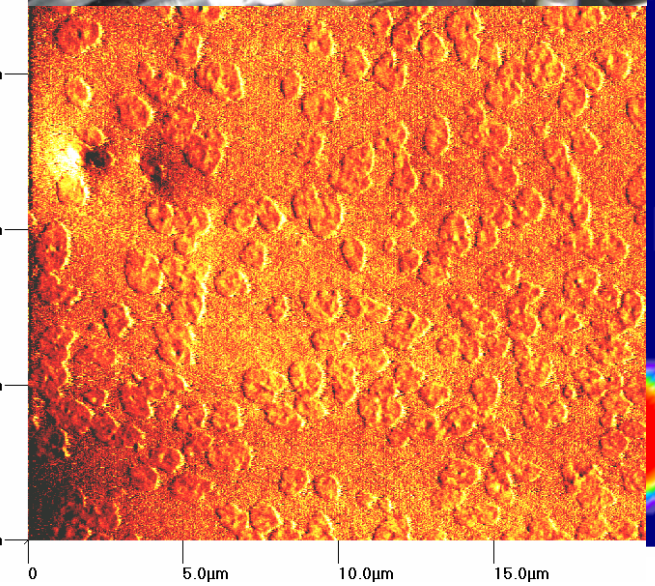

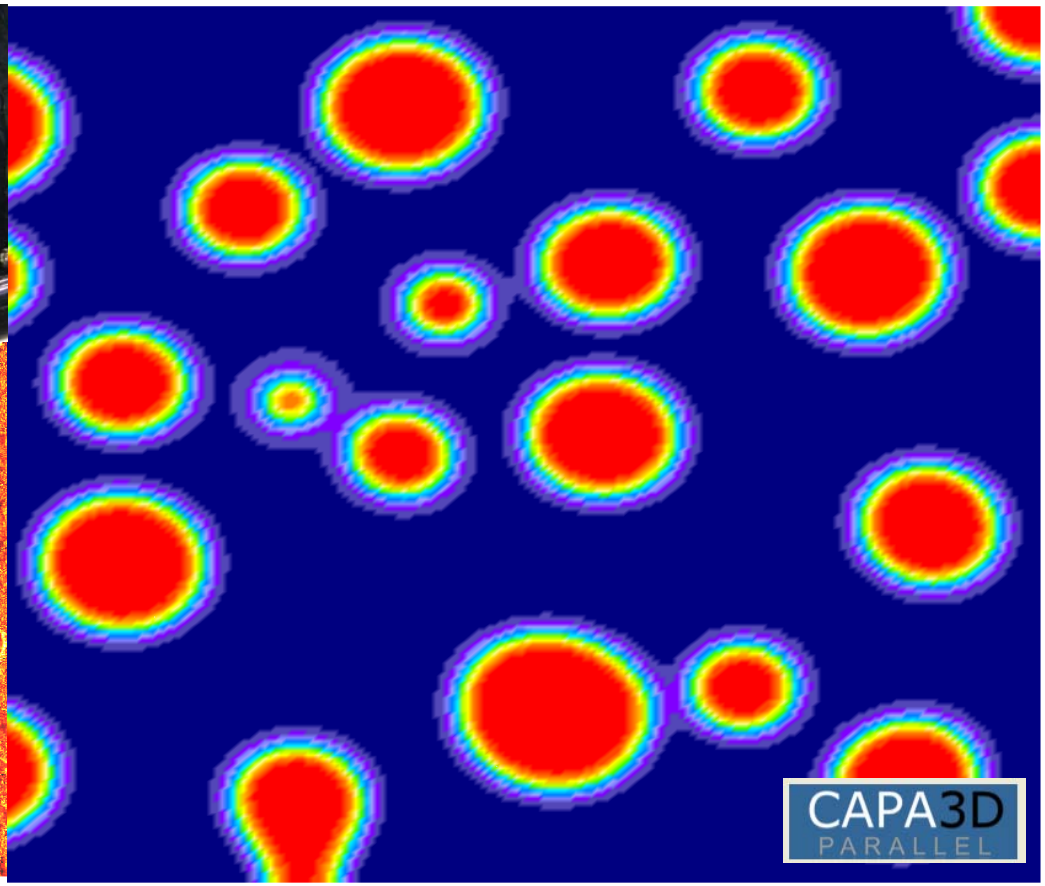

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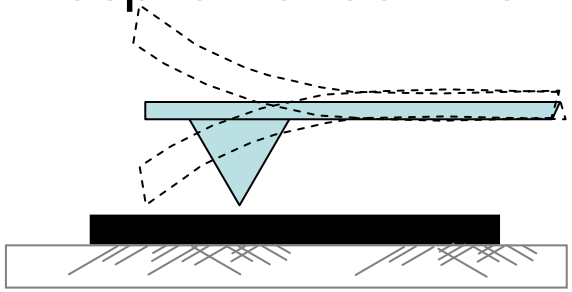

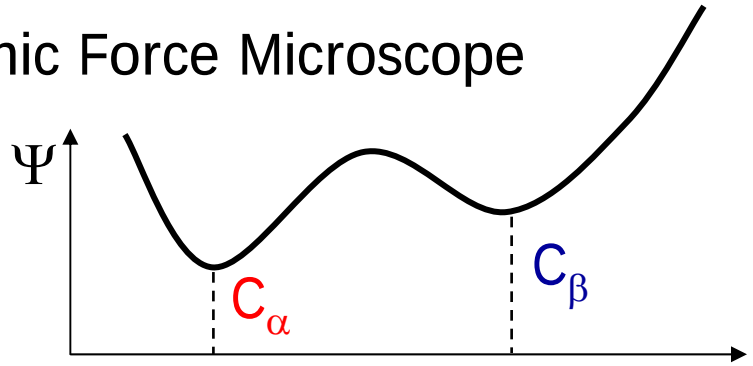

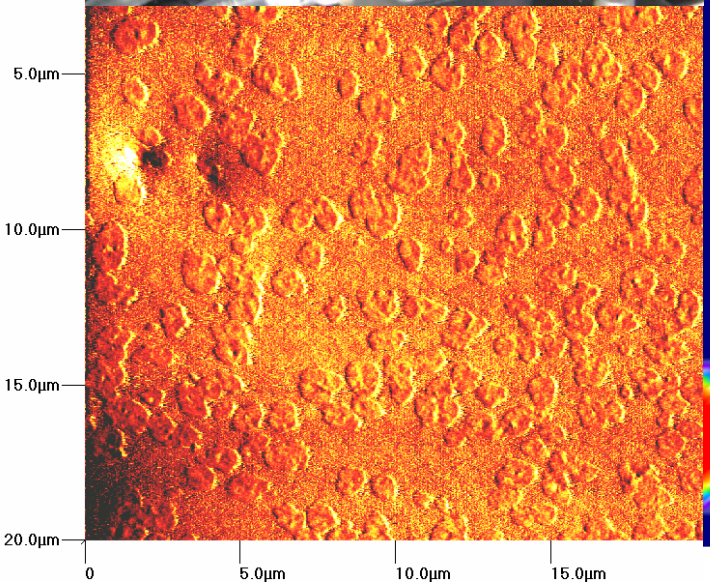

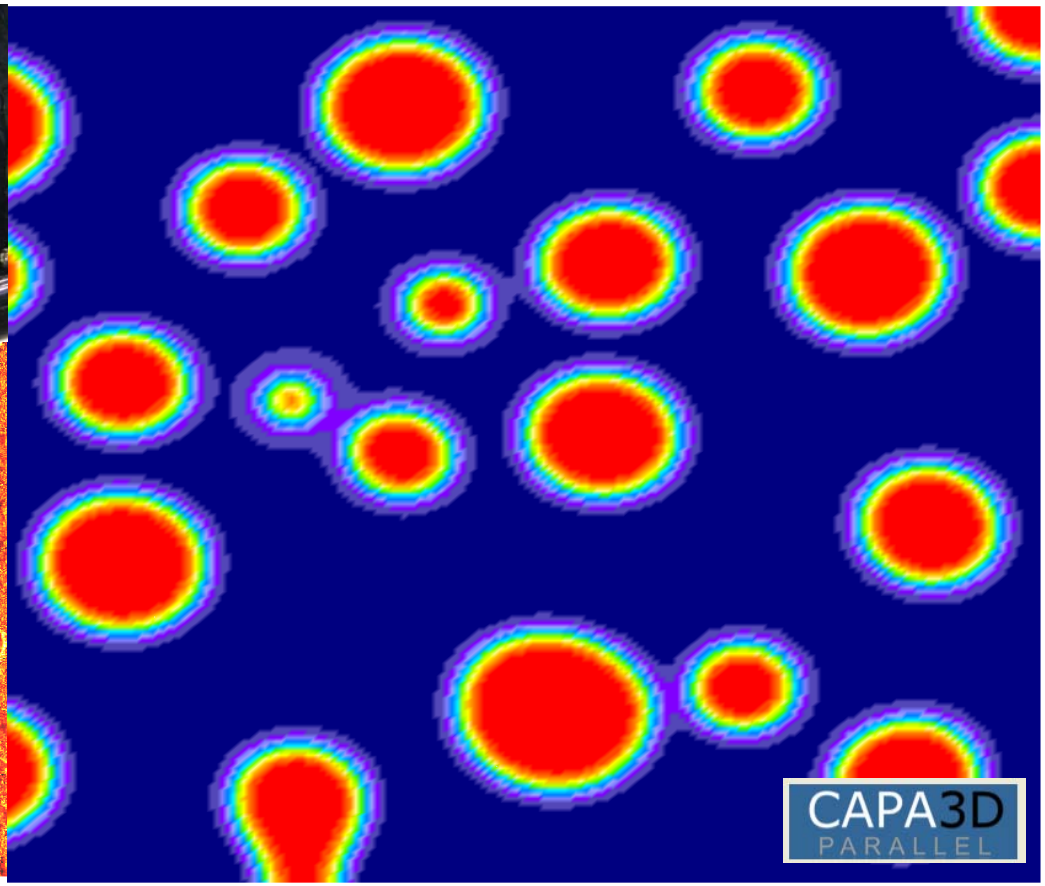

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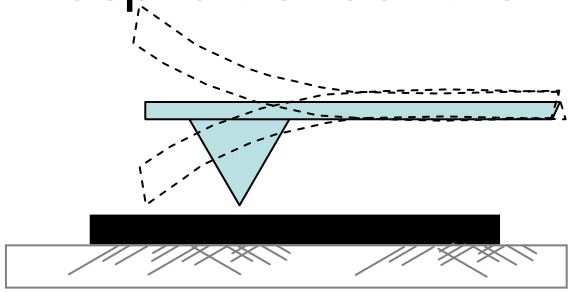

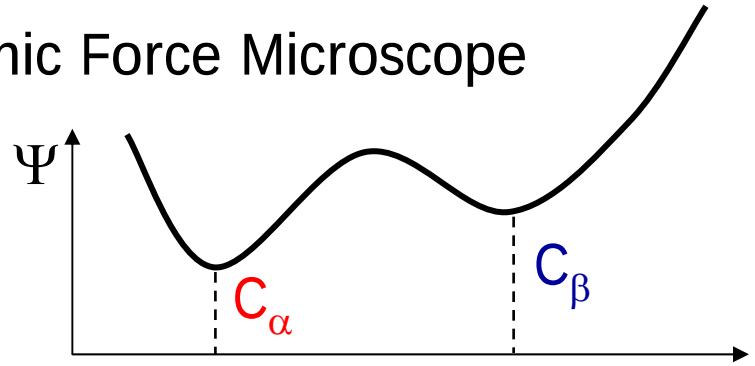

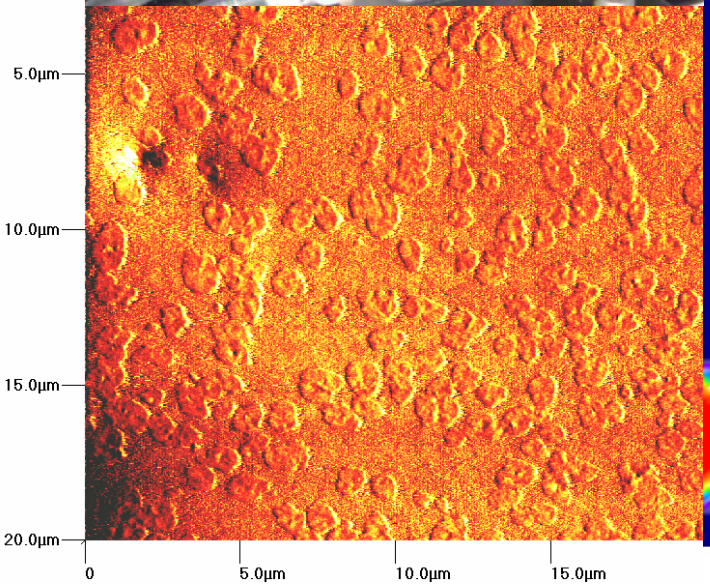

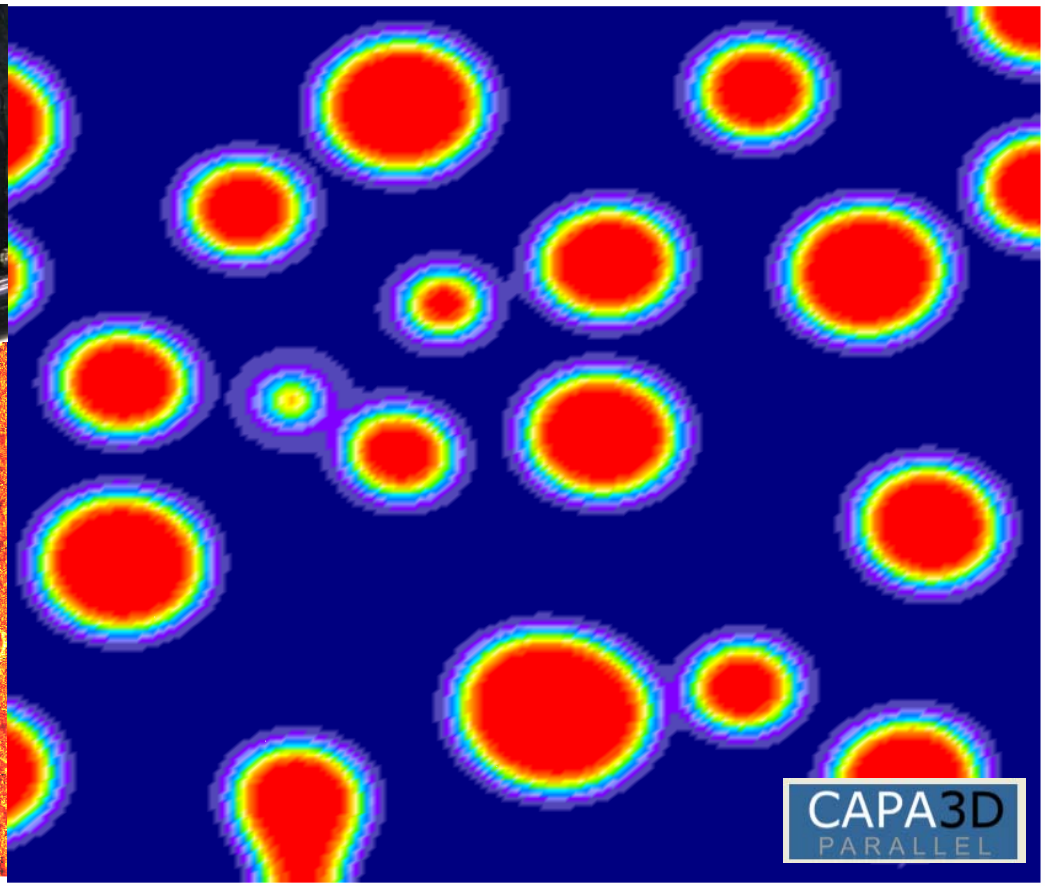

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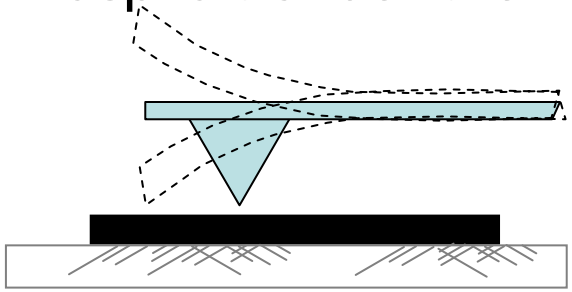

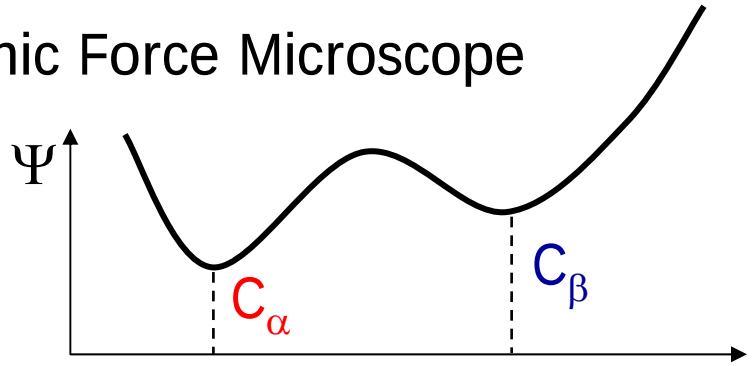

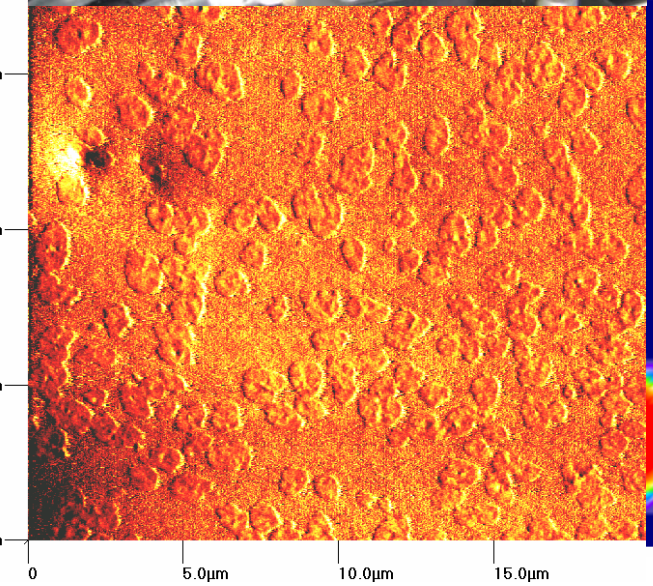

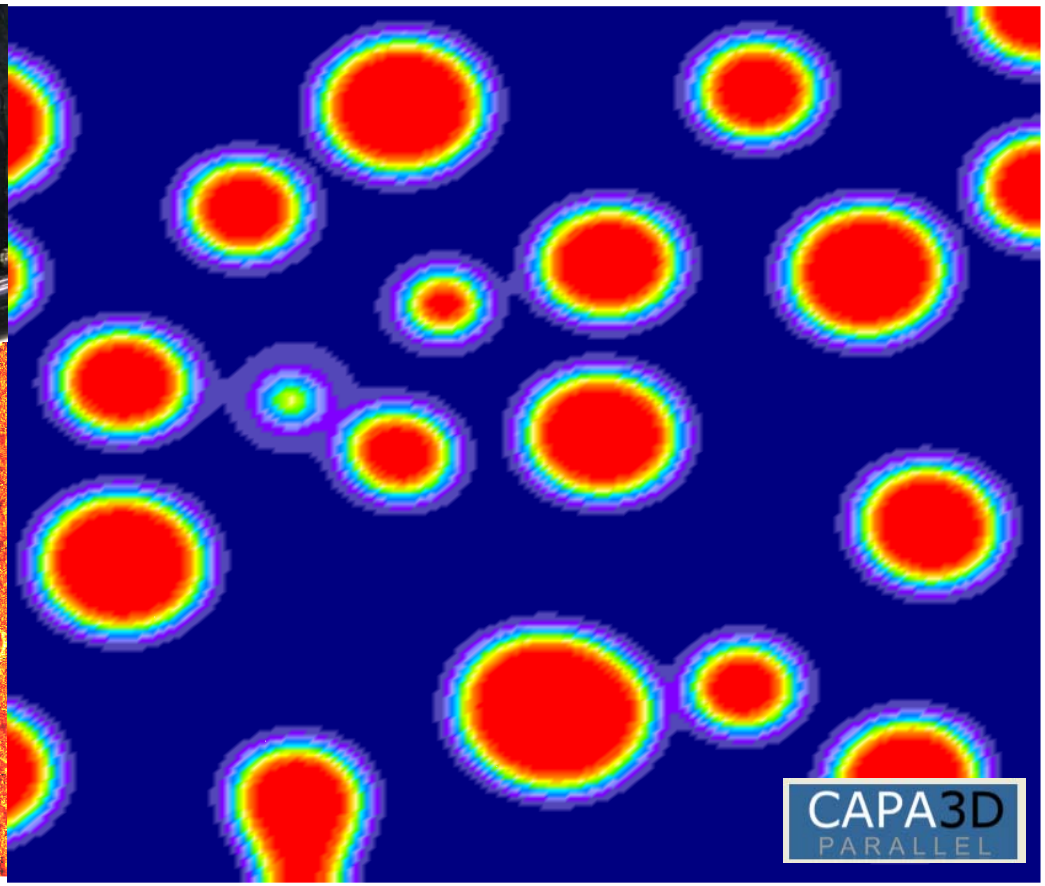

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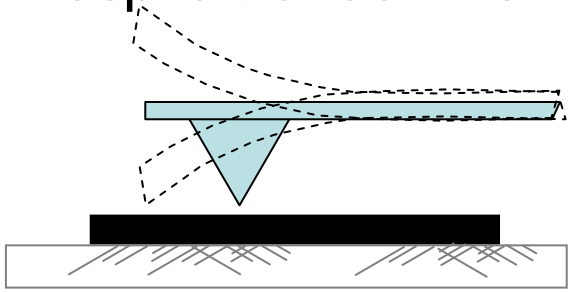

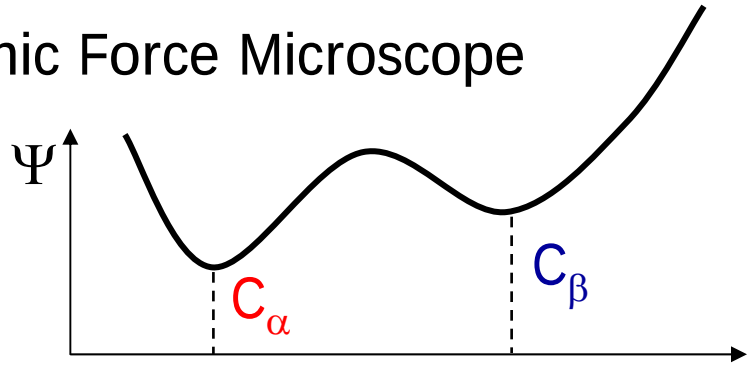

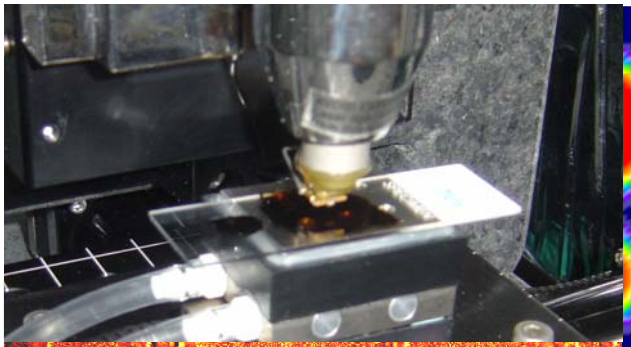

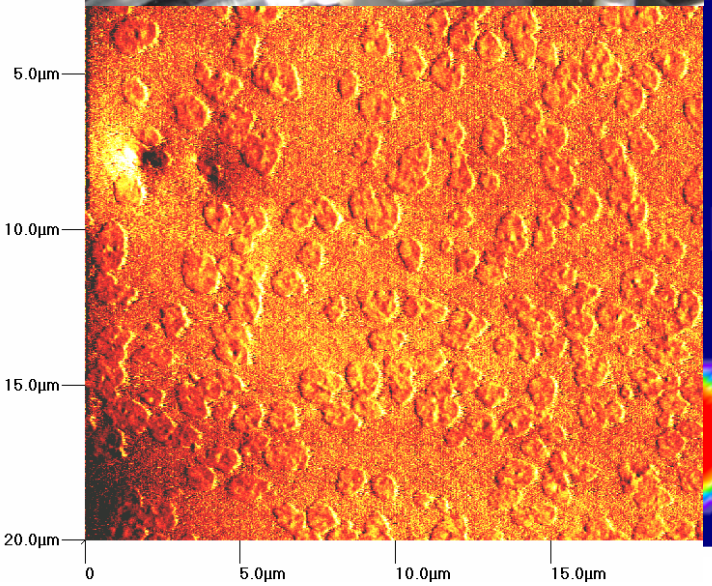

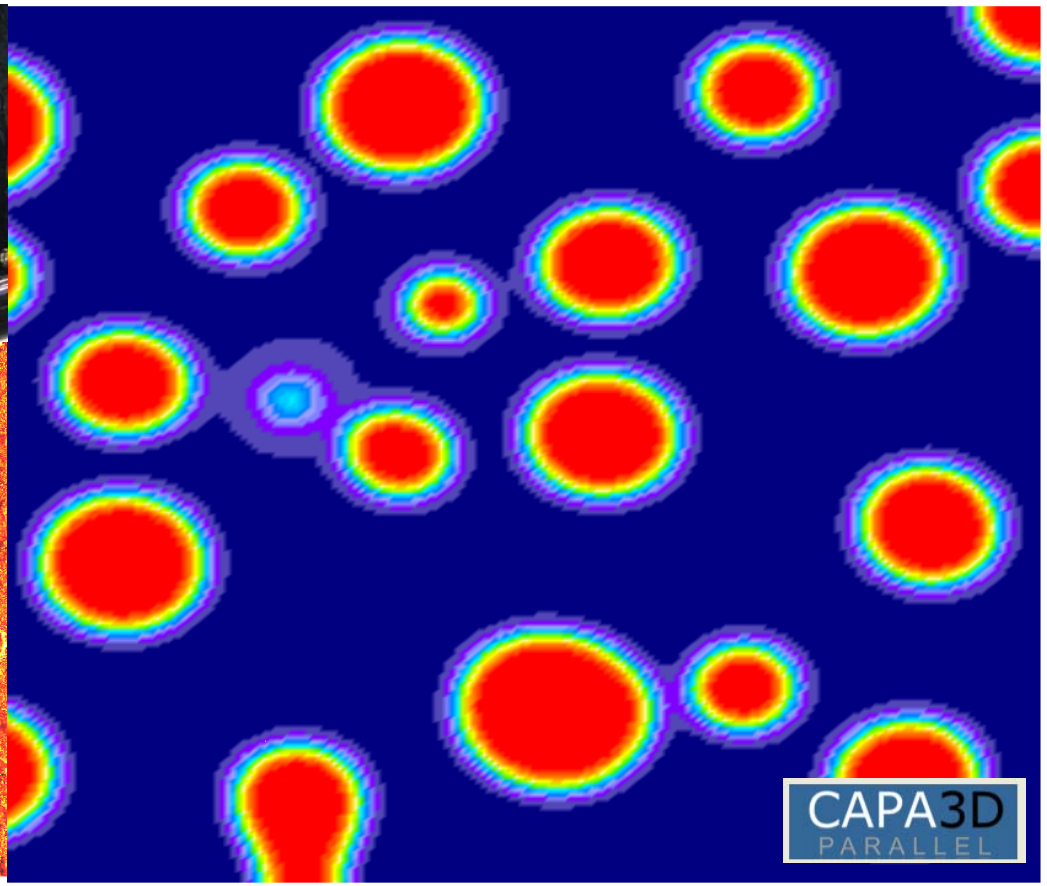

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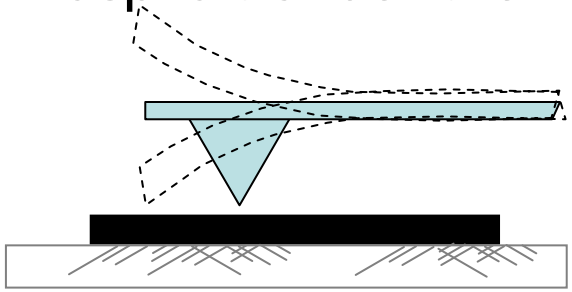

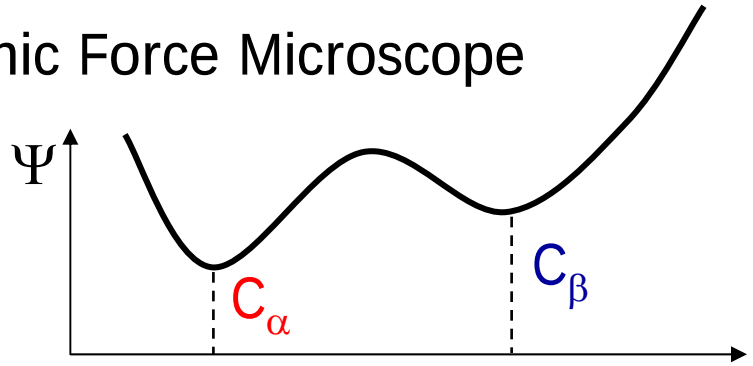

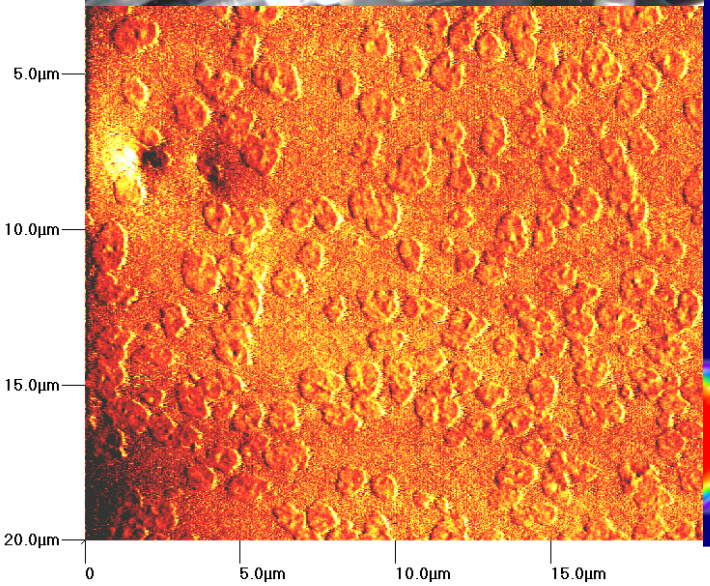

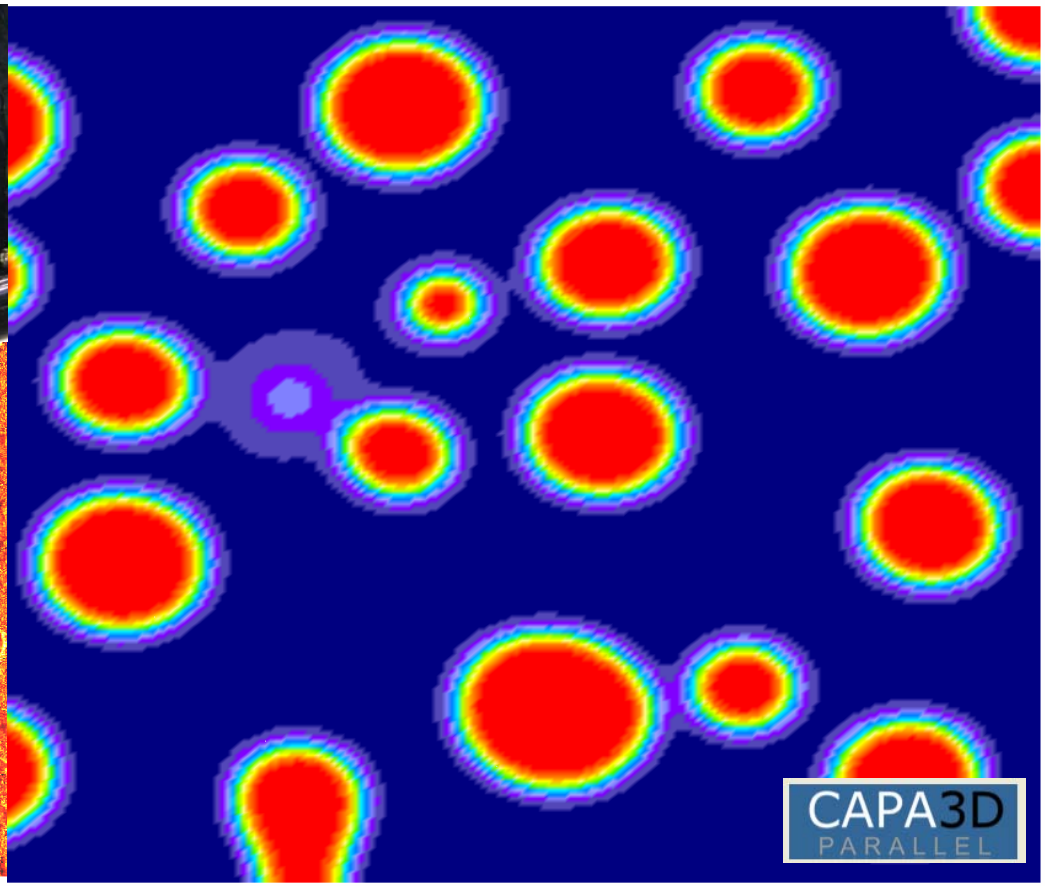

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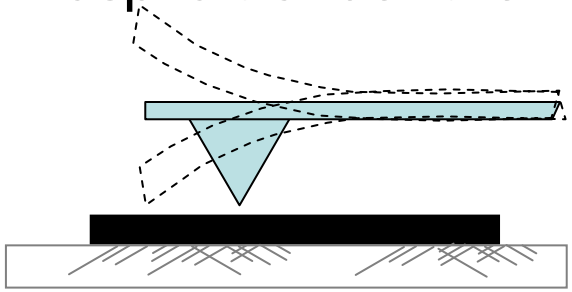

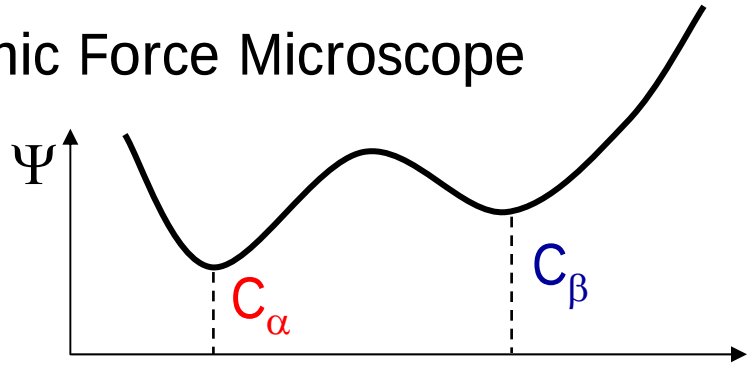

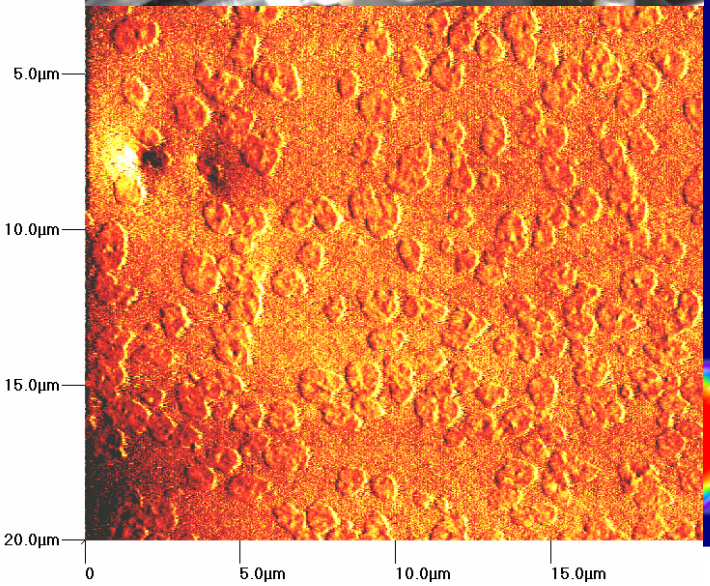

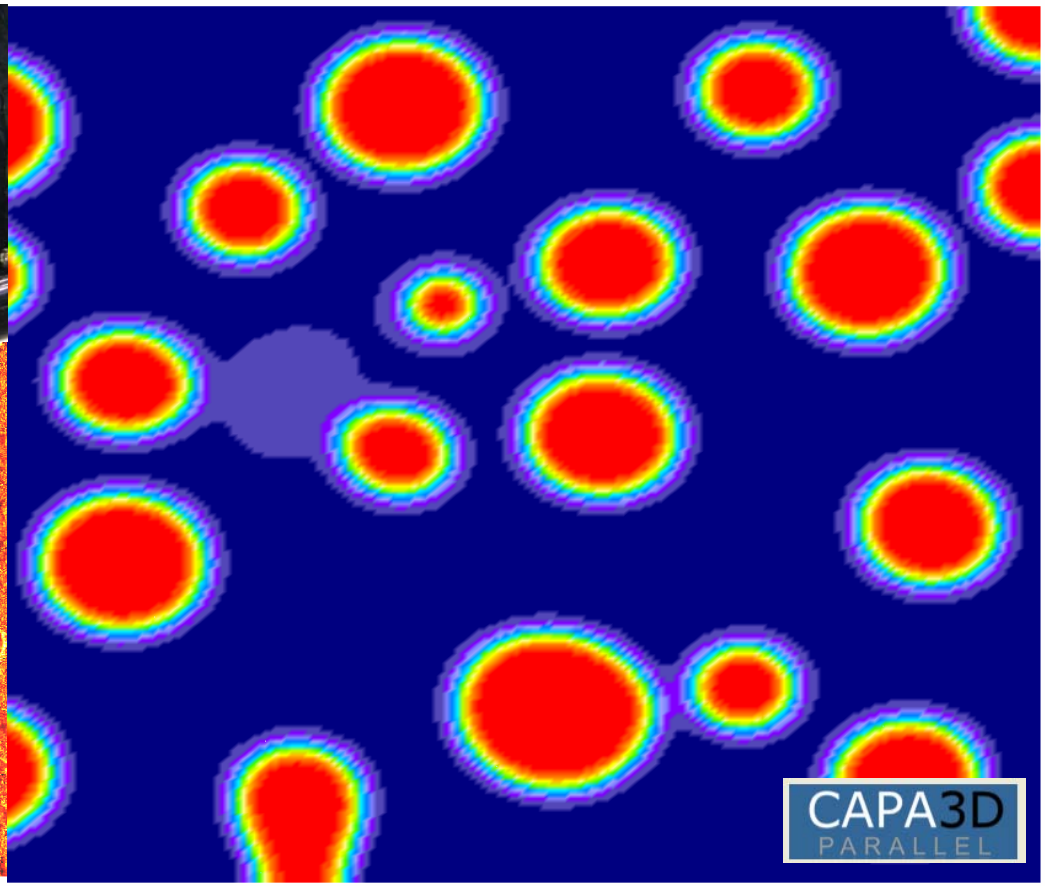

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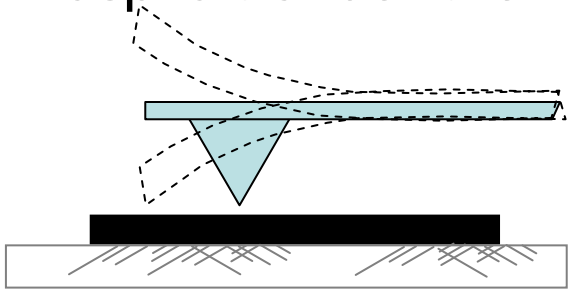

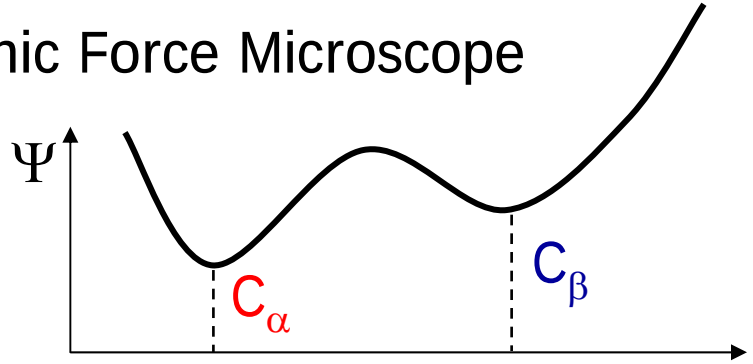

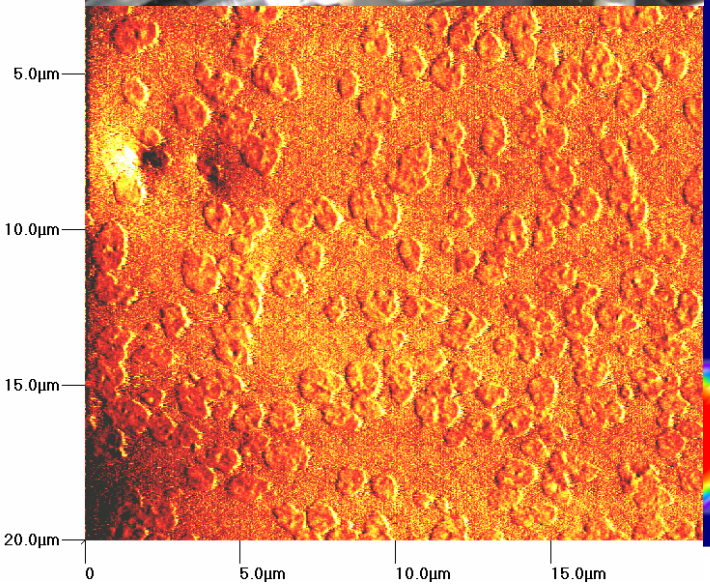

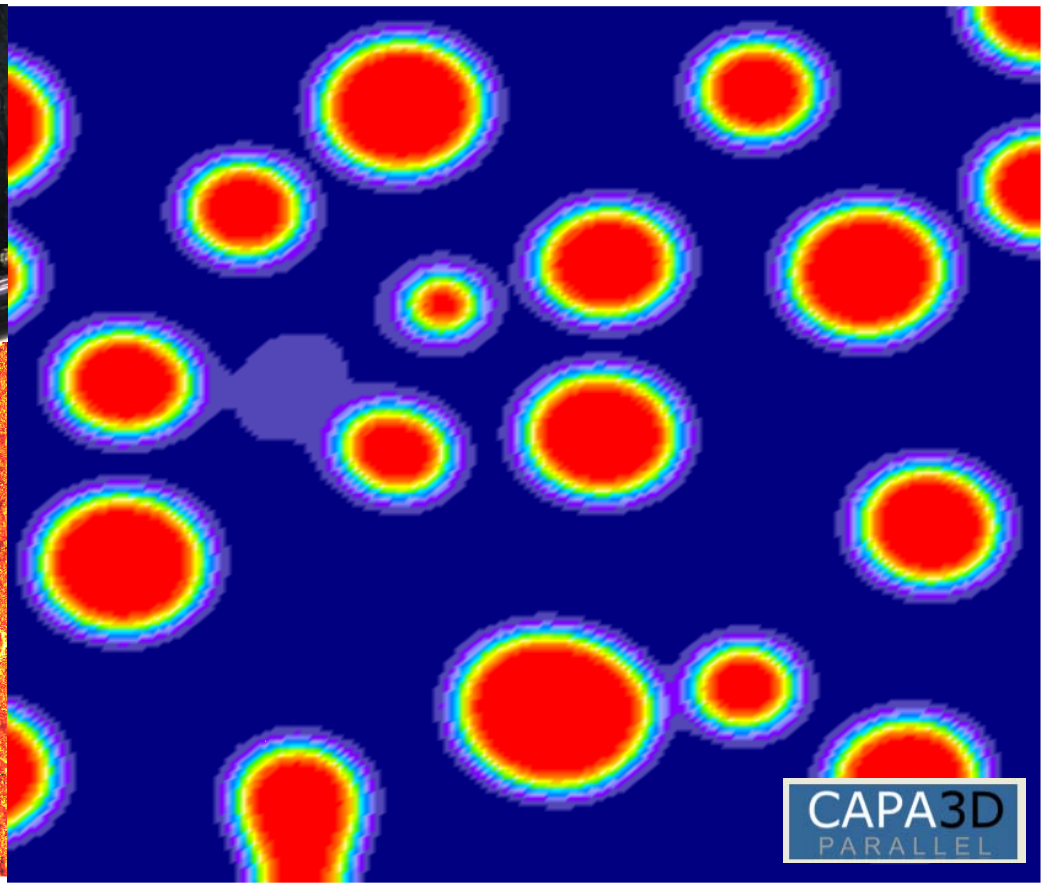

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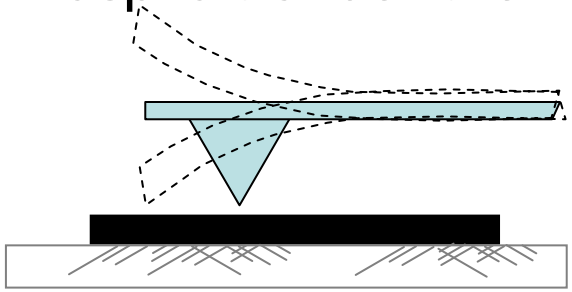

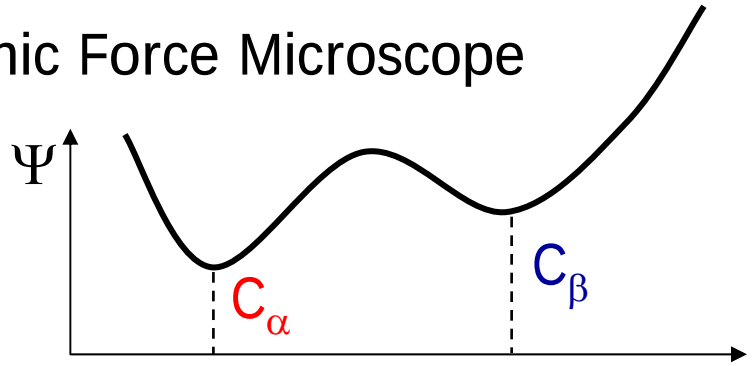

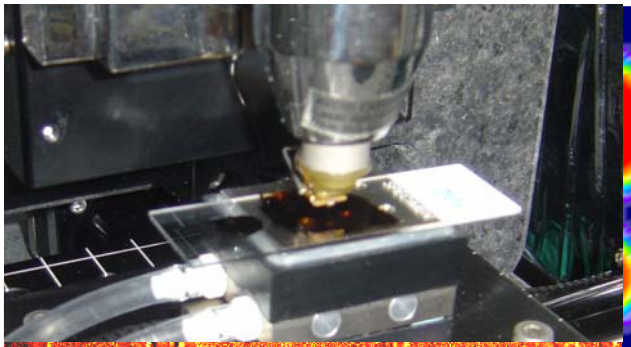

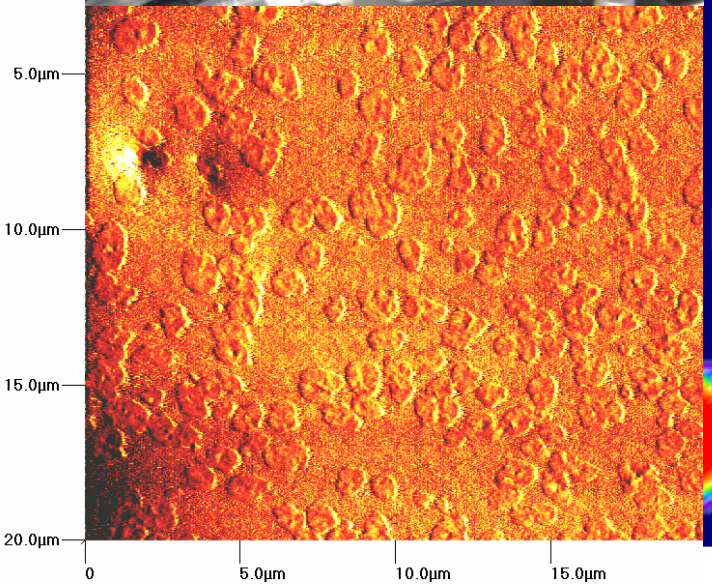

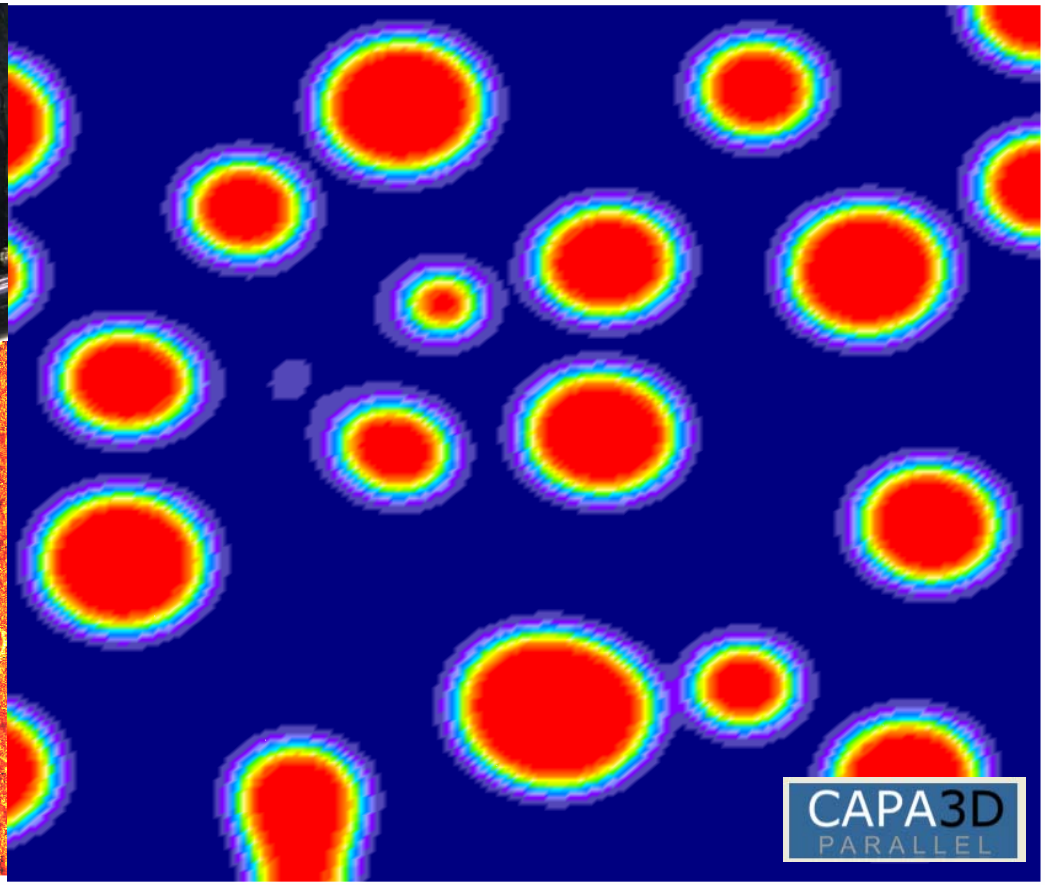

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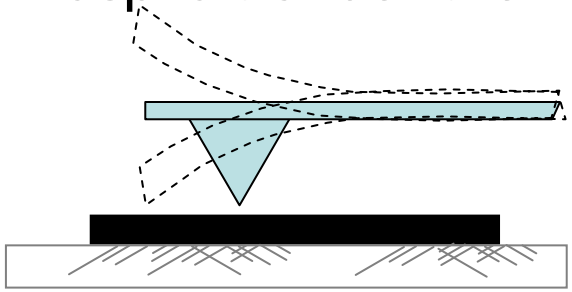

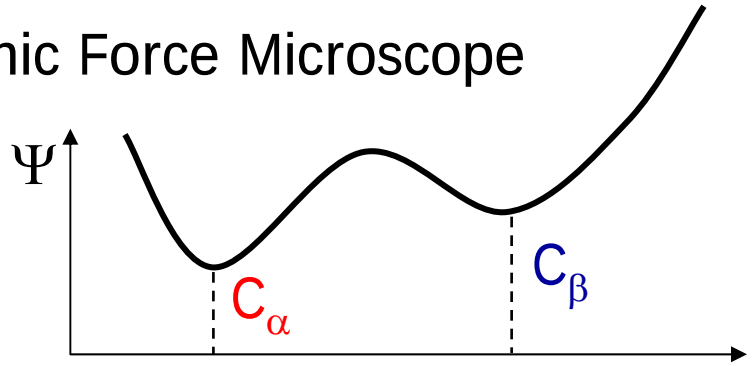

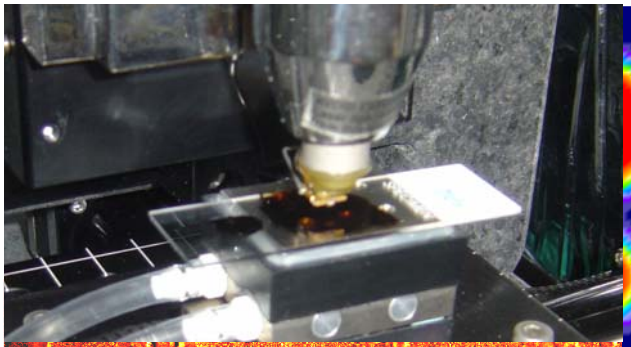

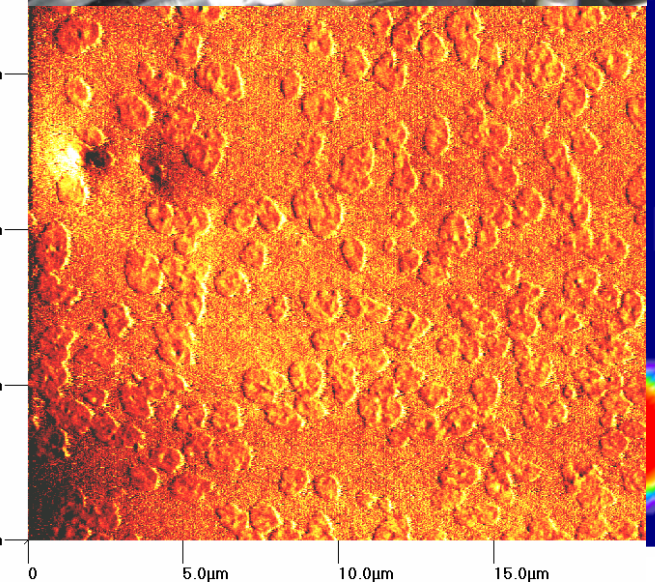

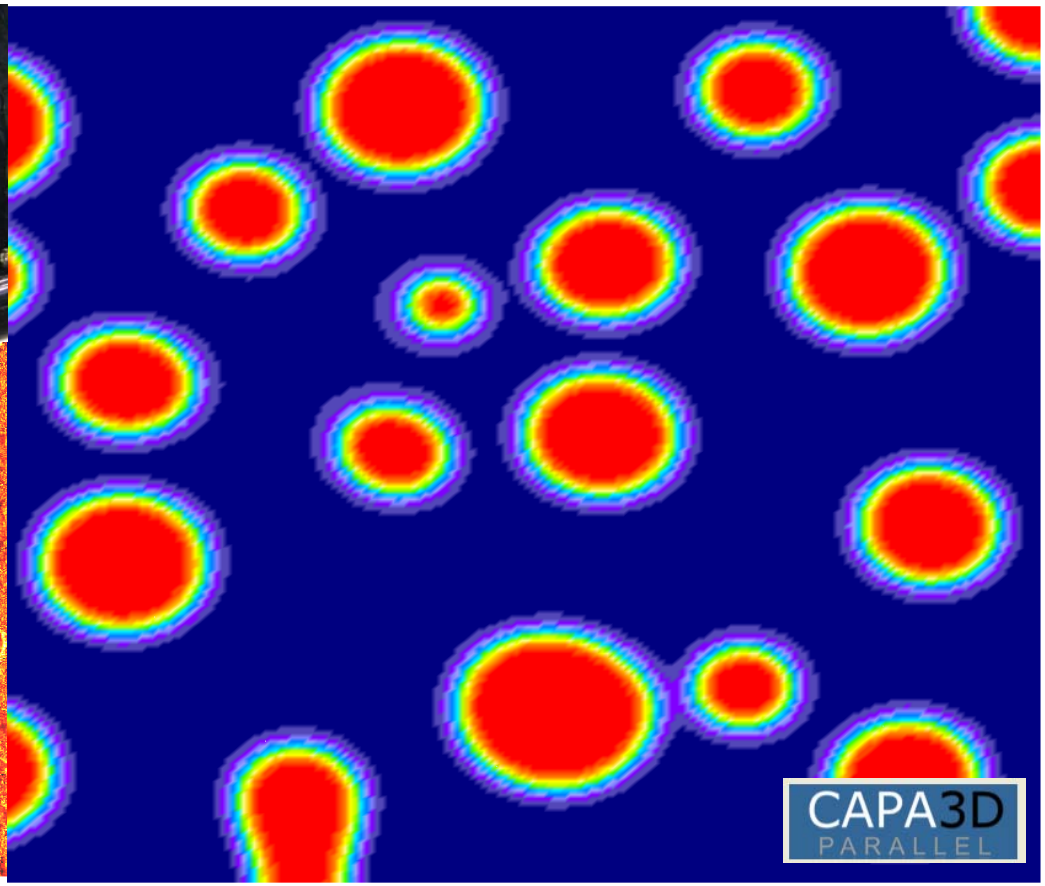

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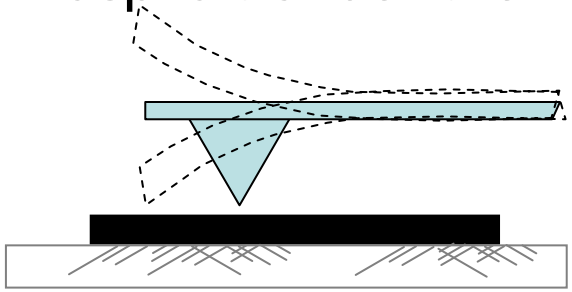
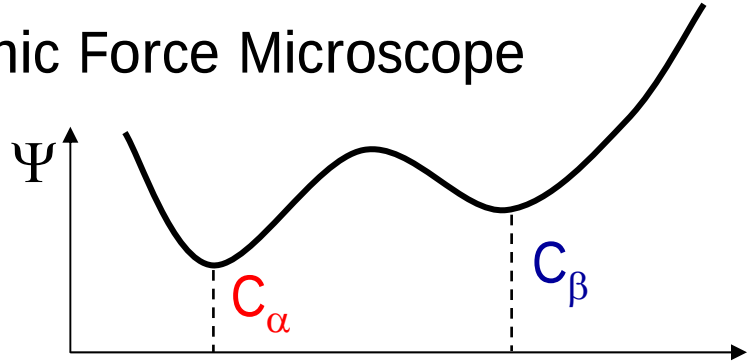
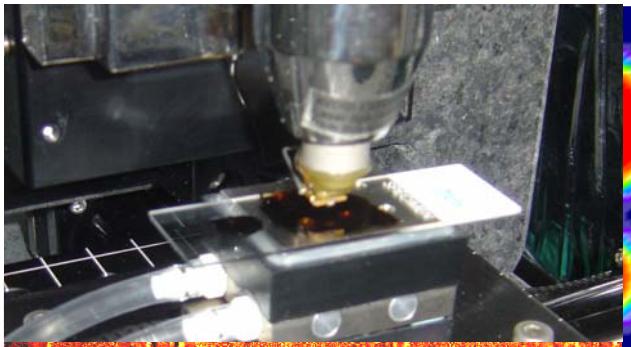
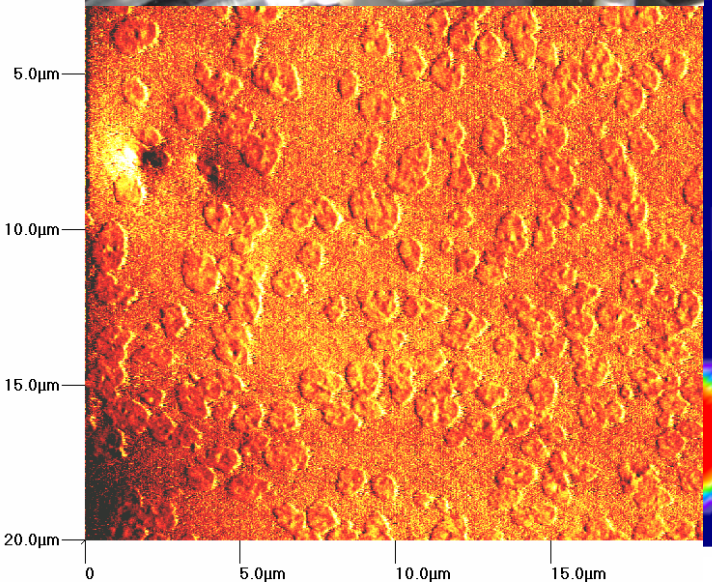
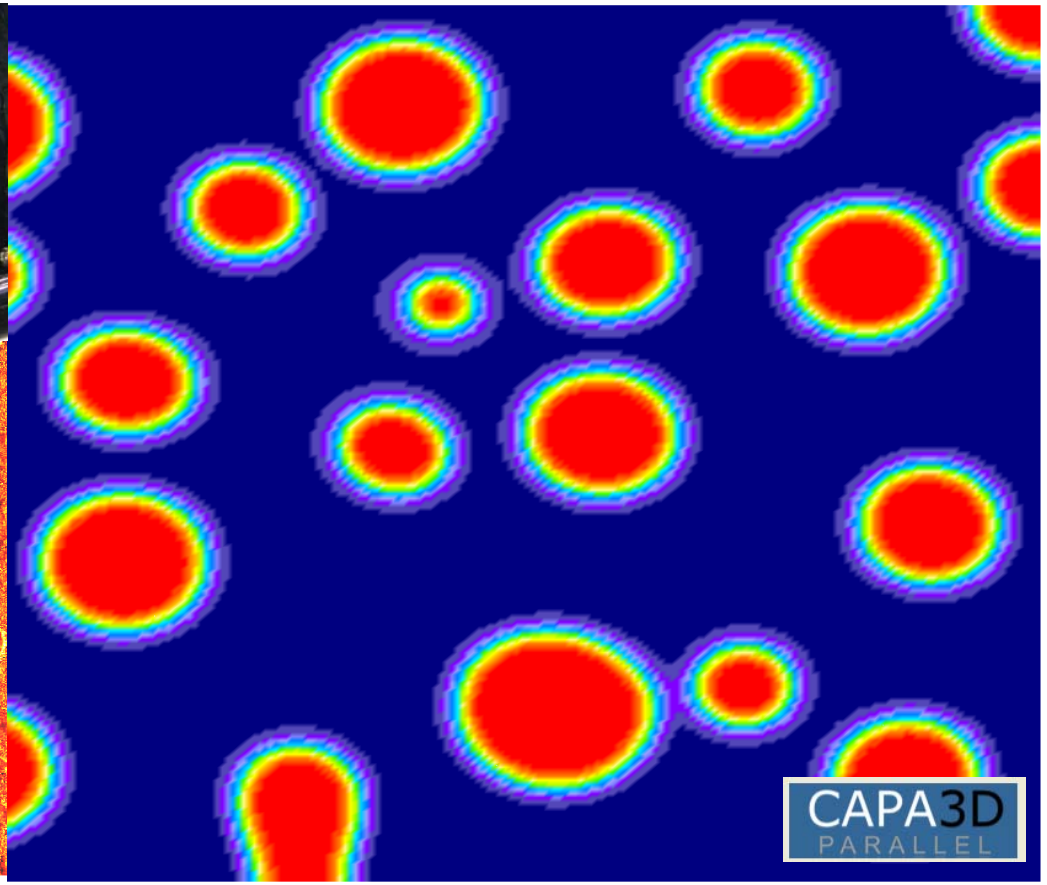


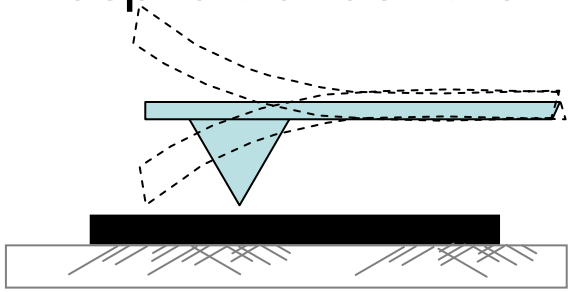


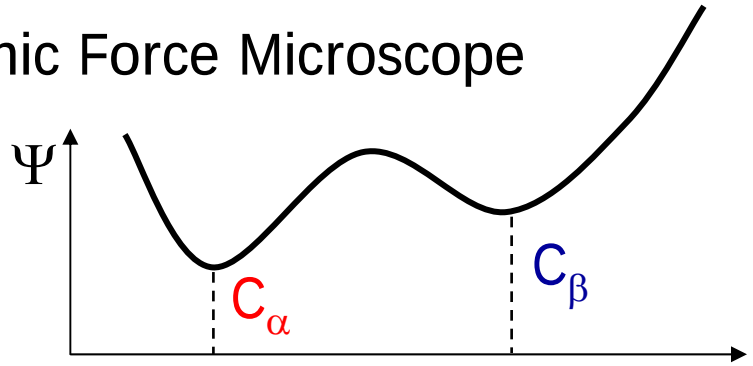


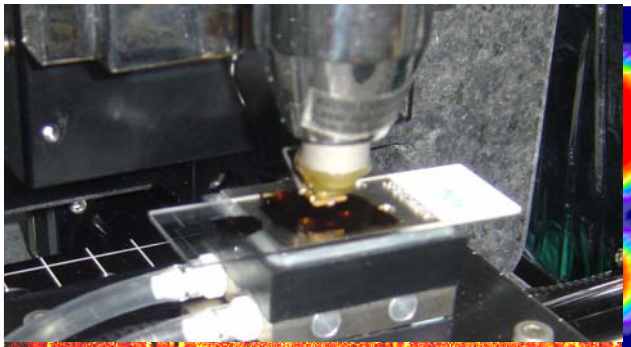


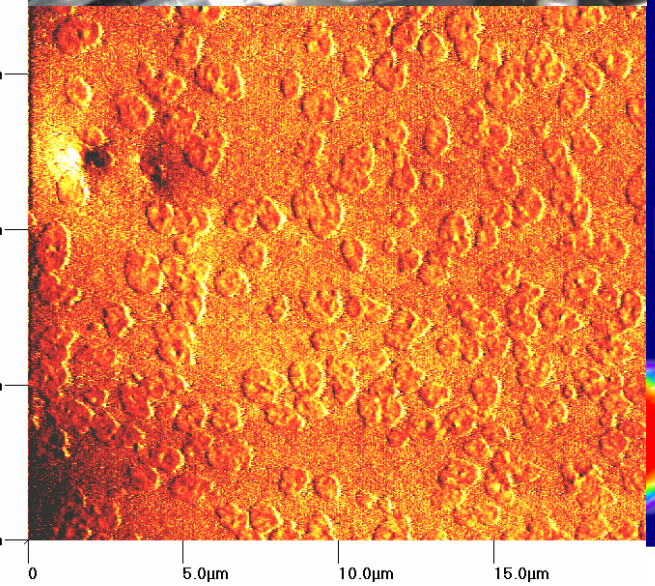


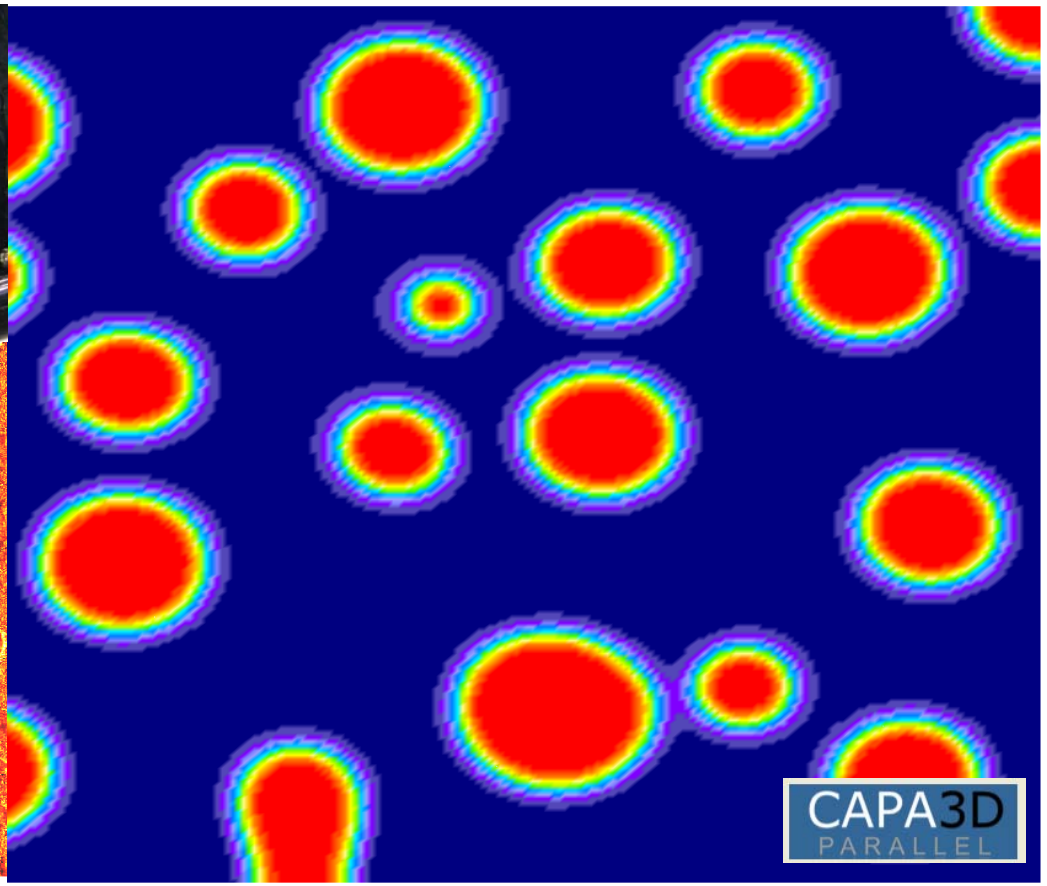
...asphalt under the Atomic Force Microscope











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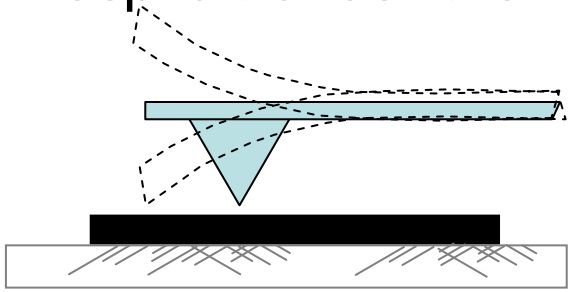

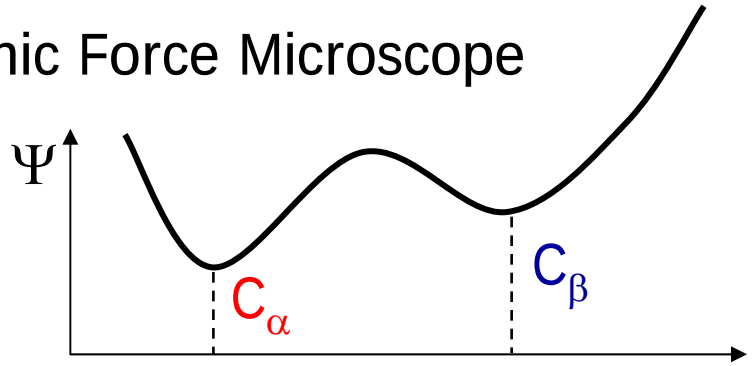

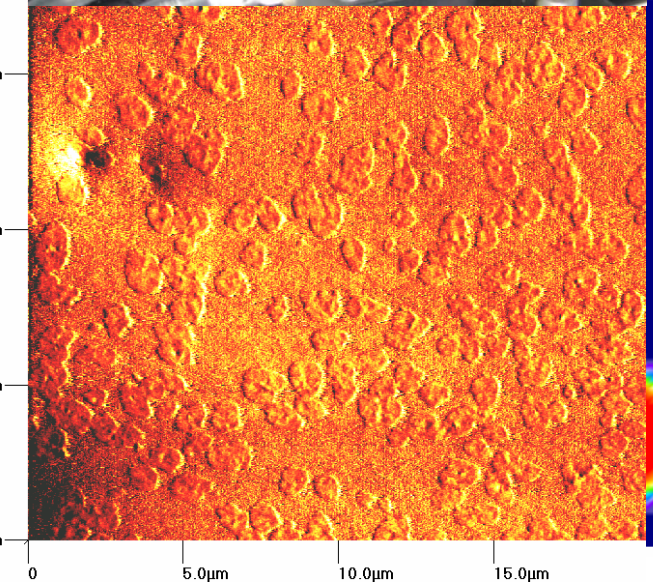

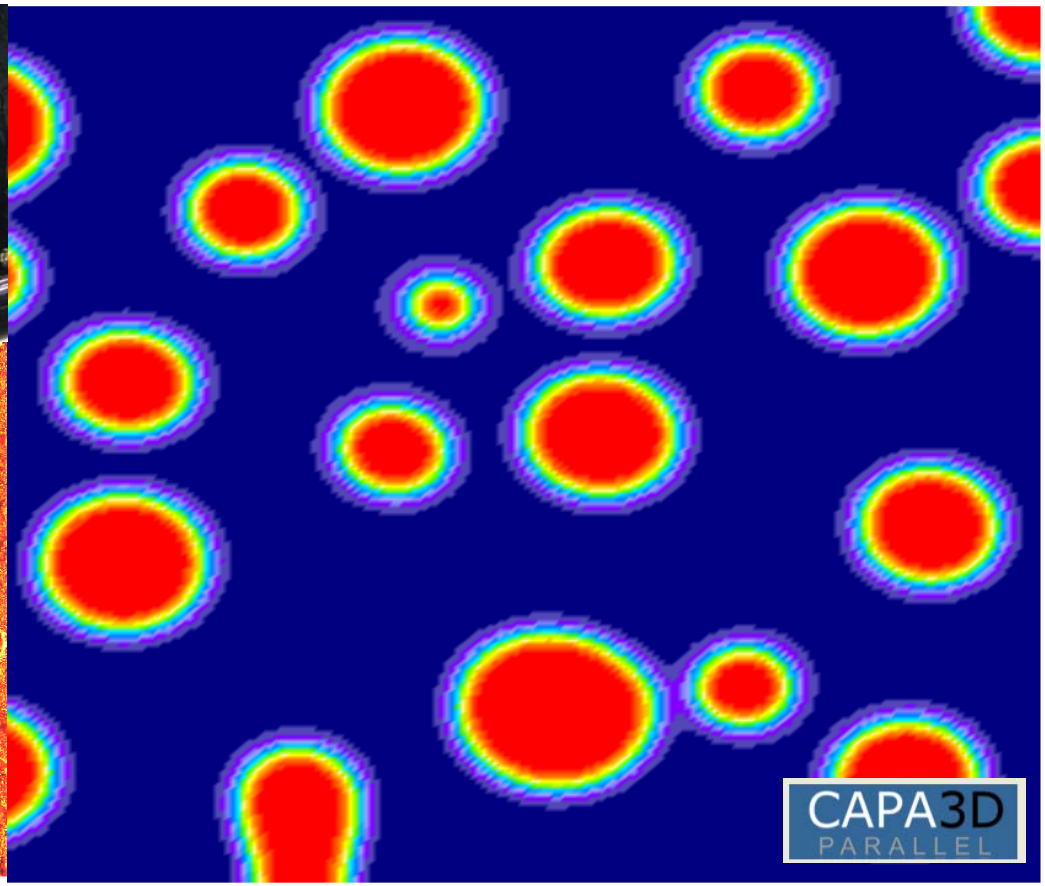

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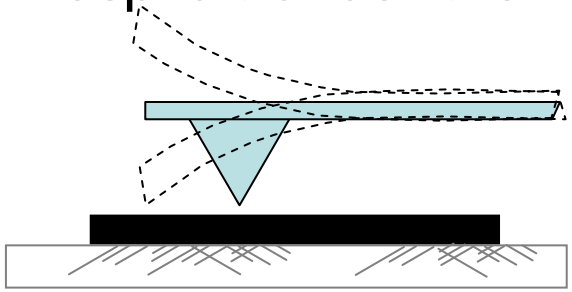

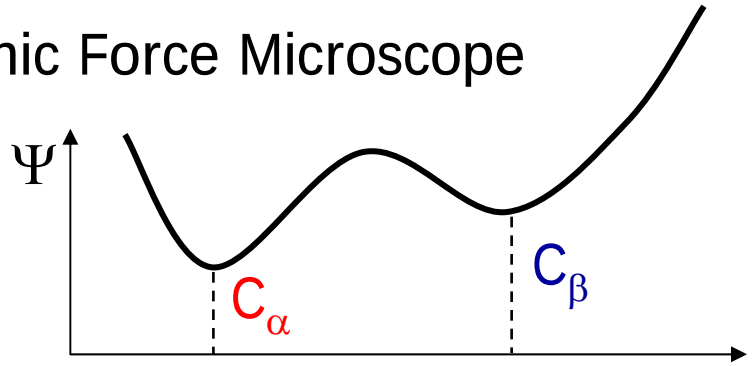

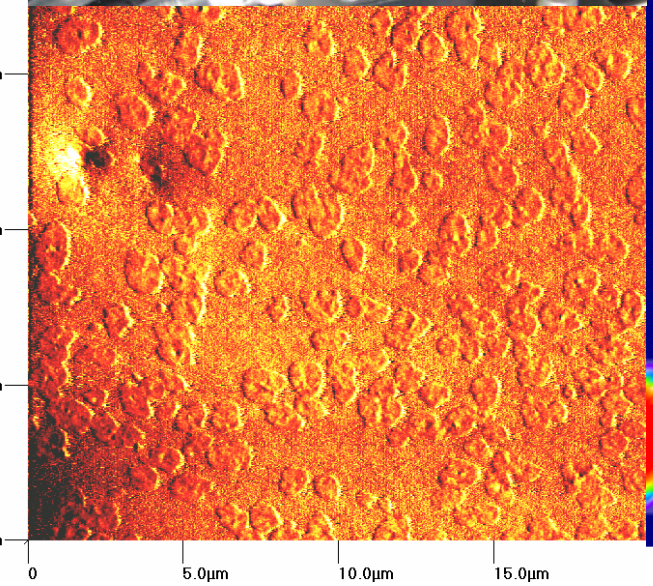

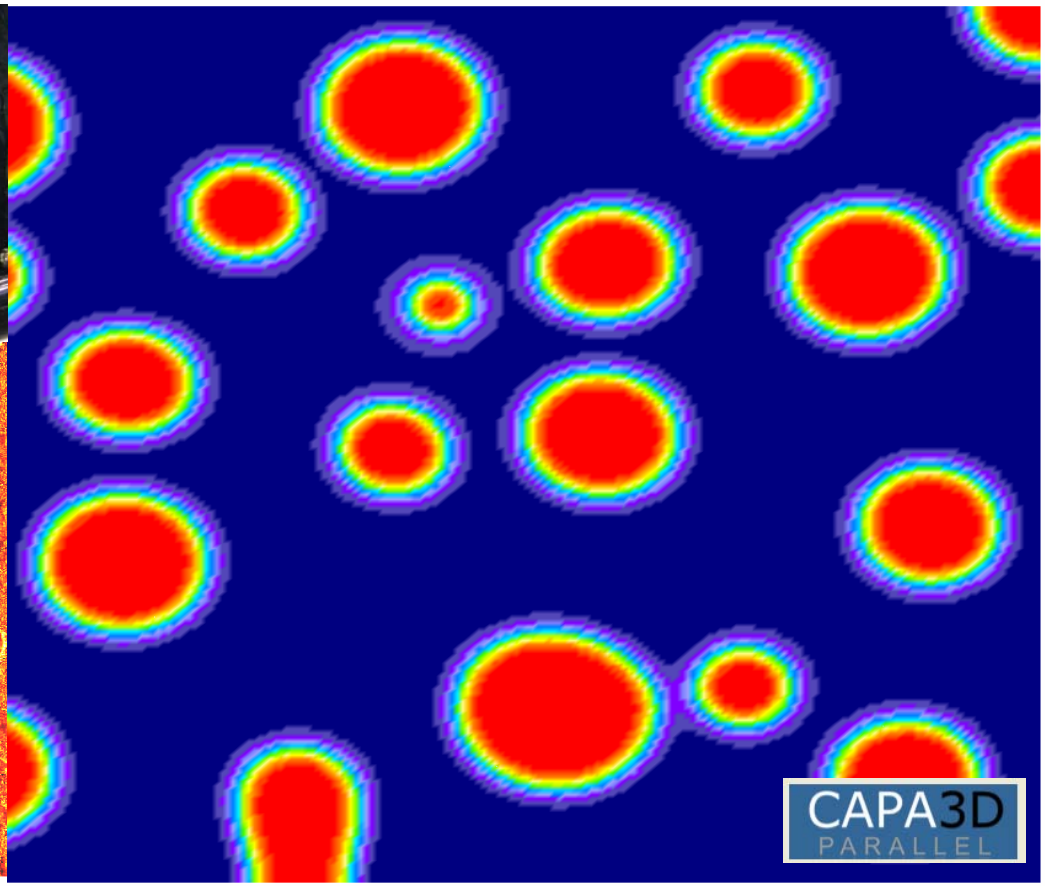

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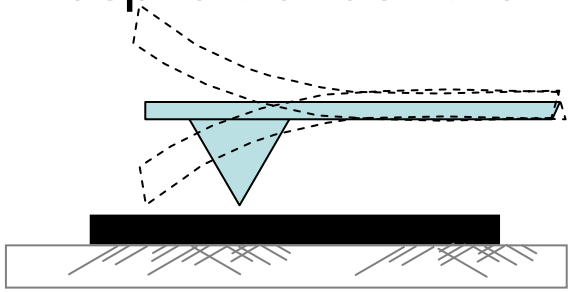

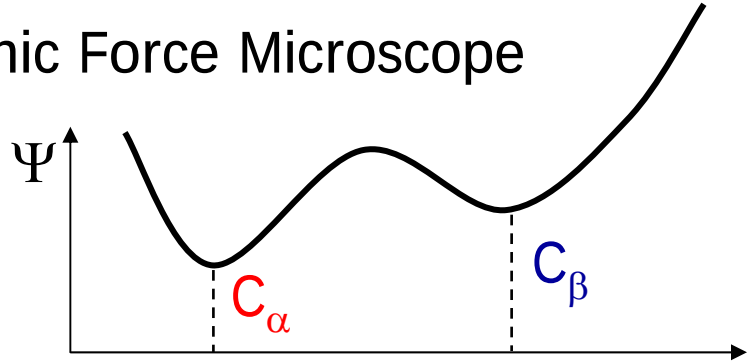

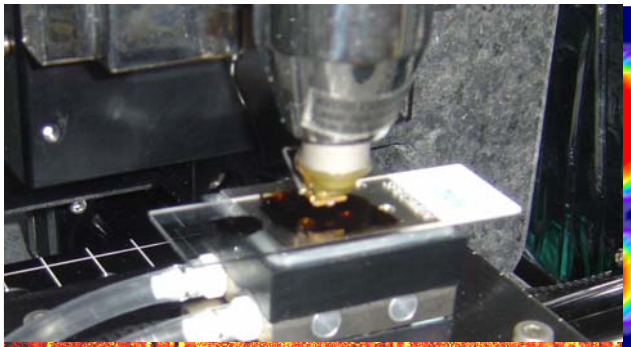

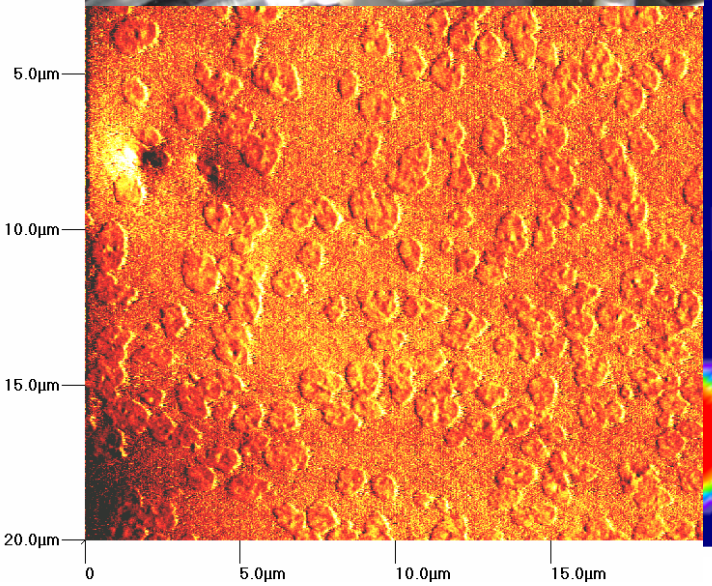

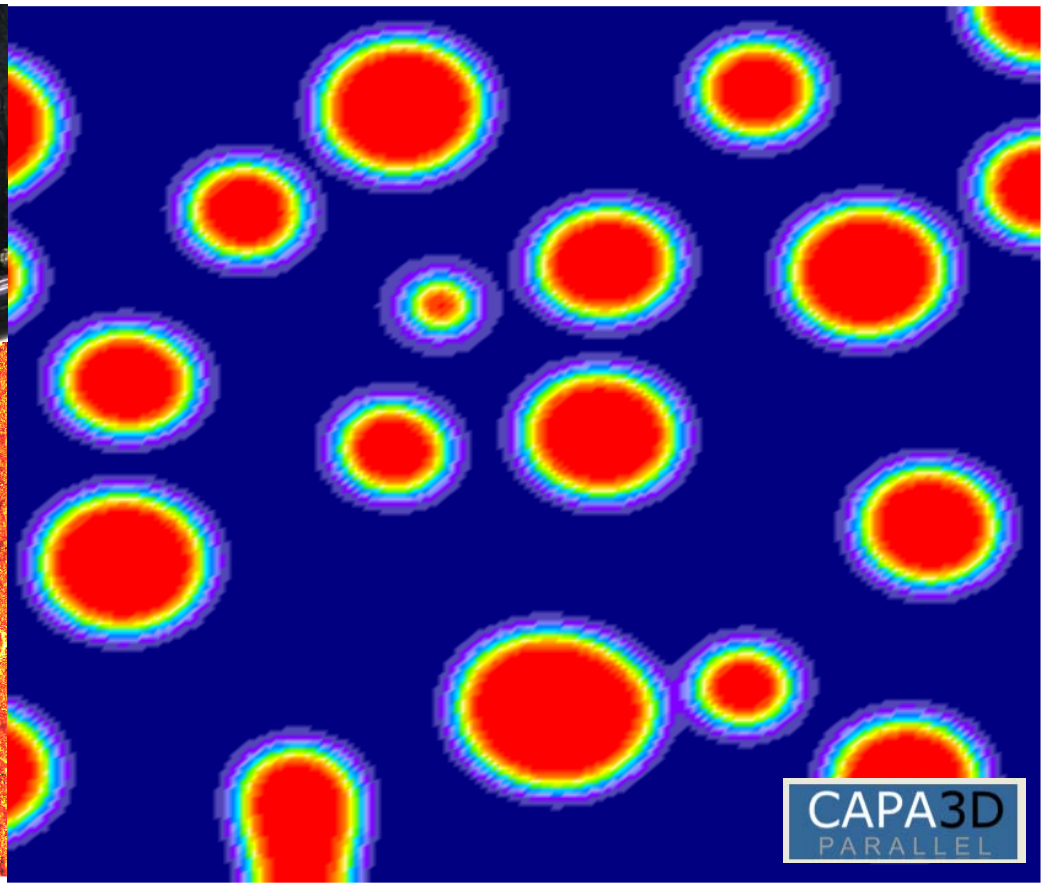

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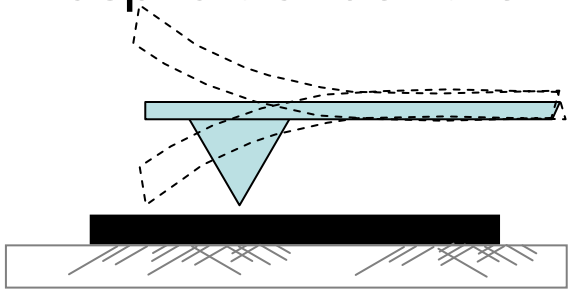

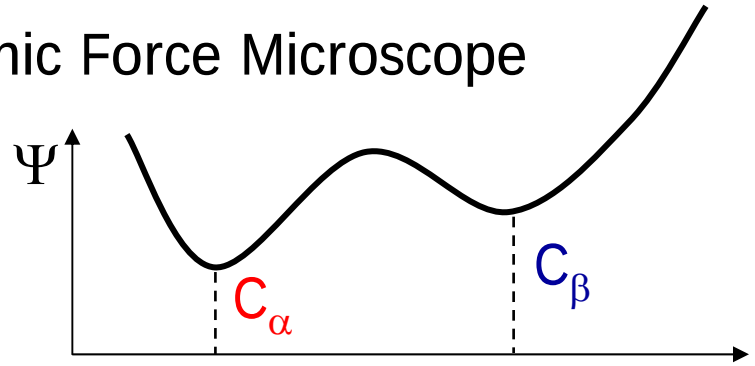

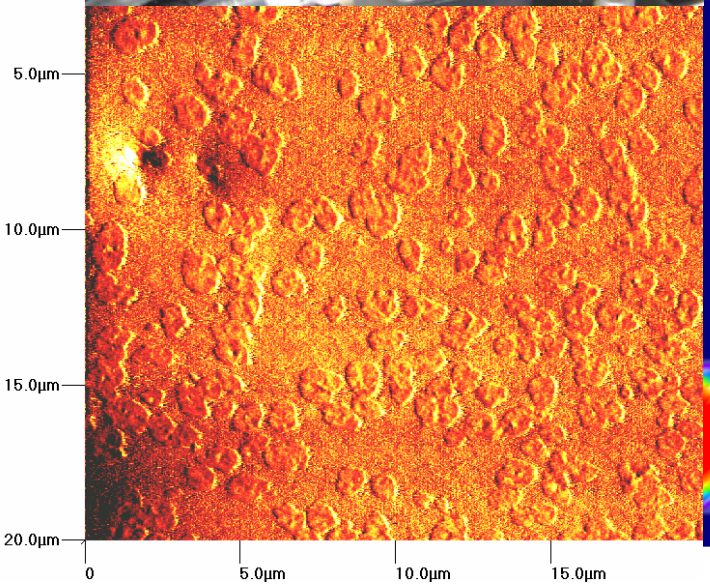

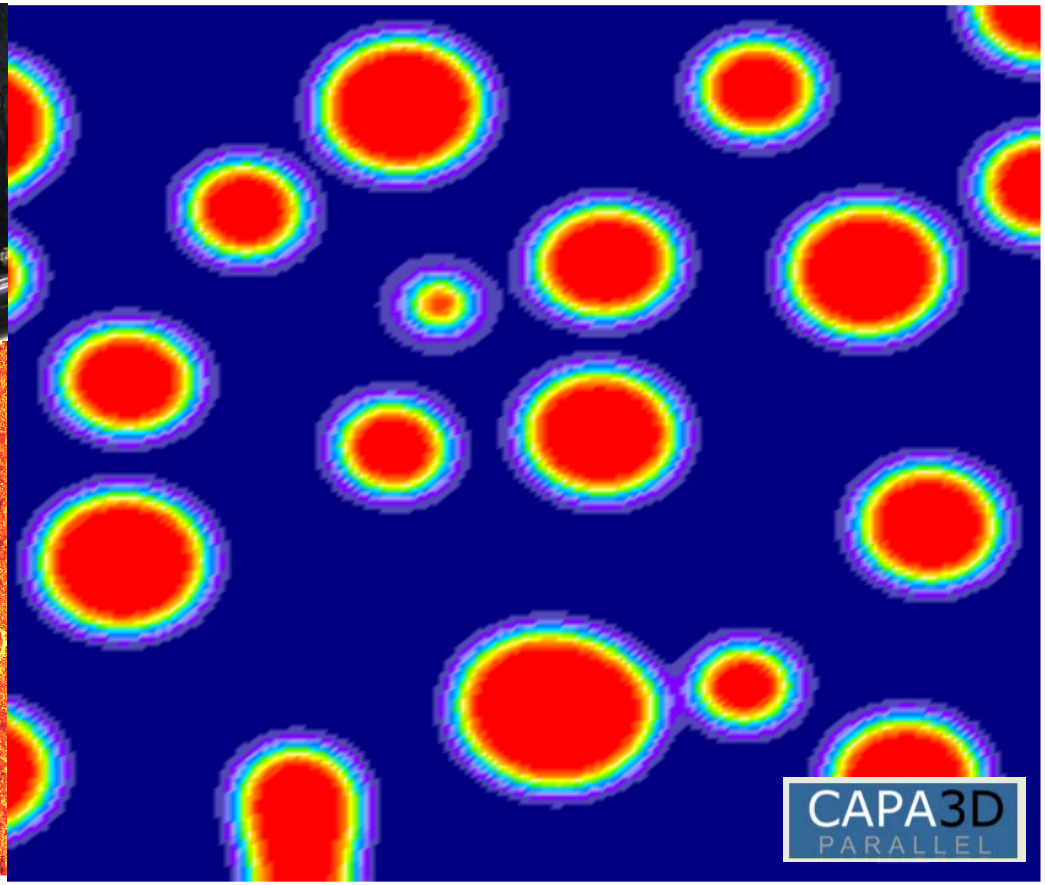

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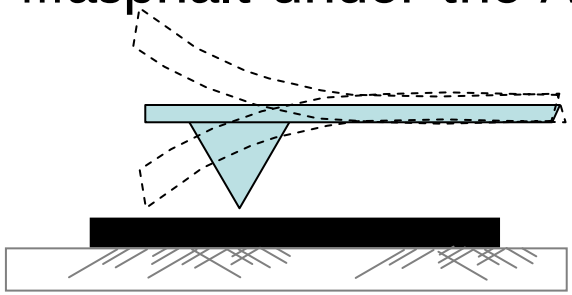
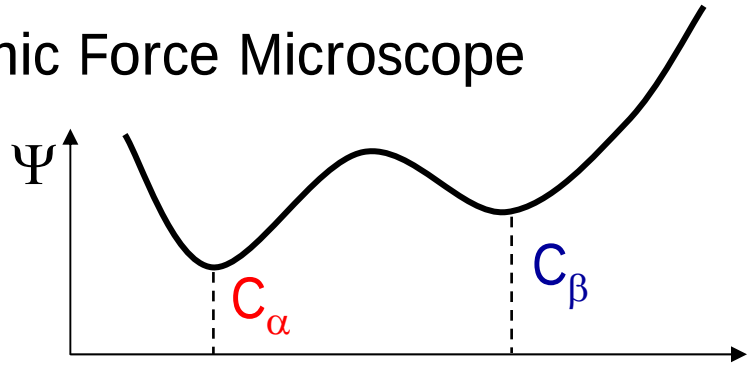
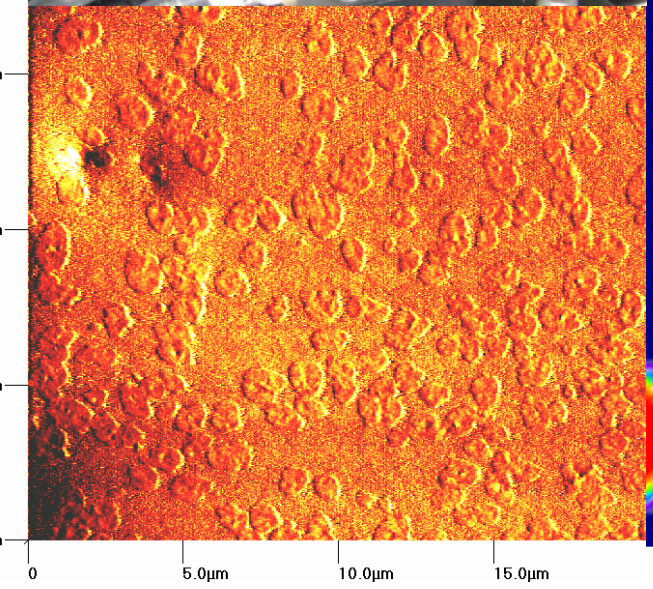
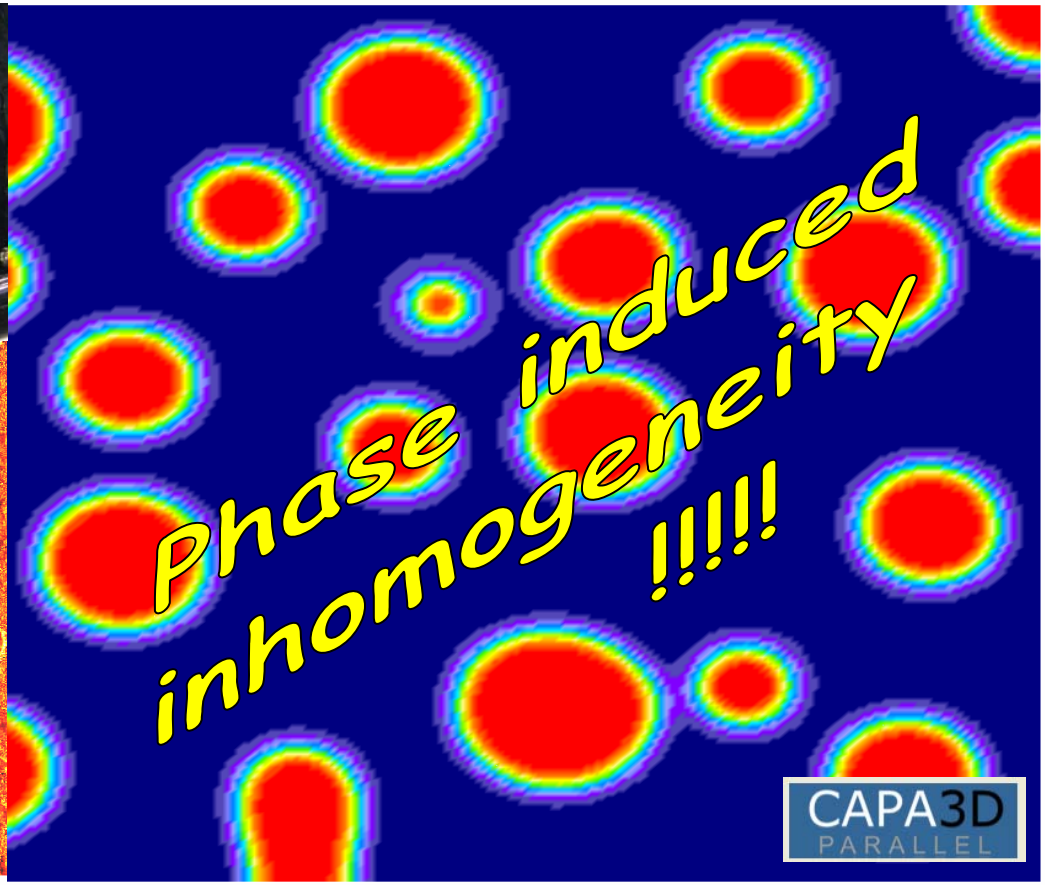
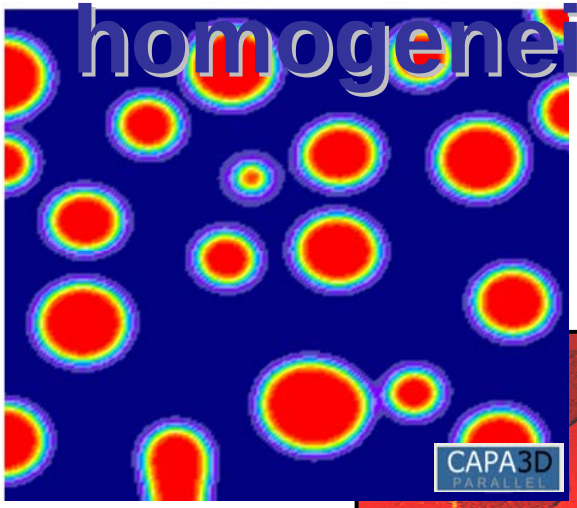


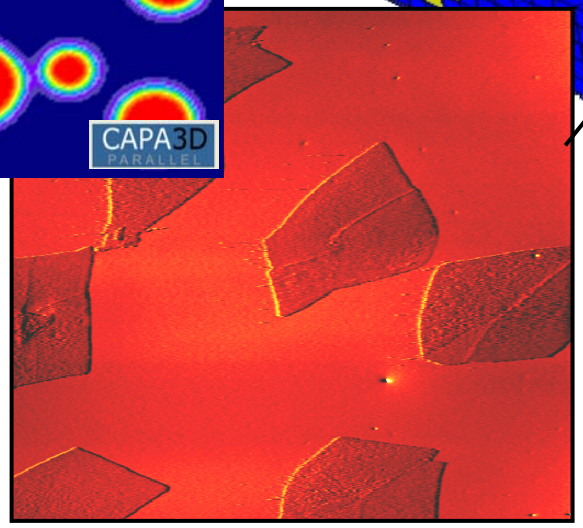


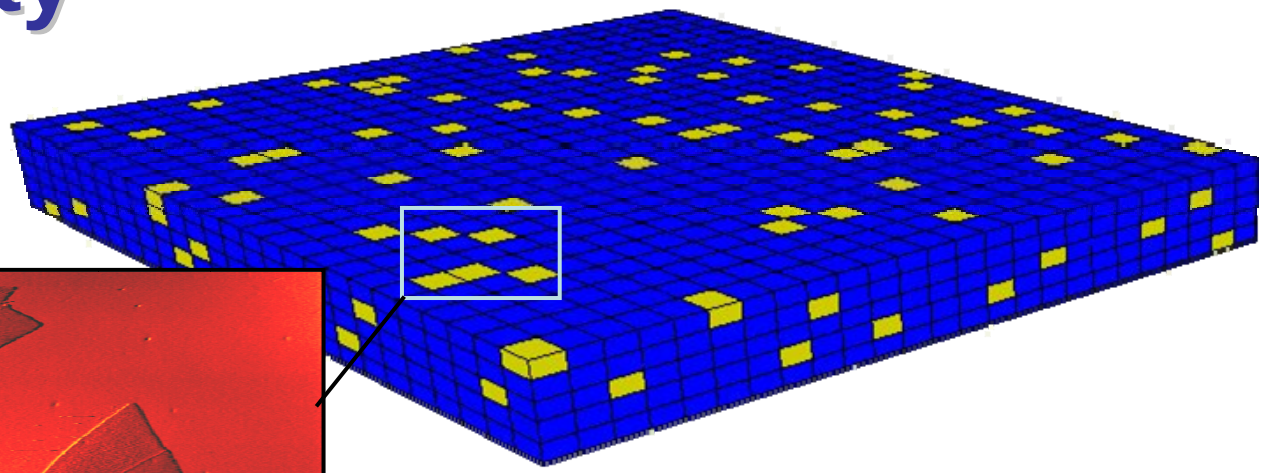




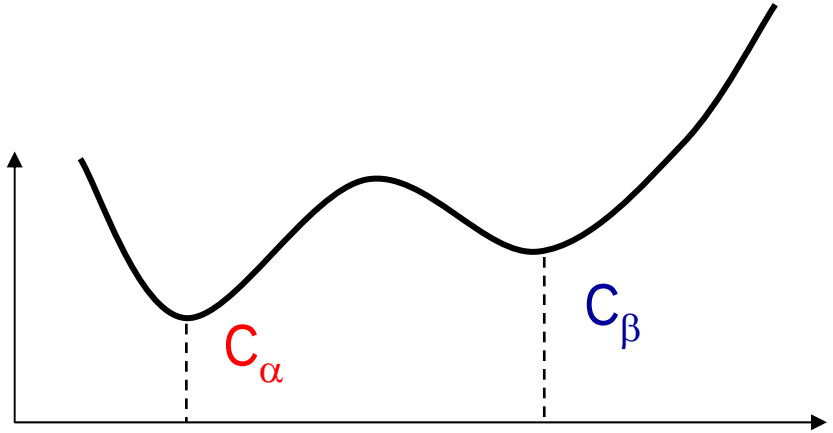
- **Phase induced material in-homogeneity**



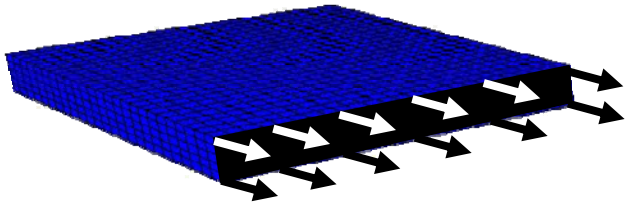


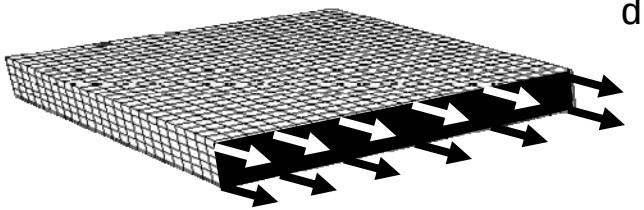


$$\rho_\alpha \frac{DC_\alpha}{Dt} - \mathrm{div}\left(\rho_\alpha \underset{\sim}{M} \cdot \nabla \mu_\alpha\right) = 0$$



Micro-scale mechanical testing of homogeneous specimen





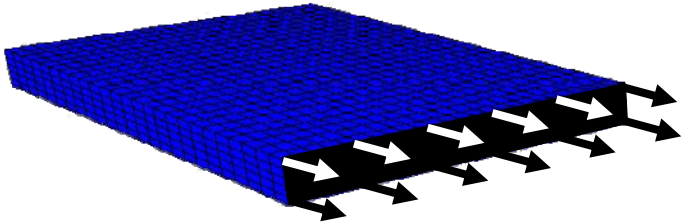
displacements

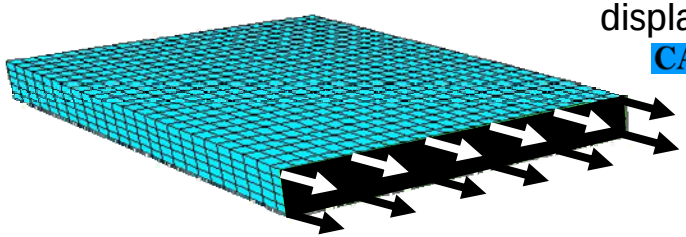
CAPA3D

normal stresses

CAPA3D

Micro-scale mechanical testing of homogeneous specimen





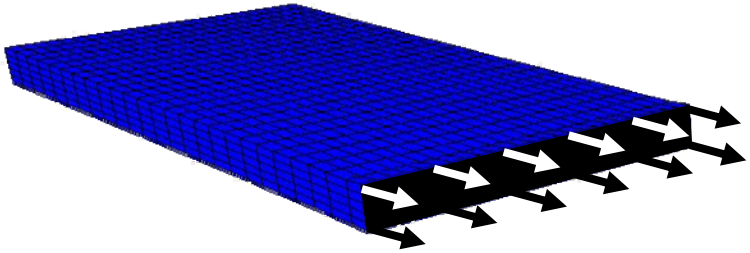
displacements

CAPA3D

normal stresses

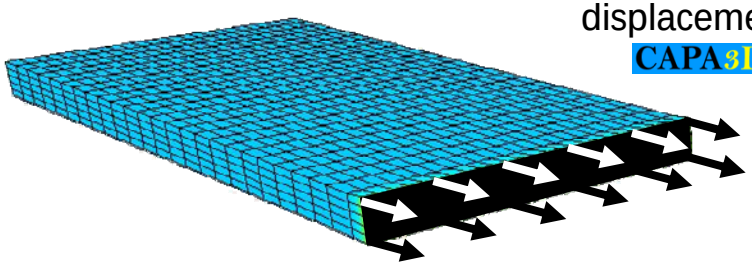
CAPA3D

Micro-scale mechanical testing of homogeneous specimen



displacements

CAPA3D



normal stresses

CAPA3D

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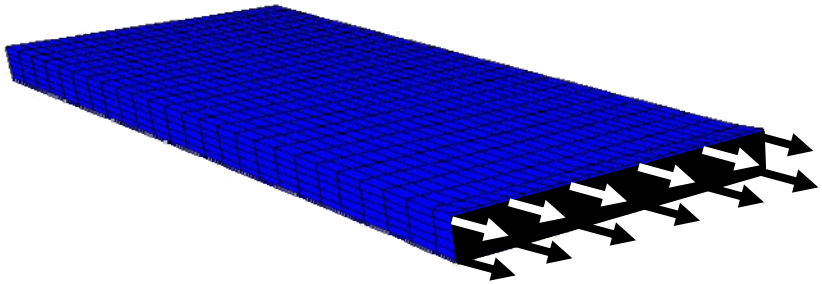
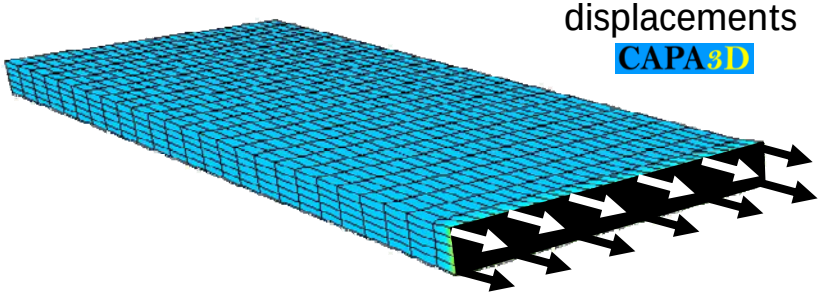


displacements

CAPA3D



normal stresses

CAPA3D

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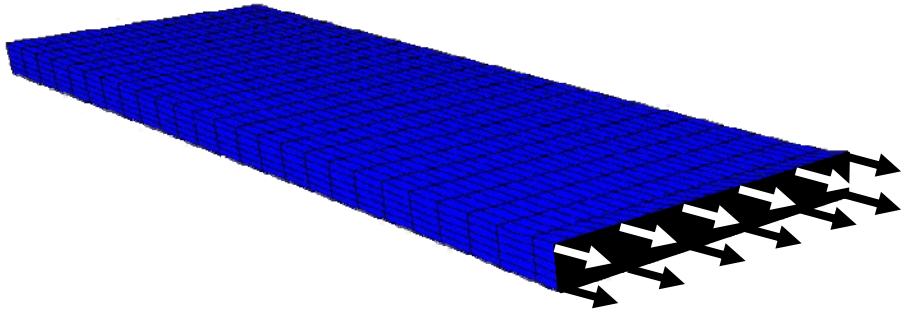
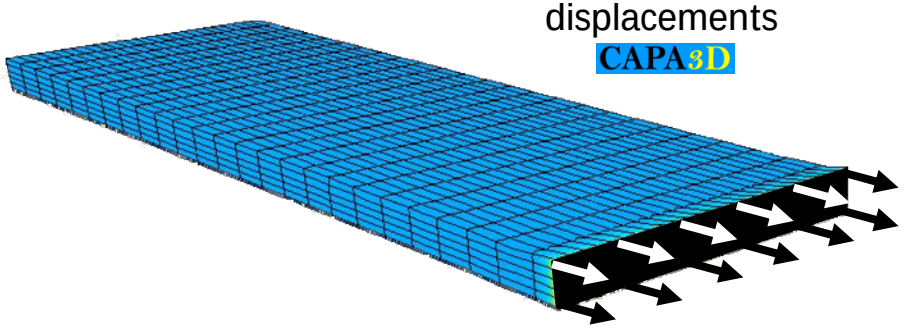


displacements

CAPA3D



normal stresses

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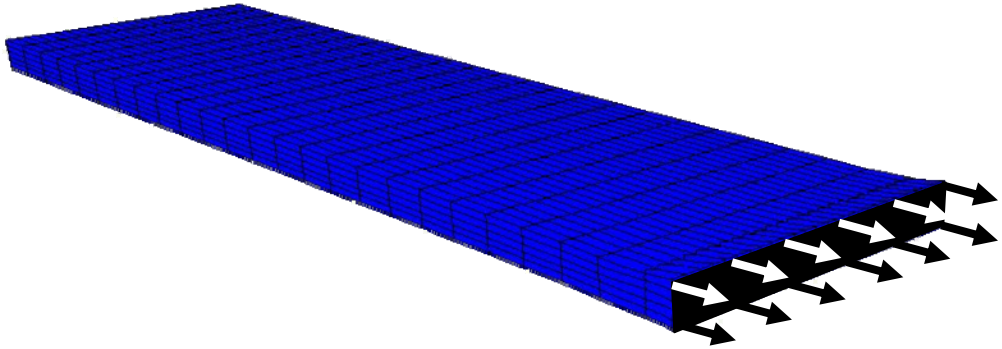
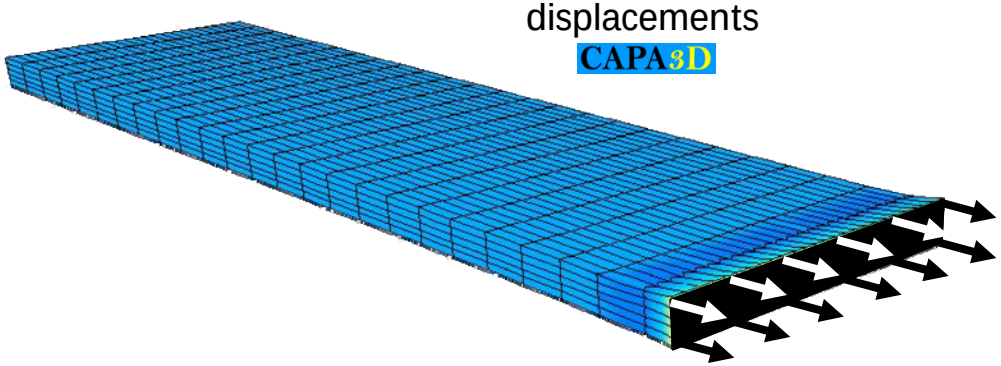


displacements

CAPA3D



normal stresses

CAPA3D

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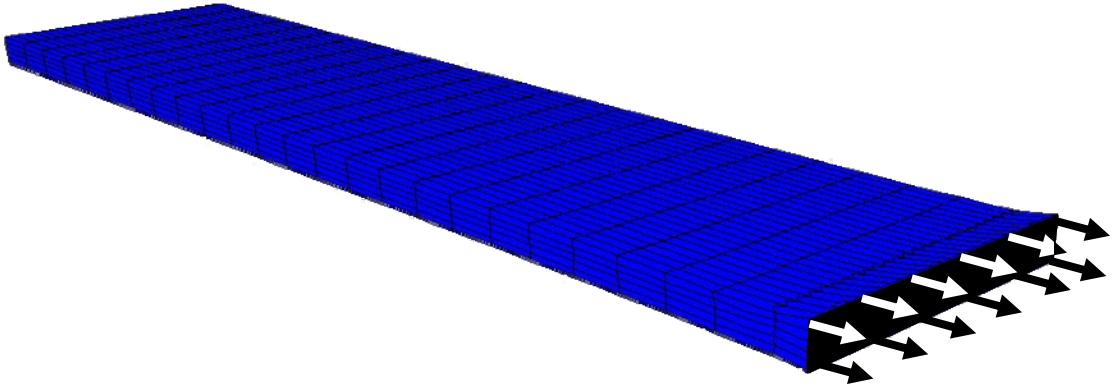

displacements

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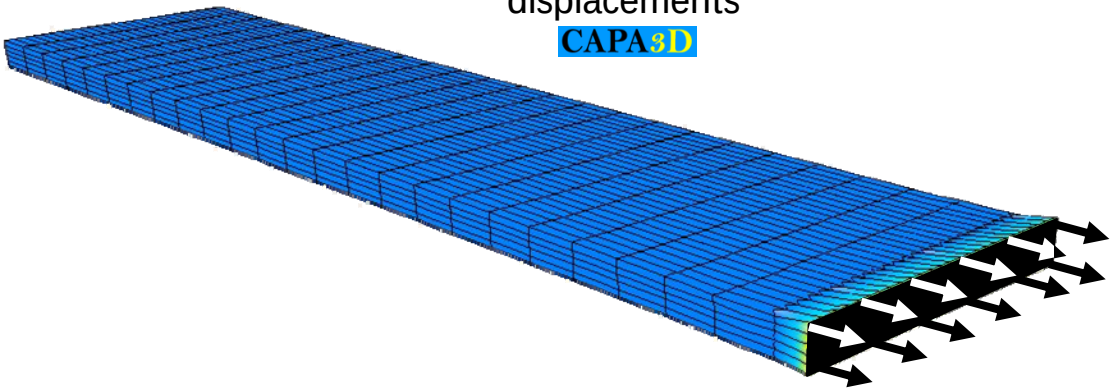

normal stresses

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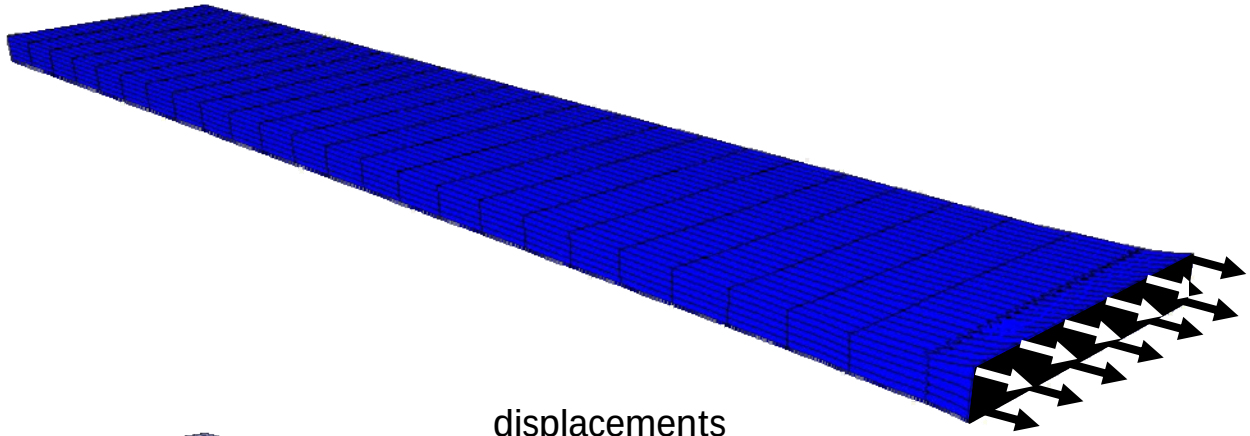
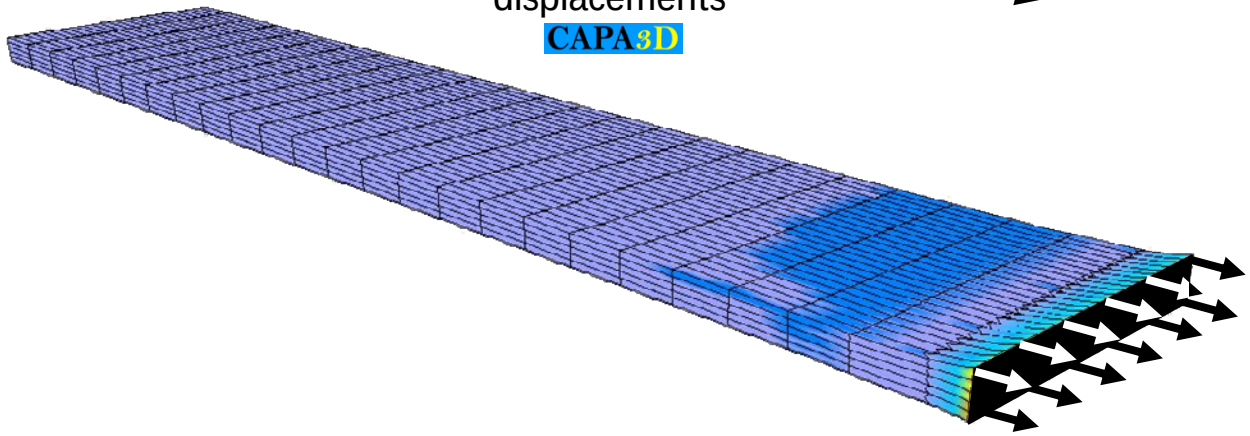


displacements

CAPA3D



normal stresses

CAPA3D

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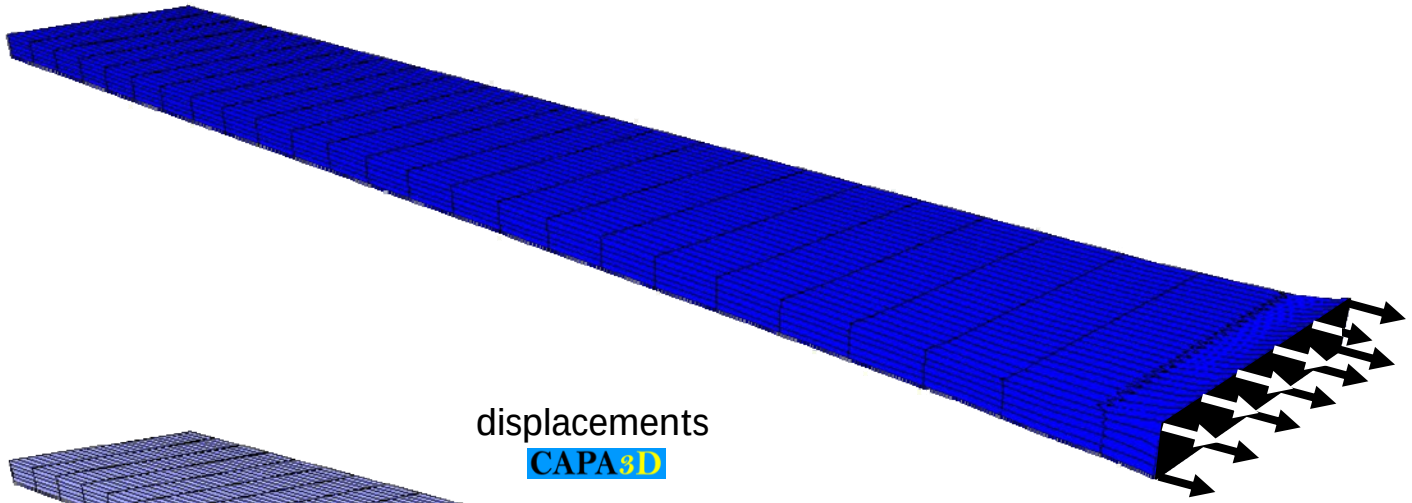
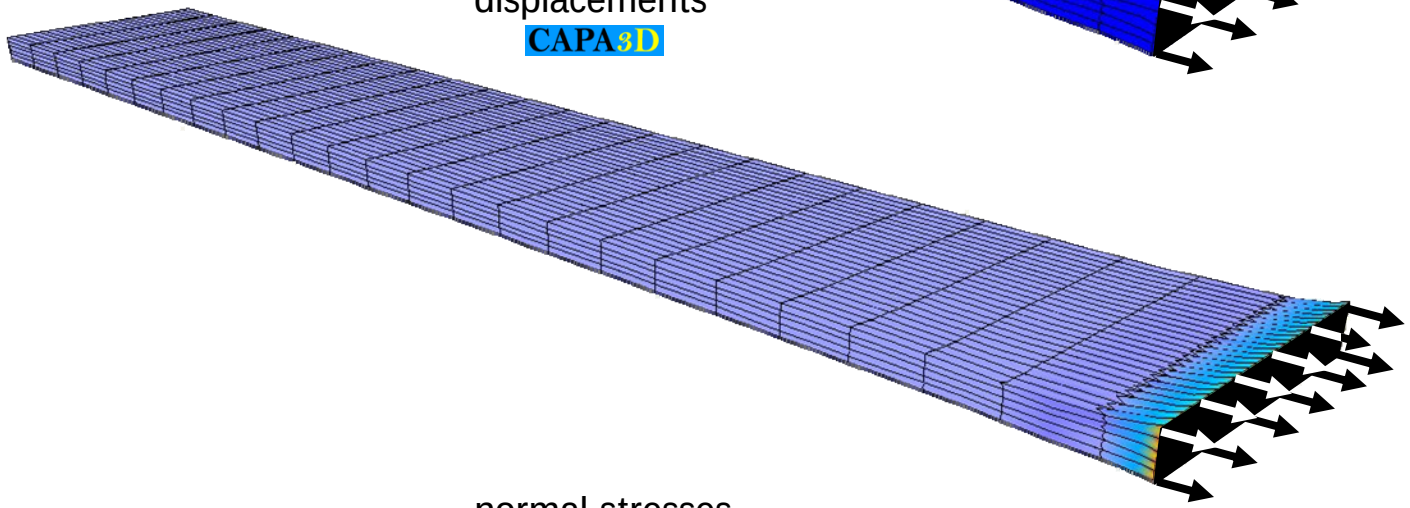


displacements

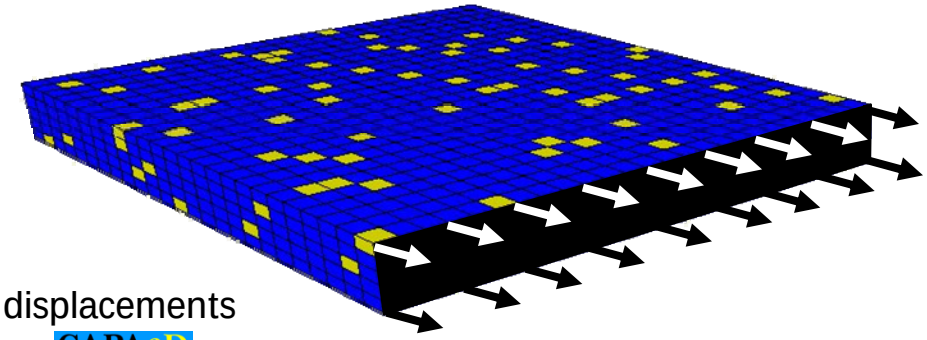
CAPA3D



normal stresses

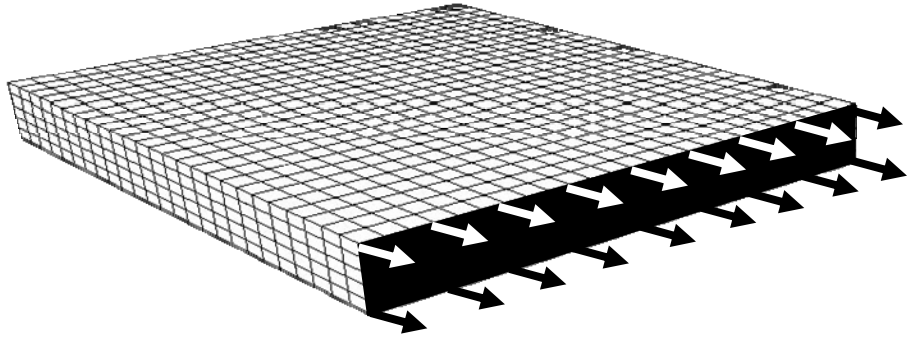
CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen



displacements

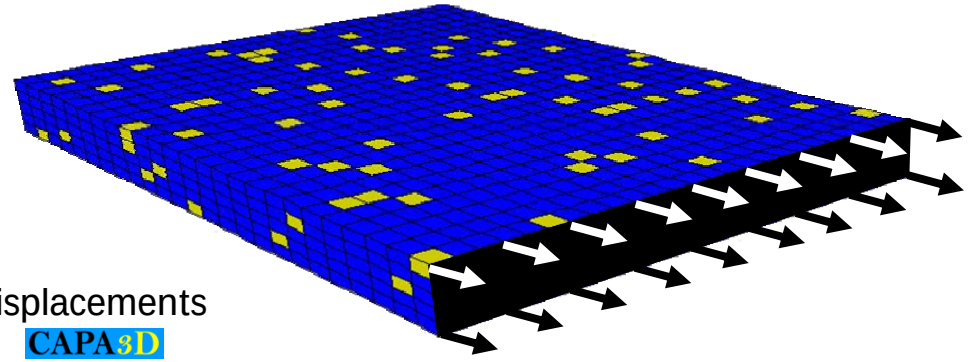
CAPA3D



normal stresses

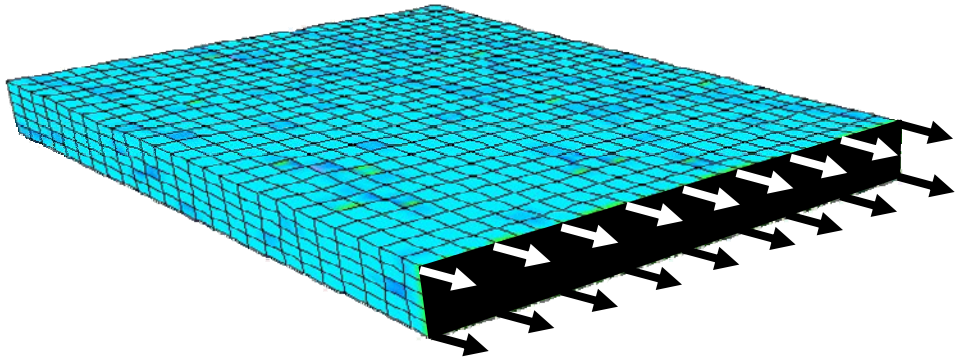
CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen



displacements

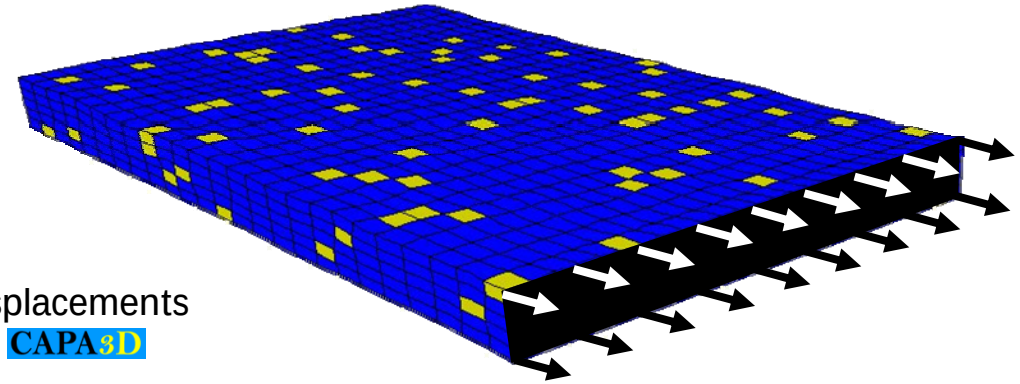
CAPA3D



normal stresses

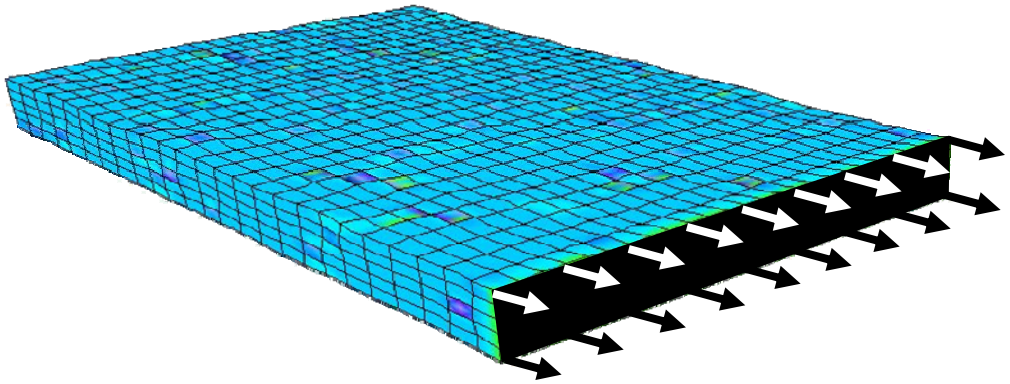
CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen



displacements

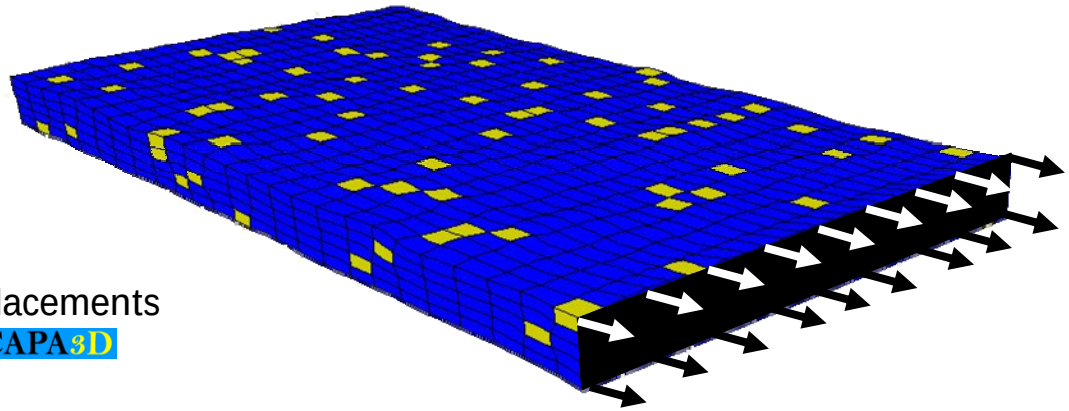
CAPA3D



normal stresses

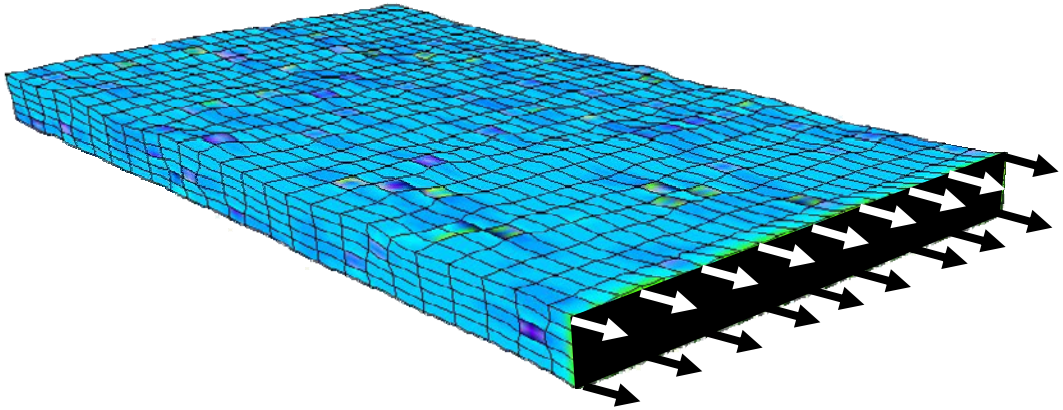
CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen



displacements

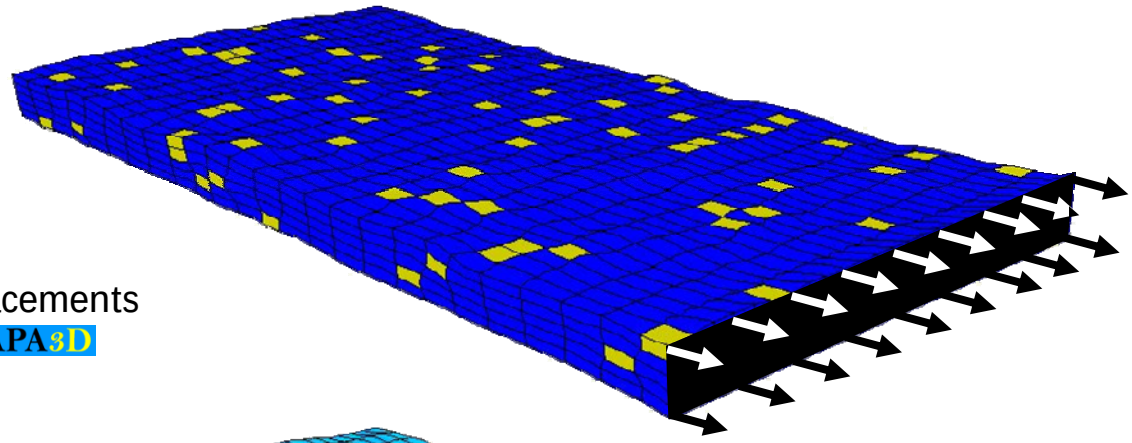
CAPA3D



normal stresses

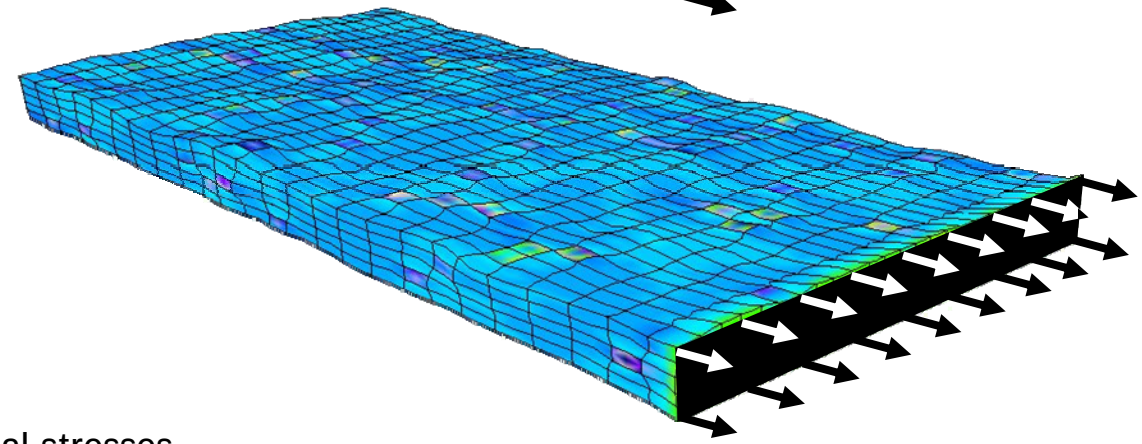
CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen



displacements

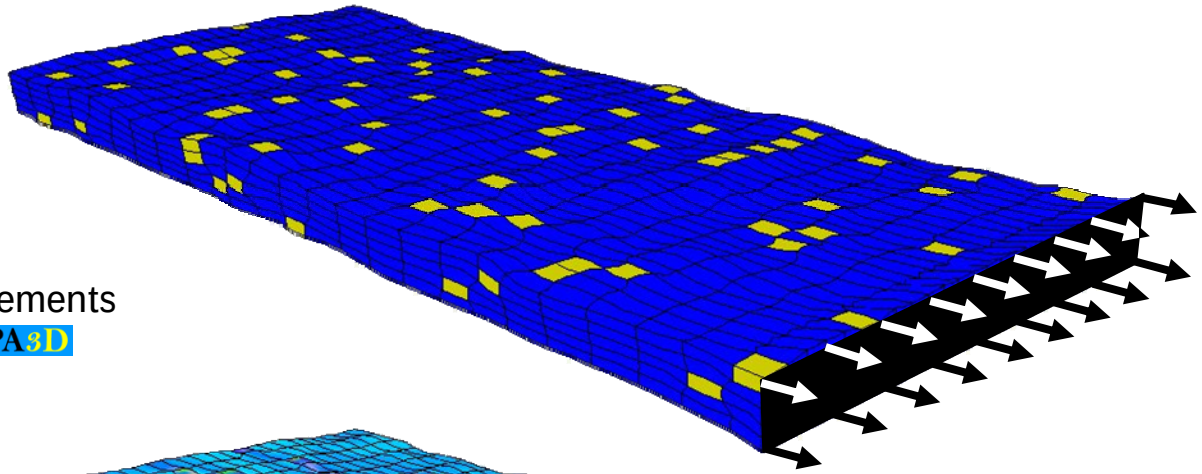
CAPA3D



normal stresses

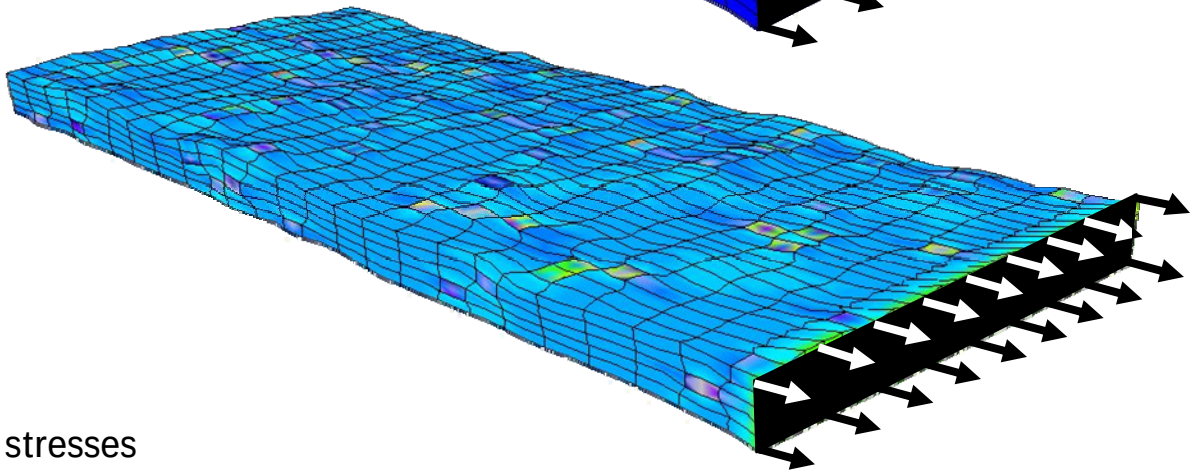
CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen



displacements

CAPA3D

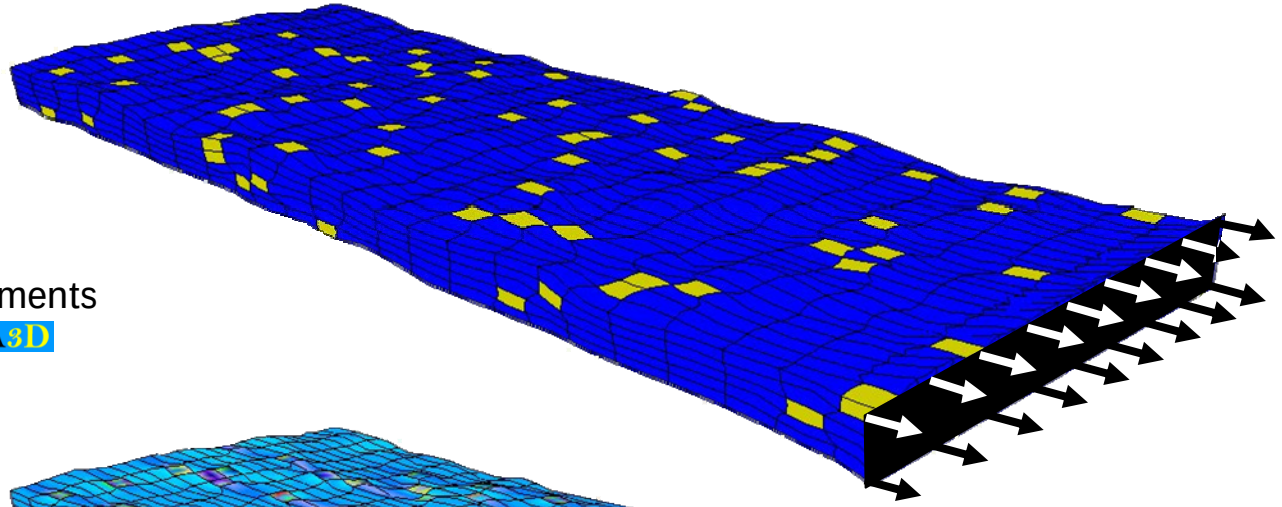


normal stresses

CAPA3D

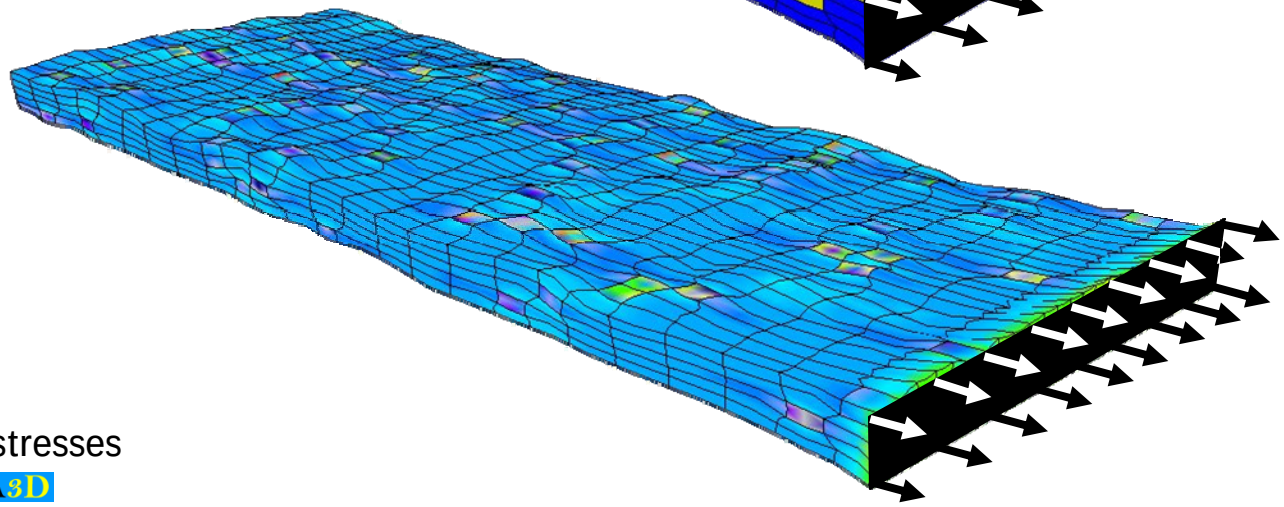
Micro-scale mechanical testing of inhomogeneous specimen

TU Delft



displacements

CAPA3D

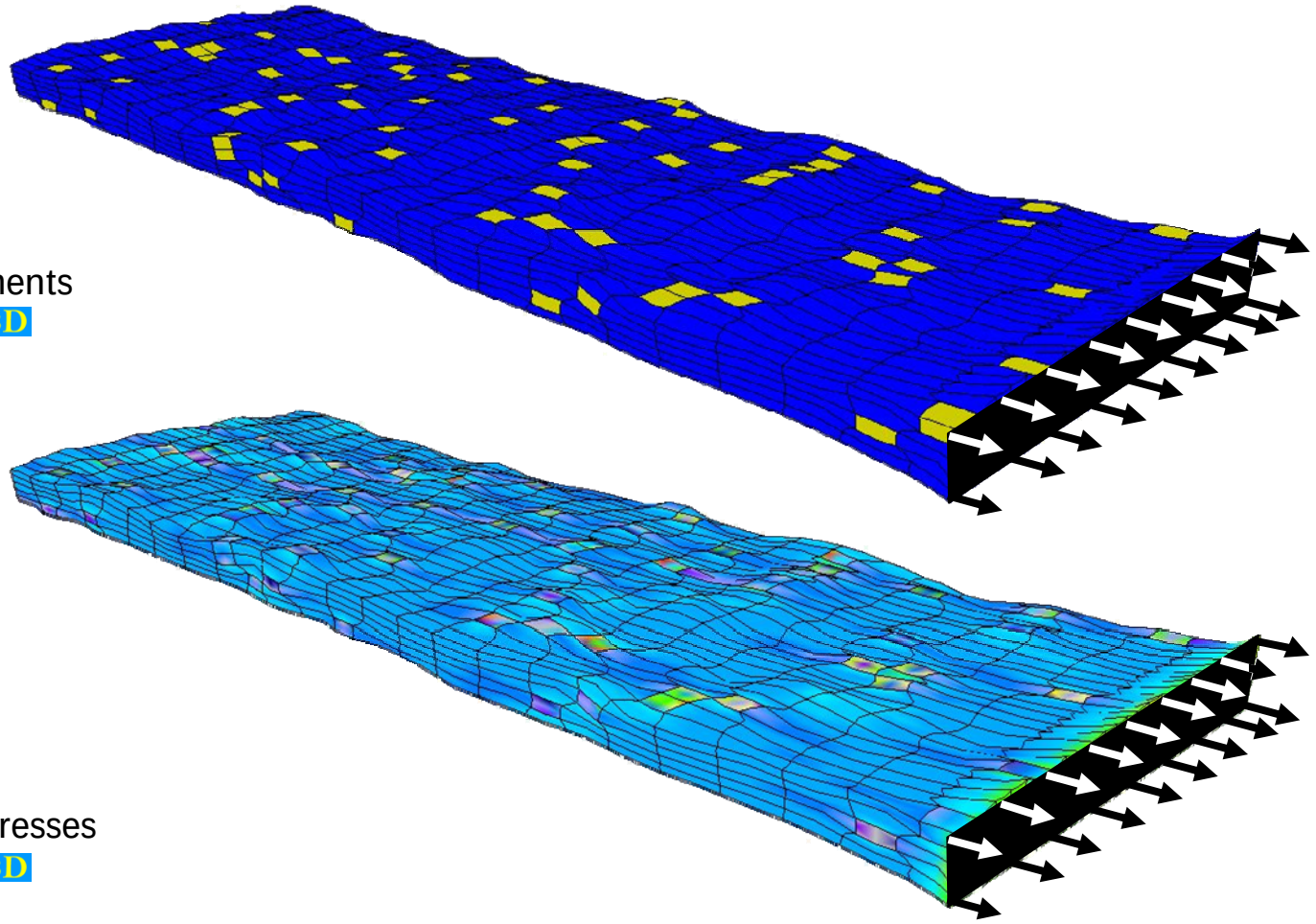


normal stresses

CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen

TU Delft



displacements

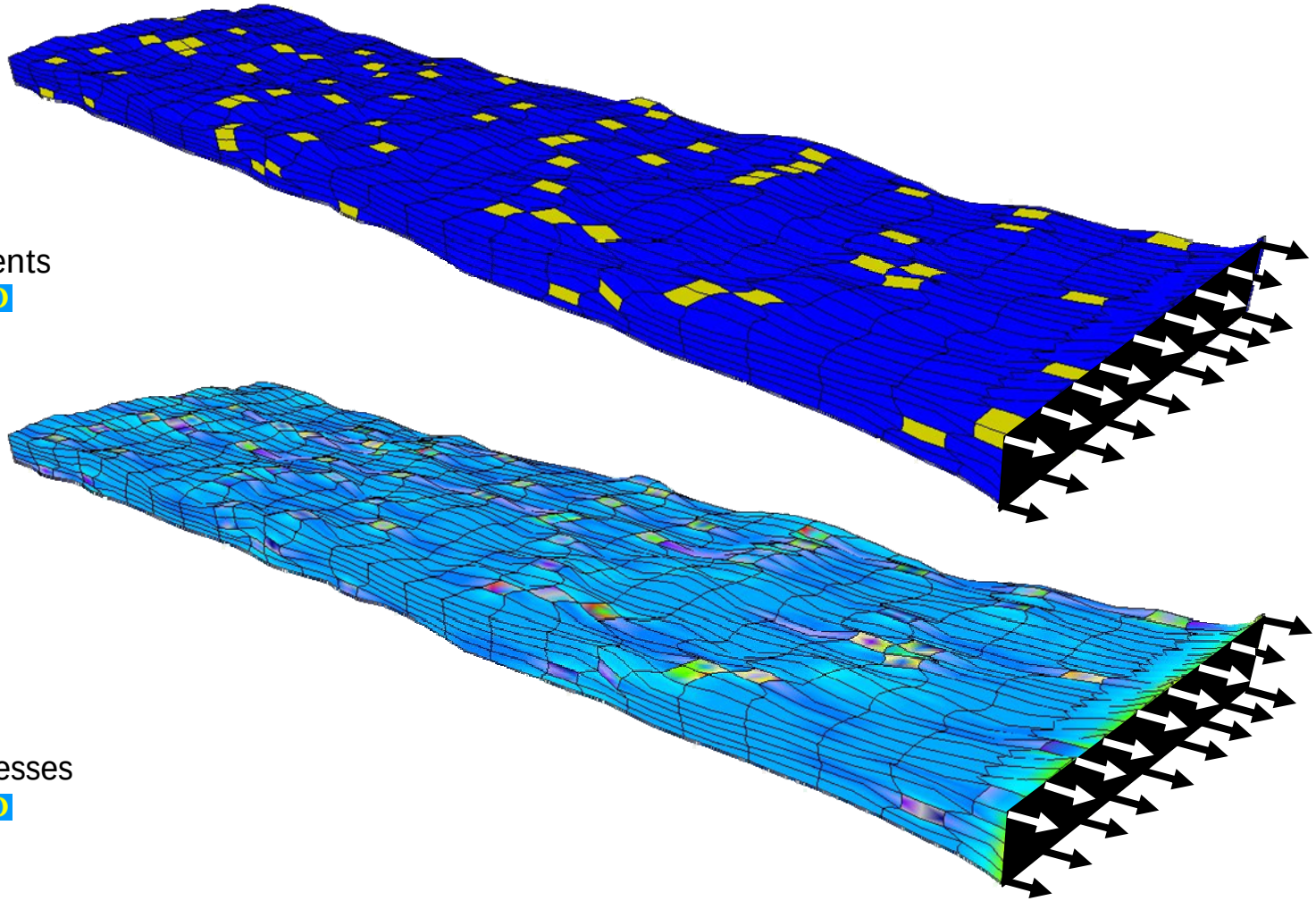
CAPA3D

normal stresses

CAPA3D

Micro-scale mechanical testing of inhomogeneous specimen

TU Delft



displacements

CAPA3D

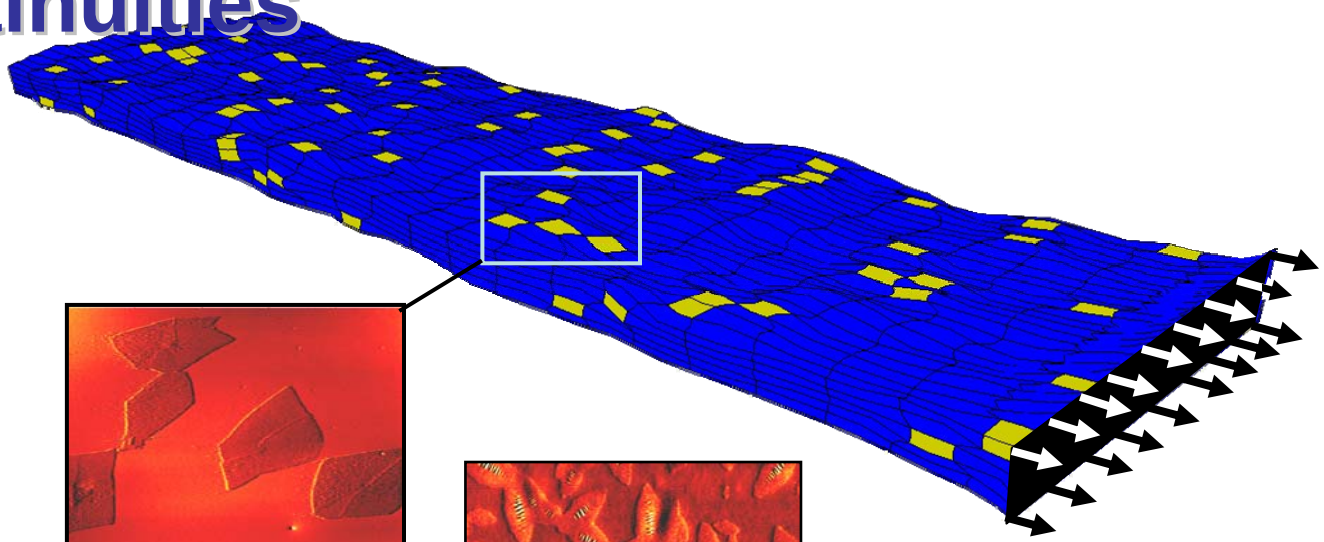
normal stresses

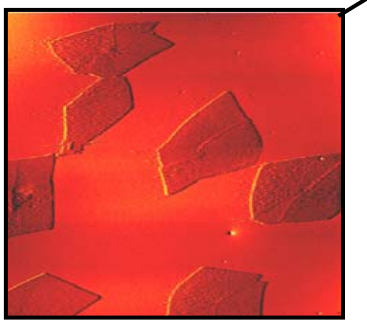
CAPA3D

- **Phase induced stiffness discontinuities**

displacements

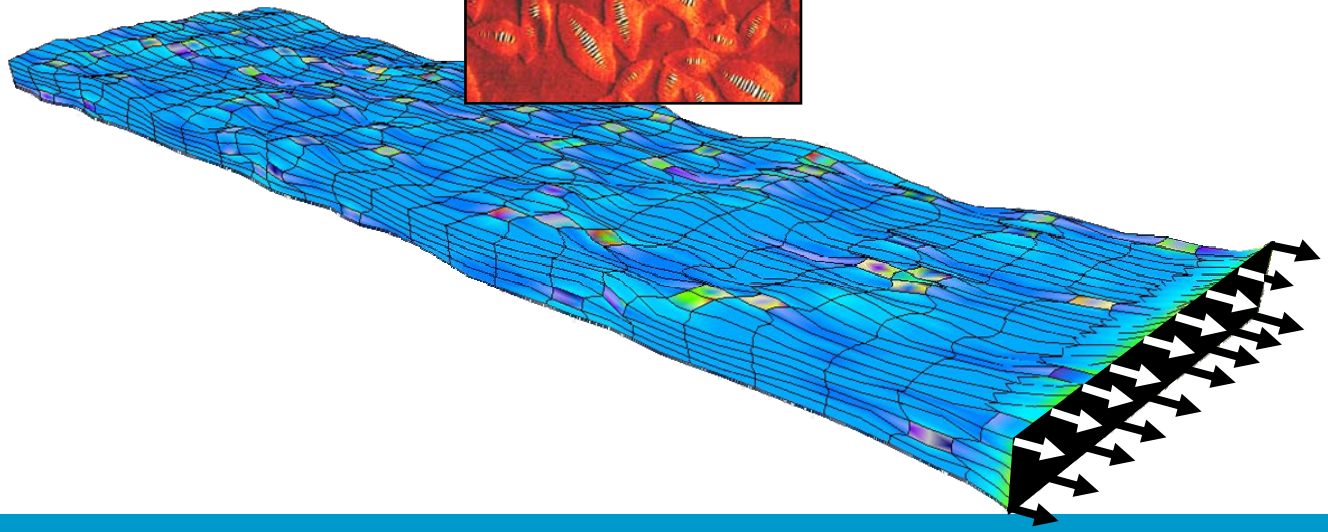
CAPA3D



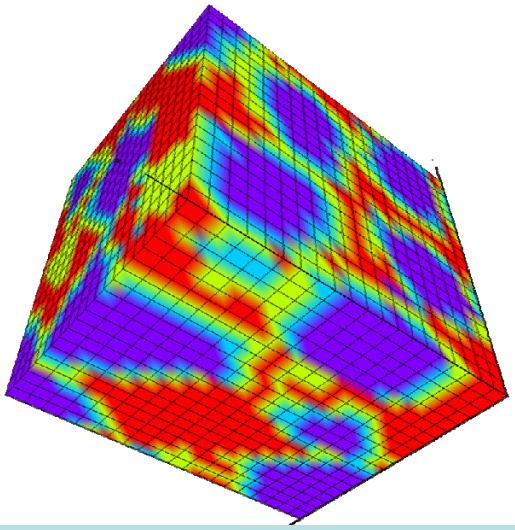


normal stresses

CAPA3D



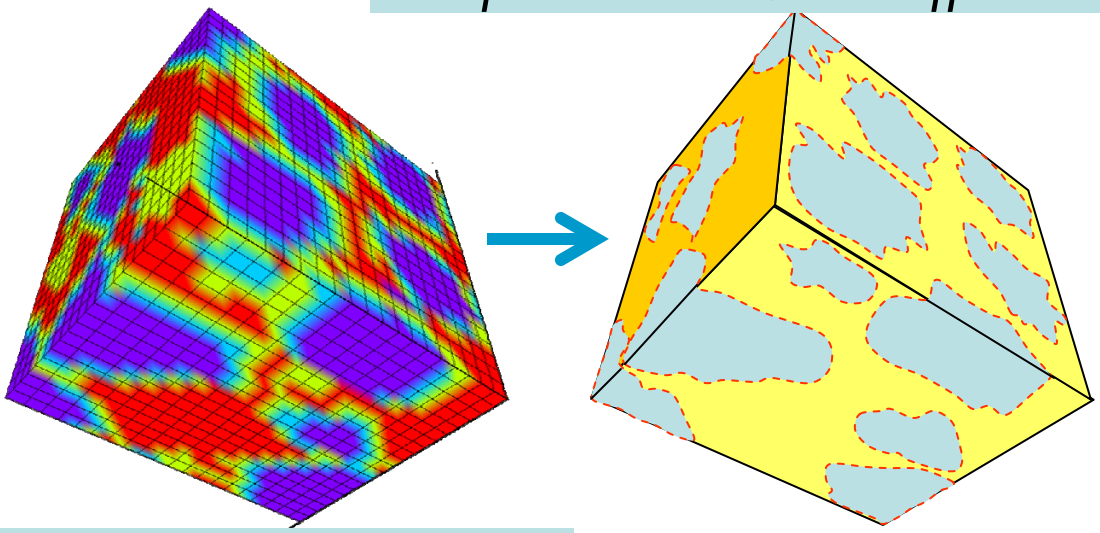
- **Mixing theory**



phase separated bitumen

- **Mixing theory**

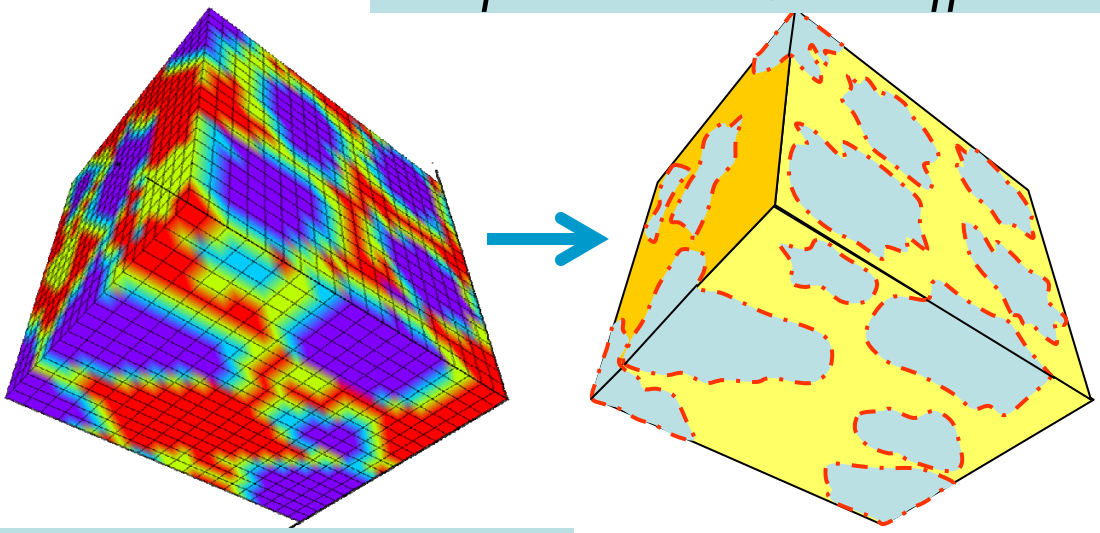
interfaces → natural stiffness discontinuities



phase separated bitumen

- **Mixing theory**

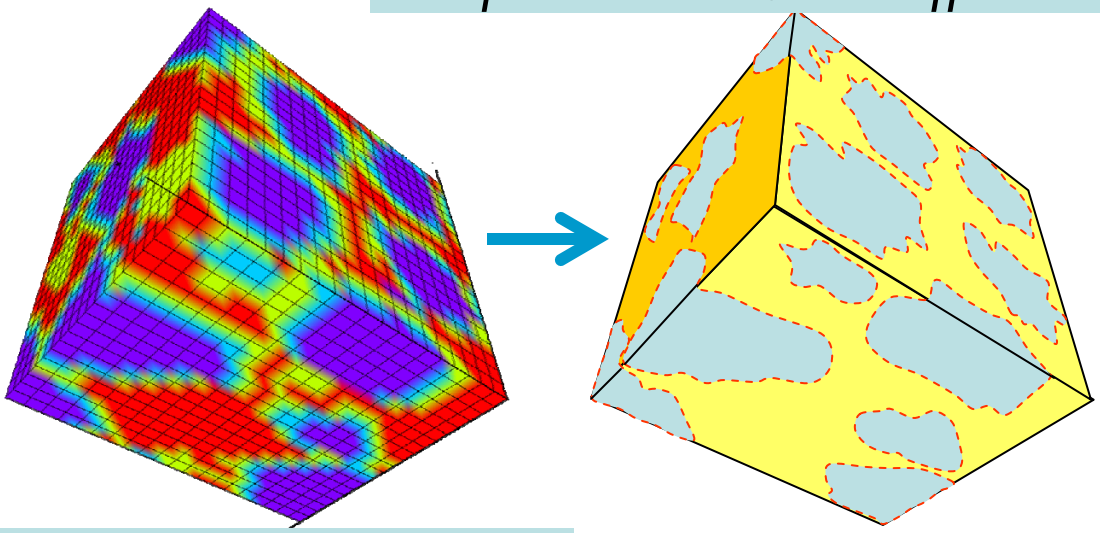
interfaces → natural stiffness discontinuities



phase separated bitumen

- **Mixing theory**

interfaces → natural stiffness discontinuities



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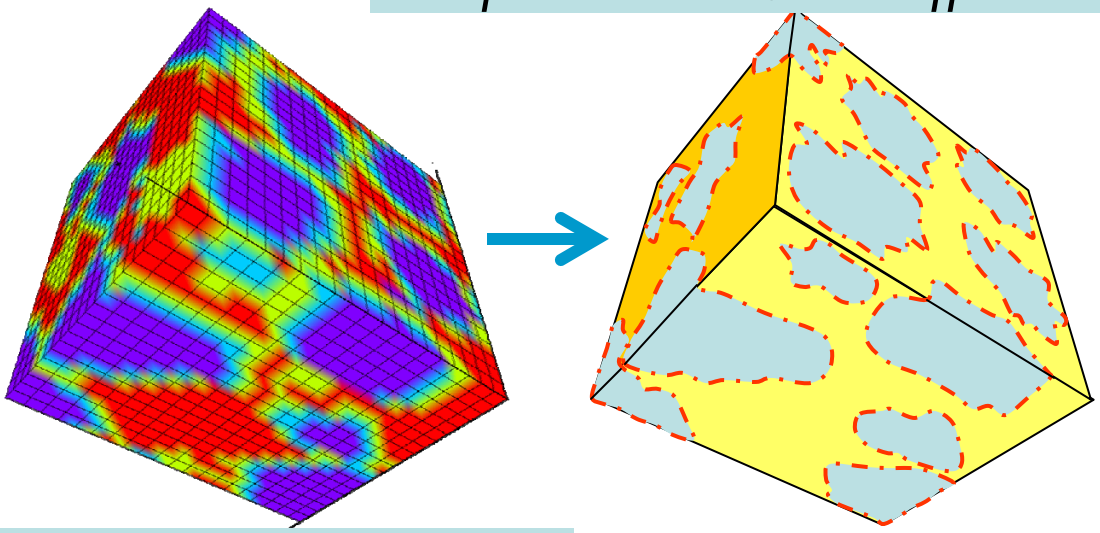

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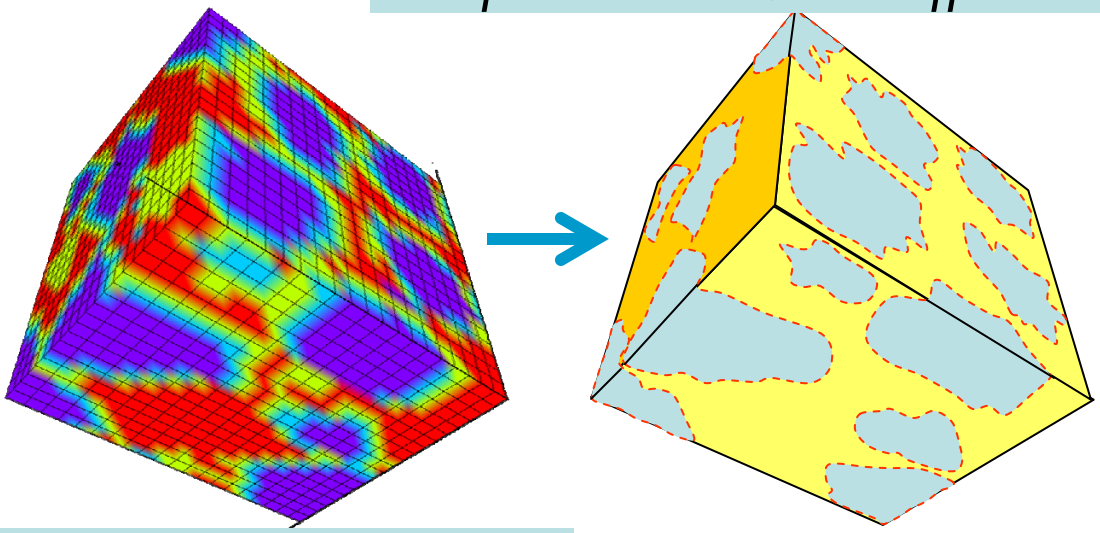

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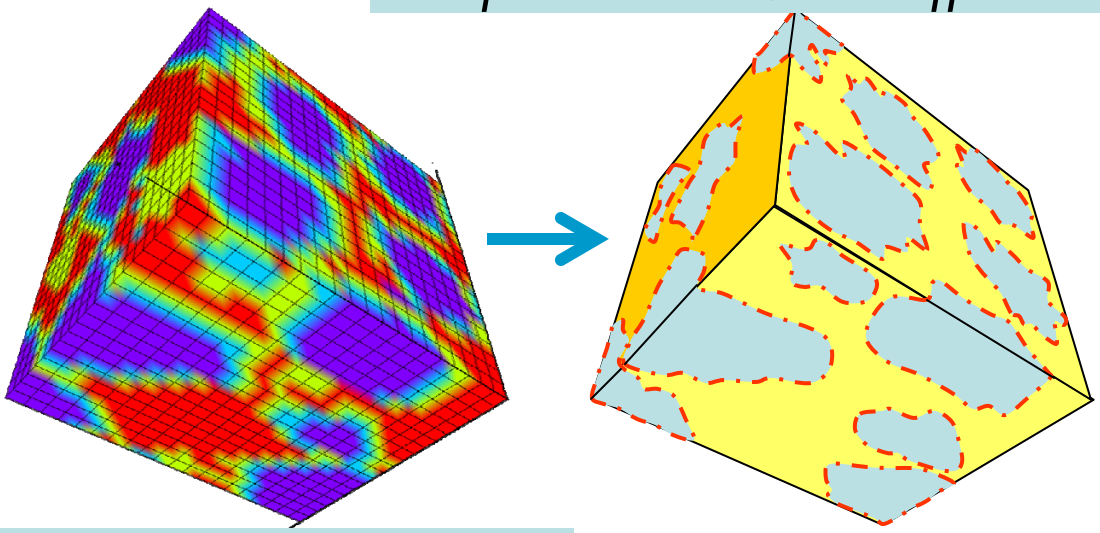

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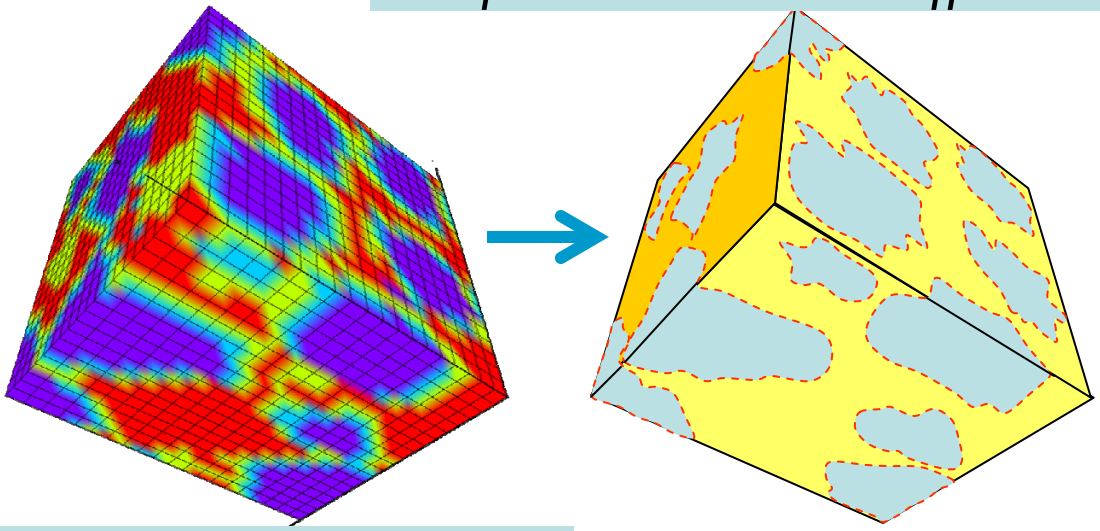
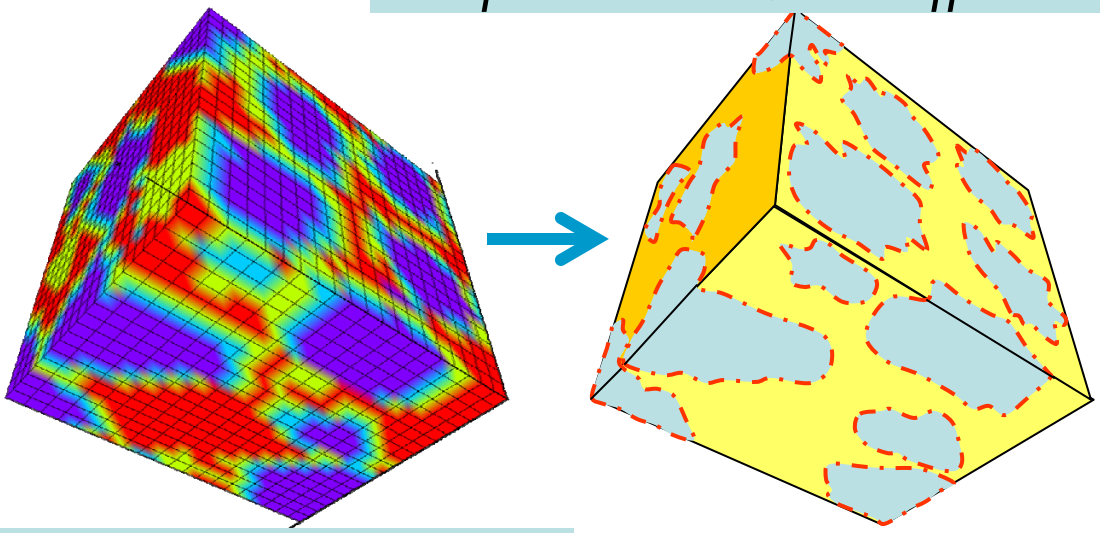


phase separated bitumen

- **Mixing theory**

interfaces → natural stiffness discontinuities



phase separated bitumen

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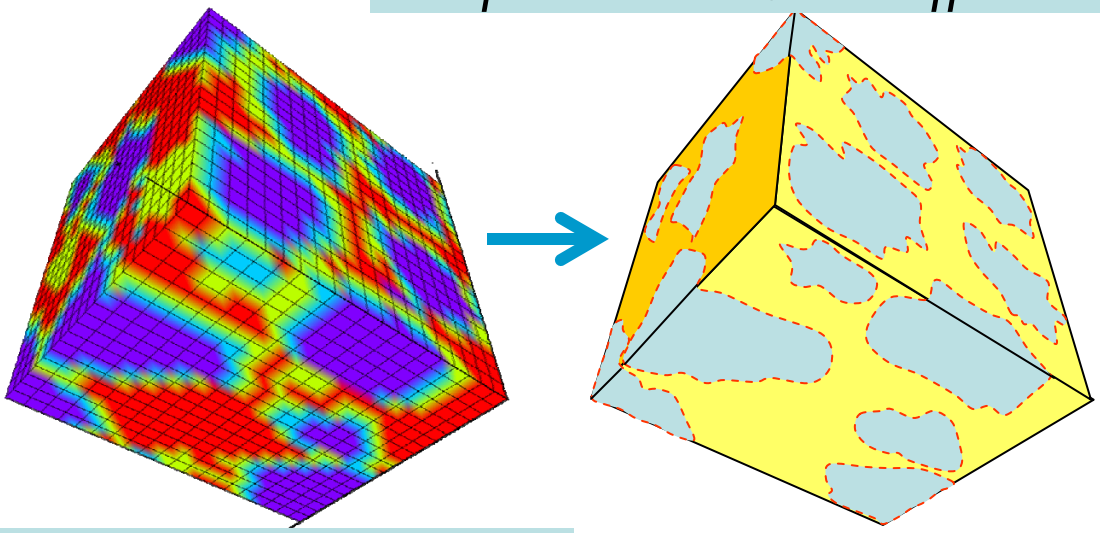

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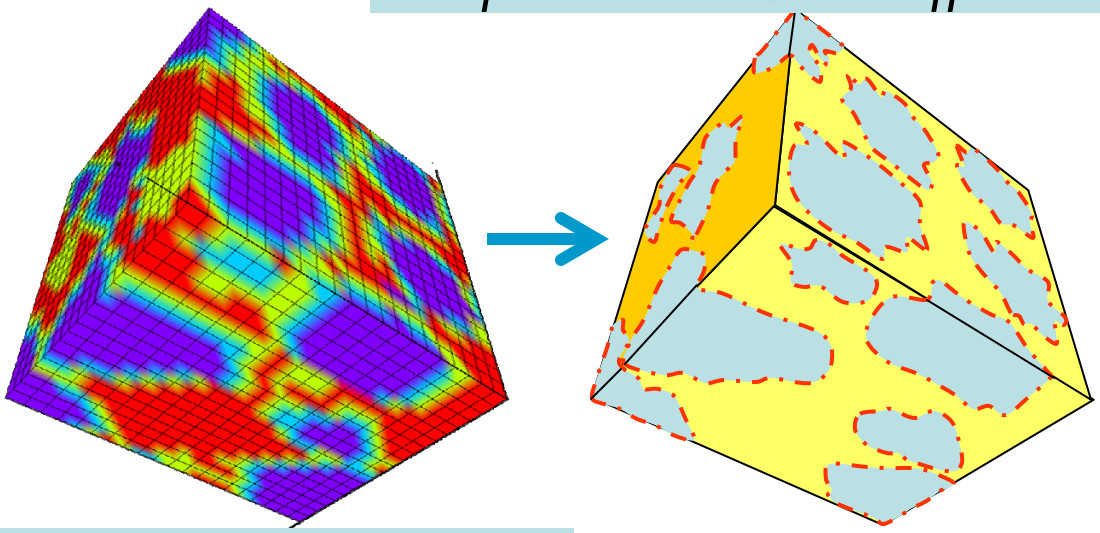
interfaces → natural stiffness discontinuities



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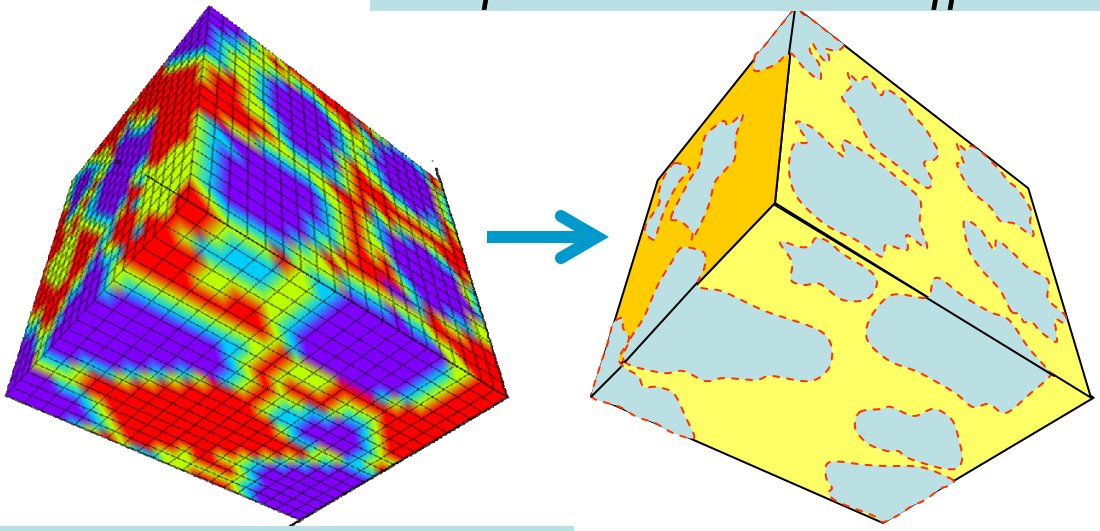

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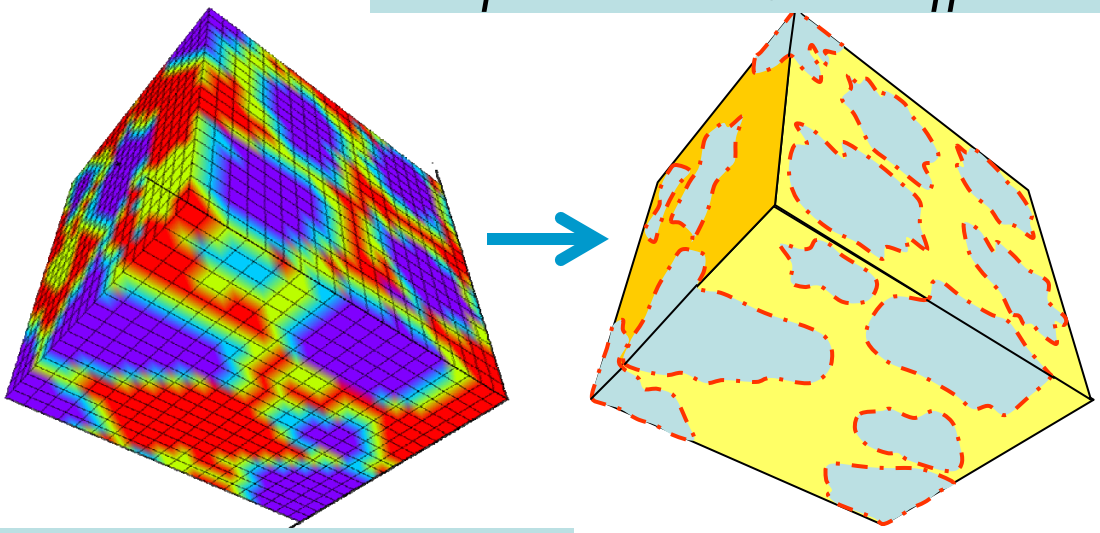
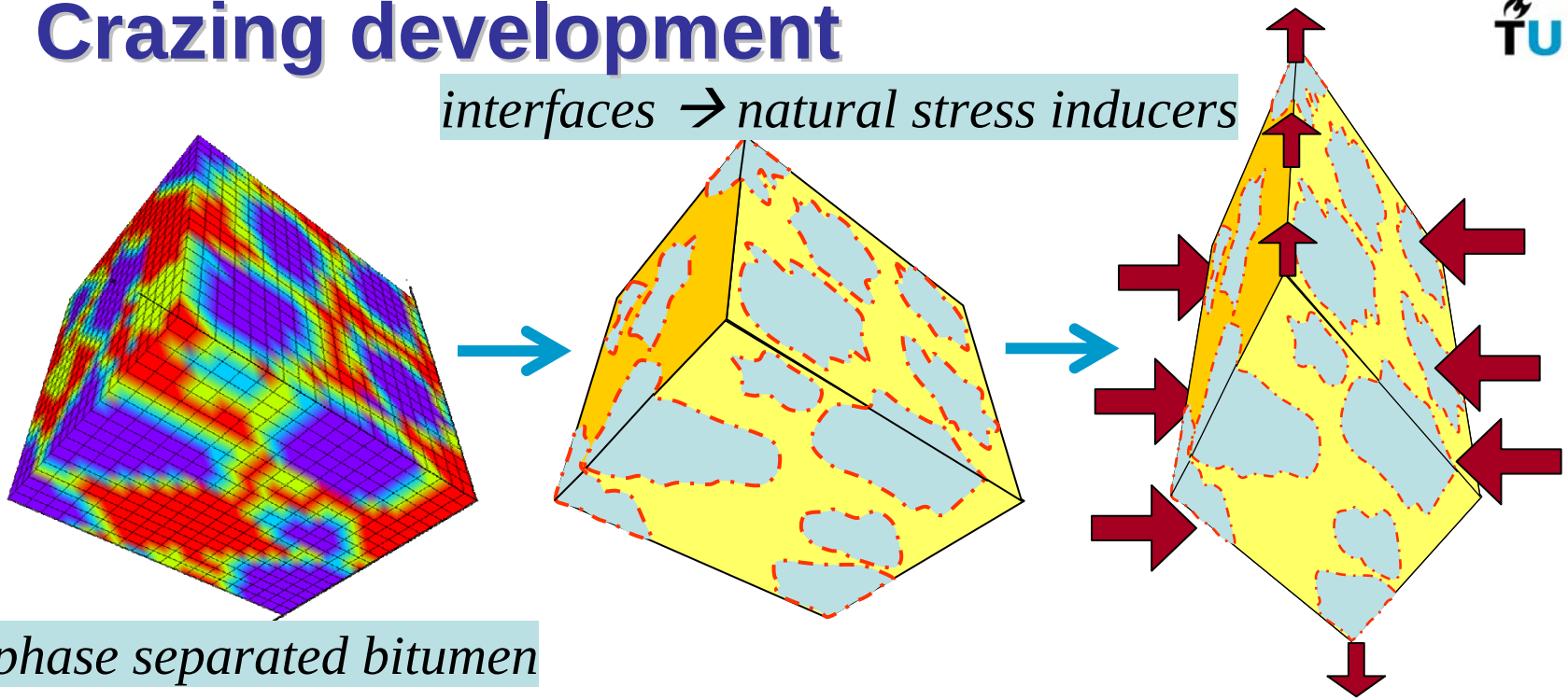


phase separated bitumen

- **Crazing development**

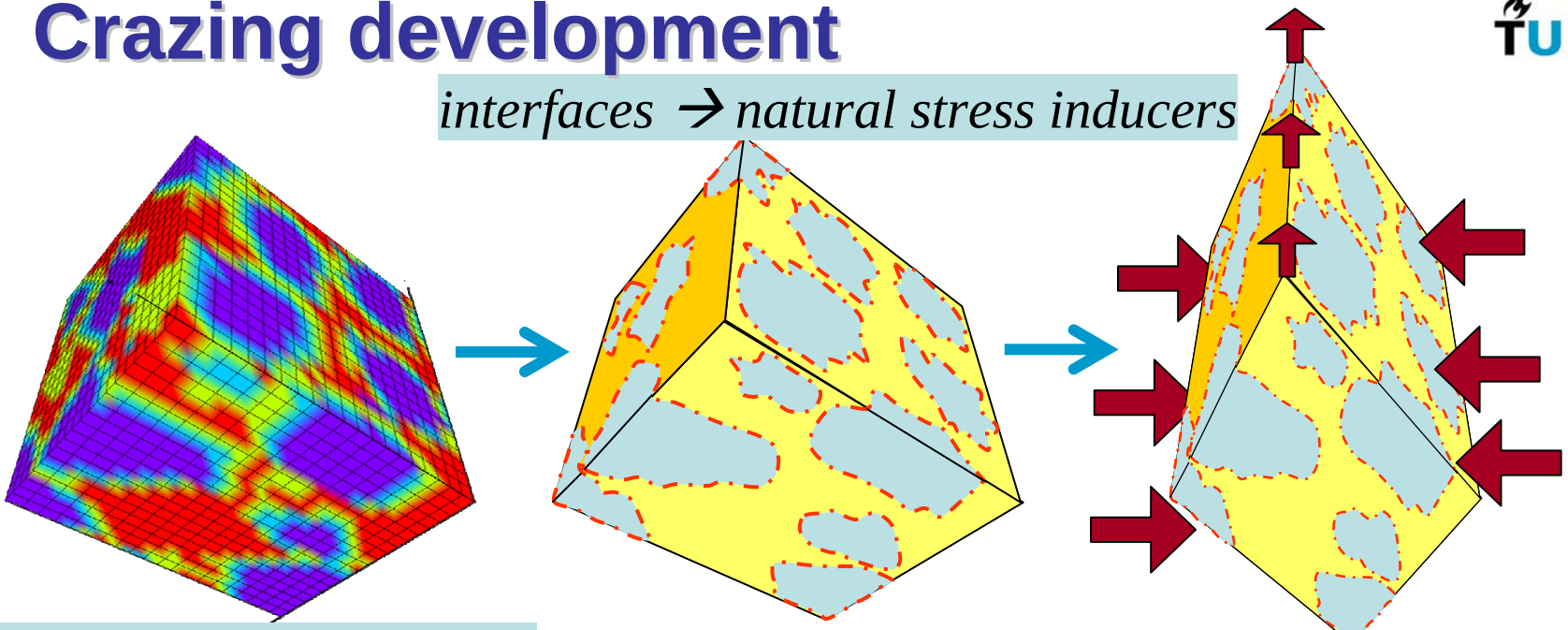
interfaces → natural stress inducers



phase separated bitumen

- **Crazing development**

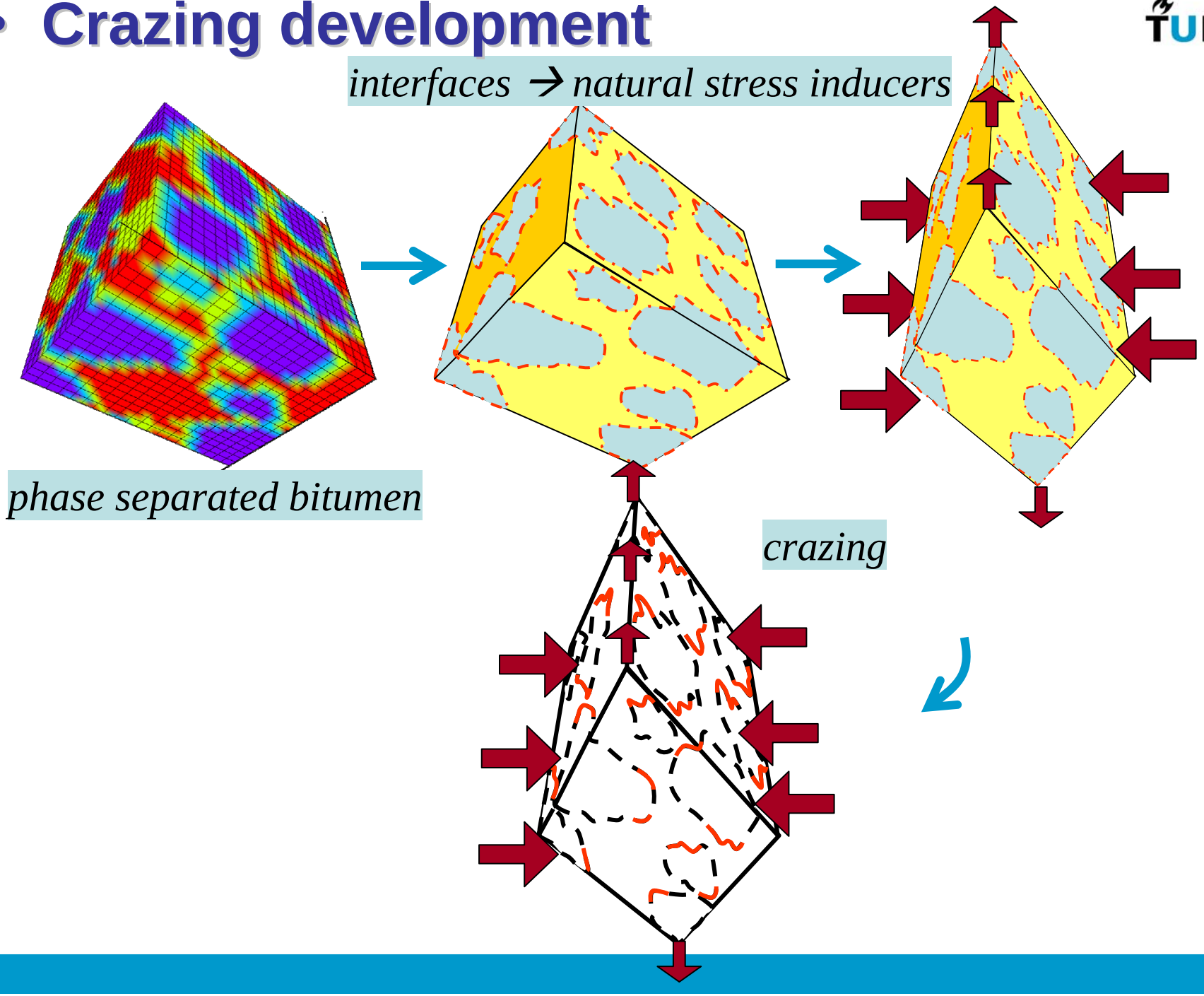
interfaces → natural stress inducers



phase separated bitumen

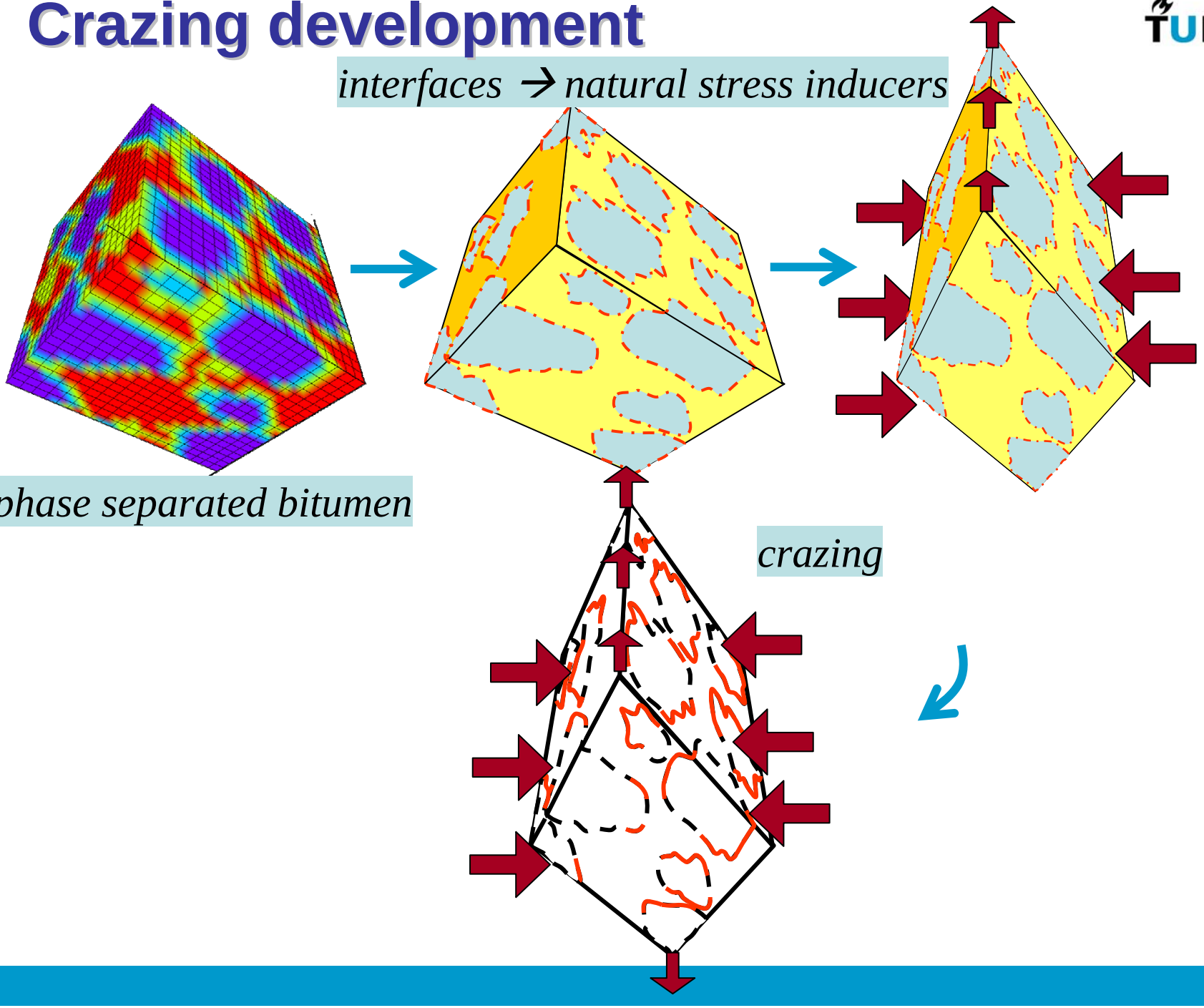
crazing

• Crazing development



• Crazing development

interfaces → natural stress inducers



phase separated bitumen

crazing

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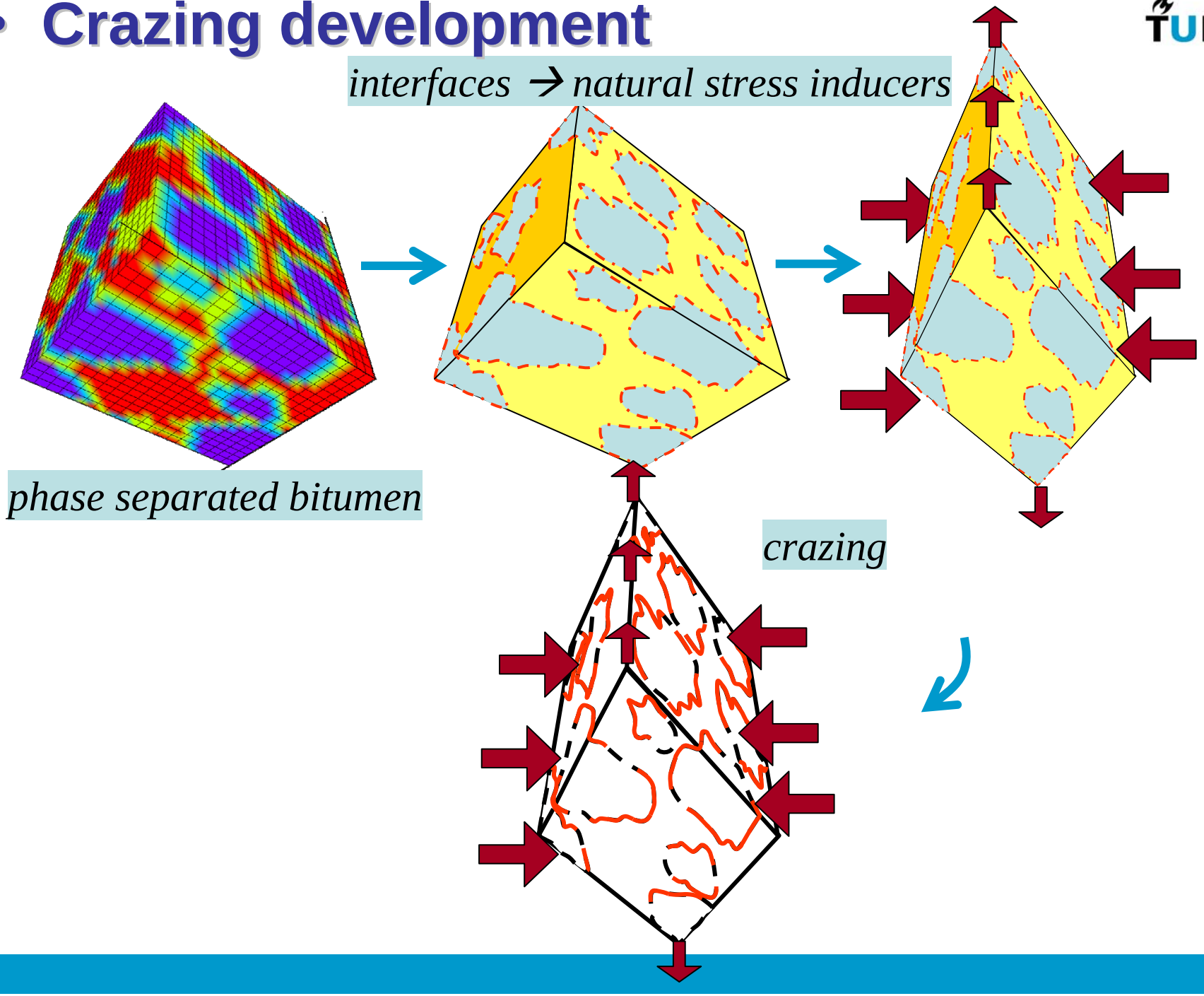

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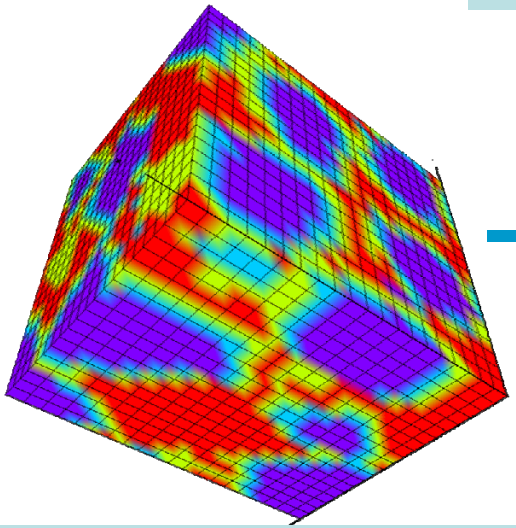
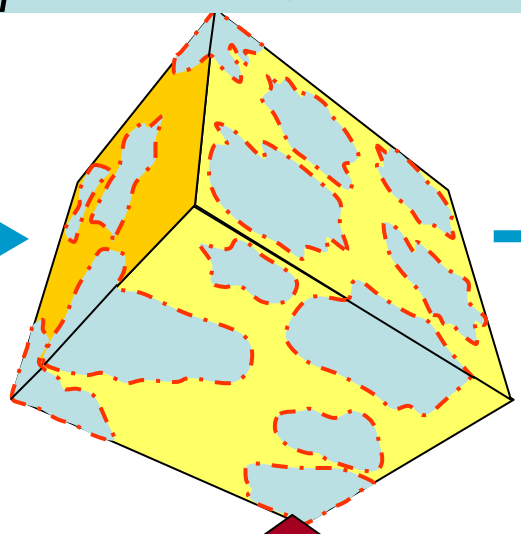
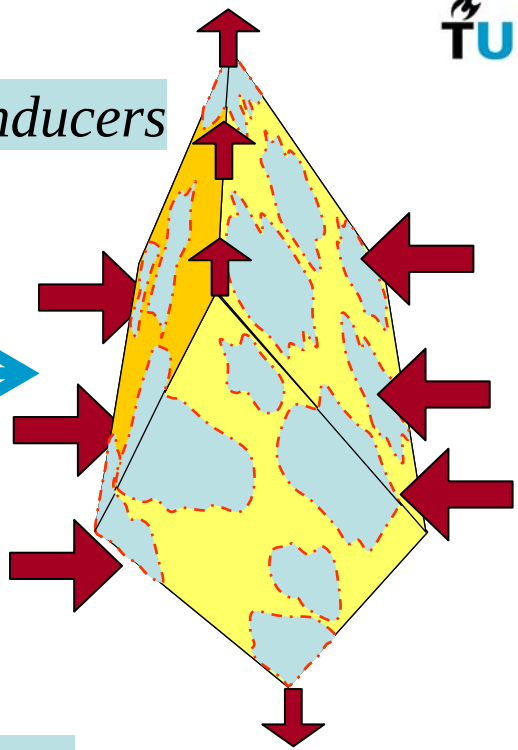
interfaces → natural stress inducers

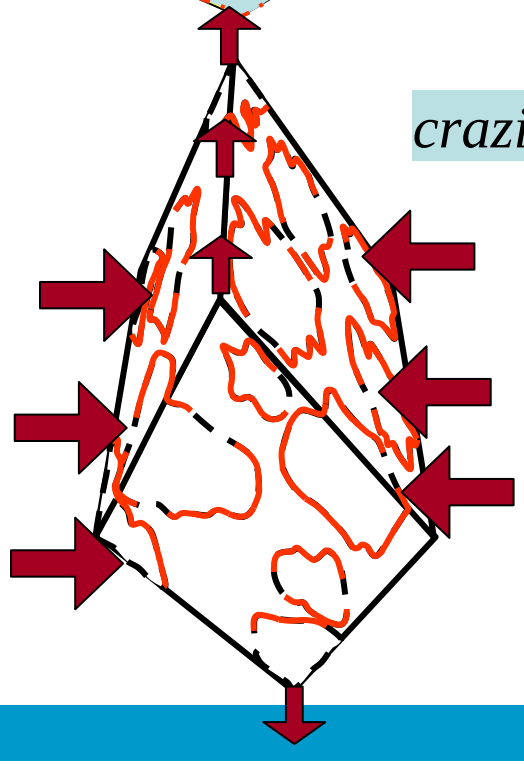


phase separated bitumen





crazing



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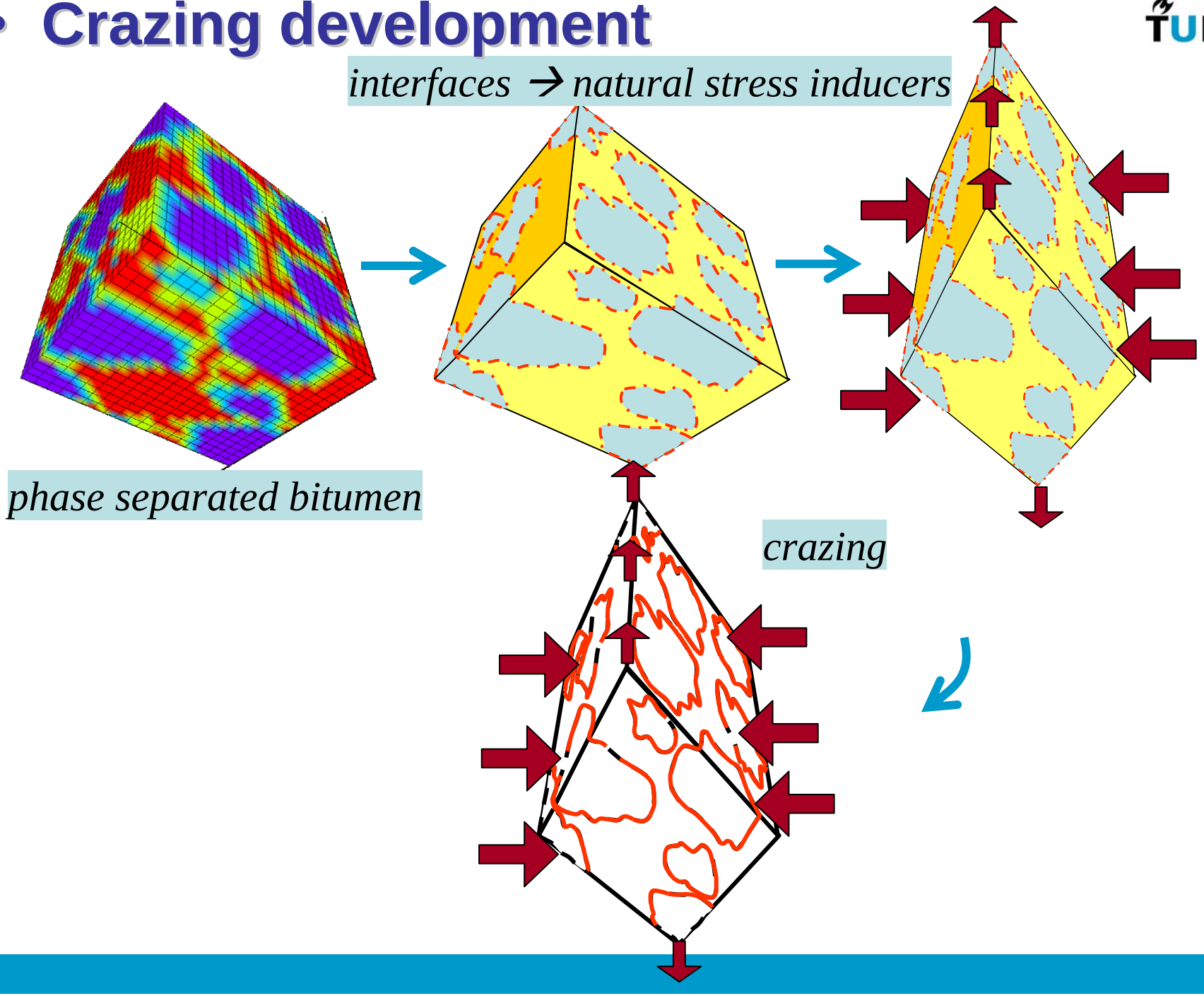

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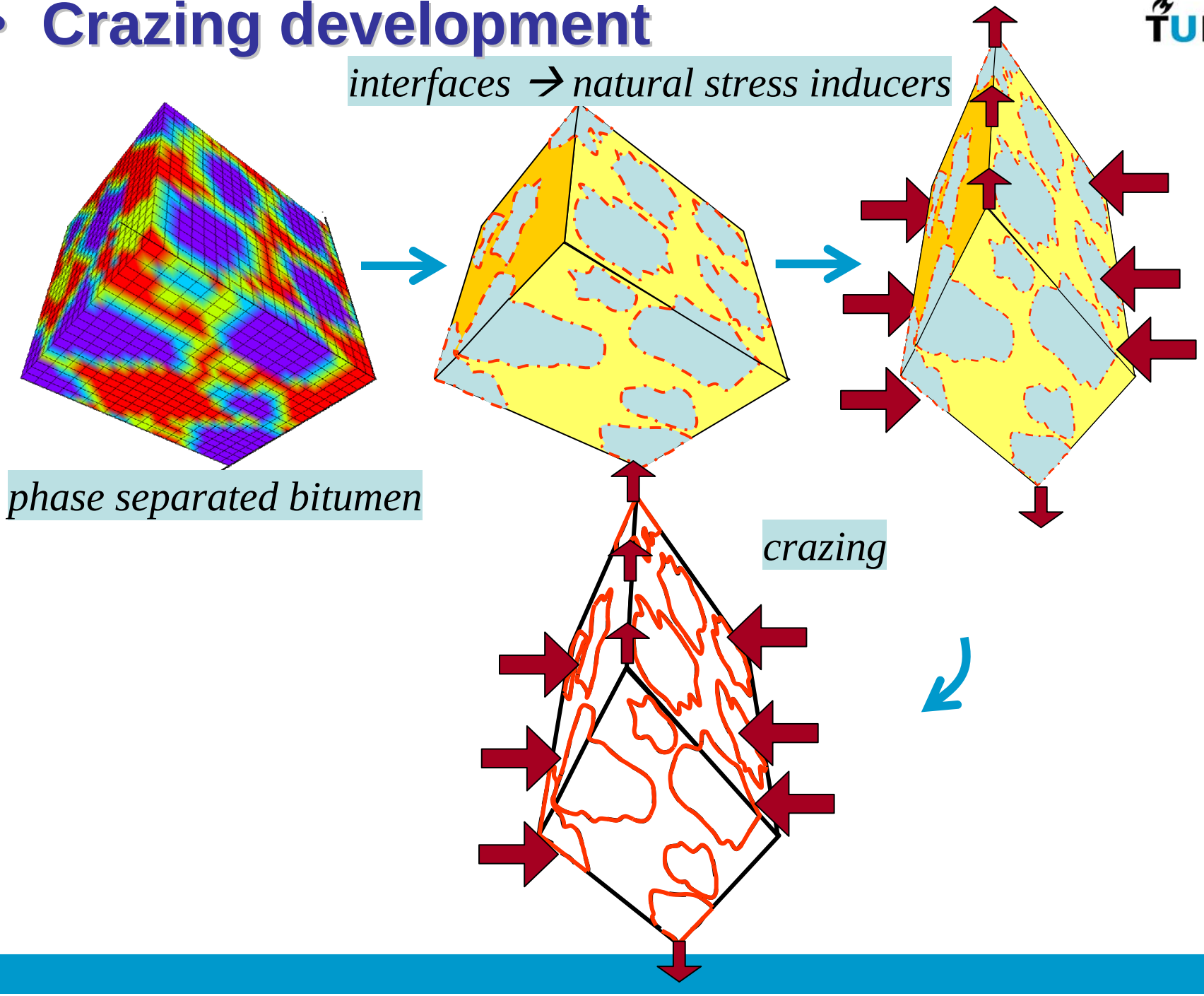
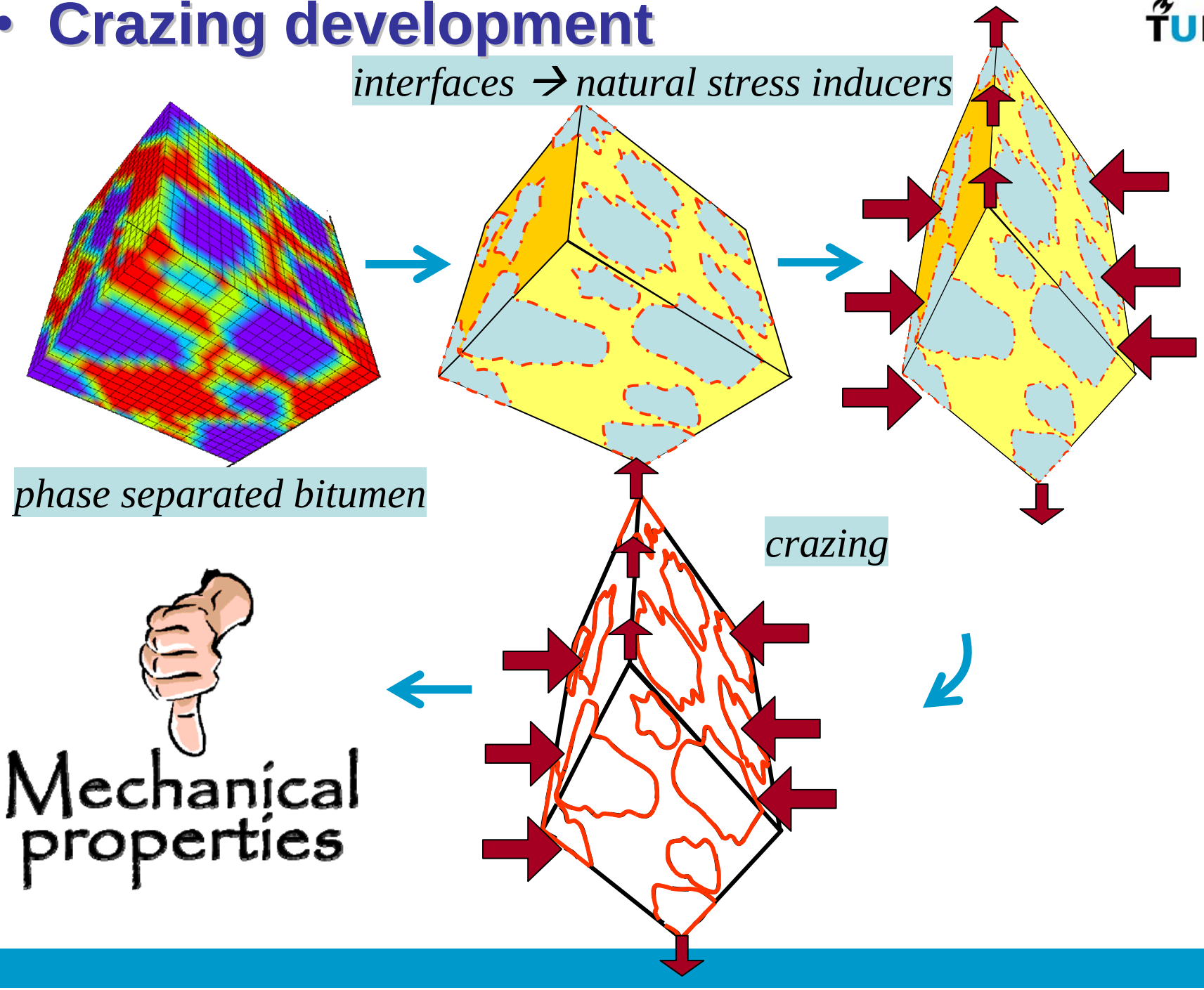
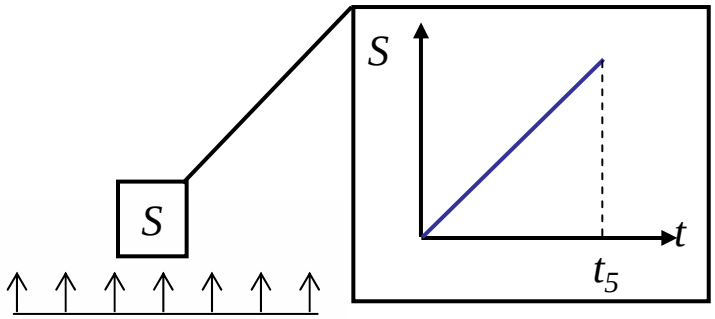
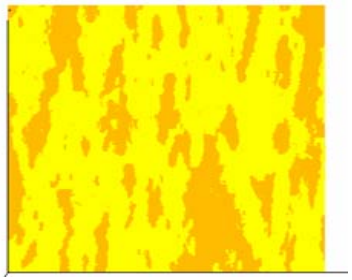


- **Crazing development**

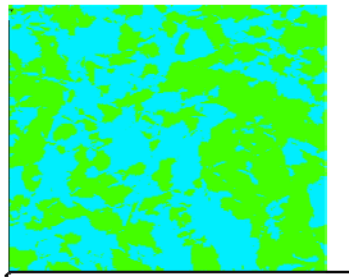


• Crazing development



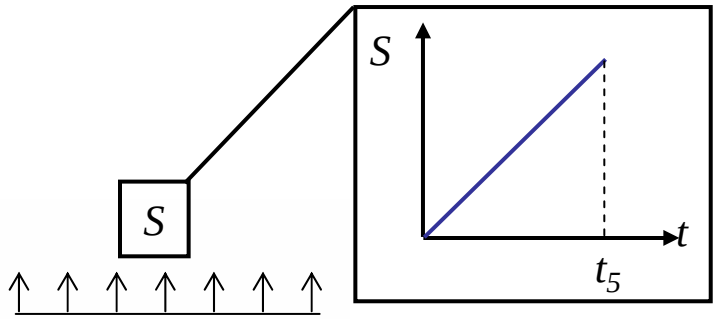


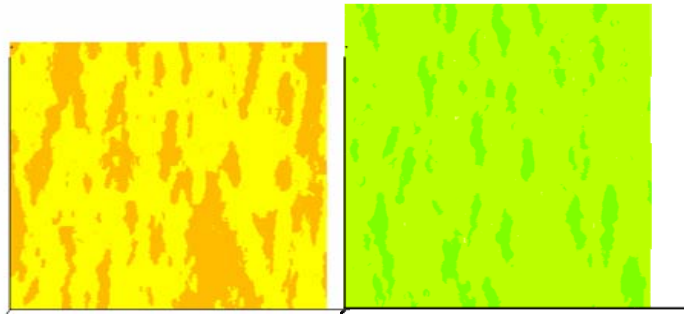
t_1

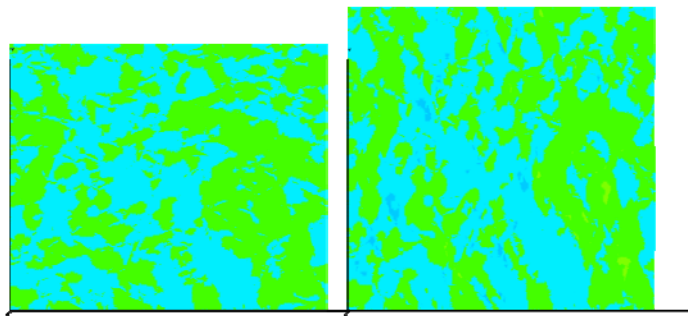


t_1

• Crazing development







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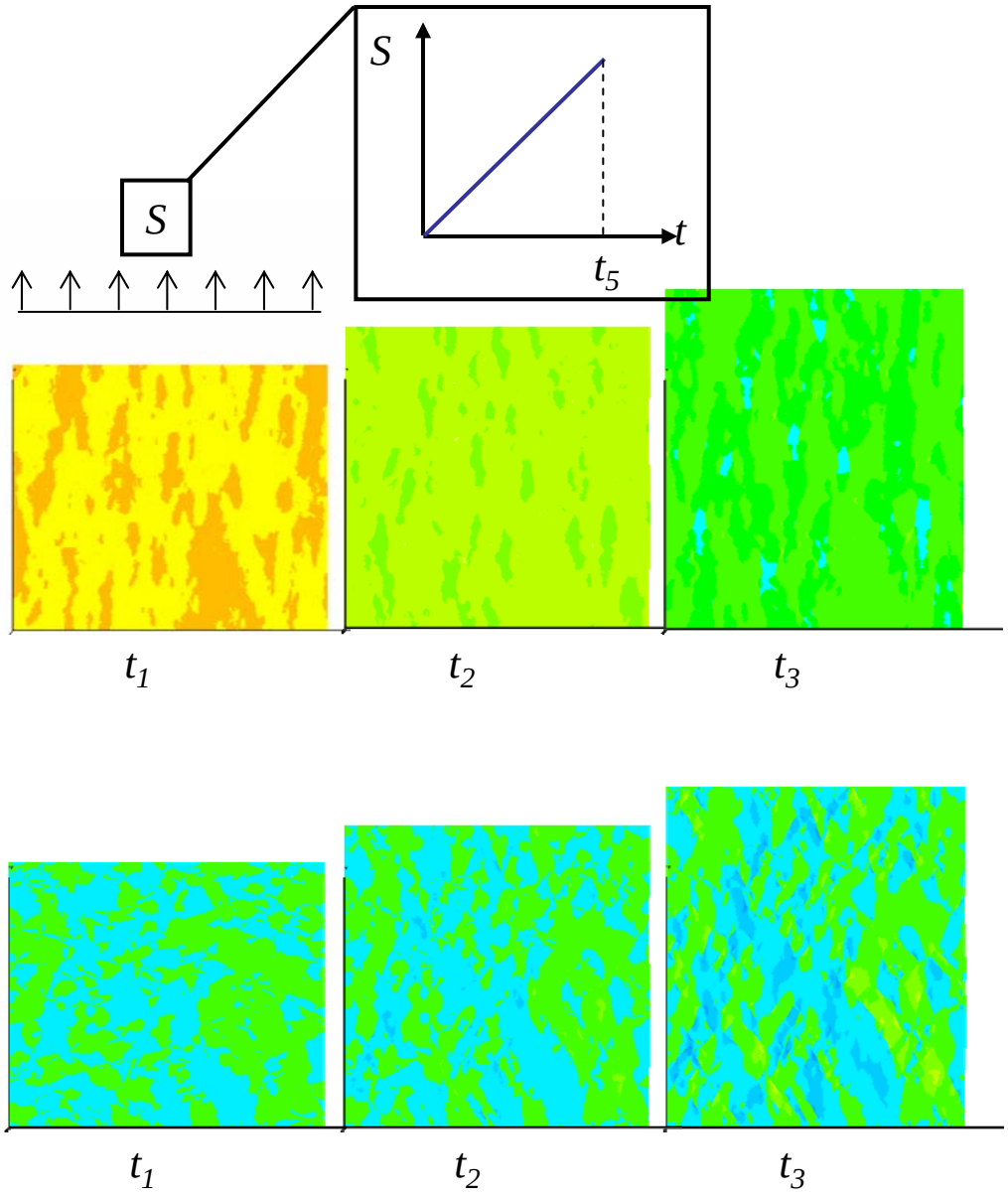

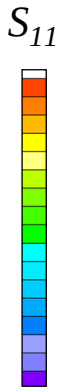

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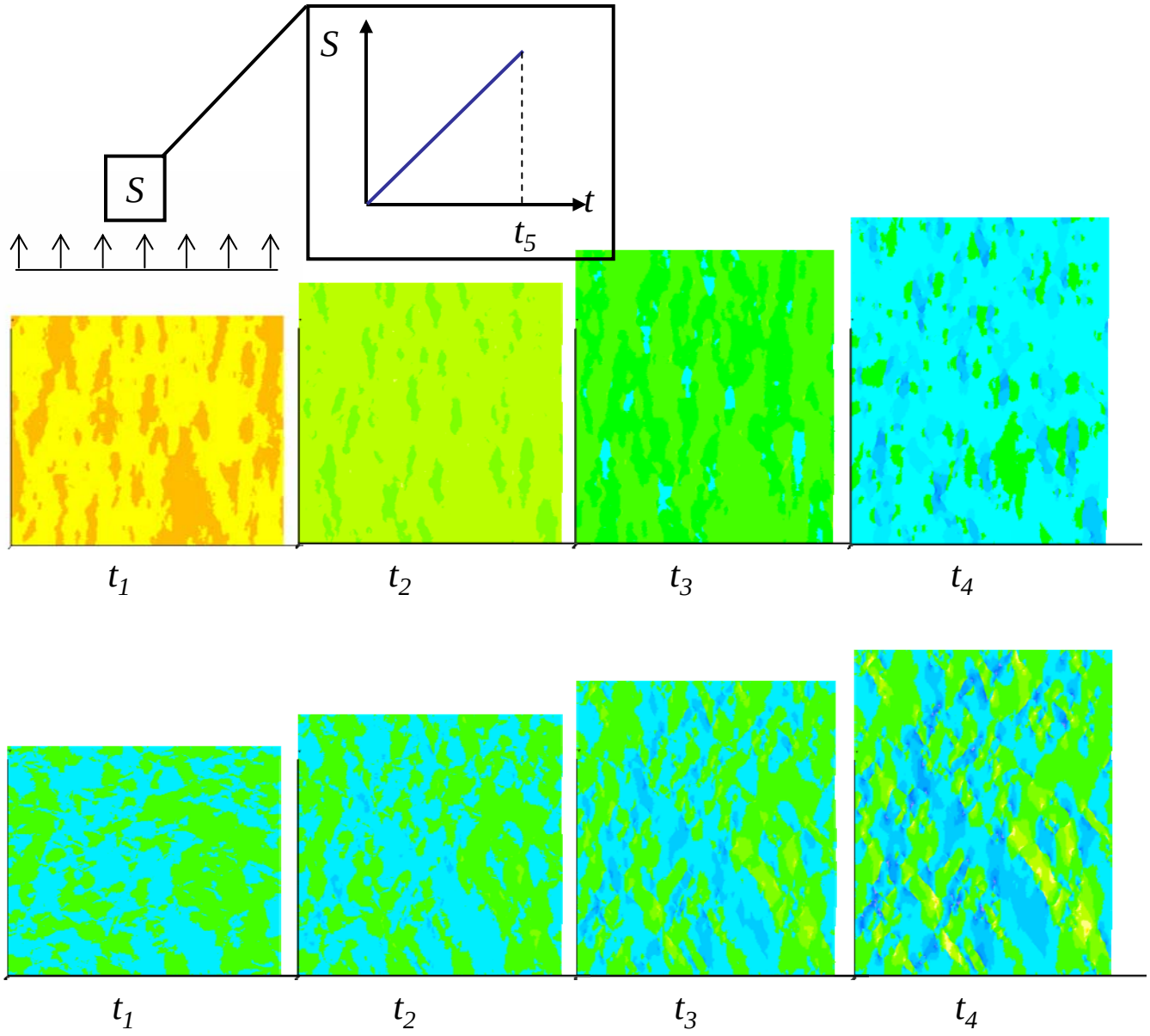
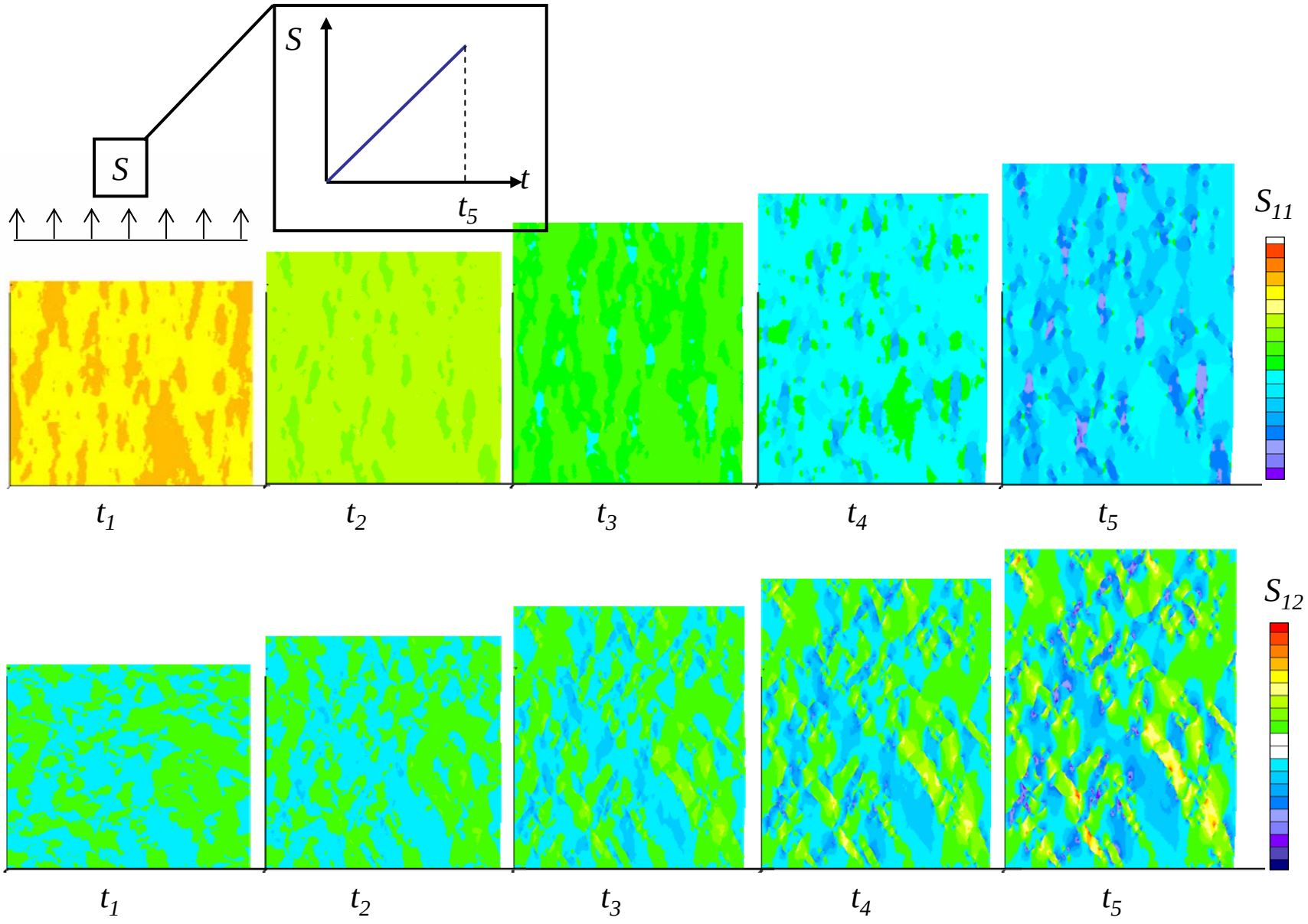
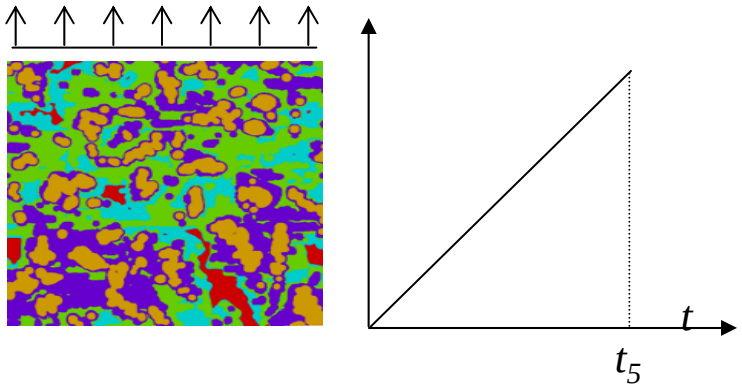


• Crazing development

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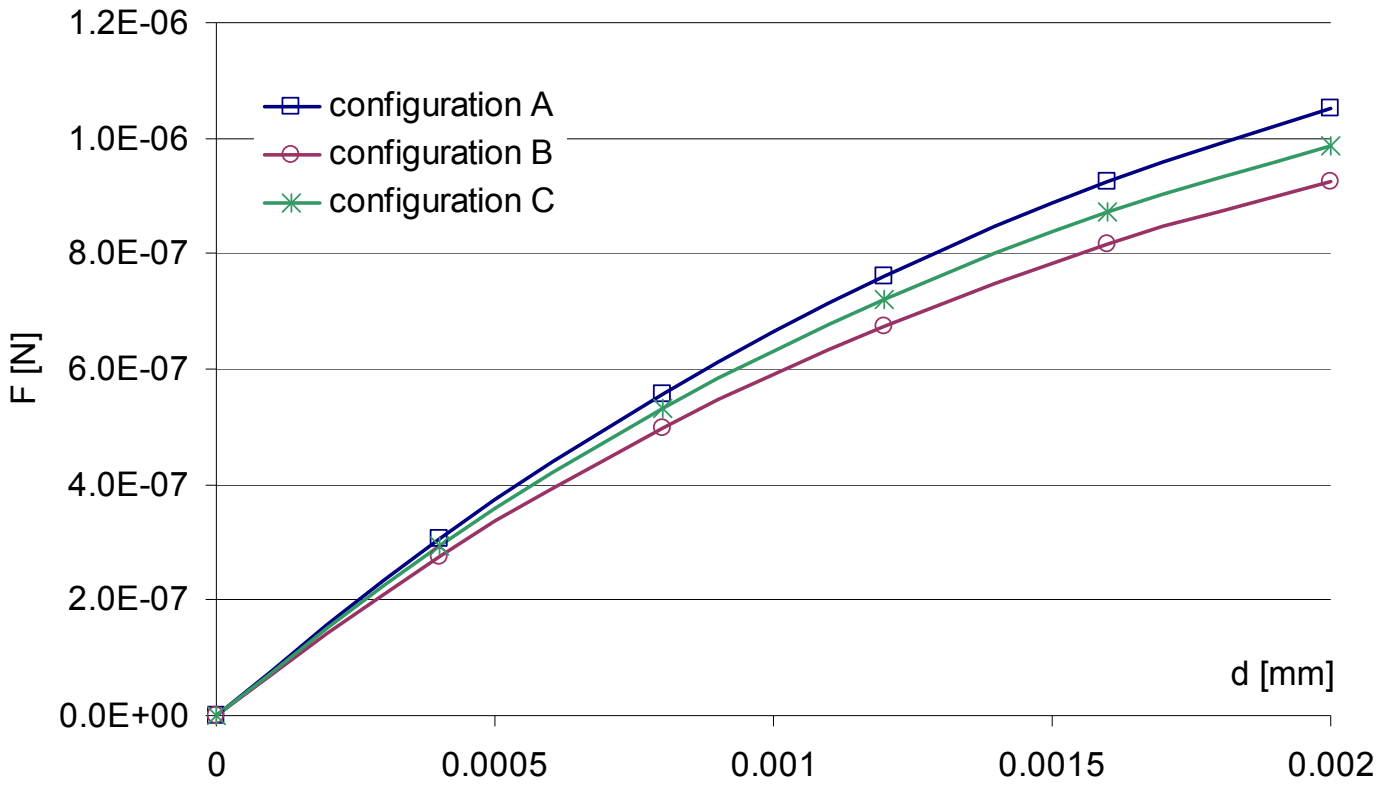
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configuration B
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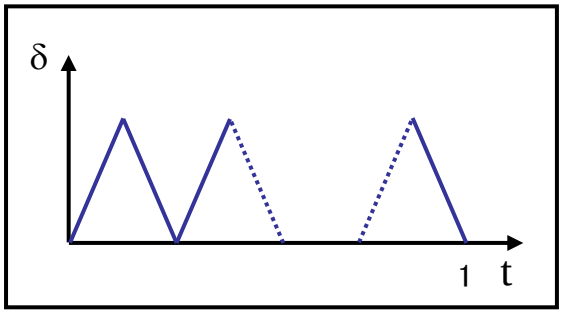
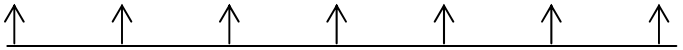
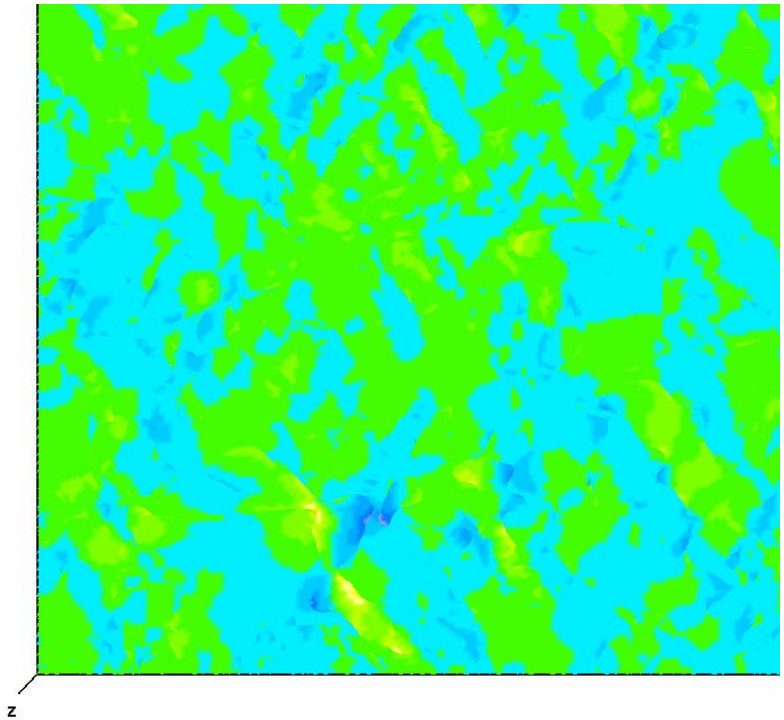
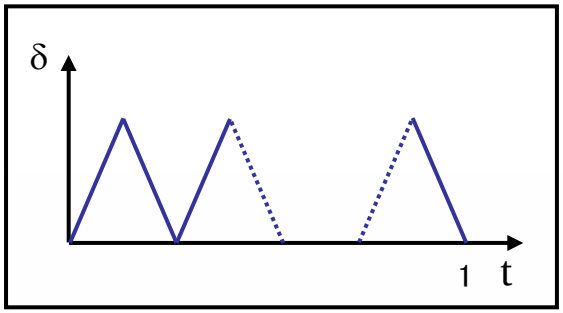
• Crazing development

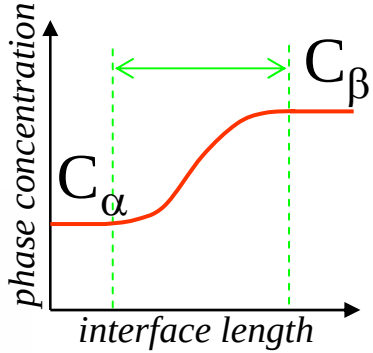


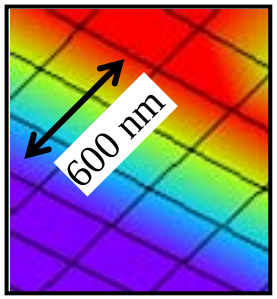


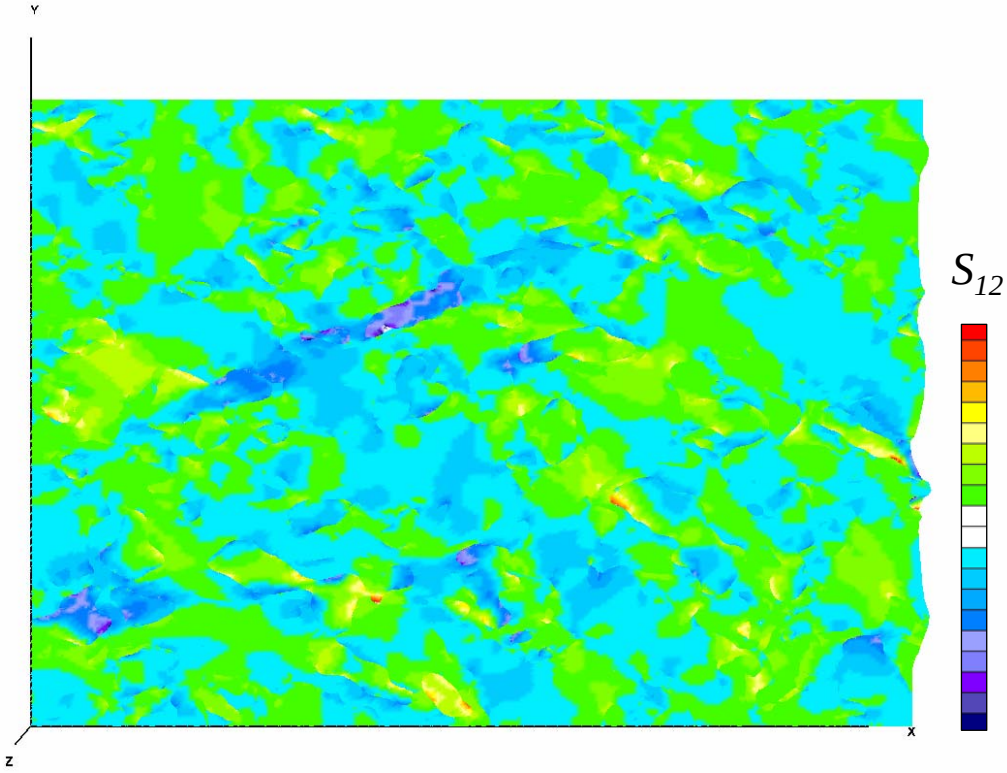


• Crazing development









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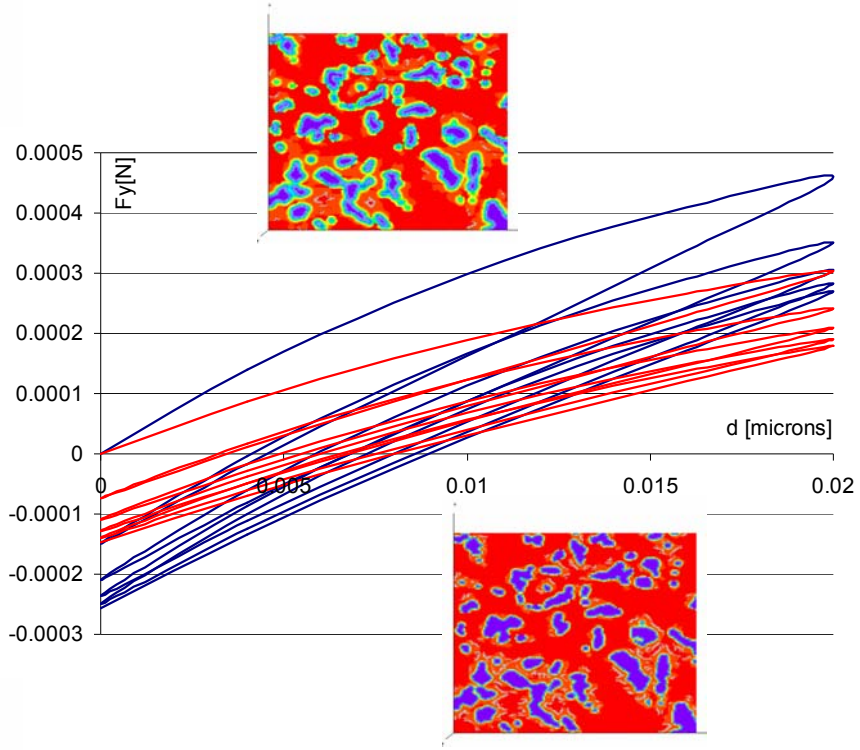
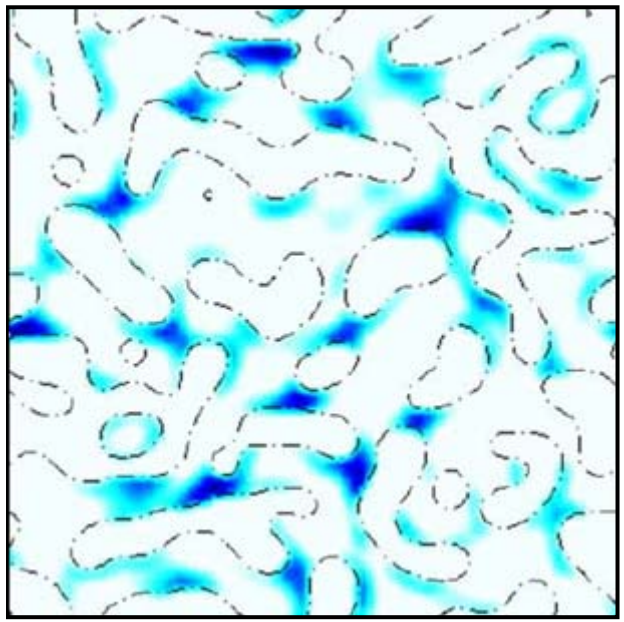
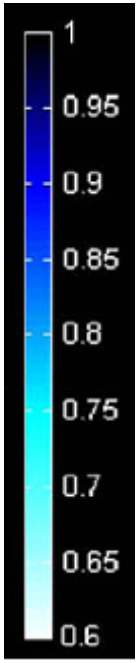


- **Crazing development**

– **damage development with cycling**



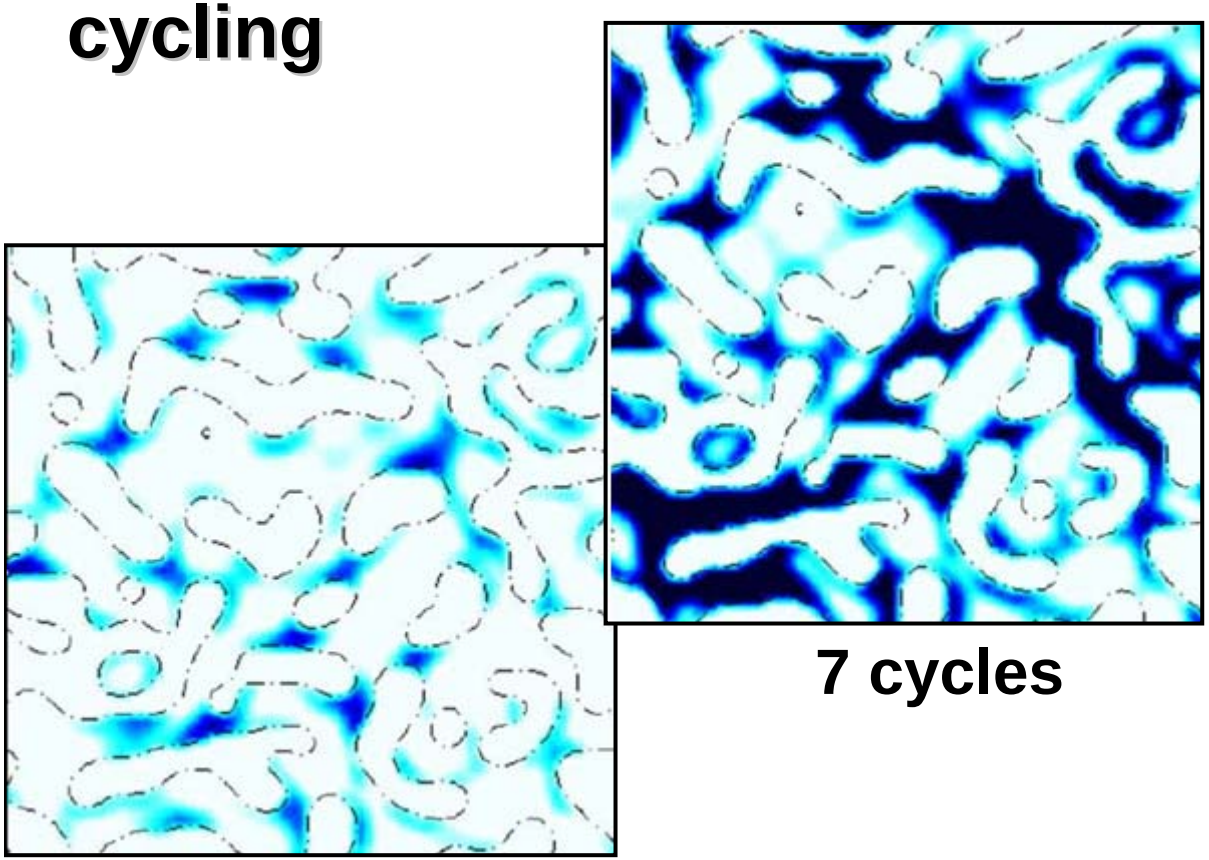
2 cycles



N. Kringos

• Crazing development

– damage development with cycling



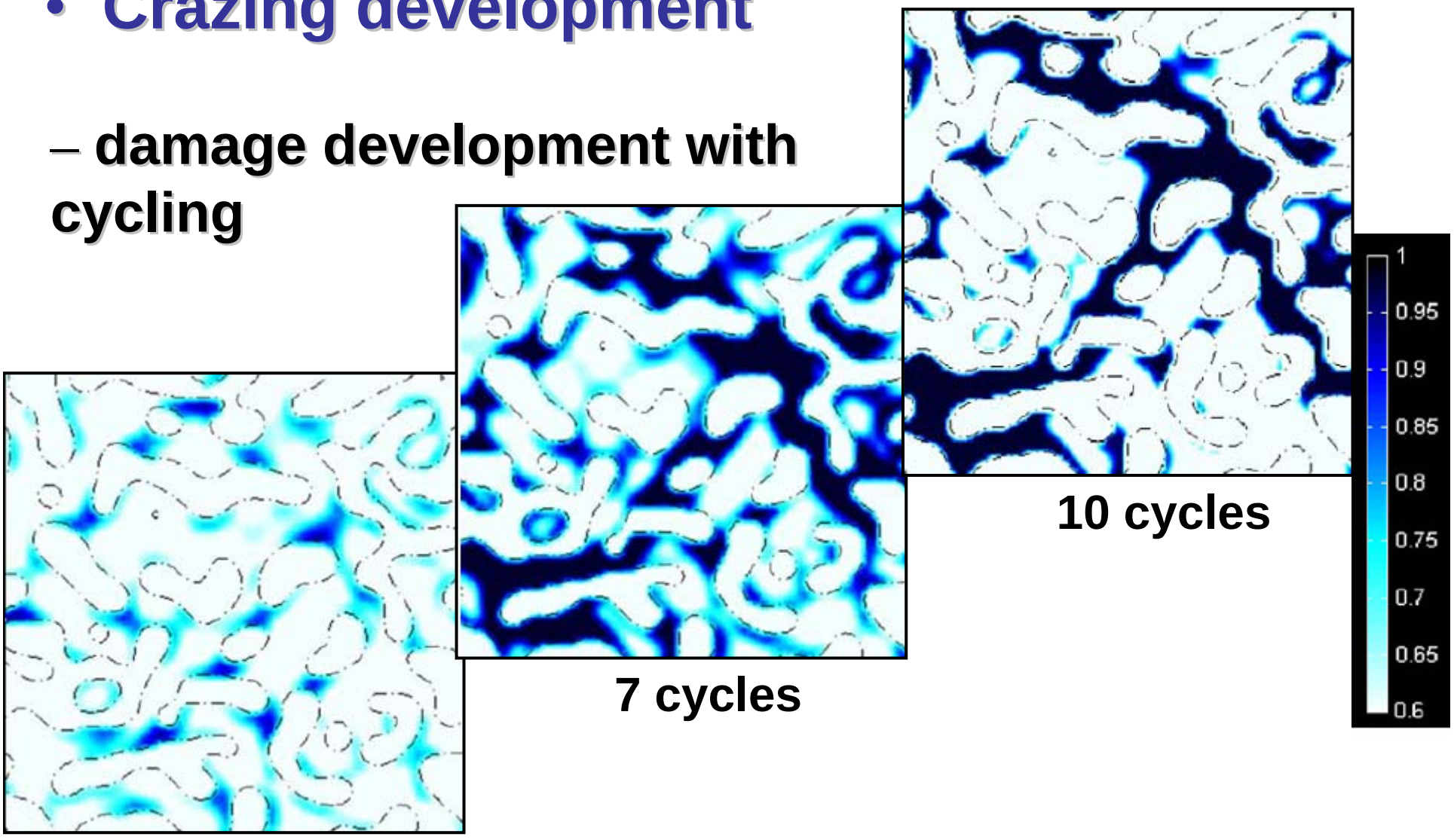
7 cycles

2 cycles

N. Kringos

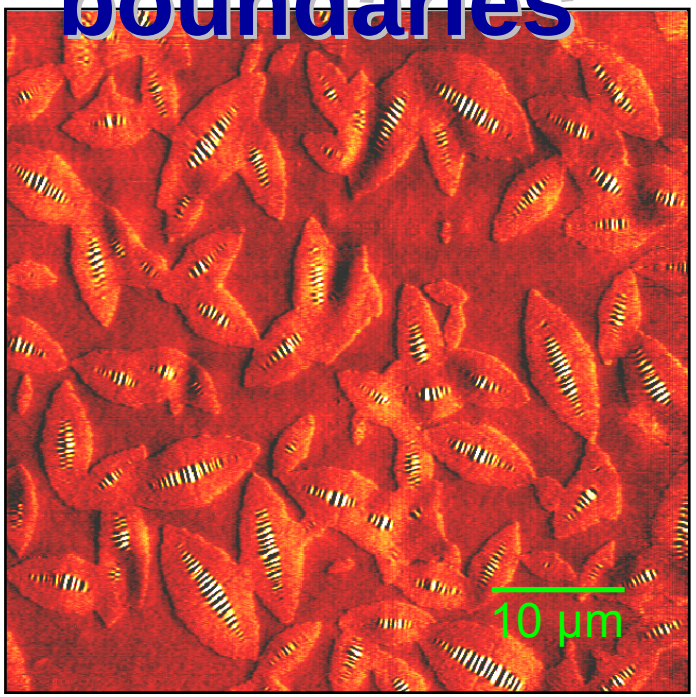
- **Crazing development**

– **damage development with cycling**

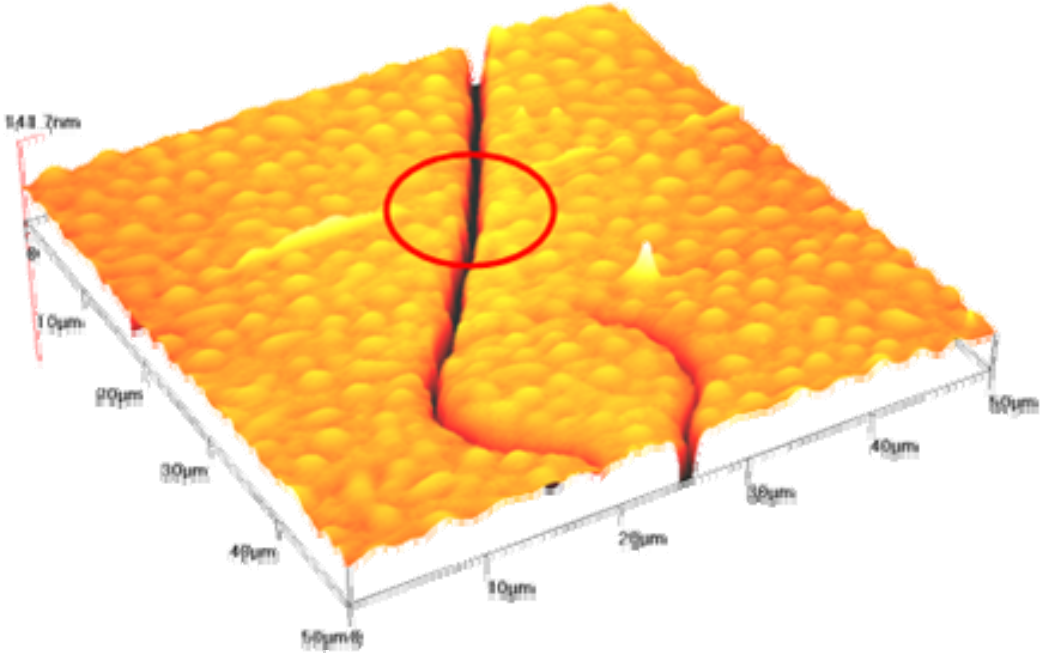


N. Kringos

- **Crazing through wax boundaries**



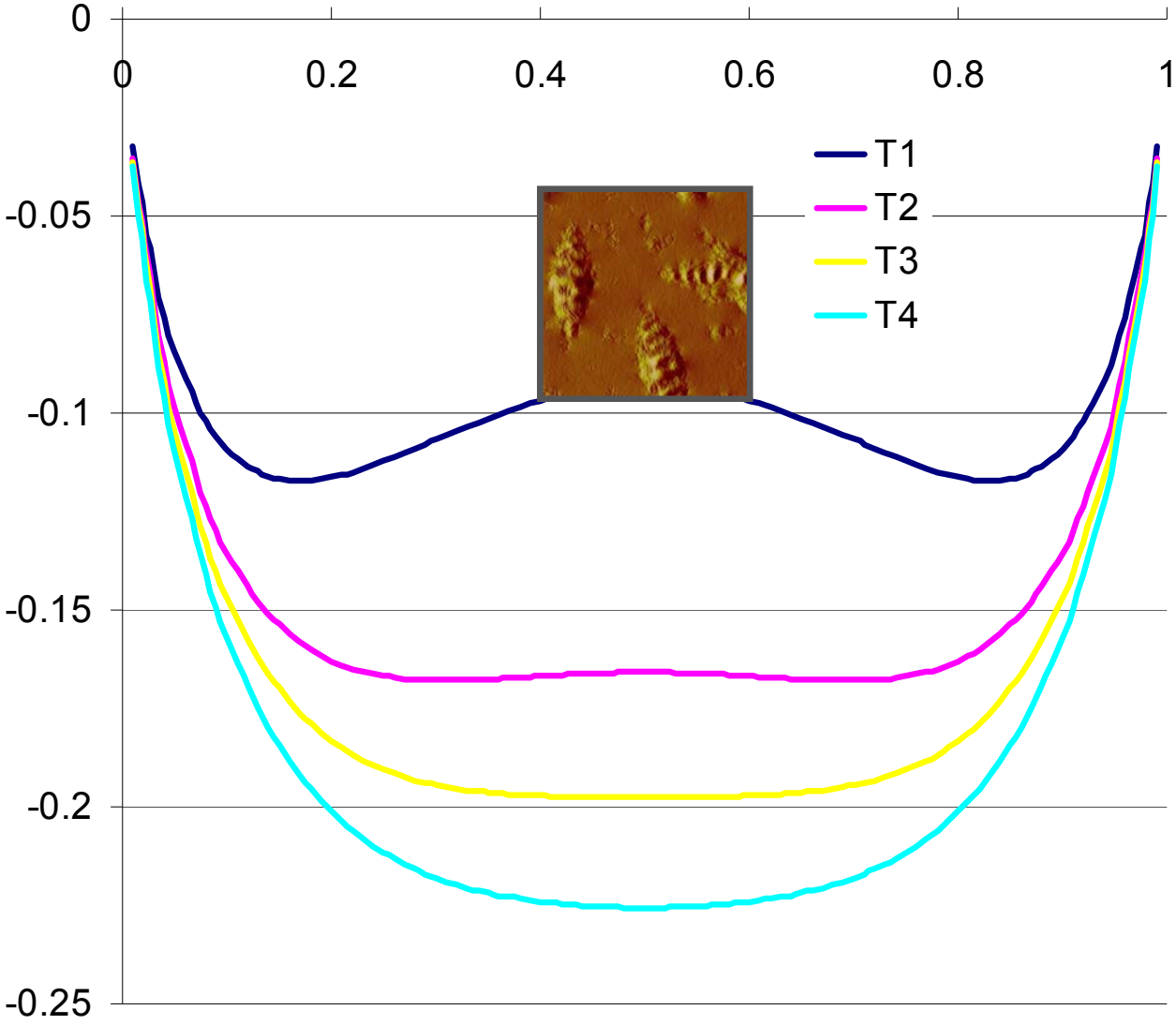
AAK-1

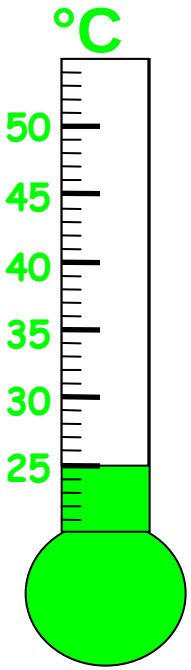


Healing ???

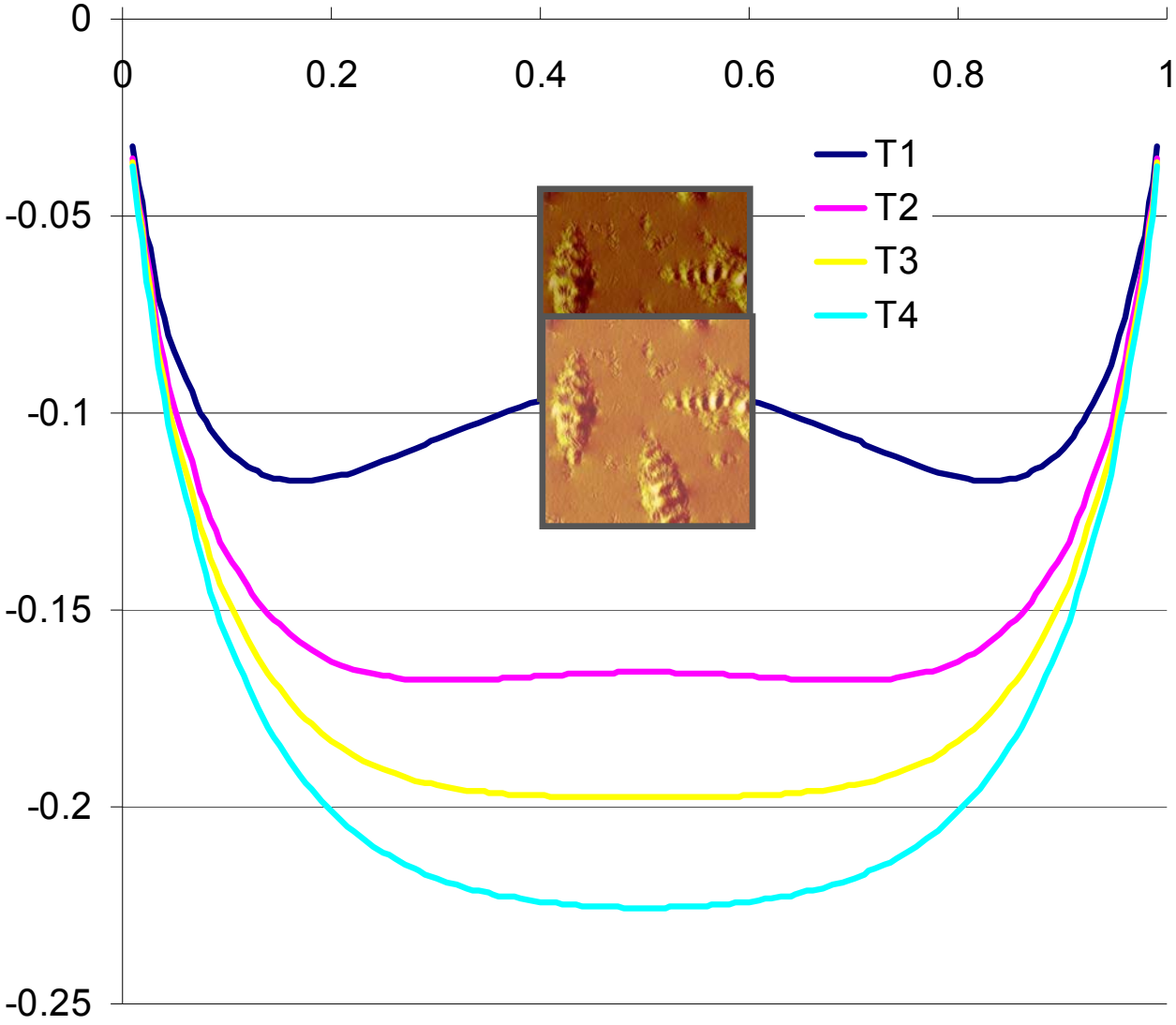
T. Pauli, WRI

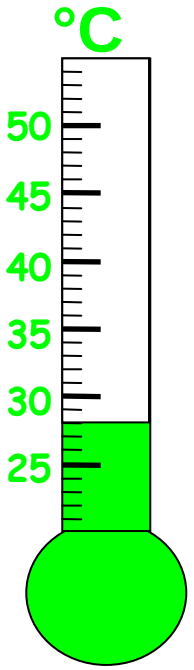
• Mixing theory



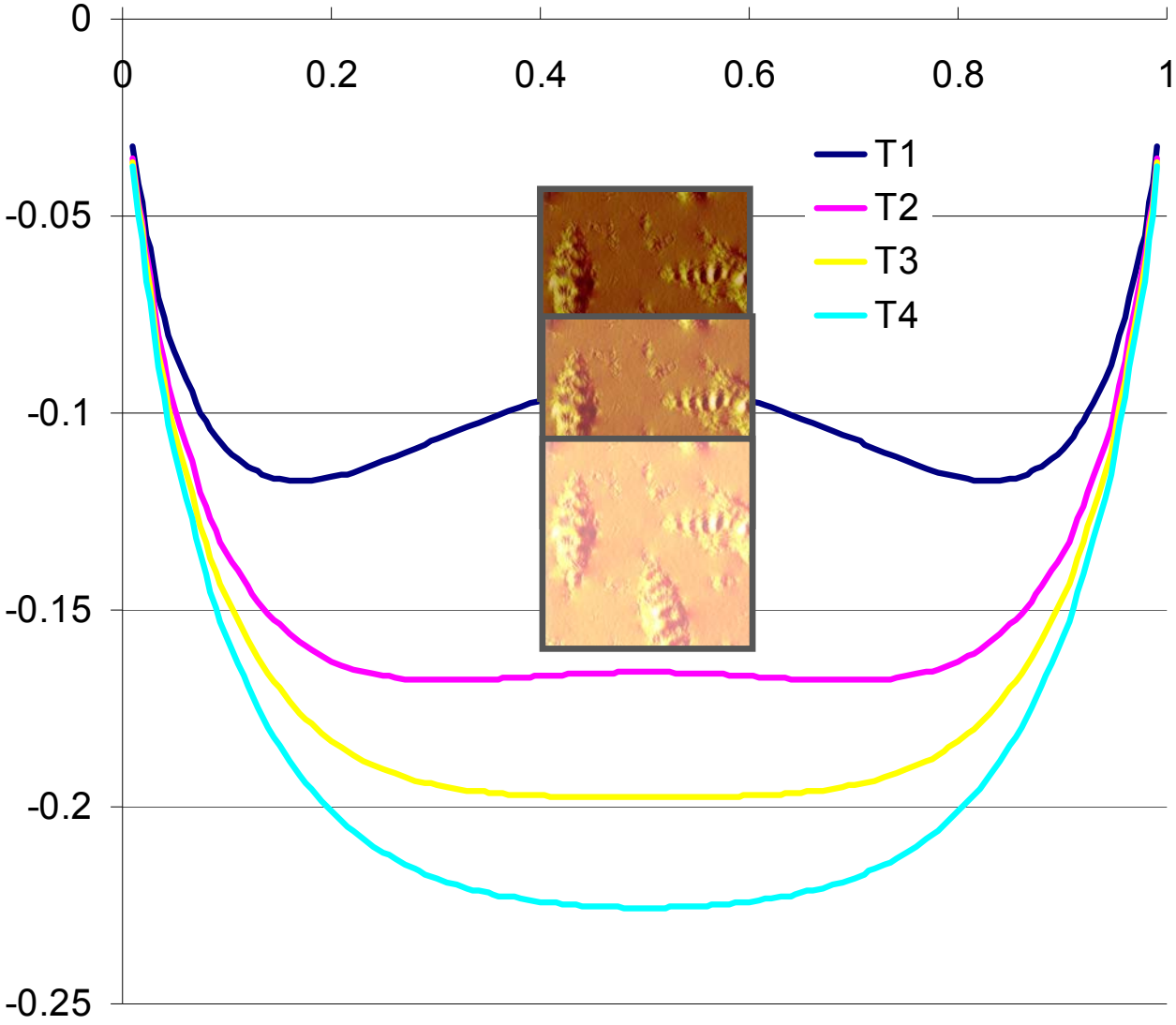


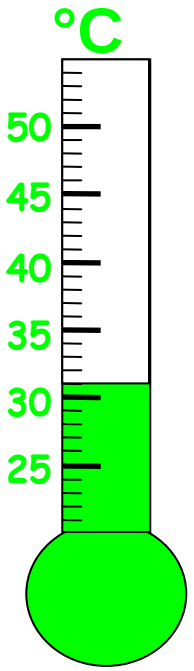
• Mixing theory



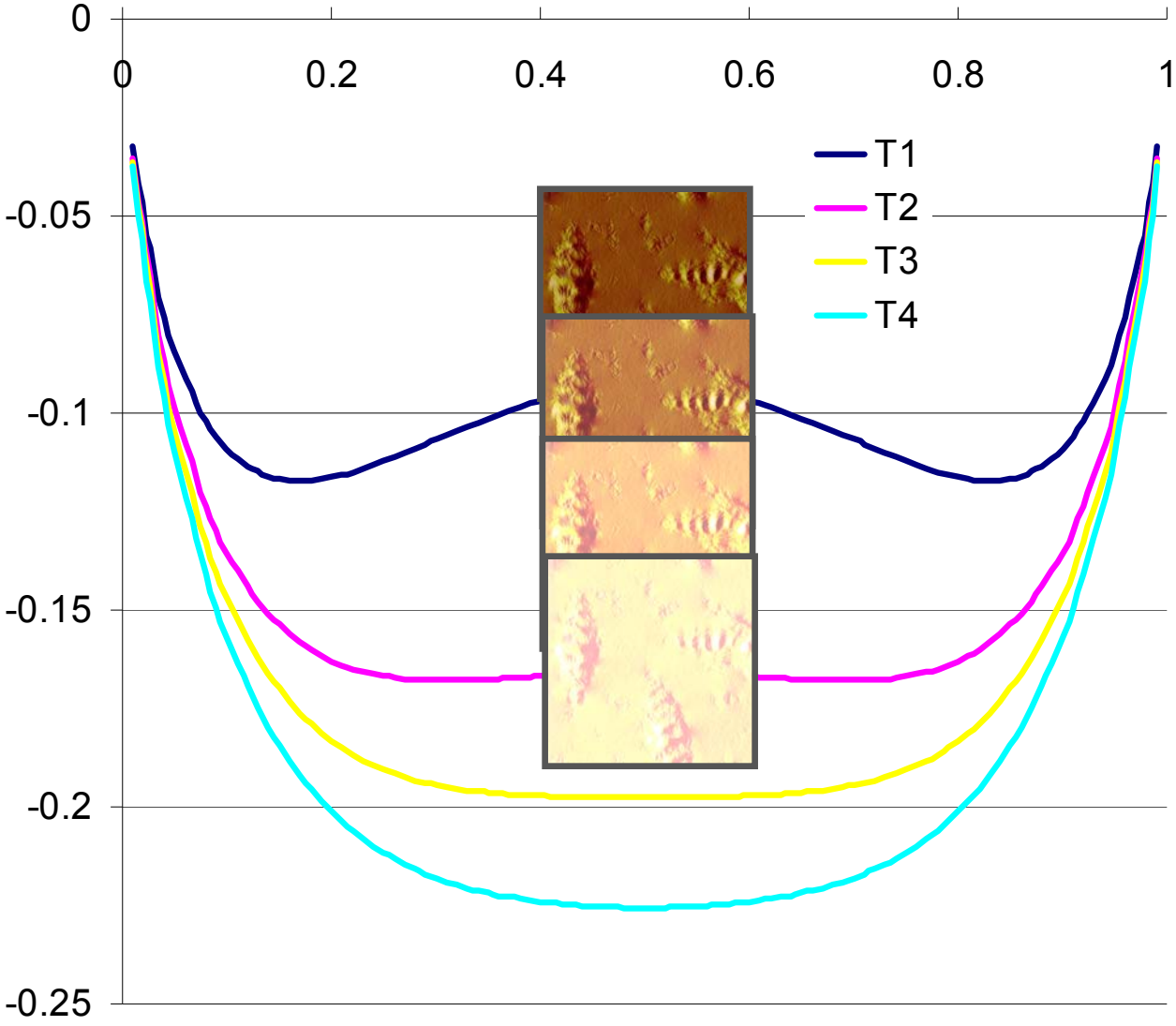


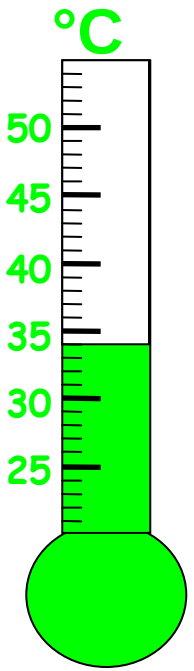
• Mixing theory



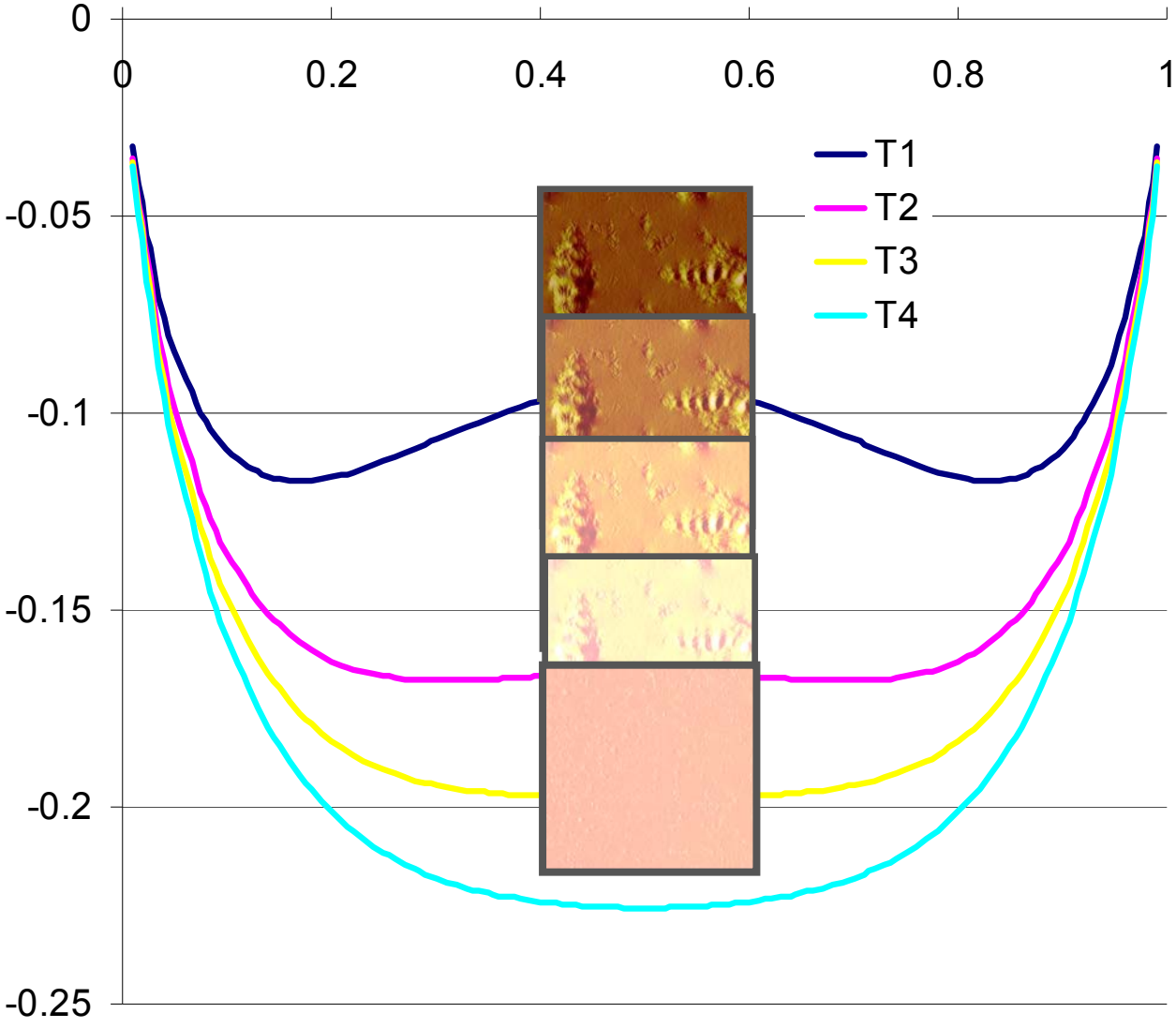


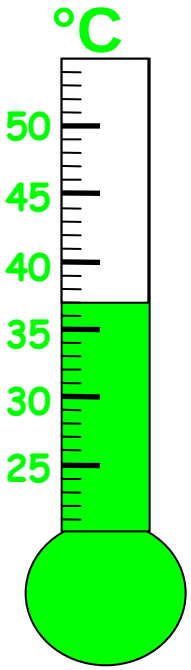
• Mixing theory





• Mixing theory





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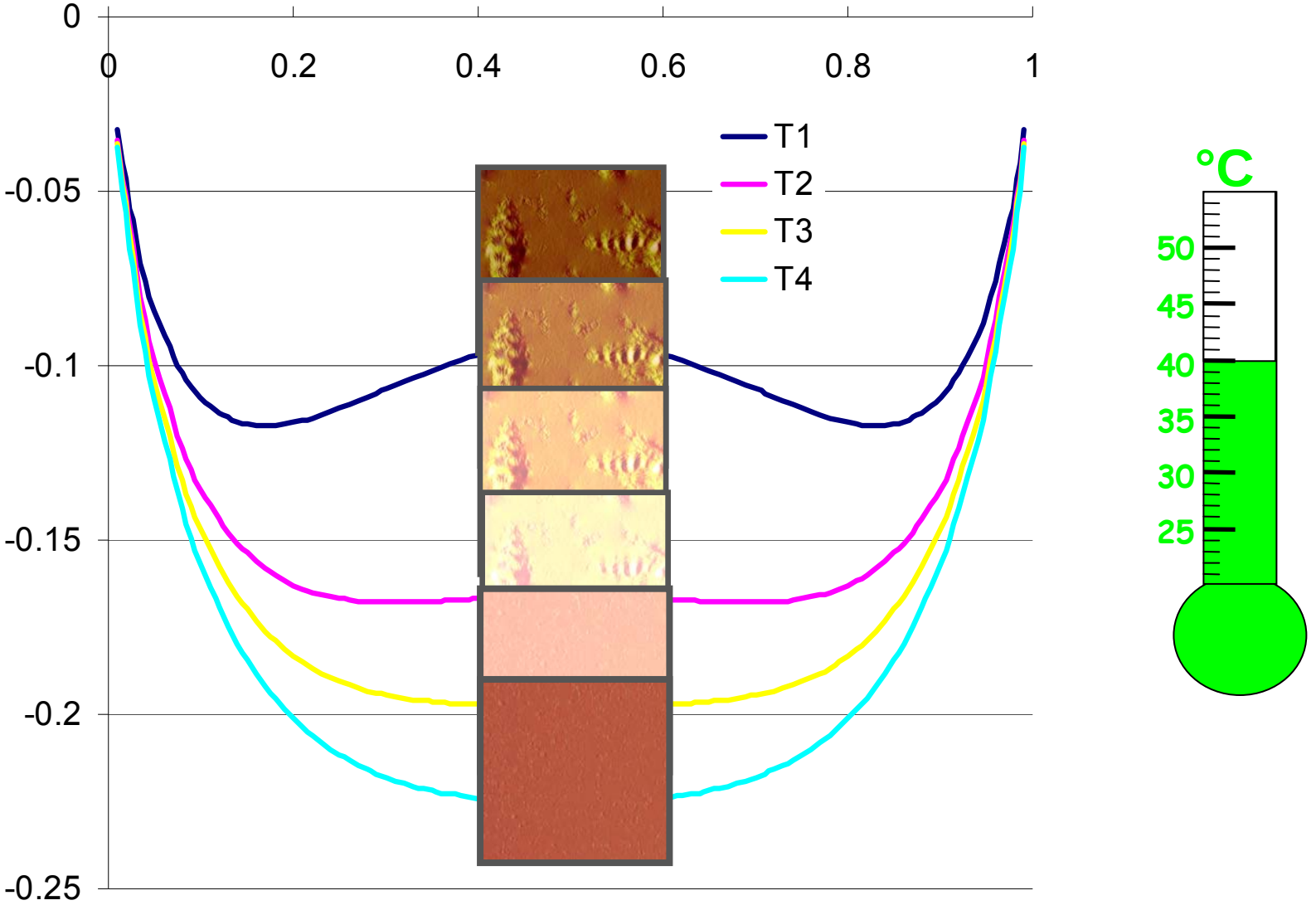

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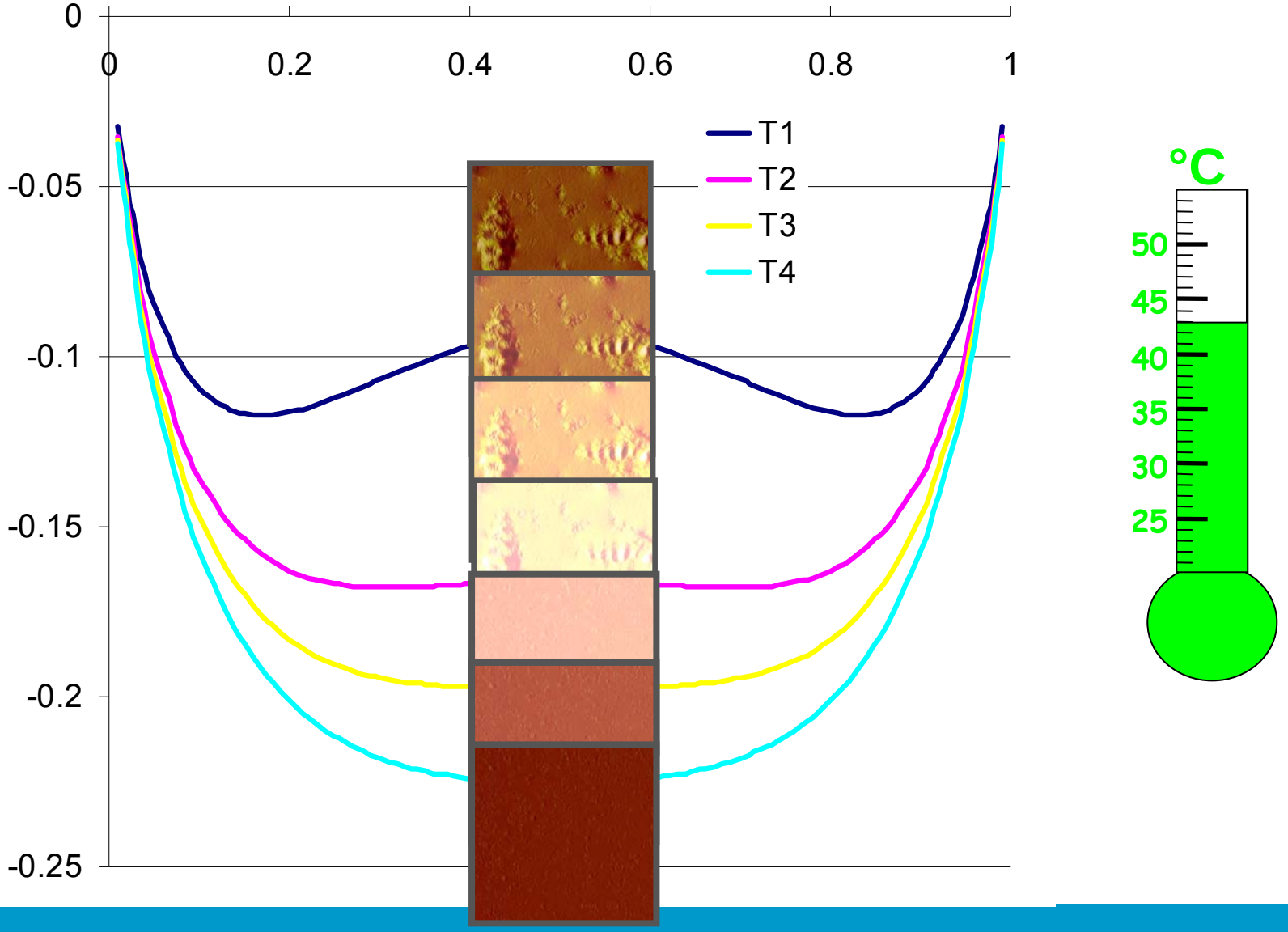
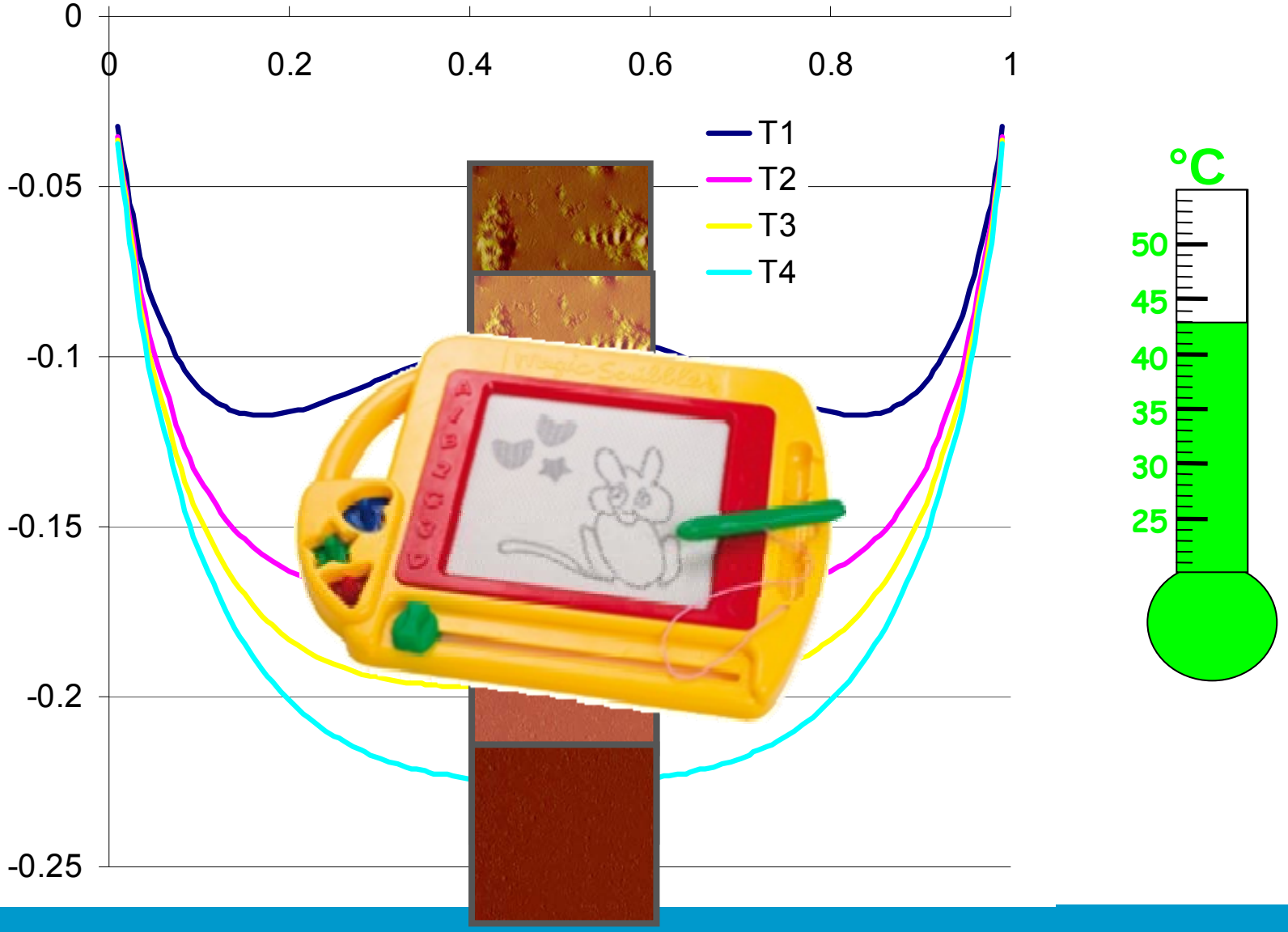


• Mixing theory



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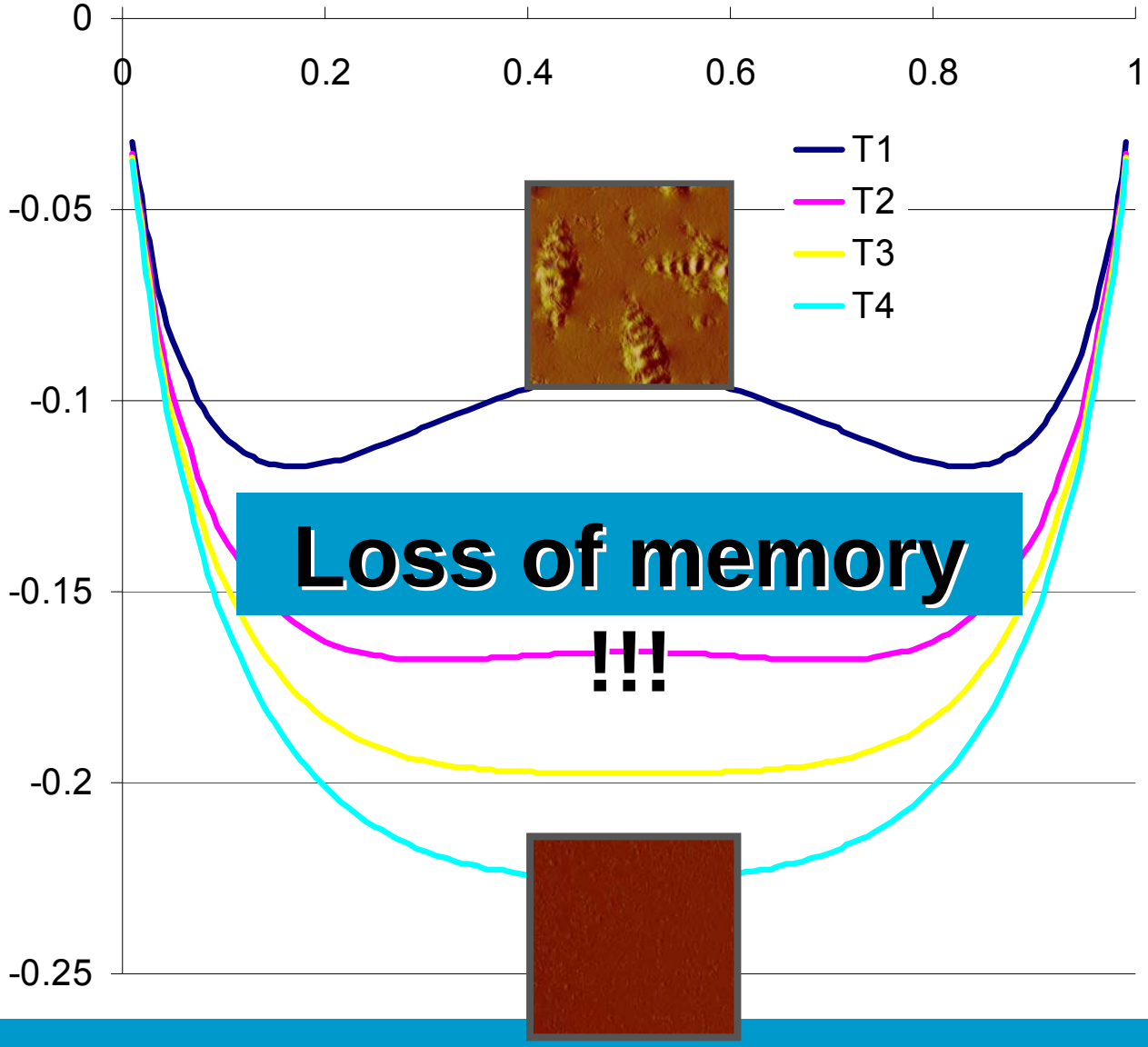
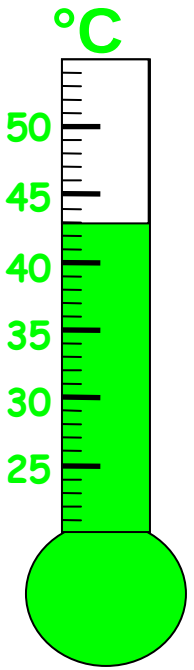
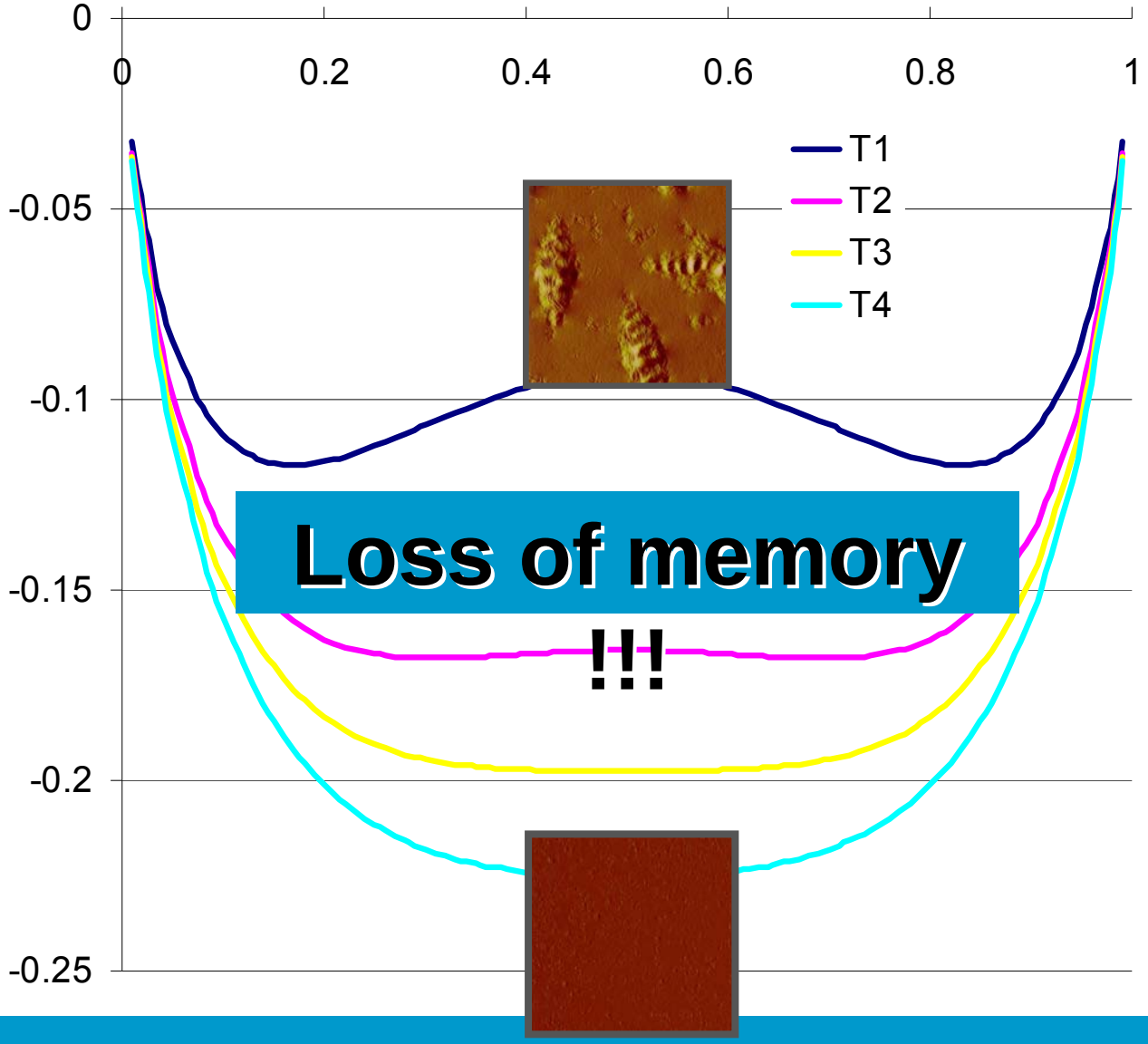
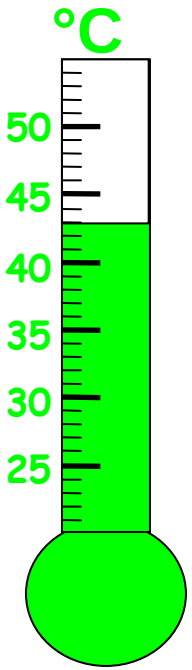


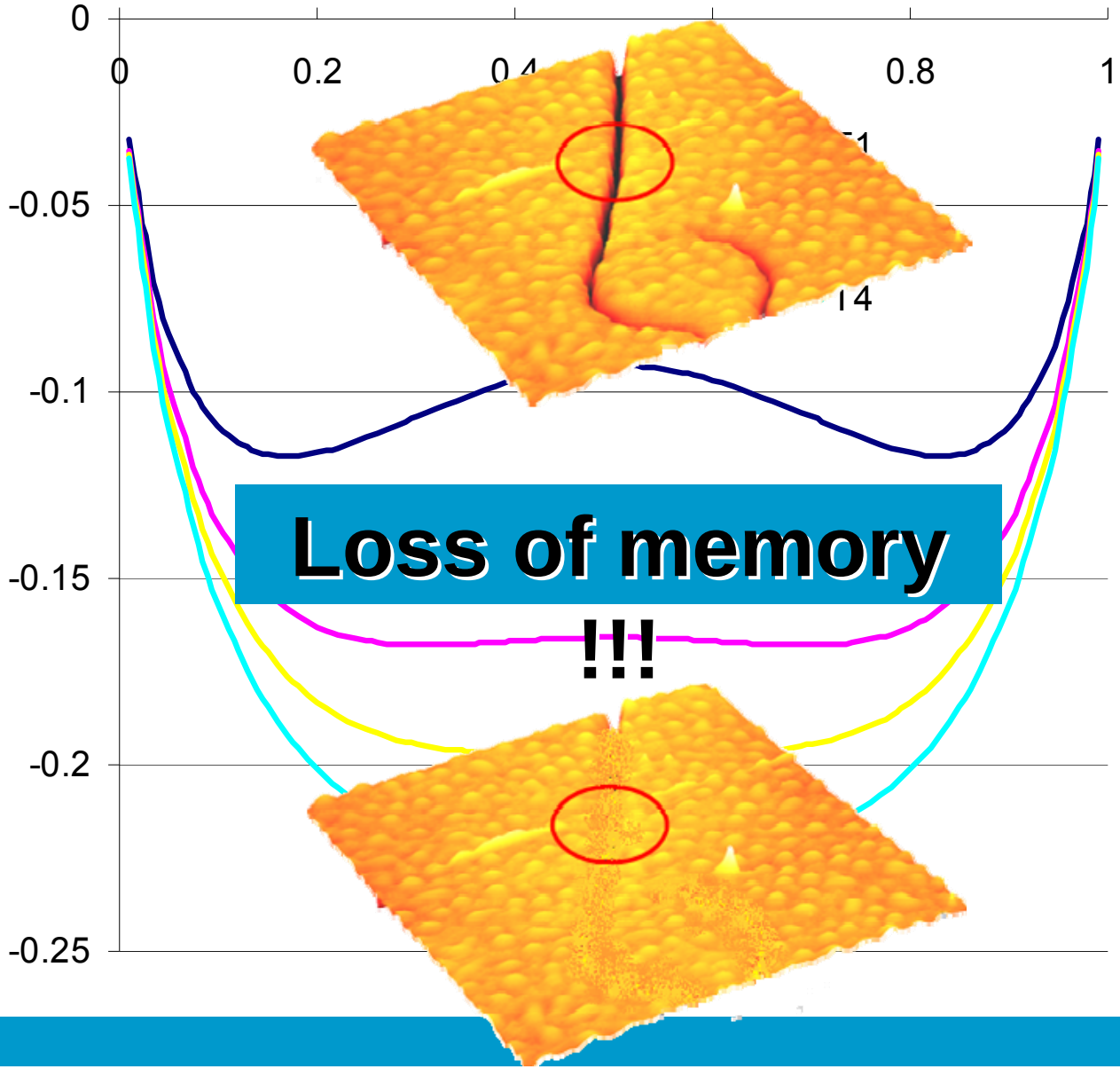


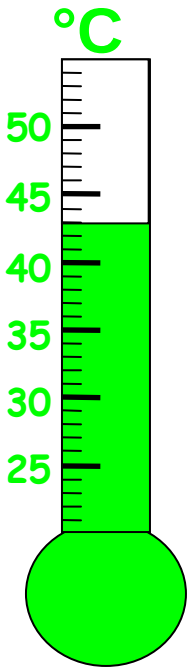
• Healing model

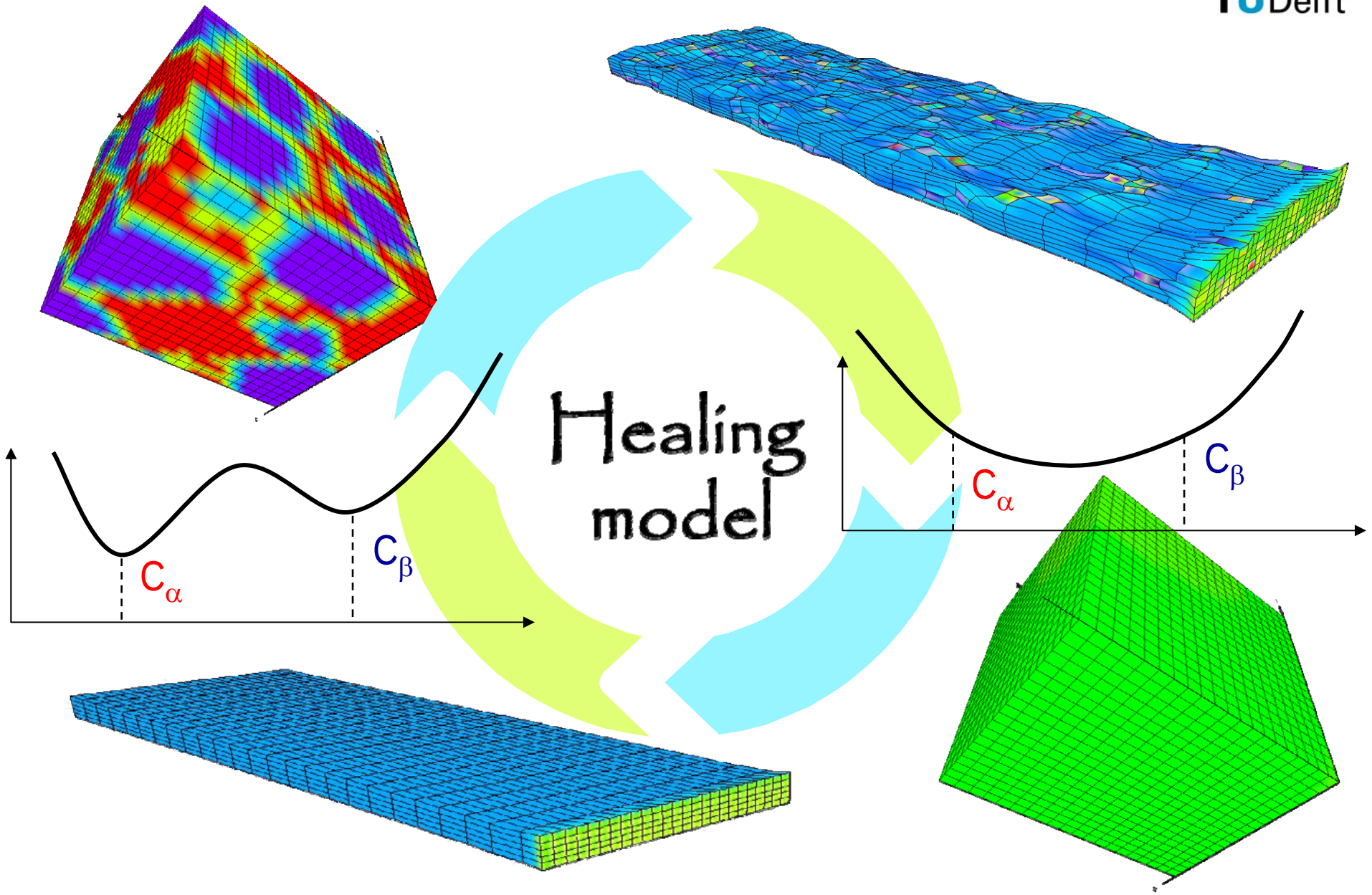


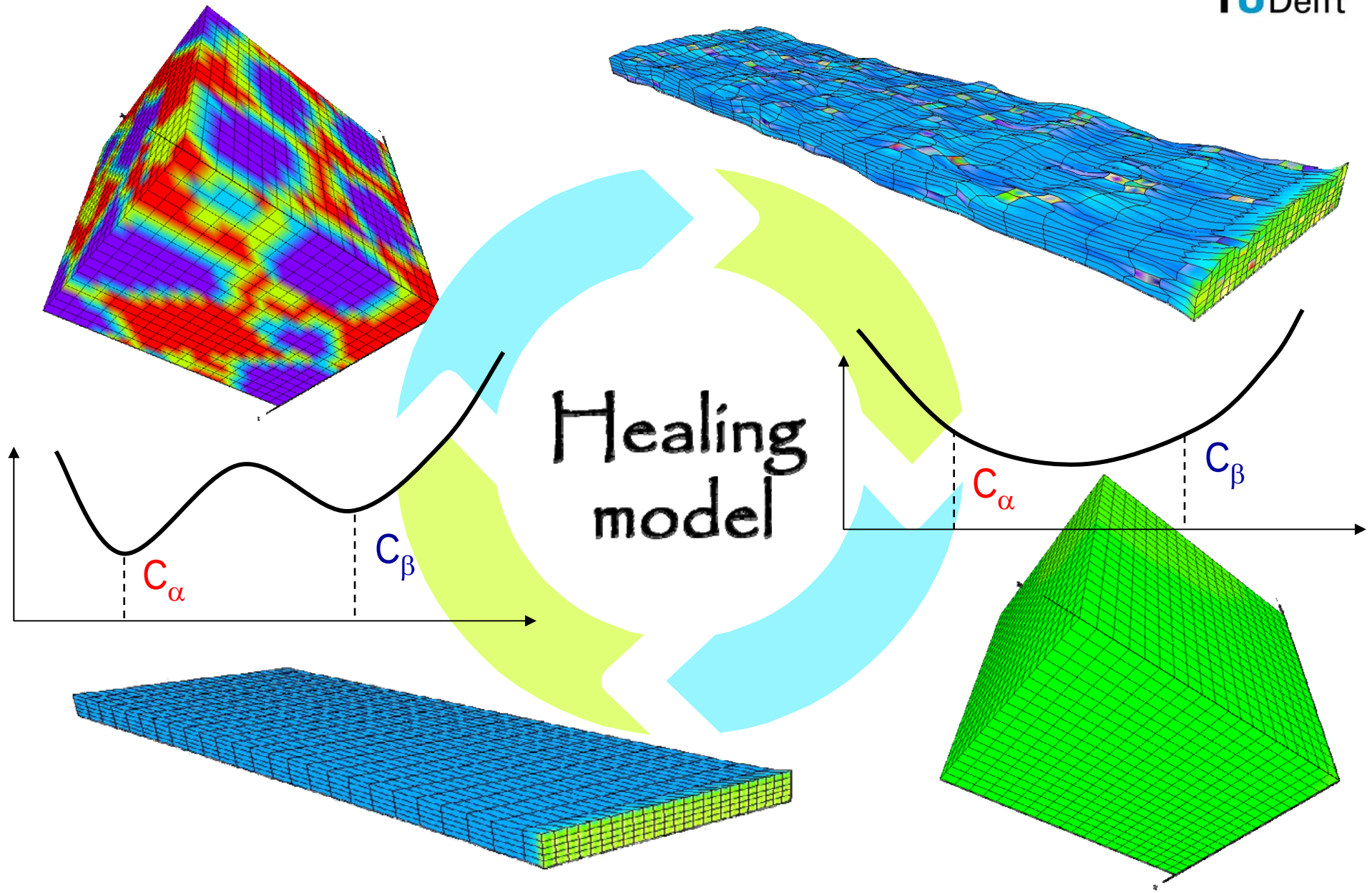


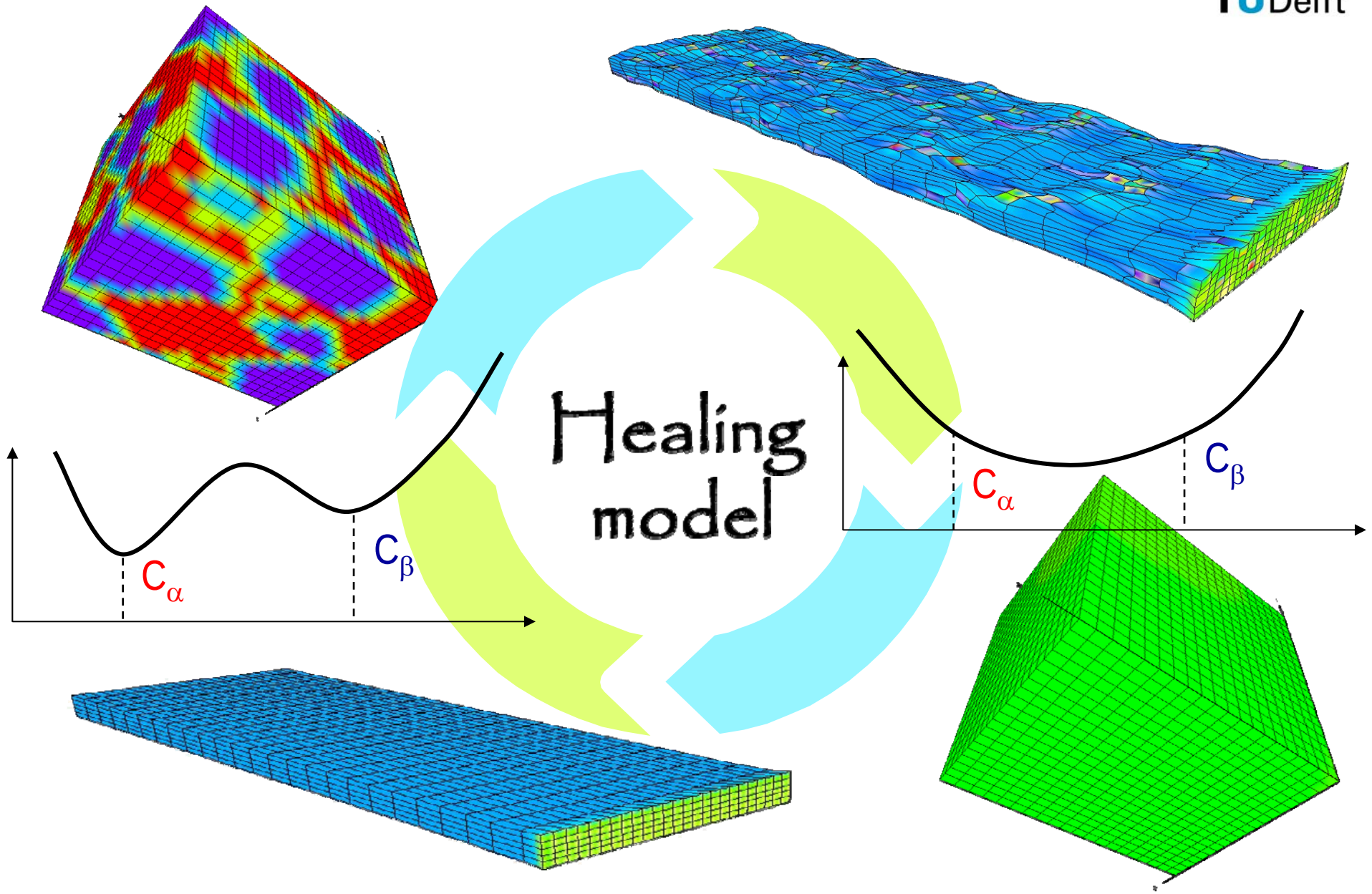
• Healing model



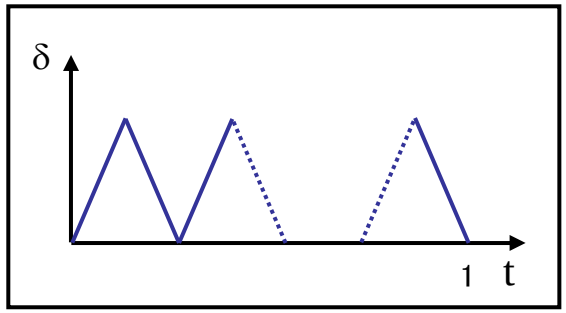


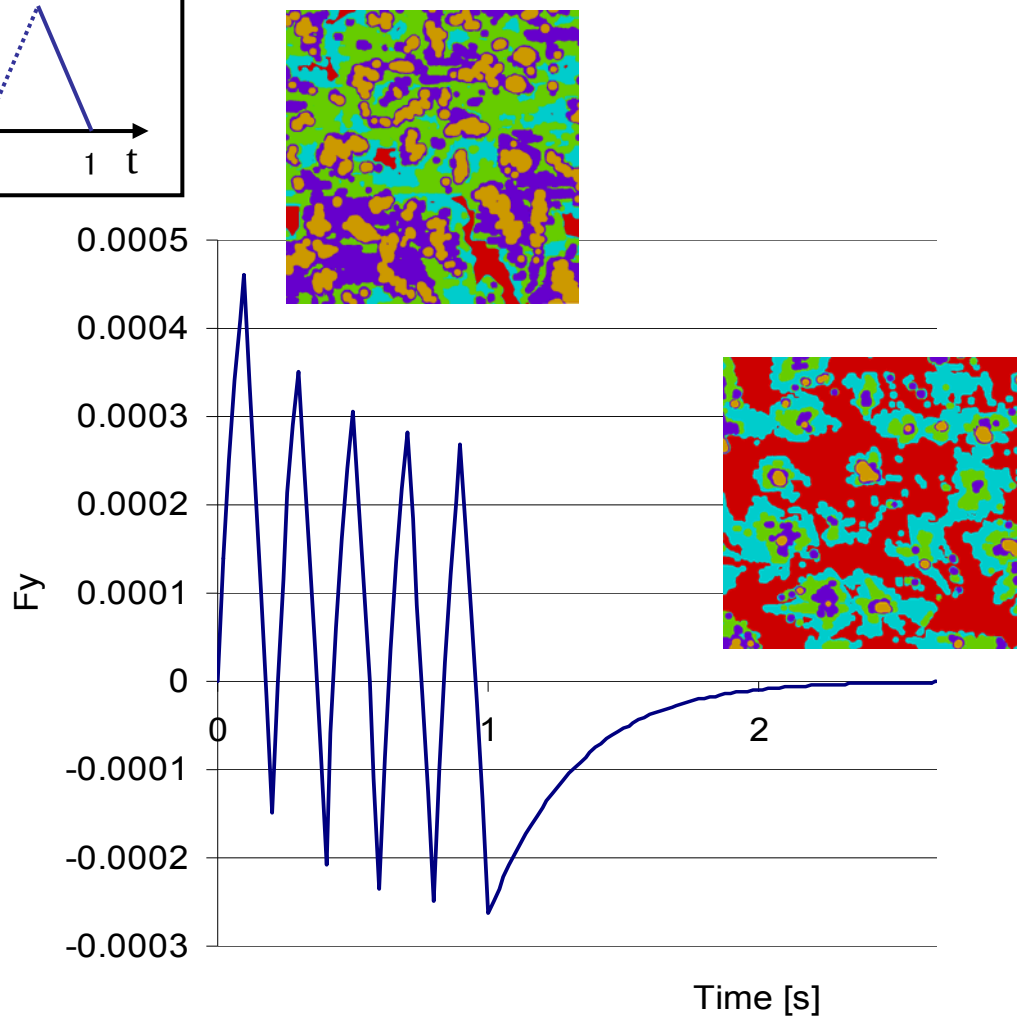

Healing model
C_α
C_β
C_α
C_β


Healing model
C_α
C_β
C_α
C_β

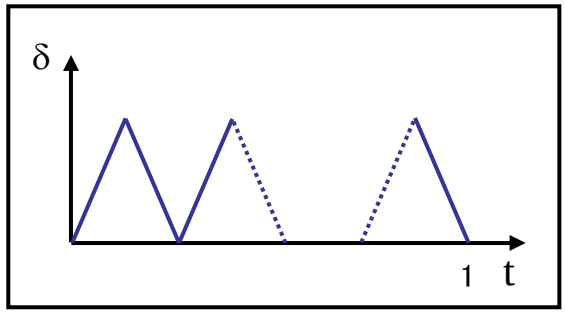

Healing model
C_α
C_β
C_α
C_β

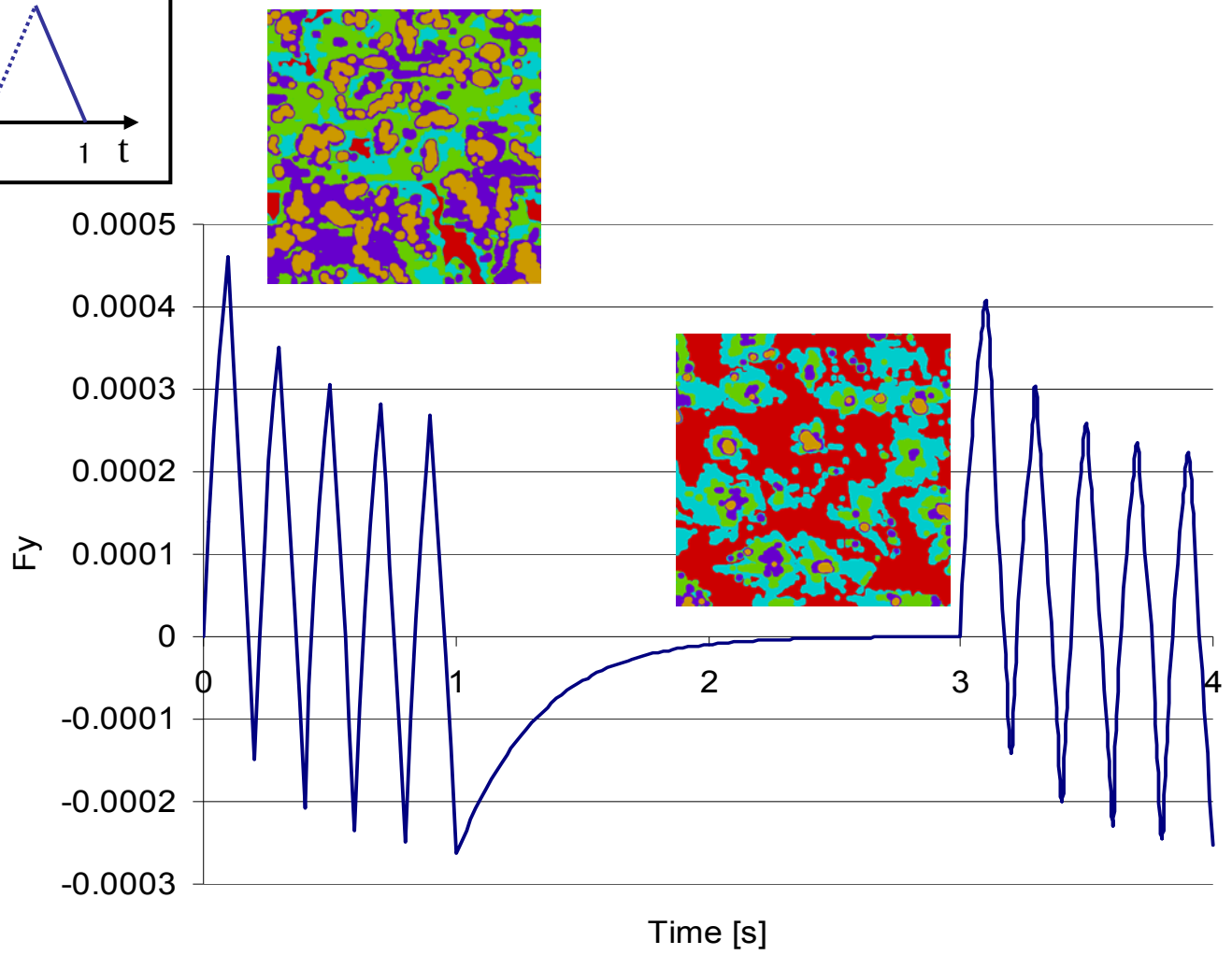
• Healing model





• Healing model





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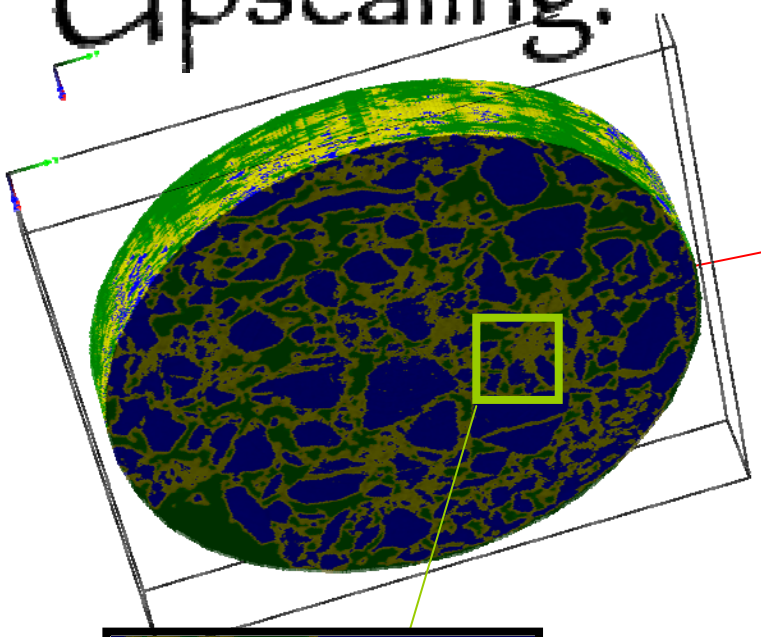

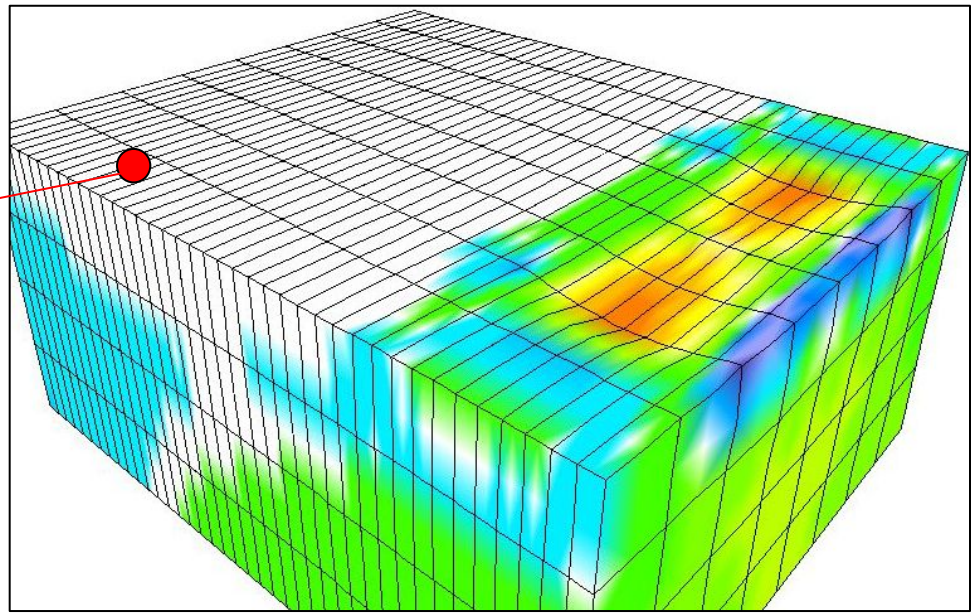

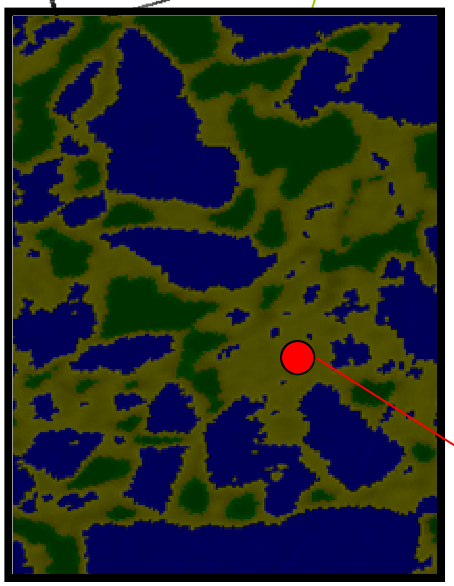

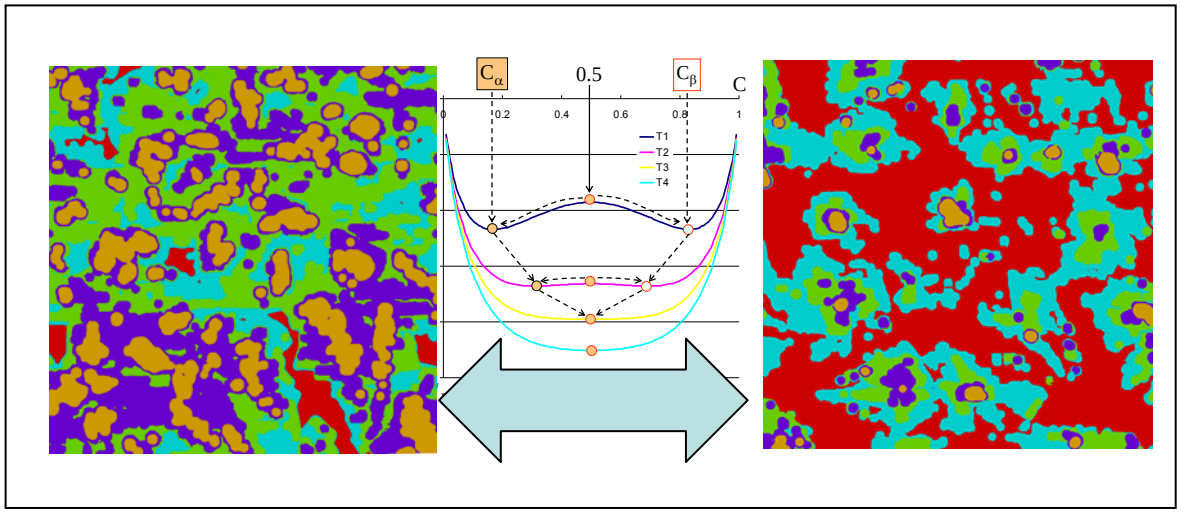

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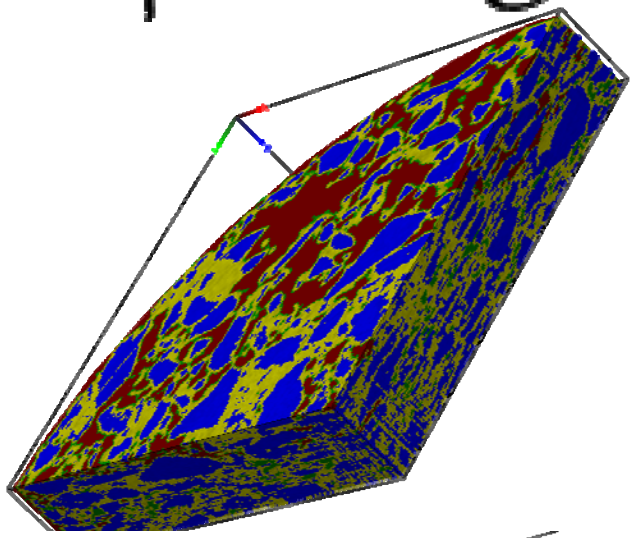
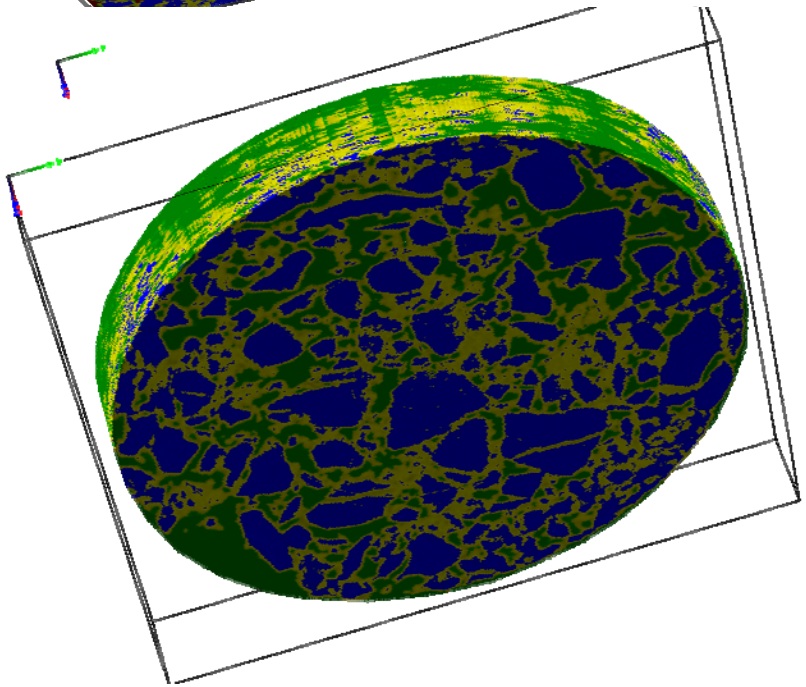
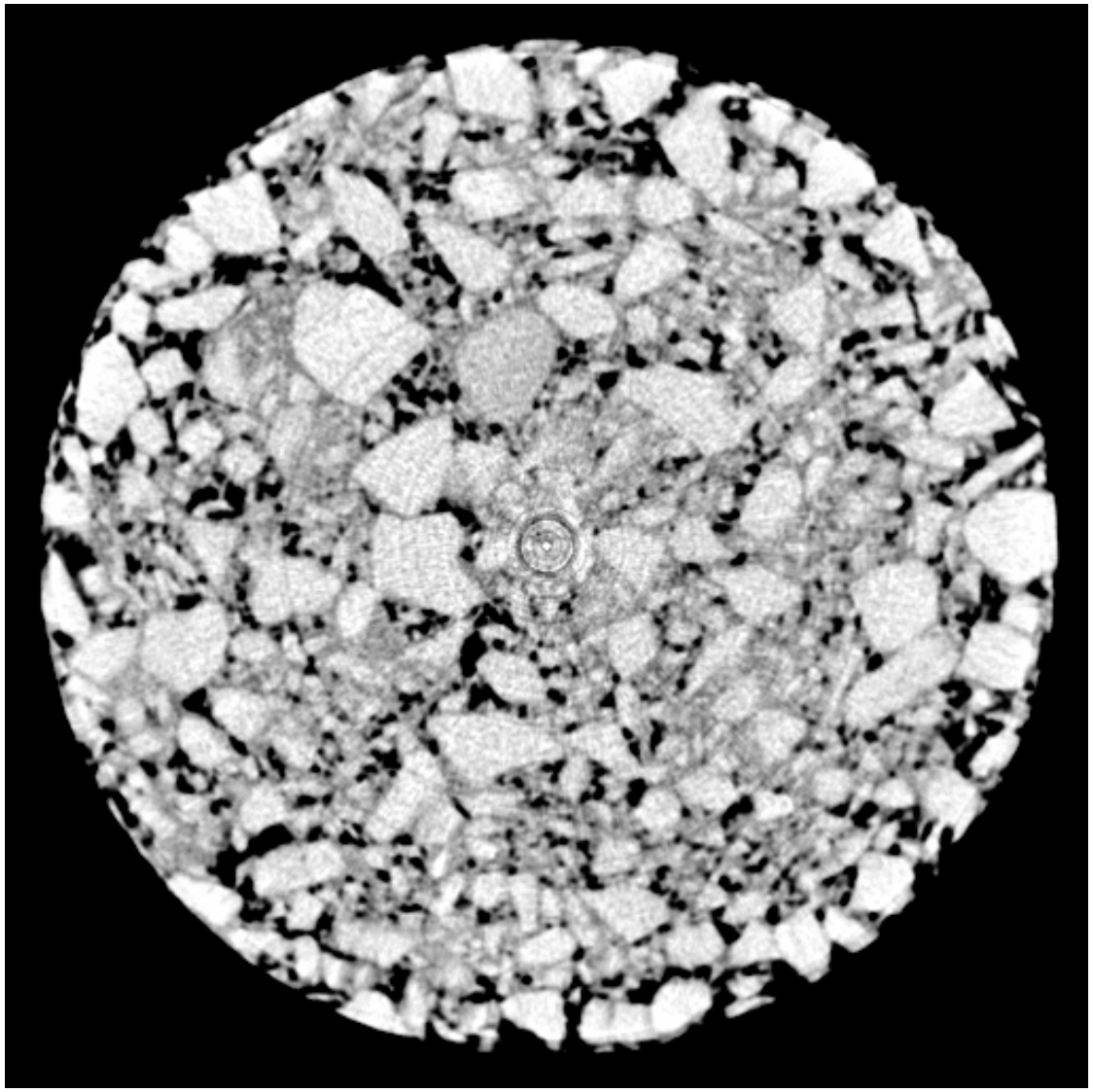
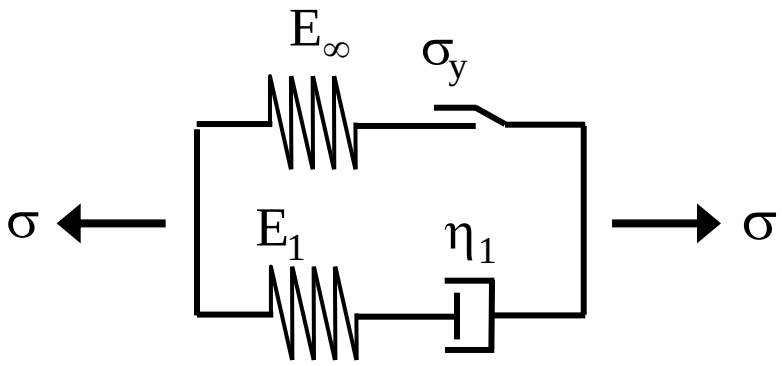
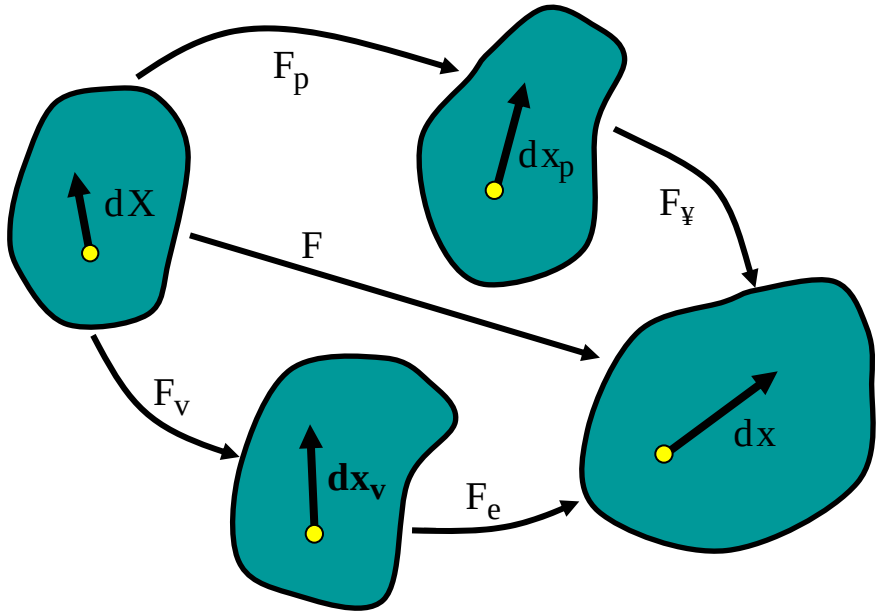






Constitutive Formulation





$$\mathbf{C}_\infty = \mathbf{F}_\infty^T \mathbf{F}_\infty \quad ; \quad \mathbf{C}_e = \mathbf{F}_e^T \mathbf{F}_e$$

Stress tensor :

$$\mathbf{S} = 2\mathbf{F}_v^{-1} \frac{\partial \Psi_v}{\partial \mathbf{C}_e} \mathbf{F}_v^{-T} + 2\mathbf{F}_p^{-1} \frac{\partial \Psi_p}{\partial \mathbf{C}_\infty} \mathbf{F}_p^{-T}$$

$$= \quad \mathbf{S}_e \quad + \quad \mathbf{S}_\infty$$

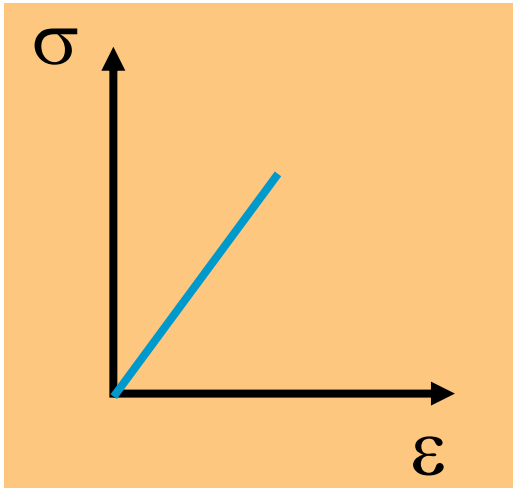
$$\Psi = \Psi_v + \Psi_p$$

Helmholtz free energy function

Constitutive Formulation

- **Elastic material**

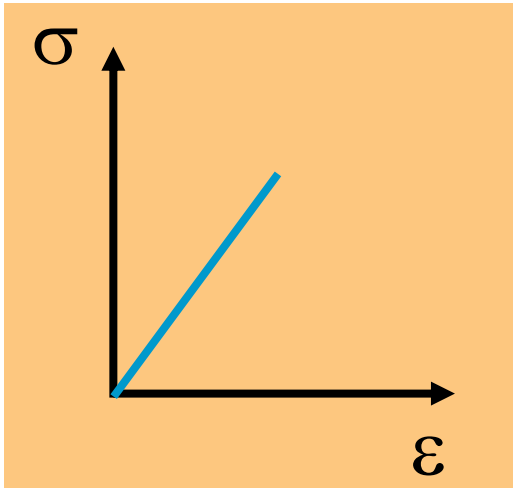
$$\Psi_e = \Psi_e(\mathbf{C})$$



Constitutive Formulation

- **Elastic material**

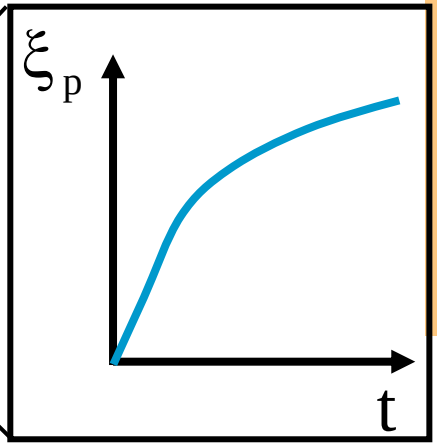
$$\Psi_e = \Psi_e(\mathbf{C})$$

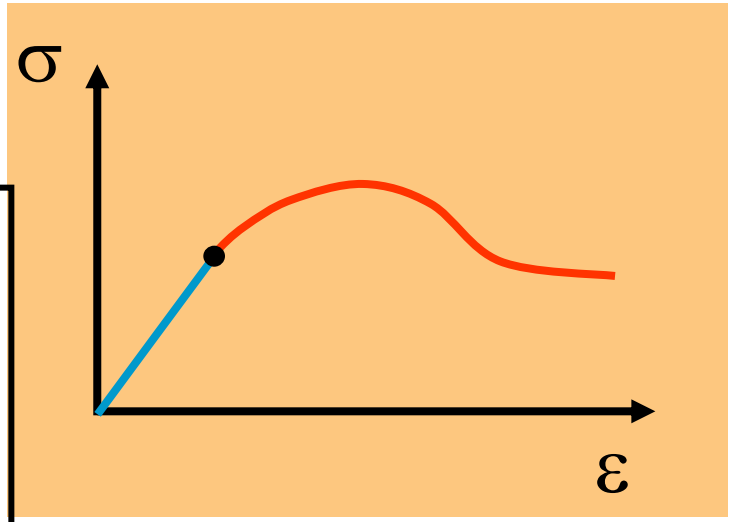


- **In-elastic material**

$$\Psi_p = \Psi_p(\mathbf{C}_\infty, \xi_p)$$

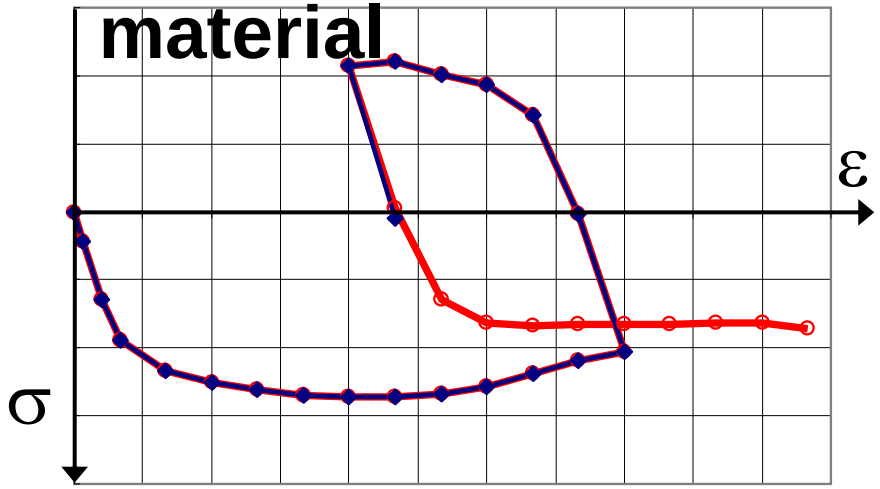
internal variable



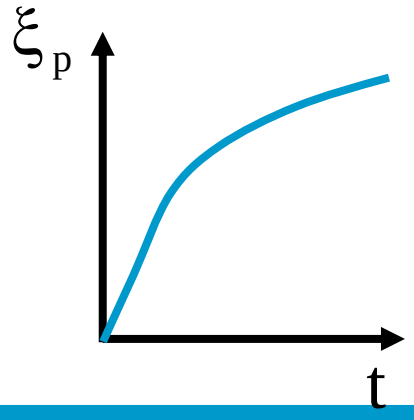


Constitutive Formulation

- **In-elastic material**

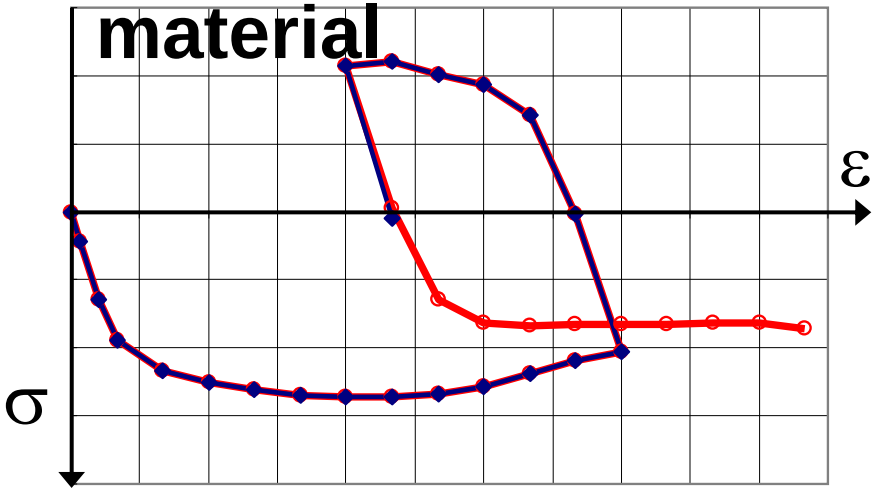


$$\Psi_p = \Psi_p\left(\mathbf{C}_\infty, \xi_p \right)$$

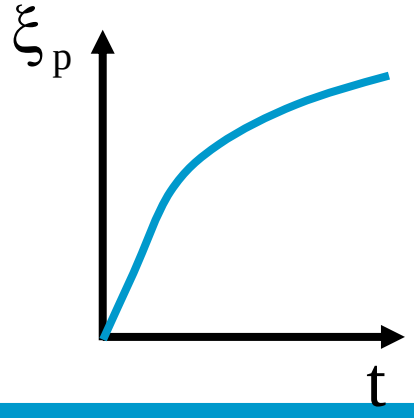


Constitutive Formulation

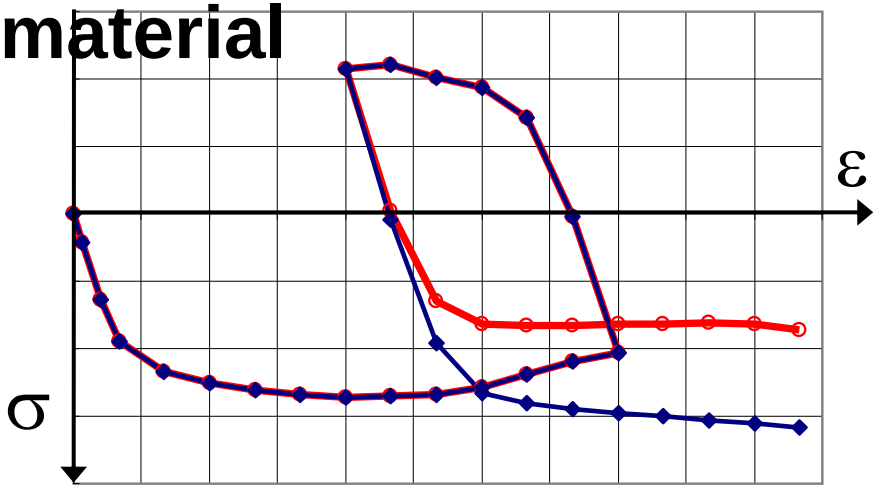
- **In-elastic material**



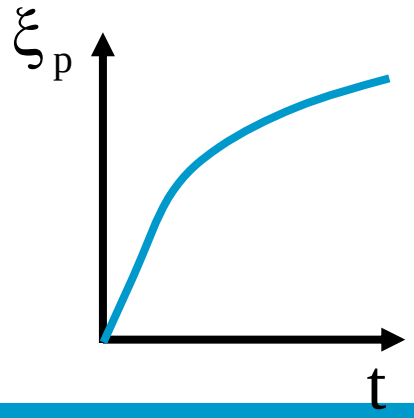
$$\Psi_p = \Psi_p\left(\mathbf{C}_\infty, \xi_p\right)$$

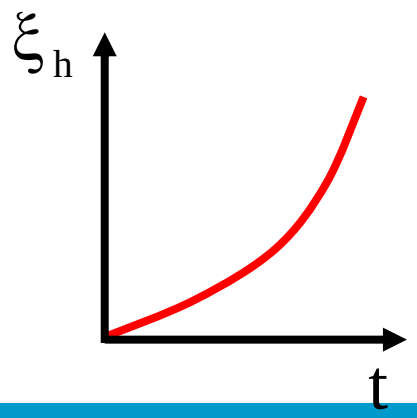


- **In-elastic healing material**



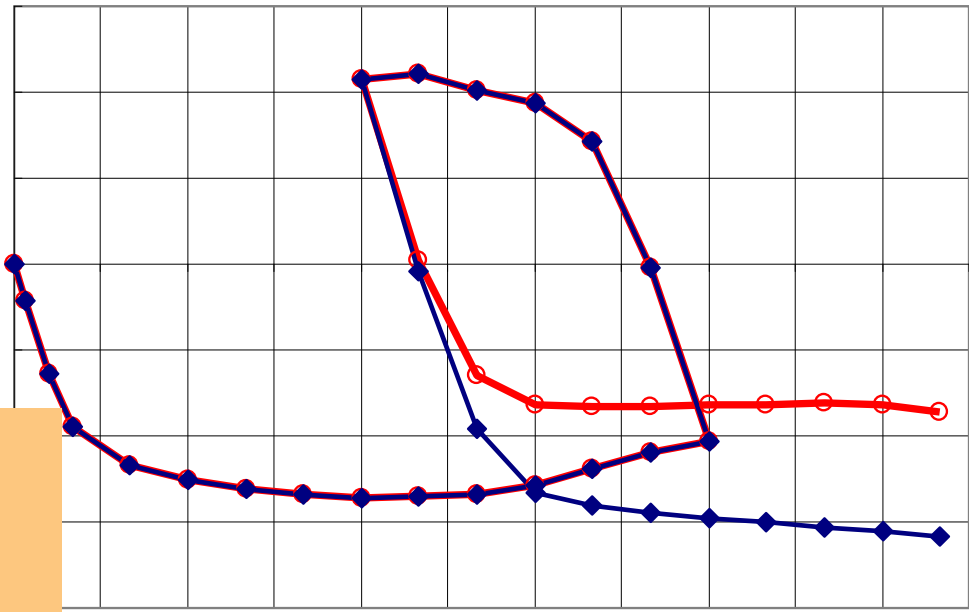
$$\Psi_{ph} = \Psi_{ph}\left(\mathbf{C}_\infty, \xi_p, \xi_h\right)$$





Constitutive Formulation

$$\Psi_p = \Psi_p\left(\mathbf{C}_\infty, \xi_p, \xi_h\right)$$

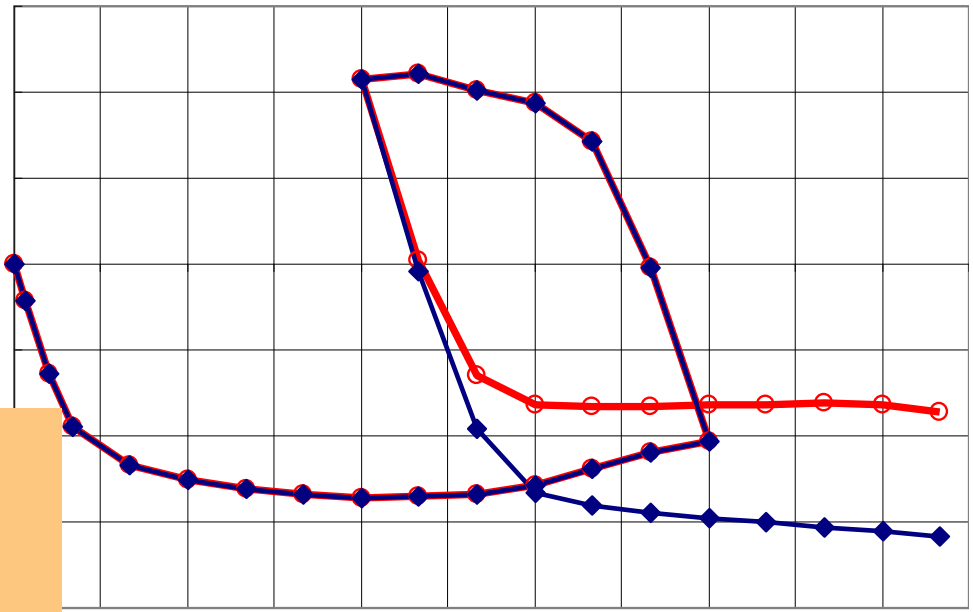


Dissipated energy :

$$2\mathbf{F}_\infty \frac{\partial \Psi_p}{\partial \mathbf{C}_\infty} \mathbf{F}_\infty^T \mathbf{F}_\infty^{-T} : \mathbf{F}_\infty \boldsymbol{l}_p - \frac{\partial \Psi_p}{\partial \xi_p} \dot{\xi}_p + \frac{\partial \Psi_p}{\partial \xi_h} \dot{\xi}_h \geq 0$$

Constitutive Formulation

$$\Psi_p = \Psi_p\left(\mathbf{C}_\infty, \xi_p, \xi_h\right)$$



Dissipated energy :

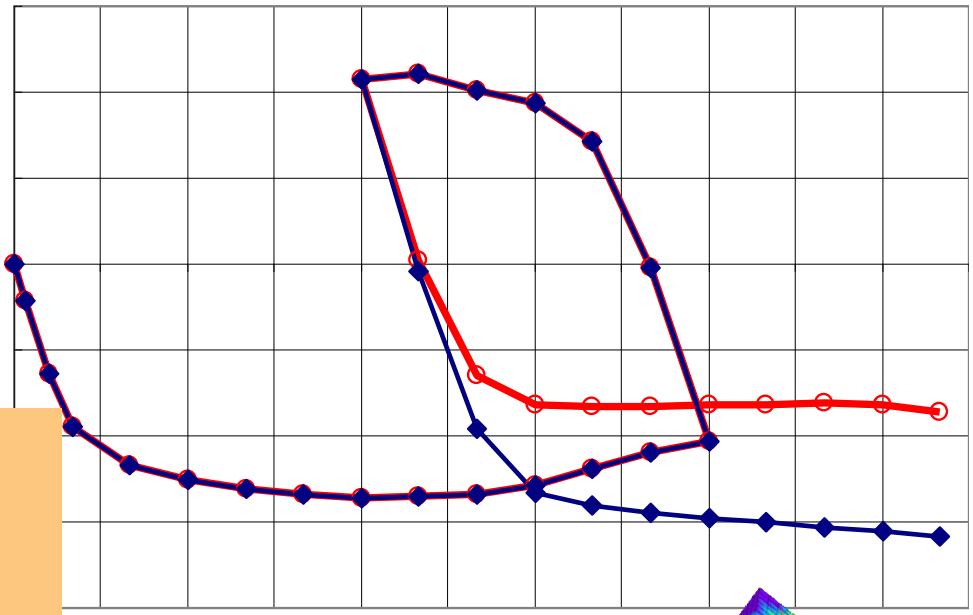
$$2\mathbf{F}_\infty \frac{\partial \Psi_p}{\partial \mathbf{C}_\infty} \mathbf{F}_\infty^T \mathbf{F}_\infty^{-T} : \mathbf{F}_\infty \boldsymbol{l}_p - \frac{\partial \Psi_p}{\partial \xi_p} \dot{\xi}_p + \frac{\partial \Psi_p}{\partial \xi_h} \dot{\xi}_h \geq 0$$

$$\xi_h = \xi_h\left(\phi_1, \phi_2, \ldots\right)$$

$$\phi_1 = \phi_1\left(\ldots, t, \ldots\right)$$

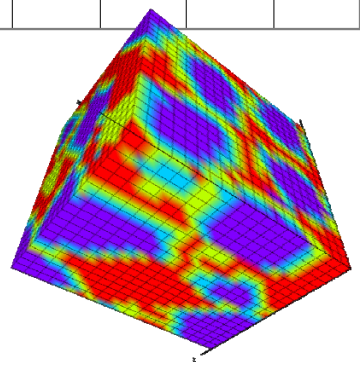
Constitutive Formulation

$$\Psi_p = \Psi_p\left(\mathbf{C}_\infty, \xi_p, \xi_h\right)$$



Dissipated energy :

$$2\mathbf{F}_\infty \frac{\partial \Psi_p}{\partial \mathbf{C}_\infty} \mathbf{F}_\infty^T \mathbf{F}_\infty^{-T} : \mathbf{F}_\infty \boldsymbol{l}_p - \frac{\partial \Psi_p}{\partial \xi_p} \dot{\xi}_p + \frac{\partial \Psi_p}{\partial \xi_h} \dot{\xi}_h \geq 0$$



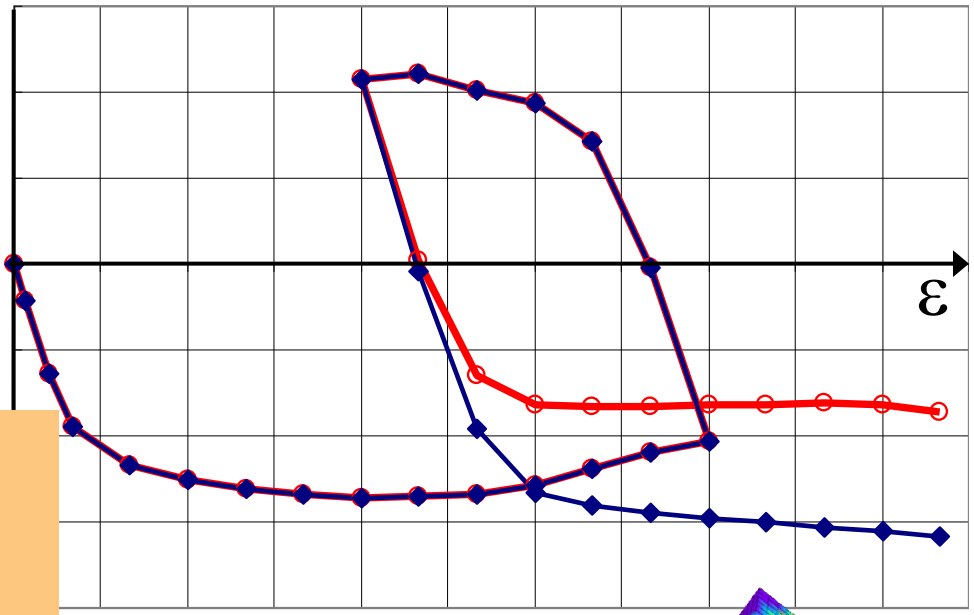
$$\xi_h = \xi_h\left(\phi_1, \phi_2, \ldots\right)$$

Interfaces (thinkness, distribution)

$$\phi_1 = \phi_1\left(\ldots, t, \ldots\right)$$

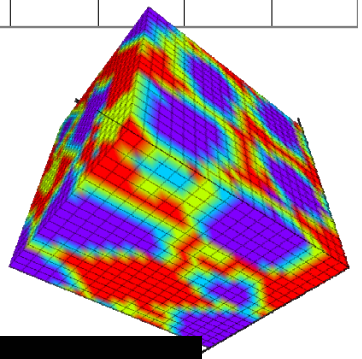
Constitutive Formulation

$$\Psi_p = \Psi_p\left(\mathbf{C}_\infty, \xi_p, \xi_h\right)$$



Dissipated energy :

$$2\mathbf{F}_\infty \frac{\partial \Psi_p}{\partial \mathbf{C}_\infty} \mathbf{F}_\infty^T \mathbf{F}_\infty^{-T} : \mathbf{F}_\infty \boldsymbol{l}_p - \frac{\partial \Psi_p}{\partial \xi_p} \dot{\xi}_p + \frac{\partial \Psi_p}{\partial \xi_h} \dot{\xi}_h \geq 0$$



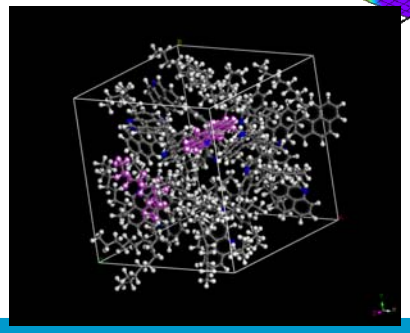
$$\xi_h = \xi_h\left(\phi_1, \phi_2, \ldots\right)$$

$$\phi_1 = \phi_1\left(\ldots, t, \ldots\right)$$

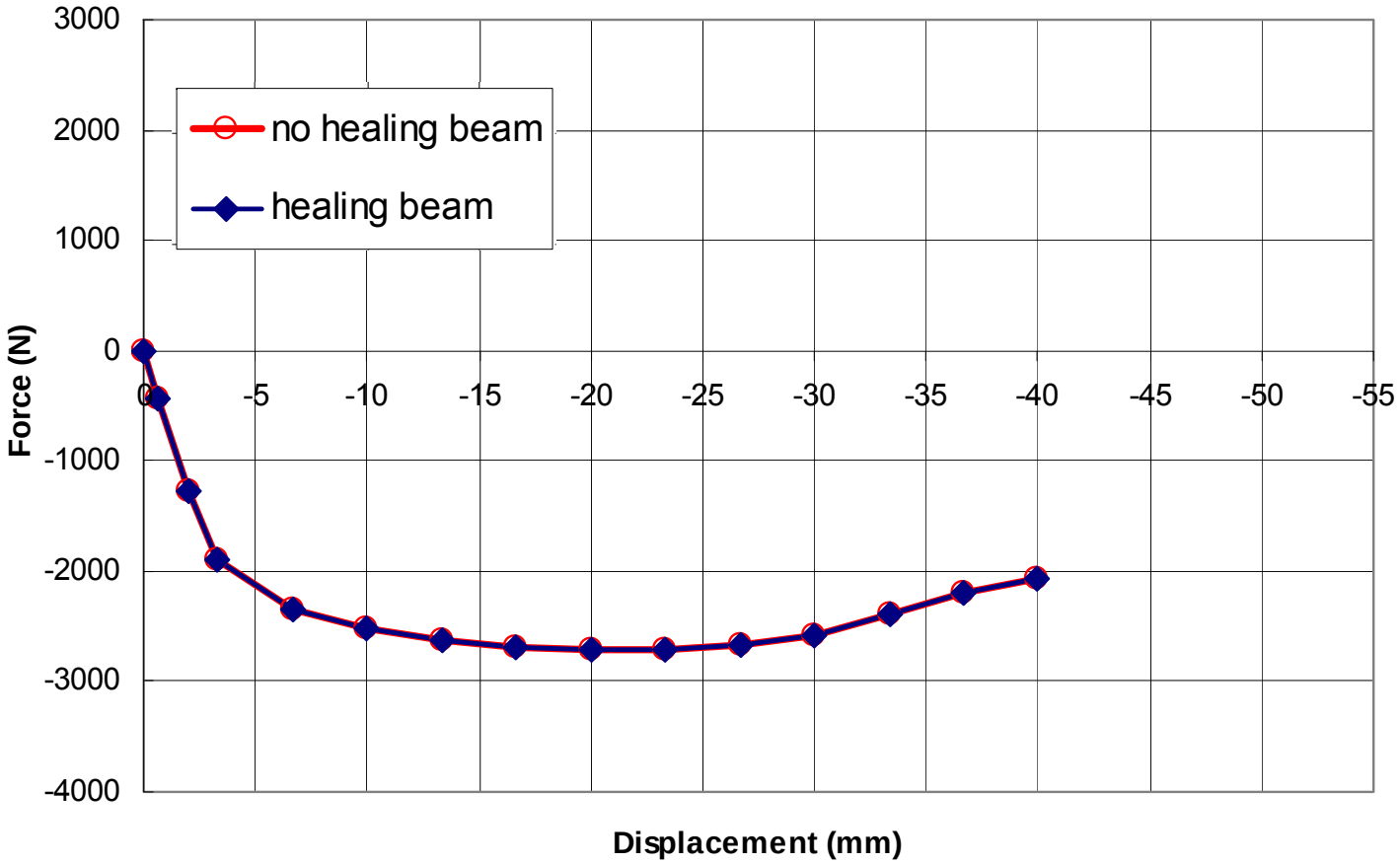
Interfaces (thinkness, distribution)

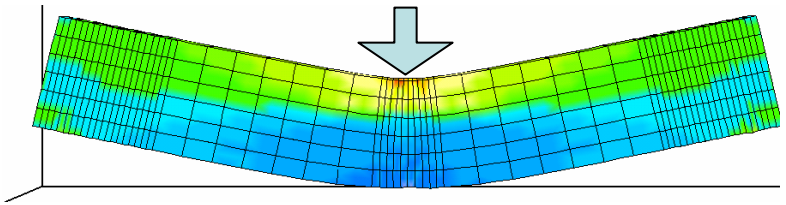
Rate of phase movement

Level of oxidation



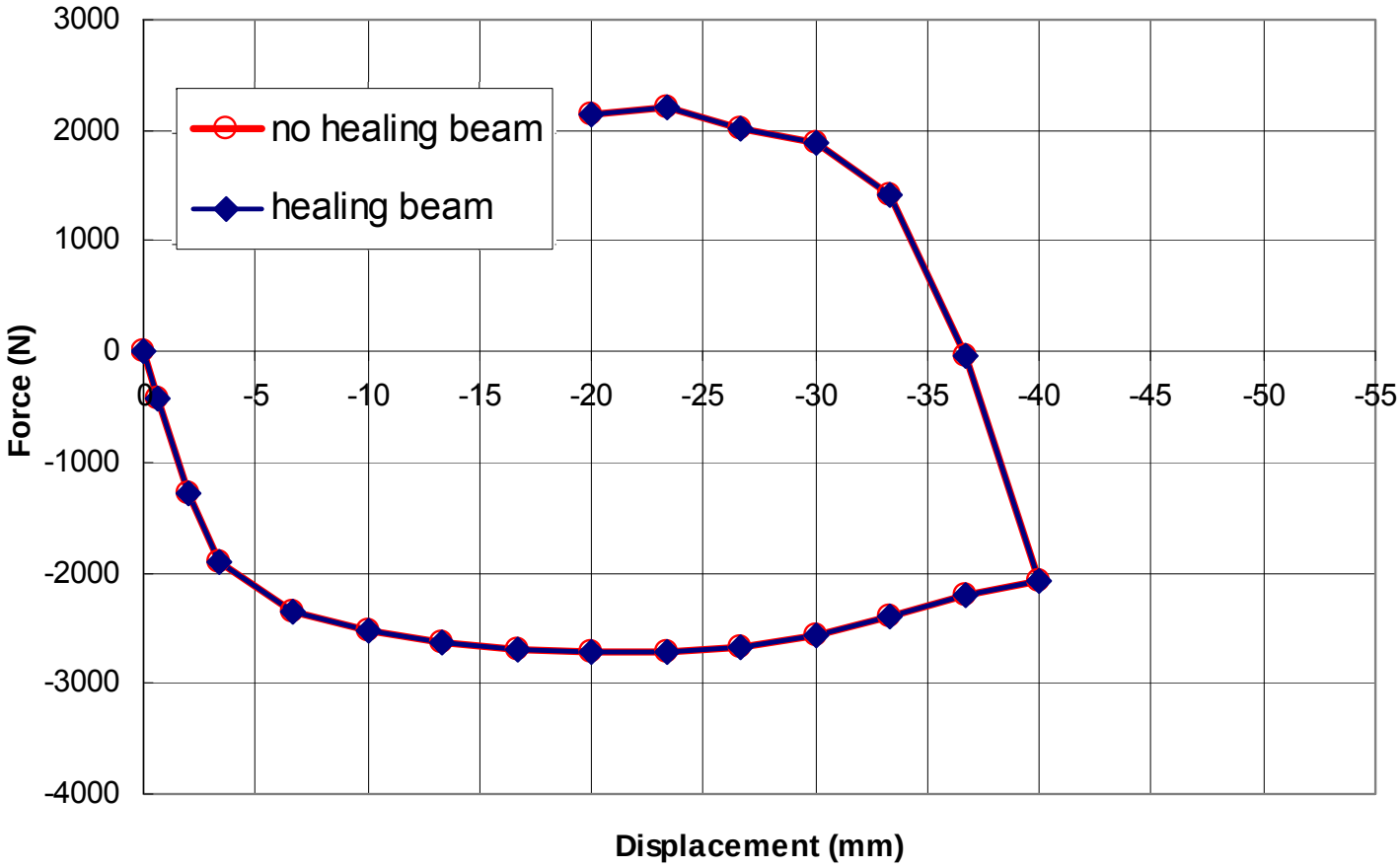
Constitutive Formulation

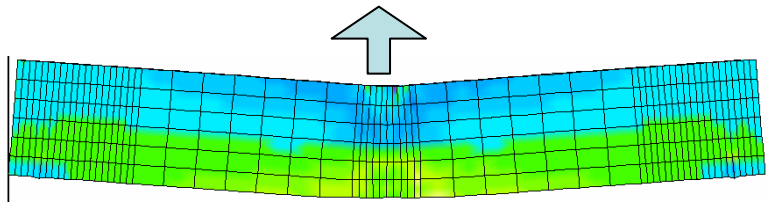




(Liu & Scarpas)

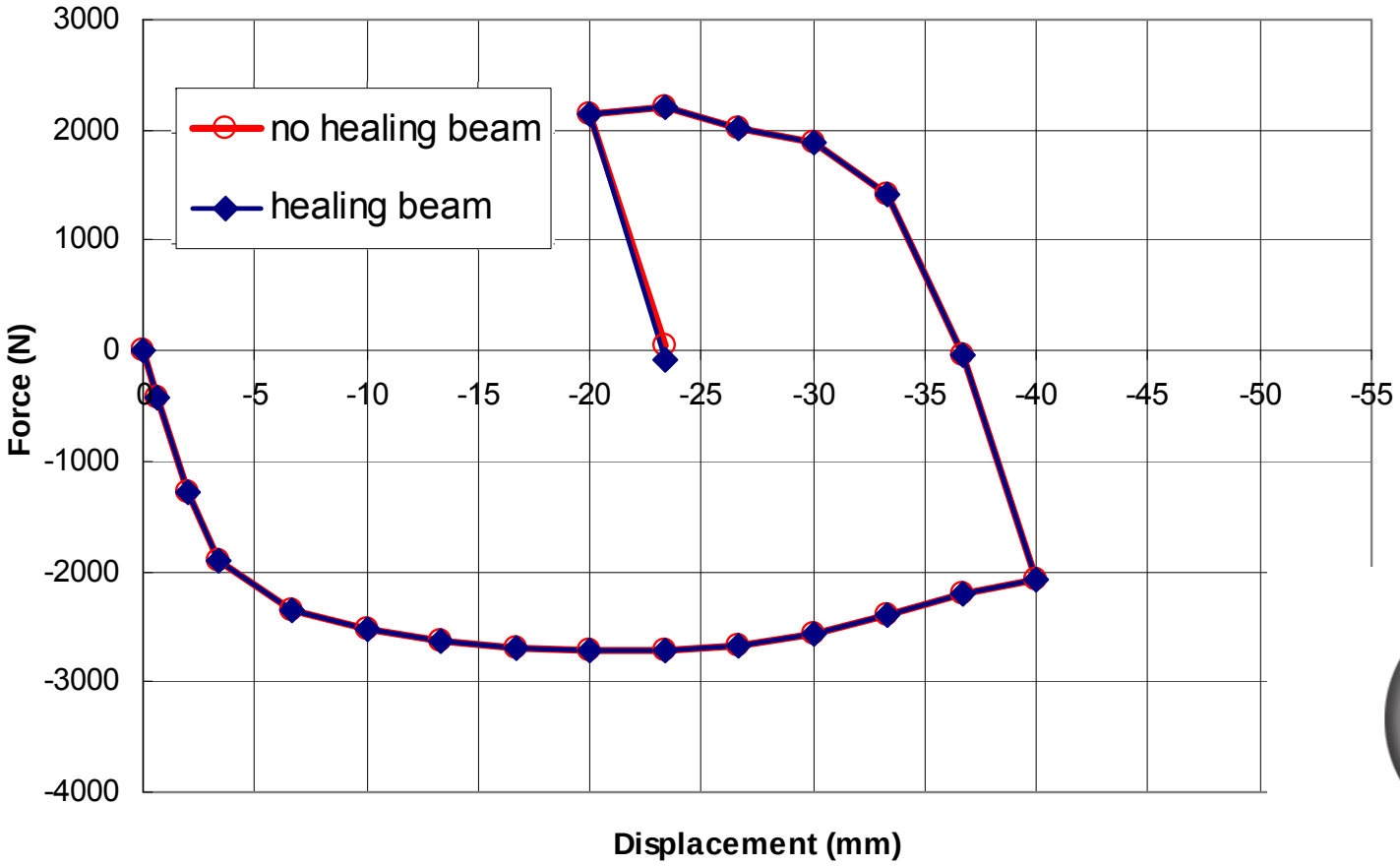
Constitutive Formulation

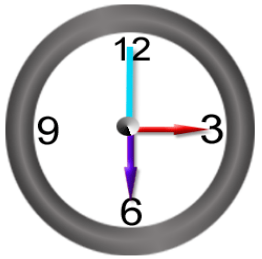


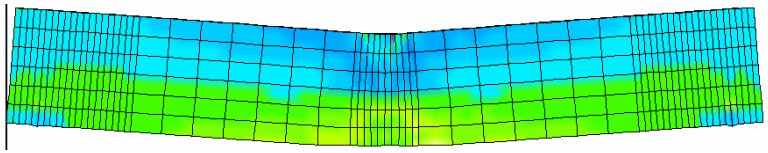


(Liu & Scarpas)

Constitutive Formulation

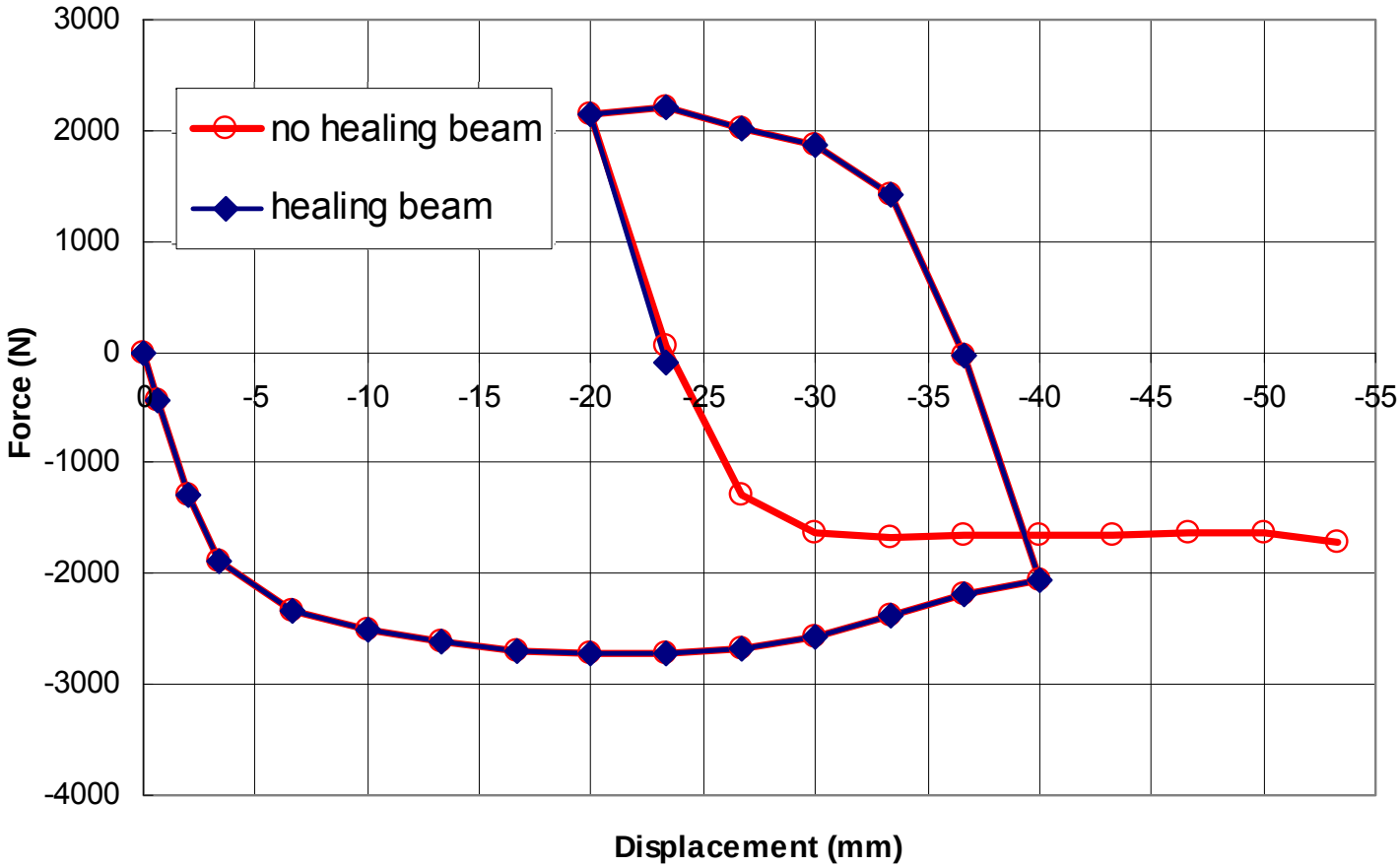


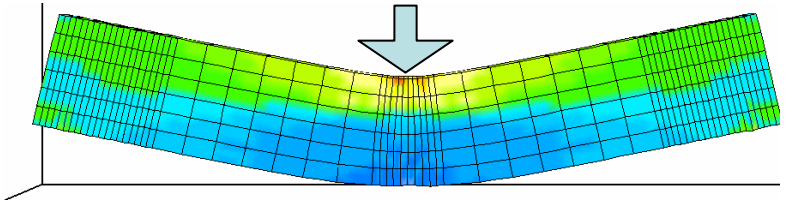




(Liu & Scarpas)

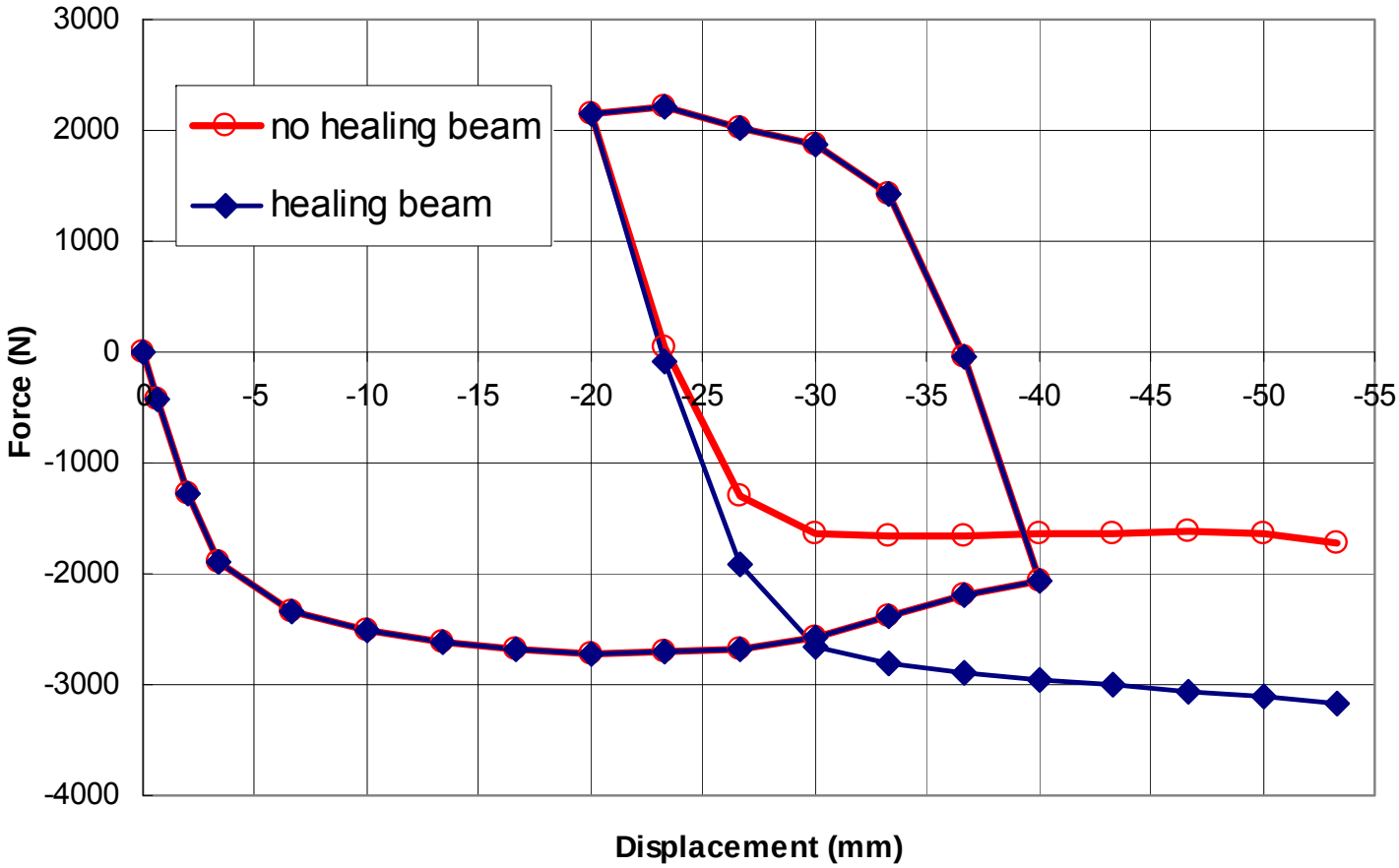
Constitutive Formulation

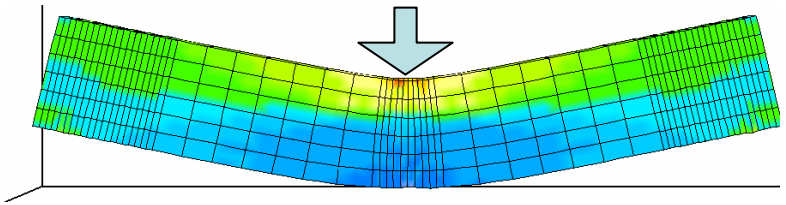




(Liu & Scarpas)

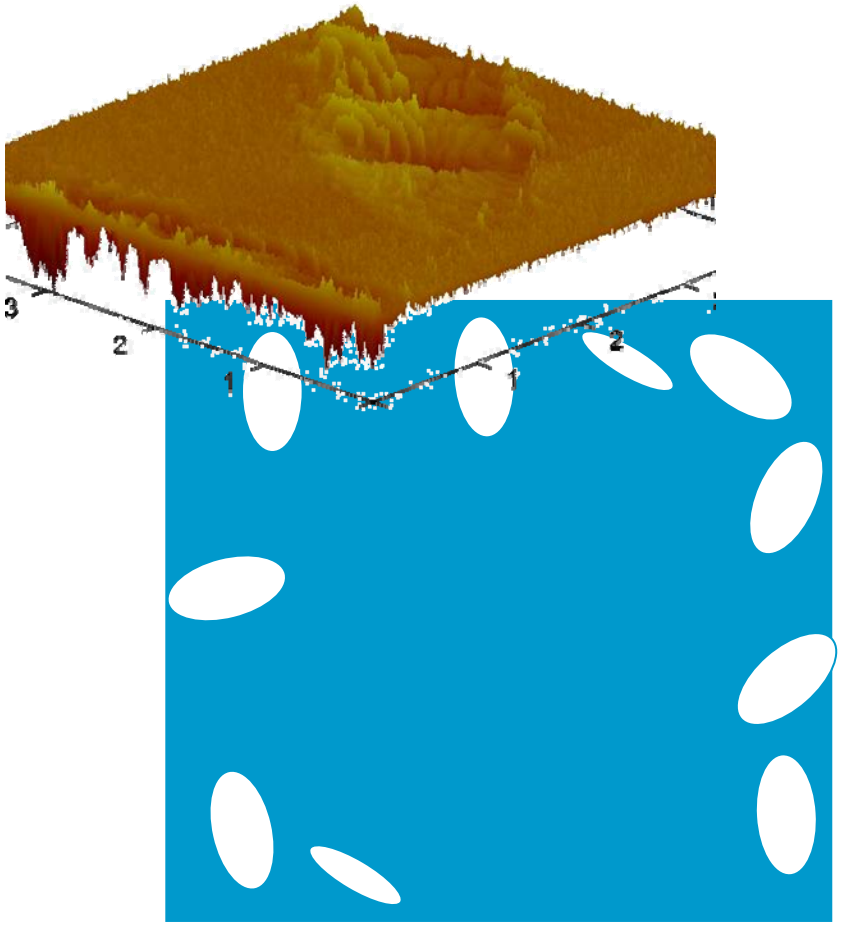
Constitutive Formulation





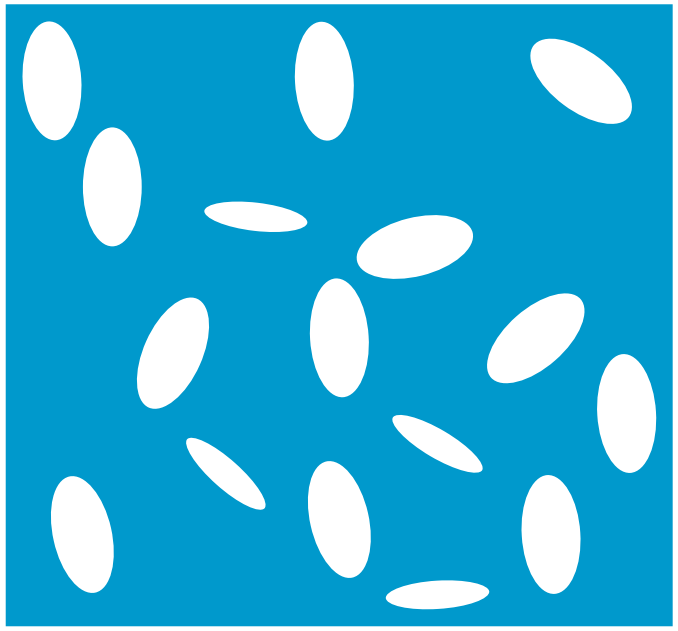
(Liu & Scarpas)

Wax induced Phase Separation !!!

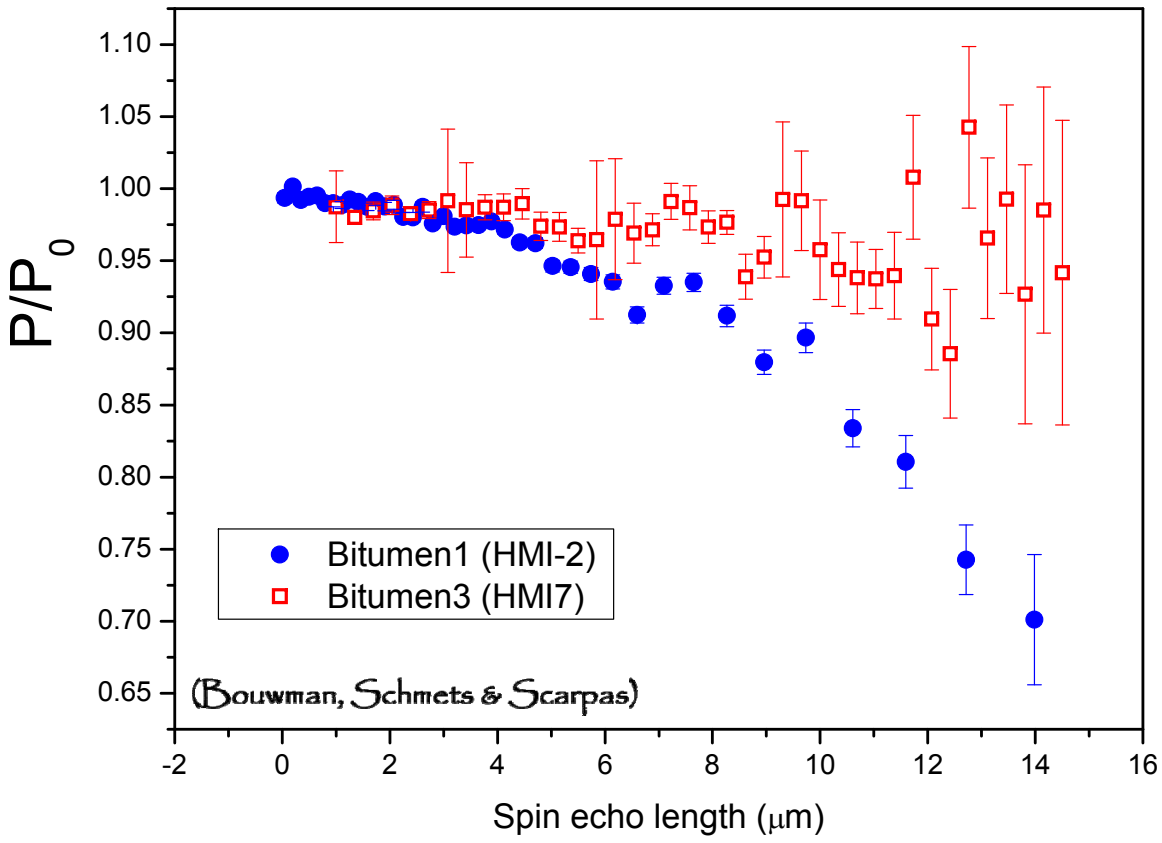


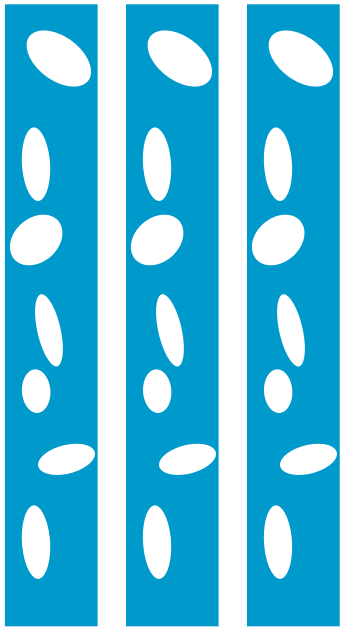
surface effect?

bulk?



Wax induced Phase Separation !!!





Spin echo small angle neutron scattering SESANS

Continued work on:

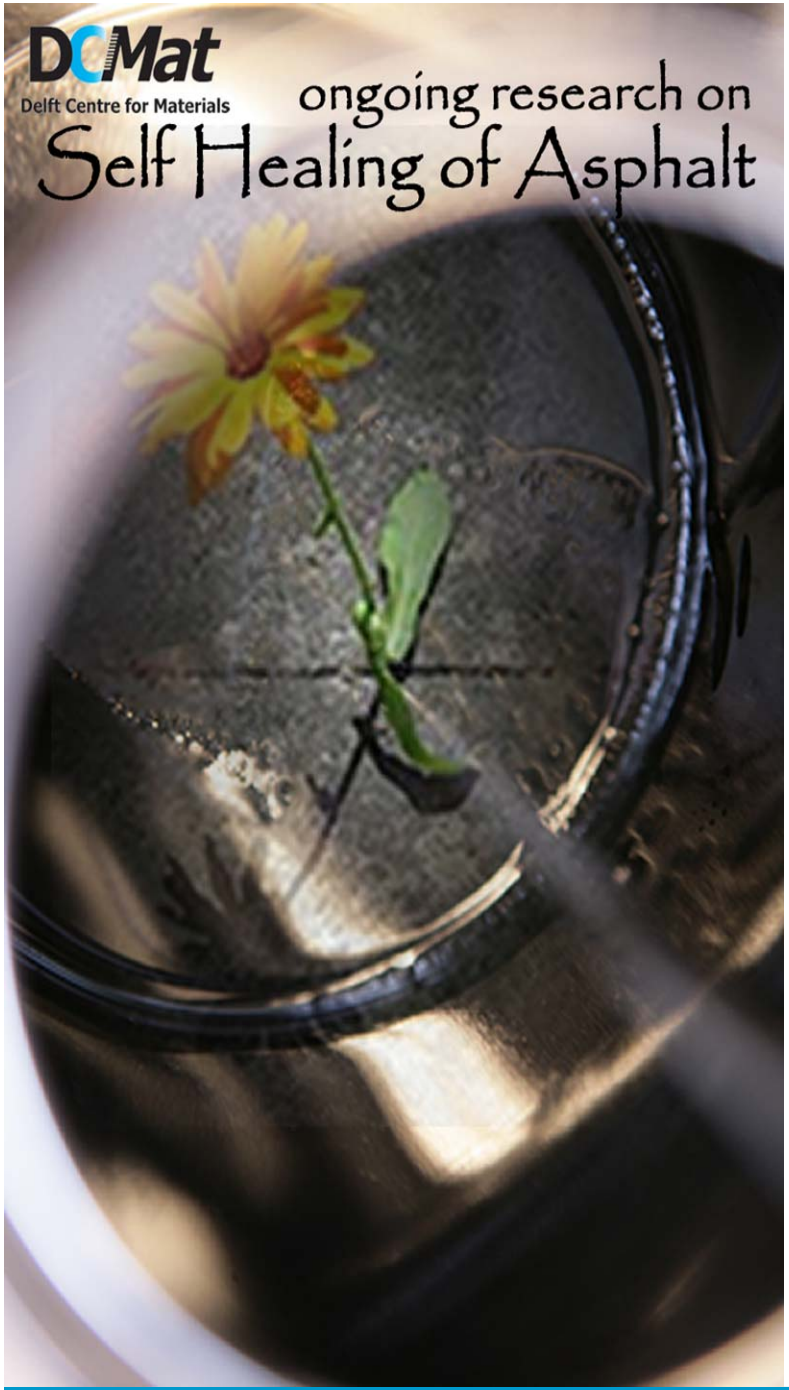
- multi-phase model (enabling the use of range of material parameters, such as solubility)
  - *interfacial kinetics*

- mechanical properties of:
  - wax (as a function of temperature, …)
  - matrix (as a function of temperature, …)
- upscaling procedure

- mobility/diffusivity/activation energy (linking to rest periods)

- linking the model to healing tests (?)

-….



TU Delft

Thank you !!!

T. Scarpas

N. Kringos, T. Pauli, A. Schmets

Group of Mechanics of Infrastructure Materials

Section of Structural Mechanics

Faculty of Civil Engineering and Geosciences

TU Delft