Physics of Glassy and Granular Materials
YITP, Kyoto, 17 July 2013

Controlling the position of desiccation cracks using memory effect of paste

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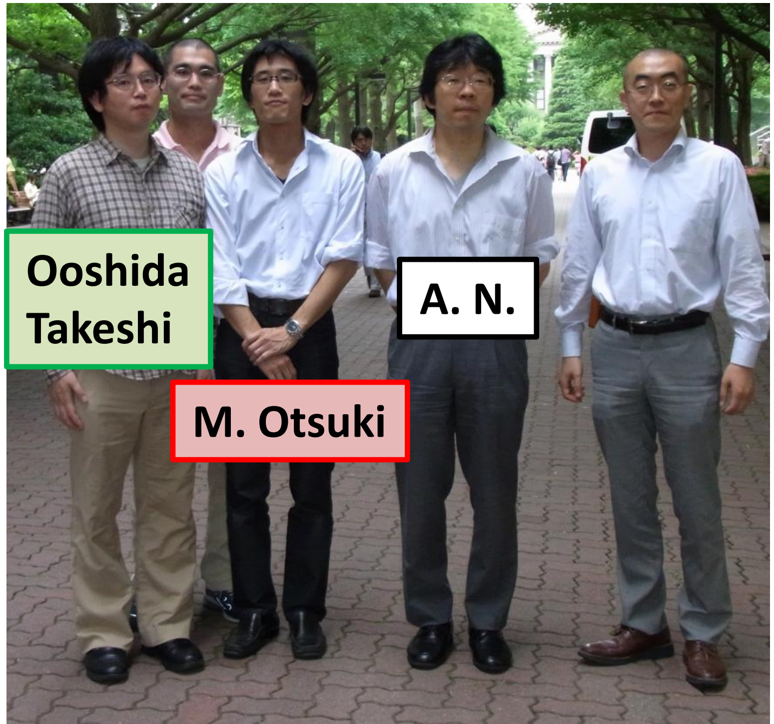
Nara Women's Univ.	S. Kitsunezaki

Nihon Univ.

Tottori Univ.

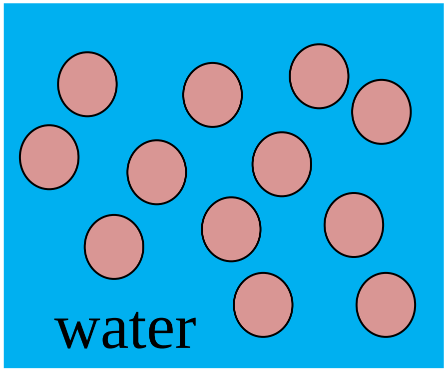
Shimane Univ.

Nara Women’s Univ.



Desiccation cracks of colloidal suspension

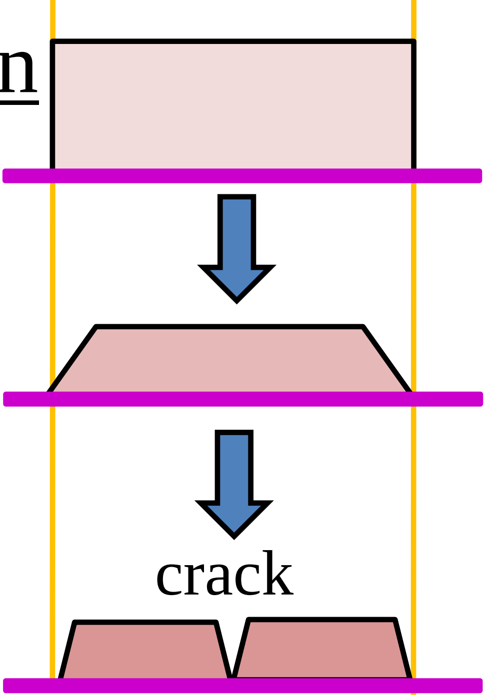
Colloidal particles
(~μm)



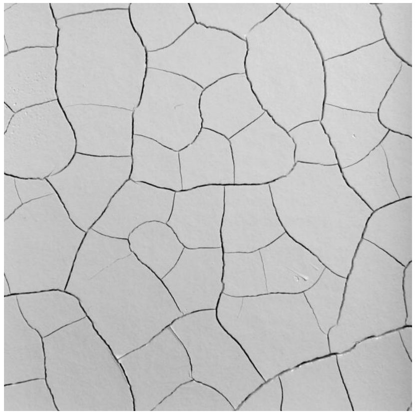
Contraction due to drying
+
Adhesion at the bottom

To release ⇩ stress horizontally

Formation of cracks
spacing ~ depth of paste

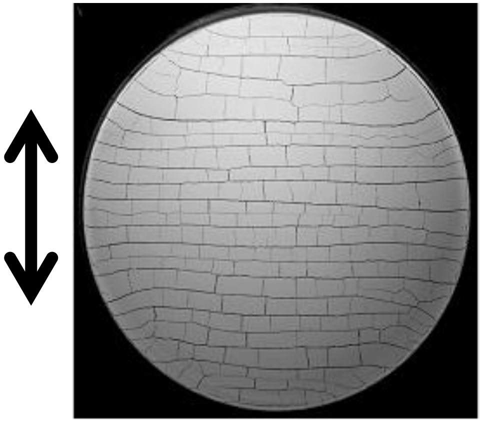


Usually cellular isotropic cracks



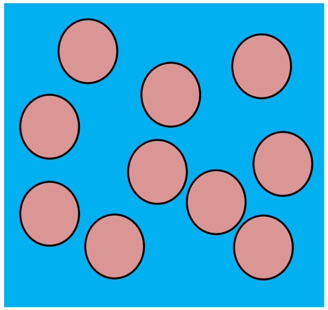
Crack patterns produced by memory effect

Memory is induced by plasticity



vibration

=

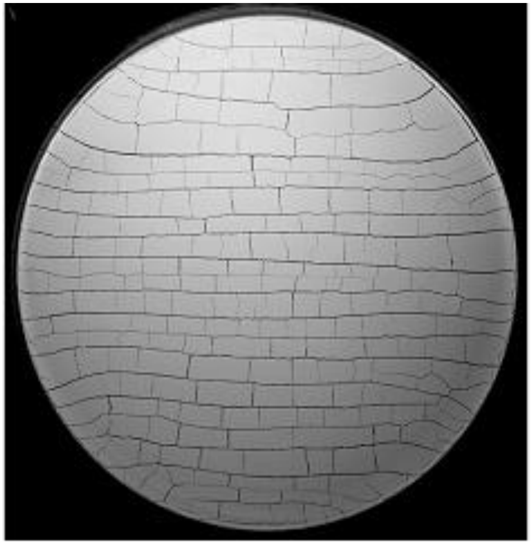


Random

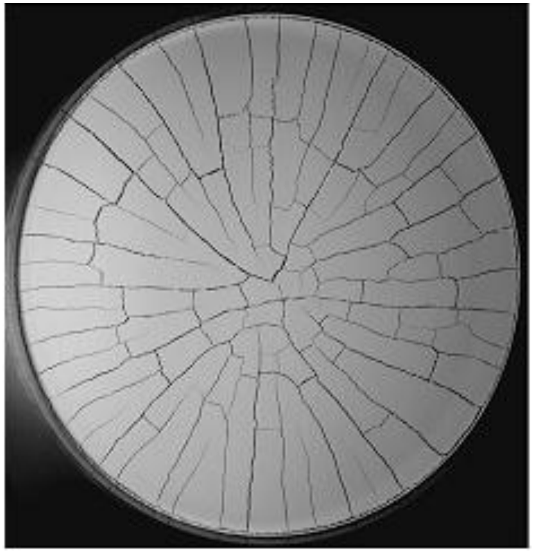
+

Structure?
(memory)

Desiccation crack patterns produced by memory effect



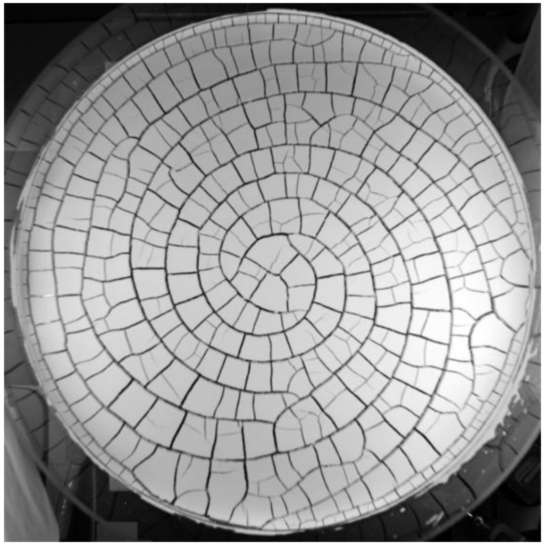
Lamellar



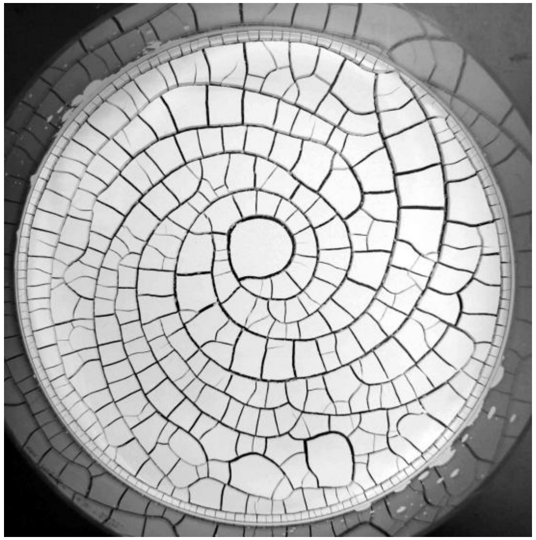
Radial

lattice

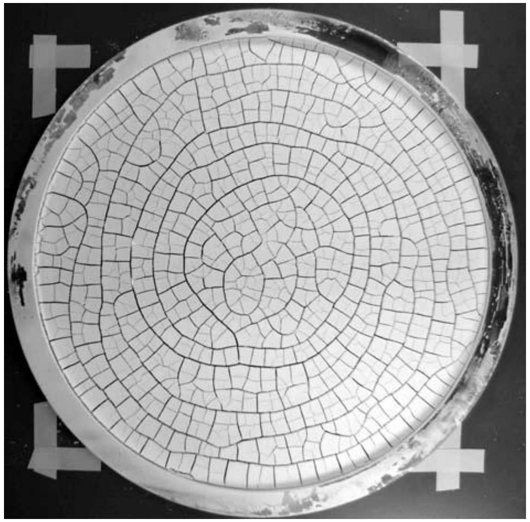
Diameter 500mm Depth ~ 10mm



Spiral

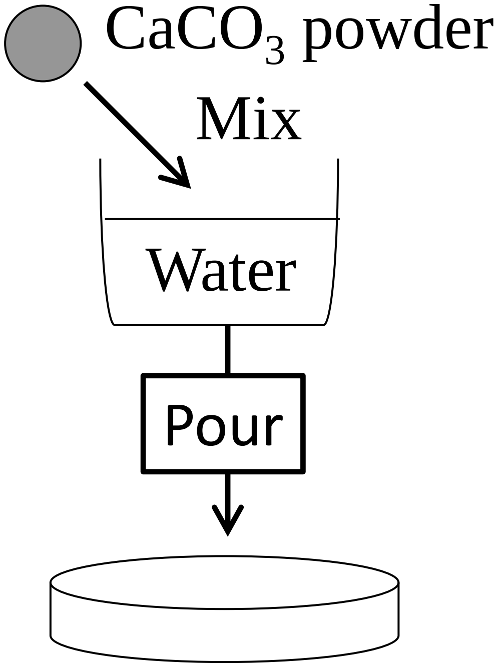


Spiral



Ring

Protocol of our drying experiments



$CaCO_3$ powder

Mix

Water

Pour

Paste remembers
the direction
of initial vibration

0

1 minute

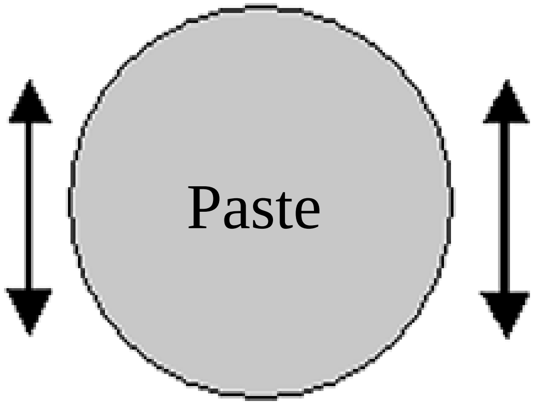
2 days
(1 month)

cracks

t

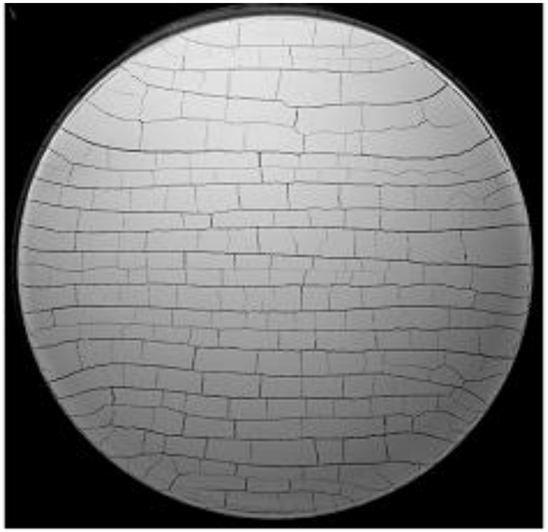
Shake horizontally

Leave still and dry

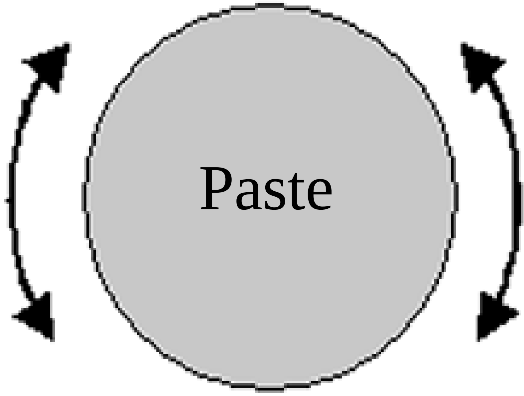


Paste

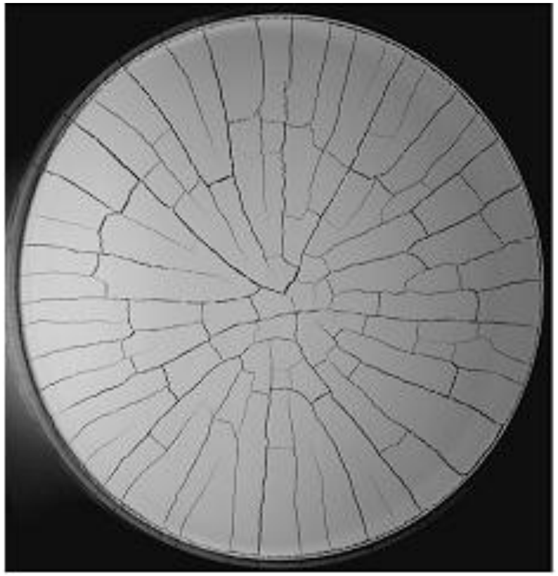
Top view



Cracks run perpendicular to initial vibration



Cracks perpendicular to vibration



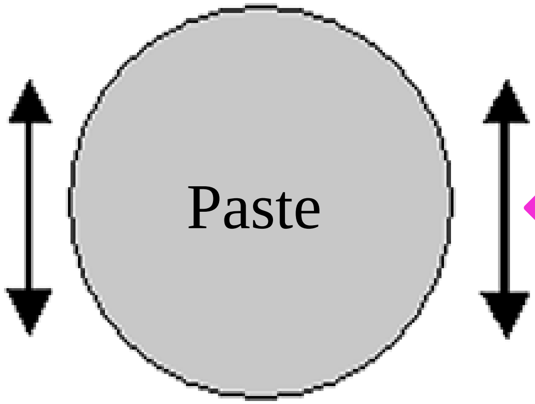
Pour

Shake horizontally

Le

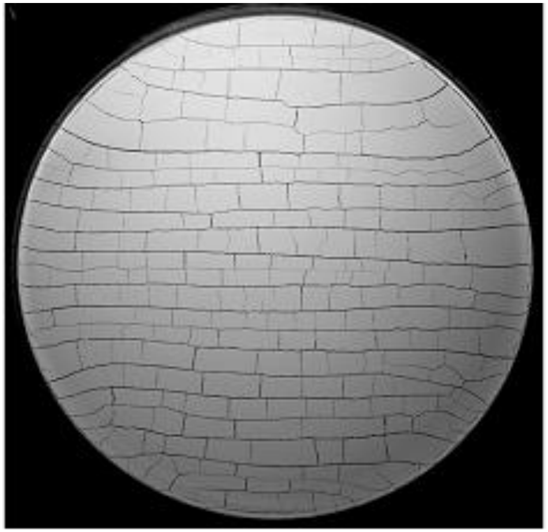
Memory of vibration

dry



Top view

Cracks perpendicular to vibration



Memory of vibration

A. Nakahara and Y. Matsuo
J. Phys. Soc. Jpn. 74 (2005) 1362.

⊕ charged

Water-poor $CaCO_3$ paste

Paste is vibrated

↕

Initial vibration (horizontally)

Stop vibration & dry

Water-rich $CaCO_3$ paste

Paste is vibrated and fluidized

Lamellar cracks

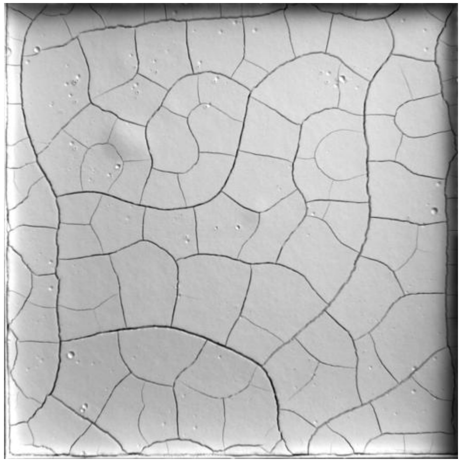
(perpendicular to vibration)

Memory of vibration

Crack formation (top view)

Cellular cracks

(isotropic and homogeneous)



No memory

Uncharged Pastes remember vibration and flow !

Magnesium Carbonate Hydroxide, Carbon, Kaolin, etc.

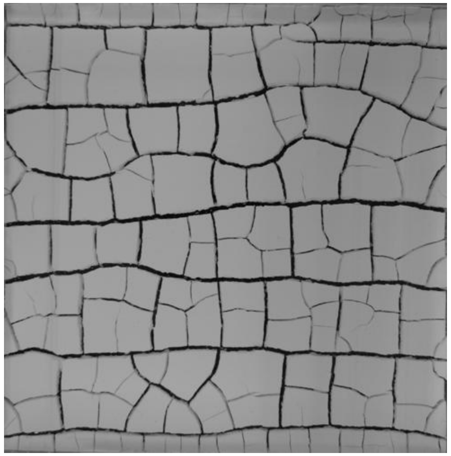
A. Nakahara and Y. Matsuo
PRE. 74 (2006) 045102.

Uncharged

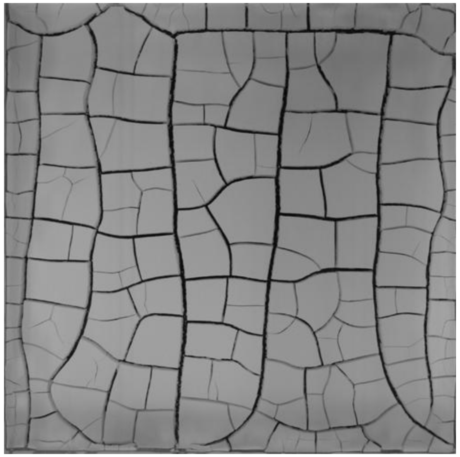
	Water-poor	Water-rich	Water-too-much
Initial vibration	paste vibration	paste flow	paste Turbulence

Stop & dry

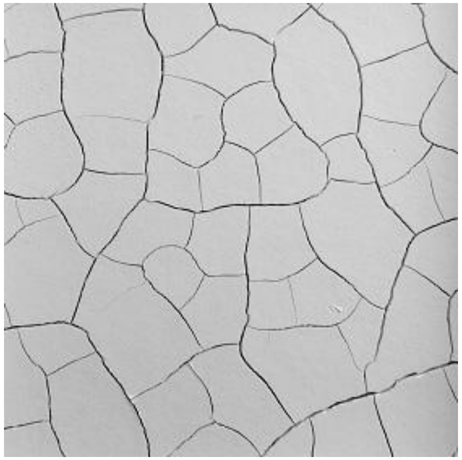
Crack formation



Memory of vibration



Memory of flow

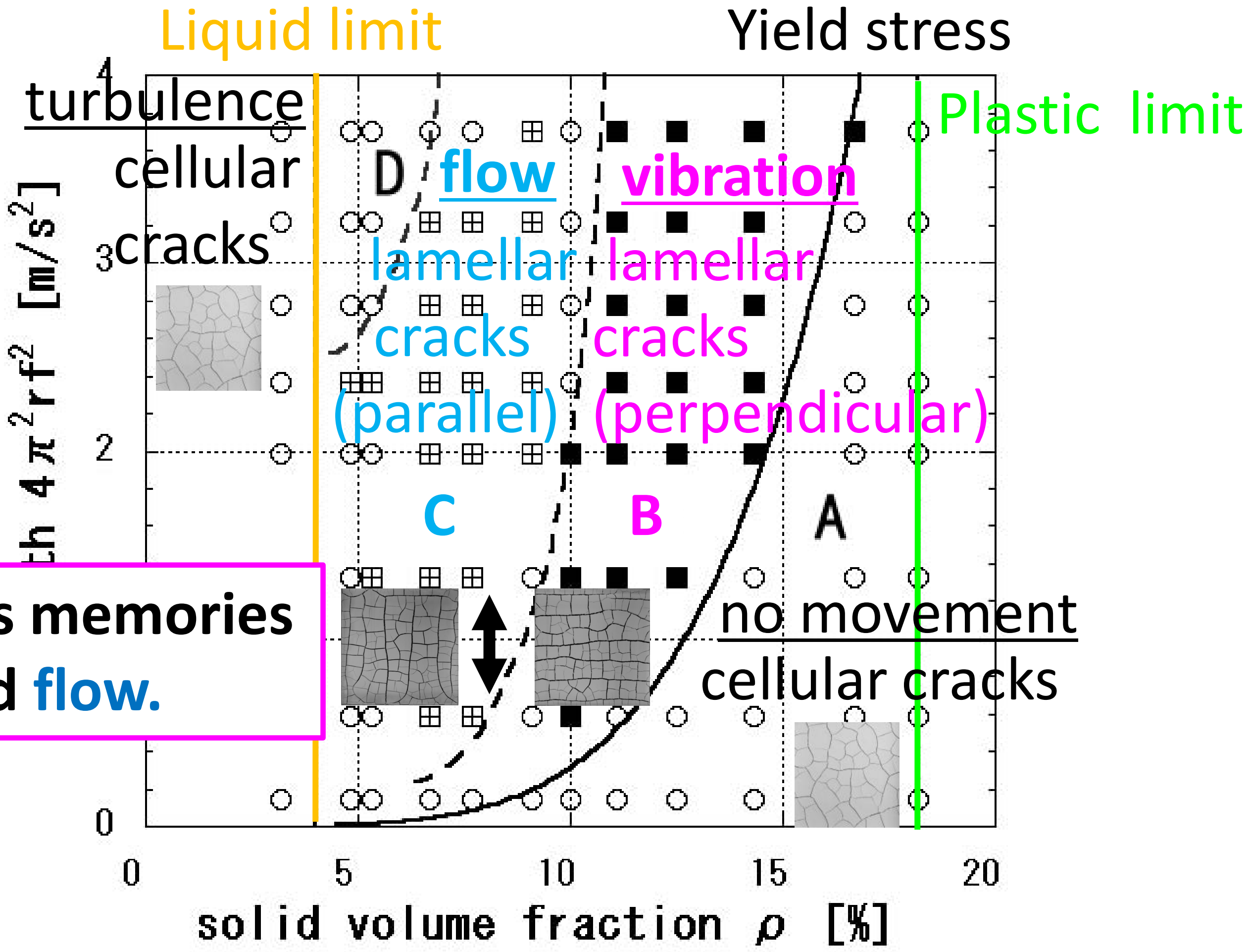


No memory

Morphological Phase Diagram of **uncharged** paste

magnesium
carbonate
hydroxide

Movies of



Uncharged paste has memories of vibration and flow.

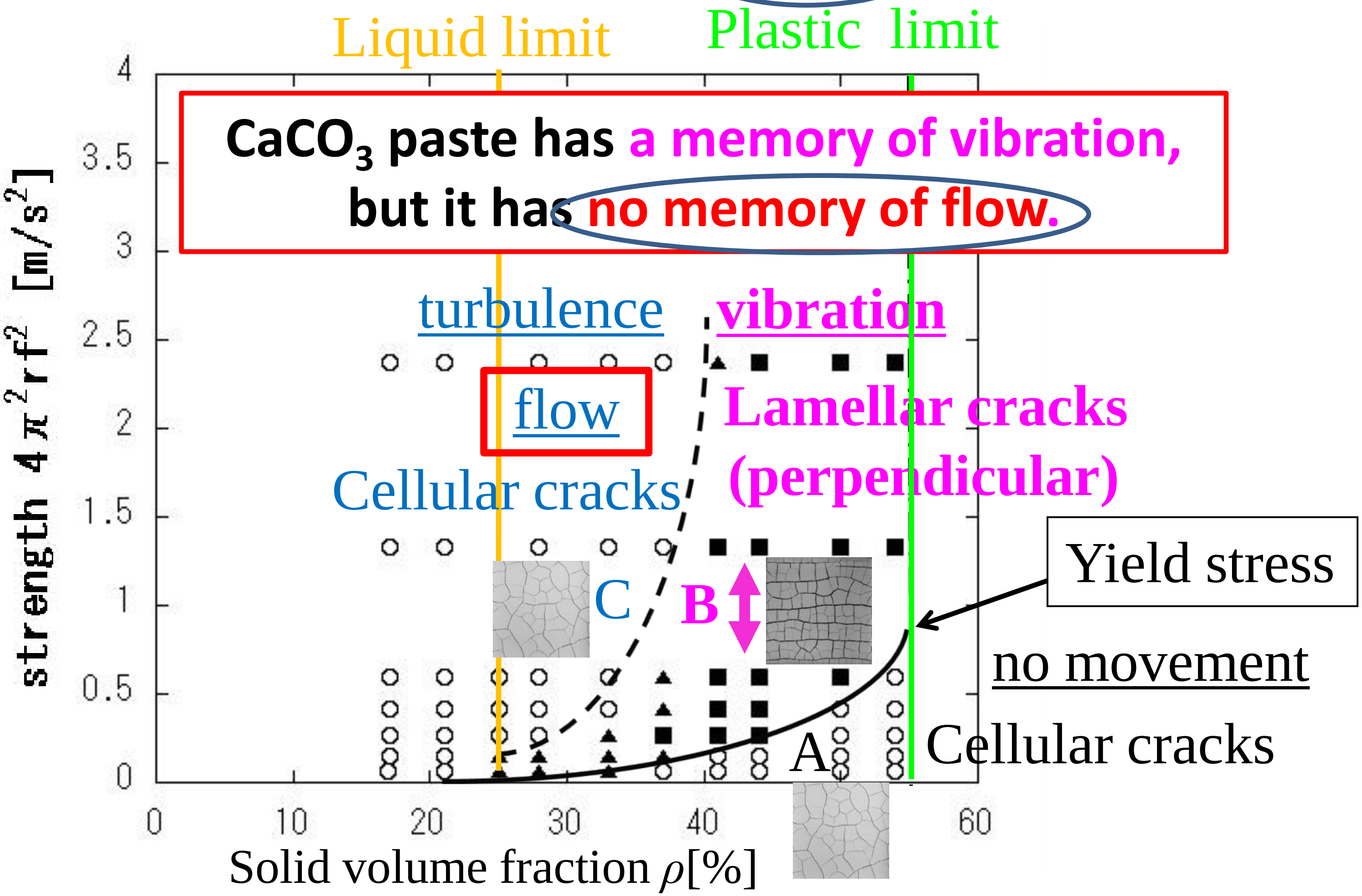
A no movement → no experience → cellular cracks (no movement)

B vibration → remember → Lamellar cracks (perpendicular)

C flow → remember → **Lamellar cracks** (parallel)

D turbulence → forget → Cellular cracks (no memory)

Morphological phase diagram of charged **$CaCO_3$** paste



$CaCO_3$ paste has a memory of vibration, but it has no memory of flow.

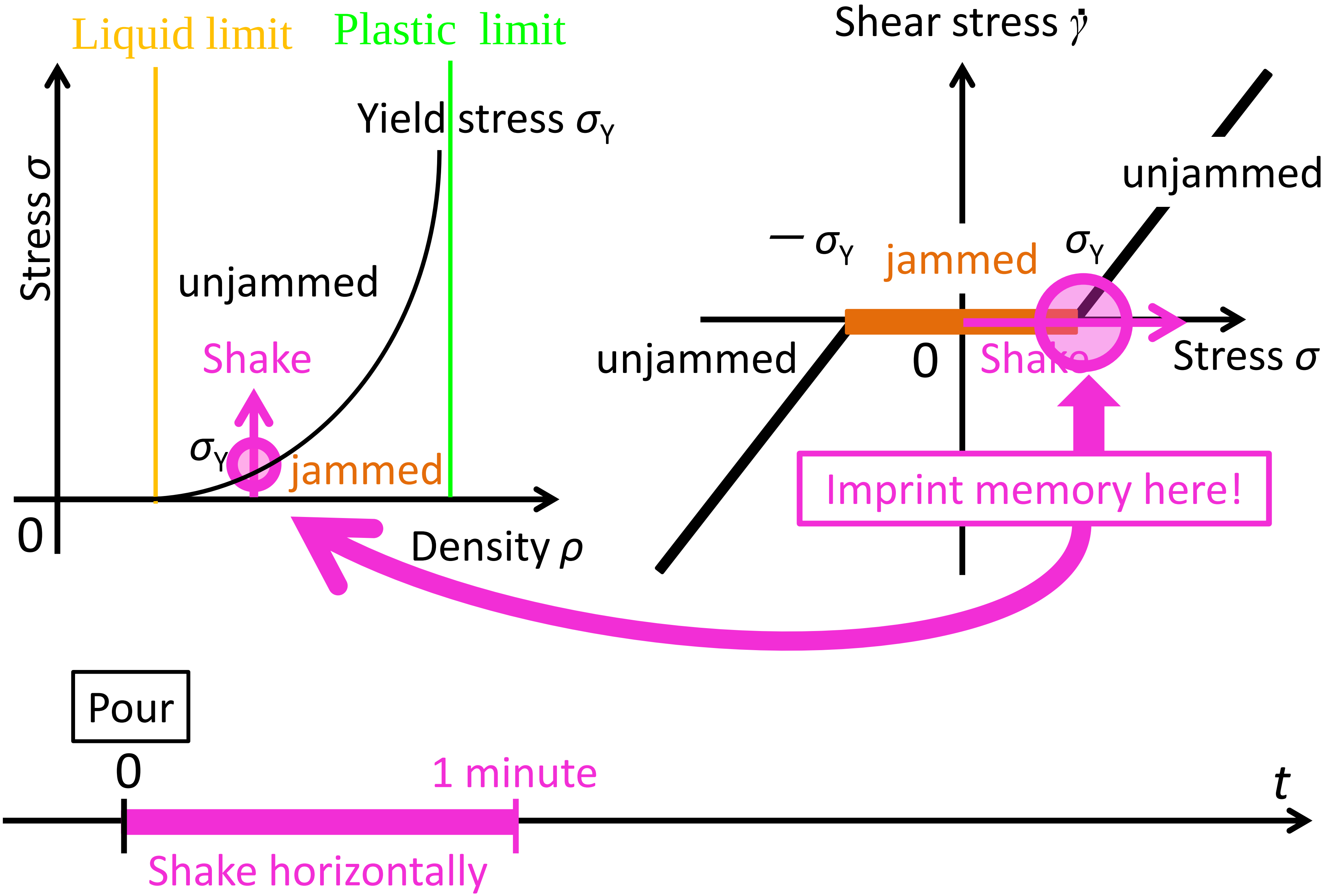
A no movement → no experience → cellular cracks (no movement)

B vibration → remember → Lamellar cracks (perpendicular)

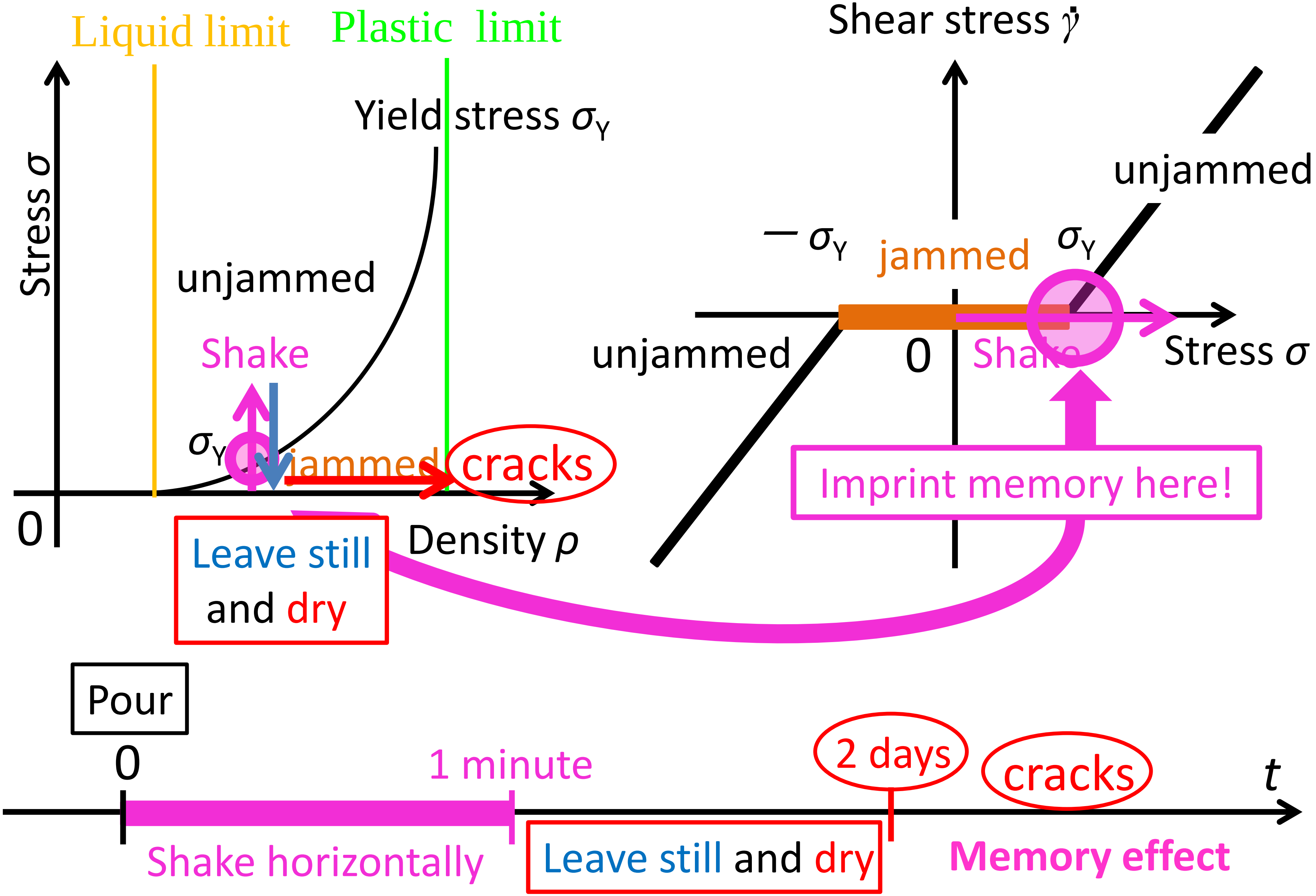
C flow → forget → Cellular cracks (no memory)

turbulence → forget → Cellular cracks (no memory)

Memory effect and jamming transition



Memory effect and jamming transition



Leave still and dry

Imprint memory here!

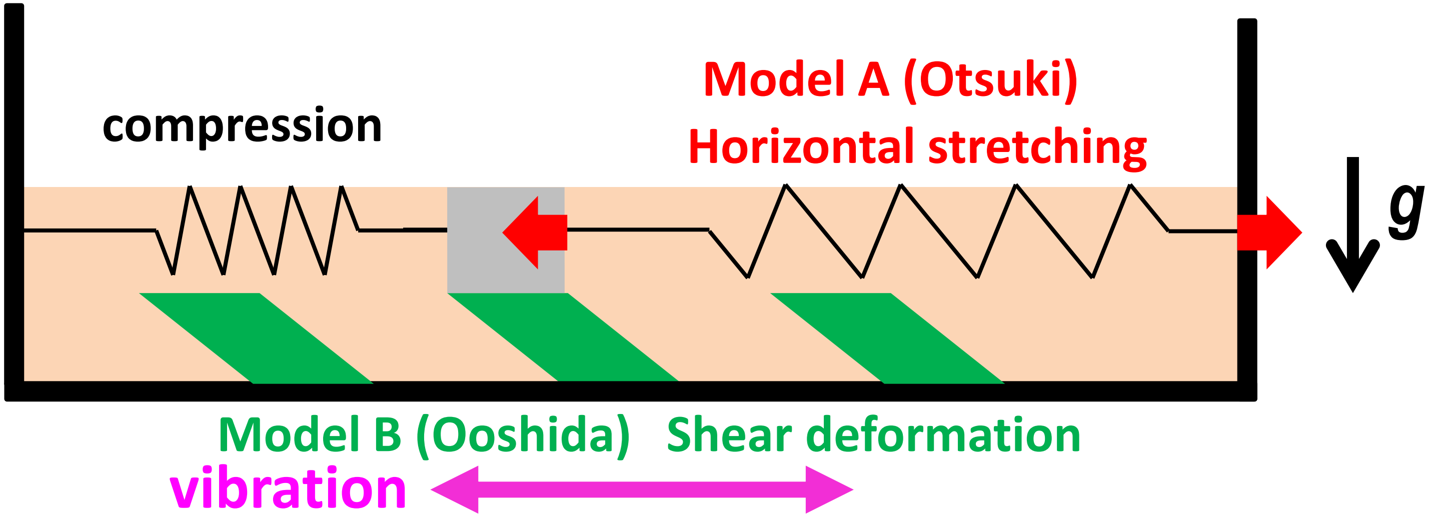
Leave still and dry

Memory effect

Residual tension models for memory of vibration

M. Otsuki,
PRE 72 (2005) 046114.

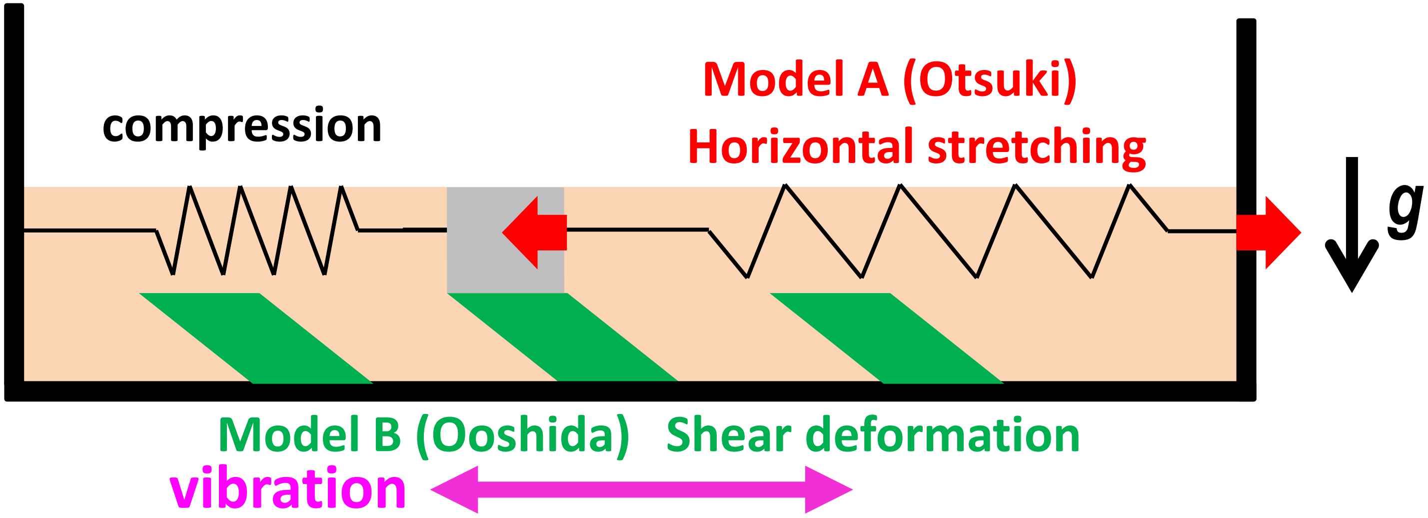
Ooshida T.,
JPSJ 78 (2009) 104801.



Where will cracks appear by Residual tension models?

M. Otsuki,
PRE 72 (2005) 046114.

Ooshida T.,
JPSJ 78 (2009) 104801.



compression

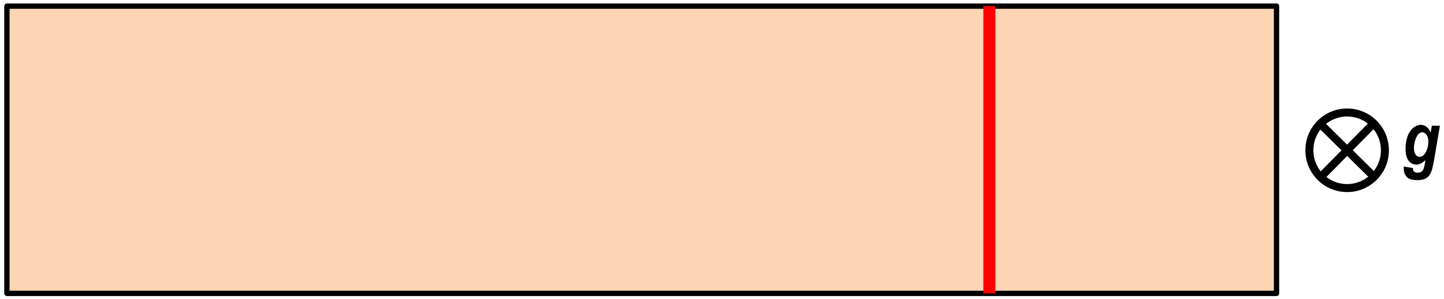
Model A (Otsuki)
Horizontal stretching

g

Model B (Ooshida) Shear deformation

vibration

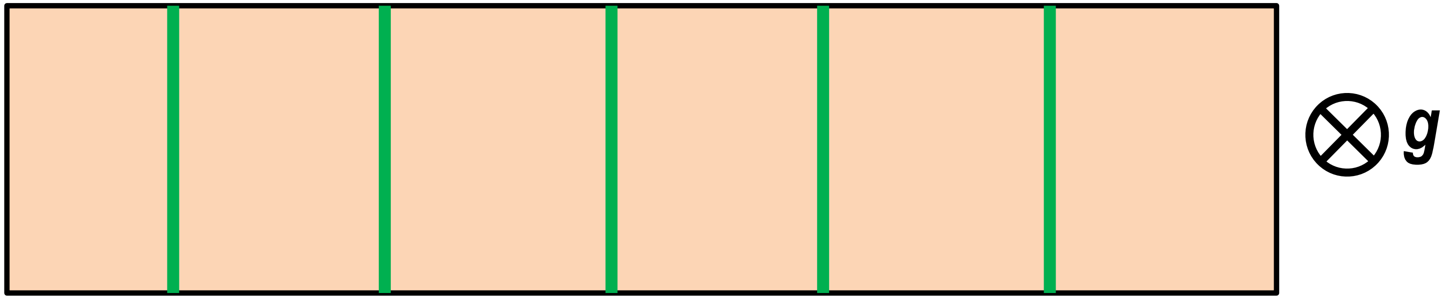
Crack here



Otsuki Model
(horizontal stretching)

$\otimes g$

Cracks anywhere



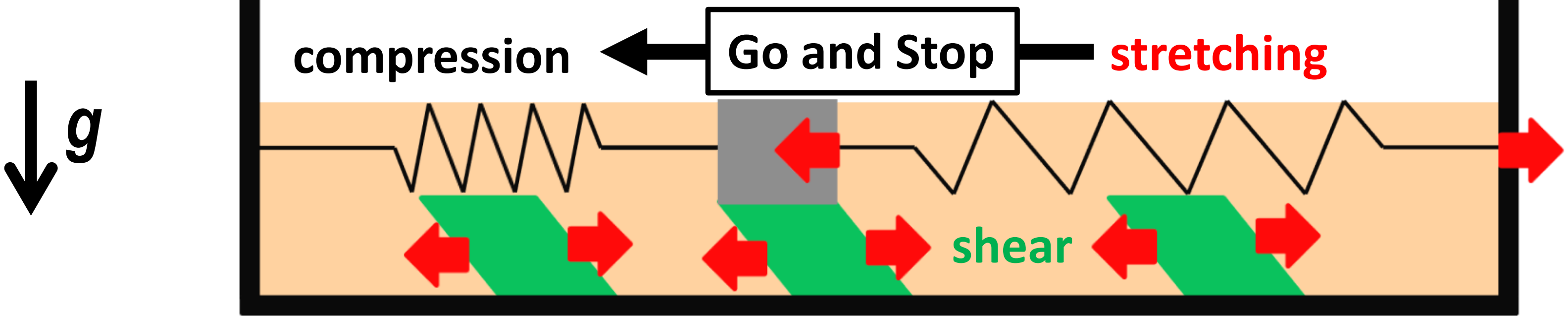
Ooshida Model
(shear deformation)

$\otimes g$

Verification of two residual tension models

Both models are needed!

Model A (Otsuki)
Horizontal stretching

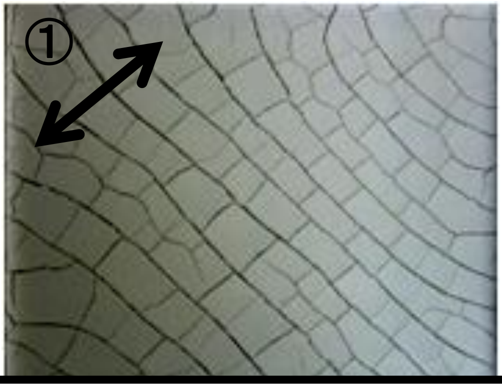


Model B (Ooshida)
Shear deformation

vibration

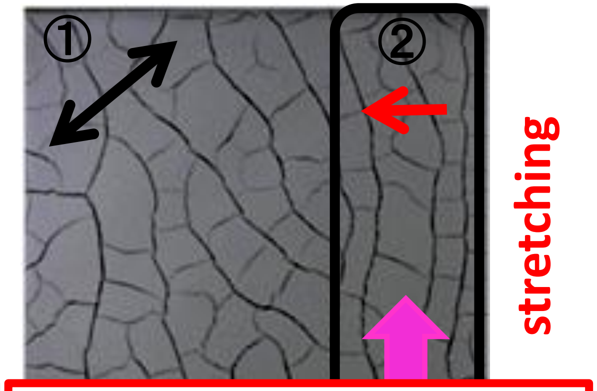
Model A (Otsuki) : Rewriting experiment

①Only vibration



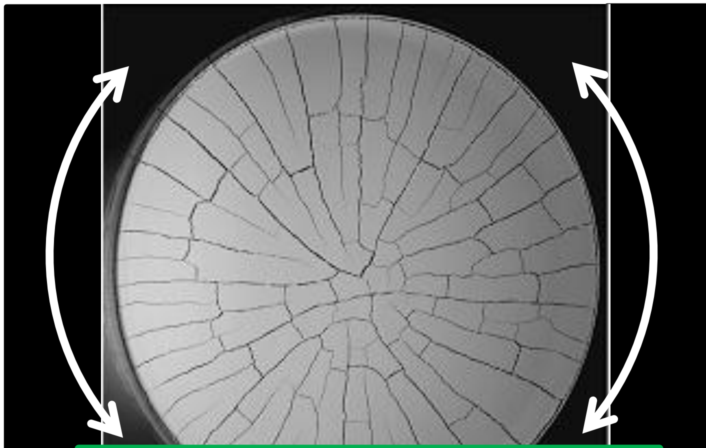
Memory of vibration

① Vibration＋② Go and Stop



Memory of vibration

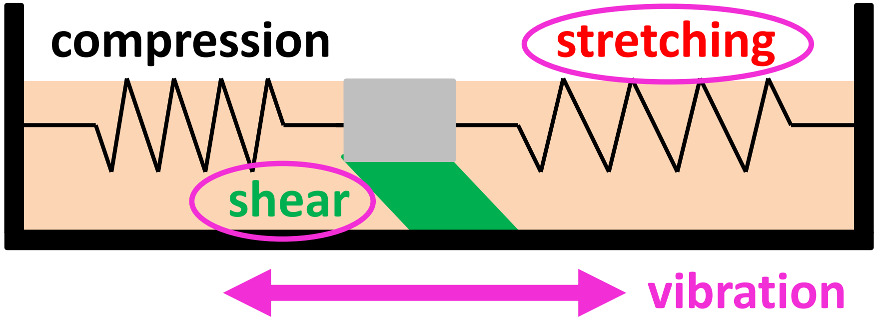
Model B(Ooshida) : Only shear



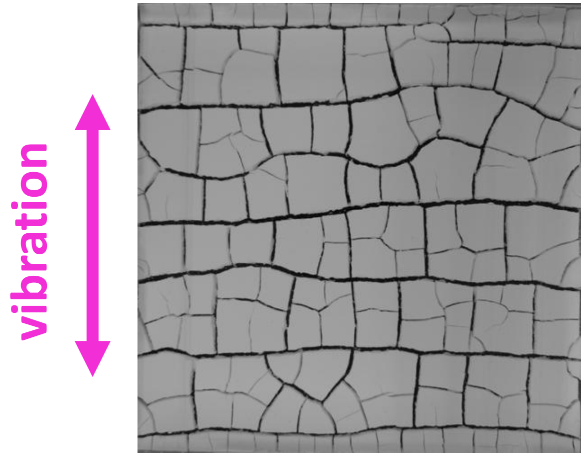
Memory of vibration

Conclusion 1

- Memory of vibration = residual tension

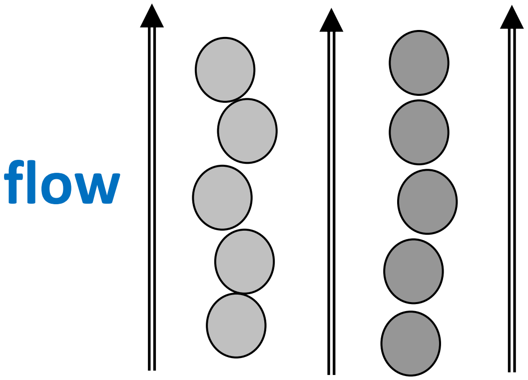


Water-poor

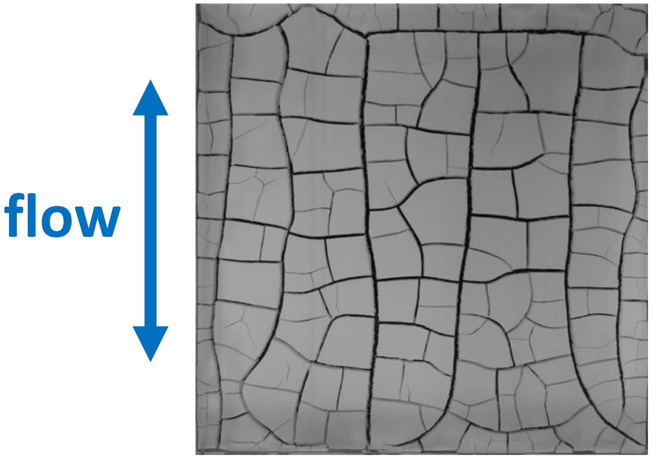


- Memory of flow = elongation of dilute network under flow

Attractive interaction is needed.



Uncharged
Water-rich



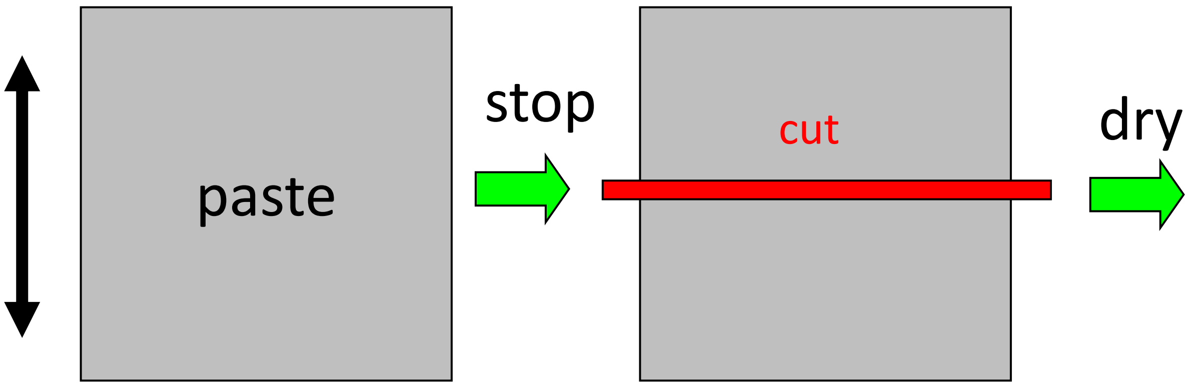
Can we control position of cracks?

By horizontal vibration… Control only Direction of crack propagation!

Direction: imprinted by memory effect

Position : stochastically formed

ρ=6.7%

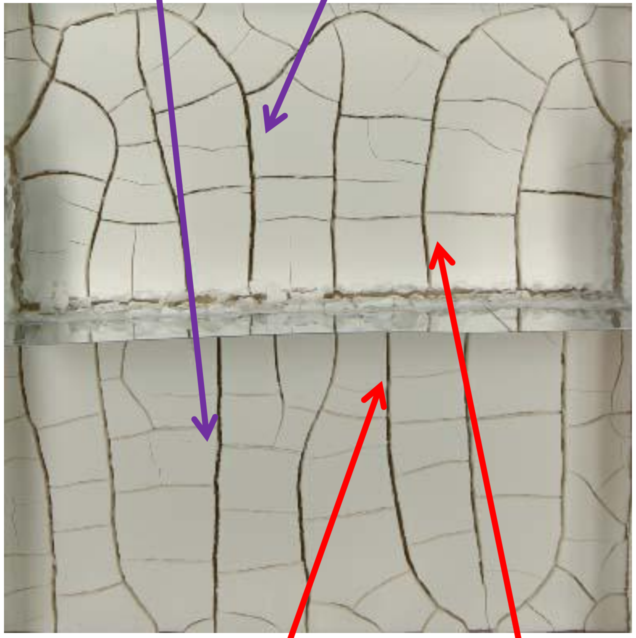


Horizontal vibration

Memory of flow

(memory of vibration)

direction・・・by same memory



position ・・・stochastic

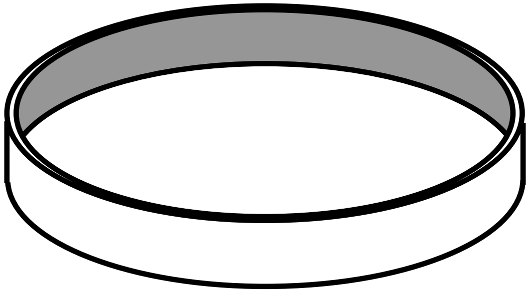
Memories are formed
not by macroscopic hydrodynamic structure
like convection.

Position control of cracks using Faraday waves

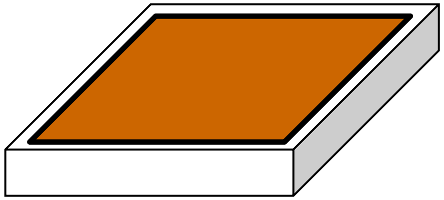
Experimental setup for vertical vibration

Paste: Water-poor $CaCO_3$ paste (only memory of vibration)

vertical vibration

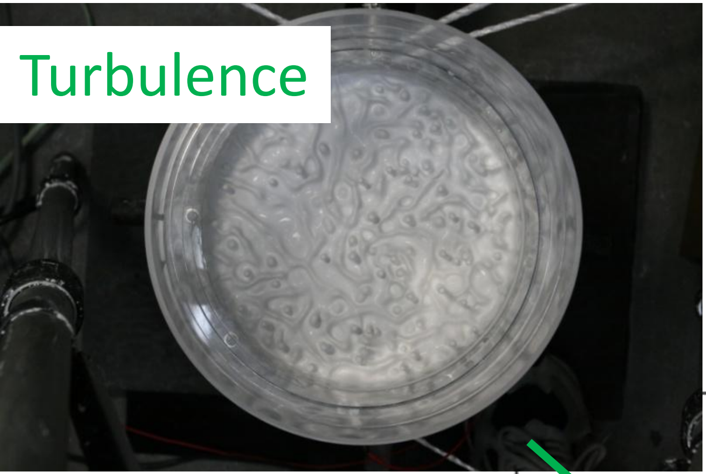


Circular container
diameter *d* = 200 cm



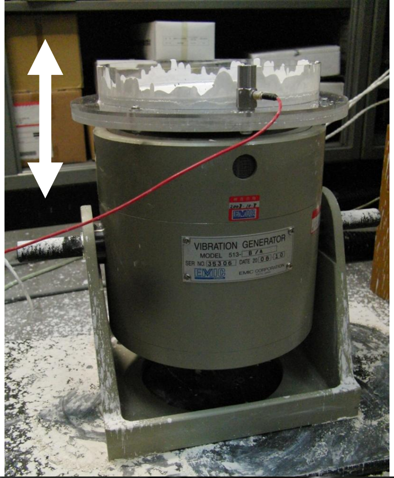
Square container
150mm side

Position control by vertical vibration



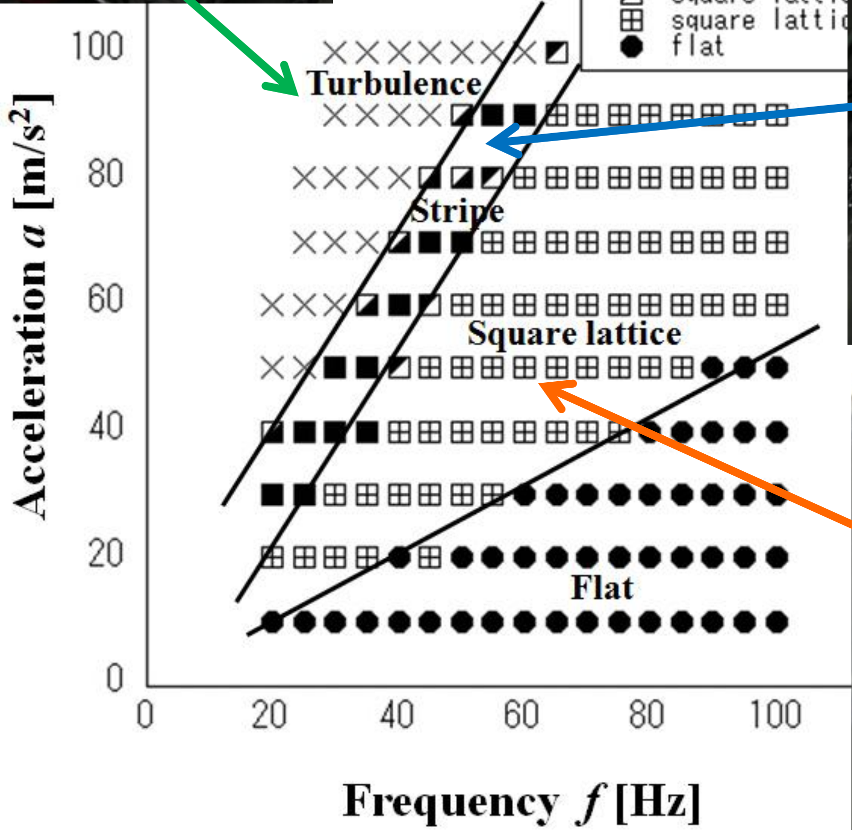
Turbulence

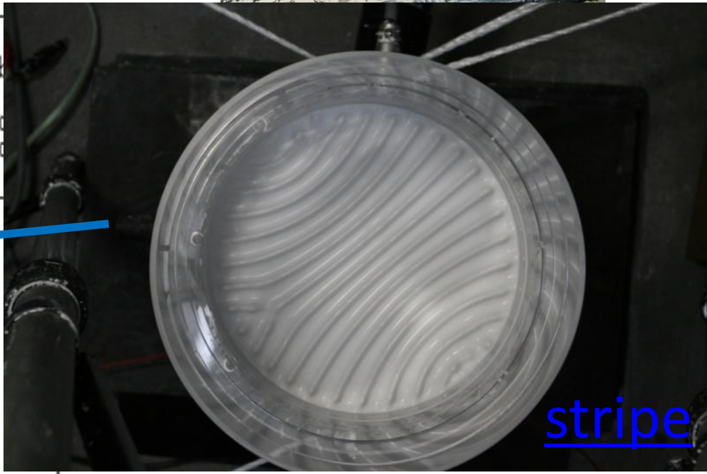
Vertical vibration
(Faraday waves)
↓
Stop and dry!



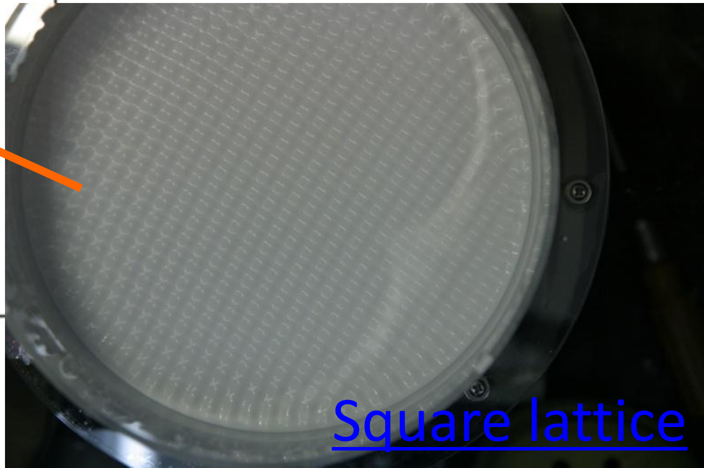
diameter
d = 200 cm

Water-poor
$CaCO_3$ paste
which has
only
memory of
vibration





stripe

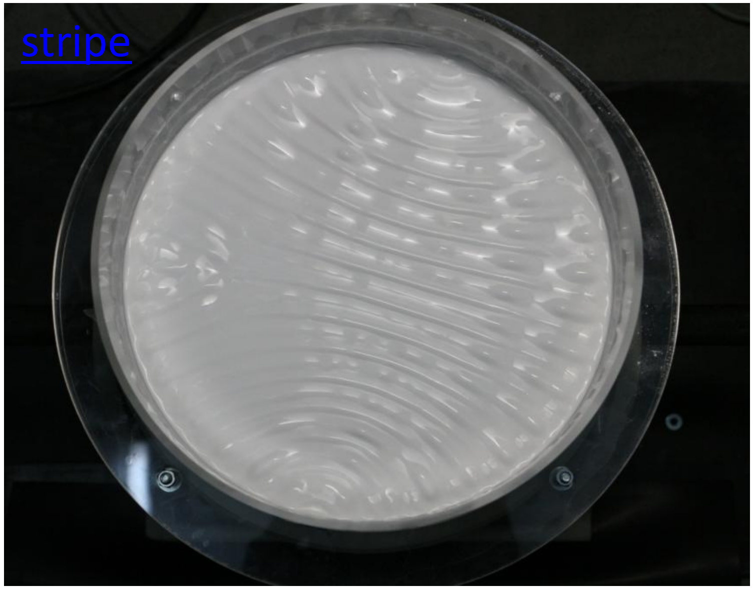


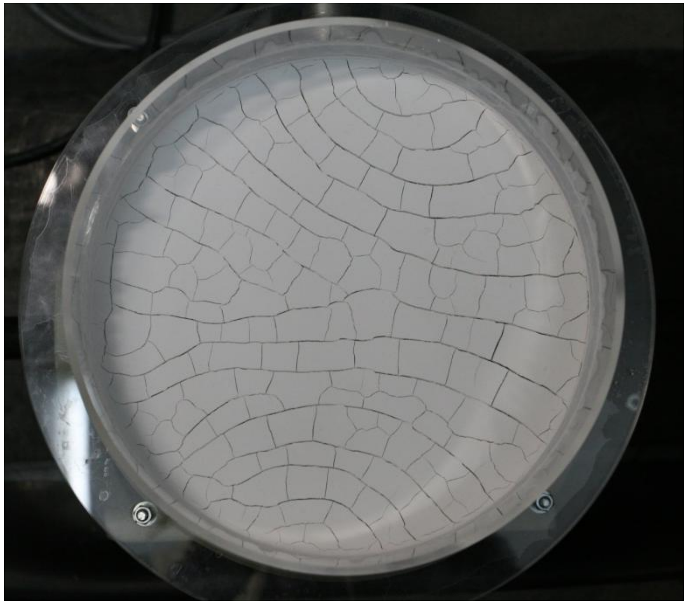
Square lattice

Stripe and ring cracks produced by vertical vibration

Vertical vibration→ Faraday waves

desiccation crack patterns





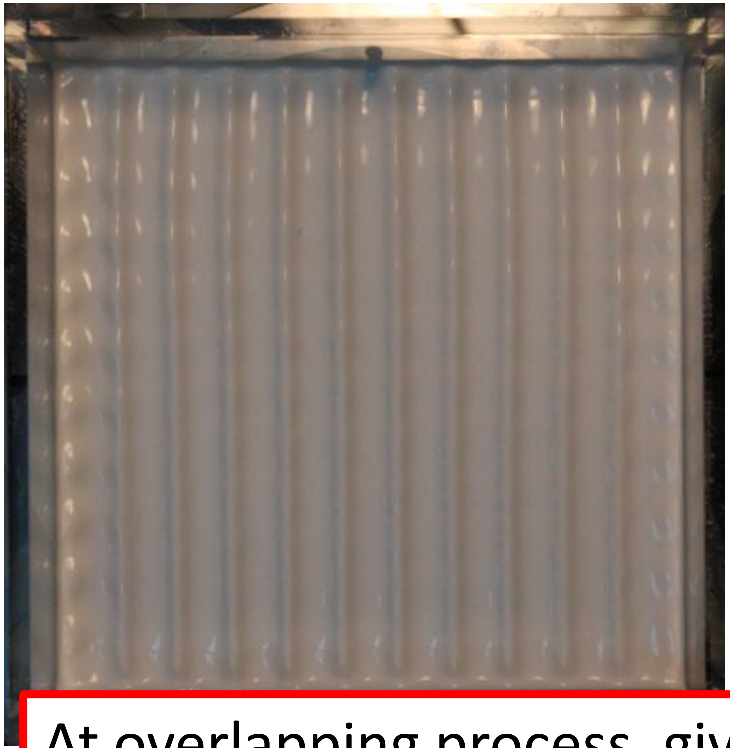
Stop vibration
& dry

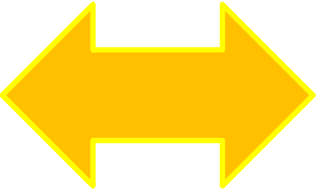
Ring

Spatial correlation between Faraday waves and cracks

Where do cracks appear?

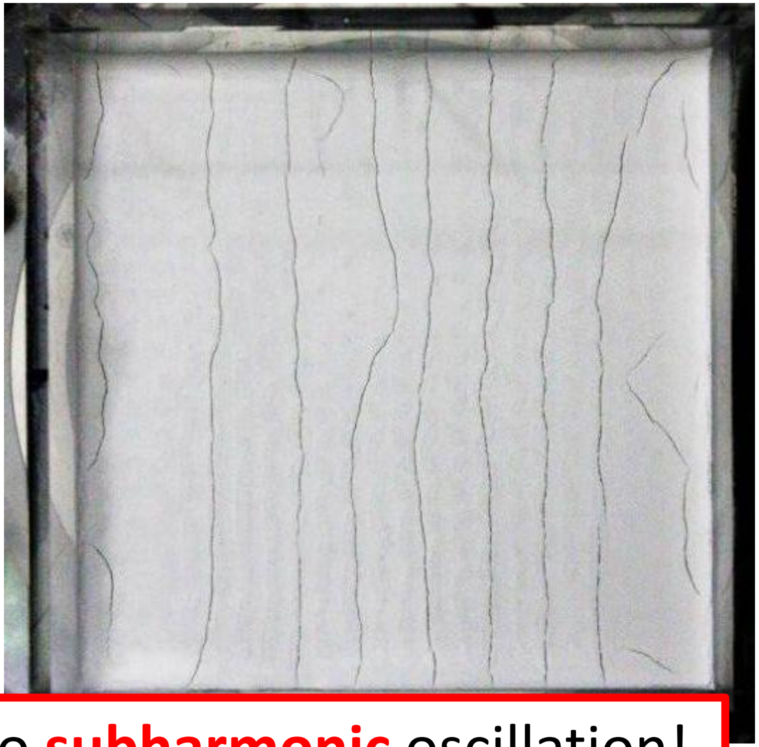
Faraday waves





overlap

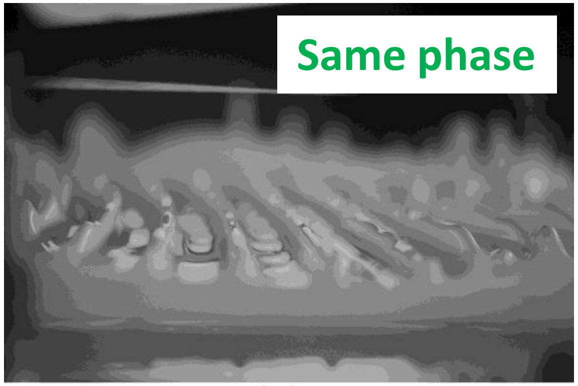
Desiccation crack pattern



At overlapping process, give attention to **subharmonic** oscillation!

Structure of Faraday waves of $CaCO_3$ paste

t

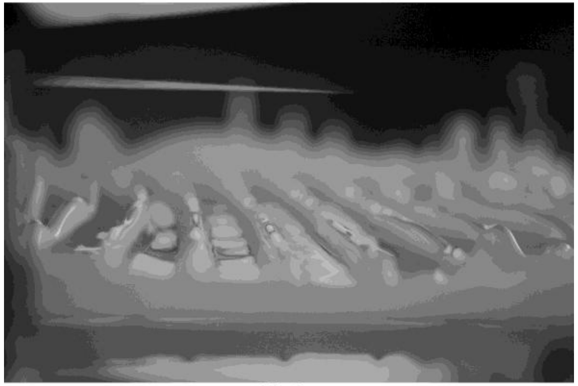


(a)

One shake

Time

$t + T_V$



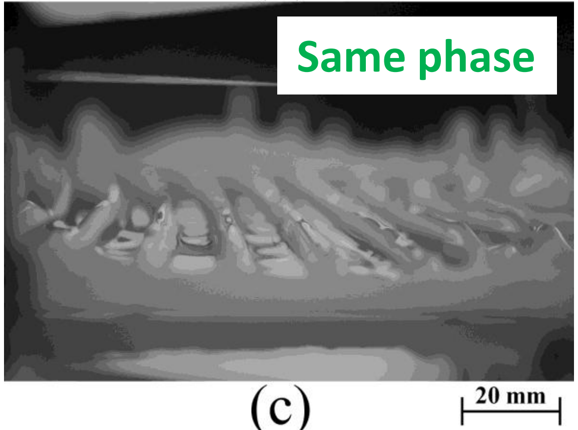
(b)

One more shake

Subharmonic oscillation

$t + 2T_V$

T_F



(c)

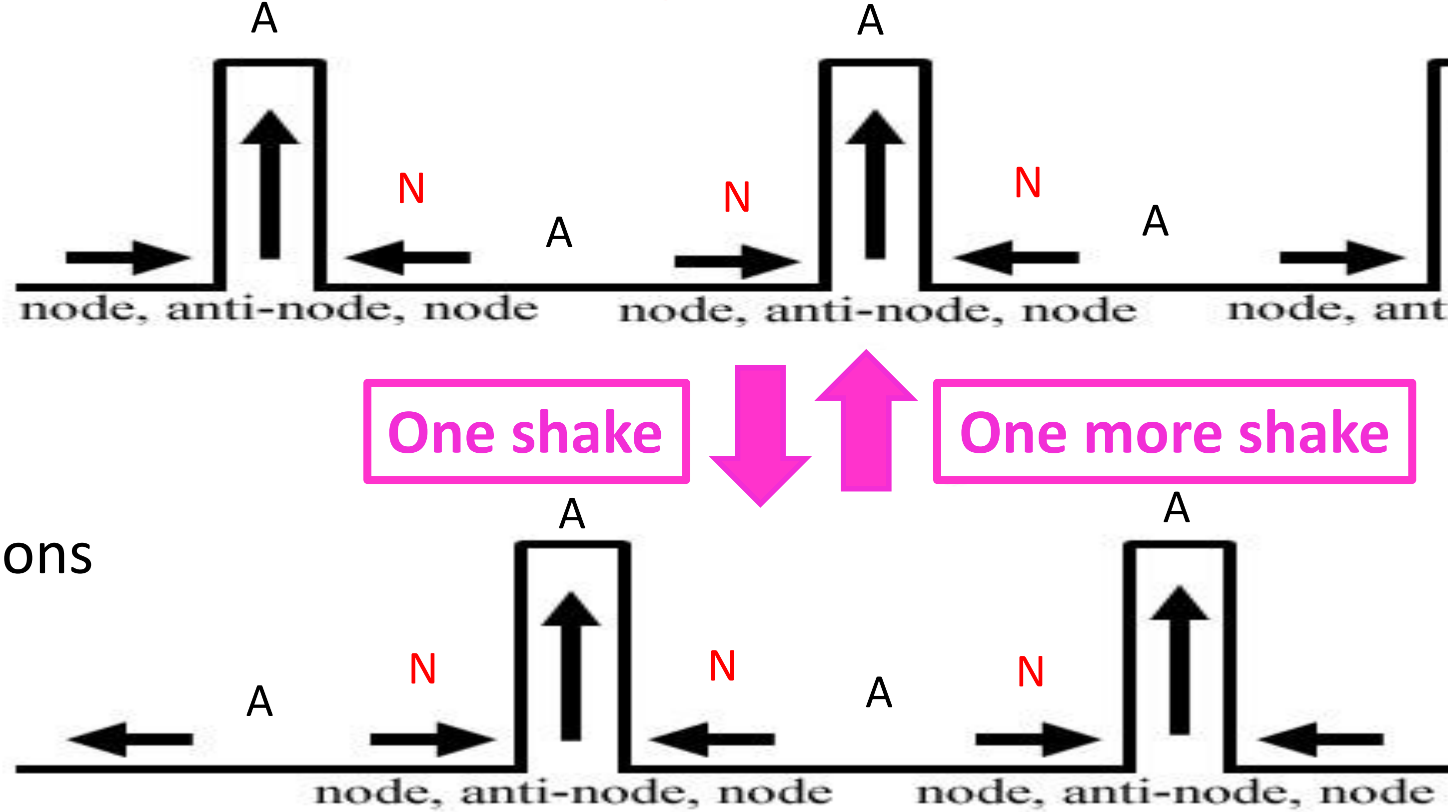
Period of Faraday waves T_F

= 2 × Period of vertical vibration T_V

Side view : Square waves

Horizontal oscillation in node regions

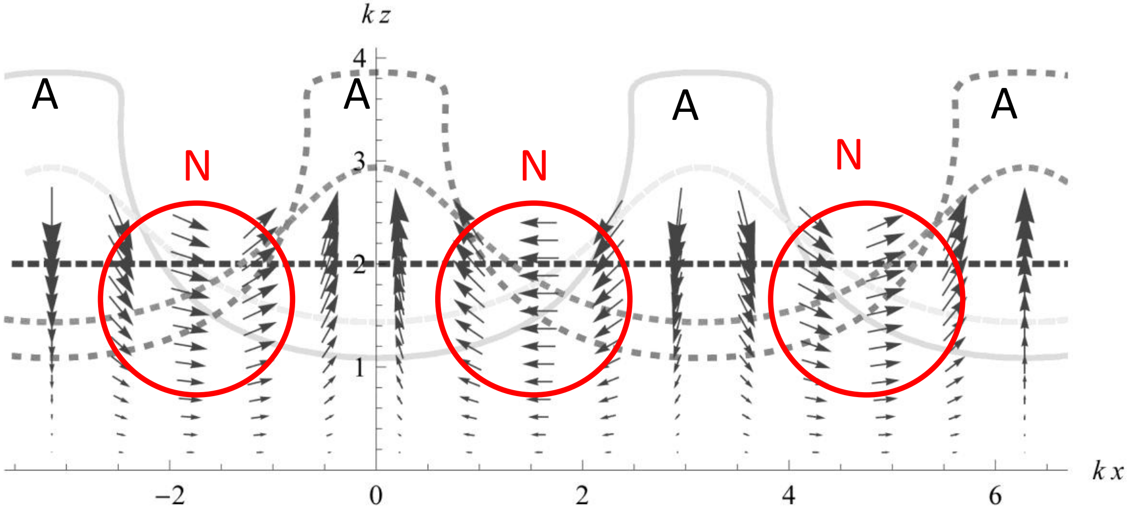
Schematic



N : Node regions

A : Anti-node regions

Analytic



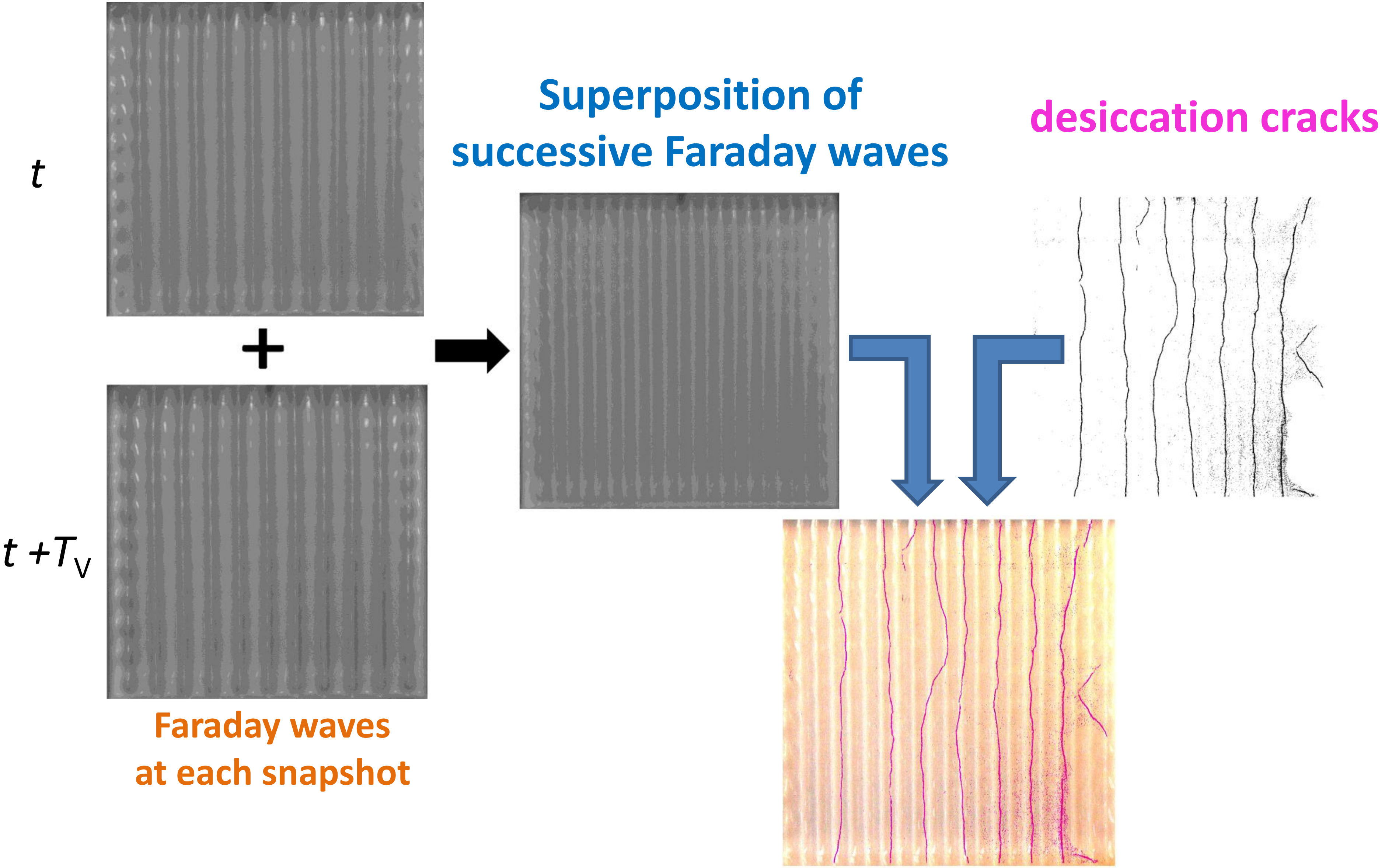
Localized

horizontal vibration

at **node regions**

(Memory of vibration)

Superposition of successive Faraday waves and desiccation cracks



t

+

$t + T_V$

Faraday waves
at each snapshot

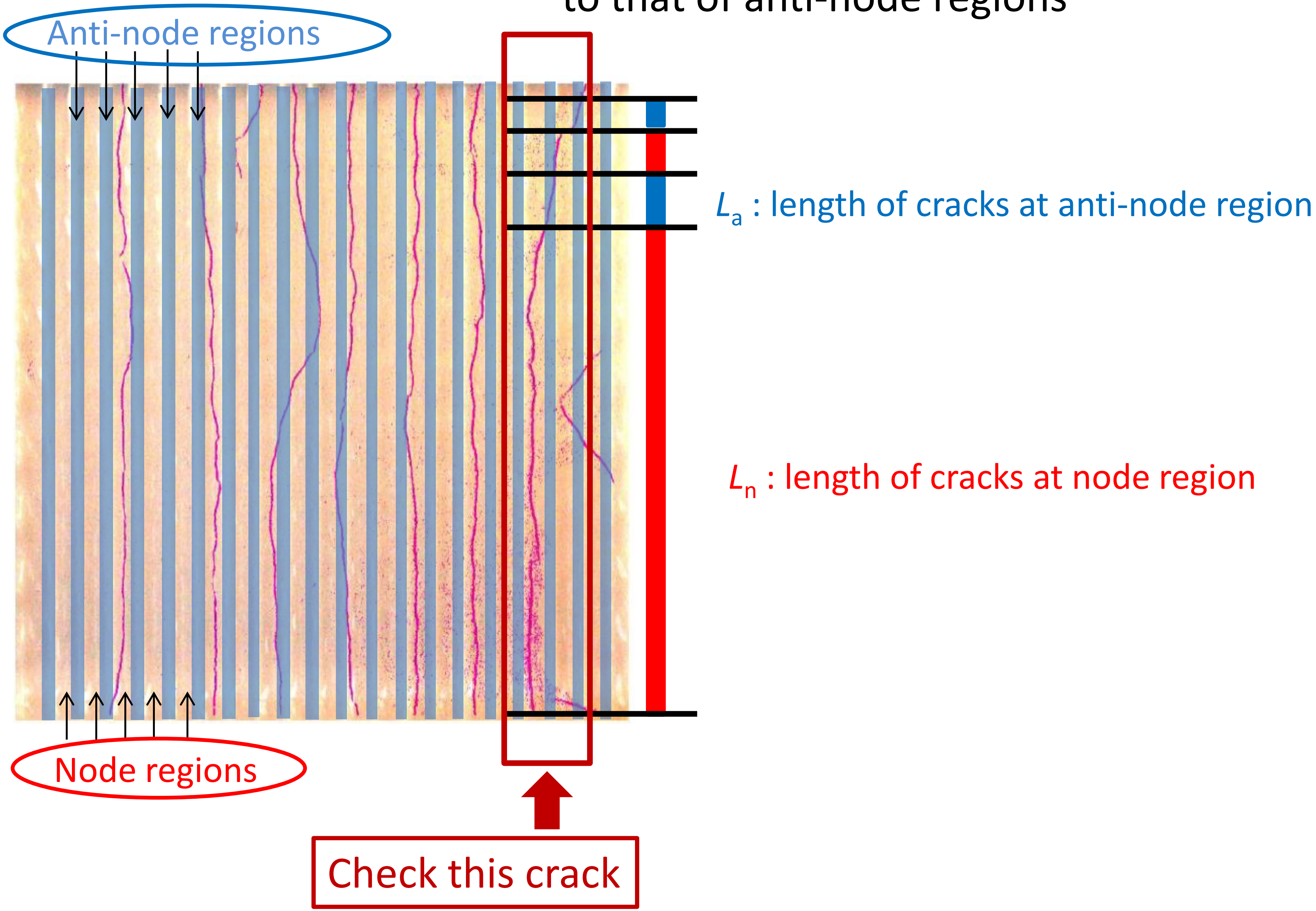
Superposition of
successive Faraday waves

desiccation cracks

Superposition of
successive Faraday waves and desiccation cracks

Statistical analysis

Ratio of observing cracks at node regions to that of anti-node regions



Anti-node regions

Node regions

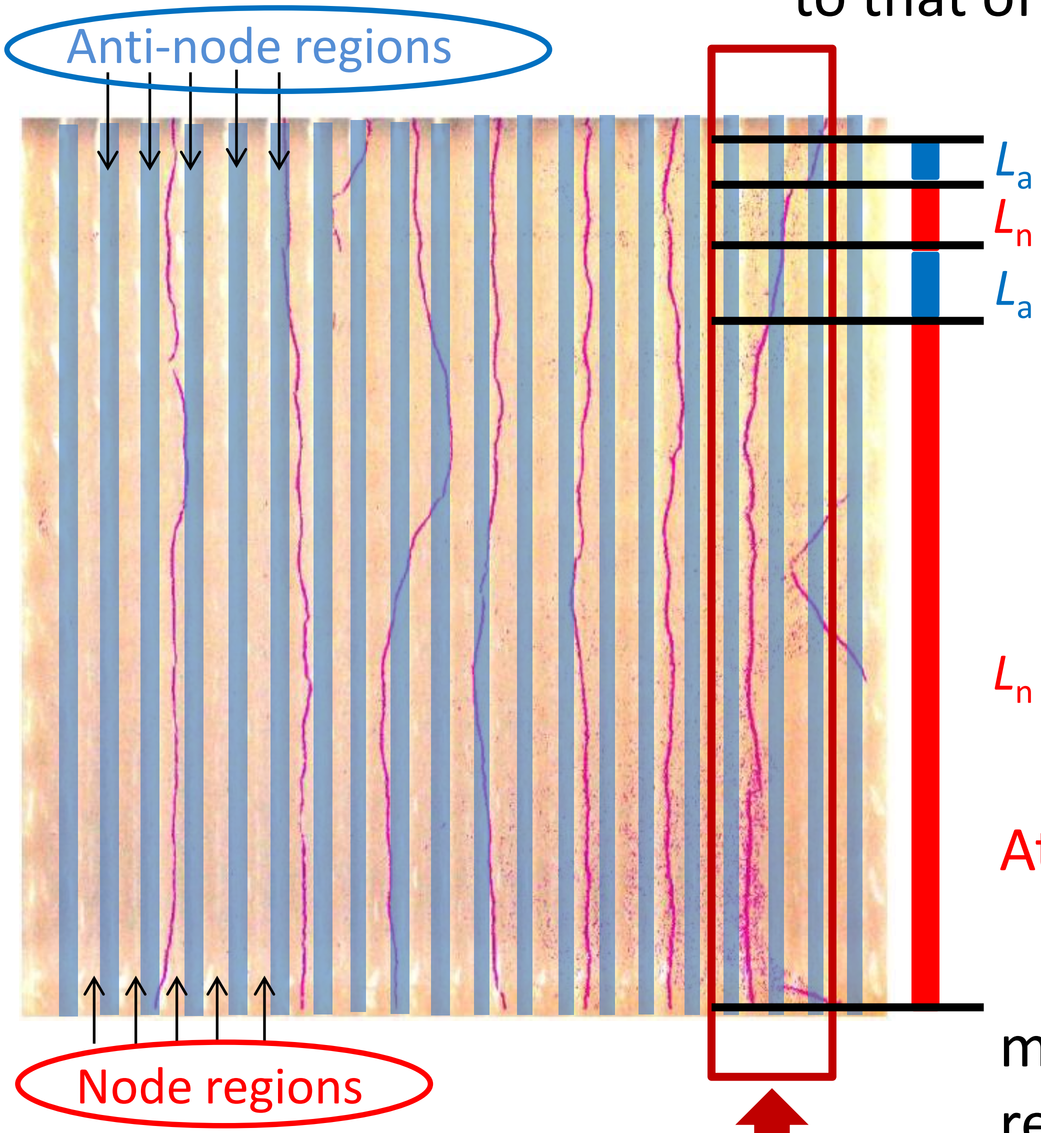
Check this crack

L_a : length of cracks at anti-node region

L_n : length of cracks at node region

Statistical analysis

Ratio of observing cracks at node regions to that of anti-node regions



Check this crack

node regions

$$P = \log_e \frac{\left(\sum L_n\right)/\left(\sum S_n\right)}{\left(\sum L_a\right)/\left(\sum S_a\right)}$$

anti- node regions

S_n : Area of node region
S_a : Area of anti-node region

From 10 experiments

$$P = 0.76 \pm 0.40$$

At node regions, cracks are formed

$$e^P = e^{0.76} = \boxed{2.1 \text{ times}}$$

more frequently than in anti-node regions.

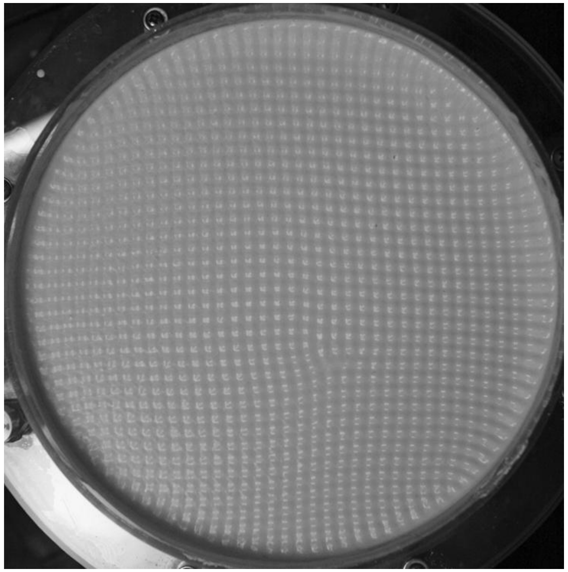
Cracks emerge at node regions.

Square lattice cracks produced by vertical vibration

Vertical vibration
→ Faraday waves

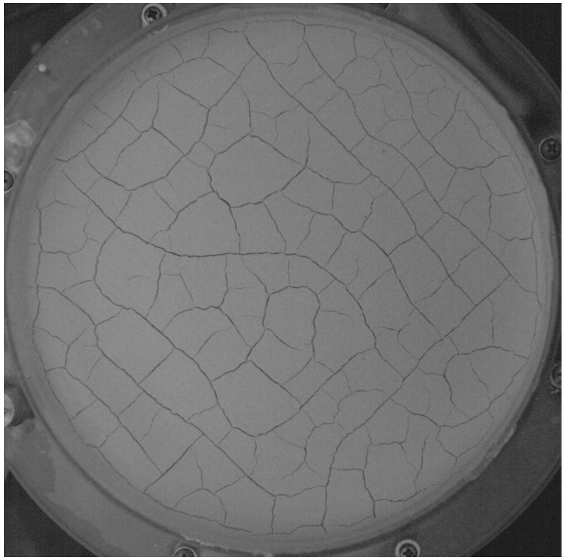
Lattice structure
desiccation crack patterns

Square
lattice

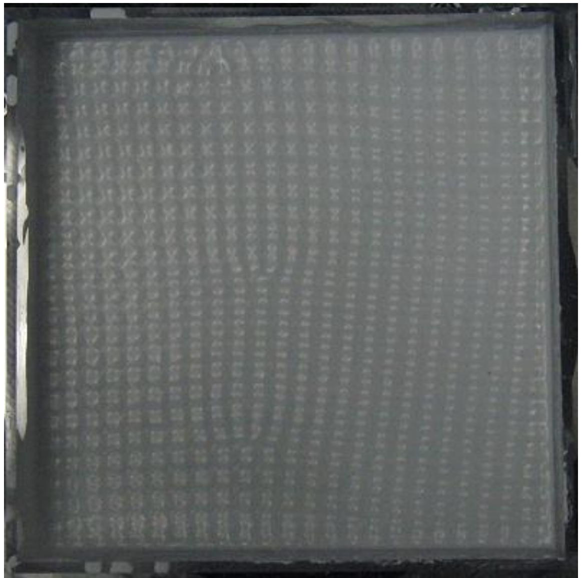


Stop & dry

Why tilt by 45° ?



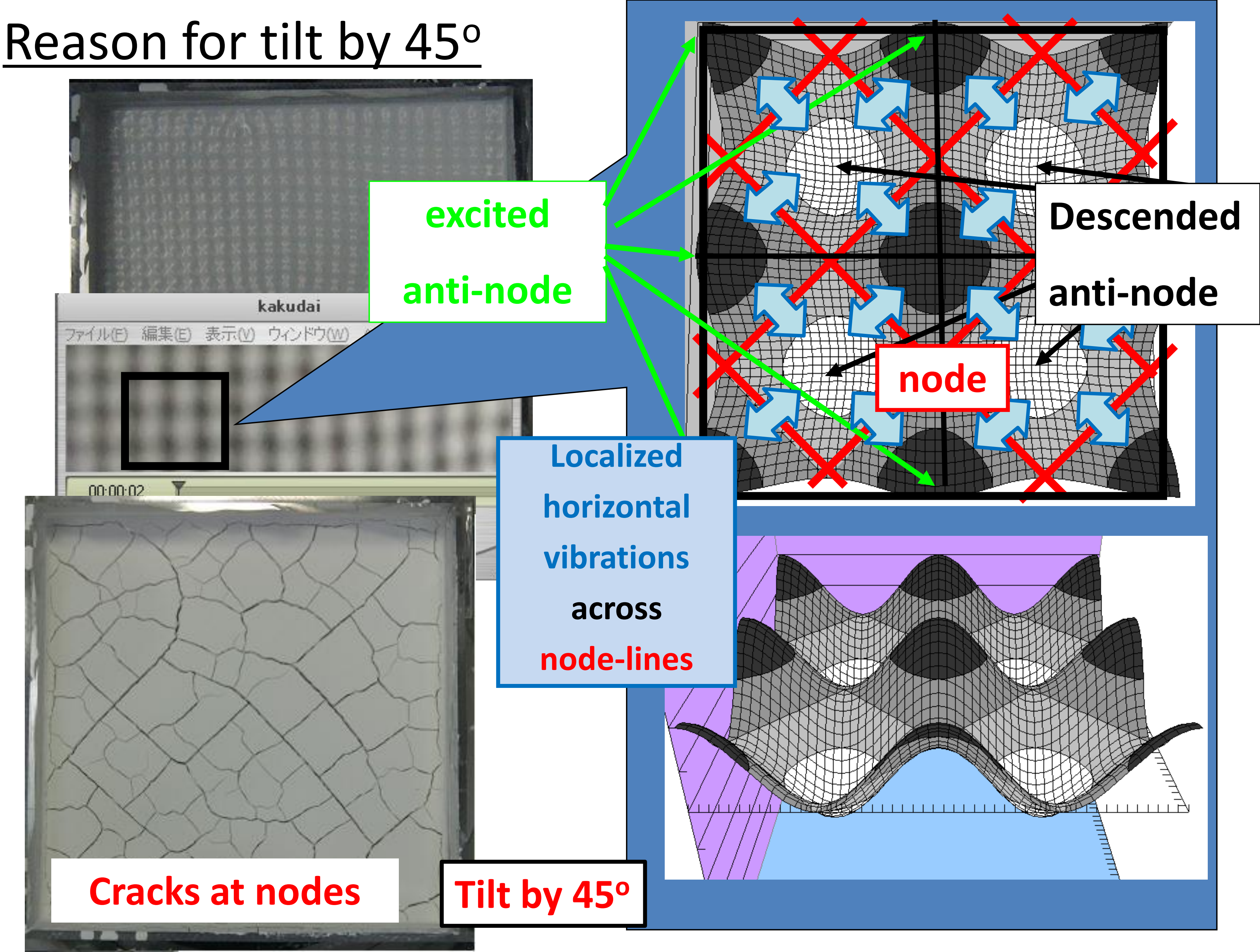
Square
lattice



Stop & dry

Why tilt by 45° ?

Reason for tilt by 45°



excited anti-node

Descended anti-node

node

Localized horizontal vibrations across node-lines

Cracks at nodes

Tilt by 45°

Conclusion 2

- Using vertical vibration, we can control

  not only the direction but also the position of cracks.

- Cracks with lattice structure can be created !

Square lattice

H. Nakayama, Y. Matsuo, Ooshida Takeshi and A. Nakahara
European Physical Journal E **36** (2013) 1.

Further applications

1. What will happen in future (Technology)

   → Control microstructure of materials,

   anisotropy in conductivity and elastic moduli,

   and macroscopic crack patterns

2. What happened before (Geoscience)

   → Know past by memories and cracks in rocks

Future plans

Flow ・・・ large deformation

- Definition and quantification of Memories in pastes

  including Memory of flow

- Theoretical model which explains Memory of flow

- Transition from Memory of vibration to Memory of flow

Future plans 2

Combine various external fields to control crack patterns

Mechanical method (vibration, flow)

A. Nakahara & Y. Matsuo

JPSJ (2005), PRE (2006)

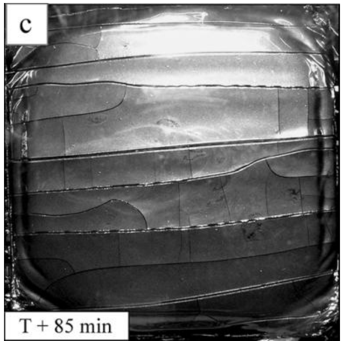
Electrical method

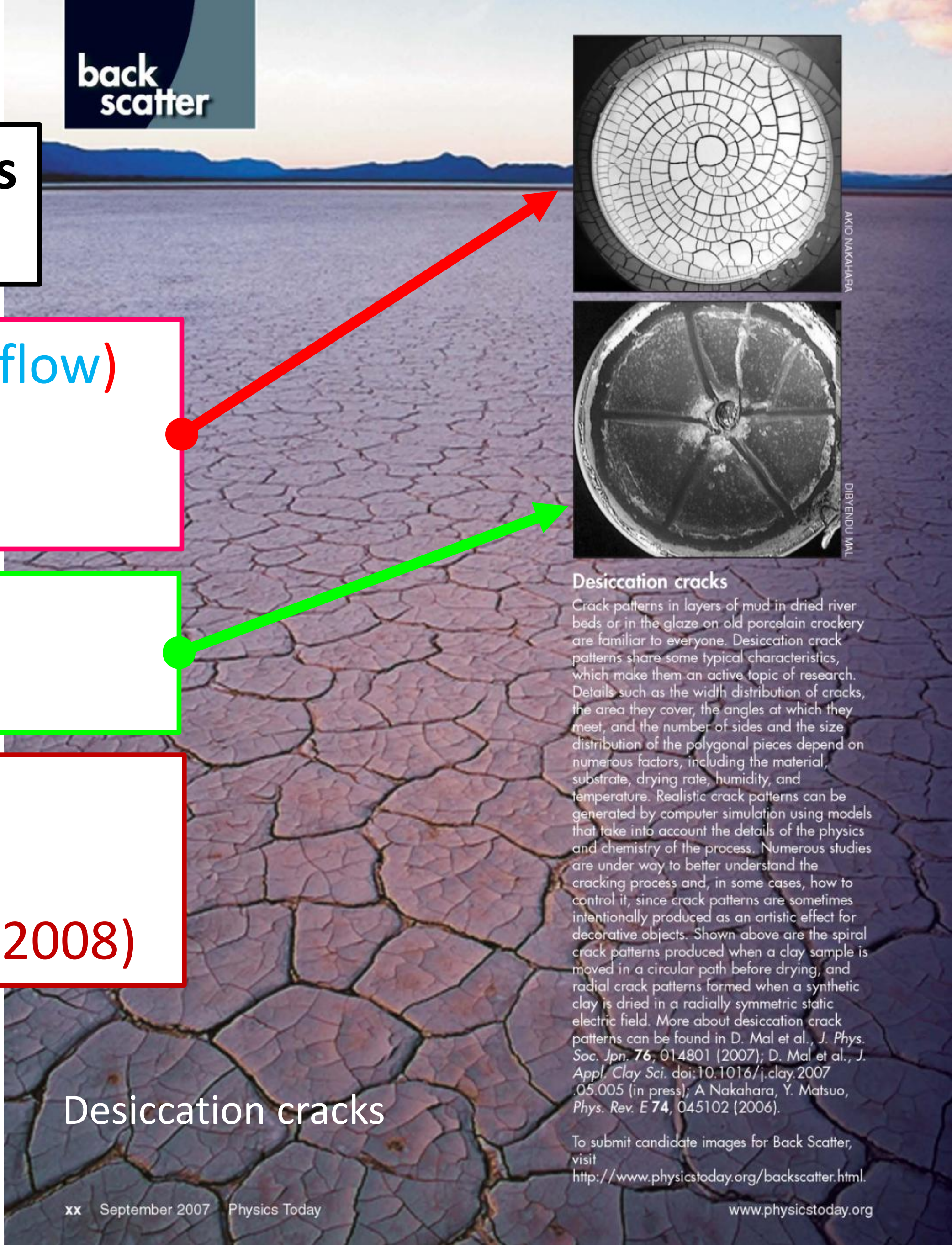
D. Mal et. al., Physica A (2007)

Magnetic method

L. Pauchard et. al., PRE, (2008)

A. T. Ngo et. el., Nano Letters (2008)





Desiccation cracks

Crack patterns in layers of mud in dried river beds or in the glaze on old porcelain crockery are familiar to everyone. Desiccation crack patterns share some typical characteristics, which make them an active topic of research. Details such as the width distribution of cracks, the area they cover, the angles at which they meet, and the number of sides and the size distribution of the polygonal pieces depend on numerous factors, including the material, substrate, drying rate, humidity, and temperature. Realistic crack patterns can be generated by computer simulation using models that take into account the details of the physics and chemistry of the process. Numerous studies are under way to better understand the cracking process and, in some cases, how to control it, since crack patterns are sometimes intentionally produced as an artistic effect for decorative objects. Shown above are the spiral crack patterns produced when a clay sample is moved in a circular path before drying, and radial crack patterns formed when a synthetic clay is dried in a radially symmetric static electric field. More about desiccation crack patterns can be found in D. Mal et al., *J. Phys. Soc. Jpn.* **76**, 014801 (2007); D. Mal et al., *J. Appl. Clay Sci.* doi:10.1016/j.clay.2007.05.005 (in press); A Nakahara, Y. Matsuo, *Phys. Rev. E* **74**, 045102 (2006).

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