One-year monitoring and digital image analysis of in-situ desiccation cracks on Tournemire argillite rock

Funded by NEEDS-MIPOR (TRASSE) program

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Objective : *To evaluate the excavation induced deformation in the rock.*

Clay rocks are considered in several industrial countries as potential repositories for high-level radioactive wastes. Among the critical issues related to the long-term safety assessment of such geological repositories, the study of the so-called **excavation damaged zone (EDZ)** is of **particular importance**.

Fractures associated with the desaturation of argillaceous medium have been observed on gallery fronts in several **underground research laboratories** (in the experimental platform at Tournemire and in the Mont Terri laboratory).

These observations of clay-rock damage have been obtained in the field using conventional crackmeters or jointmeters, and one may wonder whether similar observations could have been made using non-invasive optical methods, such as the digital image correlation (DIC) technique.

Introduction (Experimental Platform at Tournemire)

Objective : *To evaluate the excavation induced deformation in the rock.*

Initiation and extension of the Excavation Damaged Zone (EDZ) are governed by :

- ☑ Initial stress field
- ☑ Material properties
- ☑ Existence of natural fracture zones
- ☑ Local heterogeneities of the rock mass
- ☑ Geometry of gallery
- ☑ **Hydric state**

Fractures associated with the process of desaturation of argillaceous medium were observed on faces and fronts of the galleries

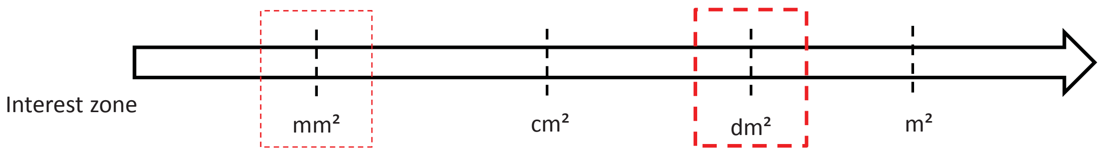
This hydric fracturing process was evidenced in situ by sub-horizontal cracks spaced out by 20 cm, on all vertical walls in contact with ambient air.

In **winter** (dry state) the corresponding crack apertures can be reach **2mm**

In **summer** (wet state) these cracks are completely **closed**

Introduction : Multi-scale approach

Study of hydromechanical behavior of Argillite.
Multi-scale approach



- sample (**2**x**2**x**1**cm^3)+**Polishing**
- Test over several **weeks**
- Variation of **RH** (ex: cycles, choc, etc.) (T cst)
- Study zone : **5.5**x**4.1mm²**
- DIC precision : ≈**0.215 µm**
- Data: **5M.im^{-1}**

- **SEM** (Scanning Electron Microscopy)
- **Mineral map** (**5.5x4.1 mm²**)
- Spatial resolution SEM : **0.625 µm**
- Number of data : **52.5M.im^{-1}**

Financial support of NEEDS

- EDZ is created (Gallery excavated **15** years ago)
- Test on **1 year** of gallery front
- Natural variation of **RH** and **T**
- Study zone : **34.4**x**27.5cm²**
- DIC precision : ≈ **27µm**
- Data : **0,3M.im^{-1}**

Images always recorded (>2,5 years)

Financial support of TRASSE

Introduction

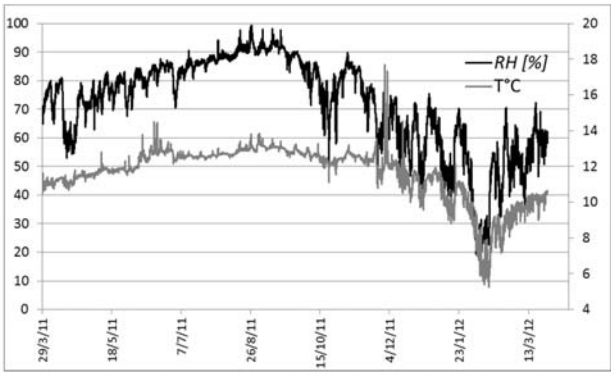
AIM : to investigate in Tournemire station this fracturing process

Seasonal cycle (T and RH)

(Beginning: March 2011)

Displacement fields and **full-field** strain measurement

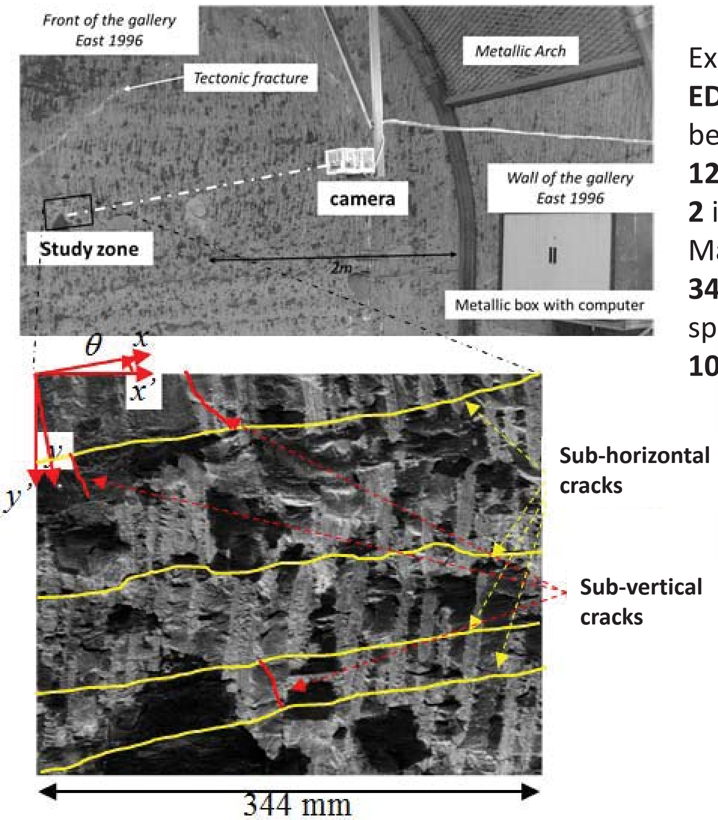
***(Digital image correlation** DIC)*



Study of desaturation crack mechanisms

This talk presents an application of the **DIC method** in the East1996 **underground gallery** at the experimental platform of **Tournemire**; during this study, the Relative Humidity (**RH**) and temperature (**T**) were measured.
The **objectives** of this experimental investigation were to assess the ability of the DIC method to measure **strain fields** and **crack apertures** induced by climatic changes in an underground gallery, and to correlate the measured strain fields and crack apertures with **climatic fluctuations** in the gallery.

Experimental setup



Excavation of gallery: **1996**
EDZ is created (15 seasonal cycles before the beginning of study)
1280x1024 pixels^2
2 images.h^{-1}
Magnification: **0.269** mm.pixel^{-1}
344x275mm^2
spotlight: **400W**
100% automatic

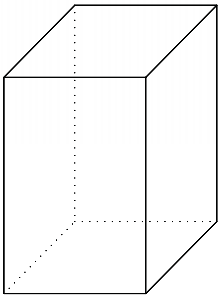
Optical extensometry technique → Digital image correlation (DIC)

(camera+speckle)

- *Displacements (U_x, U_y)*
- *Strains (ε_{xx}, ε_{yy}, ε_{xy})*
- *Principal strains (ε_1, ε_2)*
- *Principal directions (θ_1, θ_2)*

PRINCIPLE

Initial state



Digital Image Correlation (DIC)

Optical extensometry technique → Digital image correlation (DIC)

(camera+speckle)

- *Displacements (U_x, U_y)*
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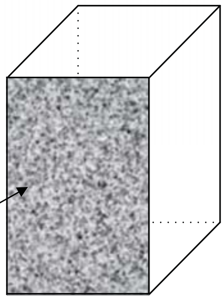
PRINCIPLE

Initial state



Optical extensometry technique → Digital image correlation (DIC)

(camera+speckle)

- *Displacements (U_x, U_y)*
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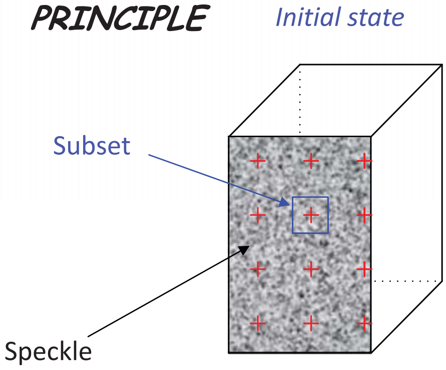
PRINCIPLE



Digital Image Correlation (DIC)

Optical extensometry technique → Digital image correlation (DIC)

(camera+speckle)

- *Displacements (U_x, U_y)*
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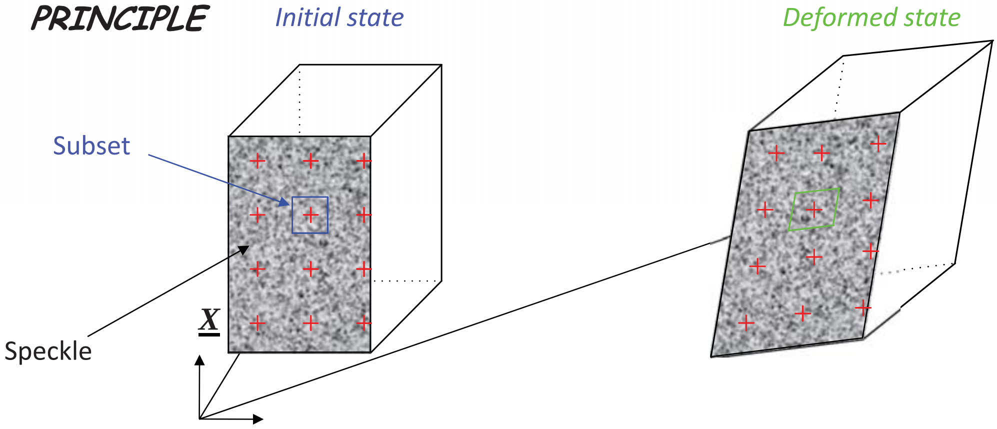
PRINCIPLE



Digital Image Correlation (DIC)

Optical extensometry technique → Digital image correlation (DIC)

(camera+speckle)

- *Displacements* (U_x, U_y)
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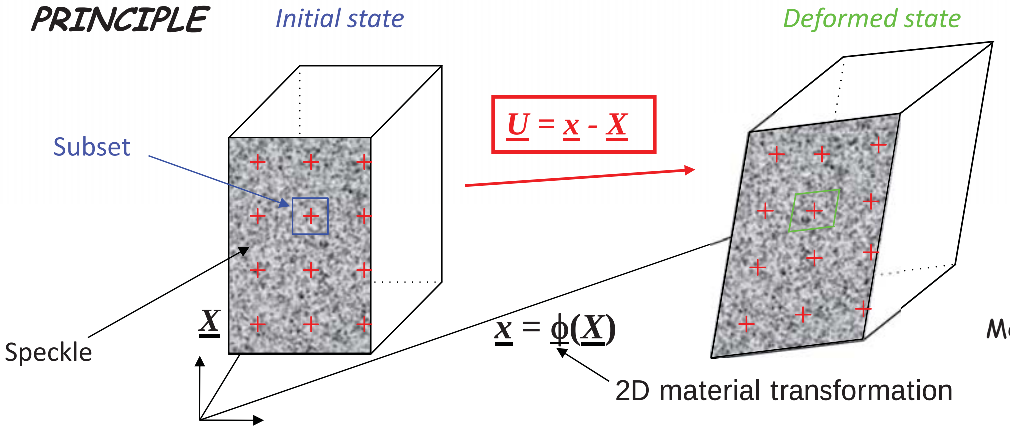
PRINCIPLE



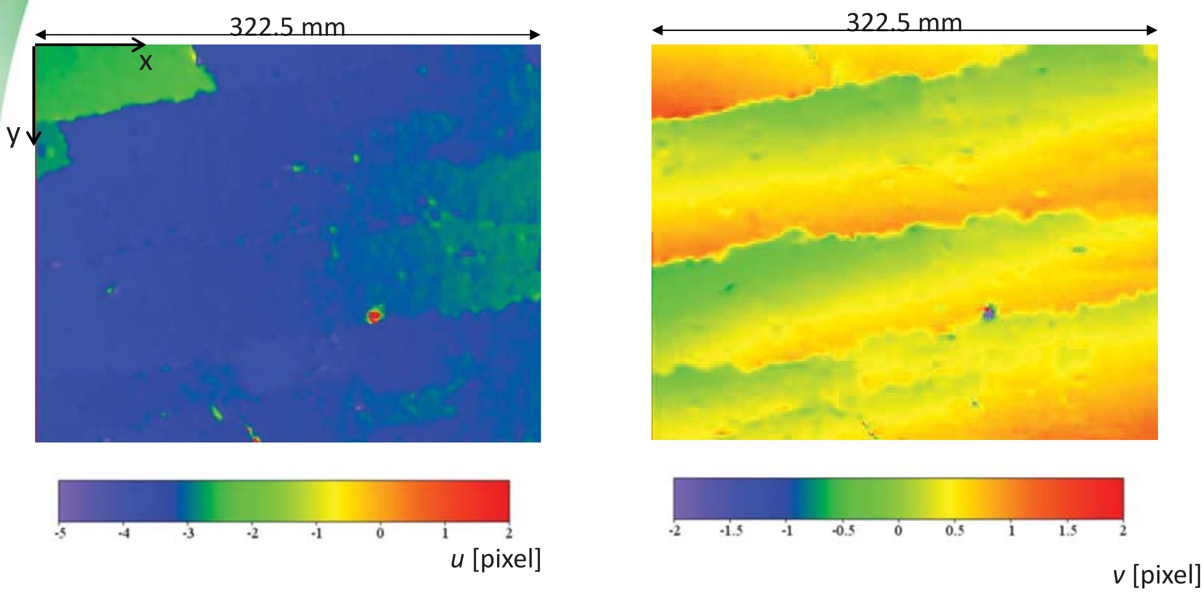
Measuring resolution

0.1 pixel

Digital Image Correlation (DIC): Displacement fields

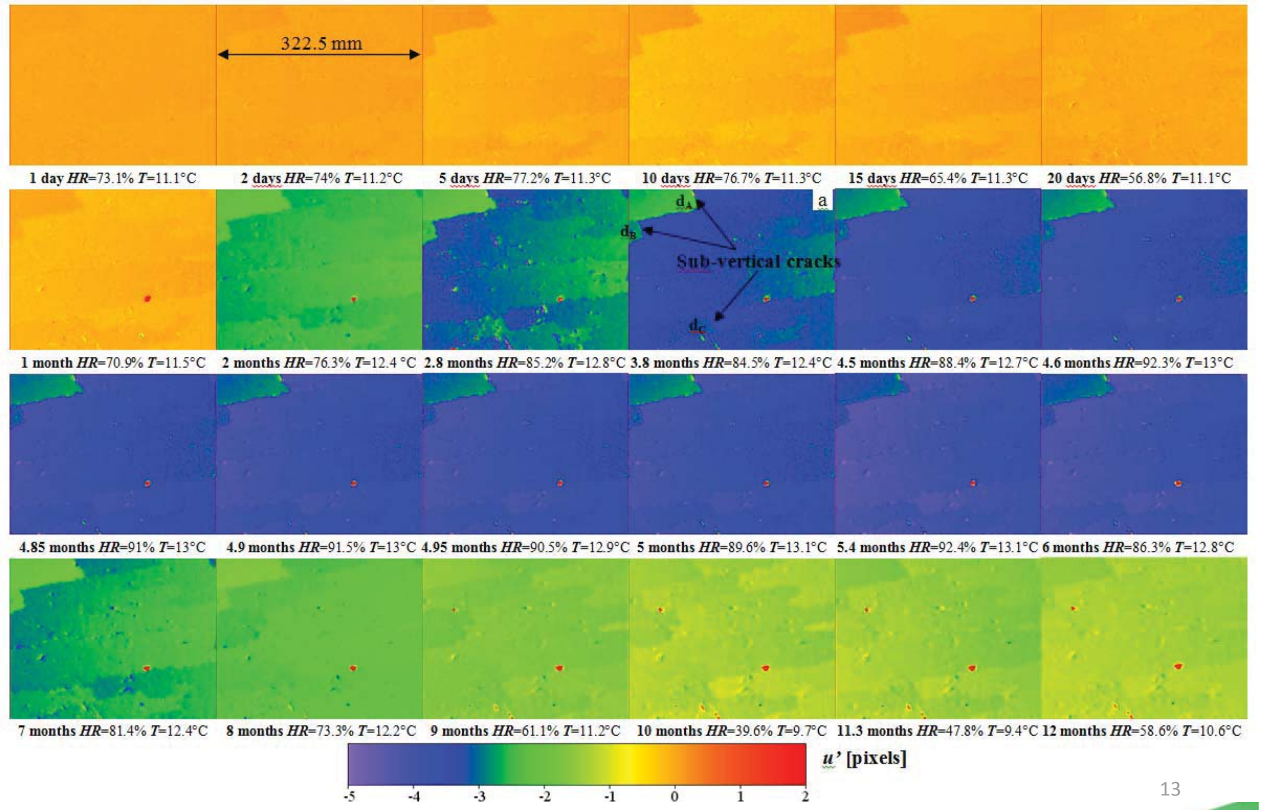
horizontal displacement field

Vertical displacement field

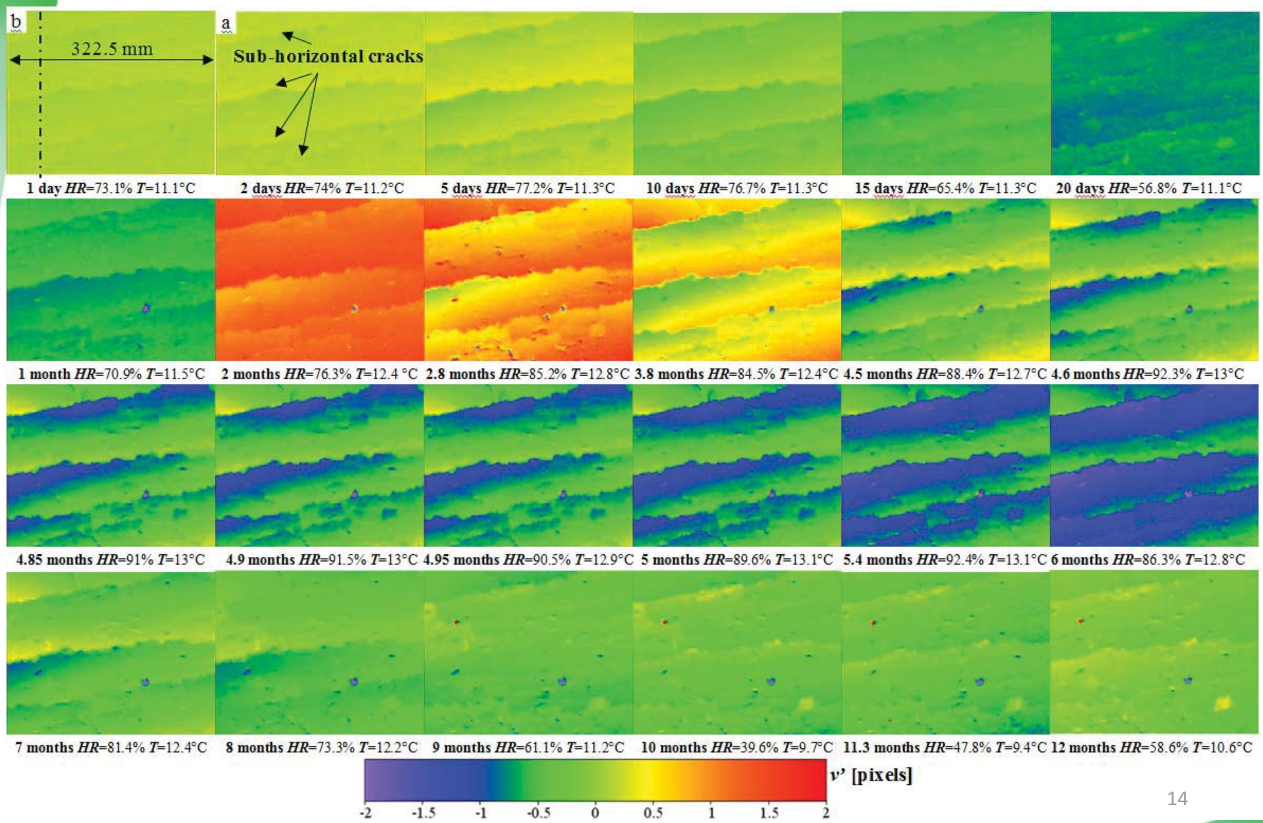


3.8 months ***HR***=84.5% ***T***=12.4°C

Digital Image Correlation (DIC): Displacement fields on one year



Digital Image Correlation (DIC): Displacement fields on one year



Limitation: Quantity of data

1 year of acquisition
2 image.h^{-1}
1.2 Mp /image
2 components of displacements.p^{-1}
3 components of strains.p^{-1}

10^5 M data/year

Limitation: Quantity of data

1 year of acquisition
0.5 image.h^{-1}
0.3 Mp /image
2 types of cracks (sub-horizontal and sub-vertical).im^{-1}
1 component of strains.im^{-1}

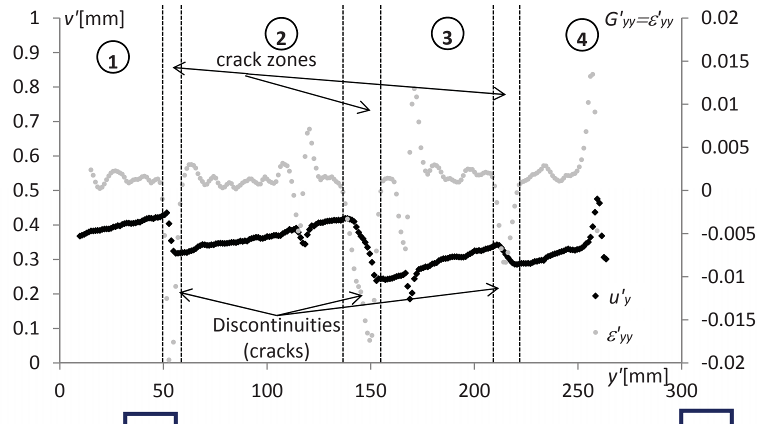
4.10^3 M data/year

Limitation

Limitation: Quantity of data

1 year of acquisition
0.5 image.h[-1]
0.3 Mp /image
2 types of cracks (sub-horizontal and sub-vertical).im[-1]
1 component of strains.im[-1]

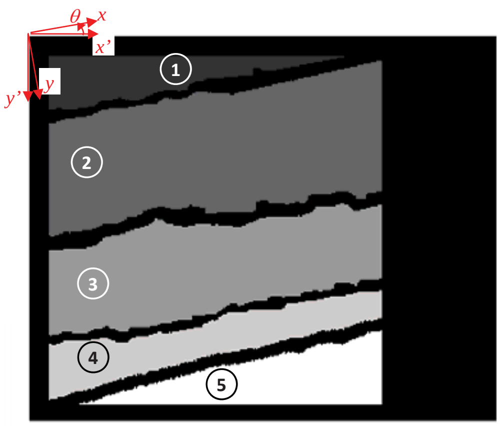
4.10³ M data/year



Relationship between **apertures** of sub-horizontal and sub-vertical cracks vs. **hydric parameters** (T and RH)

Relationship between **strains** and **hydric parameters** (T and RH)

Blocks and locations of sub-horizontal cracks

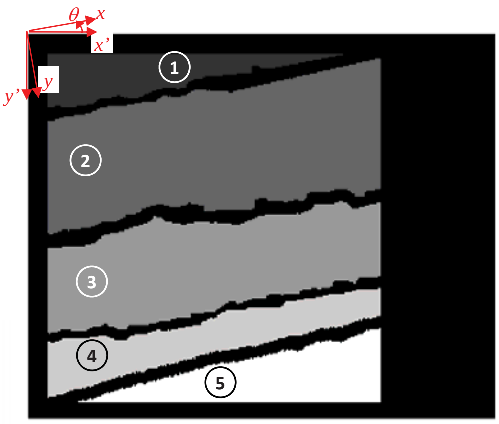


Crack aperture calculation :

$$d^{k,k+1} = \frac{1}{w_{k,k+1}} \sum_{w_{k,k+1}} \left(u_y^{k}(x,y) - u_y^{k+1}(x,y) \right)$$

where $w_{k,k+1}$ is the number of subsets defining each "crack" and $u_y^{k}(x,y)$ and $u_y^{k+1}(x,y)$ are extrema of perpendicular displacements on both sides of the cracks.

Blocks and locations of sub-horizontal cracks



Crack aperture calculation :

$$d^{k,k+1} = \frac{1}{w_{k,k+1}} \sum_{w_{k,k+1}} \left(u_y^k(x,y) - u_y^{k+1}(x,y)\right)$$

where $w_{k,k+1}$ is the number of subsets defining each "crack" and $u_y^k(x,y)$ and $u_y^{k+1}(x,y)$ are extrema of perpendicular displacements on both sides of the cracks.

Mean strain calculation :

$$\varepsilon_{ij}^k = \frac{1}{z}\sum_z \varepsilon_{ij}^k(x,y)$$

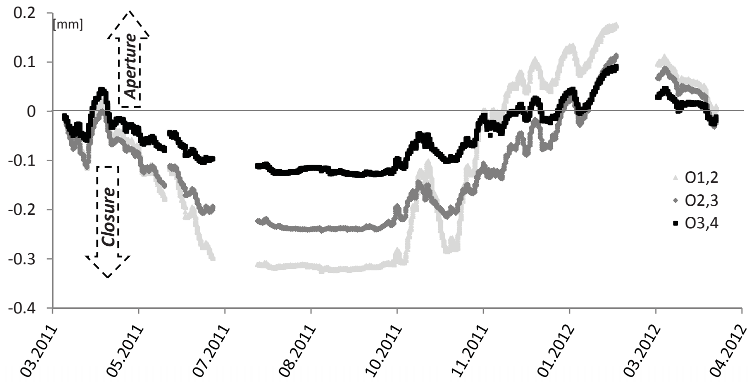
where

$$\begin{bmatrix} \varepsilon_{xx}(x,y) & \varepsilon_{xy}(x,y) \\ \varepsilon_{xy}(x,y) & \varepsilon_{yy}(x,y) \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} \varepsilon'_{xx}(x,y) & \varepsilon'_{xy}(x,y) \\ \varepsilon'_{xy}(x,y) & \varepsilon'_{yy}(x,y) \end{bmatrix}$$

ε_{ij}^k is the mean strain of each block *k* (= 1 to 5), (*i,j*) = (*x,y*), and *z* is the number of subsets of a given block *k* (=1-5)

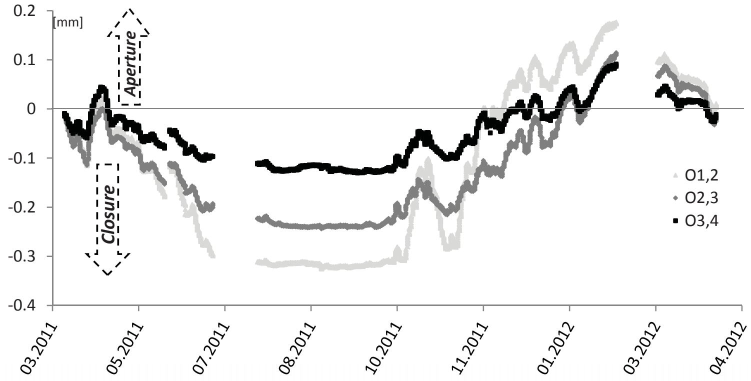
Sub-horizontal crack apertures with 2011/03/30 as Image reference

2011/03/30 (12 h 47 min 00 s GMT when RH=73,1% and T=10.8°C)

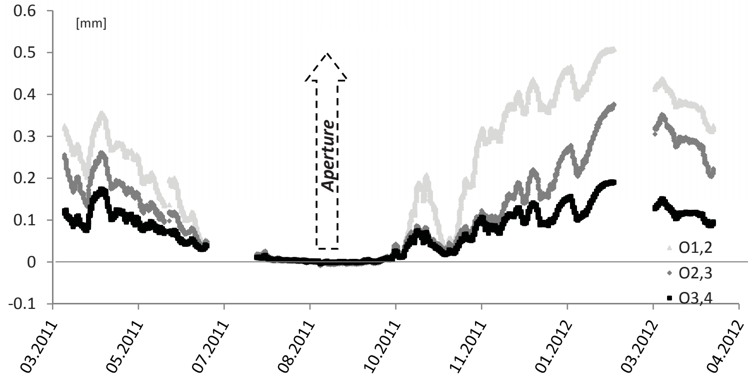


Comparison of sub-horizontal crack apertures if image reference changes

2011/03/30 (12 h 47 min 00 s GMT when RH=73,1% and T=10.8°C)



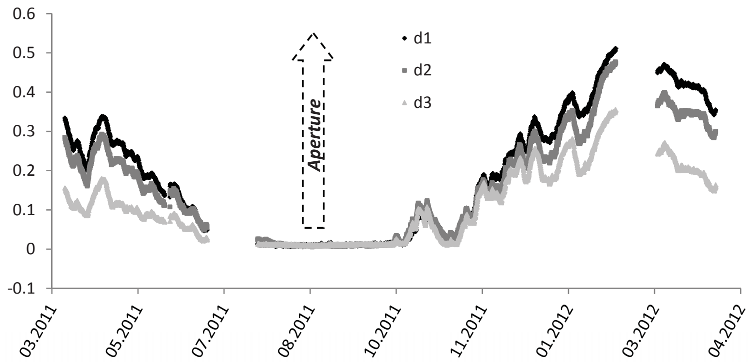
2011/08/23 (17 h 49 min 25 s GMT when RH=91.1% and T=13.0°C)



Sub-vertical crack apertures with 2011/08/23 as Image reference

Sub-vertical crack

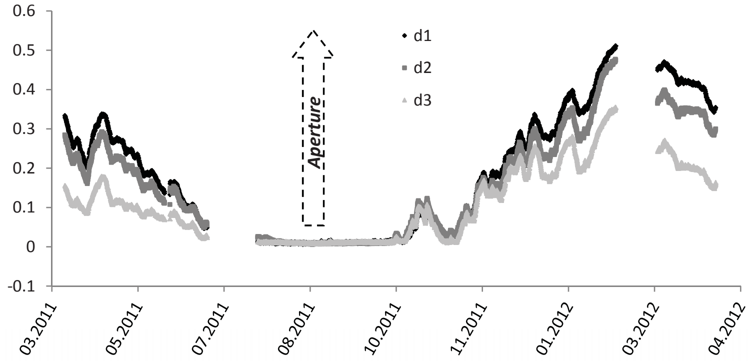
2011/08/23 (17 h 49 min 25 s GMT when RH=91.1% and T=13.0°C)



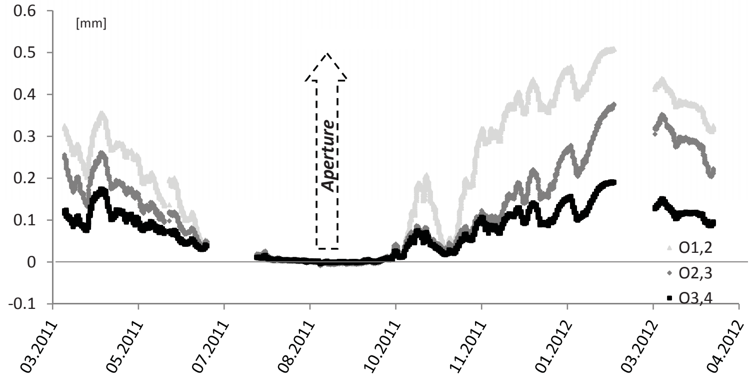
Crack apertures with 2011/08/23 as Image reference

Sub-vertical crack

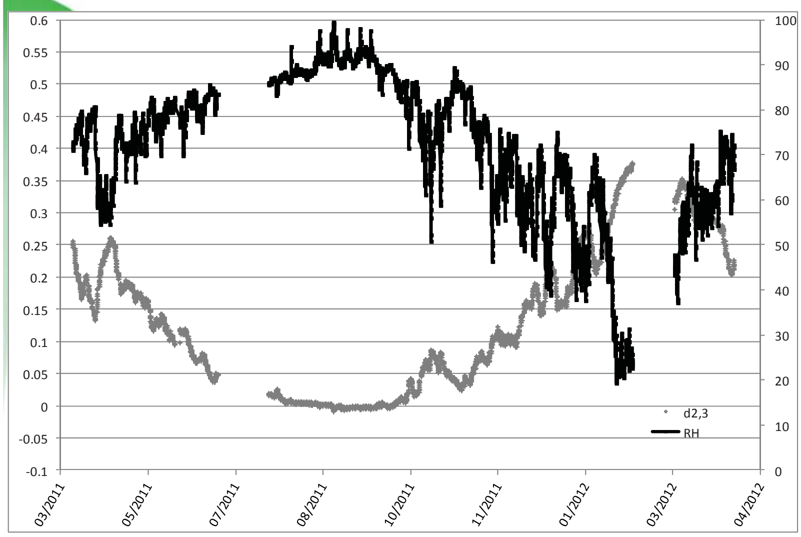
2011/08/23 (17 h 49 min 25 s GMT when RH=91.11% and T=13.05°C)



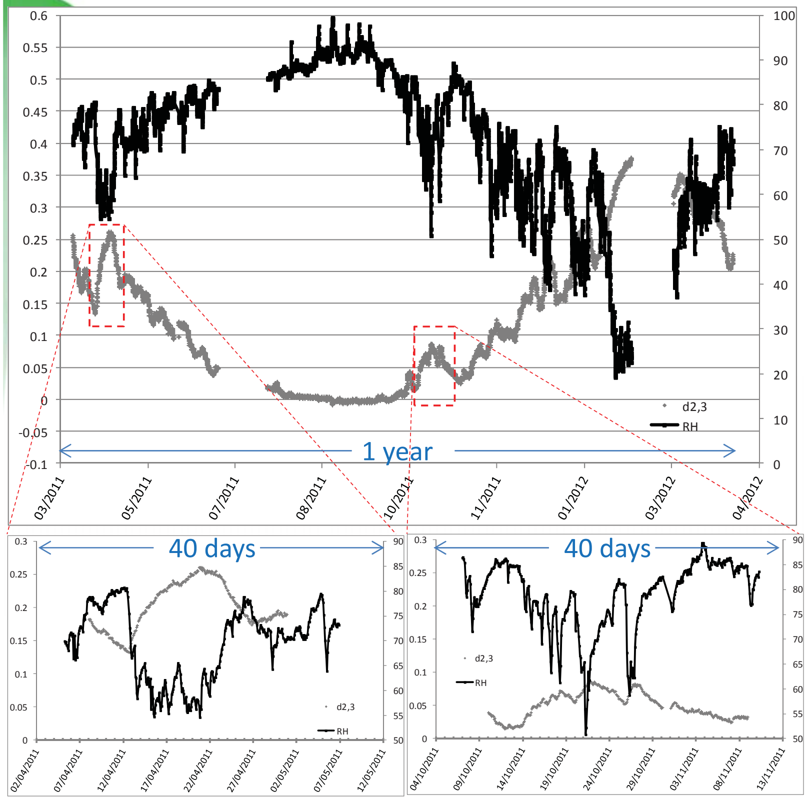
Sub-horizontal crack



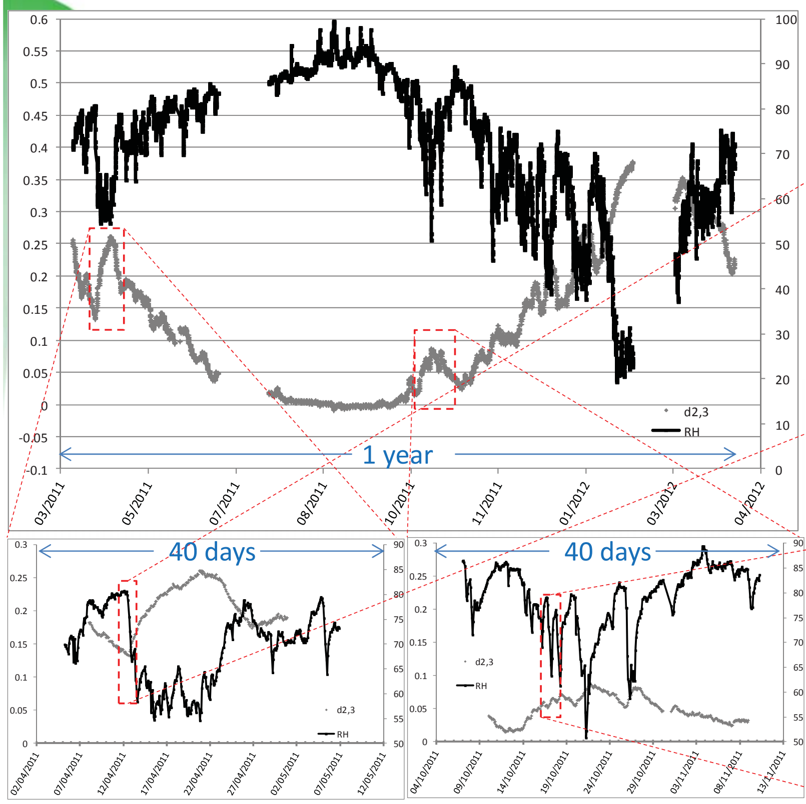
Comparison of sub-horizontal crack aperture and Relative Humidity RH



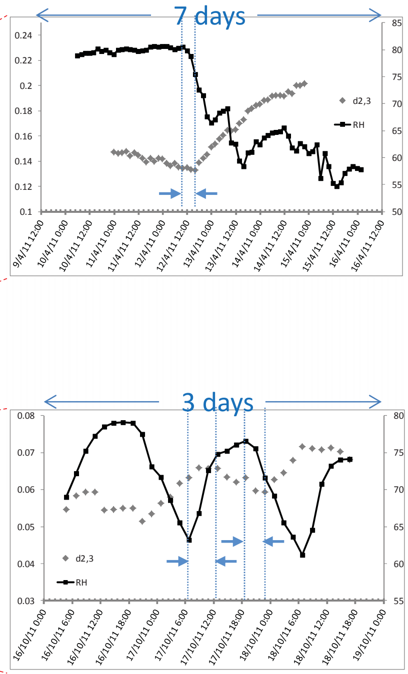
Comparison of sub-horizontal crack aperture and Relative Humidity RH



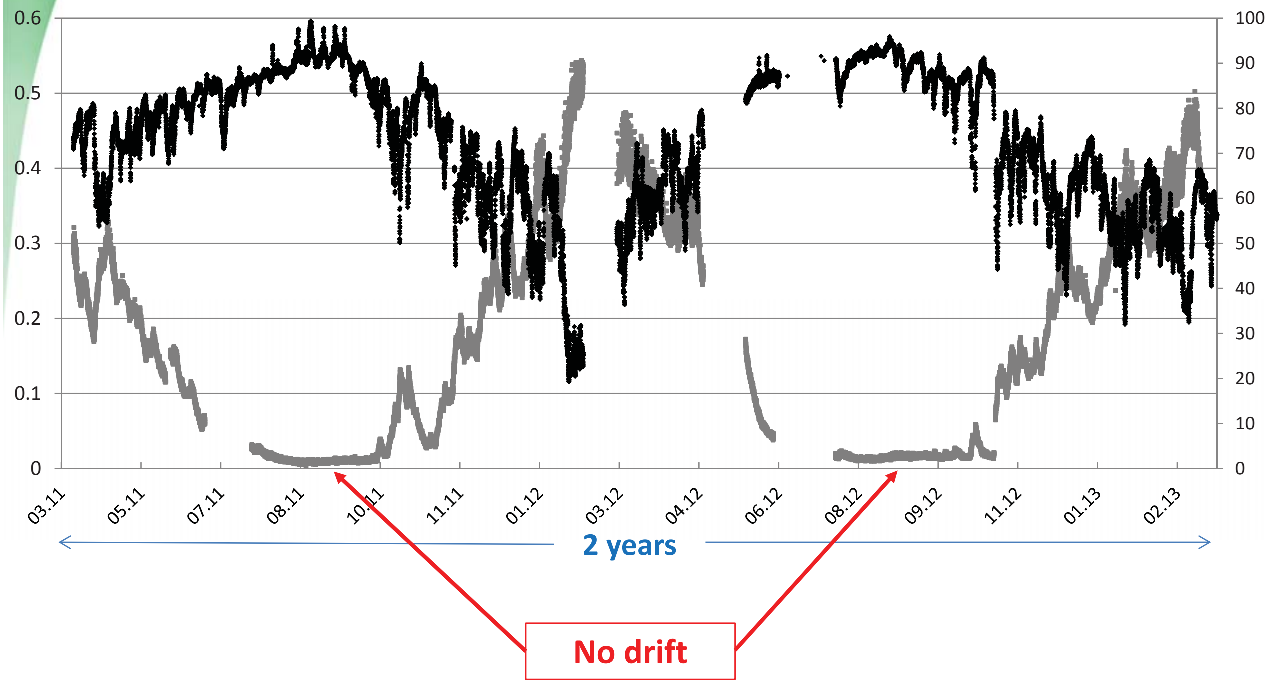
Comparison of sub-horizontal crack aperture and Relative Humidity RH



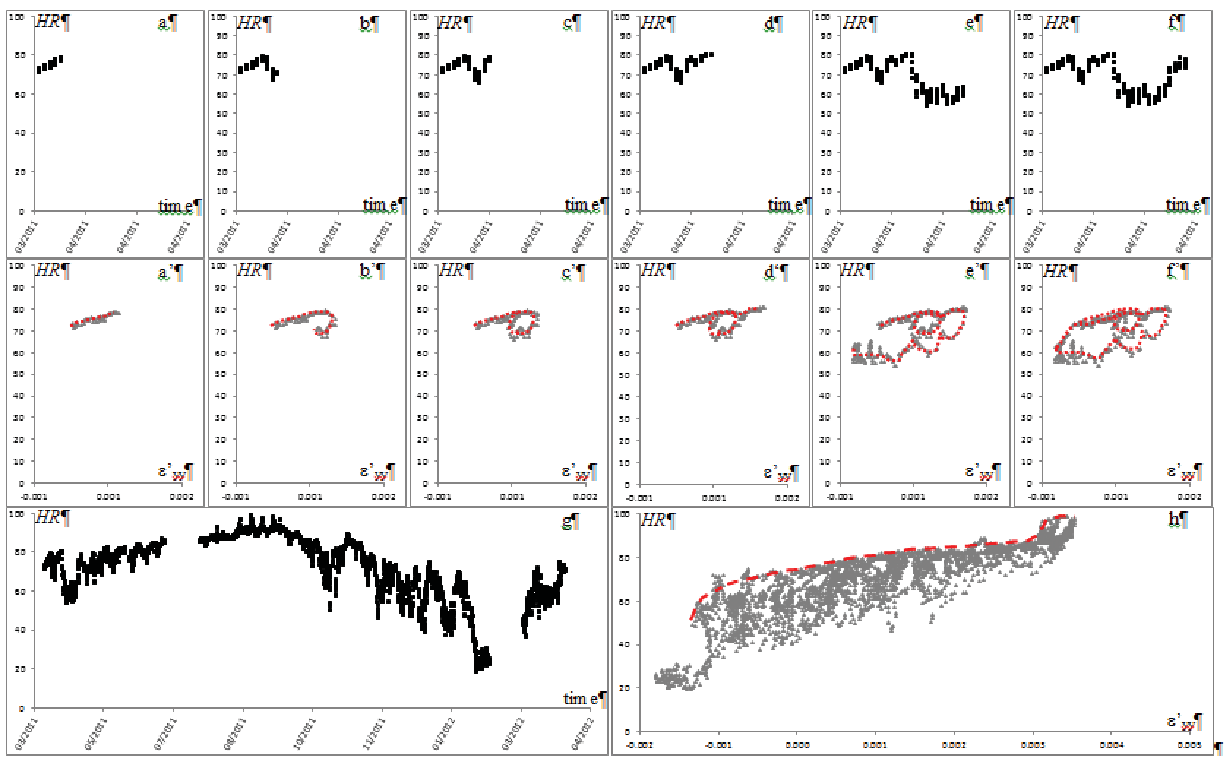
variation and **duration** of RH are greater than **15%** and **6-8 h**, respectively

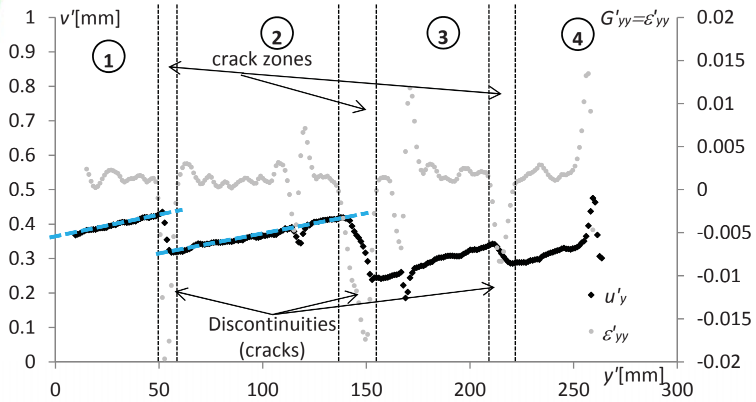


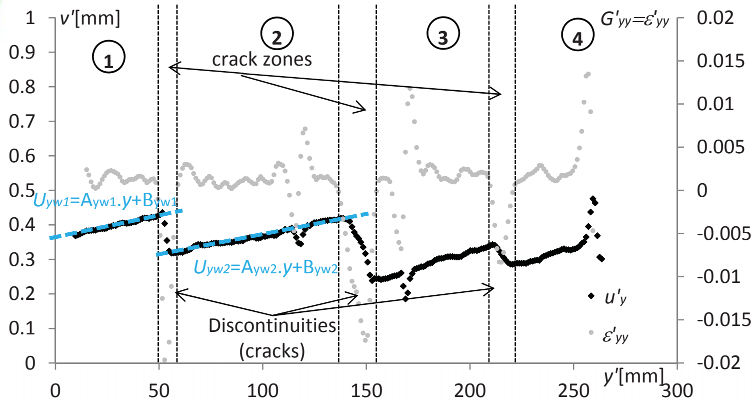
Crack aperture with 2011/08/23 as Image reference



Comparison of vertical strain ε_{yy} and Relative Humidity RH



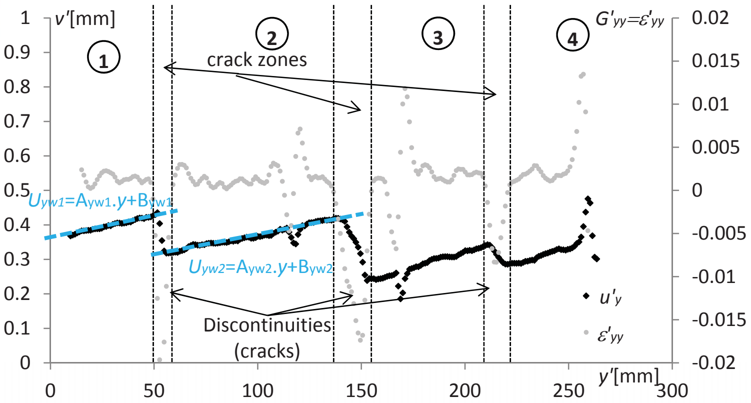




Equation of a Straight Line

$$\boxed{U_{w_y}^{k} = A_{w_y}^{k}.y + B_{w_y}^{k}}$$

where *w* is the index of a profile perpendicular to the crack, $A_{w_y}^{k}$ is the gradient of the line *w*, and $B_{w_y}^{k}$ is the $U_{w_y}^{k}$-intercept of the line *w*.



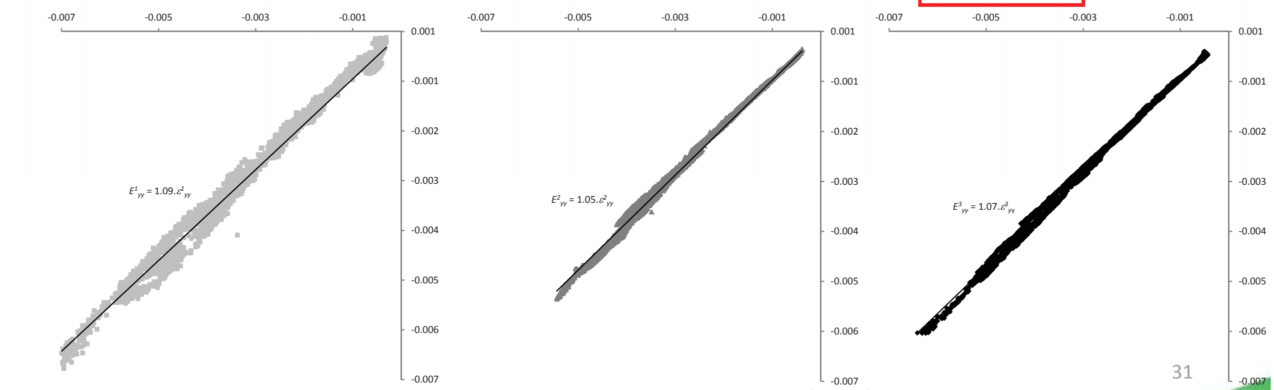
Equation of a Straight Line

$$\boxed{U_{wy}^{k} = A_{wy}^{k}.y + B_{wy}^{k}}$$

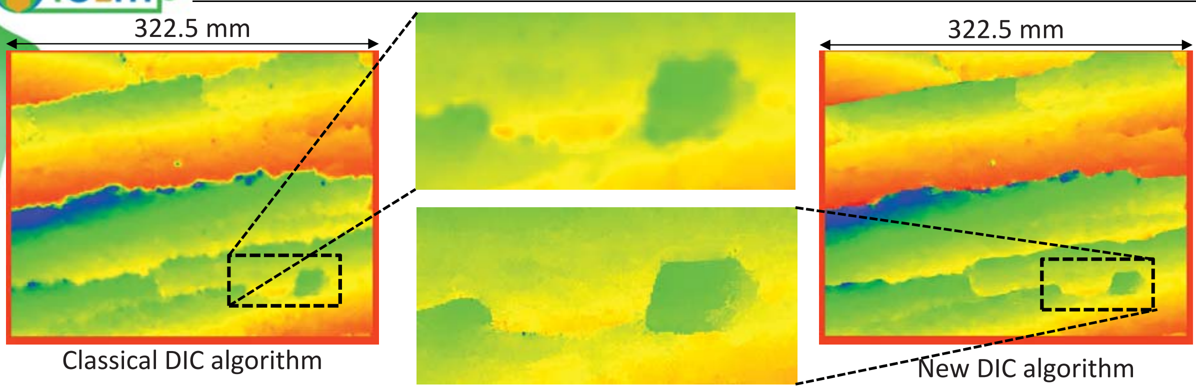
where *w* is the index of a profile perpendicular to the crack, A_{wy}^{k} is the gradient of the line *w*, and B_{wy}^{k} is the U_{wy}^{k}-intercept of the line *w*.

For each block *k*, the mean gradient E_{yy}^{k} is calculated by averaging all gradients A_{wy}^{k} over all considered lines:

$$\boxed{E_{yy}^{k} = \frac{1}{w}\sum_{w} A_{wy}^{k}}$$



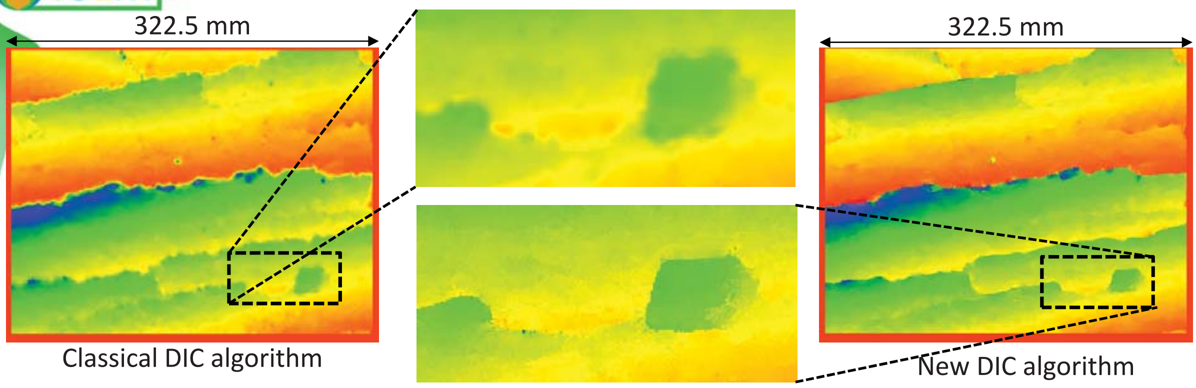
Submitted article in IJRMMS : hedan et al.(XXXX)

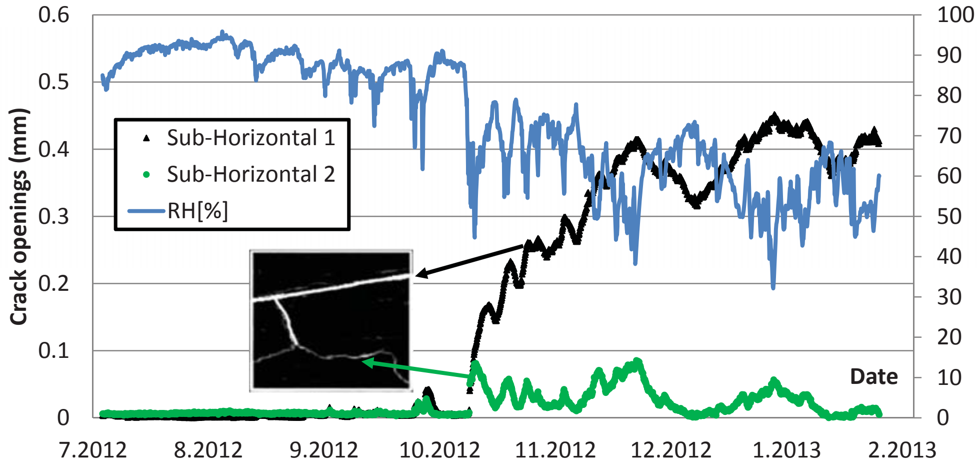


Classical DIC algorithm

New DIC algorithm

New algorithm of DIC : H^2-DIC





Two types of desiccation sub-horizontal cracks

Submitted article in EFM : valle et al.(XXXX)

Conclusions

- The non-invasive **DIC method** was used for the **first time** in an **underground gallery** at Tournemire, during which time the RH and T were continuously measured. This *in situ* experimental investigation has demonstrated the ability of the DIC method **to monitor spatial clay-rock deformations** and **openings and closures of desiccation cracks** during a natural seasonal variation.

- The narrow zones or bands were desiccation cracks (**typical aperture ≤0.5 mm**) that were observable from the displacement fields. The **strain** fields between these desiccation cracks were **homogeneous** at the spatial resolution used in this study (269 µm).

- The **crack apertures** calculated from the displacement fields and the **mean strain** perpendicular to the cracks were clearly correlated to changes in **RH** and **T**. **A delay or viscous effect** was observed; the mechanical responses of clay rock began after approximately **6-8 h** when the variations of RH were greater than **15%** of the same period.

- As observed at the **Mont-Terri site**, desiccation cracks close in summer and open in winter. However, contrary to the measurements acquired at the Swiss site, the **crack apertures** of the desiccation cracks were **reversible after one year** of data acquisition.

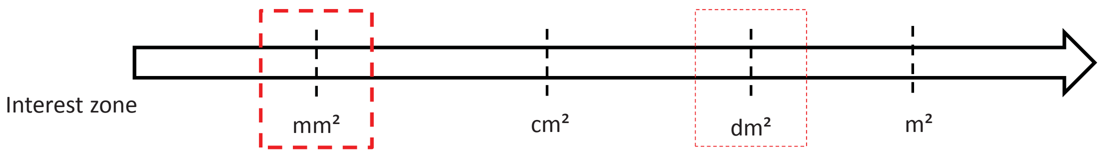
- Our work has shown that climatic changes can also induce some **sub-vertical cracks**.

Acknowledgments

The authors would like to express their acknowledgment to the GNR TRASSE (Transfert des Radionucléides dans les Sols, les Sous-sols et vers les Ecosystèmes) and NEEDS program (Nucléaire, Energie, Environnement, Déchets, Société), and to the French Institute for Nuclear Safety and Radioprotection (IRSN) for supporting and funding these works.

Thank you for your attention

Study of hydromechanical behavior of Argillite. Multi-scale approach



- sample (**2**x**2**x**1**cm³)+**Polishing**
- Test over several **weeks**
- Variation of **RH** (ex: cycles, choc, etc.) (T cst)
- Study zone : **5.5**x**4.1mm²**
- DIC precision : ≈**0.215 µm**
- Data: **5M.im⁻¹**

- **SEM** (Scanning Electron Microscopy)
- **Mineral map** (**5.5x4.1 mm²**)
- Spatial resolution SEM : **0.625 µm**
- Number of data : **52.5M.im⁻¹**

Financial support of NEEDS

- EDZ is created (Gallery excavated **15** years ago)
- Test on **1 year** of gallery front
- Natural variation of **RH** and **T**
- Study zone : **34,4**x**27,5cm²**
- DIC precision : ≈ **27µm**
- Data : **0,3M.im⁻¹**

Images always recorded (>2,5 years)

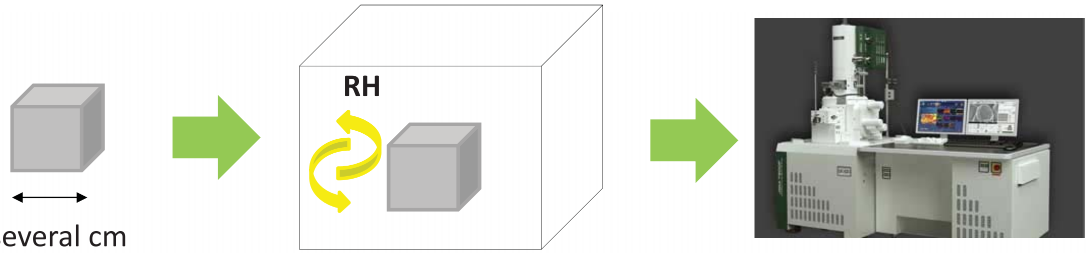
Financial support of TRASSE

objectives

Objectives:
- See the **desiccation cracks** and to measure the deformation on interest zone during the **variations of RH**
- Knowledge of mineralogy of rock in the same interest zone

3 steps

1. polishing ***2. desiccation*** ***3. Mineralogy***



sample

Measurement of hydric strains by DIC during variation of RH

Observation of sample with SEM

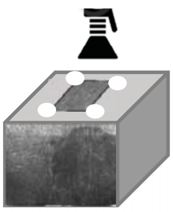
Difficulty : Same surface was used for DIC and SEM

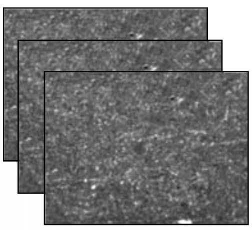
Experimental setup : Desiccation (DIC)

During the desiccation

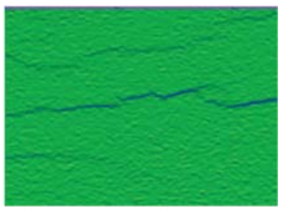
Method : Digital Image Correlation (DIC)

Camera → **Images** → **Displacement fields Strain fields**





Zoomed field: 5 Mp (2560x1920 pixels)
Spatial Resolution=2,15µm.pixel^{-1}



Localization of desiccation cracks

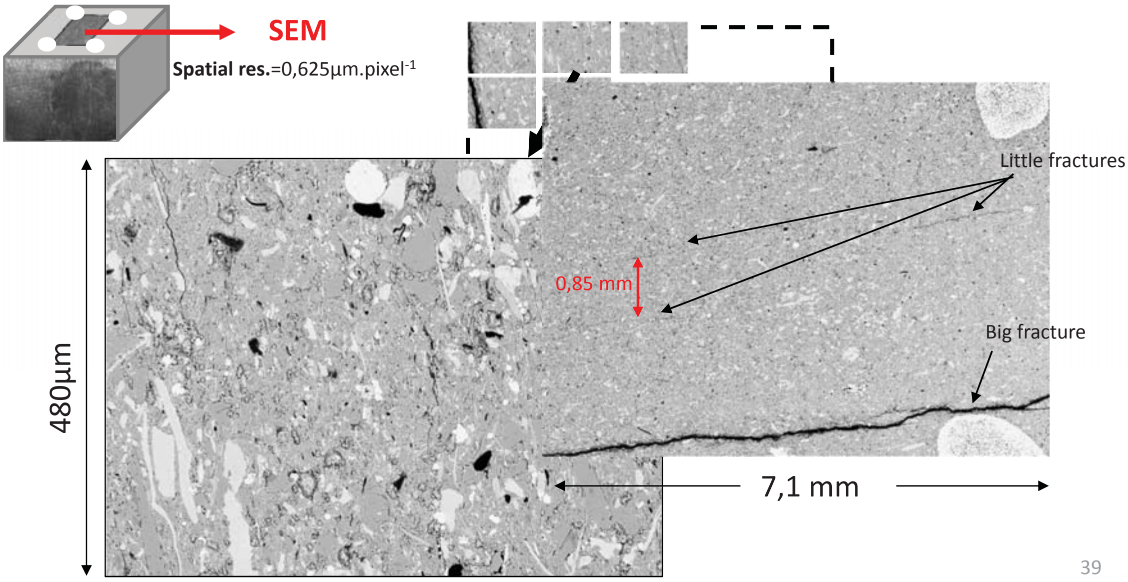
Experimental setup : Mineralogy (SEM)

big fractures + small fractures + texture

Spatialisation of data (>mm²)

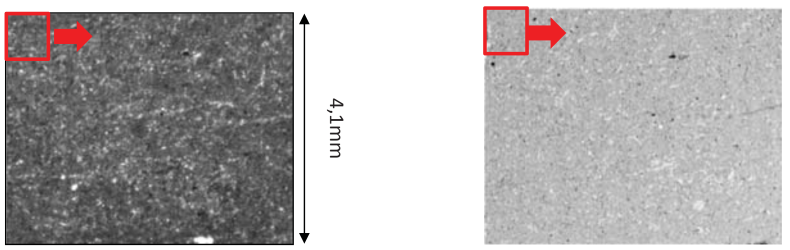
After the desiccation

Full field (17x9 images², 52,5 Mp)



Characterization of texture

Texture map

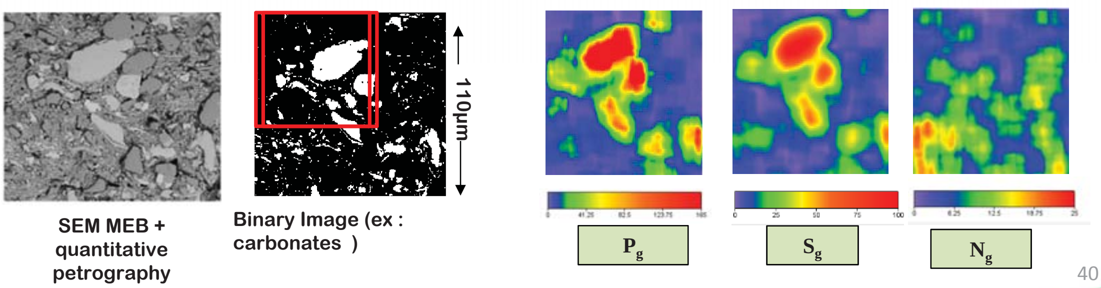


Measurement of strains for each subset

Measurement of textural parameters on the same subsets

For each subset

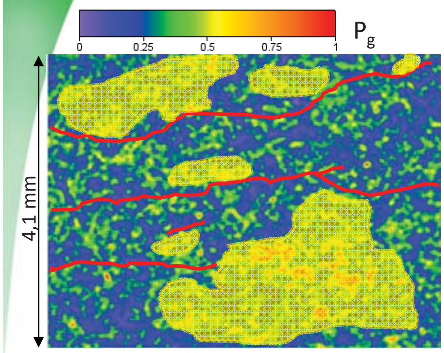
1. **Proportion:** percentage of coarse grains (P_g) , clay matrix (P_m)
2. **Grain size** (S_g)
3. **Orientation of coarse grains:** angle (α)
4. **Morphology :** (L/h)
5. **Quantity :** number of coarse grains (N_g)



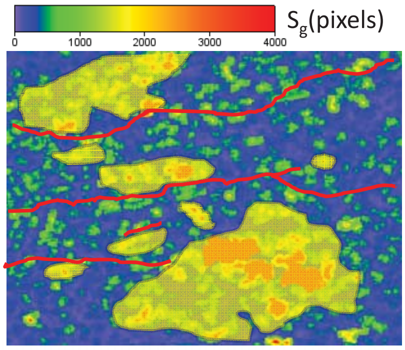
SEM MEB + quantitative petrography

Binary Image (ex : carbonates)

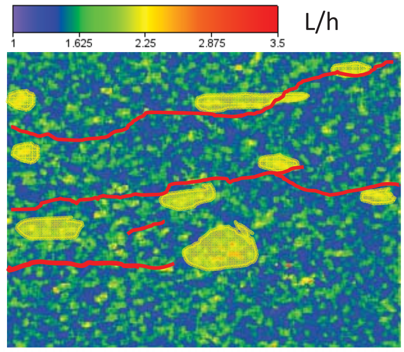
Results : comparison localization of cracks vs. texture



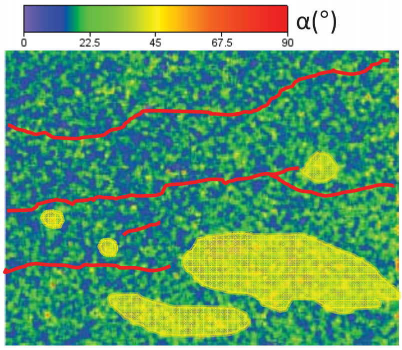
Percentage of coarse grains



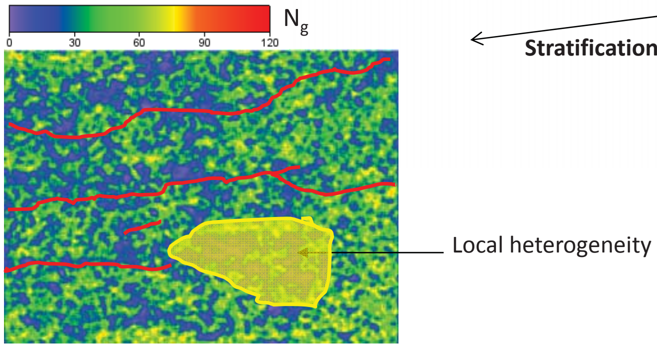
Grain size



Morphology



Orientation of coarse grains

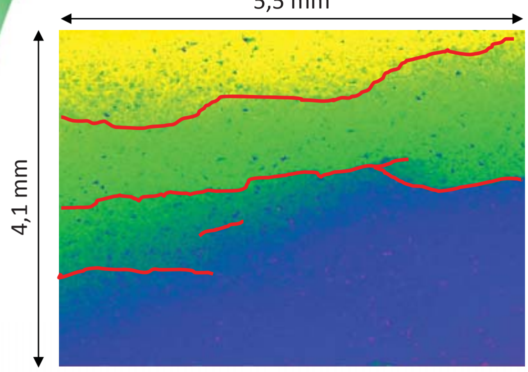


Number of coarse grains

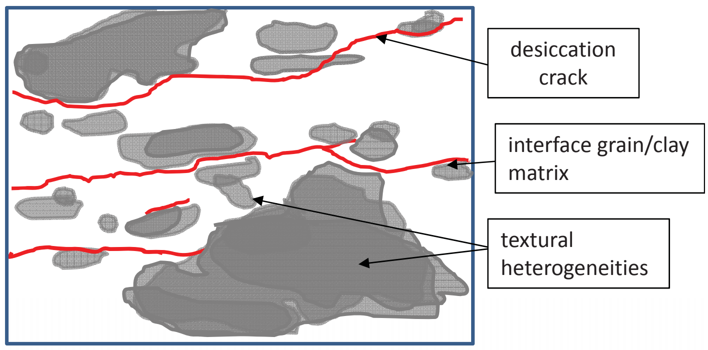
Stratification

Results : comparison localization of cracks vs. texture

Vertical displacement field



Localization of desiccation cracks



Localization of textural heterogeneities

The localization of desiccation cracks seems to be influenced by several textural heterogeneities as the percentage, size, orientation and morphology