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Sub-boundary characterization of crept uranium dioxide fuel pellets, by EBSD and ECCI

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EBSD: Electron BackScattered Diffraction
ECCI: Electron Channeling Contrast Imaging

Creep 2015, June 01– June 04, 2015, Toulouse, France

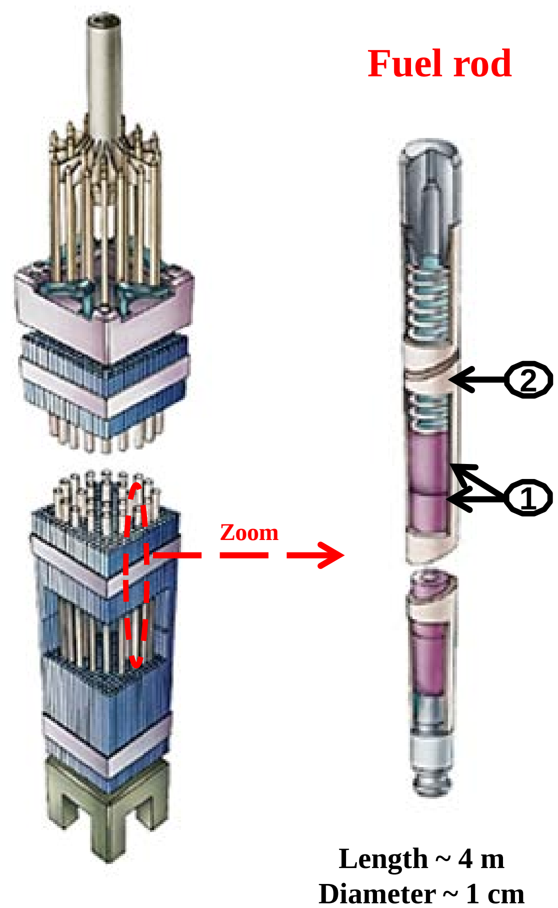
Sintered Uranium Dioxide UO_2 pellets are commonly used in nuclear Pressurized Water Reactors (PWR)

The fuel rods consist of:

(1) UO_2 pellets pilled up in

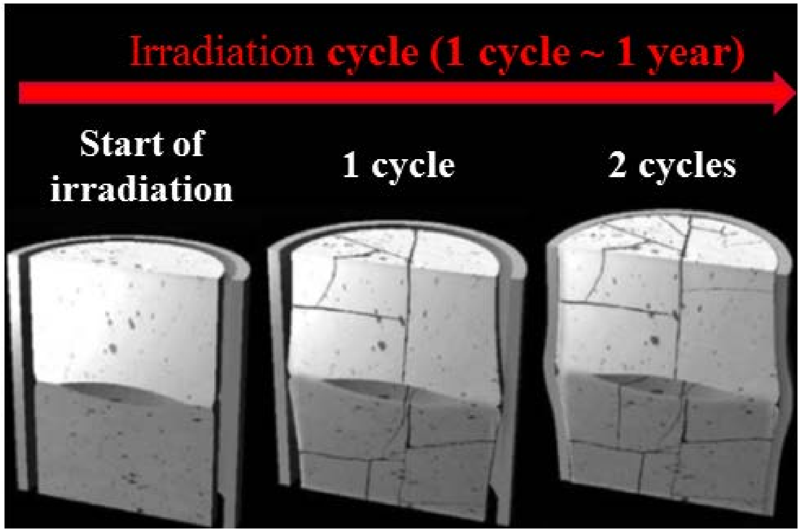
(2) a zirconium alloy cladding tube cooled by pressurized water

PWR fuel assemblies



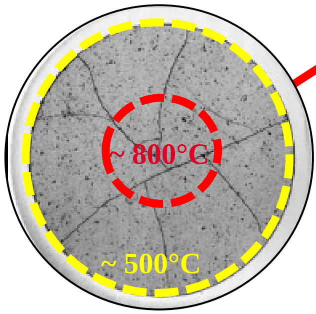
In service the UO_2 pellets undergo significant plastic deformation by creep

Nominal conditions



9,5 mm

Under irradiation:



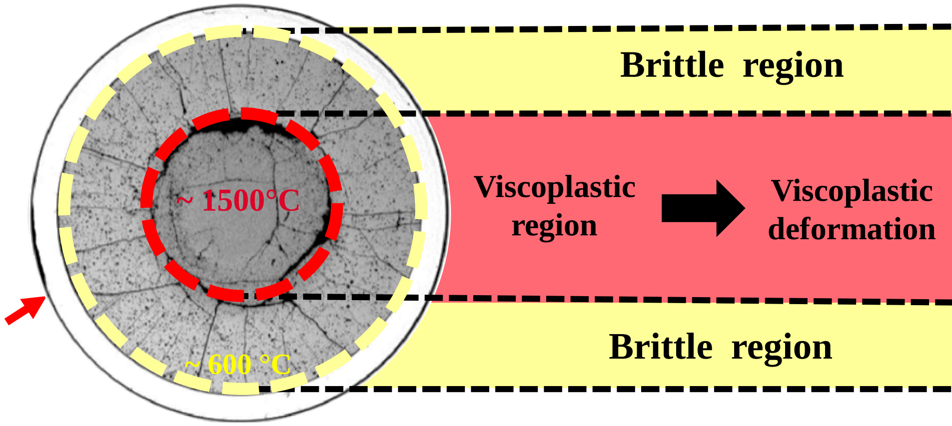
Temperature increase (pellet center)

thermal gradient + fission products

⟶ Fuel swelling

⟶ Large stresses and cracks in the pellet

Power transient



Cracking in a UO_2 pellet subjected to 2 annual PWR cycles, followed by 12 hours at a linear power of 430 W/cm.

Increasing power causes:

- **An increase of pellet temperature up to about 1500-2000°C in its central part**

  ➔Viscoplastic-deformation: Creep of the pellet

➢ To avoid cladding failure

⟶ Increase the creep of the fuel (viscoplastic deformation)

This creep process is partly reproduced by compression creep tests on non-irradiated UO_2 sintered samples

Grain size : 25µm

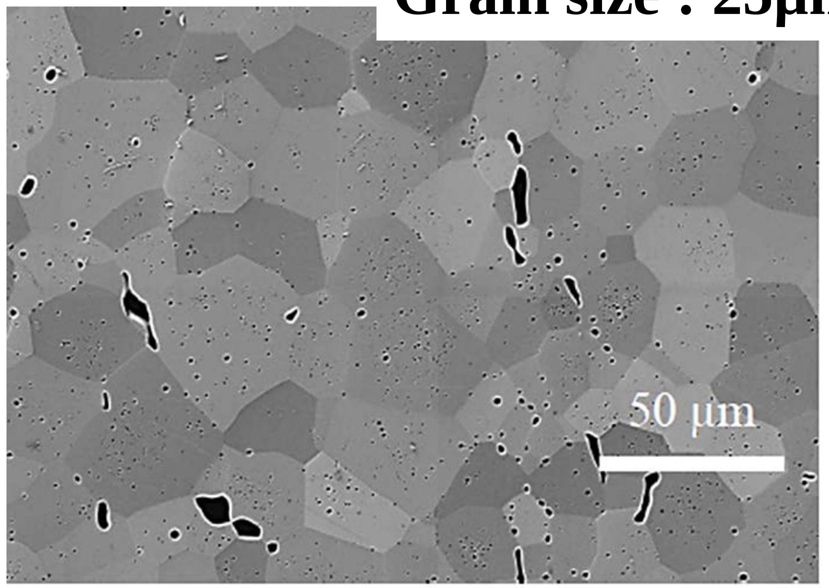
Sintering conditions [1,2]

Uniaxial pressing of the powder under 400 MPa

+

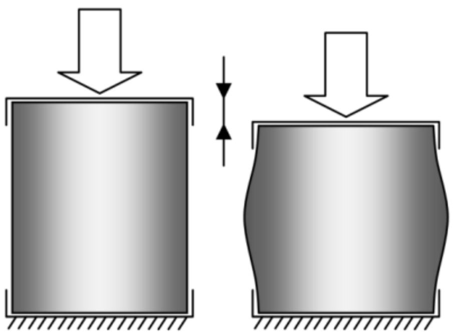
Sintering heat treatment at 1900°C for 4h, under an atmosphere of Ar + 5% H_2

⟹



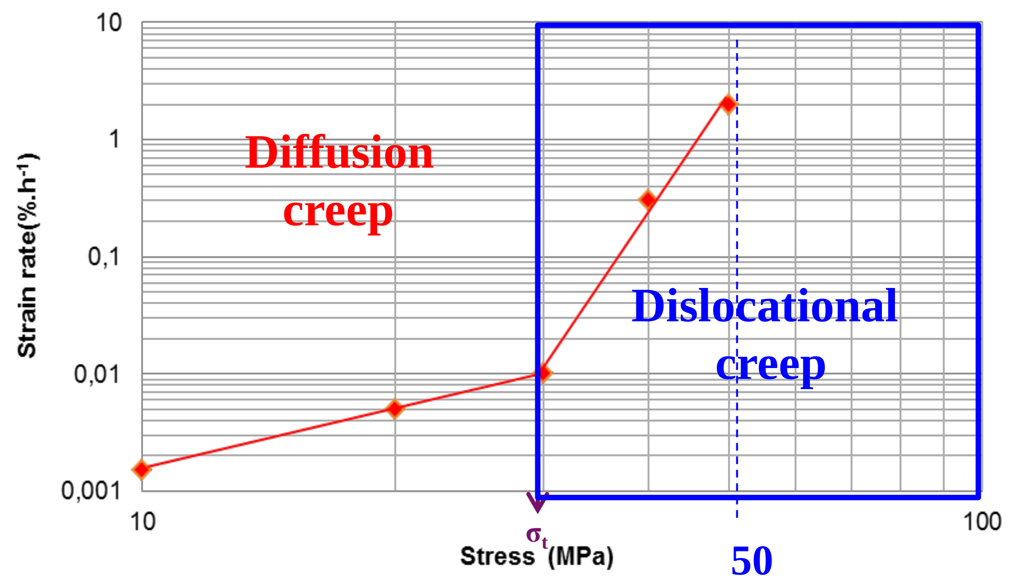
SEM micrograph (BSE mode) of an UO_2 sample

Compression creep tests at 1500°C [1,2]



Our reference sample

- **50 MPa**
- **test duration: 2.7h**
- **mean deformation: ~ 8%**



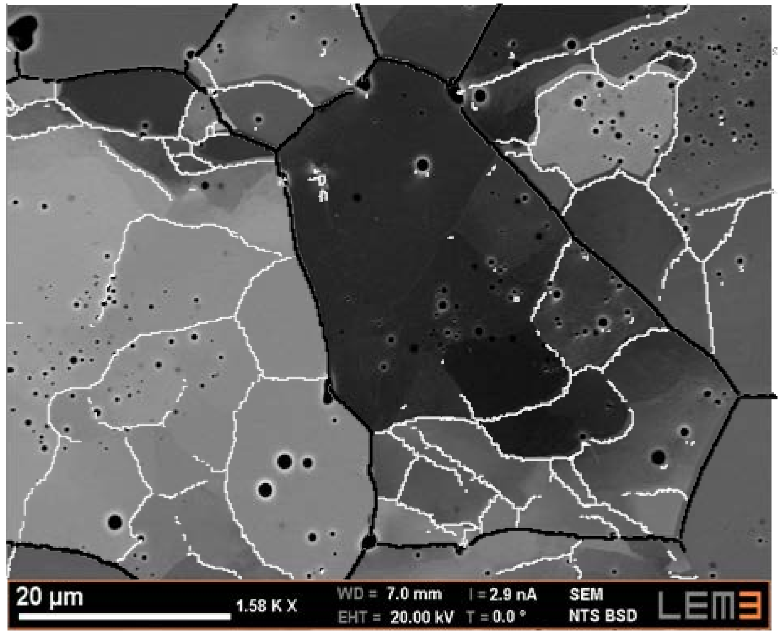
Strain rates measured in the creep test at 1500°C under various stresses [2]

Creep damage was previously evidenced by Scanning and Transmission Electron Microscopy (SEM and TEM)

Creep damage

- Intergranular cavities
- Sub-grains formation
- Dislocations density increase

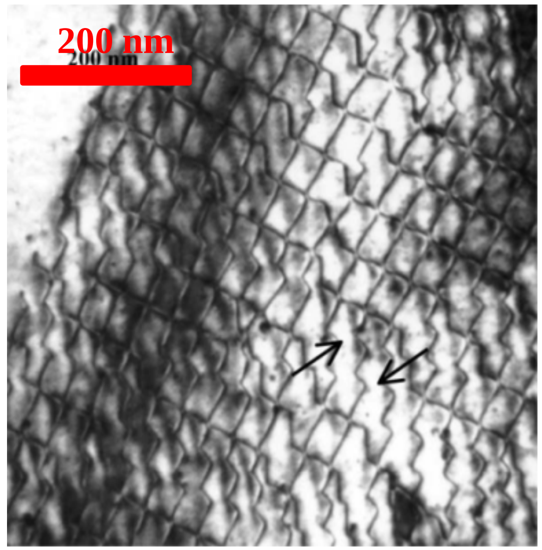
- SEM studies



- TEM studies

1978	2002	2014
A. Alamo *et al.*	F. Dherbey *et al.**	J. Fouet *et al.*
CEA Fontenay aux Roses	CEA Grenoble	CEA Cadarache

Primary slip {001}<110> $\xrightarrow{\varepsilon \nearrow}$ (Density of dislocations) **Primary slip** + **Cross slip** {110}<110> {111}<110> ⇒



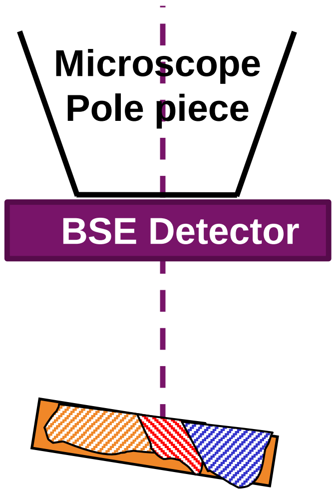
Dislocation network*

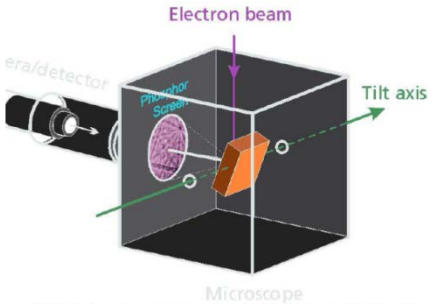
OUR AIM is to characterize the sub-boundaries created by dislocational creep in UO_2

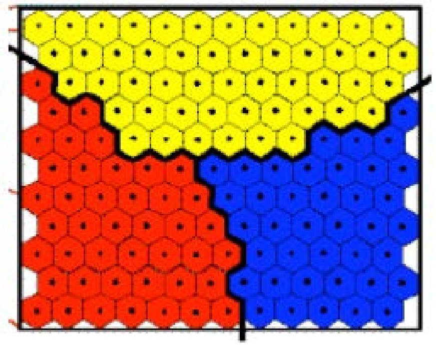
EBSD
Electron BackScattered Diffraction

BULK MATERIAL SEM

ECCI
Electron Channeling Contrast Imaging [3]



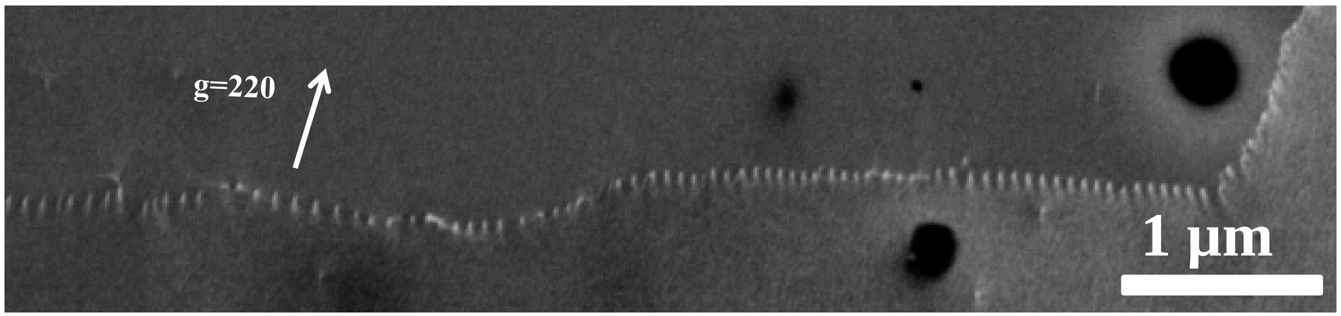




Acquisition of Orientation map to:

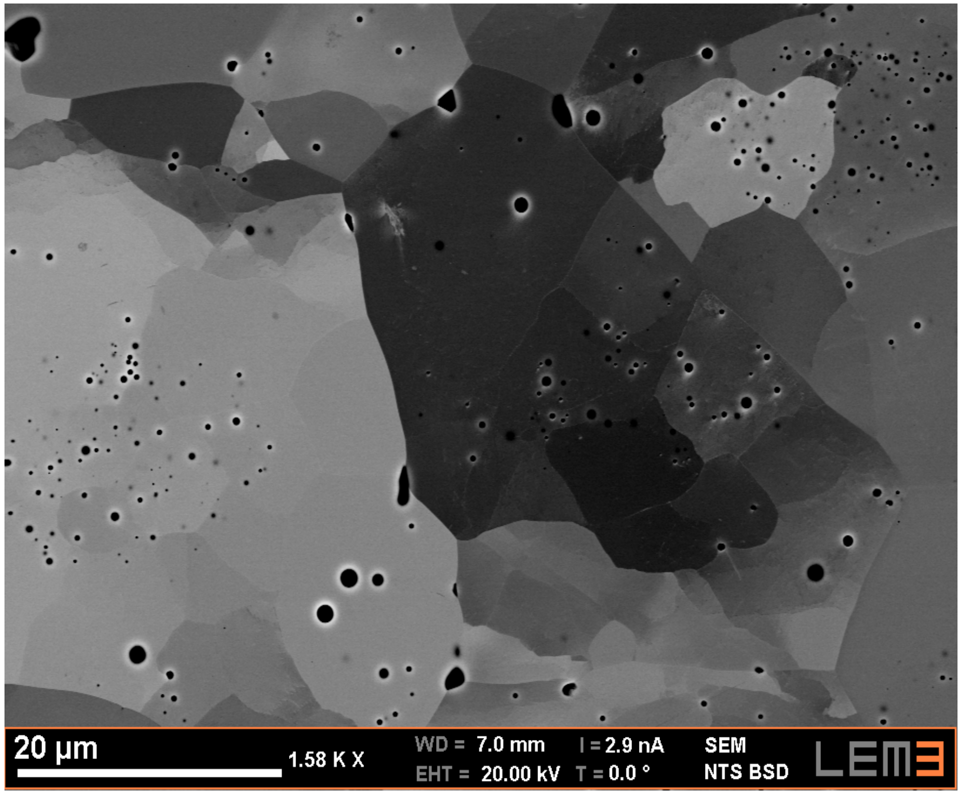
- **Identify the low angle boundaries (sub-grains),**
- **Quantify the Geometrically Necessary Dislocations (GND)**

To identify crystallographic defects like dislocations and their arrangement in sub-grains boundaries [4]



BSE image at high magnification in specific diffraction condition

RESULTS: EBSD ANALYSIS ON THE REFERENCE SAMPLE ε=8%

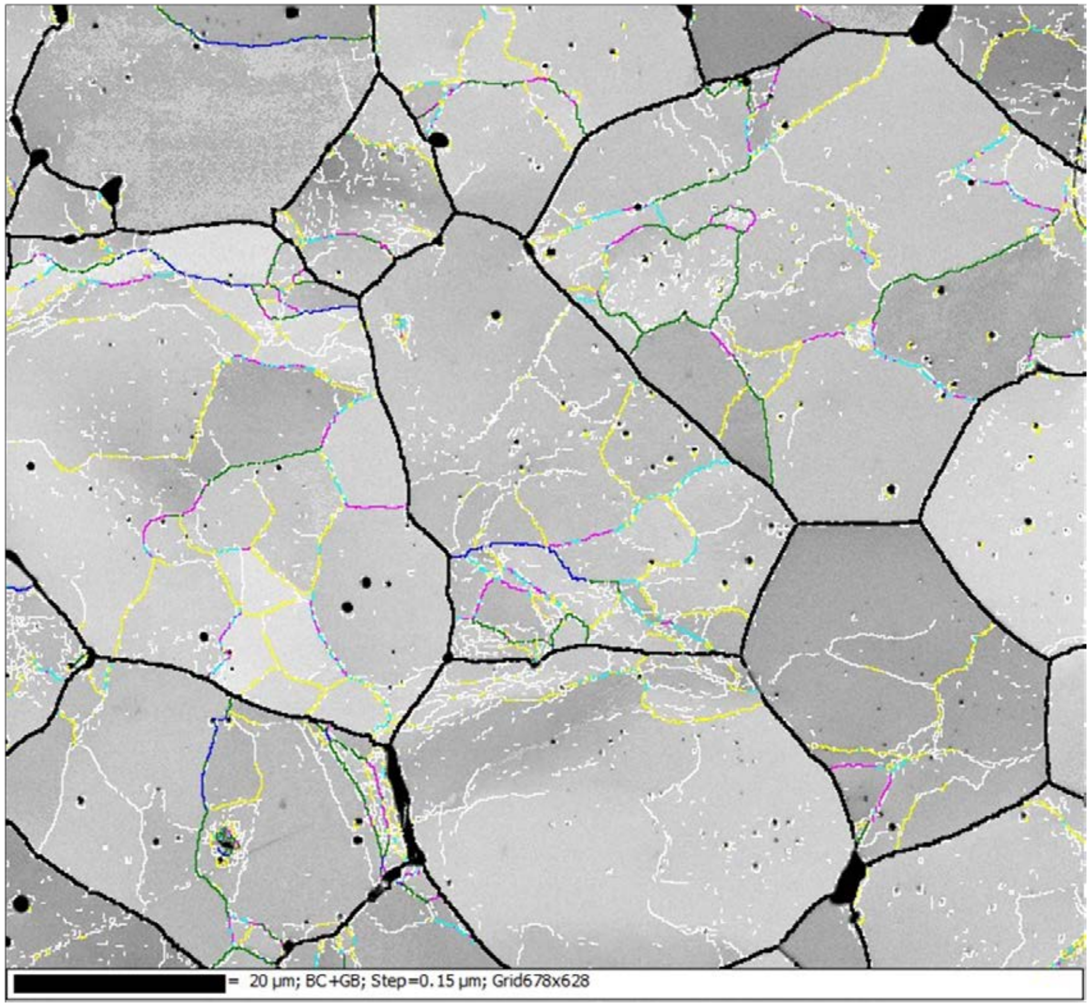


BSE micrograph of an UO_2 sample tested at 1500°C, under 50 MPa

The deformation induced a network of low angle boundaries

EBSD resolves low angle boundaries revealed by misorientations down to 0.1° !

Misorientation map



Misorientation angle Θ
Color code

0.1 0.25 0.5 0.75 1 2 5>

The lattice curvature measured by EBSD can be used to evaluate the local density of GNDs

From the disorientation between two neighboring points : $\Delta\theta$

separated spatially by Δx,

the lattice curvature: $$k = \frac{\Delta\theta}{\Delta x}$$

and the GND's density: $$\rho = \frac{k}{b}$$

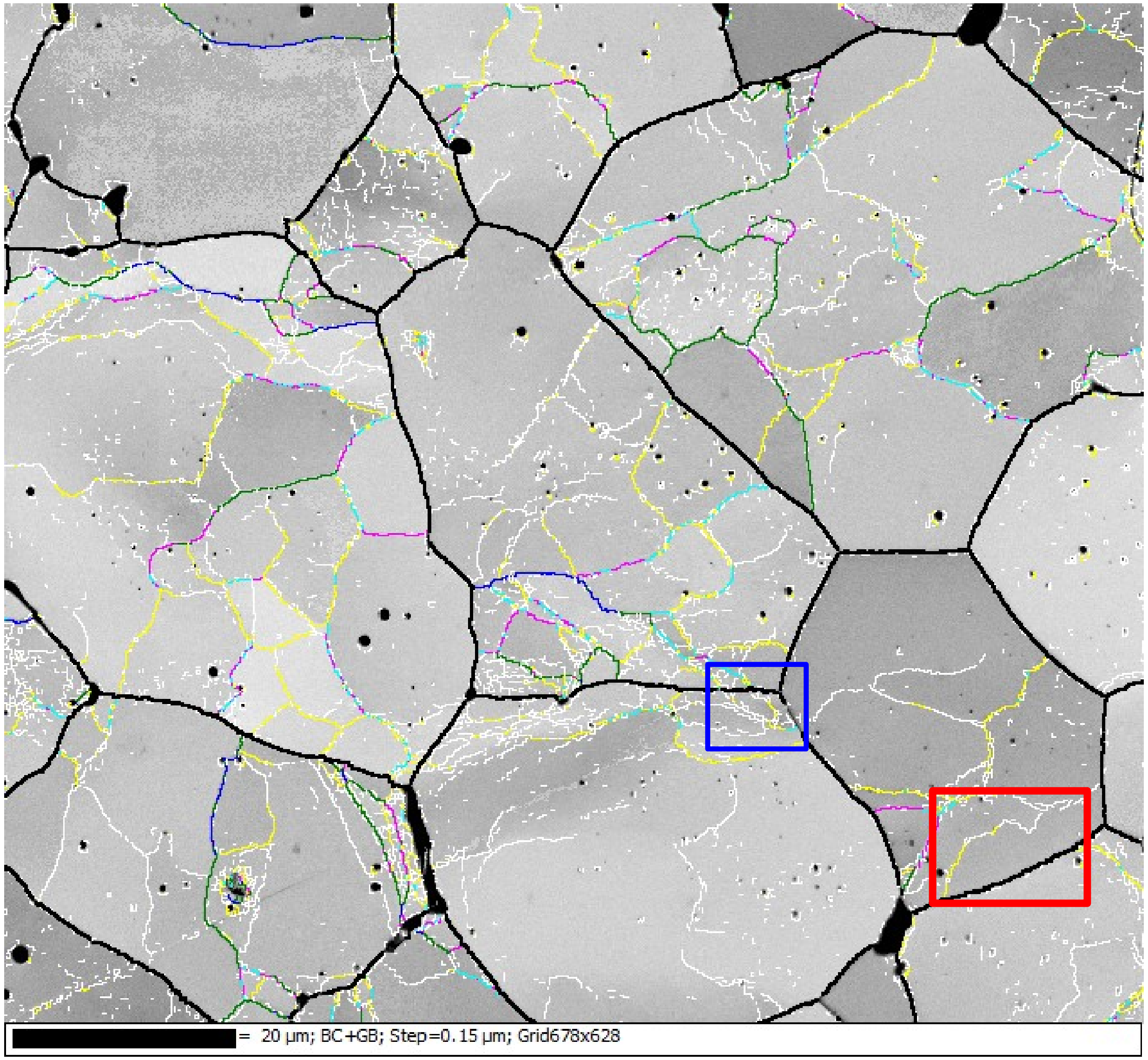
Per EBSD step unit

b=a/2<110>

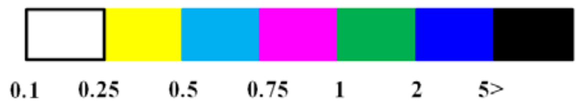
Nye dislocation density tensor

$$\alpha = \begin{bmatrix} ? & a_{12} & a_{13} \\ a_{21} & ? & a_{23} \\ ? & ? & a_{33} \end{bmatrix}$$

LEM3 Software



Misorientation angle Θ color code



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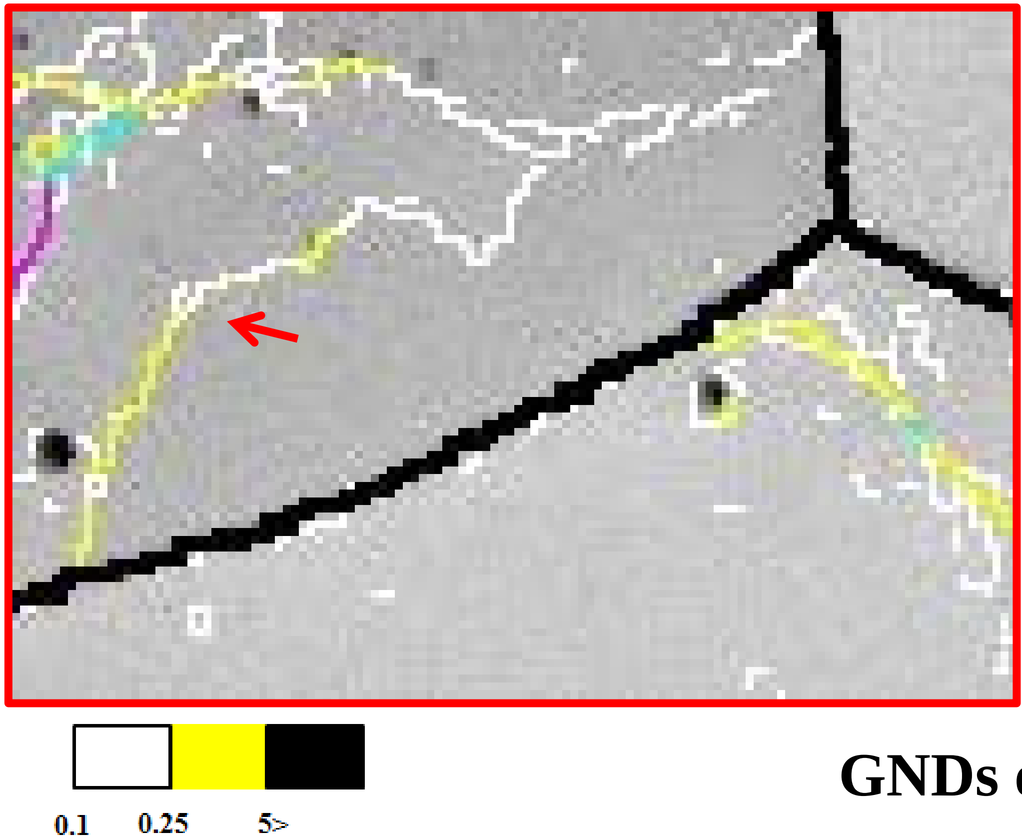
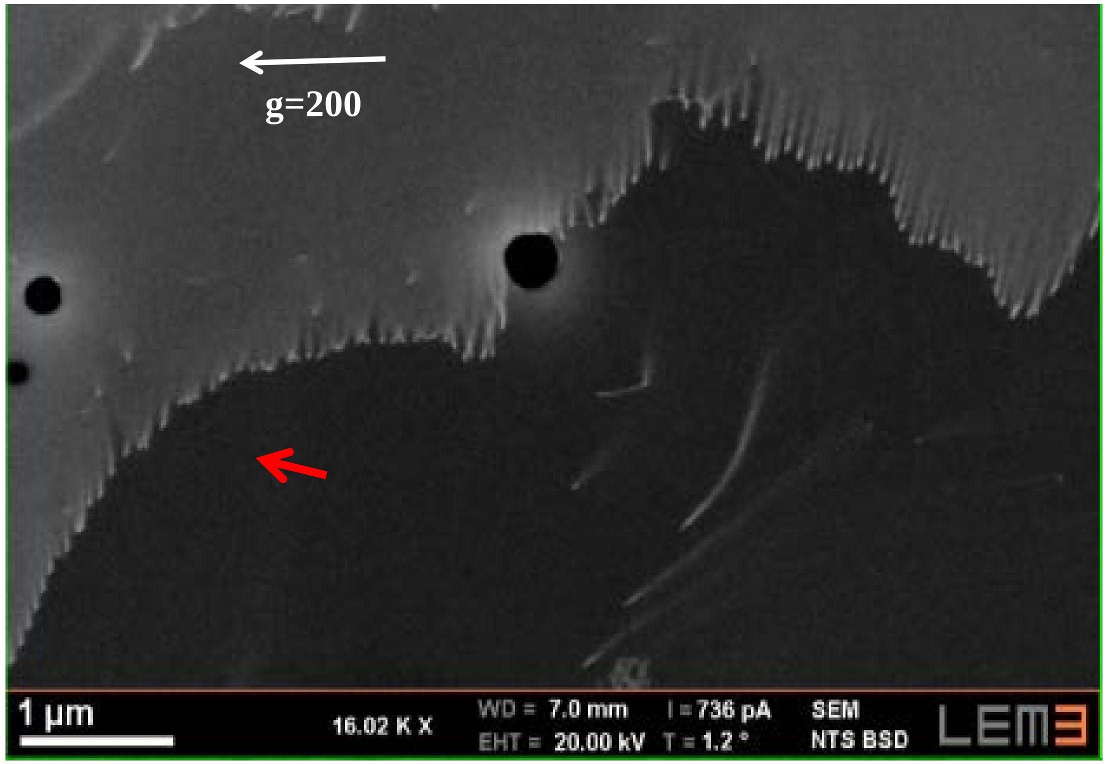
Sub-grain n°1

EBSD: GND evaluation from lattice curvature

ECCI: Dislocations arrangement in low angle boundaries





GNDs density

$\Delta\theta \in [0.1° \text{ to } 0.3°]$

$\rho_{EBSD} = k/b = 3*10^{13} \text{ to } 9*10^{13} m^{-2}$

$\rho_{ECCI} = 8*10^{13} m^{-2}$

RESULTS: SUB-BOUNDARIES ANALYSIS BY EBSD AND FURTHER BY ECCI

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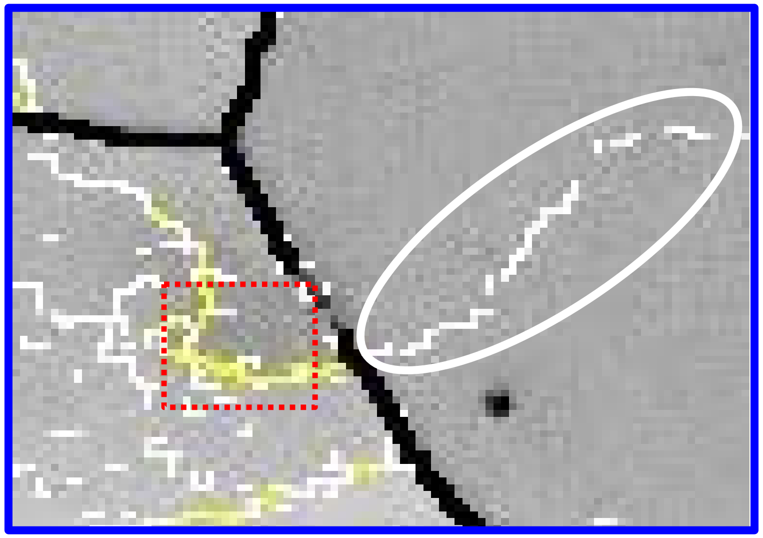
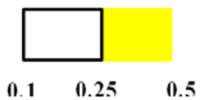
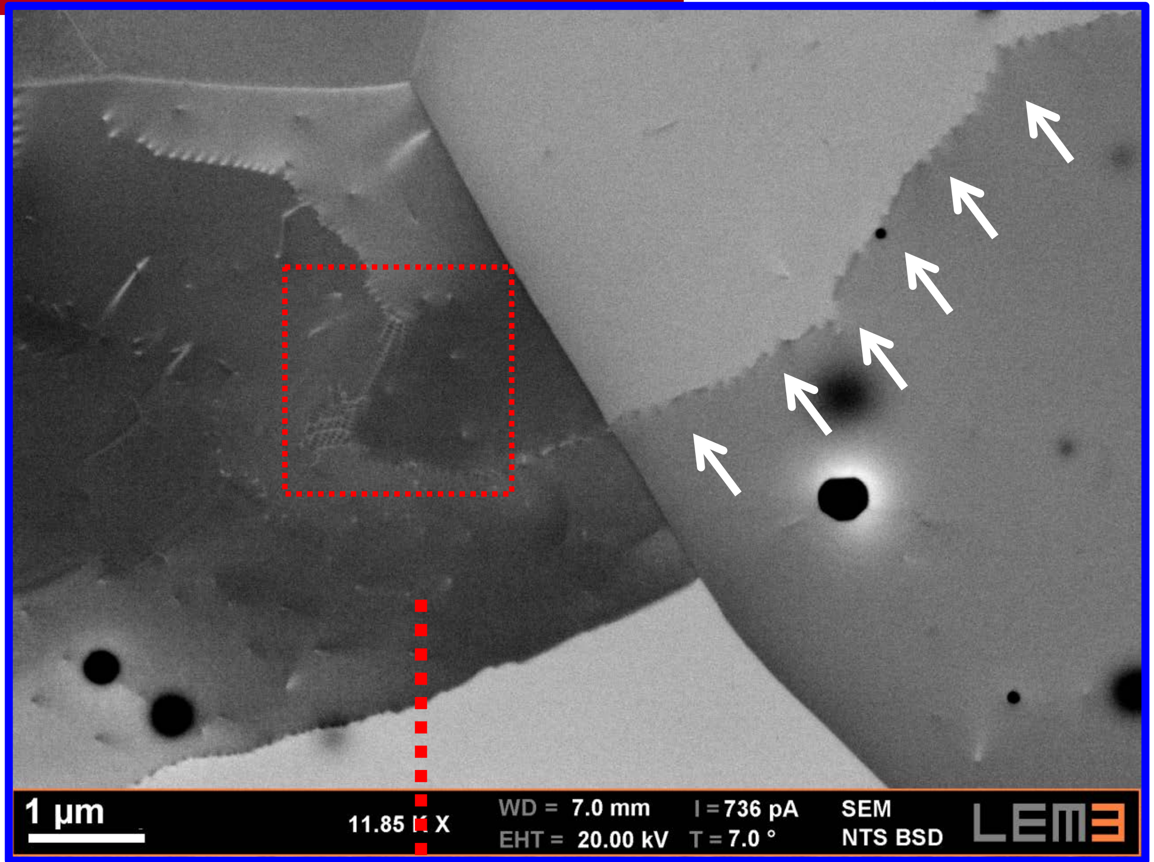
Sub-grain n°2:



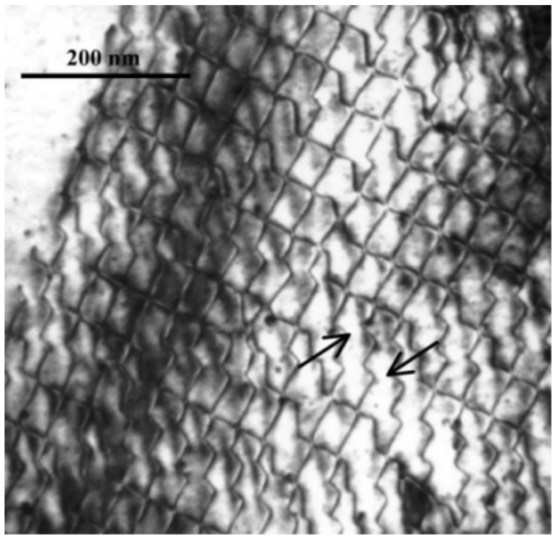
Misorientation angle ϴ color code



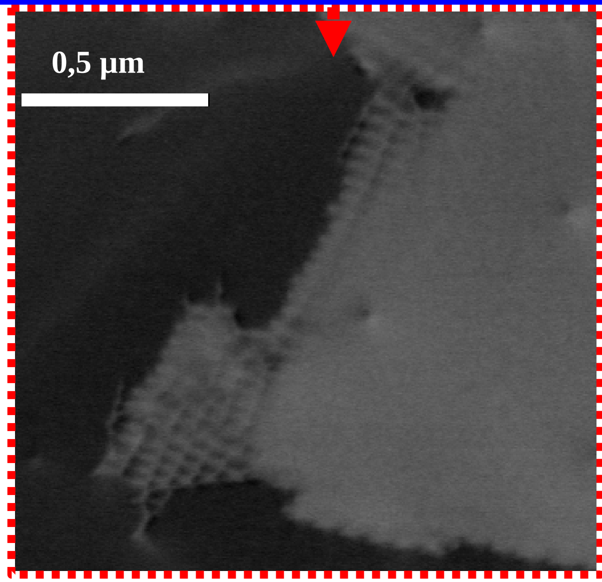
ECCI



Previous TEM result



F. Dherbey *et al. 2002*



Dislocation Network shown by ECCI

CONCLUSION: EBSD and ECCI are powerful tools to analyse creep damage in UO_2

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- EBSD: Quantification of low angle boundaries down to 0.1°,

  Their evolution with the creep deformation,

  Evaluation of the dislocation density

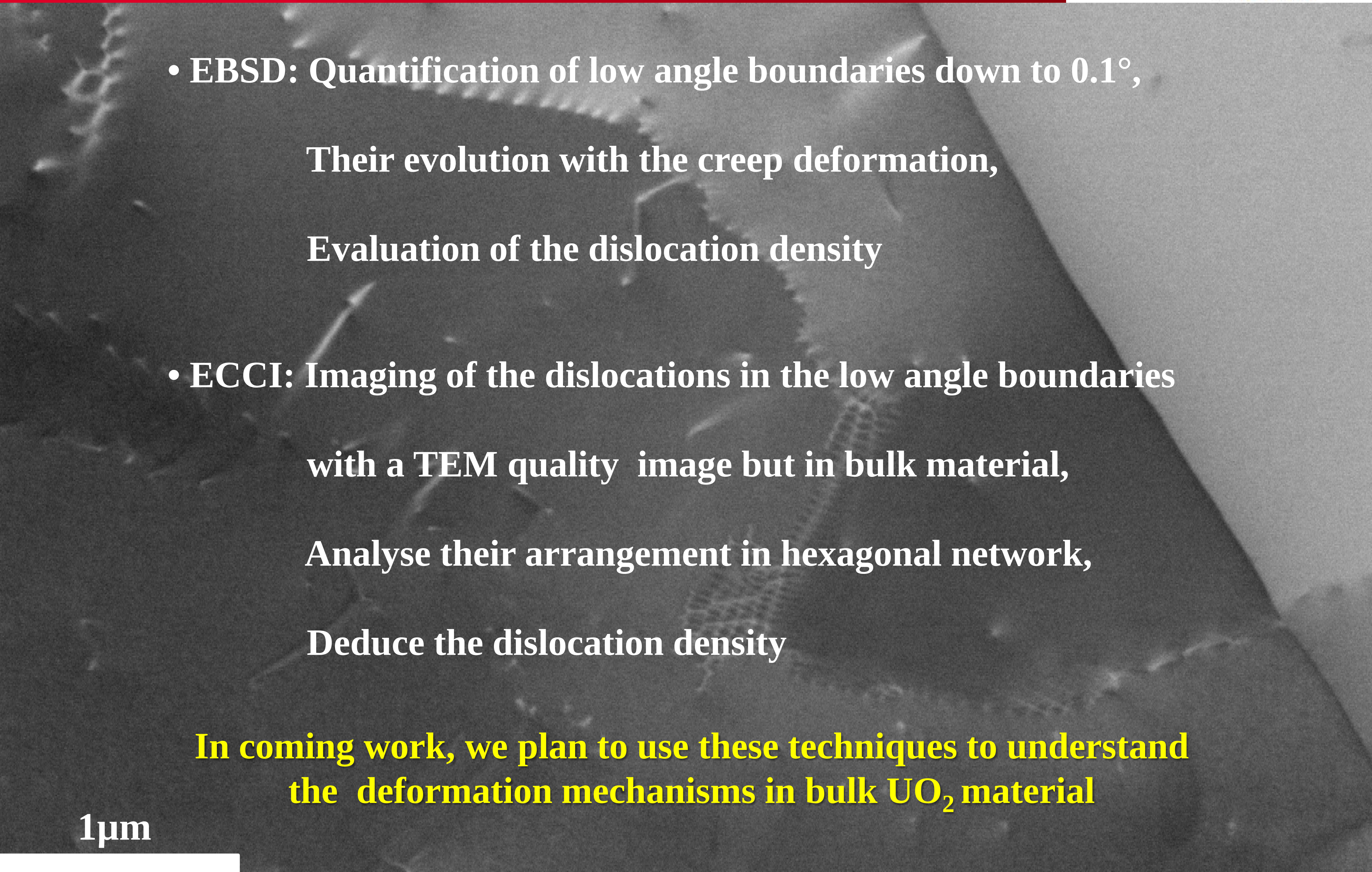
- ECCI: Imaging of the dislocations in the low angle boundaries

  with a TEM quality image but in bulk material,

  Analyse their arrangement in hexagonal network,

  Deduce the dislocation density

In coming work, we plan to use these techniques to understand the deformation mechanisms in bulk UO_2 material



Thank you for your attention

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[3]. H. MANSOUR, J. GUYON, M.A. CRIMP, N. GEY, B. BEAUSIR, N. MALOUFI, Accurate electron contrast analysis of dislocations in fine grained bulk materials, Scripta Materiala 84-85 (2014) pp. 11-14.

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