Neutron (and X-ray) imaging for coupled processes in porous media

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Laboratoire
Sols Solides Structures Risques

NEUTRONS
FOR SCIENCE

- *Relatively* new (2015) Neutron Tomograph
- Born from the collaboration between

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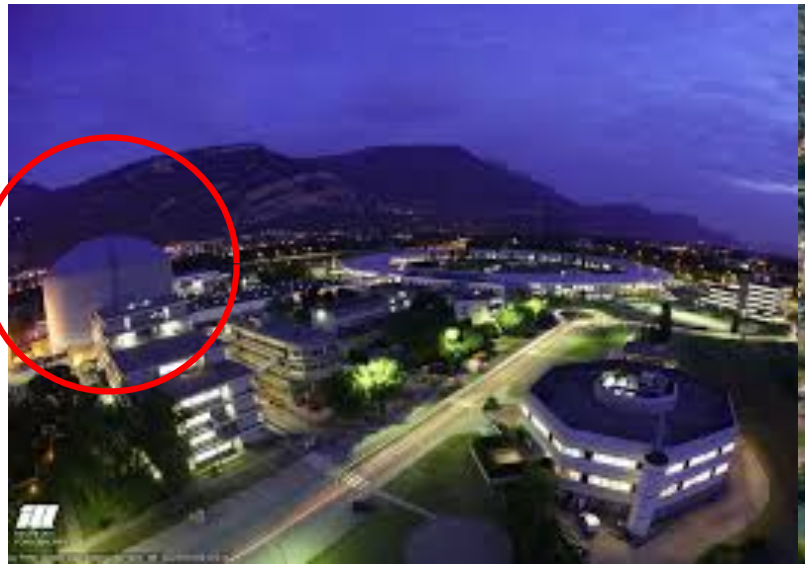

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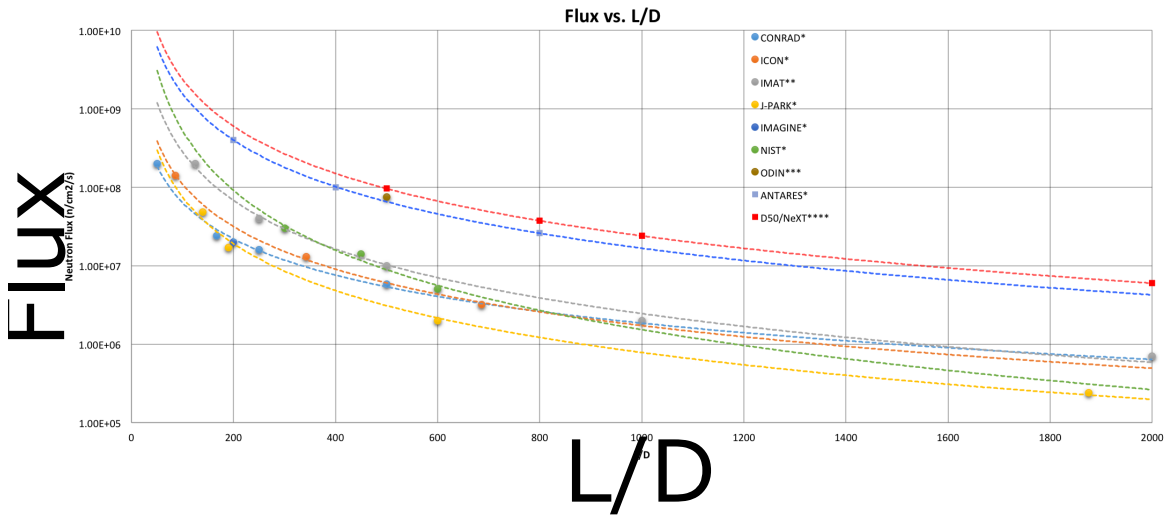

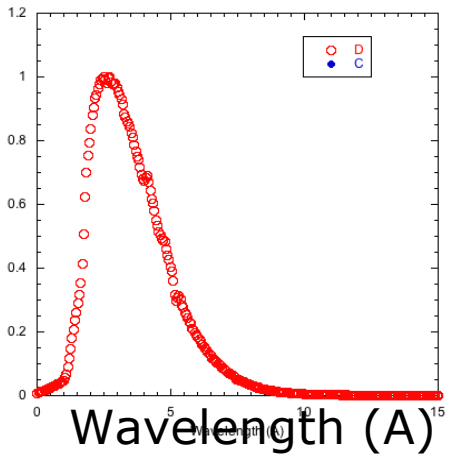

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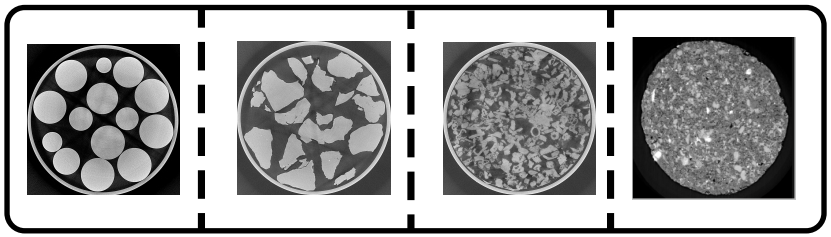
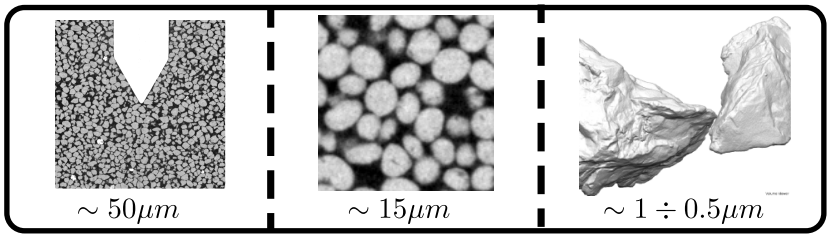
geometry

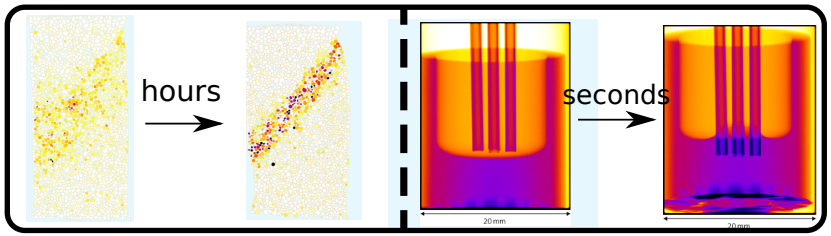


scale

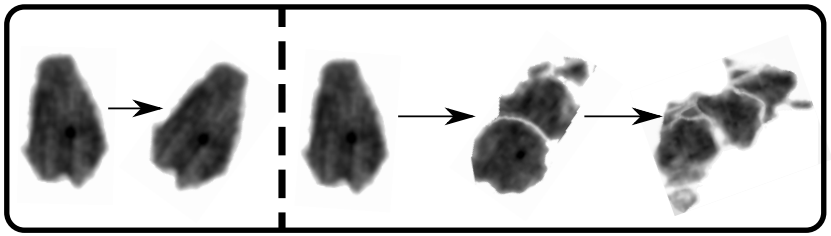


speed

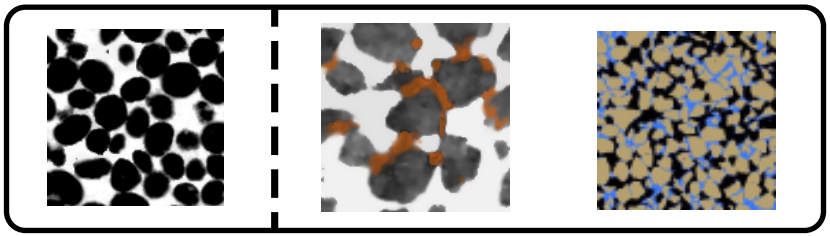
slow tomograph (at 3SR) ultrafast (ESRF)



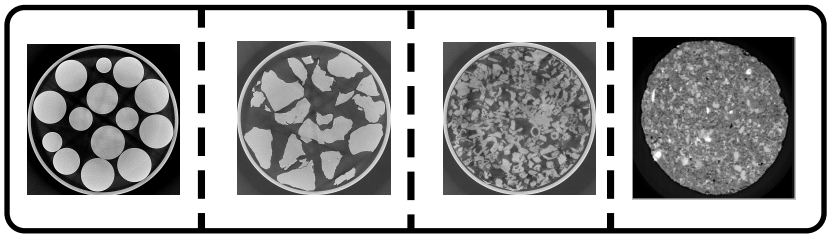
material persistance



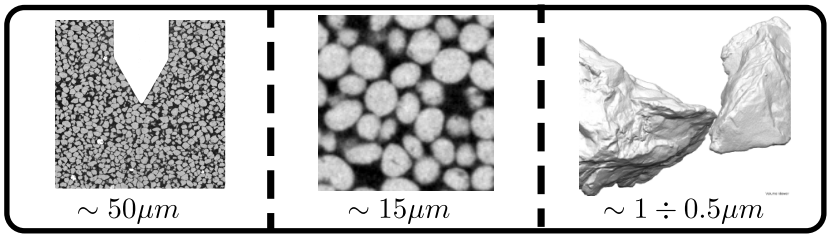
# of mechanically relevant phases



geometry



scale



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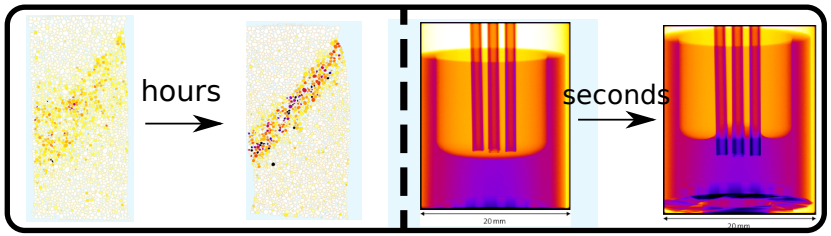
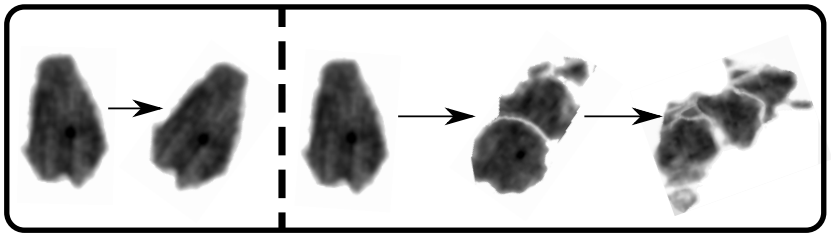


material persistance



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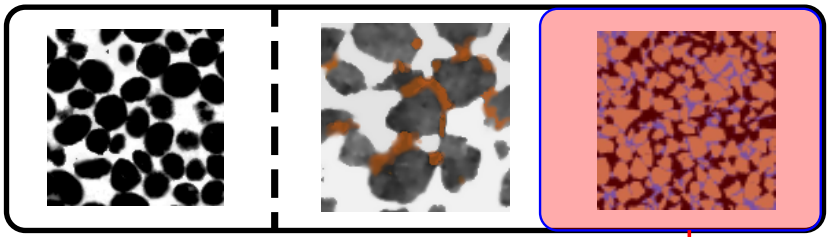
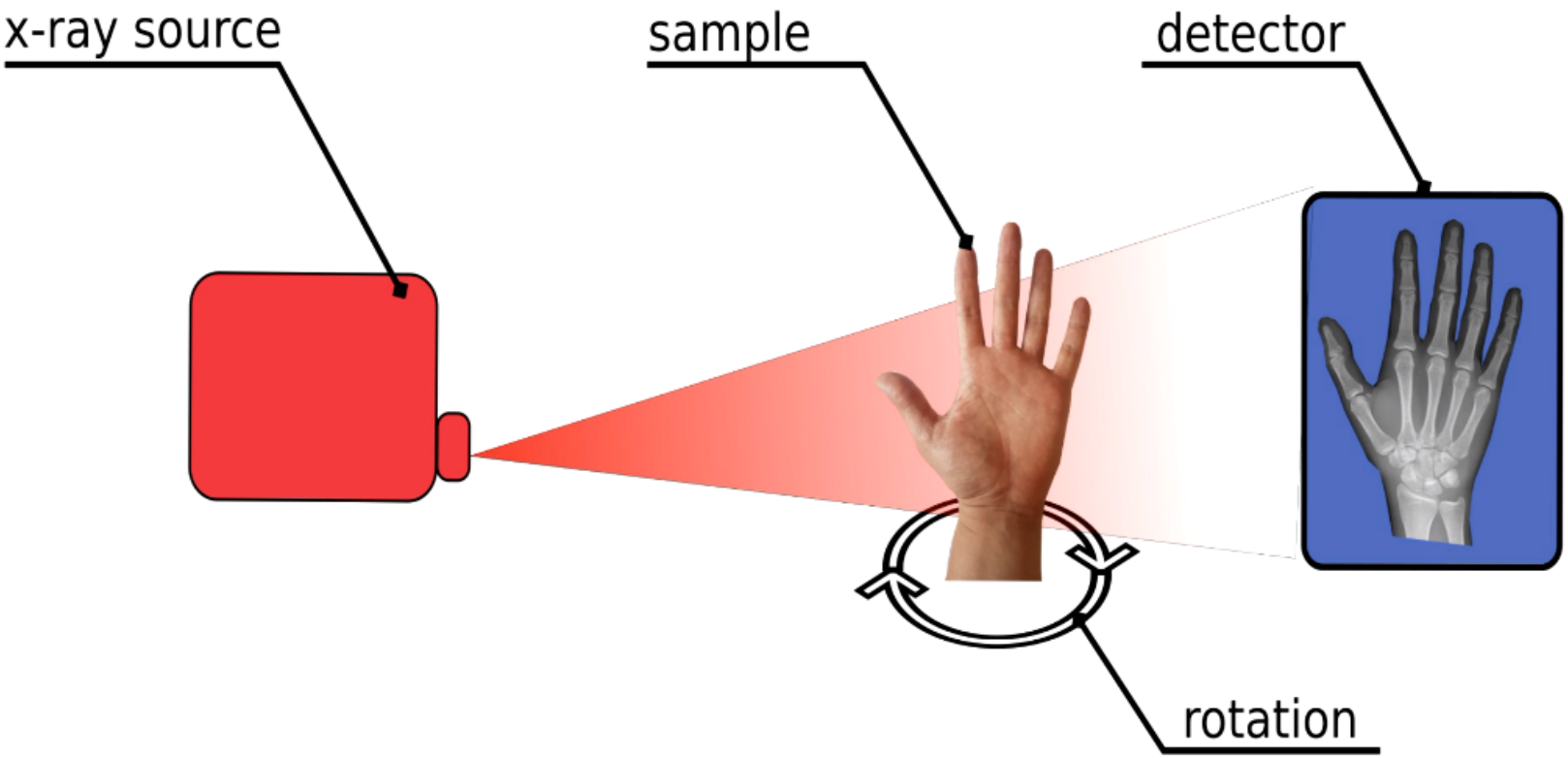
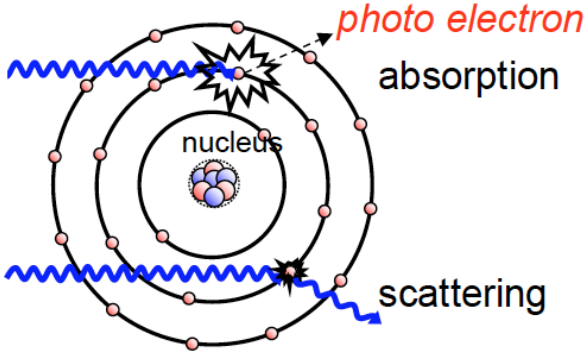


imaging fluids (e.g. hydrocabons)
in geomaterials


x-ray source
sample
detector
rotation

X-rays

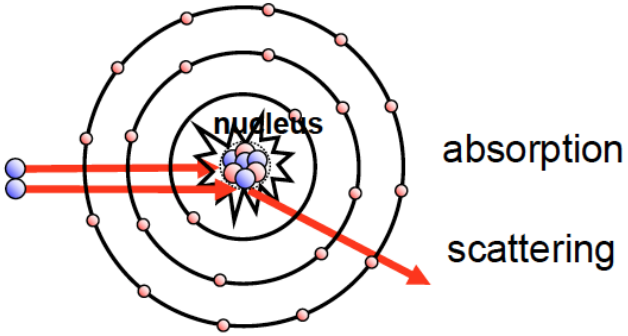


Attenuation coefficients with X-ray [cm²¹]

1a	2a	3b	4b	5b	6b	7b	8	1b	2b	3a	4a	5a	6a	7a	0
H 0.02															He 0.02
Li 0.06	Be 0.22									B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24									Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													

*Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
**Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray

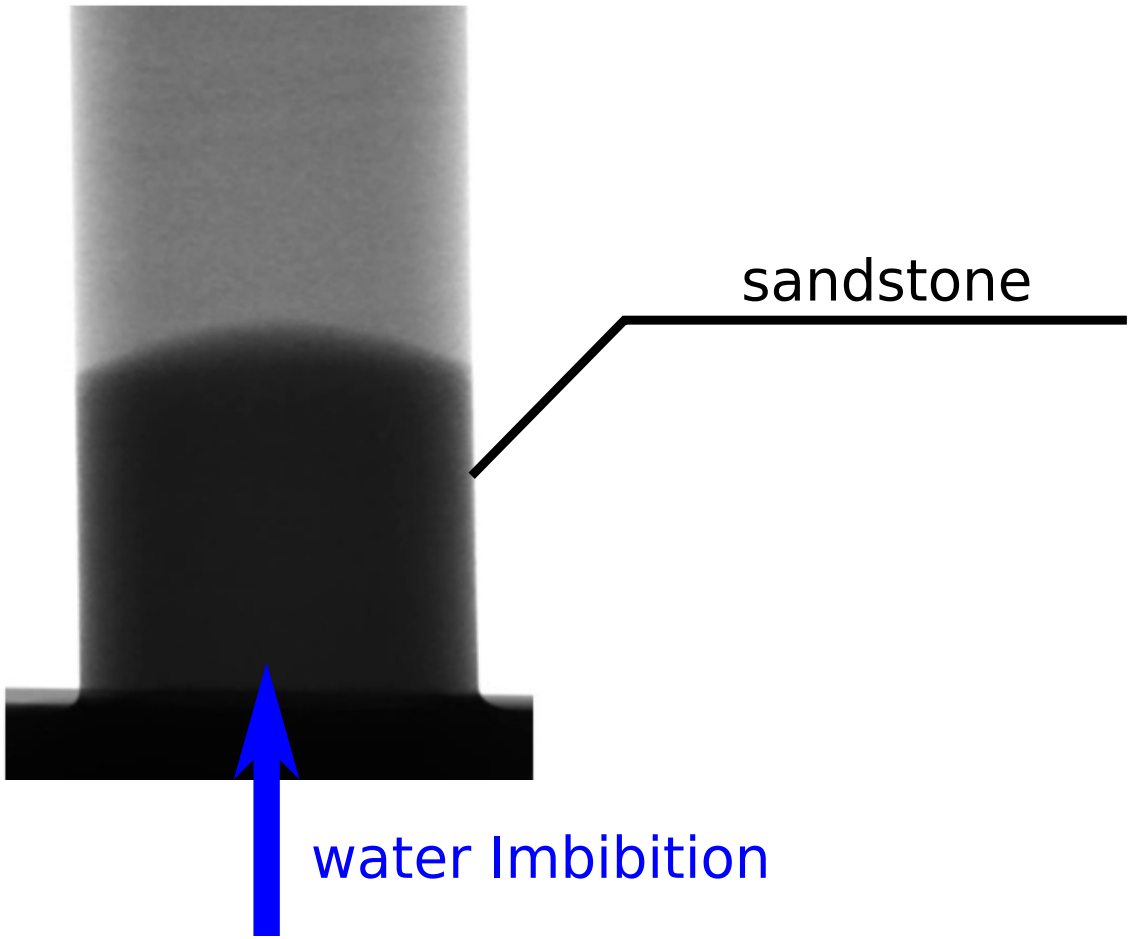
neutrons



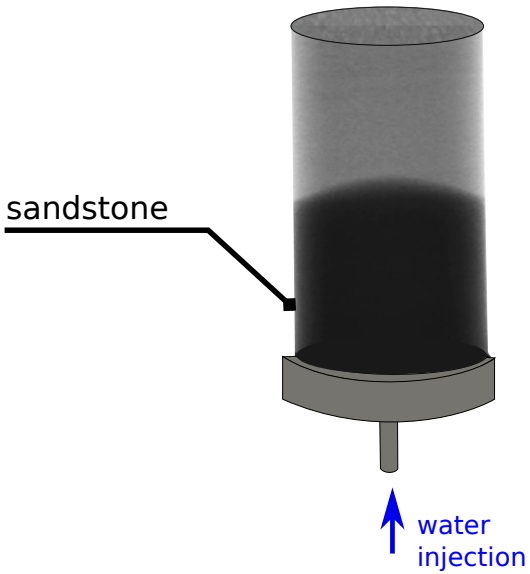
Attenuation coefficients with neutrons [cm²¹]

1a	2a	3b	4b	5b	6b	7b	8	1b	2b	3a	4a	5a	6a	7a	0
H 3.44															He 0.02
Li 3.30	Be 0.79									B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15									Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													

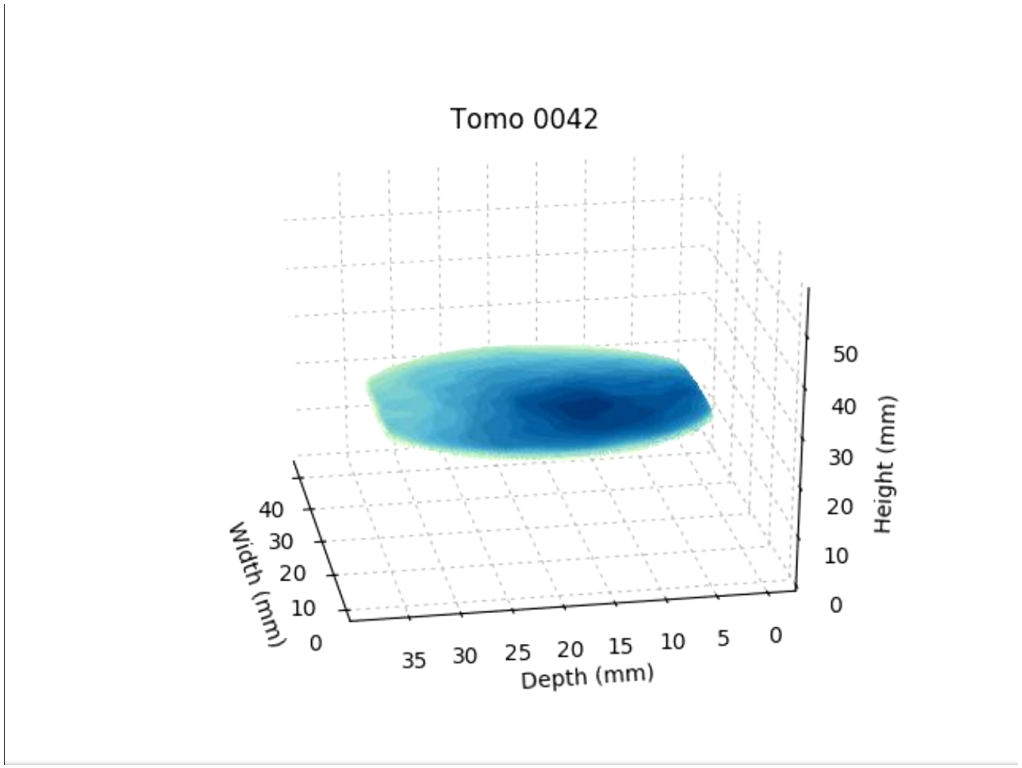
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.


sandstone
water Imbibition

Fluid flow within an intact rock

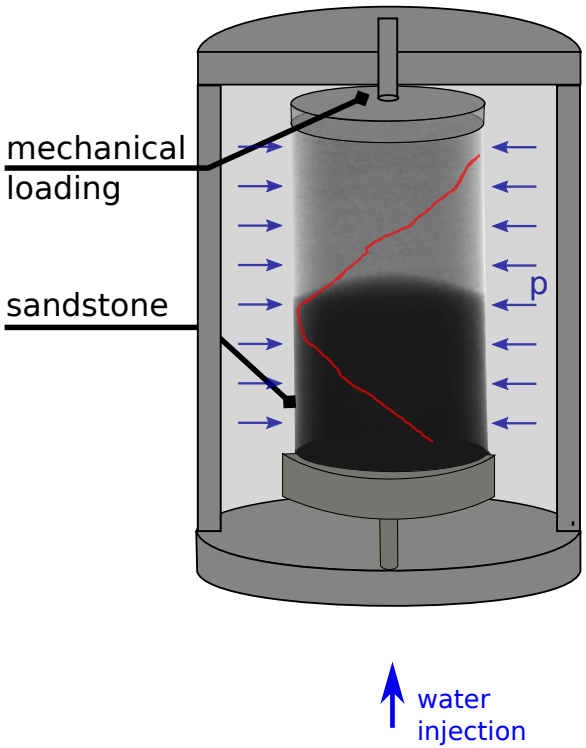


Quantification of front position, speed, permeability

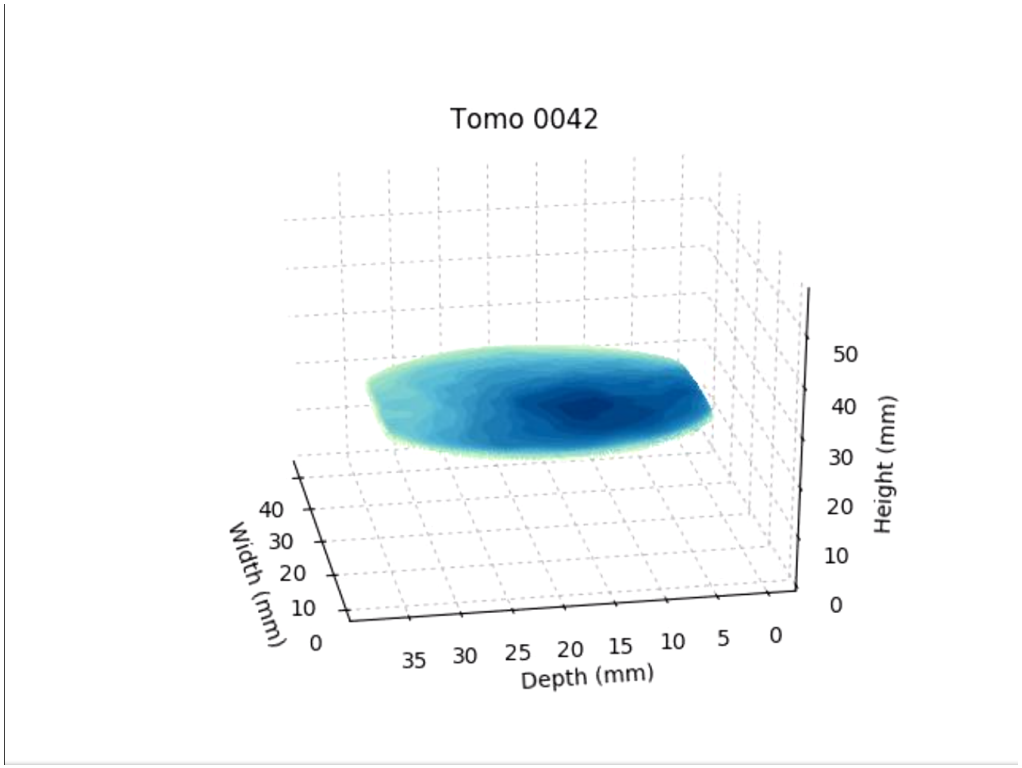


Tudisco, *et al.*, Journal of Geophysical Research: Solid Earth (2019)
Extegarai, *et al.*, Journal of Imaging (2021)
Viera-Lima, *et al.*, submitted (2023)

Fluid flow within a damaged rock



Quantification of front position, speed, permeability



Tudisco, *et al.*, Journal of Geophysical Research: Solid Earth (2019)
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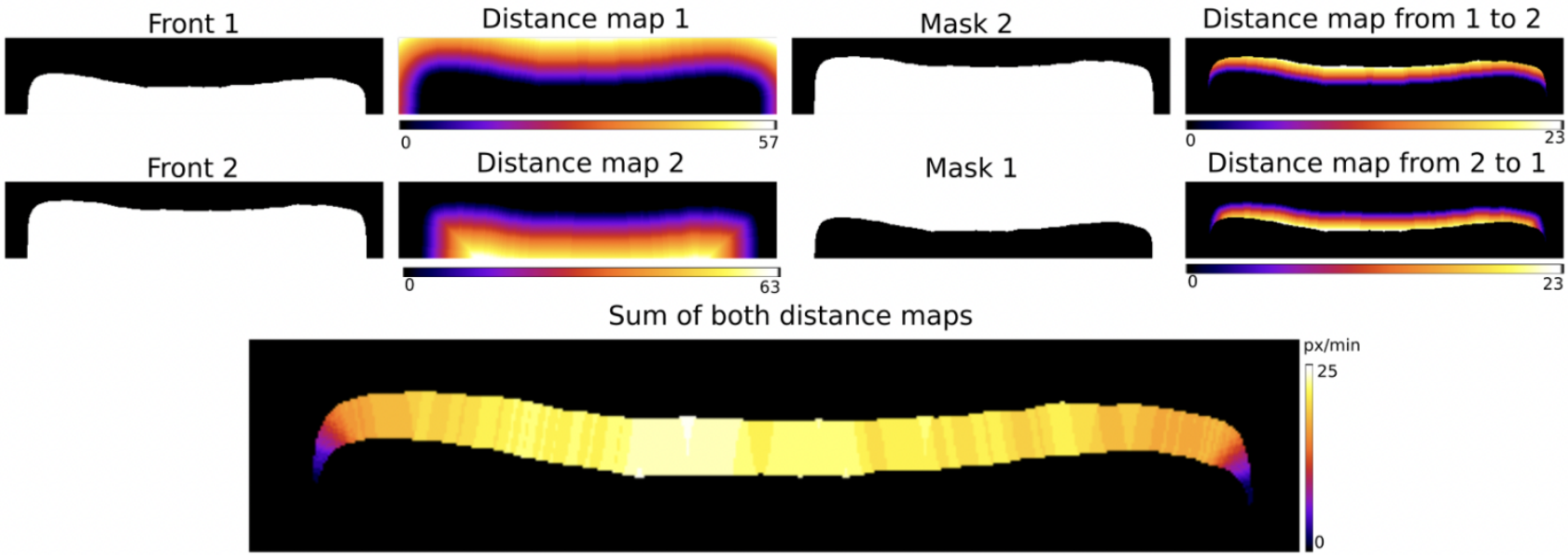
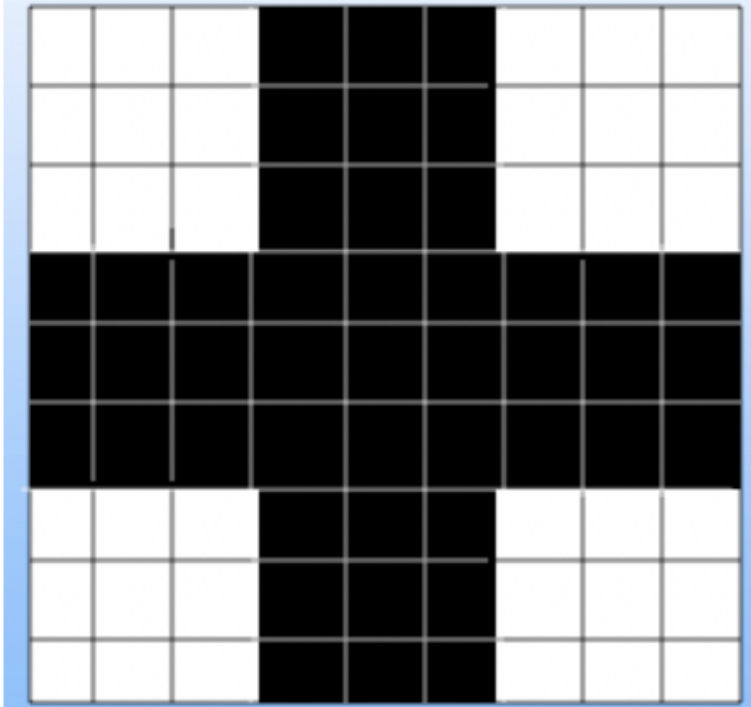
An example of "Bespoke analysis"– speed maps



A "go-to keystone Tool" Digital Volume Correlation (*e.g.*, SPAM)



100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

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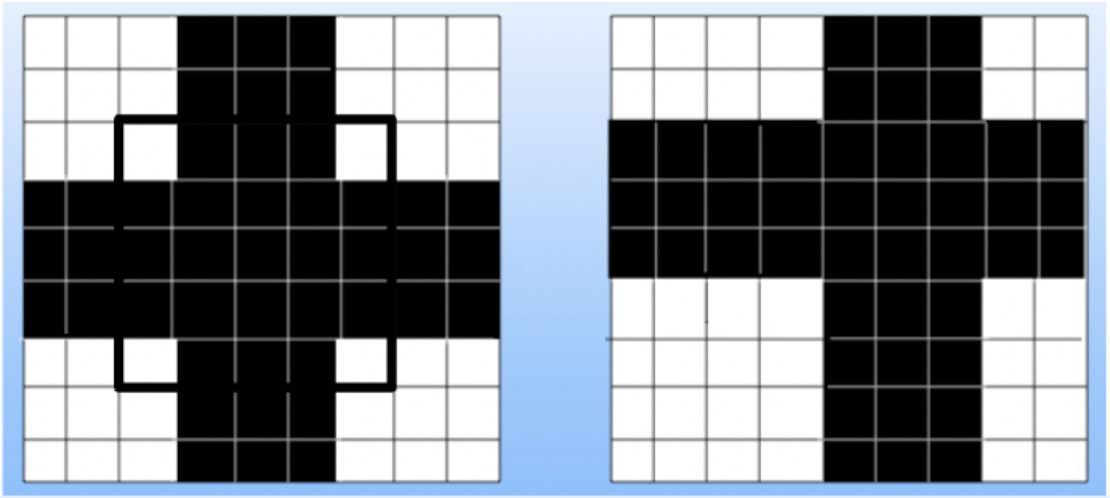

100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
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0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

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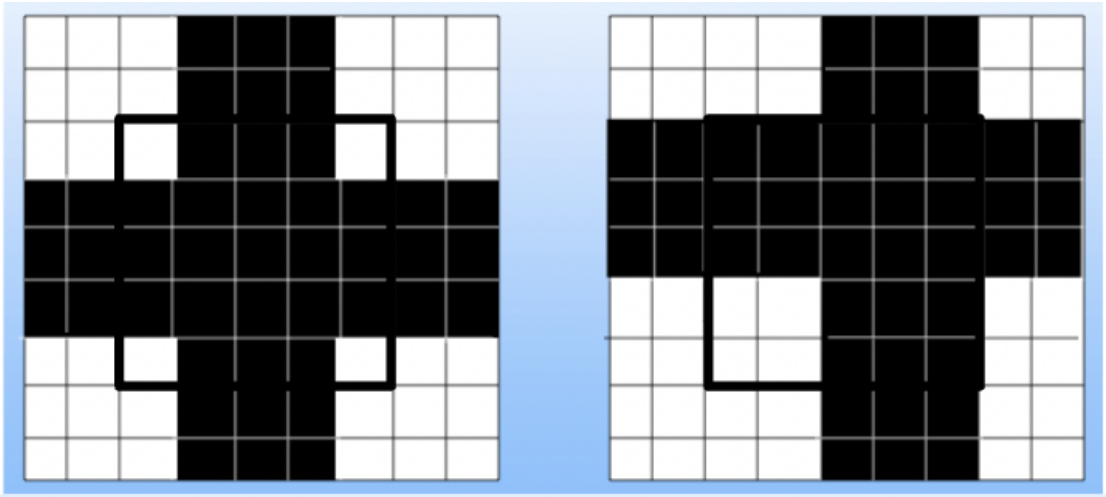

100	100	100	0	0	0	100	100	100
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100	100	100	0	0	0	100	100	100
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0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

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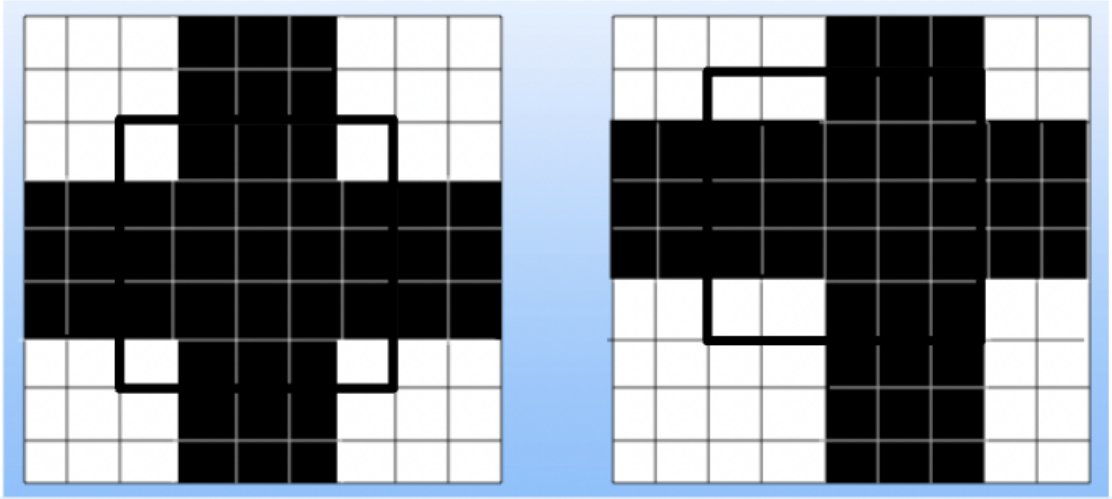

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100	100	100	0	0	0	100	100	100
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0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
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0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

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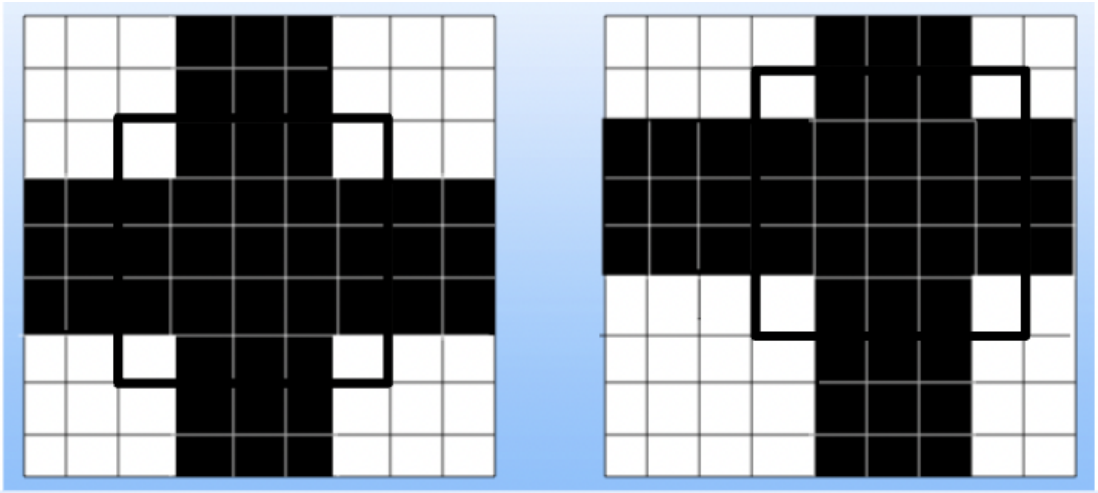

100	100	100	0	0	0	100	100	100
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100	100	100	0	0	0	100	100	100
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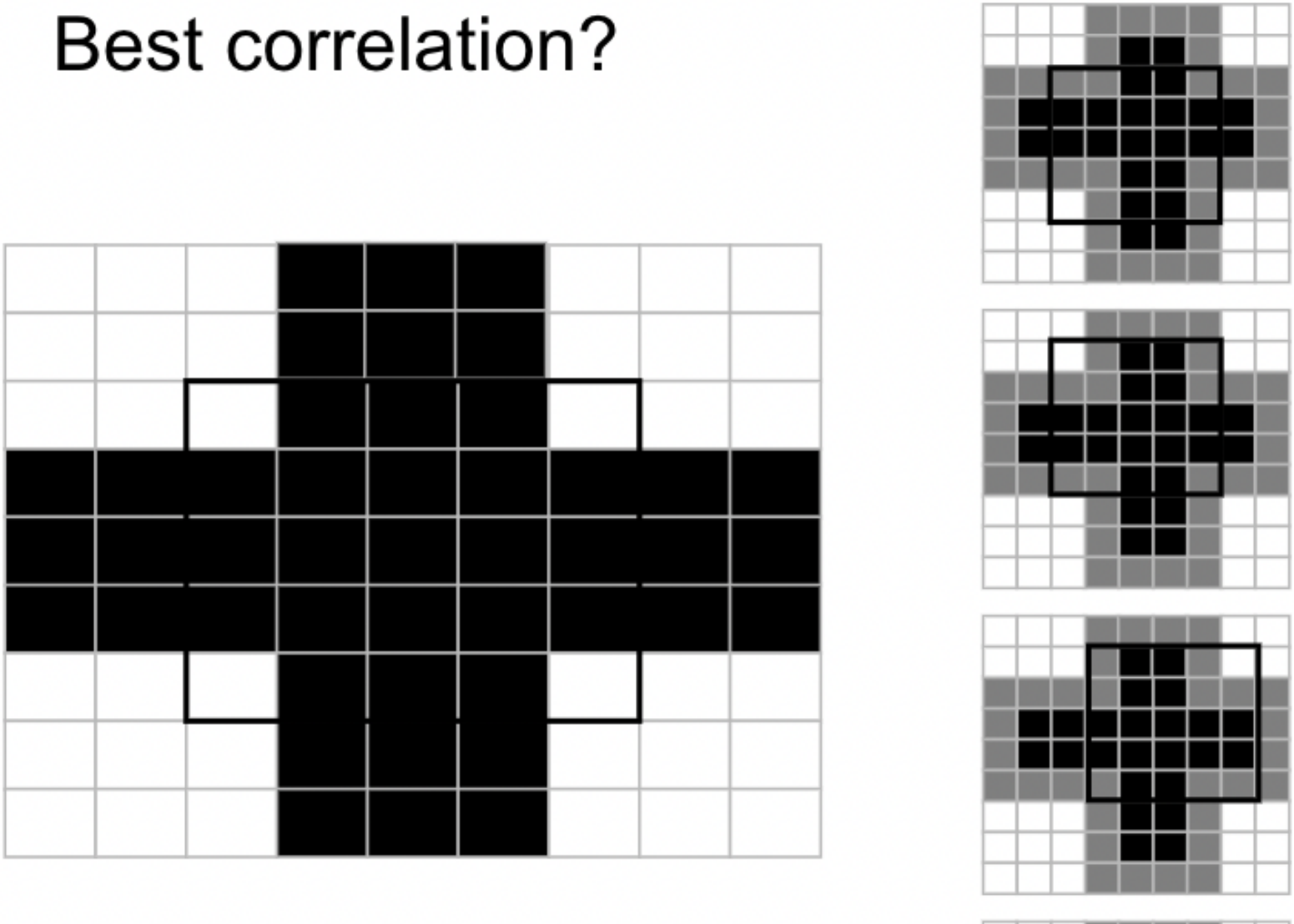
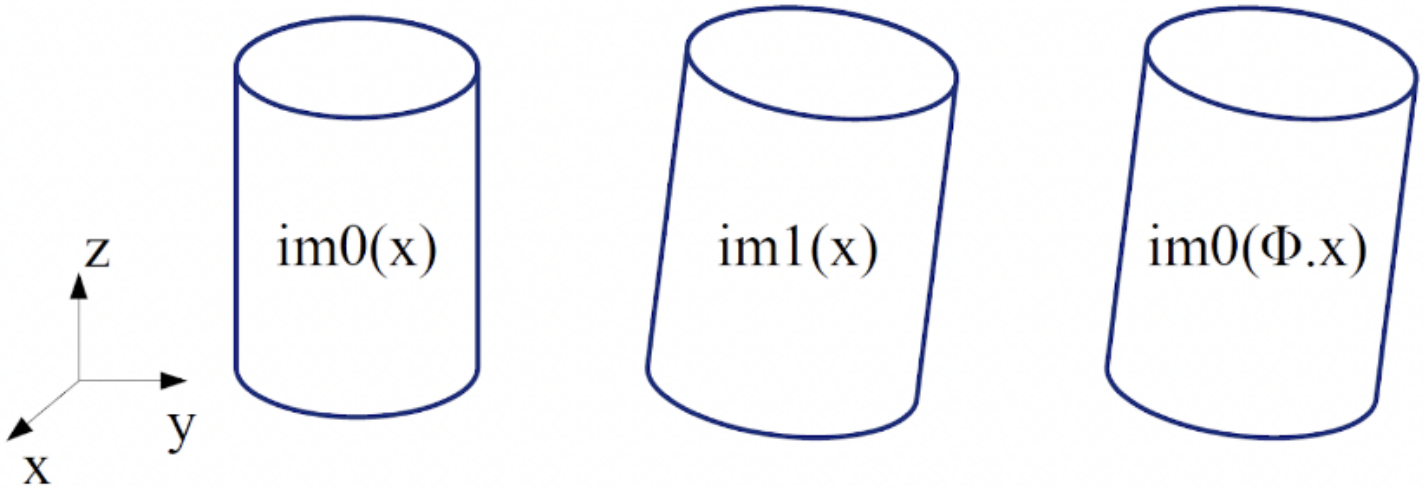
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

A "go-to keystone Tool" Digital Volume Correlation (*e.g.*, SPAM)



A "go-to keystone Tool" Digital Volume Correlation (*e.g.*, SPAM)



Transformation Gradient Tensor

Displacement

$$im0(\Phi.x) = im1(x) \qquad \Phi = \begin{bmatrix} F_{zz} & F_{zy} & F_{zx} & t_z \\ F_{yz} & F_{yy} & F_{yx} & t_y \\ F_{xz} & F_{xy} & F_{xx} & t_x \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

A "go-to keystone Tool" Digital Volume Correlation (*e.g.*, SPAM)

Error function:

$$\tau(\Phi) = \frac{1}{2} \sum_{x \in ROI} (im0(x) - im1(\Phi x))^2$$

Minimisation problem:

$$\nabla \tau(\Phi) = 0$$

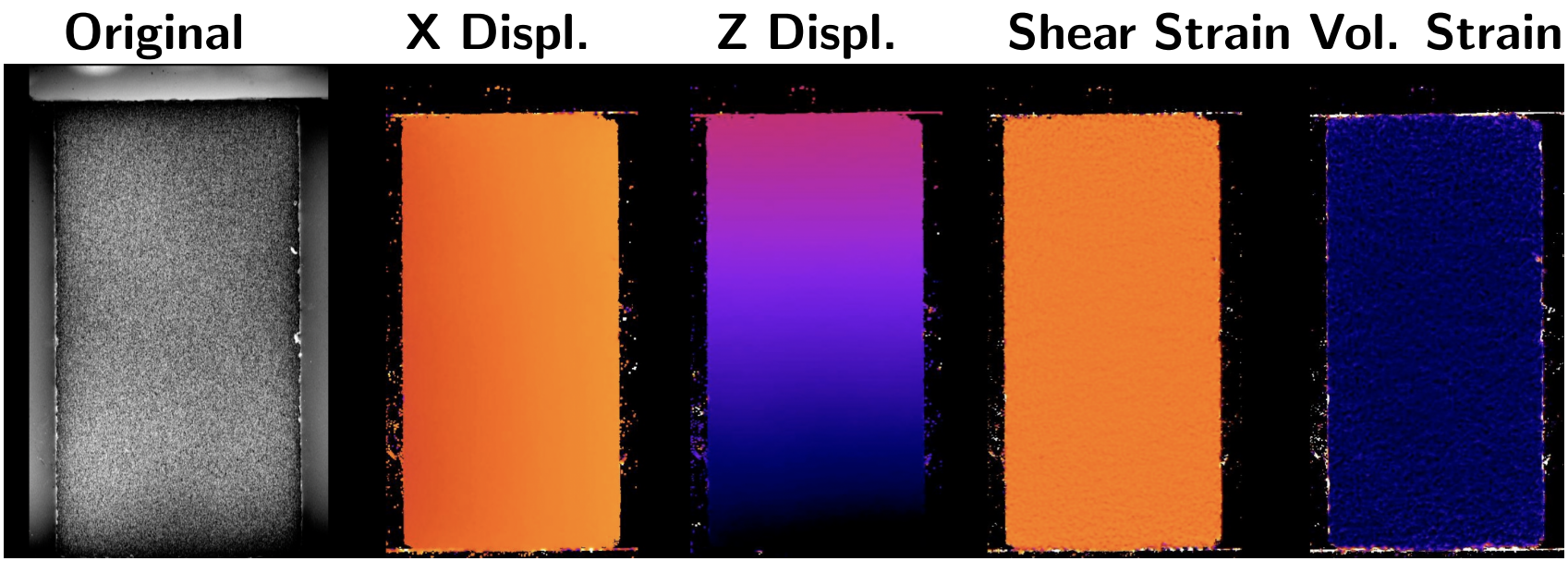
Newton's method:

$$\nabla \tau(\Phi^n) + \nabla^2 \tau(\Phi^n) : \delta\Phi^{n+1} = 0$$

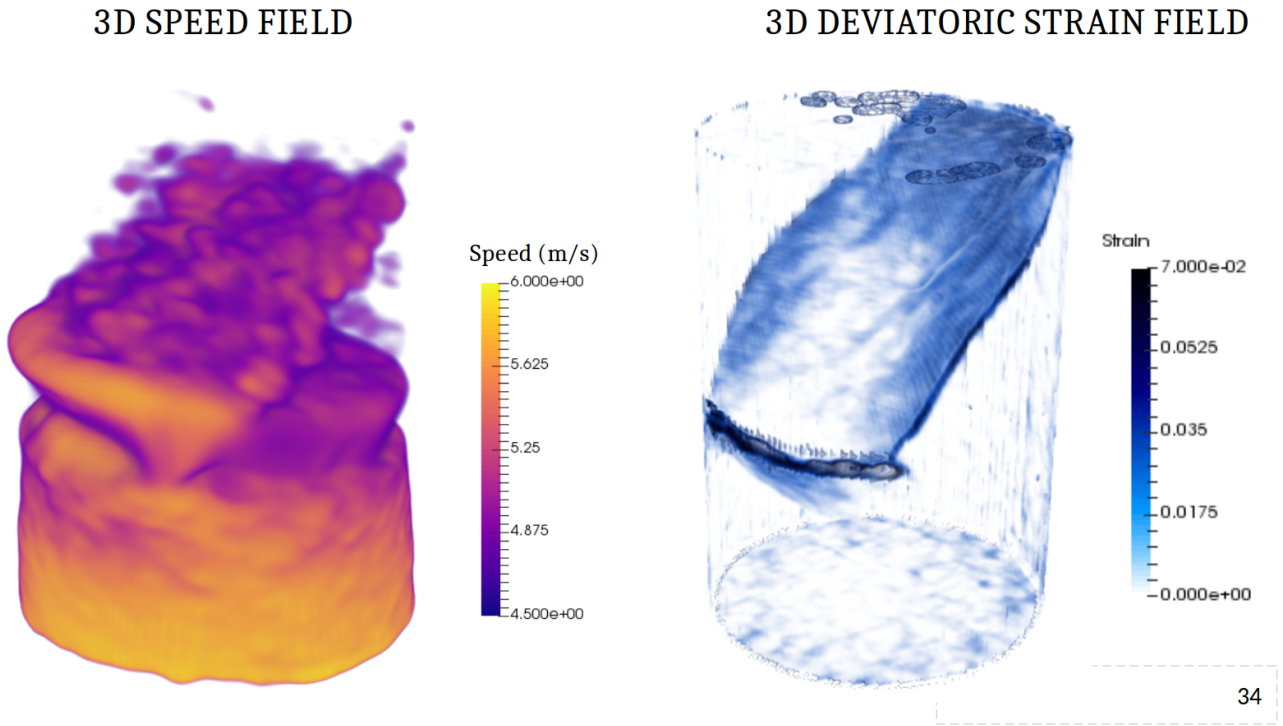
Implementation [*]:

$$\delta\Phi^{n+1} = (M^n)^{-1} A^n$$

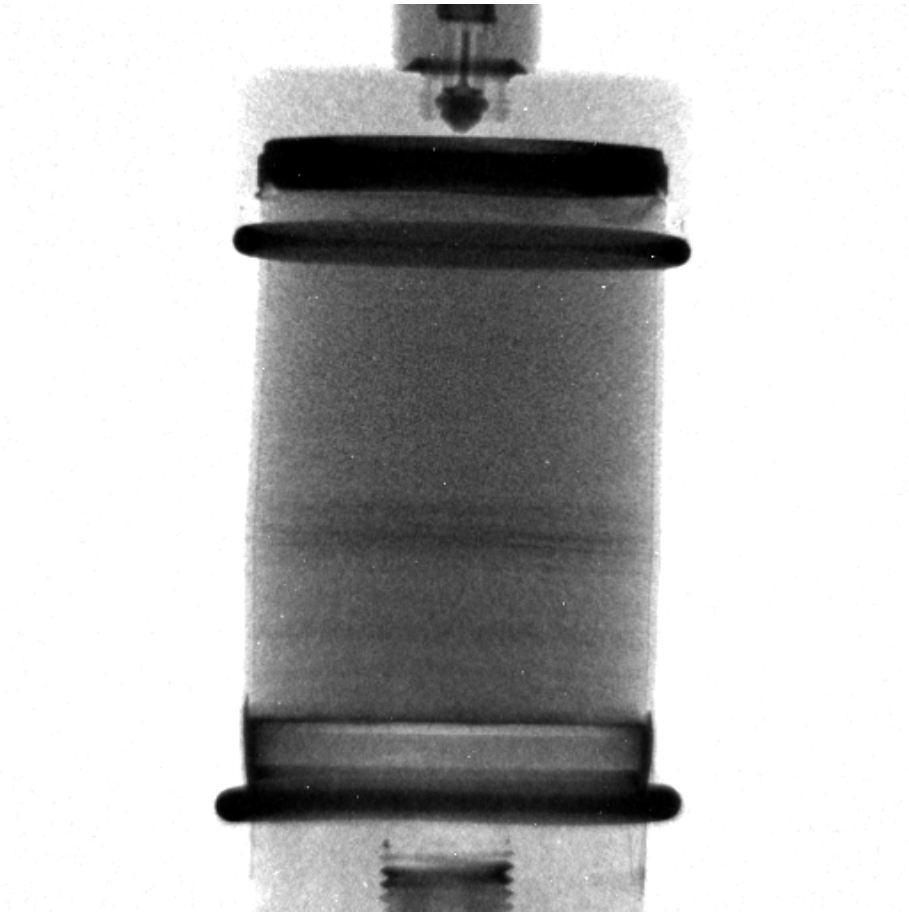
A "go-to keystone Tool" Digital Volume Correlation (*e.g.*, SPAM)



Quantification of incremental strain through Digital Volume correlation of the map of fluid Speed

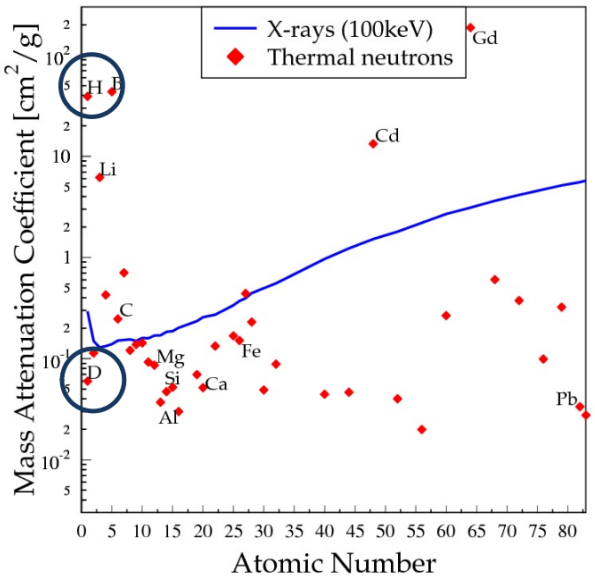


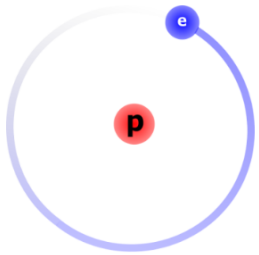
How about more complex geometries?



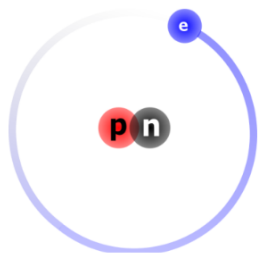
Lewis *et al.*, EGU (2017)
Lewis *et al.*, Transport in Porous Media (2023)

Neutron are isotope sensitive, "**normal water**" and **heavy water** have an order of magnitude difference in opacity
Can be used to **track fluid in an already saturated sample**



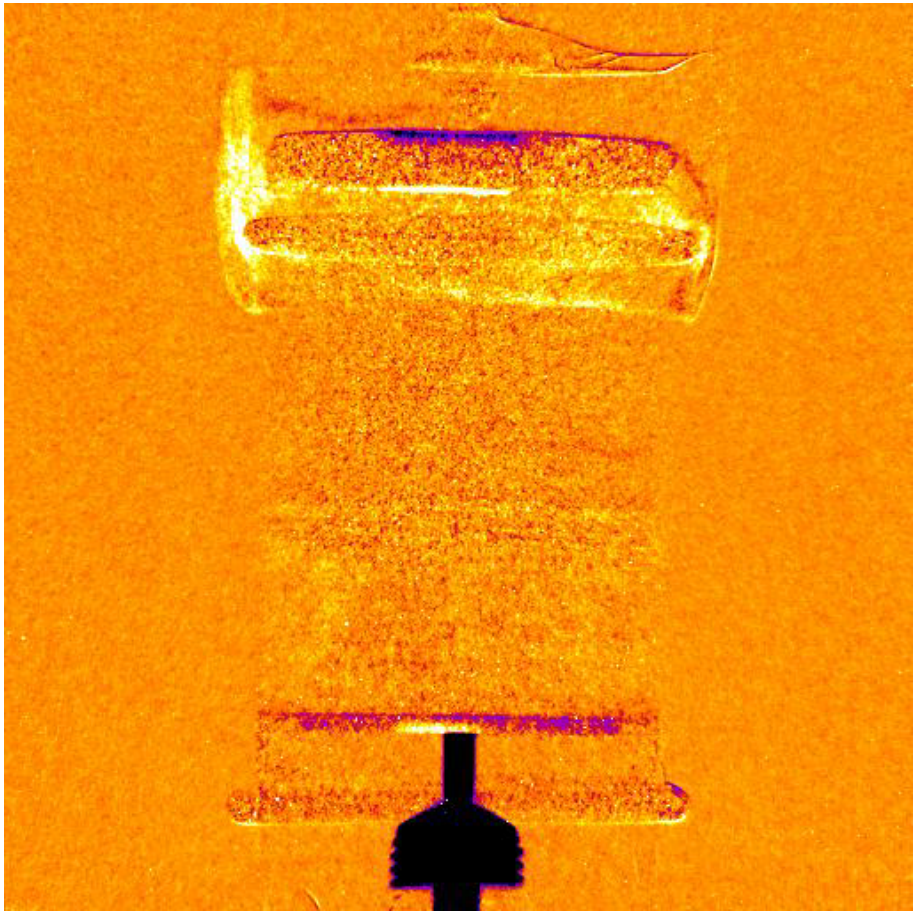


$^{1}_{1}H$
Hydrogen



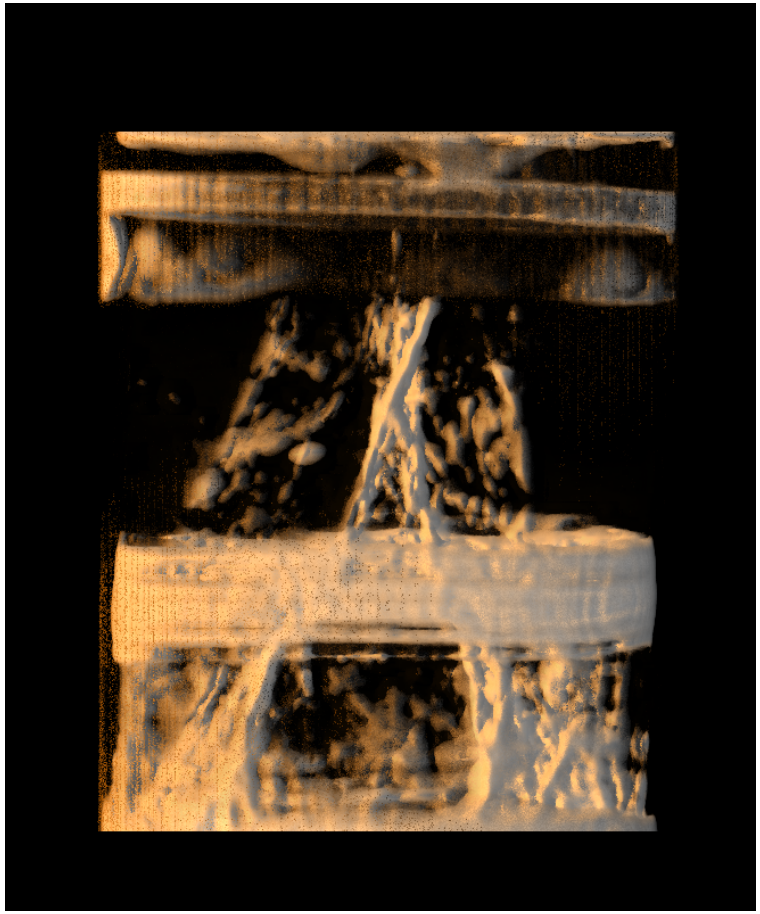
$^{2}_{1}H$
Deuterium

Injection in D20-saturated sample



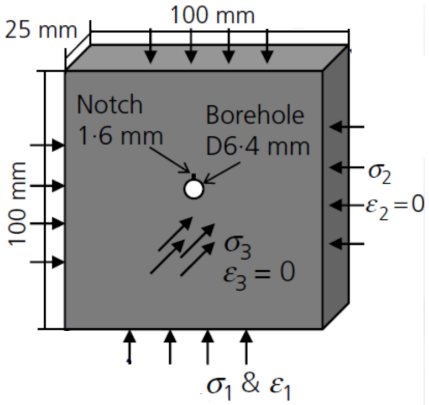
Lewis *et al.*, EGU (2017)
Lewis *et al.*, Transport in Porous Media (2023)

and in 3D?



Lewis *et al.*, EGU (2017)
Lewis *et al.*, Transport in Porous Media (2023)

Hydrofracking of rocks

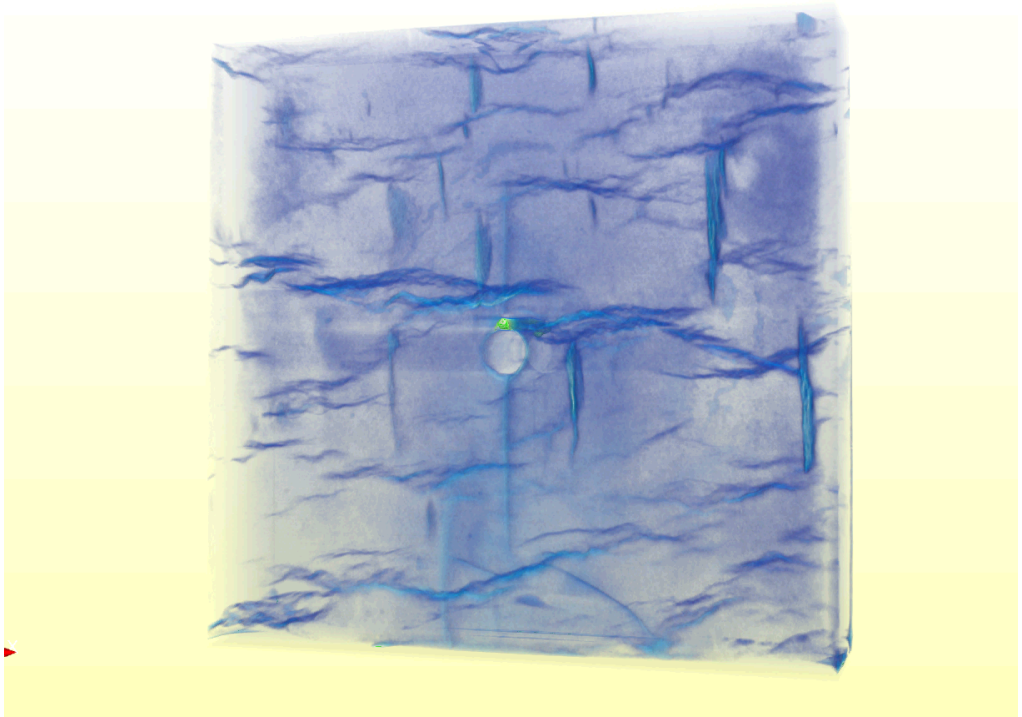


Marcellus shale

$\sigma_1 = 70$ MPa

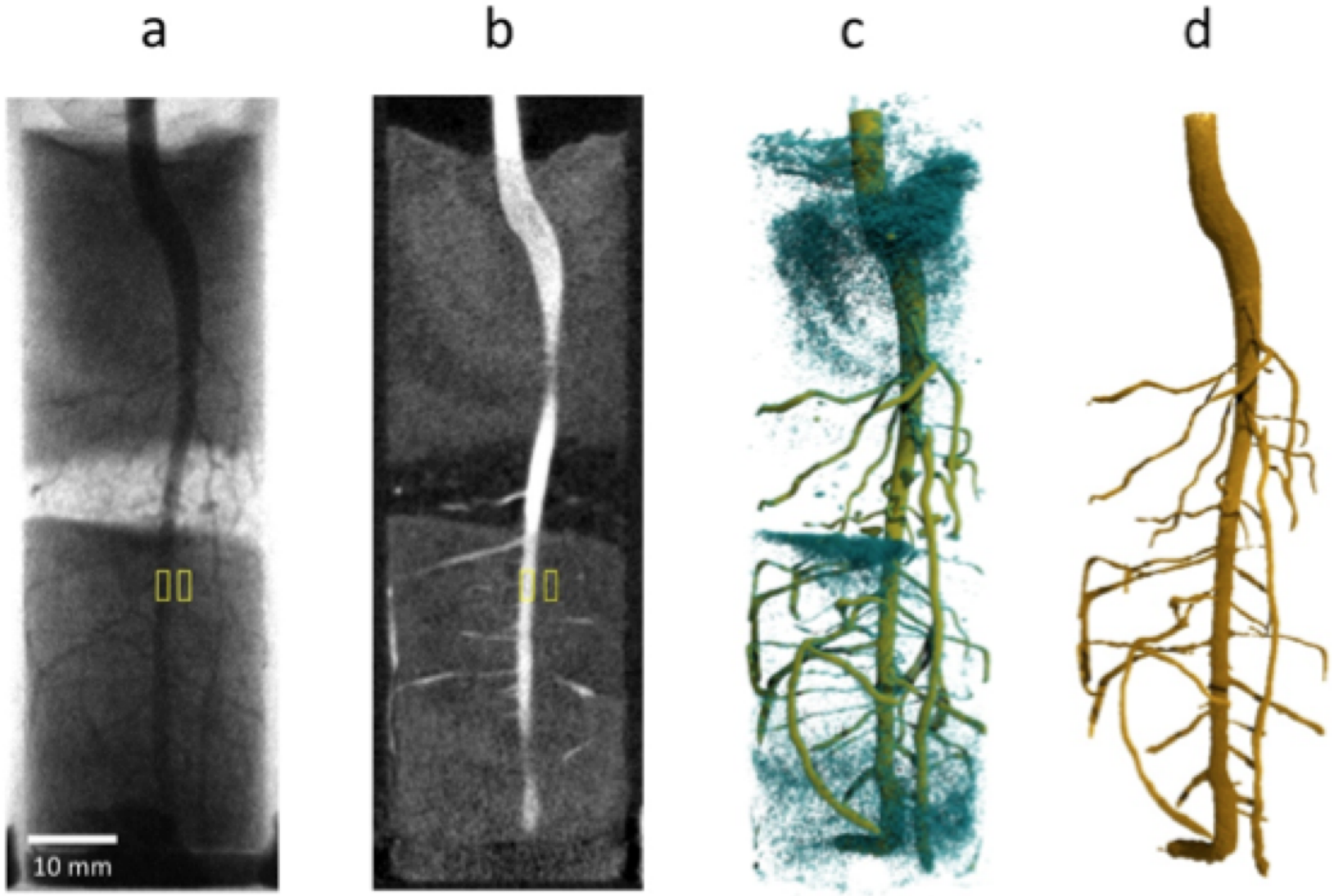
Flow rate /6/12 ml/min

Quantification of front position, speed, permeability



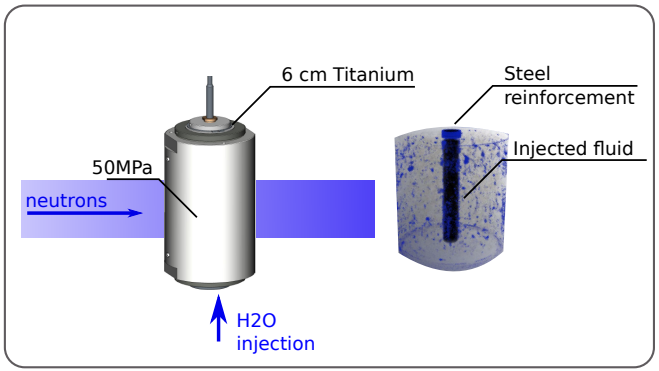
Roshankhah, *et al.*, Géotechnique letters (2018)
Roshankhah, *et al.*, USRMS (2019)

Other applications

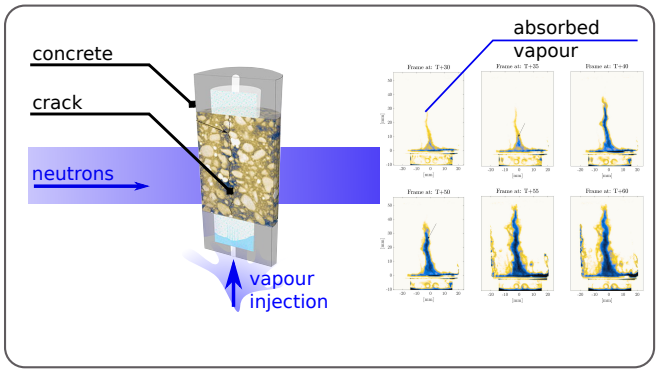


Other applications

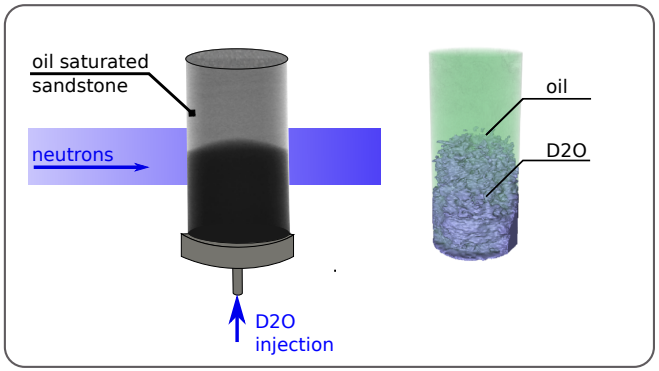
Neutrons can penetrate through thick enviromental cells [1]



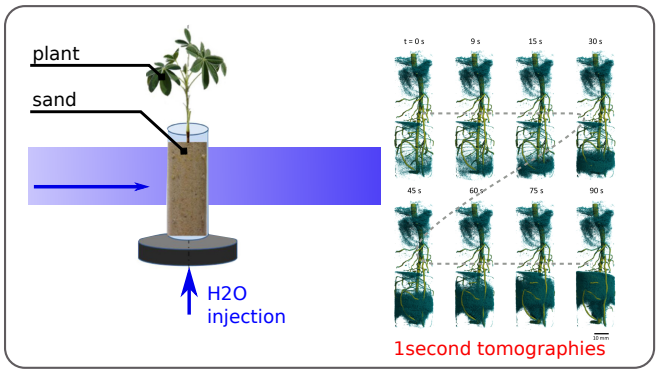
Neutrons can help track even vapour low into fractures [2]



Neutrons can help track flow into immiscible fluids (e.g., oil) [3]

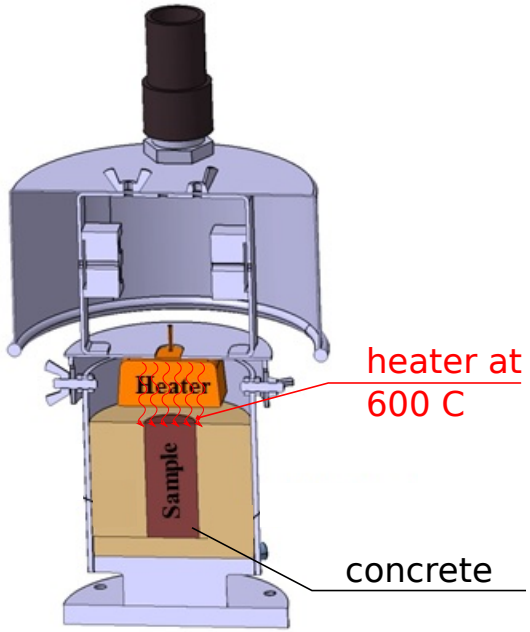


Neutrons tomographies can be acquired as fast as 1s per tomography [4]



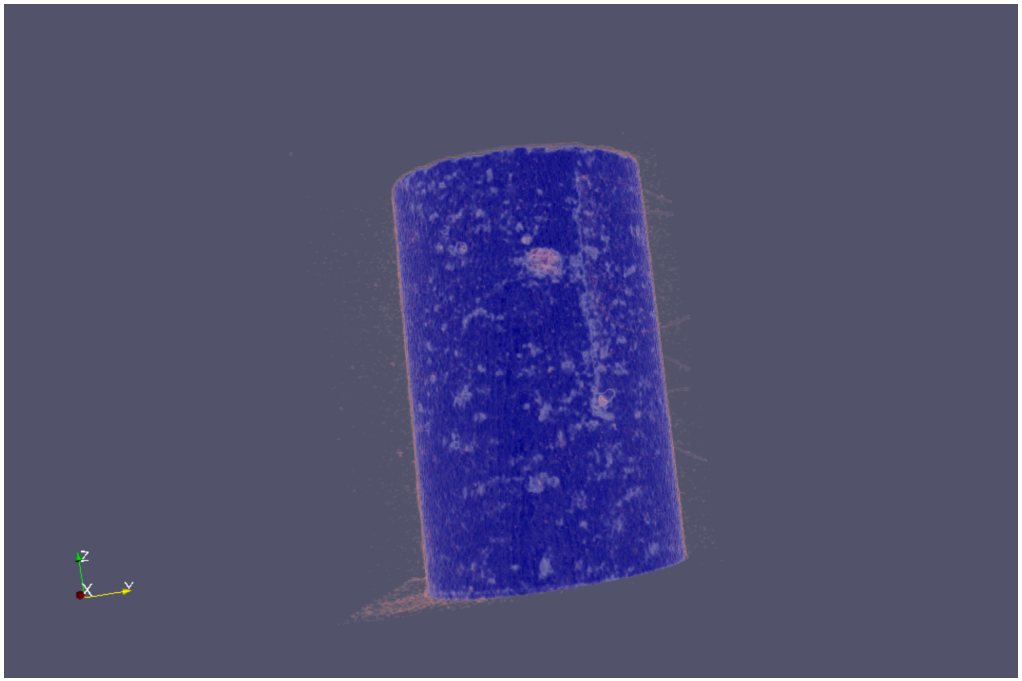
[1] Yehya *et Al,*. Nucl. Inst. Met. Phys. Res. A (2018)
[2] Lukich *et al.*, Mat. Letters (2021)
[3] Madankan *et al.*, Ready for submission (2021)
[4] Totzke *et al.*, Optics Express (2019)

Heating construction materials to fire-like conditions



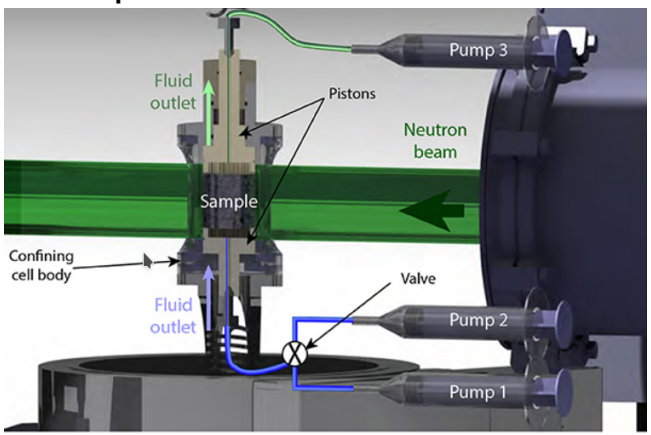
Understanding of explosive spalling for fire safety of buildings

Quantification of moisture migration, accumulation for different materials, 20 second tomographies



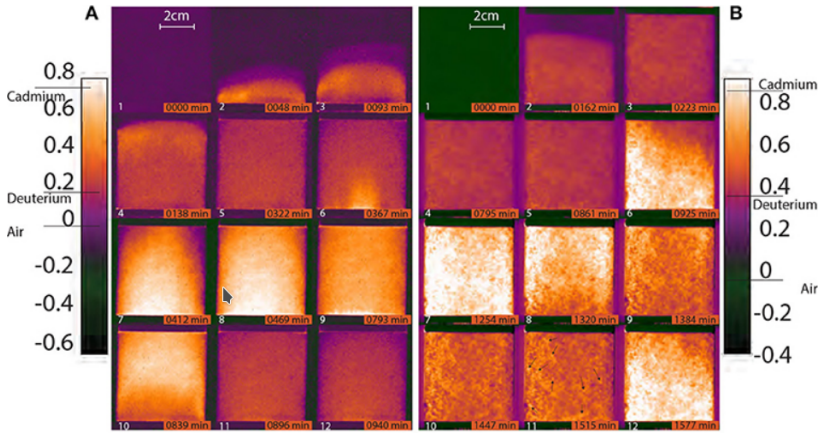
Dauti *et al.*,, Cement and Concrete Research (2018)
Dauti *et al.*, Transport in Porous Media (2019)
Tengattini *et al.*, Strain (2020)

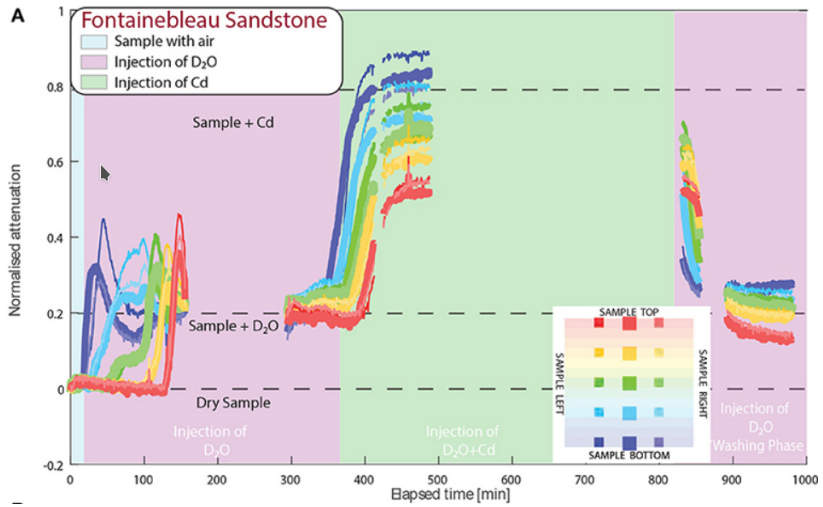
Cadmium Sorption and Transport in Porous Rocks



Study of Cd concentration

Quantification of Cd sorption and displacement of Contaminants



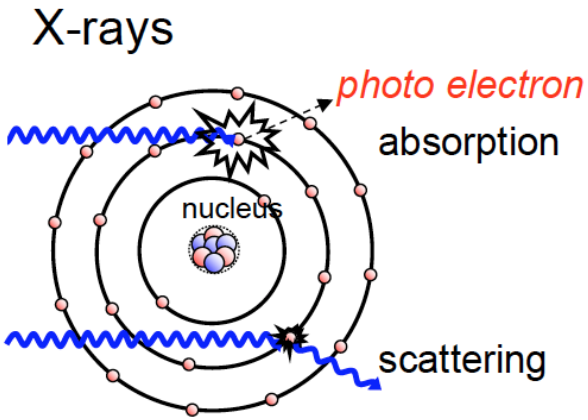


Cordonnier *et al.*, Front. Earth Sci (2019)

In summary

- Neutrons have a different contrast from x-rays
- Neutrons can see light elements (such as hydrogen, lithium) and their compounds (*e.g.*, water, oil)
- Neutrons are isotope sensitive; for example can distinguish deuterated fluids as D20 vs H2O
- Neutron can penetrate through thick metal casings for extreme conditions (pressure, temperature, acids)

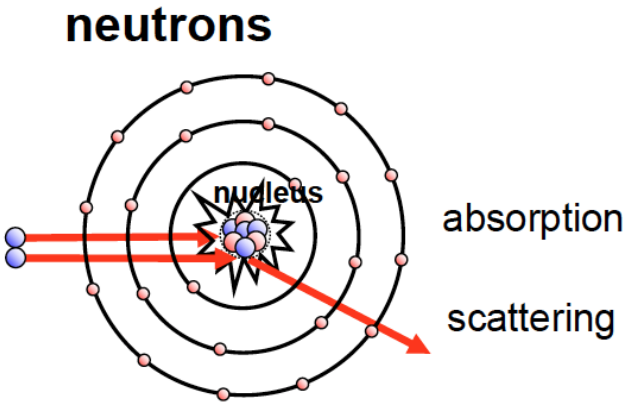
Neutrons or X-Rays?



Attenuation coefficients with X-ray [cm²¹]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 0.02																	He 0.02
Li 0.06	Be 0.22											B 0.28	C 0.27	N 0.11	O 0.16	F 0.14	Ne 0.17
Na 0.13	Mg 0.24											Al 0.38	Si 0.33	P 0.25	S 0.30	Cl 0.23	Ar 0.20
K 0.14	Ca 0.26	Sc 0.48	Ti 0.73	V 1.04	Cr 1.29	Mn 1.32	Fe 1.57	Co 1.78	Ni 1.96	Cu 1.97	Zn 1.64	Ga 1.42	Ge 1.33	As 1.50	Se 1.23	Br 0.90	Kr 0.73
Rb 0.47	Sr 0.86	Y 1.61	Zr 2.47	Nb 3.43	Mo 4.29	Tc 5.06	Ru 5.71	Rh 6.08	Pd 6.13	Ag 5.67	Cd 4.84	In 4.31	Sn 3.98	Sb 4.28	Te 4.06	I 3.45	Xe 2.53
Cs 1.42	Ba 2.73	La 5.04	Hf 19.70	Ta 25.47	W 30.49	Re 34.47	Os 37.92	Ir 39.01	Pt 38.61	Au 35.94	Hg 25.88	Tl 23.23	Pb 22.81	Bi 20.28	Po 20.22	At	Rn 9.77
Fr	Ra 11.80	Ac 24.47	Rf	Ha													

Lanthanides	Ce 5.79	Pr 6.23	Nd 6.46	Pm 7.33	Sm 7.68	Eu 5.66	Gd 8.69	Tb 9.46	Dy 10.17	Ho 10.91	Er 11.70	Tm 12.49	Yb 9.32	Lu 14.07
*Actinides	Th 28.95	Pa 39.65	U 49.08	Np	Pu	Am	Cm	Bk	Vf	Es	Fm	Md	No	Lr x-ray

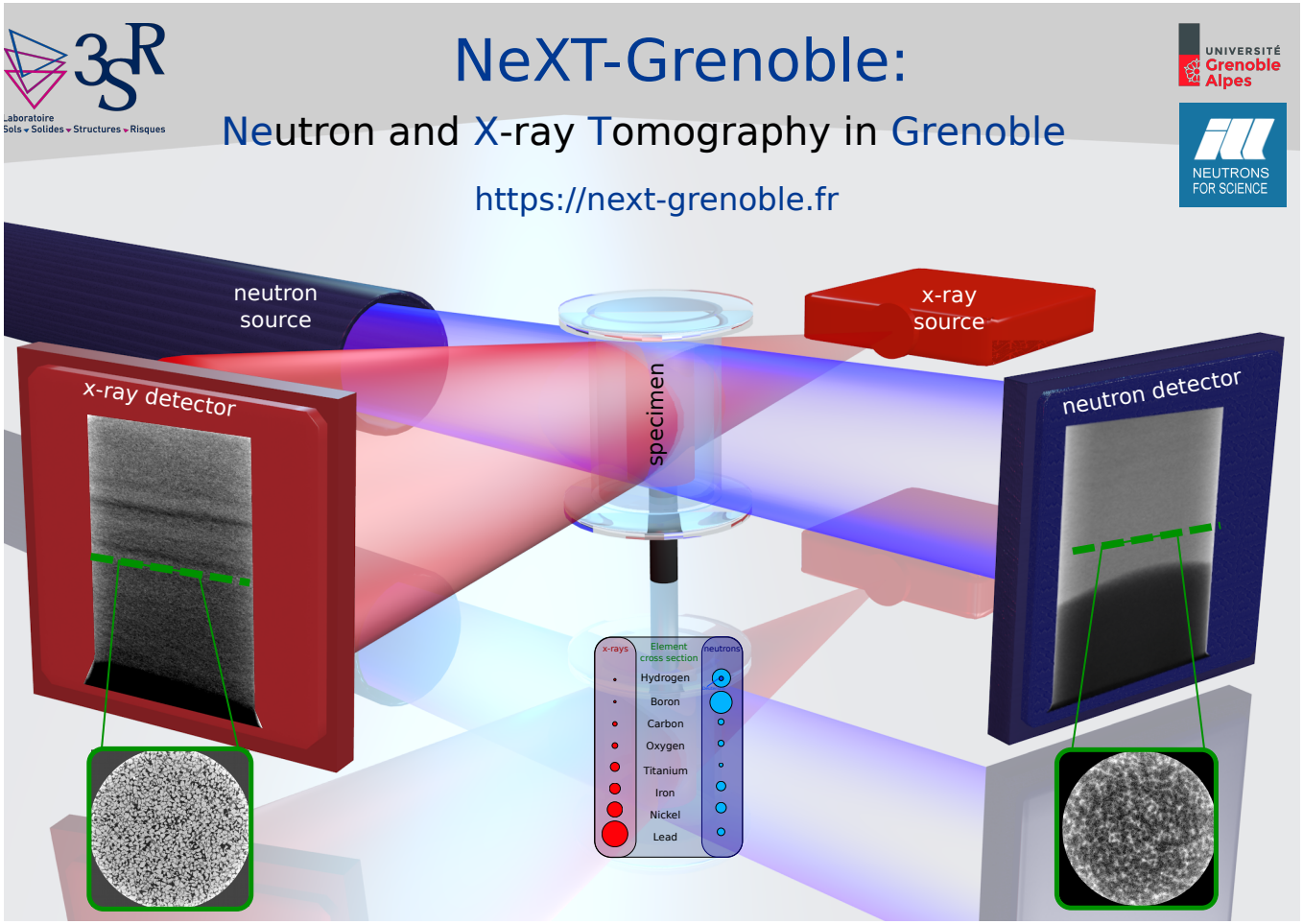


Attenuation coefficients with neutrons [cm²¹]

1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
H 3.44																	He 0.02
Li 3.30	Be 0.79											B 101.60	C 0.56	N 0.43	O 0.17	F 0.20	Ne 0.10
Na 0.09	Mg 0.15											Al 0.10	Si 0.11	P 0.12	S 0.06	Cl 1.33	Ar 0.03
K 0.06	Ca 0.08	Sc 2.00	Ti 0.60	V 0.72	Cr 0.54	Mn 1.21	Fe 1.19	Co 3.92	Ni 2.05	Cu 1.07	Zn 0.35	Ga 0.49	Ge 0.47	As 0.67	Se 0.73	Br 0.24	Kr 0.61
Rb 0.08	Sr 0.14	Y 0.27	Zr 0.29	Nb 0.40	Mo 0.52	Tc 1.76	Ru 0.58	Rh 10.88	Pd 0.78	Ag 4.04	Cd 115.11	In 7.58	Sn 0.21	Sb 0.30	Te 0.25	I 0.23	Xe 0.43
Cs 0.29	Ba 0.07	La 0.52	Hf 4.99	Ta 1.49	W 1.47	Re 6.85	Os 2.24	Ir 30.46	Pt 1.46	Au 6.23	Hg 16.21	Tl 0.47	Pb 0.38	Bi 0.27	Po	At	Rn
Fr	Ra 0.34	Ac	Rf	Ha													

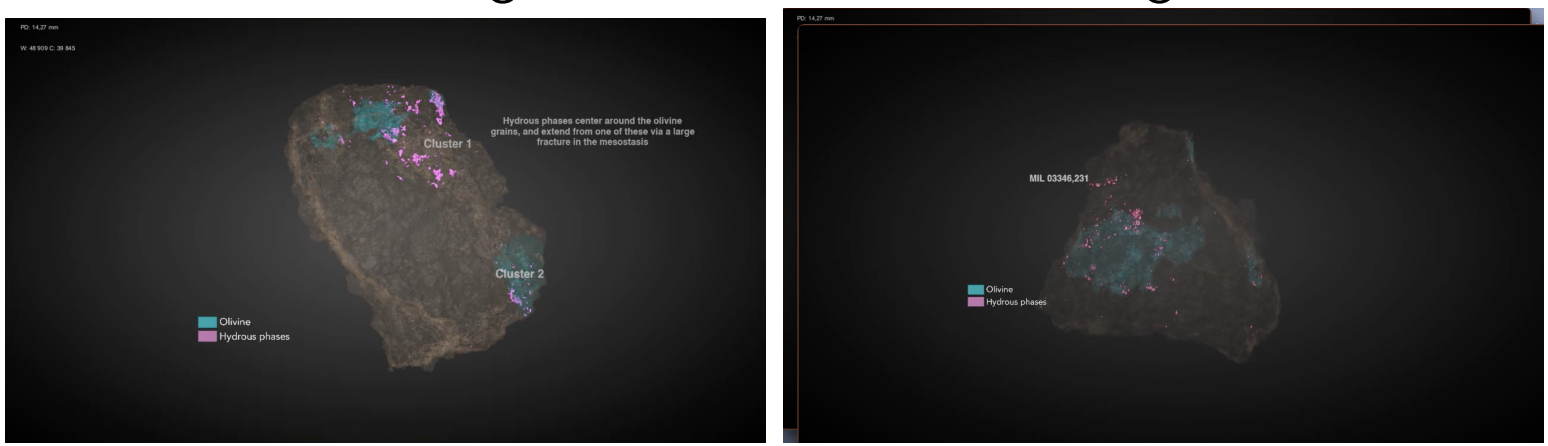
*Lanthanides	Ce 0.14	Pr 0.41	Nd 1.87	Pm 5.72	Sm 171.47	Eu 94.58	Gd 1479.04	Tb 0.93	Dy 32.42	Ho 2.25	Er 5.48	Tm 3.53	Yb 1.40	Lu 2.75
**Actinides	Th 0.59	Pa 8.46	U 0.82	Np 9.80	Pu 50.20	Am 2.86	Cm	Bk	Cf	Es	Fm	Md	No	Lr neut.

Neutrons ~~or~~ **and** X-Rays!



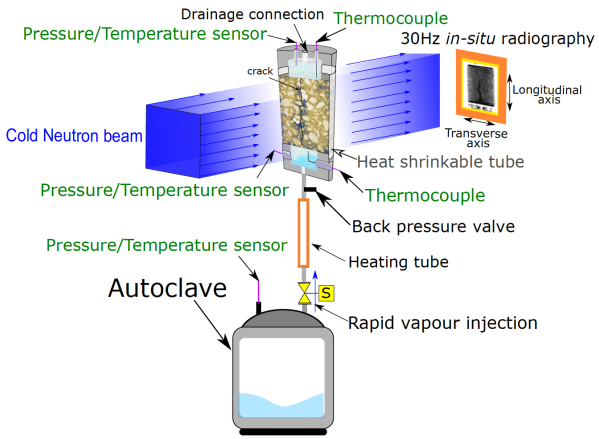
Martian Meteorite

Miller Range 03346 Mill.Range 230



Martell *et al.*, Science Advances, 2022

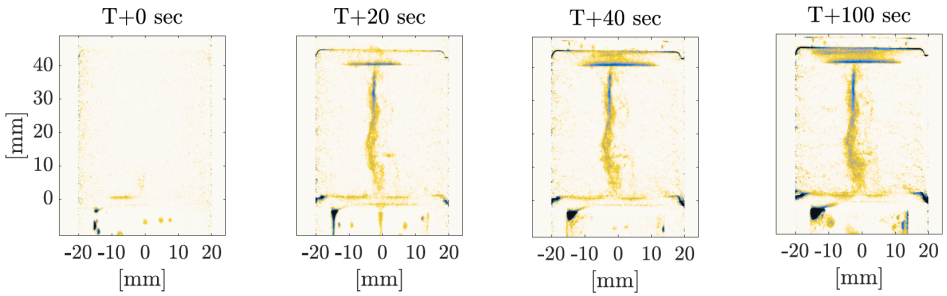
Vapour Injection



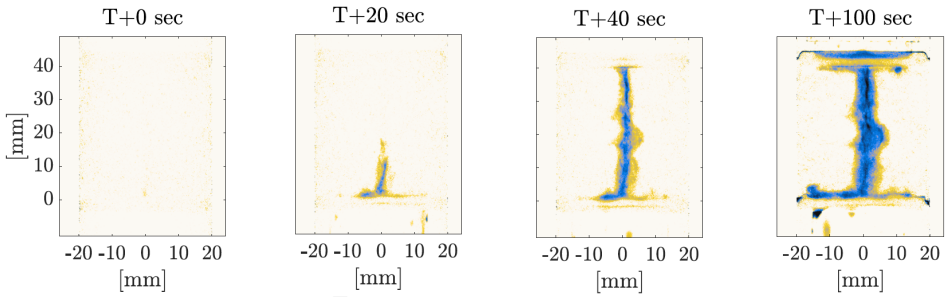
Emulating Loss of Coolant Accident in Reactor

anr

Initially saturated

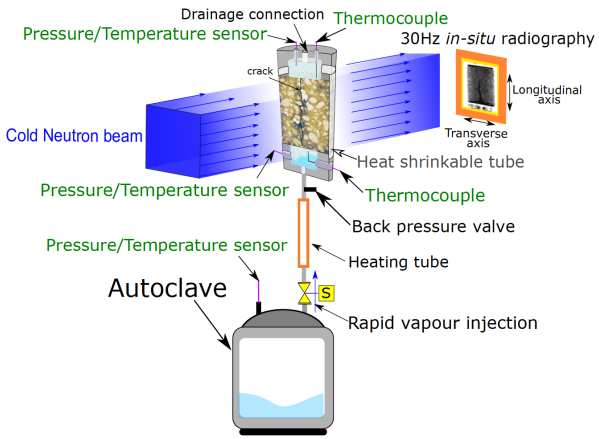


Initially dry

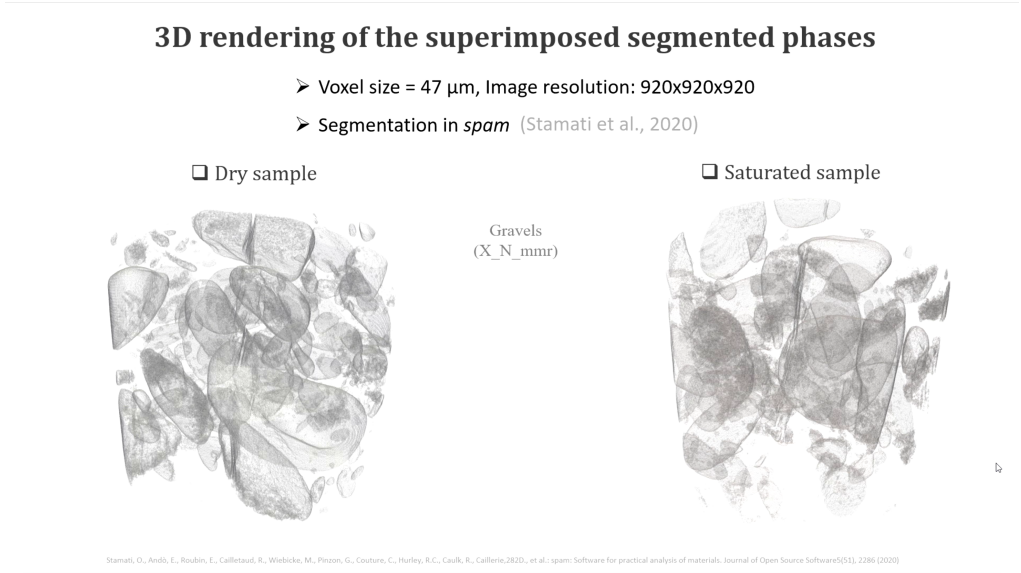


Gupta, *et al.*, Cem Concrete Research (2022)
Lukich, *et al.*, Material Letters (2021)

Vapour Injection

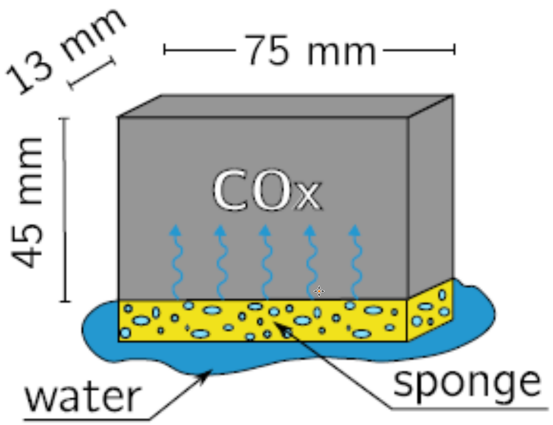


Emulating Loss of Coolant Accident in Reactor

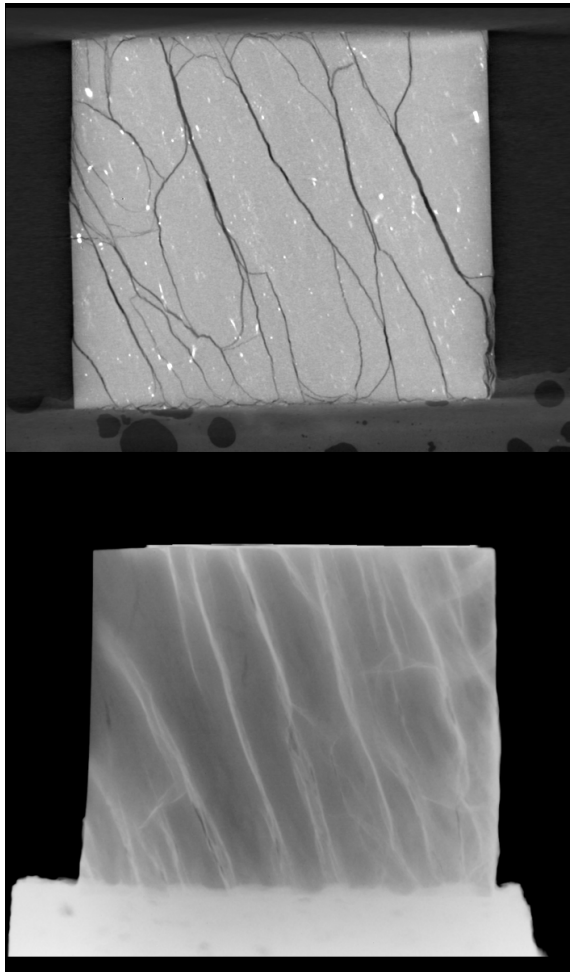


Gupta, *et al.*, Cem Concrete Research (2022)
Lukich, *et al.*, Material Letters (2021)

Hydo-mechanical coupling of Callovo-Oxfordian Clayrock



Rock used for long-term storage of radioactive contaminants

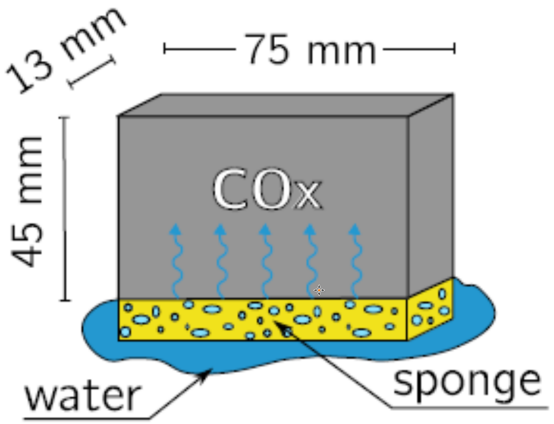


x-rays (structure)

neutrons (fluids)

Stavropoulou, *et al.*, Acta Geotechnica (2018)
Stavropoulou, *et al.*, Front. in Earth Science (2020)

Hydo-mechanical coupling of Callovo-Oxfordian Clayrock



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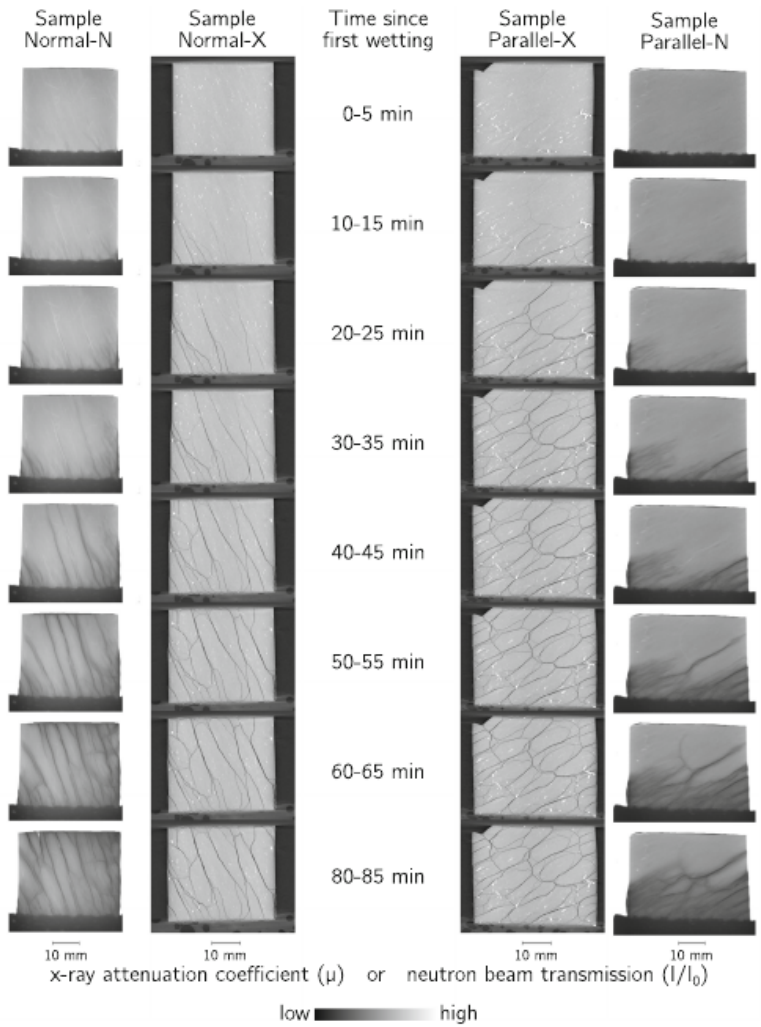
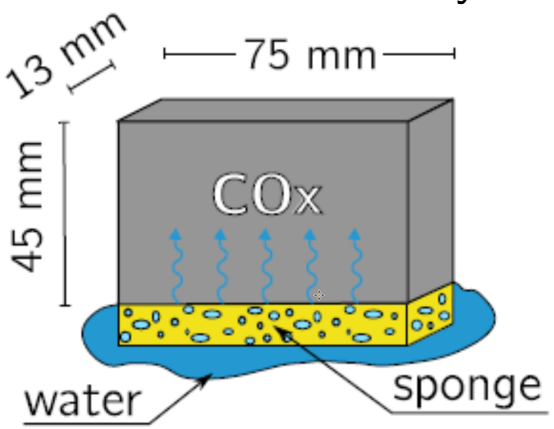
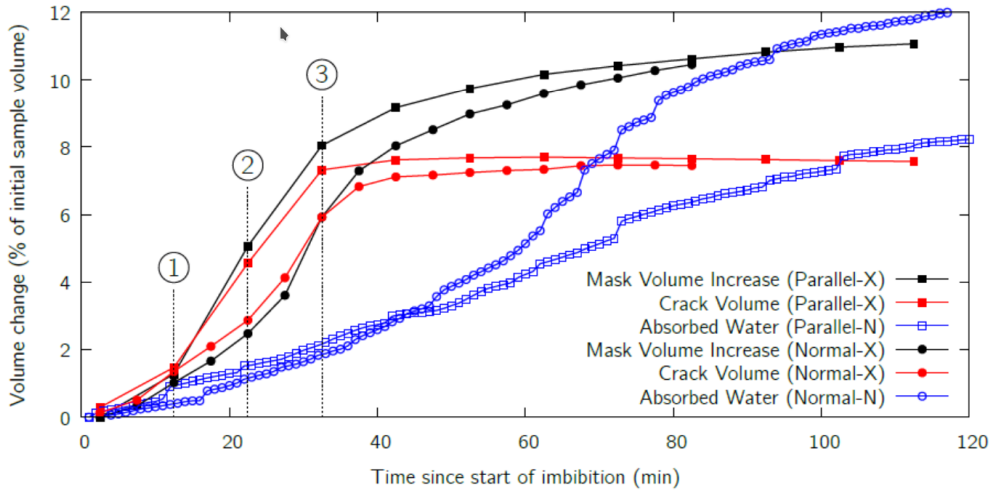


Stavropoulou, *et al.*, Acta Geotechnica (2018)
Stavropoulou, *et al.*, Front. in Earth Science (2020)

Hydo-mechanical coupling of Callovo-Oxfordian Clayrock

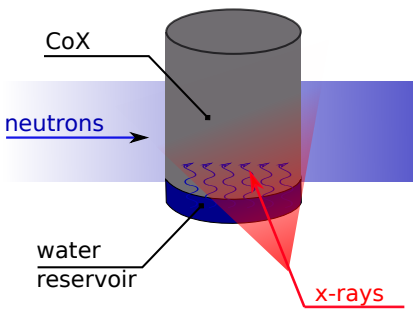


Rock used for long-term storage of radioactive contaminants

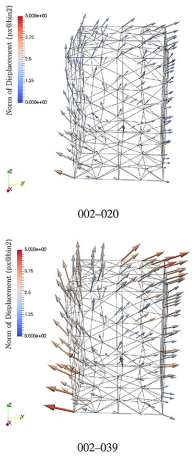


Stavropoulou, *et al.*, Acta Geotechnica (2018)
Stavropoulou, *et al.*, Front. in Earth Science (2020)

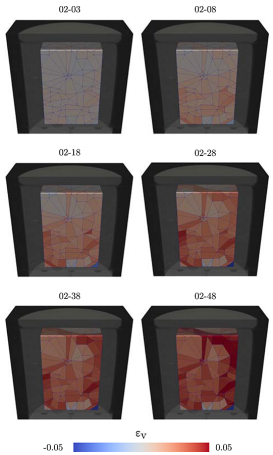
Test absorption water in COX



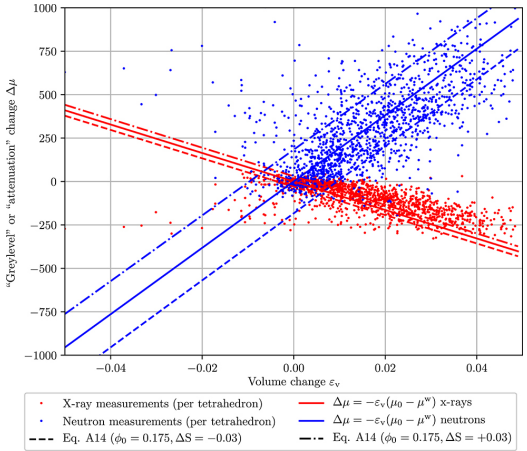
3D strain field through DVC



Correction of grayscale by deformation

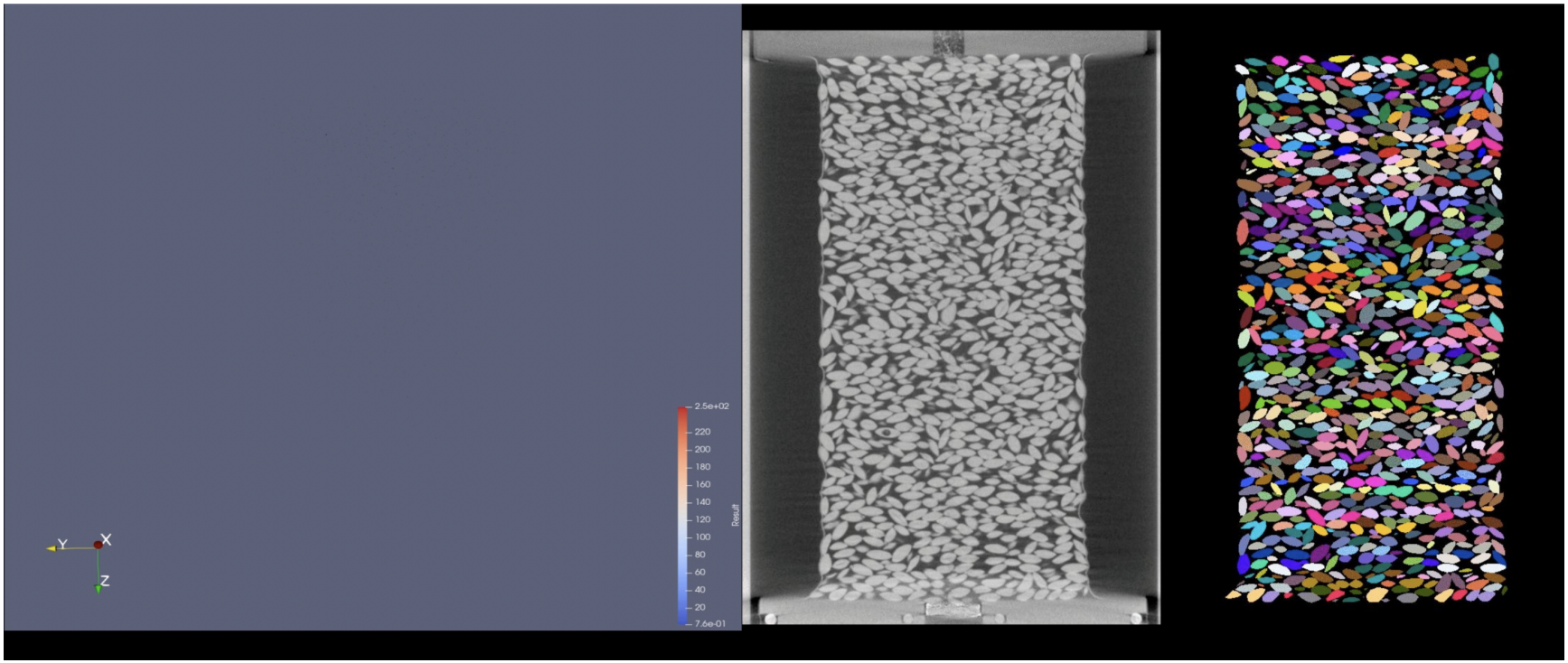


Accurate estimation water uptake

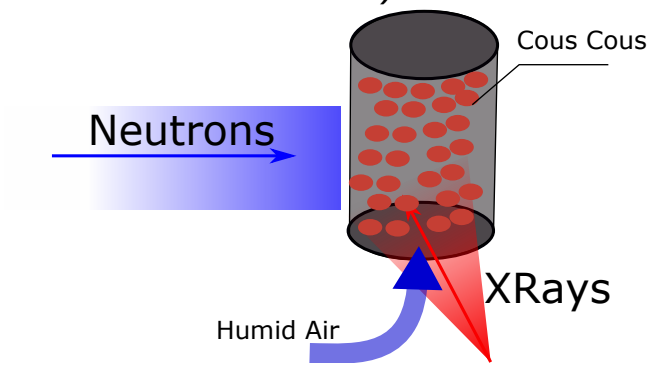


Stavropoulou, *et al.*, Front. in Earth Science (2020)

How about **Granular Media** – Discrete DVC!



Water sensitive material (e.g., Medidicines, food)

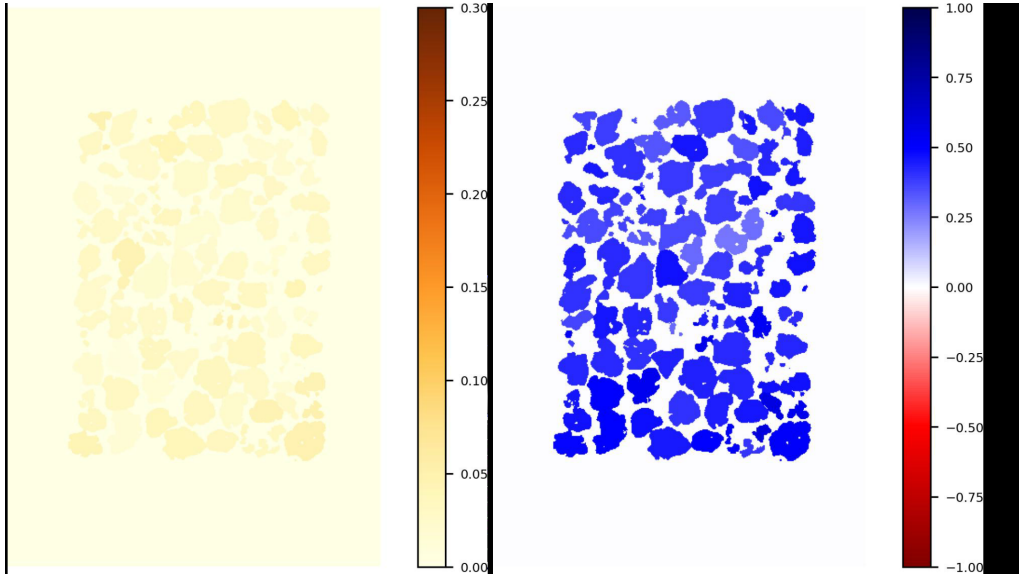


Societal problem: Caking – loss of usability of food exposed to humidity

Horizon 2020 ITN

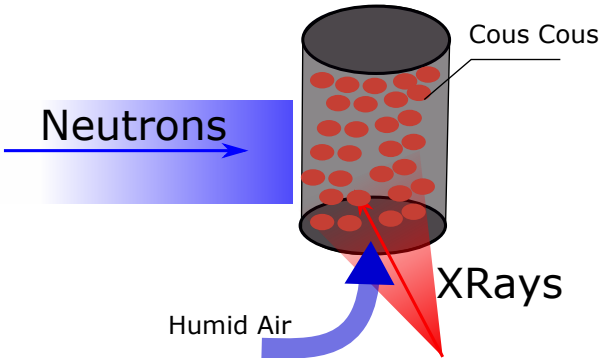
CALIPER Unilever

Xrays(Vol Strain) Neutrons(H20 content)



Vego, Tengattini, *et al.*, Soft Matter (2022)
Vego, Tengattini, *et al.*, Granular Matter (2023)

Water sensitive material (e.g., Medidicines, food)

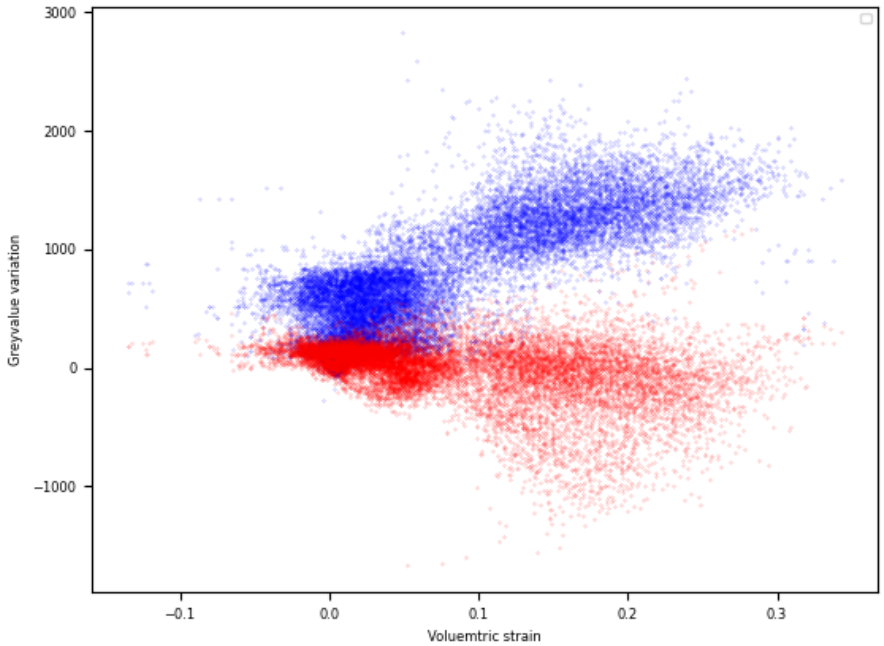


Societal problem: Caking – loss of usability of food exposed to humidity

Horizon 2020 ITN

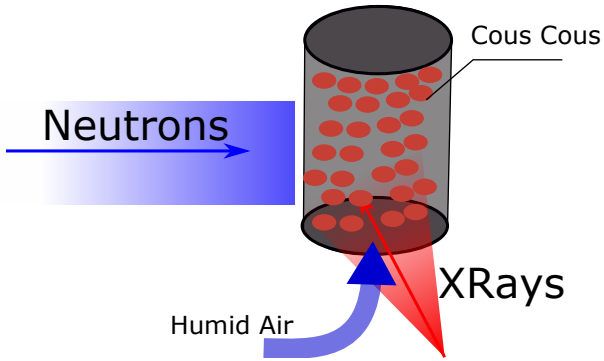
CALIPER Unilever

Statistical correlation of Vol. Strain to H20 content



Vego, Tengattini, *et al.*, Soft Matter (2022)
Vego, Tengattini, *et al.*, Granular Matter (2023)

Water sensitive material (e.g., Medidicines, food)

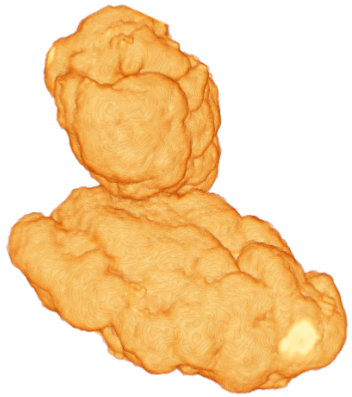


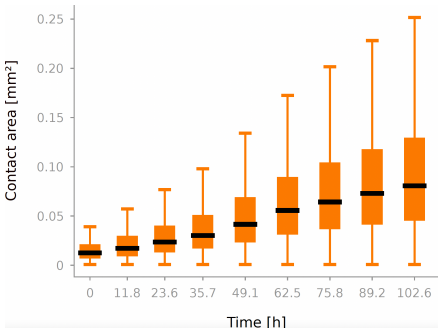
Societal problem: Caking – loss of usability of food exposed to humidity

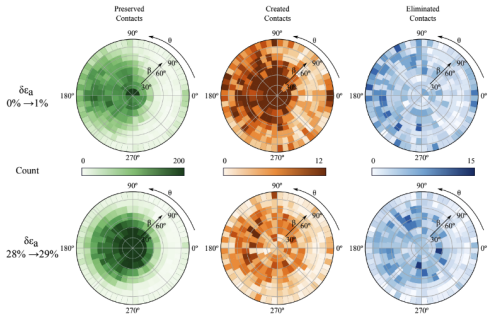
Horizon 2020 ITN

CALIPER Unilever

Contact Analysis

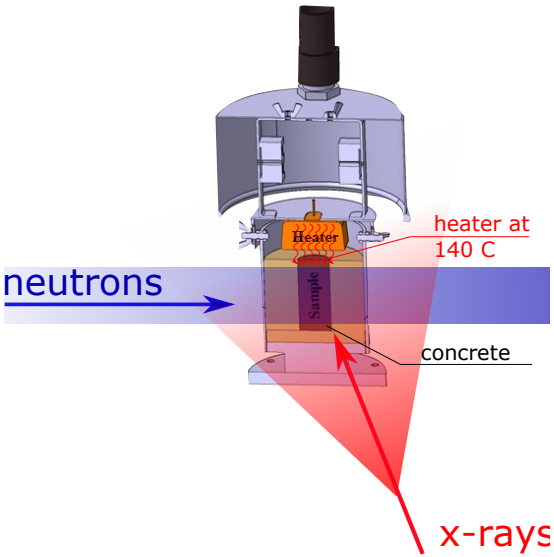




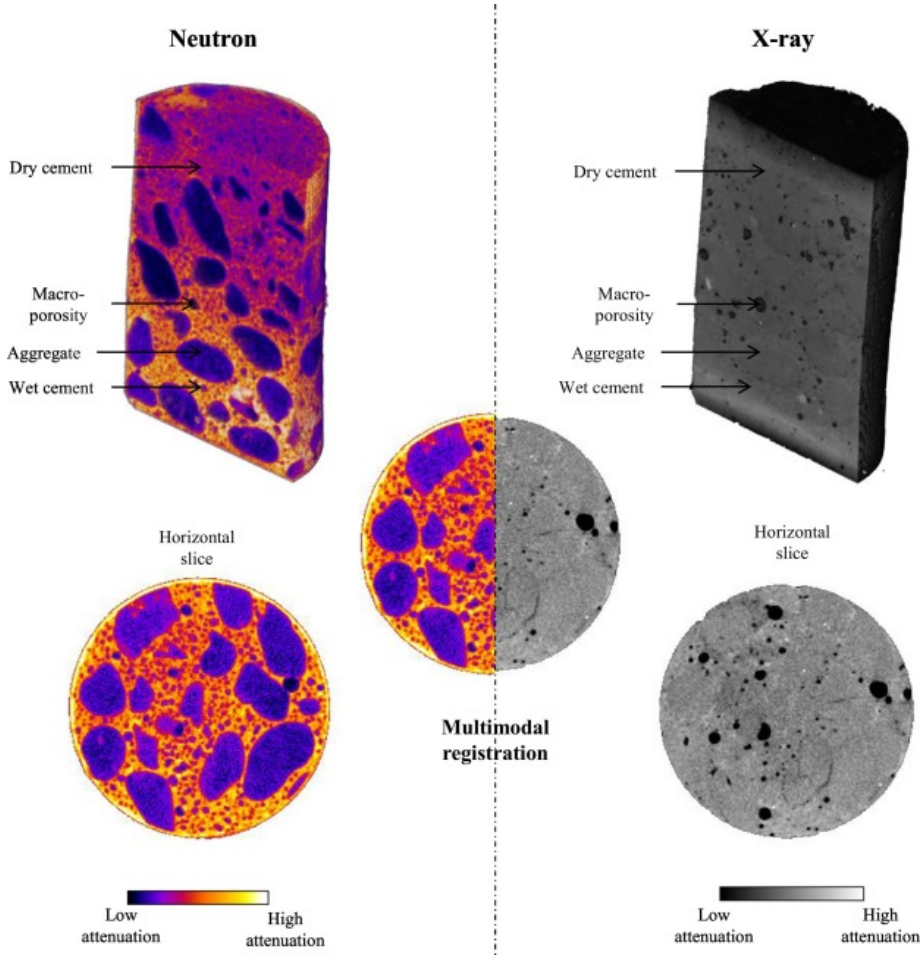


Vego, Tengattini, *et al.*, Soft Matter (2022)
Vego, Tengattini, *et al.*, Granular Matter (2023)

Heating construction materials to high temperatures

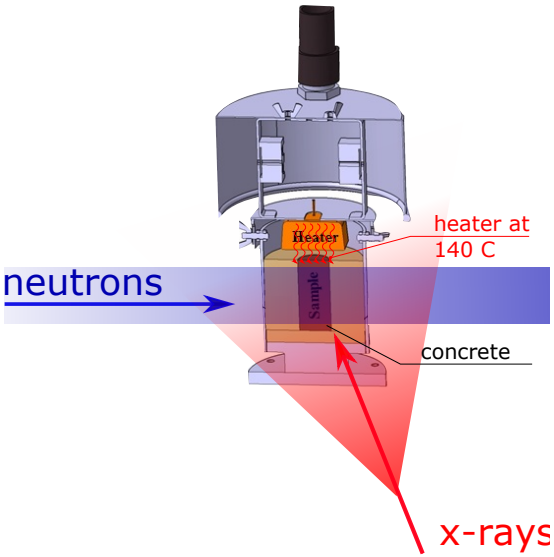


LafargeHolcim



Tudisco *et al.*, Measurement Science and Technology (2017)
Roubin *et al.*, Cement and Concrete Composites (2019)
Sleiman, Cement and Concrete Research (2021)

Heating construction materials to high temperatures



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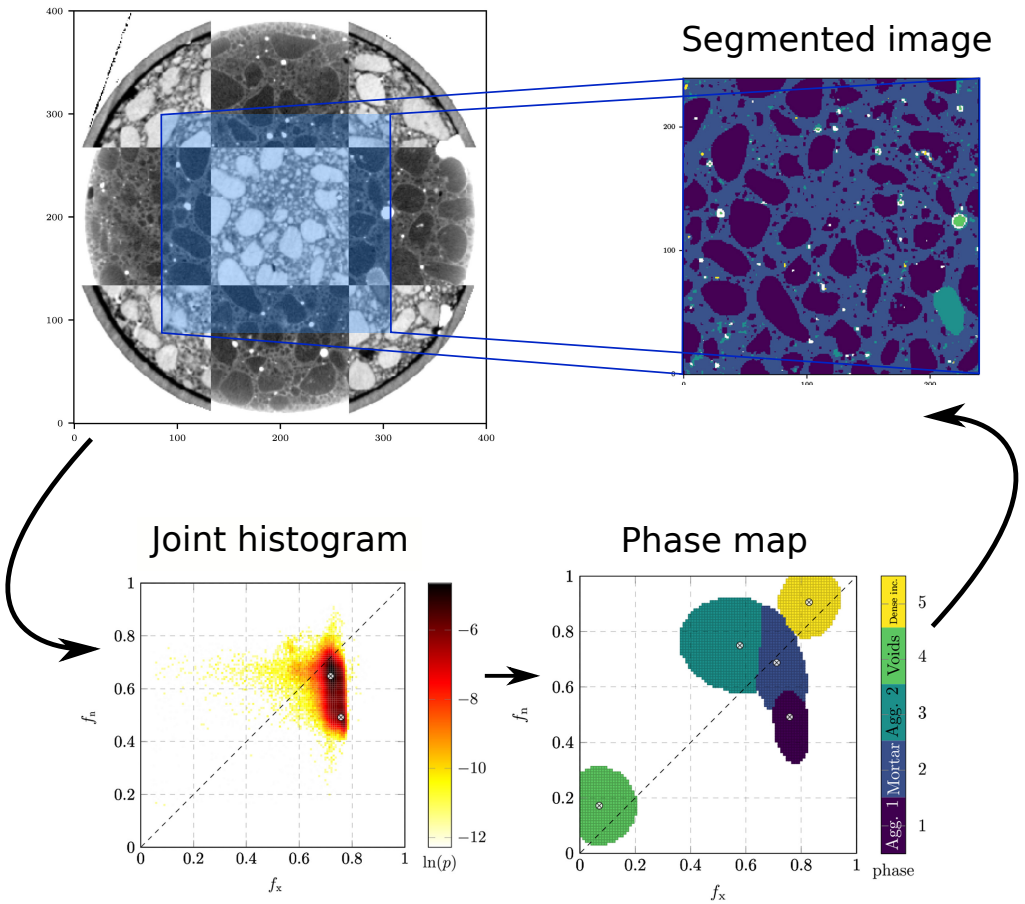
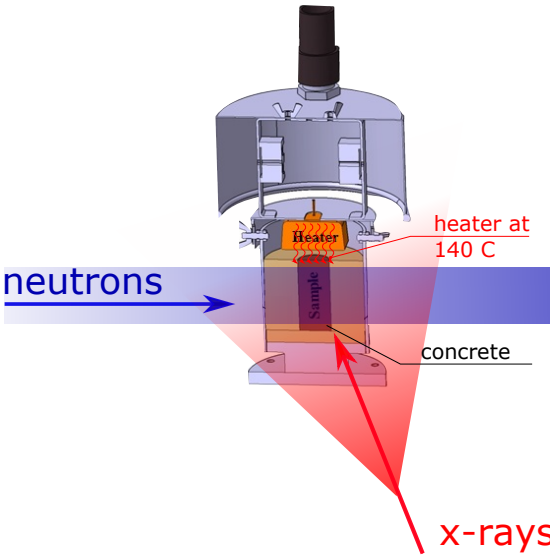


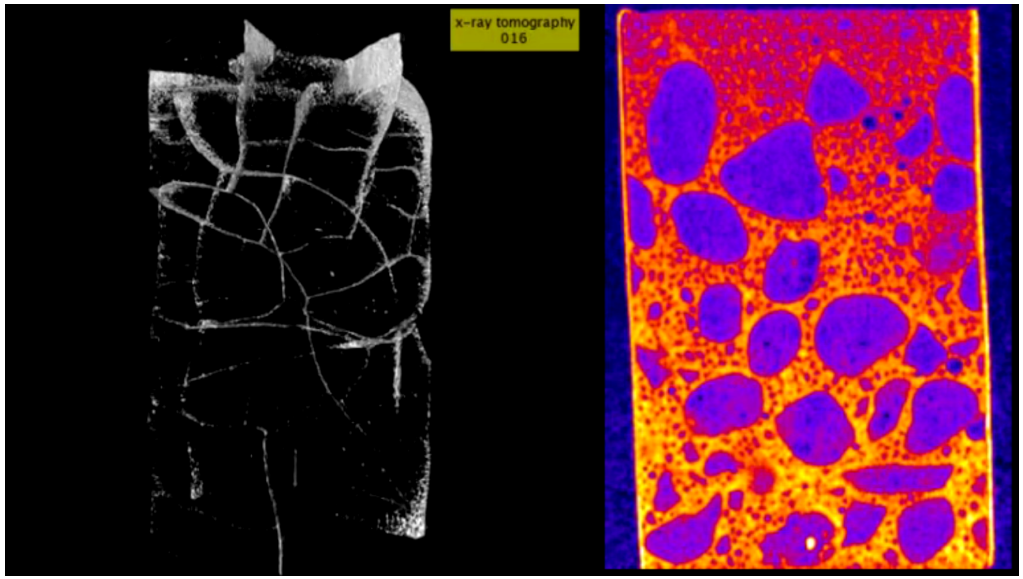
Tudisco *et al.*, Measurement Science and Technology (2017)
Roubin *et al.*, Cement and Concrete Composites (2019)
Sleiman, Cement and Concrete Research (2021)

Heating construction materials to high temperatures



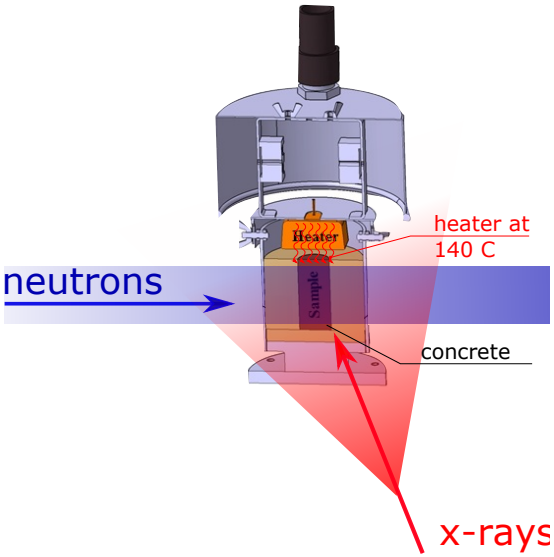
LafargeHolcim

x-ray neutrons



Tudisco *et al.*, Measurement Science and Technology (2017)
Roubin *et al.*, Cement and Concrete Composites (2019)
Sleiman, Cement and Concrete Research (2021)

Heating construction materials to high temperatures



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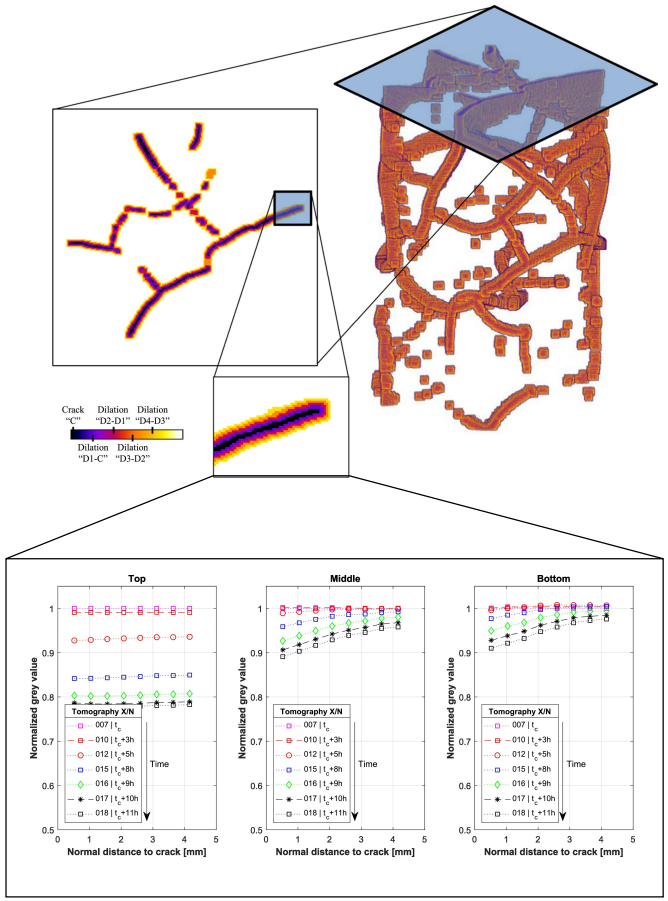

Tudisco *et al.*, Measurement Science and Technology (2017)
Roubin *et al.*, Cement and Concrete Composites (2019)
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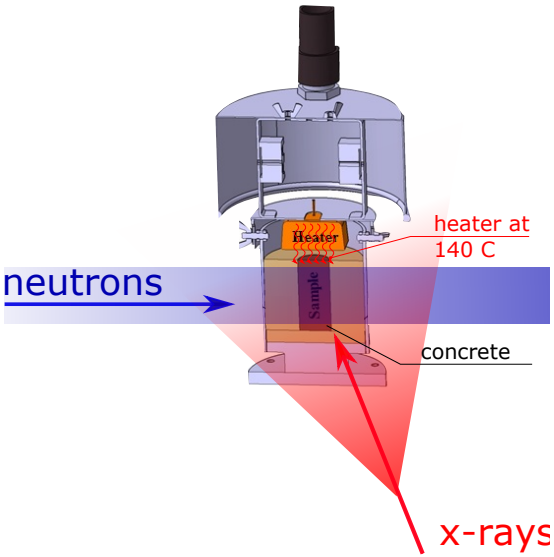
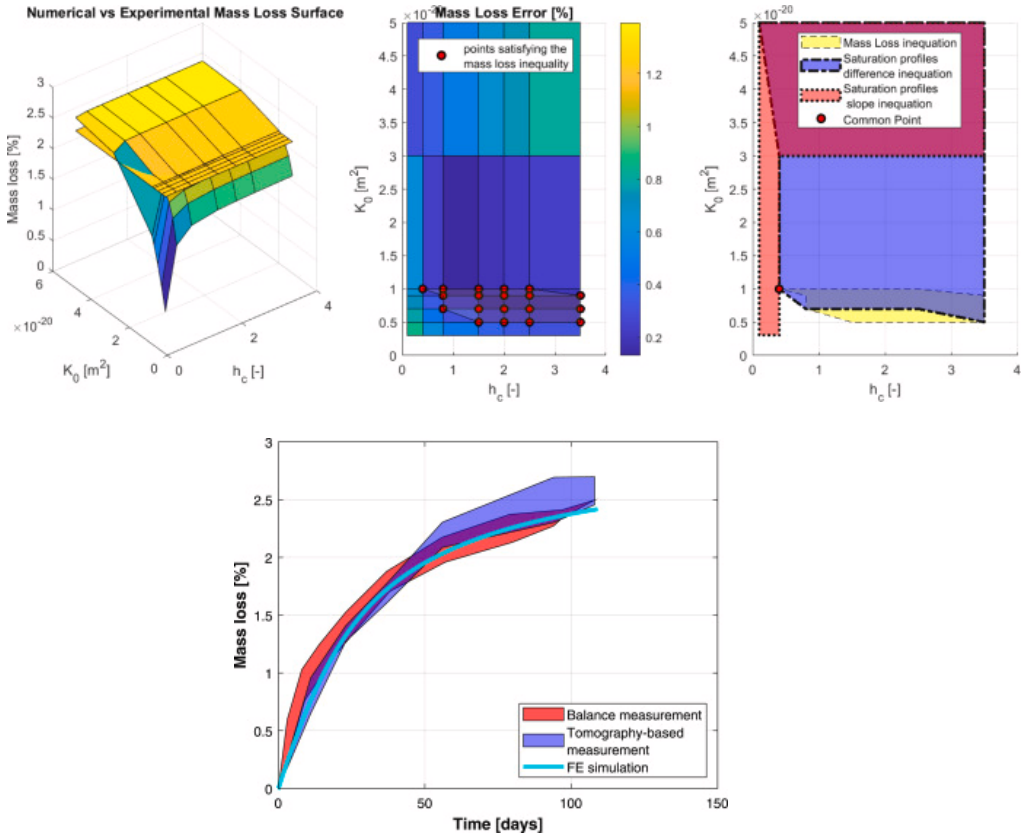
Heating construction materials to high temperatures



LafargeHolcim

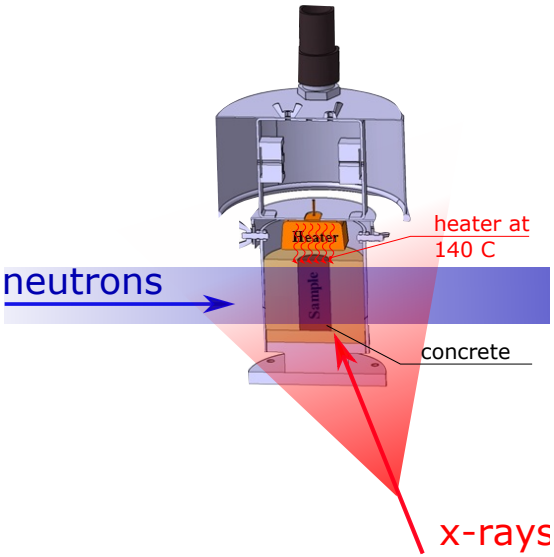
Towards more realistic numerical models



Sleiman, *et al.* Cement and Concrete Composites (2022)

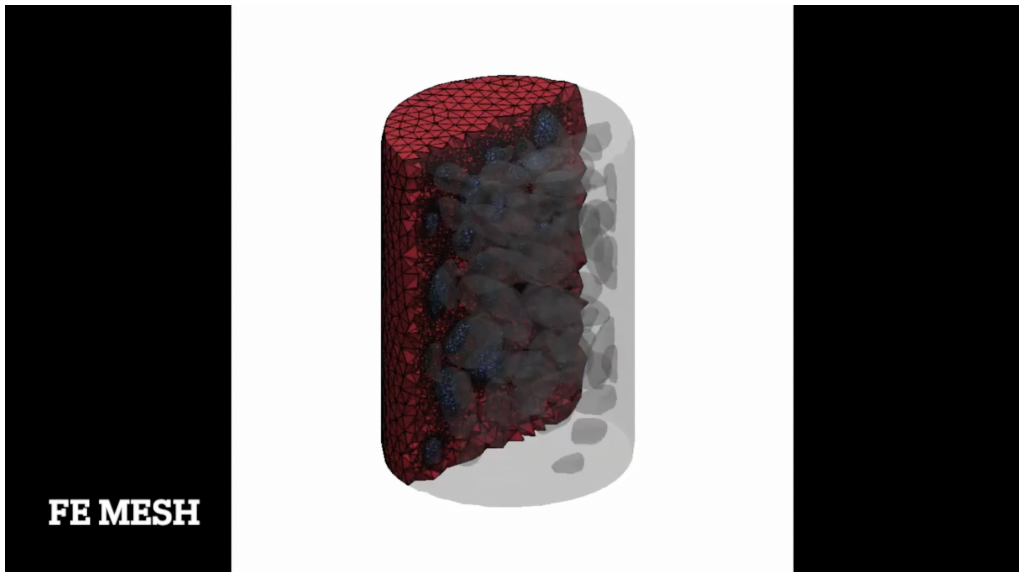
Tudisco *et al.*, Measurement Science and Technology (2017)
Roubin *et al.*, Cement and Concrete Composites (2019)

Heating construction materials to high temperatures



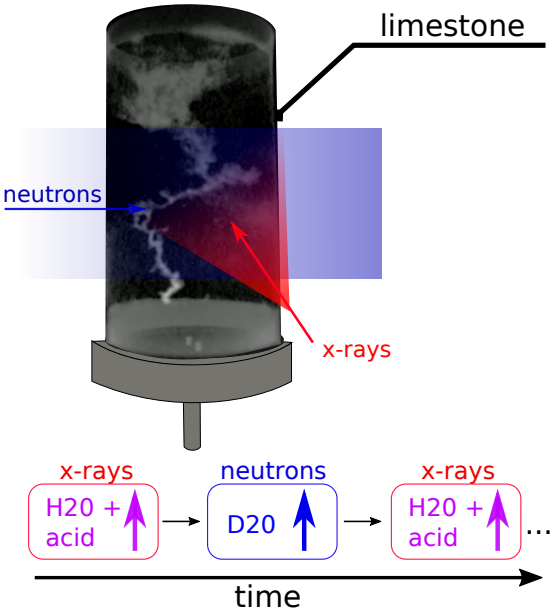
LafargeHolcim

Towards more realistic numerical models



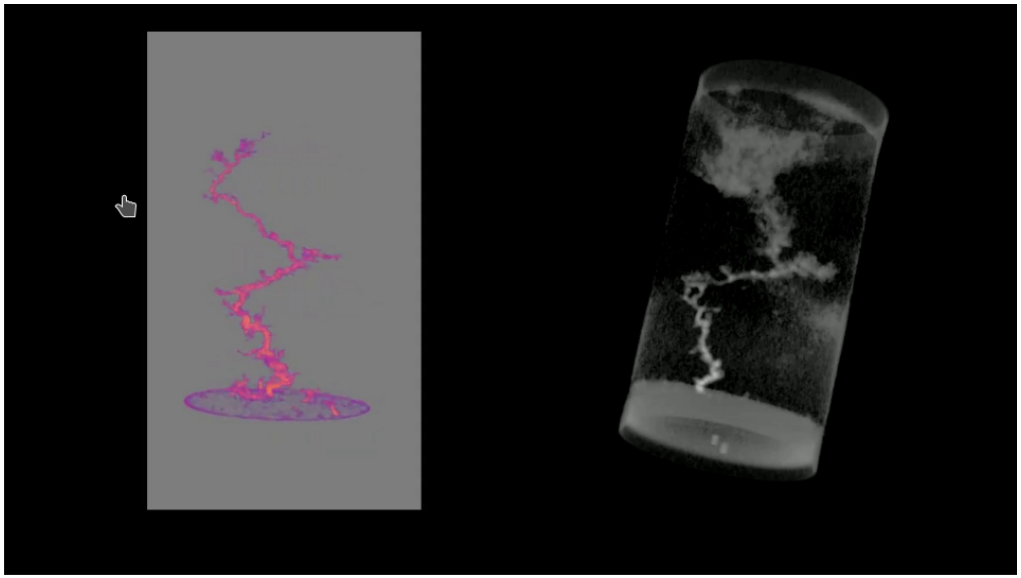
Tudisco *et al.*, Measurement Science and Technology (2017)
Roubin *et al.*, Cement and Concrete Composites (2019)
Sleiman, Cement and Concrete Research (2021)

Wormhole Growth in Dissolving Limestones



From X-ray: wormhole development by acid dissolution

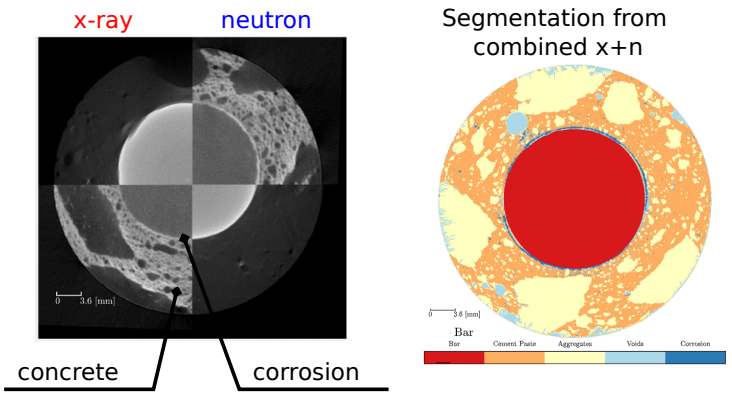
From neutron: evolution hydraulic propertie



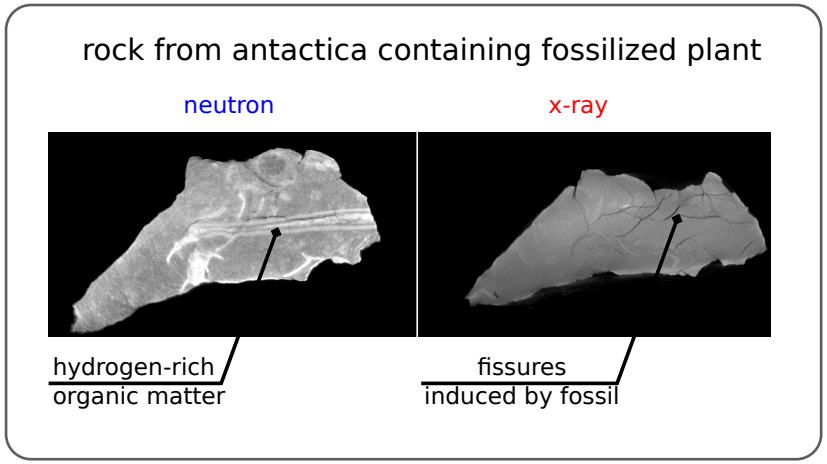
Szymczak *et al.*, EGU (2021)
Szymczak *et al.*, AGU (2020)
Cooper *et al.*, Advances in Water Resources(2023)
Cooper *et al.*, under redaction(2023)

Other applications

The combination of neutron and x-rays allow for advanced segmentation and image processing [1-3]

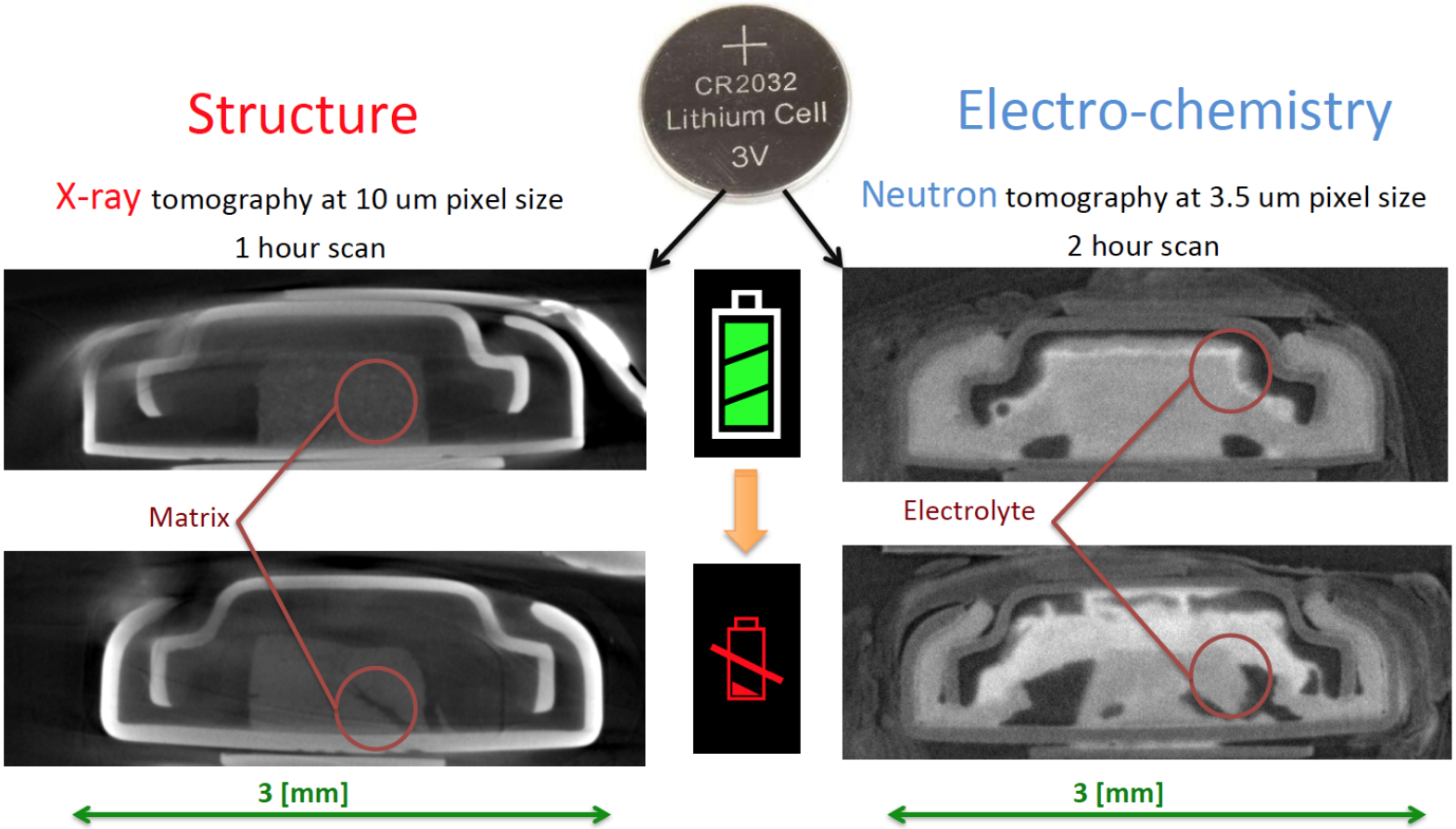


Neutron and x-ray imaging are highlty complementary *e.g.*, to identify organic material

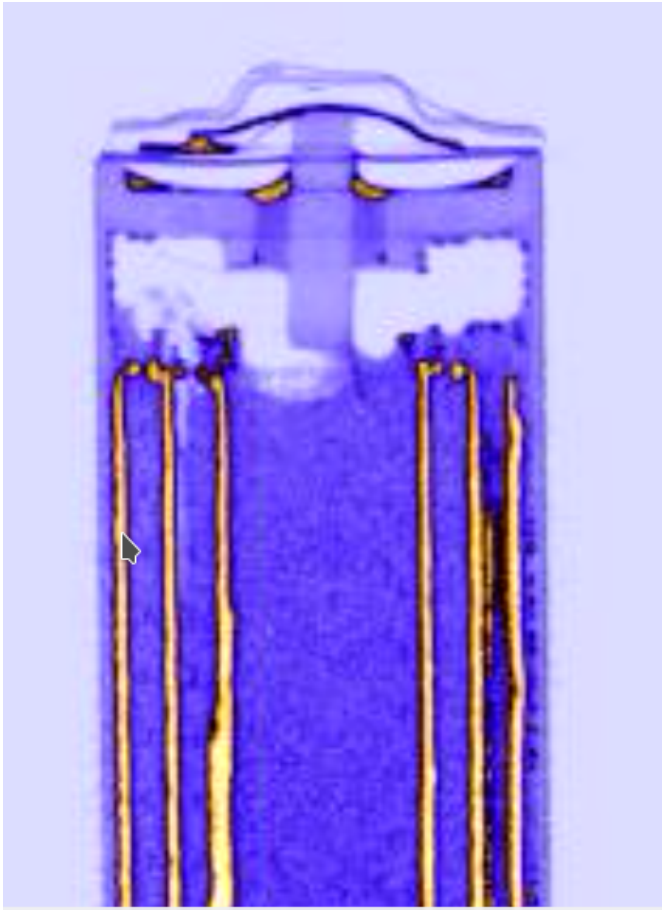


[1]Robuschi et *Al.*, Cement and Concrete Research (2021)
[2]Tudisco et *Al.*, Measurement Science and Technology (2017)
[3]Roubin et *Al.*, Cement and Concrete Composites (2019)

Other applications

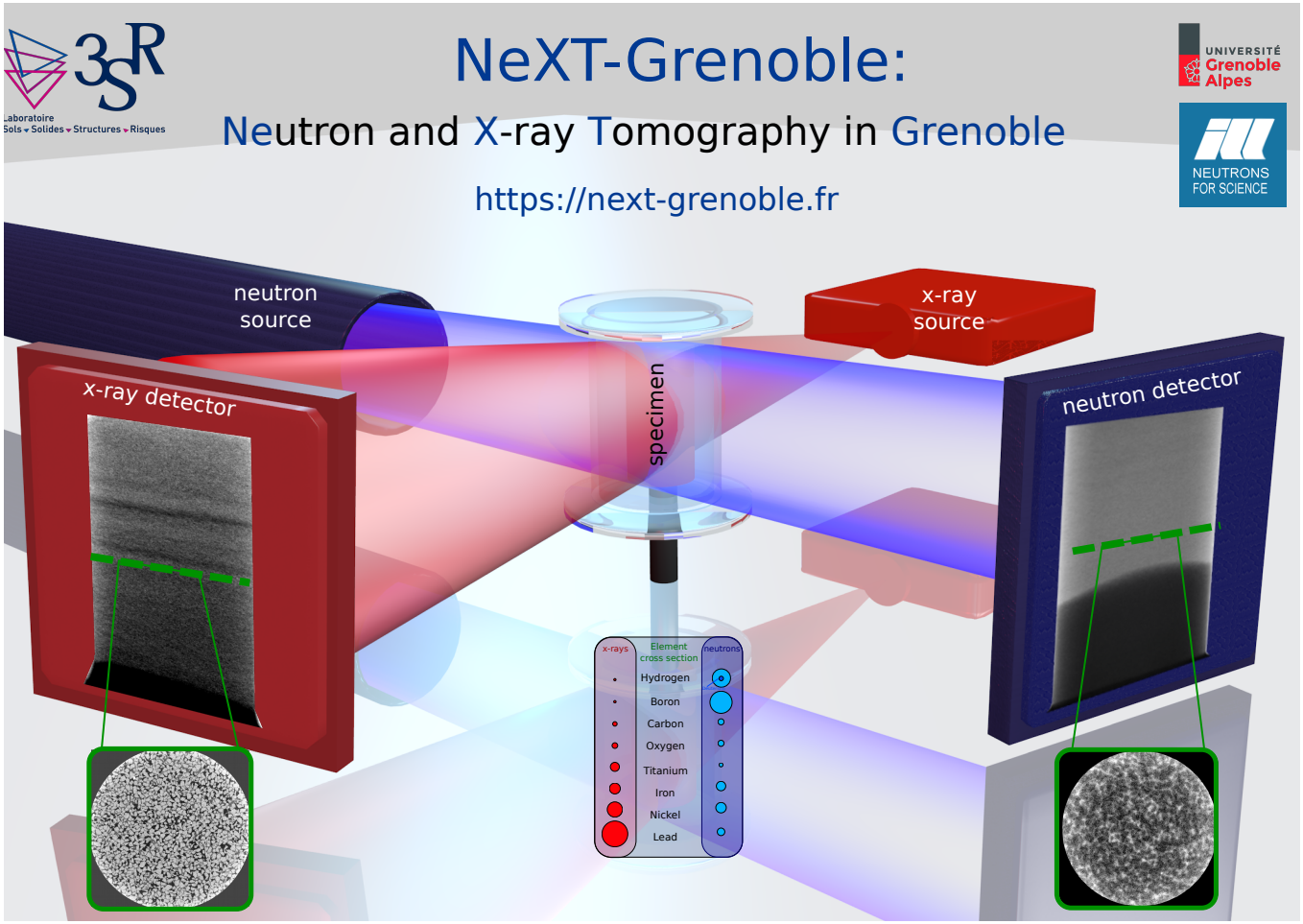


30 minute tomographies at 30um

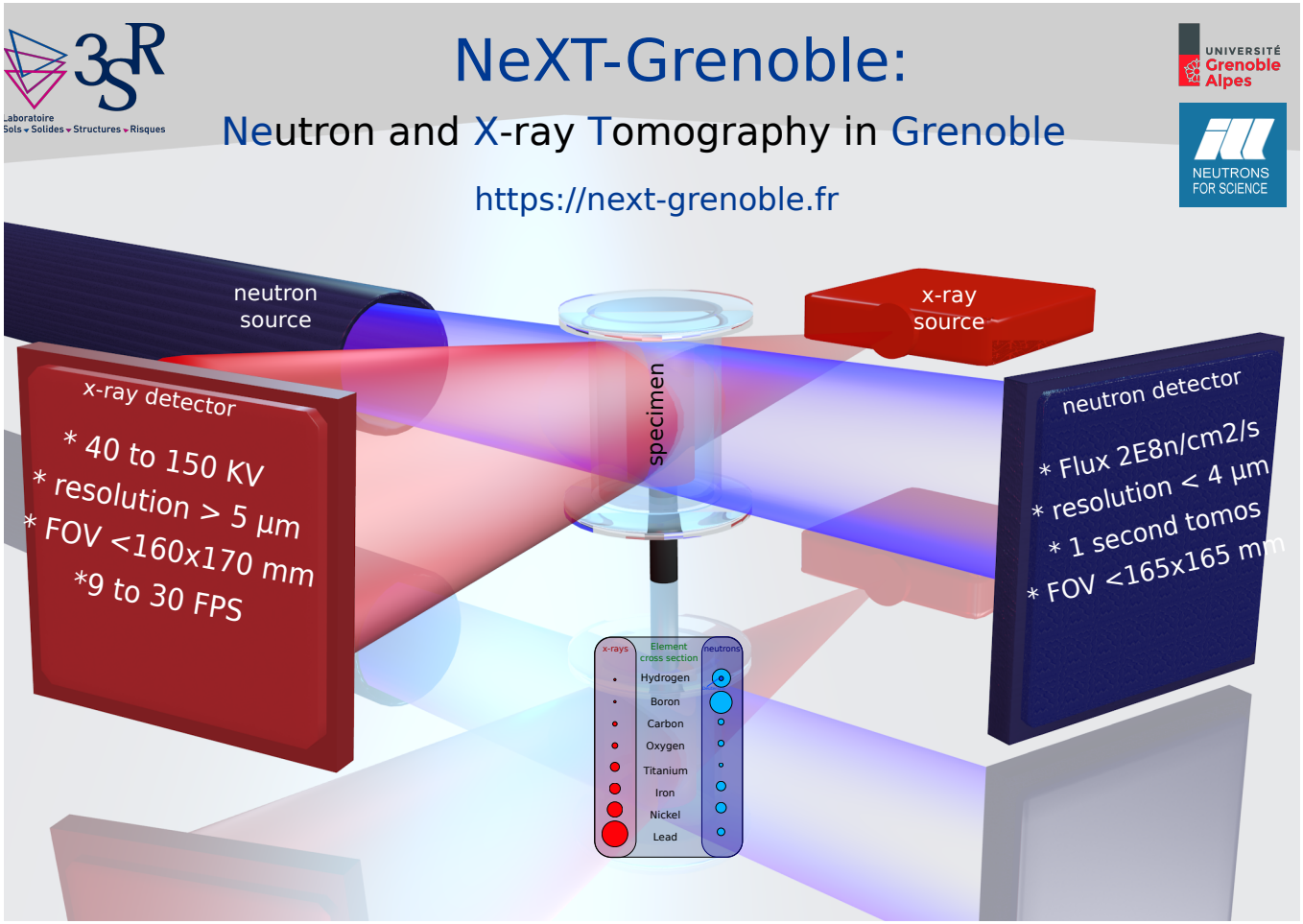


Ziesche et Al. 2020 Nature Comm.
Ziesche et Al. 2020 J. Electrochem. Soc.

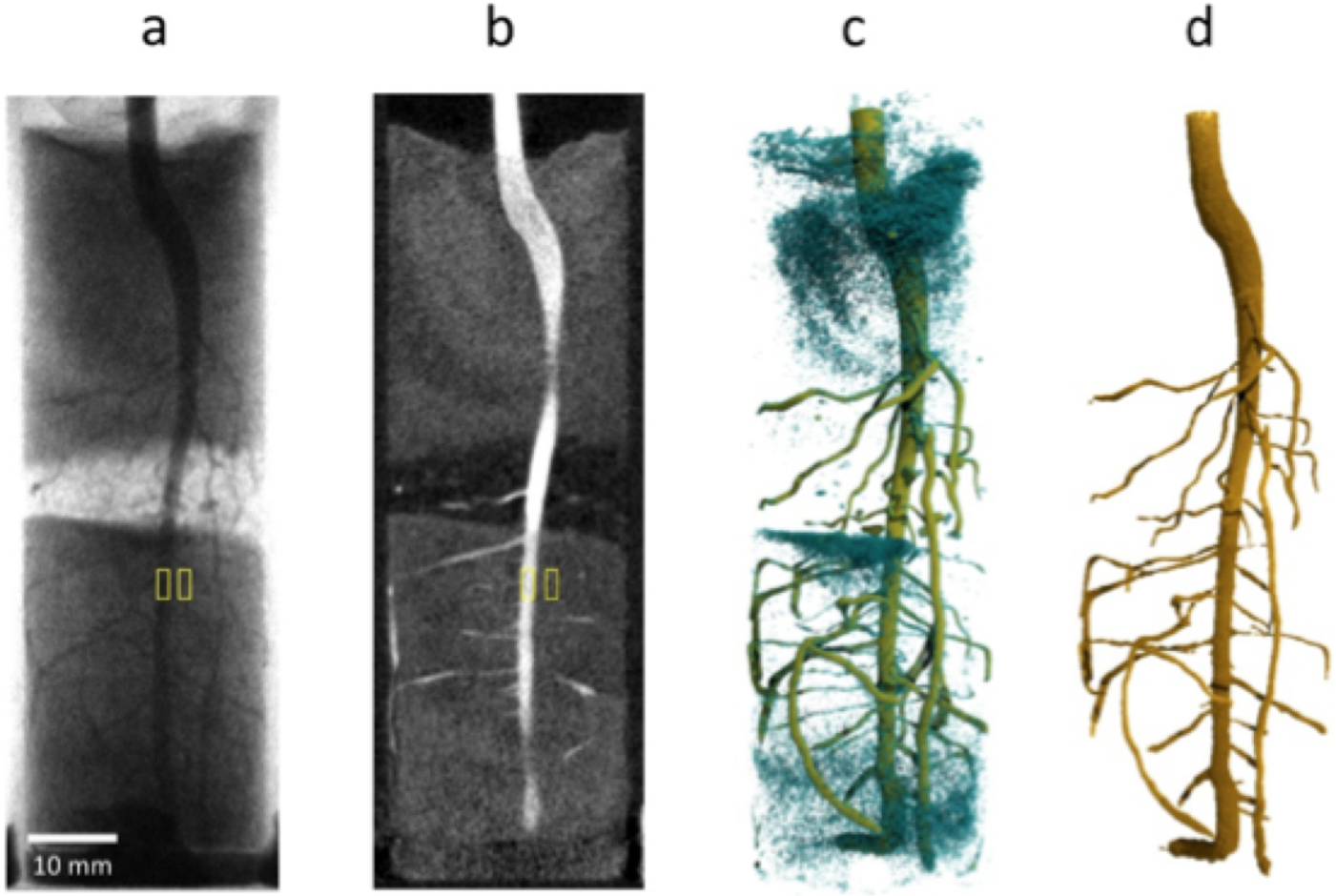
Neutrons ~~or~~ **and** X-Rays!



Neutrons ~~or~~ **and** X-Rays!

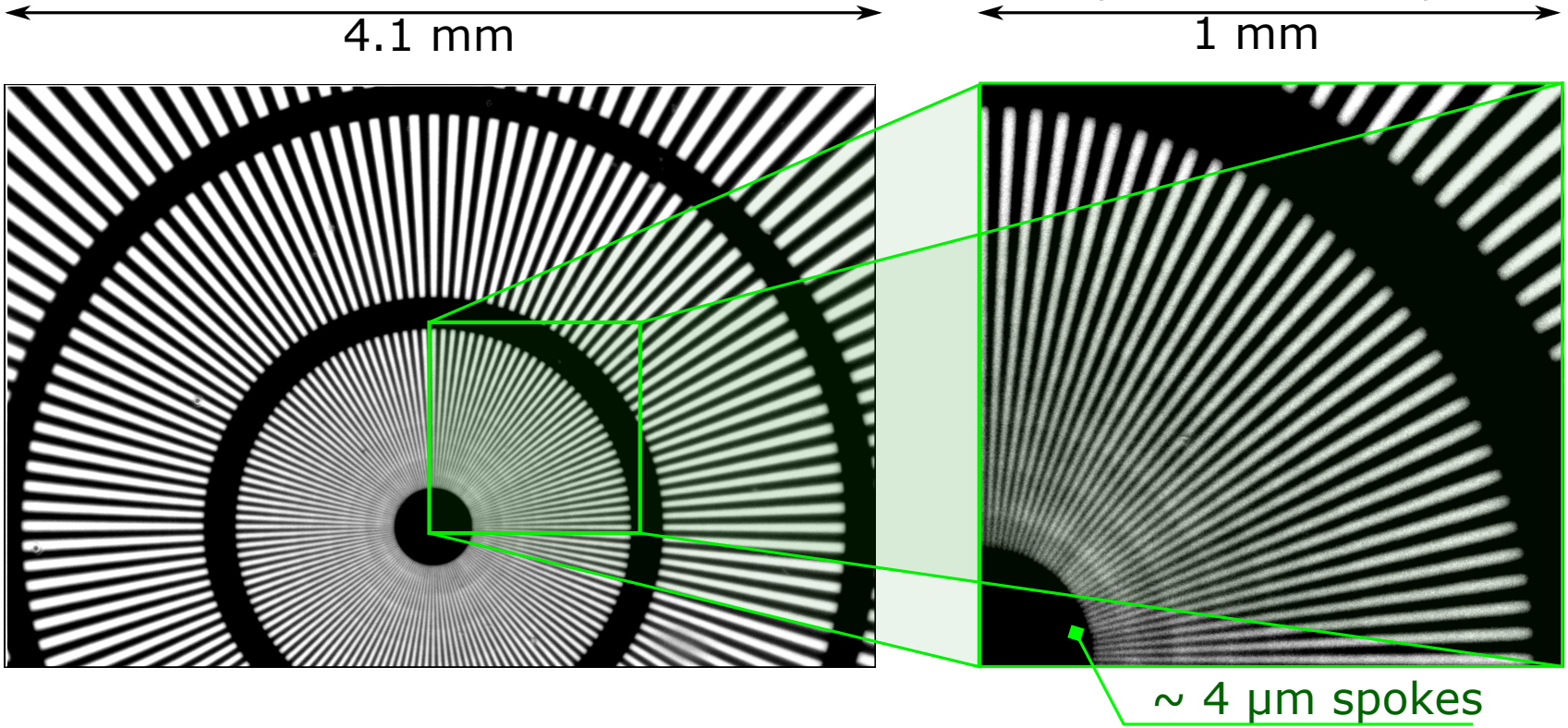


temporal resolution: 1.5s tomographies



Totzke *et al.*, 2019 Optics Express

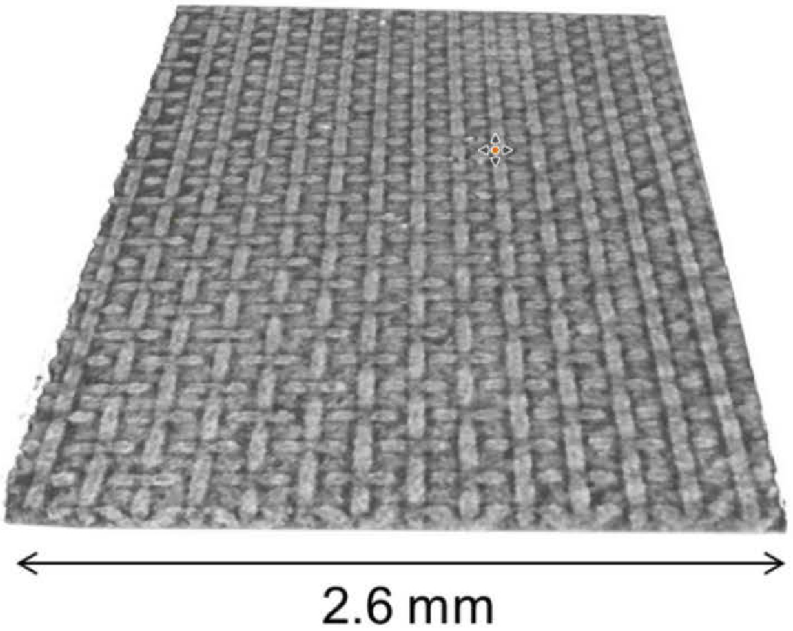
spatial resolution: $\leq$ **3** μ**m resolution** (pixel 0.75 um)



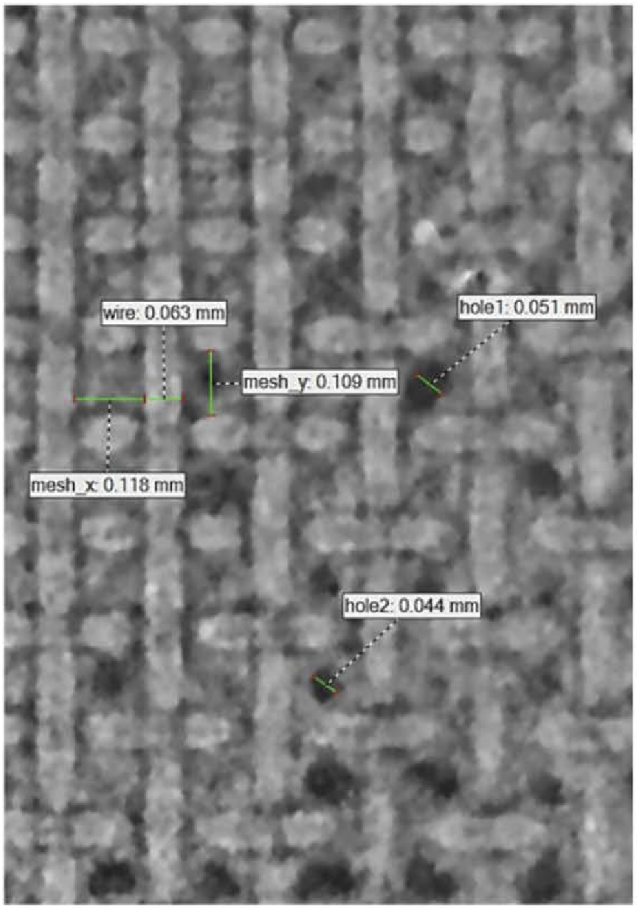
Tengattini, Kardjilov, Helfen *et al.*, 2022 Optics Express

spatial resolution: $\leq$ 3 μm resolution (pixel size 1.5μm)

a)

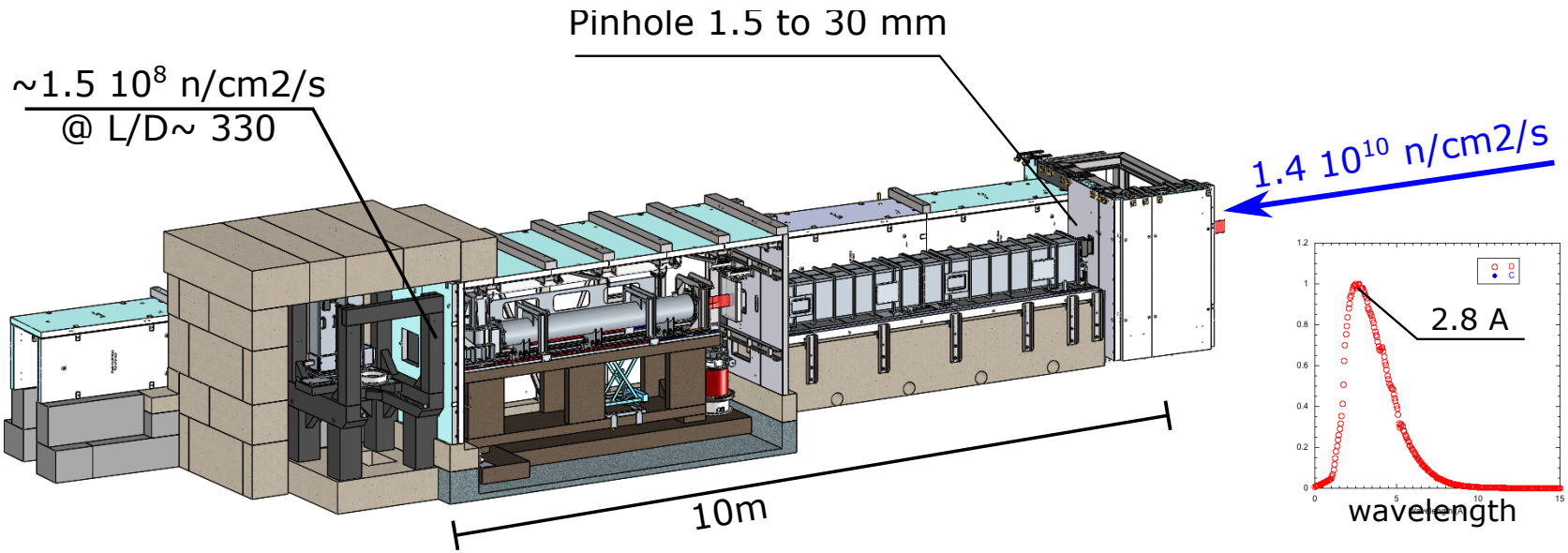


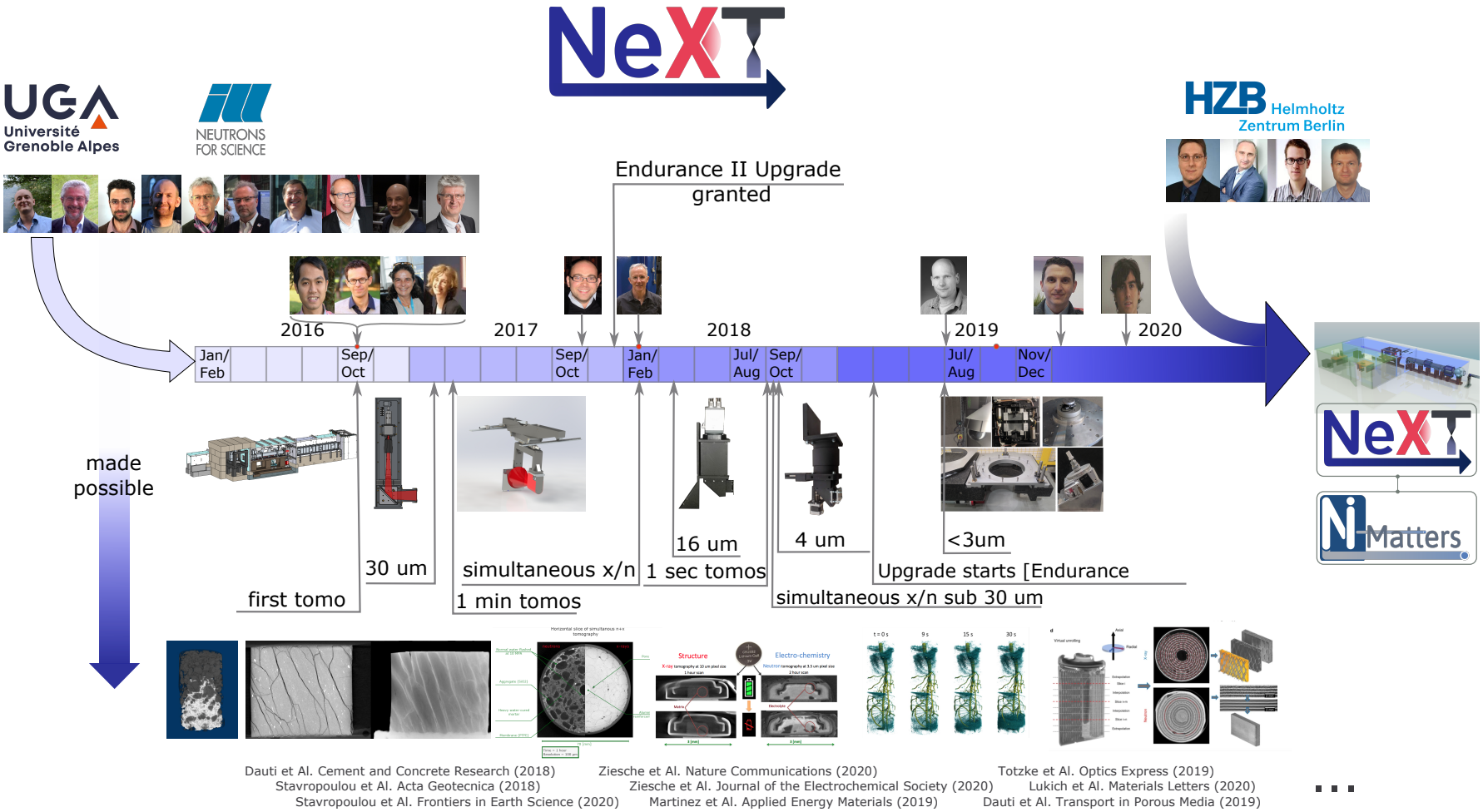
b)



$\sim$10h tomo Tengattini, *et al.*, 2022 Optics Express

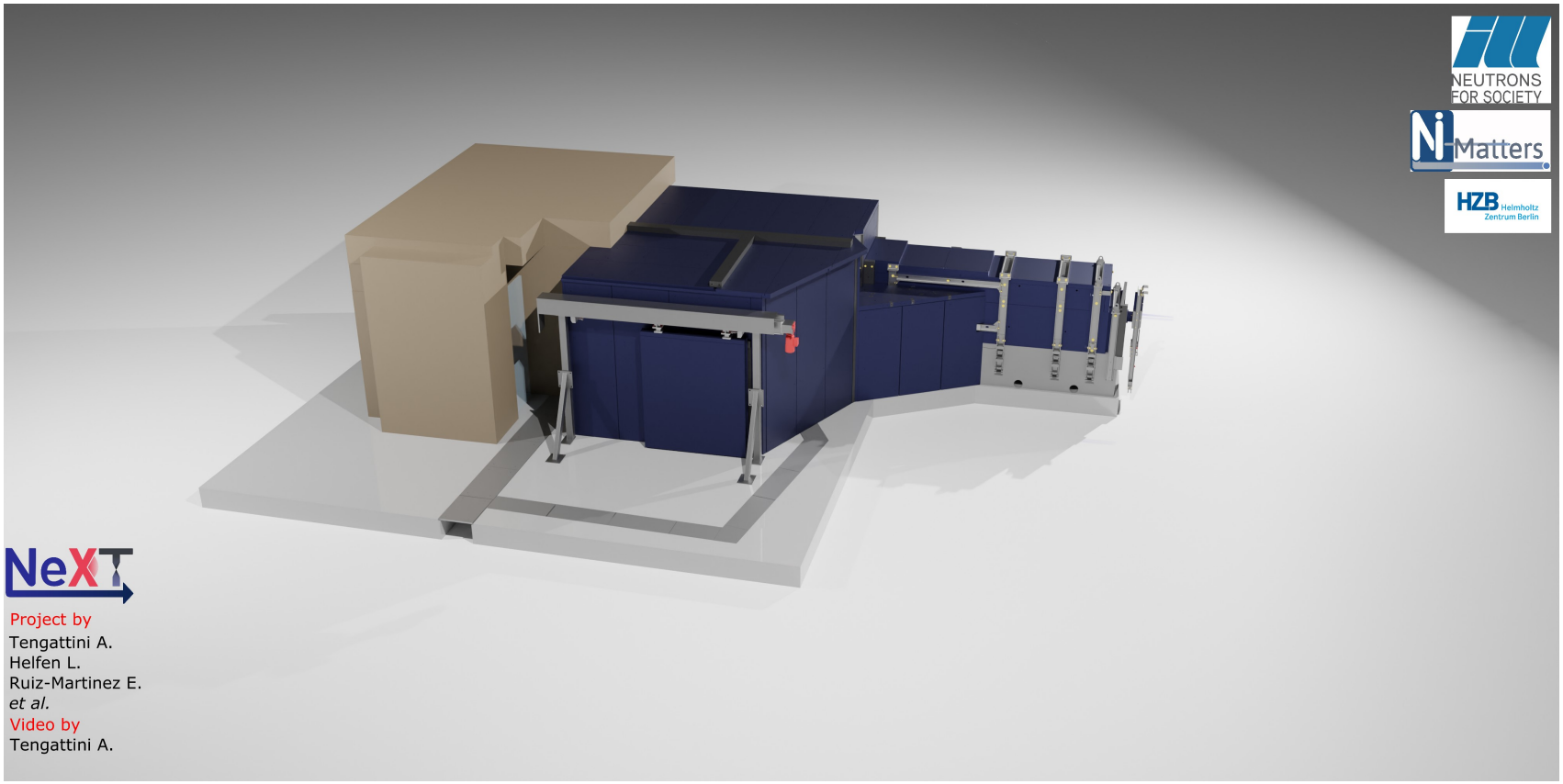
The old instrument (NeXT V.1.0)/ D50Tomo

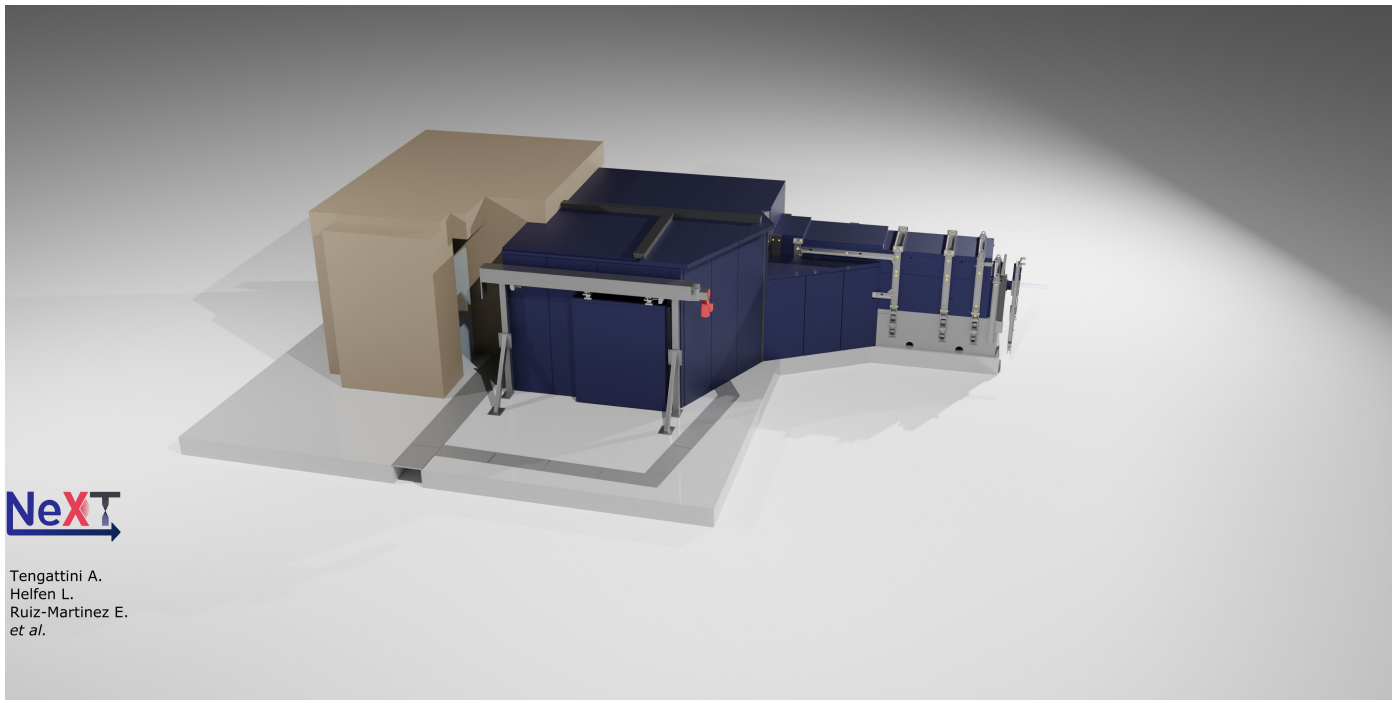




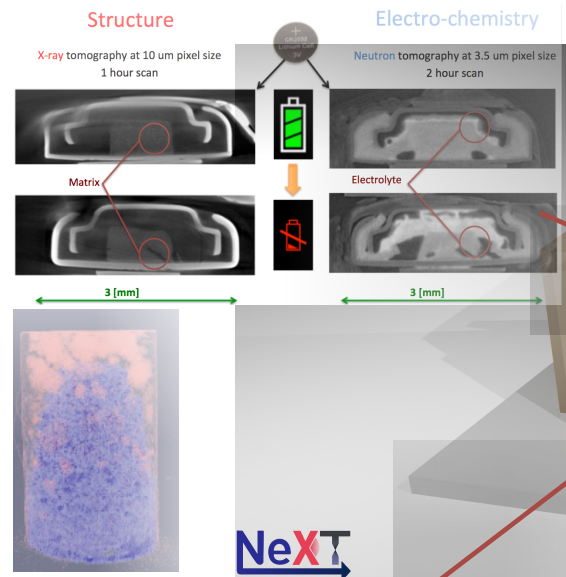
Dauti et Al. Cement and Concrete Research (2018)
Stavropoulou et Al. Acta Geotecnica (2018)
Stavropoulou et Al. Frontiers in Earth Science (2020)
Ziesche et Al. Nature Communications (2020)
Ziesche et Al. Journal of the Electrochemical Society (2020)
Martinez et Al. Applied Energy Materials (2019)
Totzke et Al. Optics Express (2019)
Lukich et Al. Materials Letters (2020)
Dauti et Al. Transport in Porous Media (2019)
...

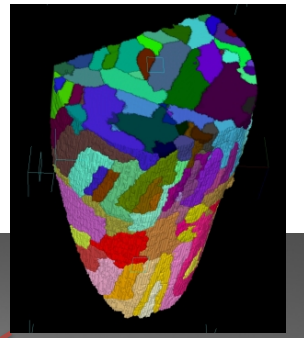
NeXT 2.0


NEUTRONS FOR SOCIETY
Ni-Matters
HZB Helmholtz Zentrum Berlin
NeXT
Project by
Tengattini A.
Helfen L.
Ruiz-Martinez E.
et al.
Video by
Tengattini A.


NeXT
Tengattini A.
Helfen L.
Ruiz-Martinez E.
et al.

Simultaneous 5D x+n at high speeds



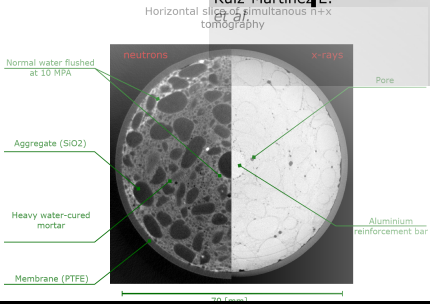


Grating Interferometry

NeXT

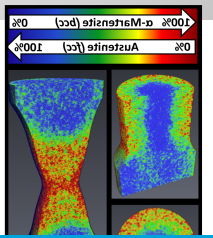
Advanced processing

Tengattini A.
Hall C.
Ruiz-Martinez E.
et al.

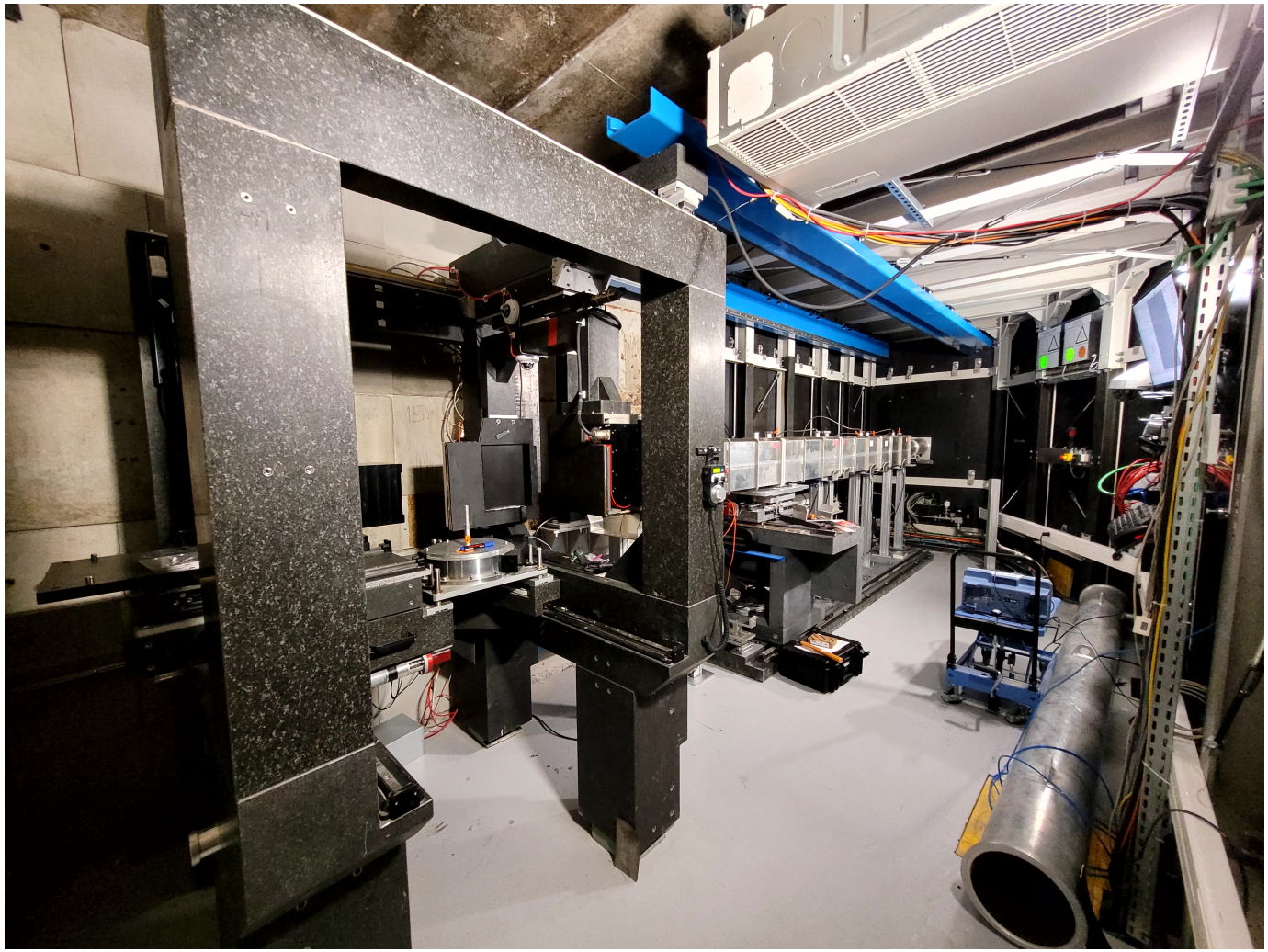


Polarised

Energy Selective



The status quo



- Temendous possibilities from Neutron and x-ray imaging
- Neutron Imaging now down to $\leq 4\mu$m resolution and up to 1s tomographies (at much coarser resolutions)
- These images are *quantitative*, *i.e.*, they are **data**
- Plenty of things to fix, plenty of things to develop, in particular in the joint use of x-rays and neutrons

there is still plenty of work (and fun) ahead!

Want to know more?

- About neutron (plus x-ray) imaging review papers:
  - *For Geomechanics:* Tengattini *et al.*, Geom. Ener. Envir. (2021)
  - *For Material science :* Kardjilov *et al.*, Materials today (2018)
  - *For Fluid Flow:* Perfect *et al.*, Earth Science Review (2014)
- about NeXT-Grenoble:
  - Tengattini *et al.*, Nucl. Inst. Met. Phys. Res. A (2020)
  - `contact@next-grenoble.fr`
  - `https://next-grenoble.fr/`

Many many people to thank!


C. Viggiani


E. Ando'


S. Hall


L. Helfen

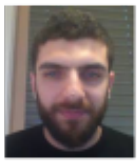

N. Lenoir


N. Kardjilov


C. Couture


D. Atkins


S. Dal Pont


H. Cheick-Sleiman


M. Briffaut


D. Dauti


F. Dufour


E. Stavropoulou


B. Lukich


M. Extegarai


E. Tudisco


P. Besuelle


E.M. Charalampidou


H. Lewis


G. Couples


M. Madankan


P. Szymczak


M. Cooper


S. Robuschi


J. Dijkstra


J Andrade


S. Roshankhah


F. Renard


A. Pluymakers


B. Cordonnier


D. Gregoire