

Modelling the deformation of an X-ray micro-CT based 3D structure

Semester project – Final presentation

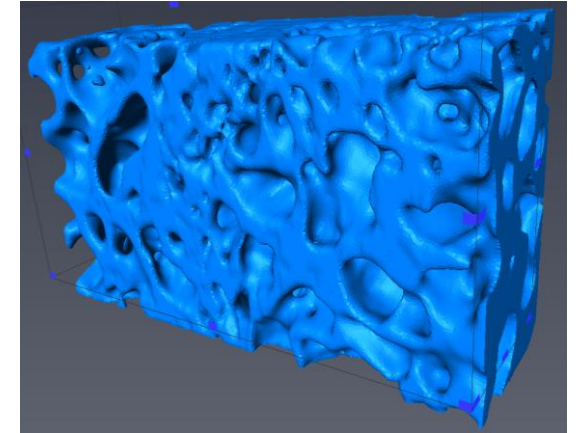
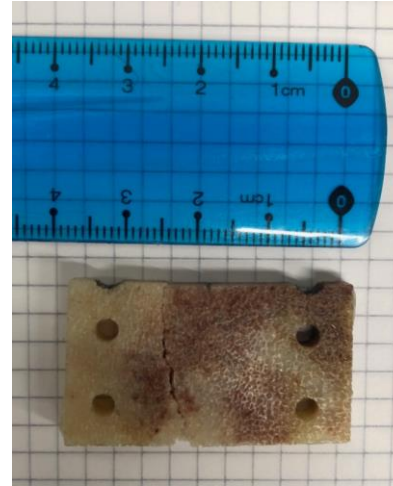
Olivier Schöpfer – EPFL – GC MA3



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Project objective

- From an existing sample
- to a numerical model
- to use with the software “Akantu”
from the EPFL LSMS lab
- in order to perform numerical testing of the sample



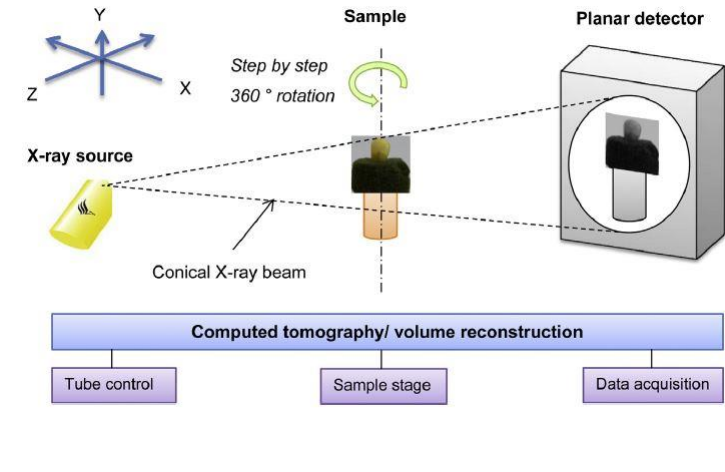
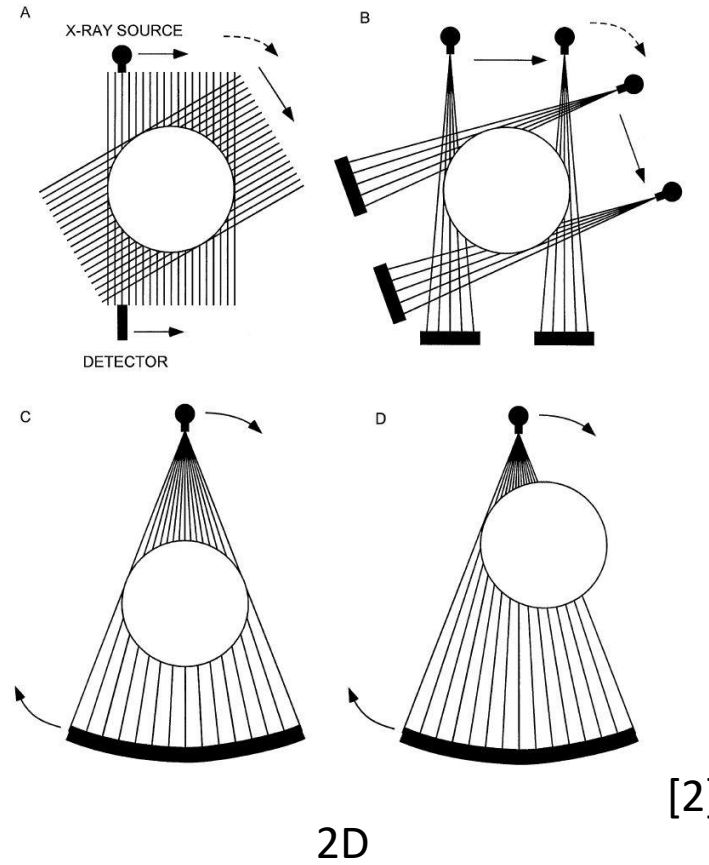
[1]

X-ray micro-CT : What is it?

- CT : Computed tomography
- Before the X-ray CT, the slices had to be taken manually and examined by hand, one by one
 - Very long
 - Sample destroyed
- Produces images similar to an X-ray, but in 3D
 - Non destructive
 - High resolution
 - Fast + no sample preparation needed
 - Automated

X-ray micro-CT : How does it work?

- Procedure:



X-ray micro-CT : How does it work?

- The receptor is there to read the intensity of the X-ray in comparison to the intensity that was emitted
- The attenuation of the X-ray signal will give an indication on the material properties
- Final intensity :
$$I = I_0 \cdot \exp[-\mu \cdot x]$$
 - μ : attenuation coefficient
 - x : length of the x – ray path through the sample
- The attenuation coefficient depends on material properties

X-ray micro-CT : How does it work?

- Need for a good calibration

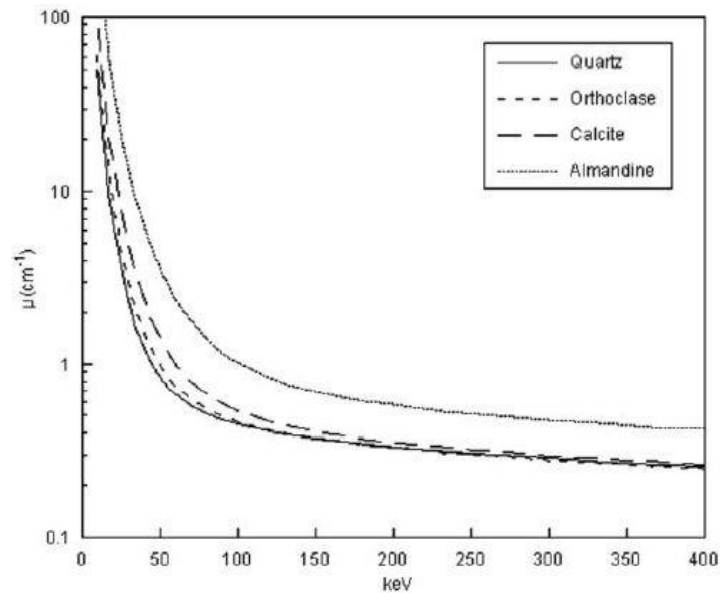


Fig. 3. Linear attenuation coefficient as function of X-ray energy for four rock-forming minerals. Such curves, when combined with the X-ray spectrum utilized for scanning (Fig. 2), allow prediction of ability to differentiate between minerals in CT images.

[4]

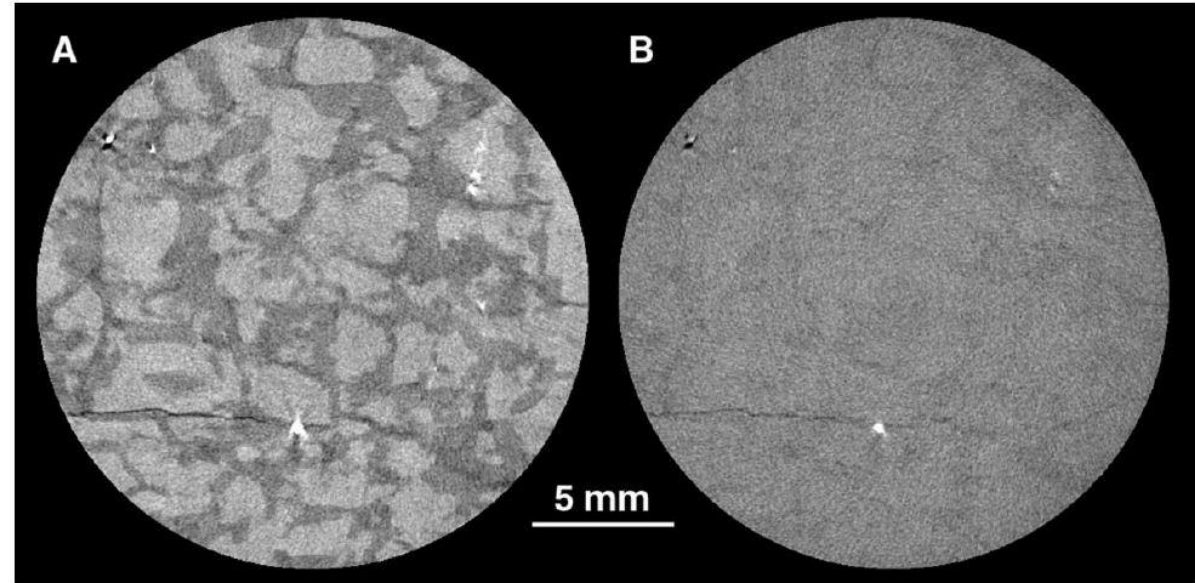


Fig. 4. Core of graphic granite imaged at various energy conditions. Field of view diameter for each image is 22 mm, and slice thickness is 100 μm . Scan (A) was created using X-ray energy of 100 keV and no beam filtration; scan (B) was acquired with X-ray energy of 200 keV and 1/8" brass filter. Both scans employed "self-wedge" calibration.

[5]

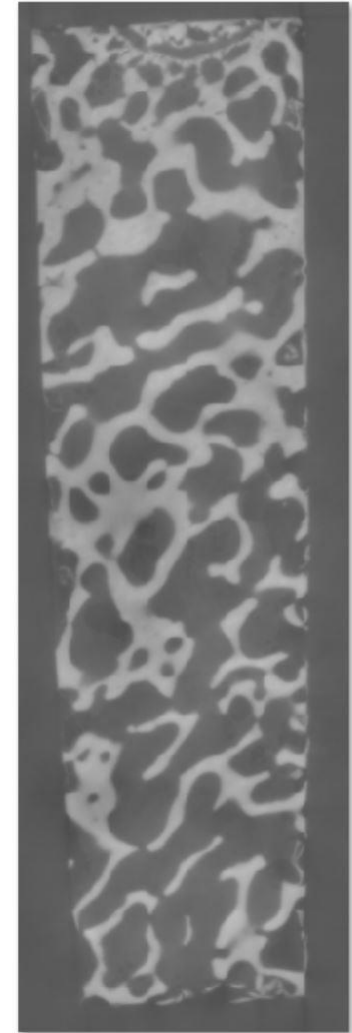
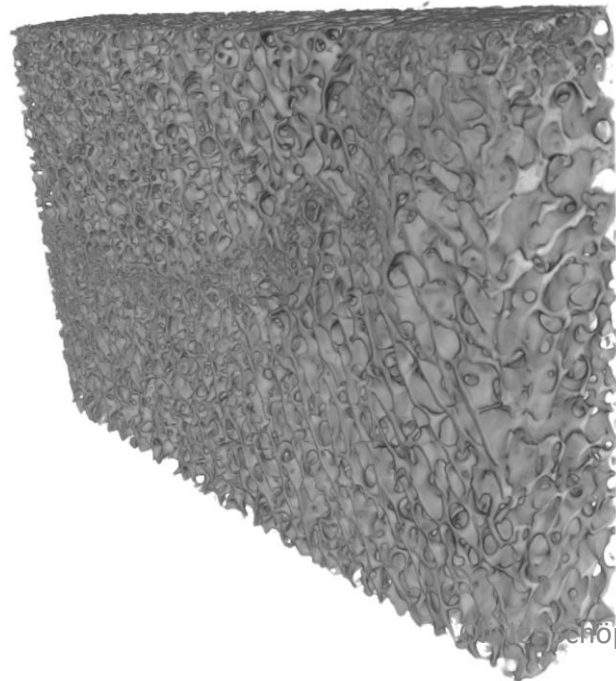
Low energy

High energy

Procedure to get a 3D model

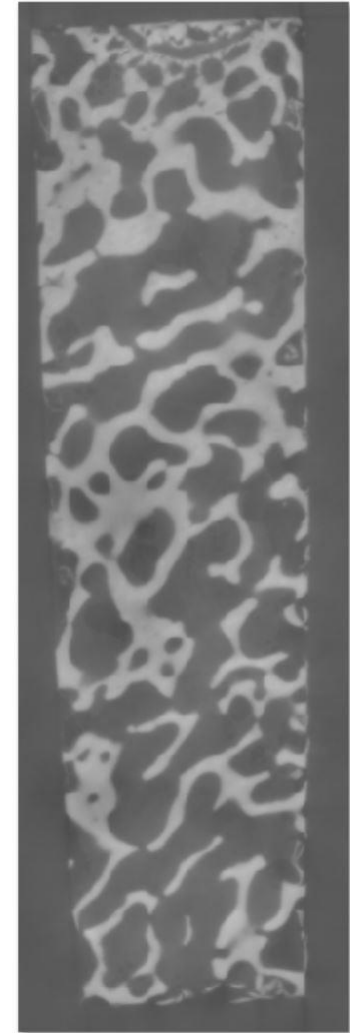
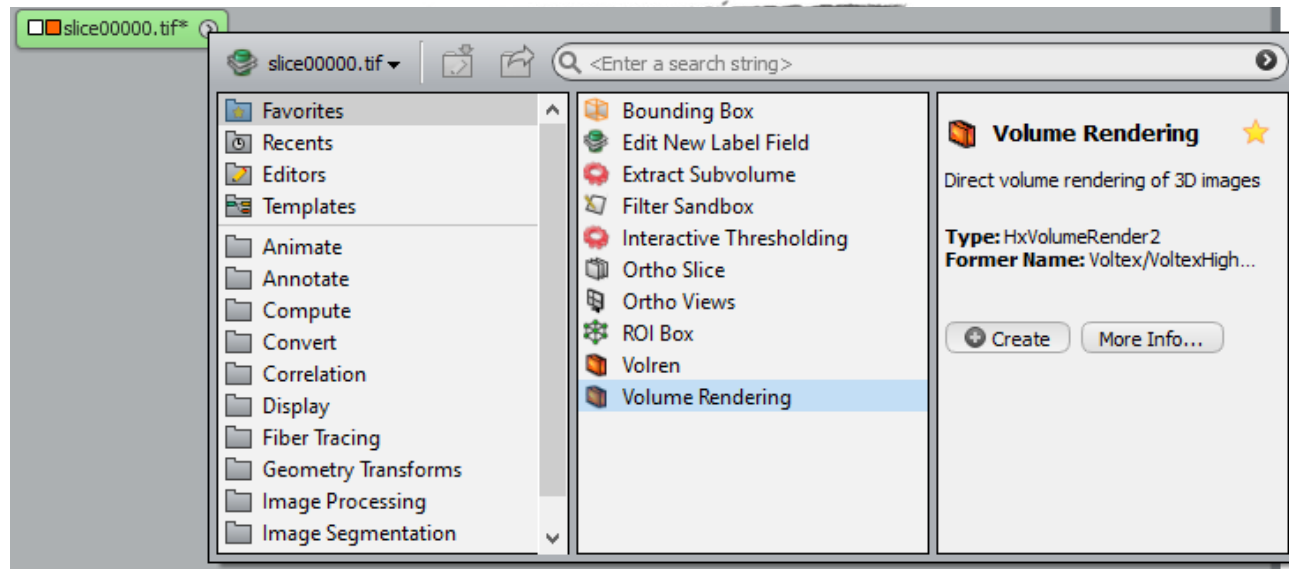
From a stack of slices to a 3D model

- What comes out of the X-ray CT scan
- What the 3D model looks like at first



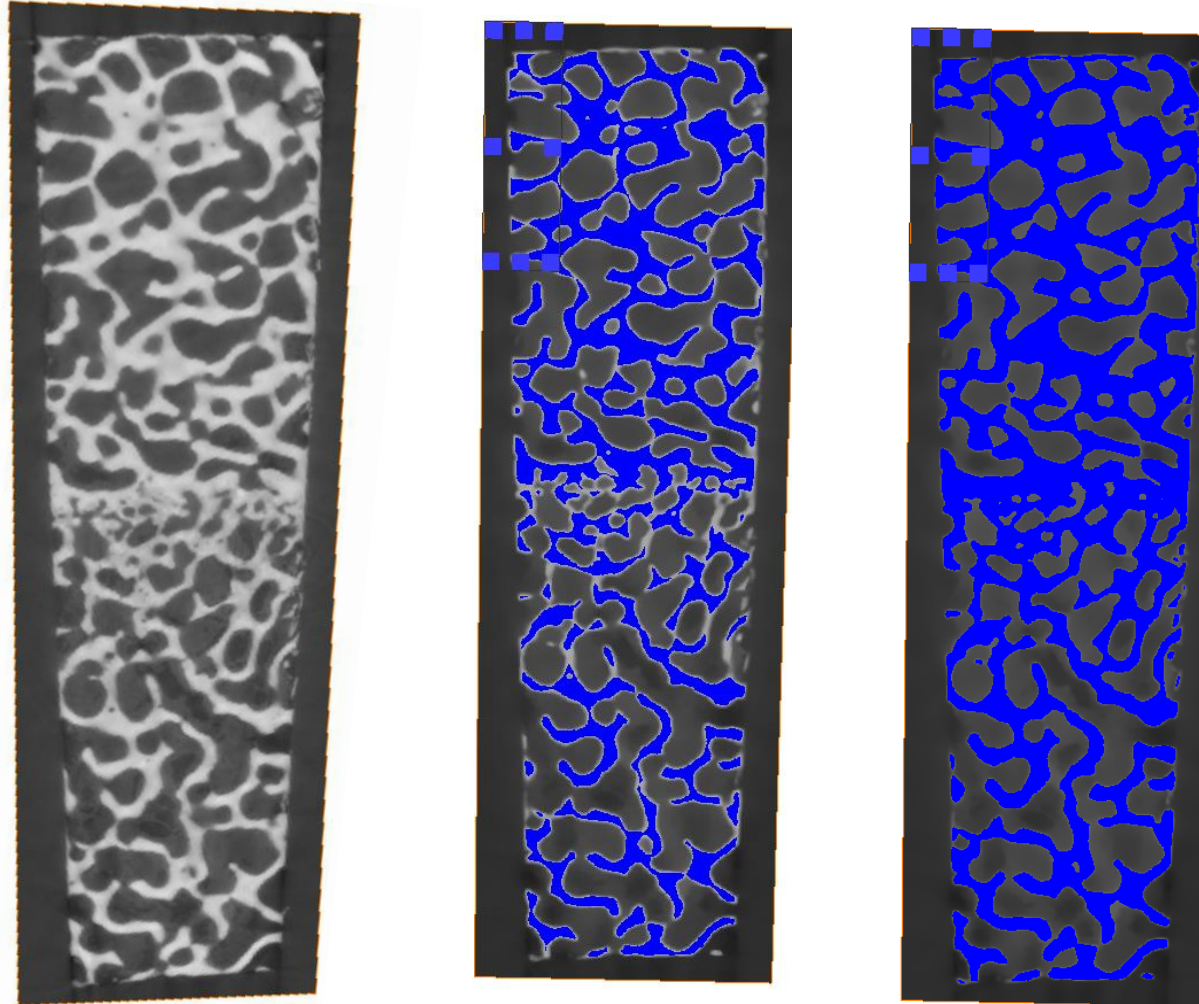
From a stack of slices to a 3D model

- What comes out of the X-ray CT scan
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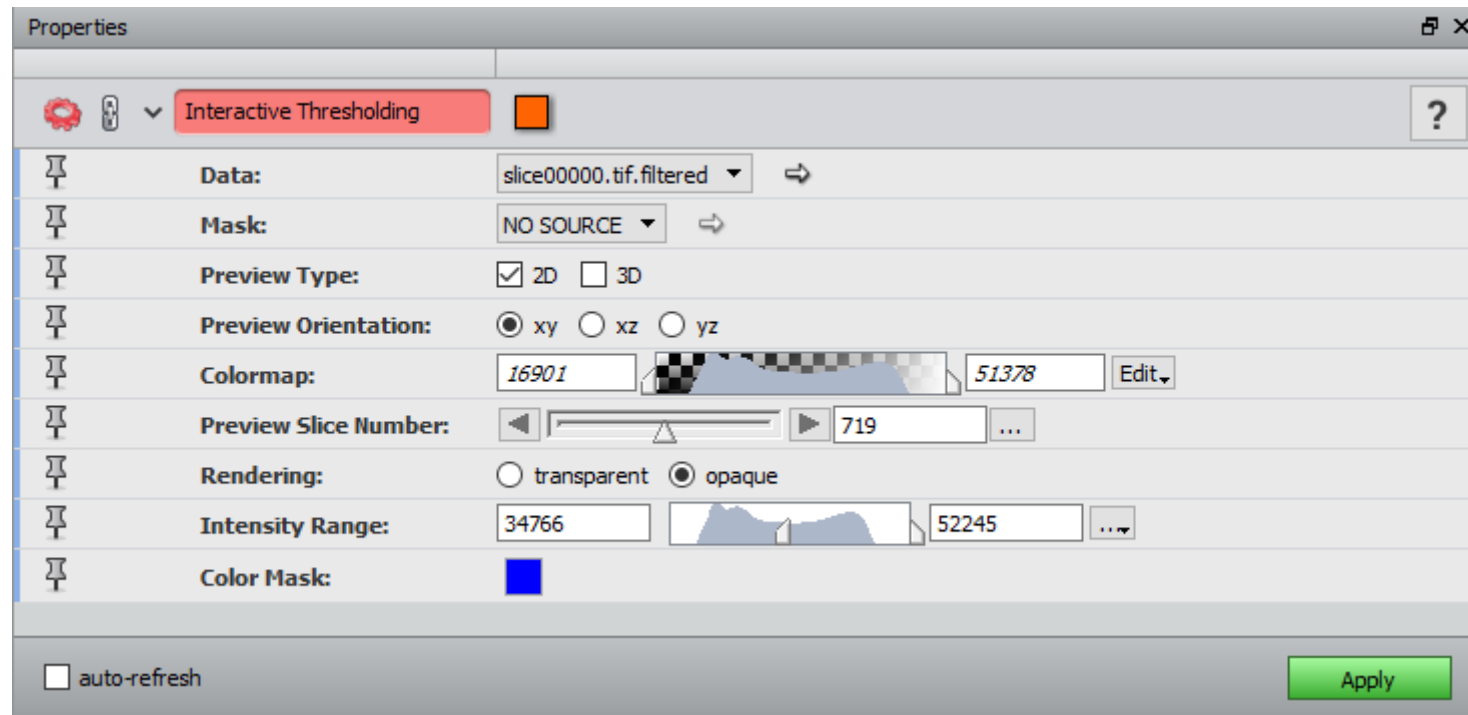
From a stack of slices to a 3D model

- Binarize the slices



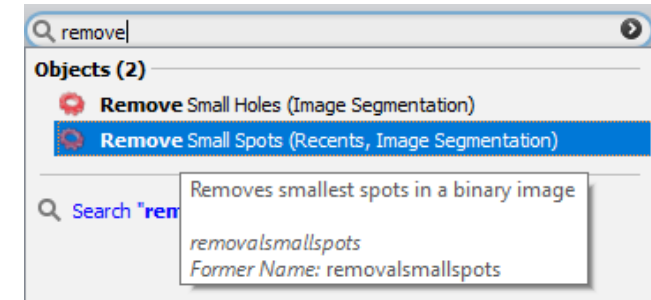
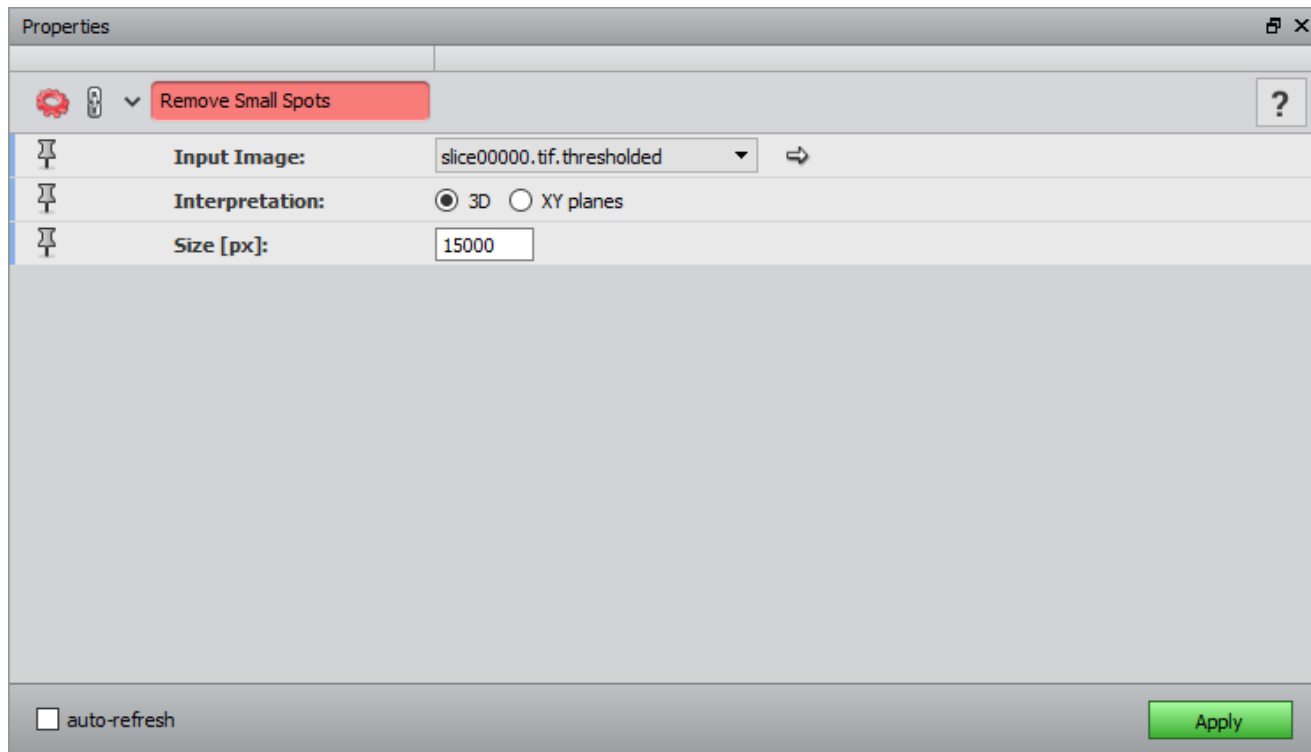
From a stack of slices to a 3D model

- Binarize the slices



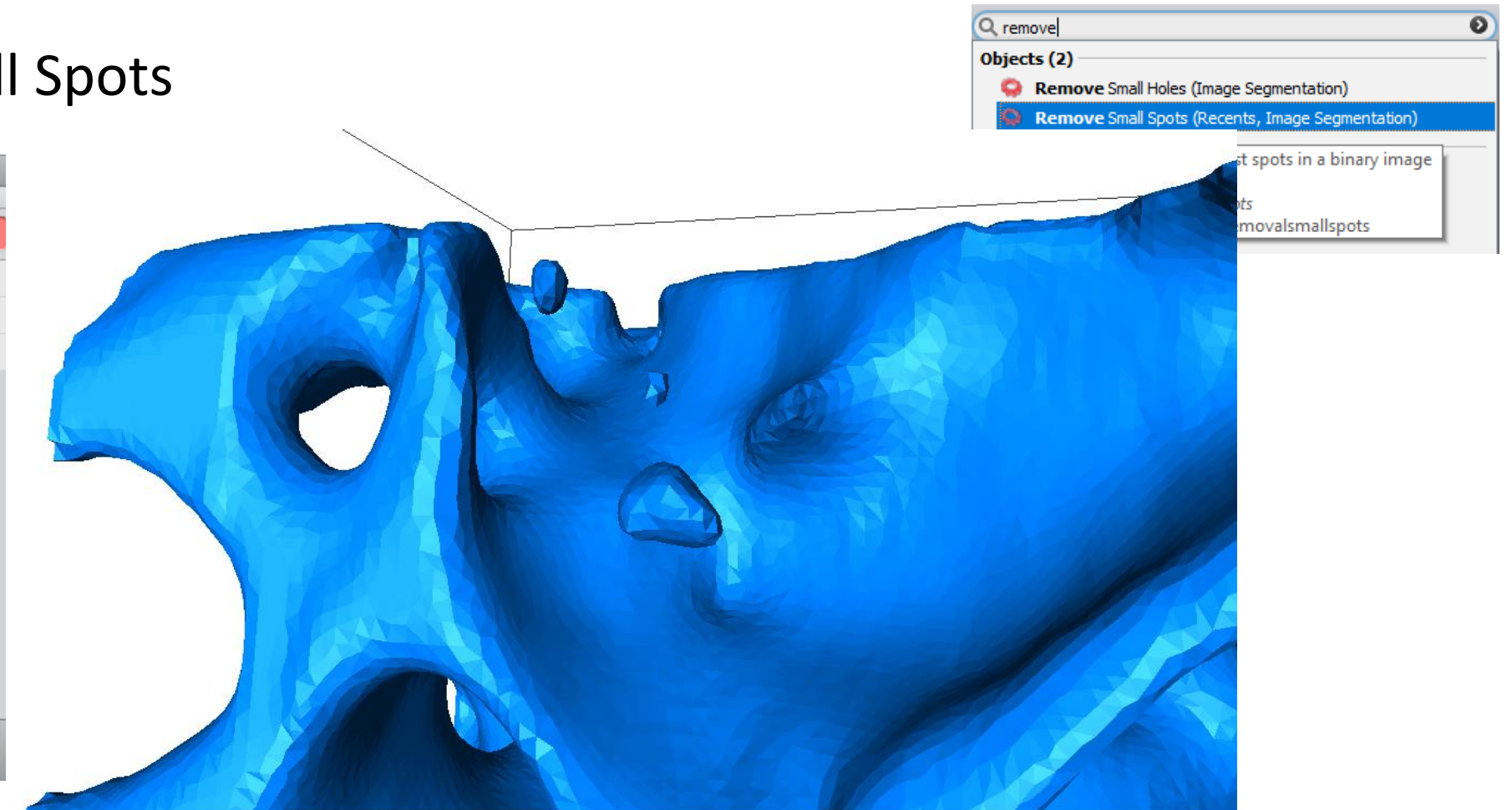
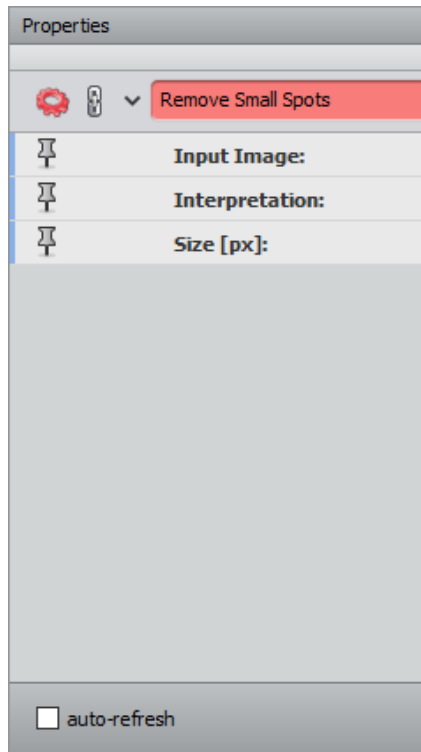
From a stack of slices to a 3D model

- Remove Small Spots



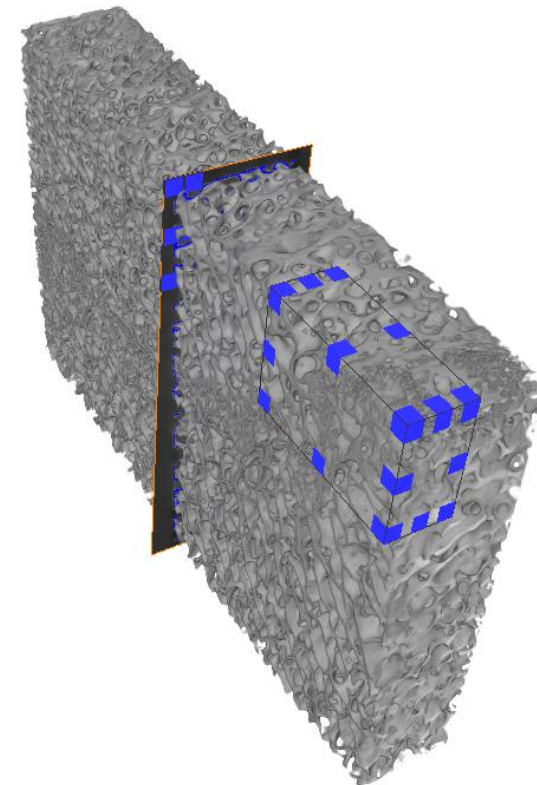
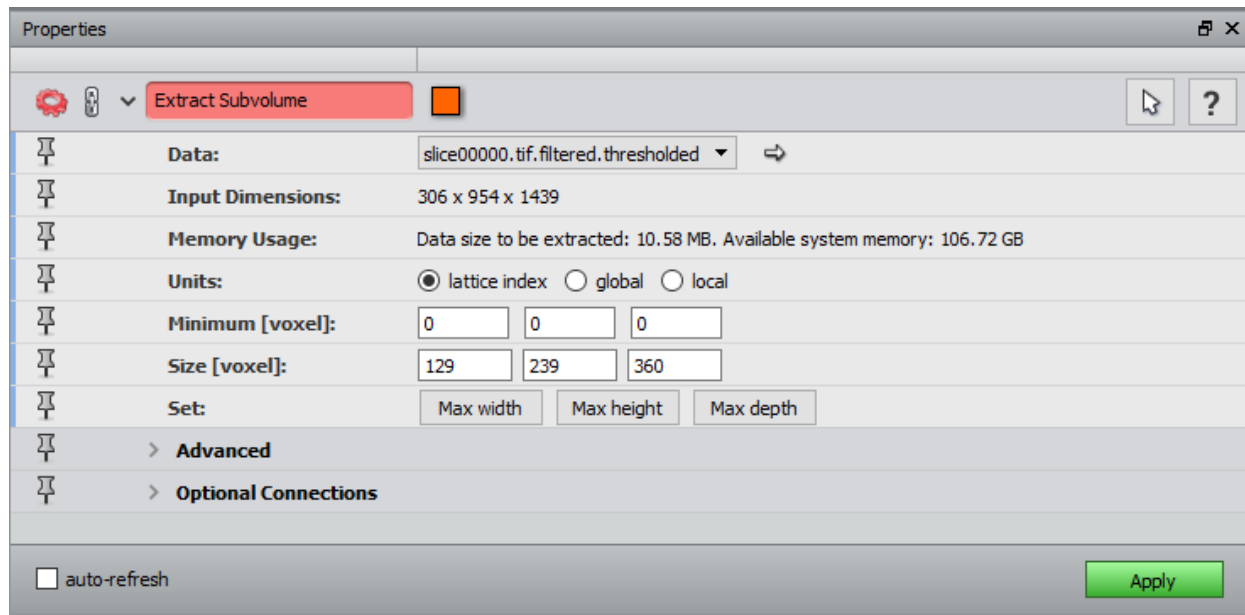
From a stack of slices to a 3D model

- Remove Small Spots



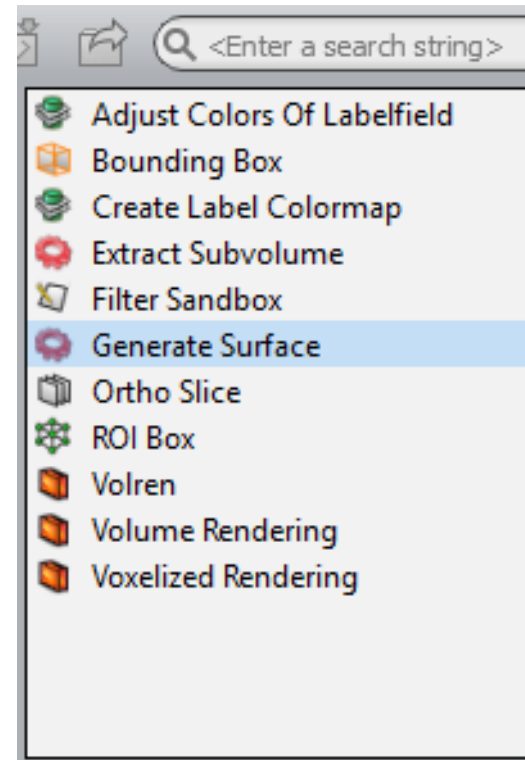
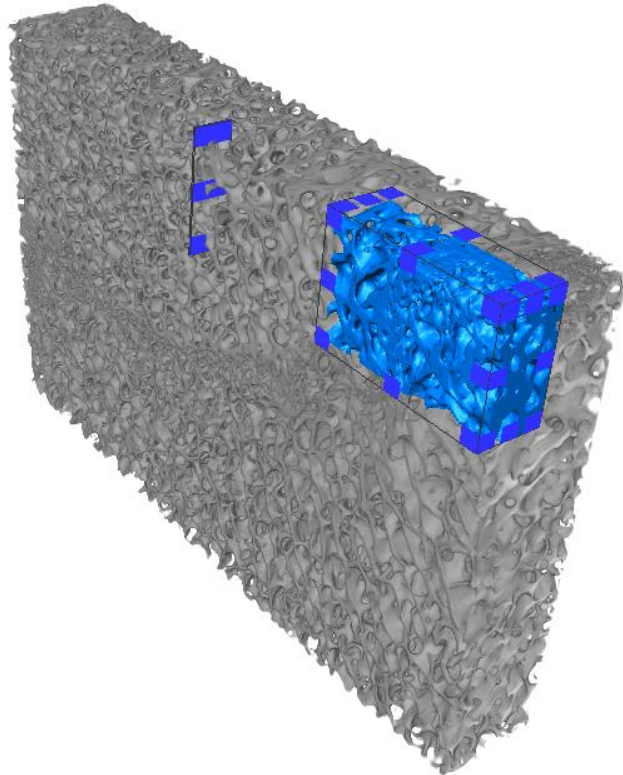
From a stack of slices to a 3D model

- Possible to extract a subvolume to have lower computation requirements



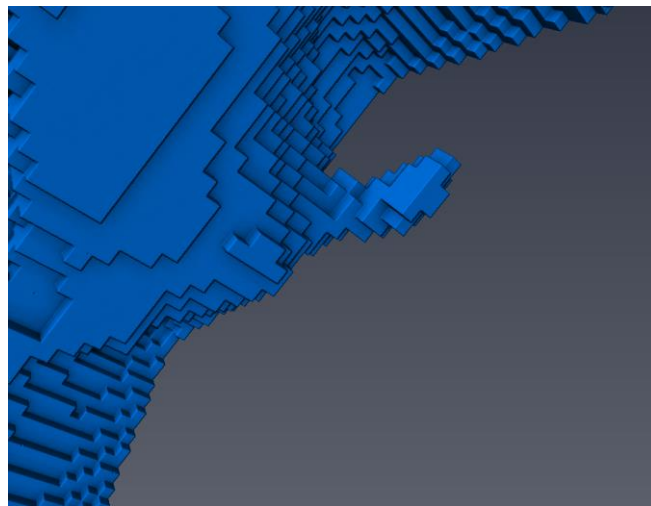
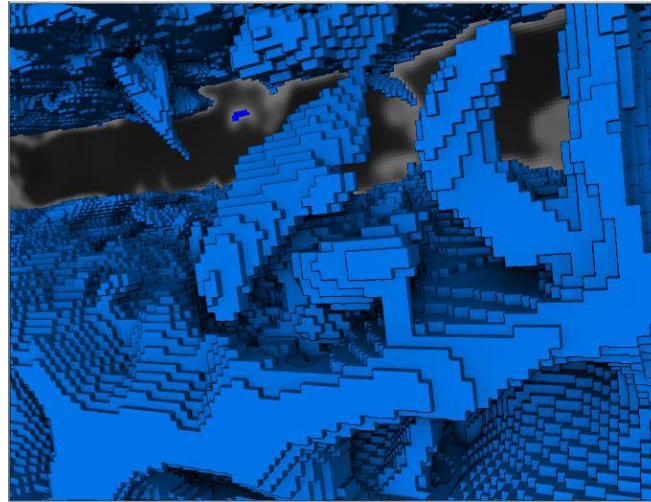
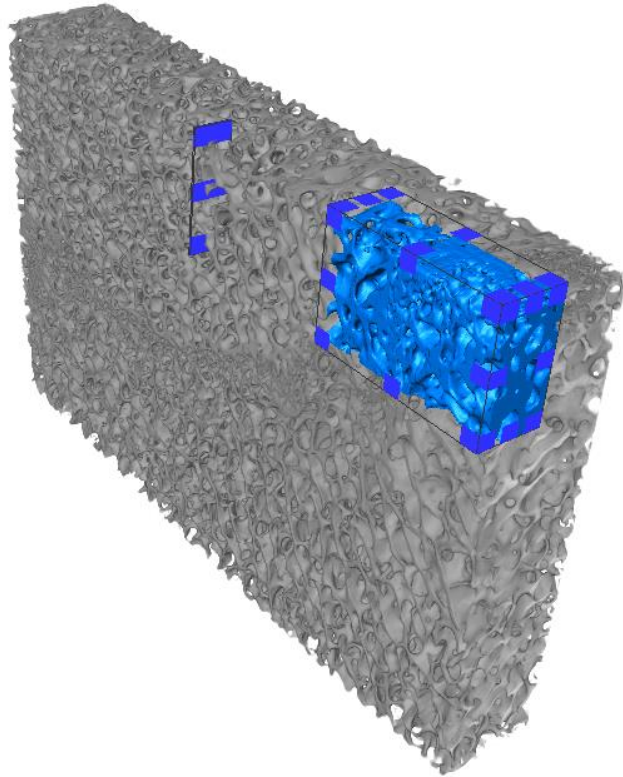
From a stack of slices to a 3D model

- Generate a surface



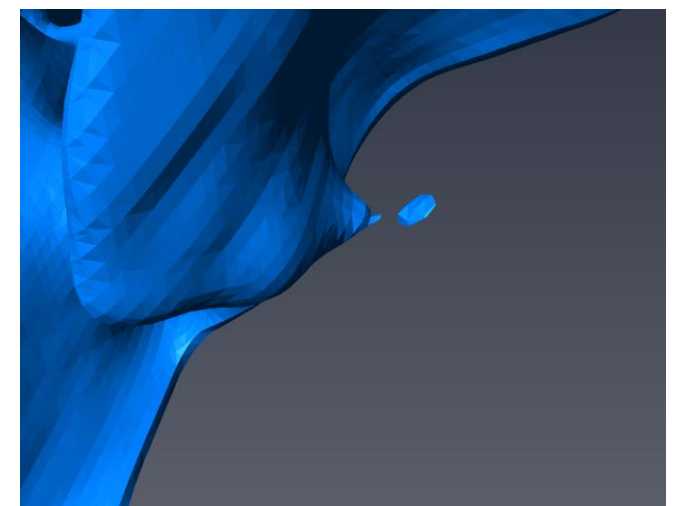
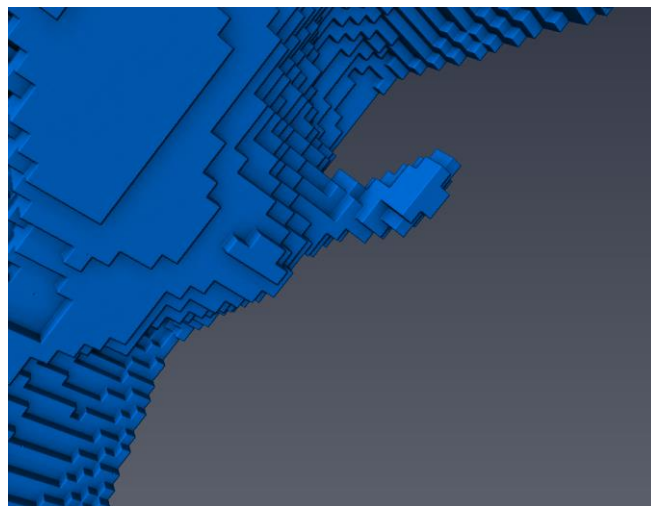
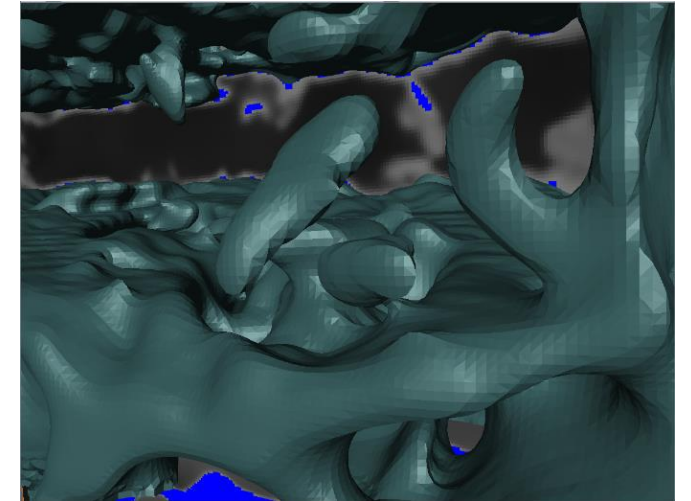
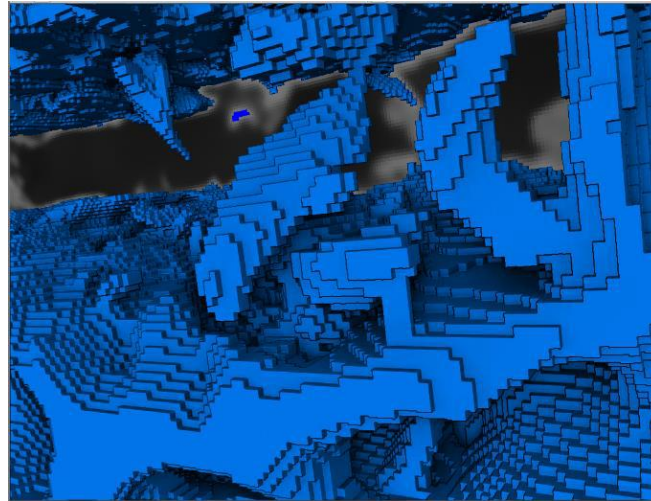
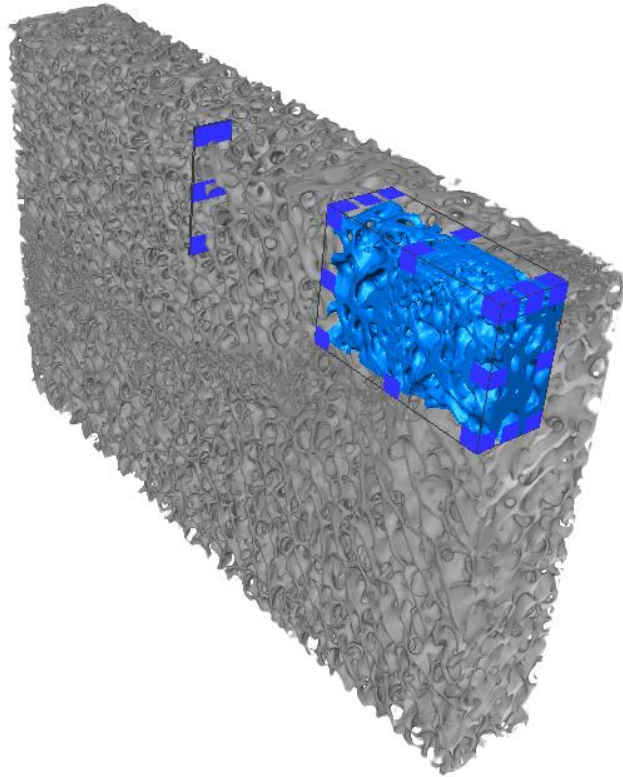
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- Generate a surface



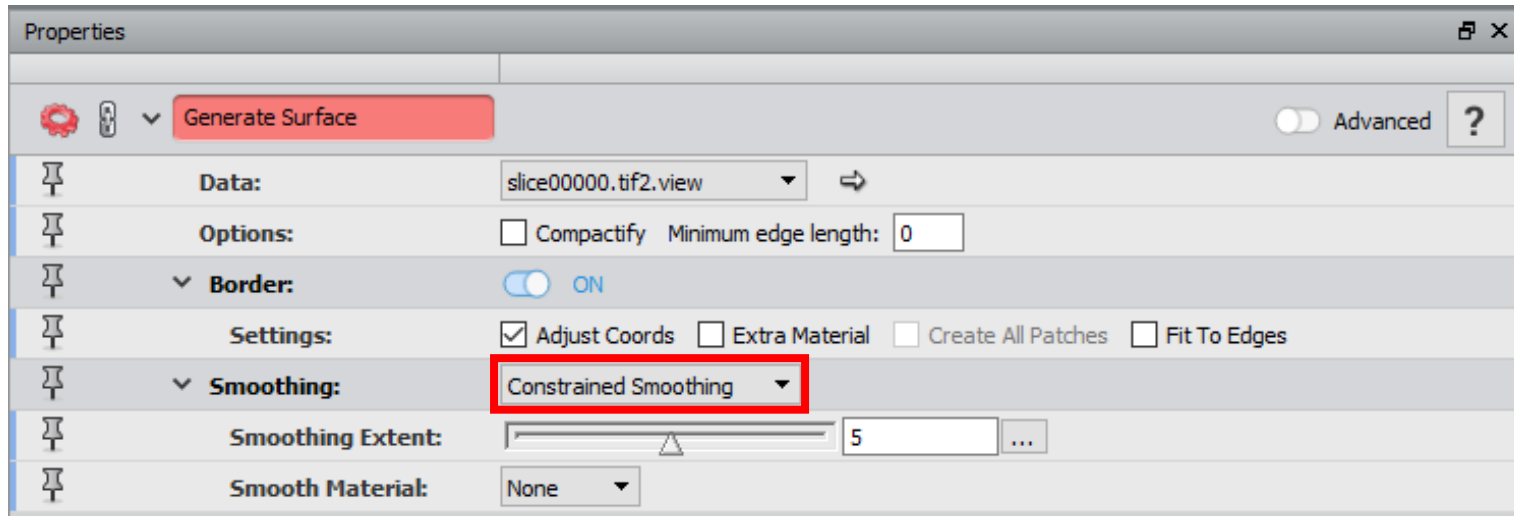
From a stack of slices to a 3D model

- Generate a surface



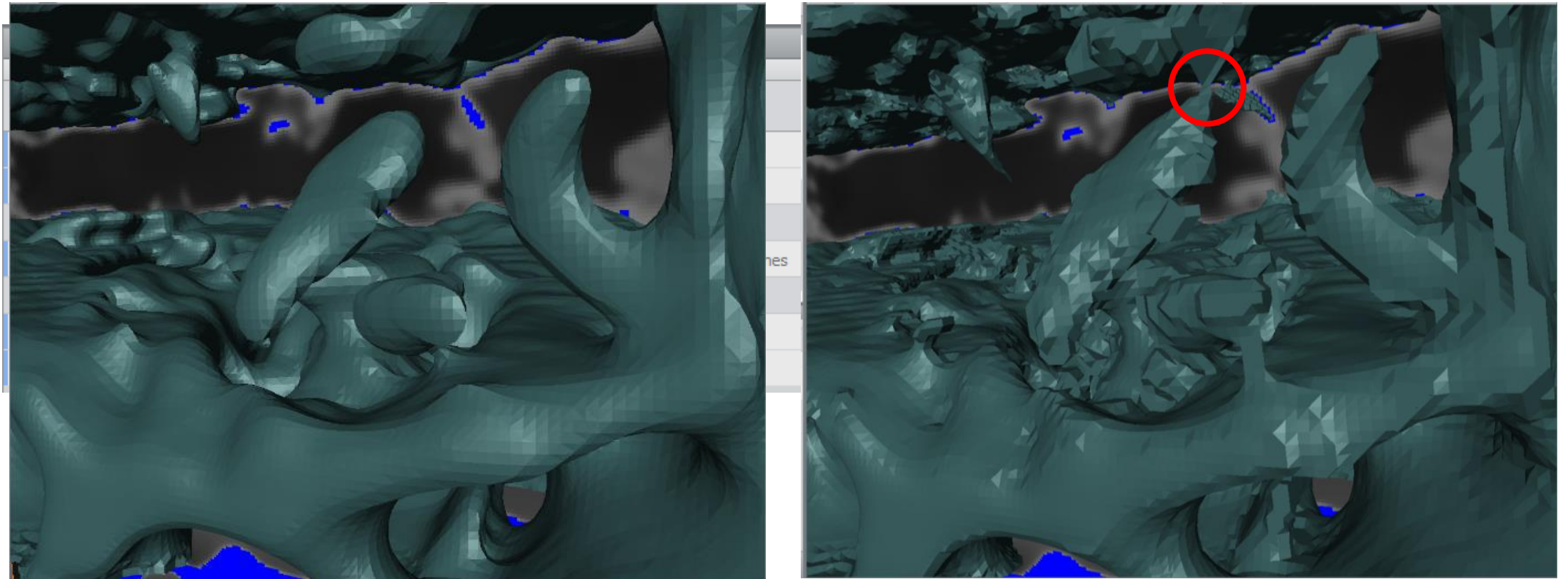
From a stack of slices to a 3D model

- Generate a surface - Constrained Smoothing



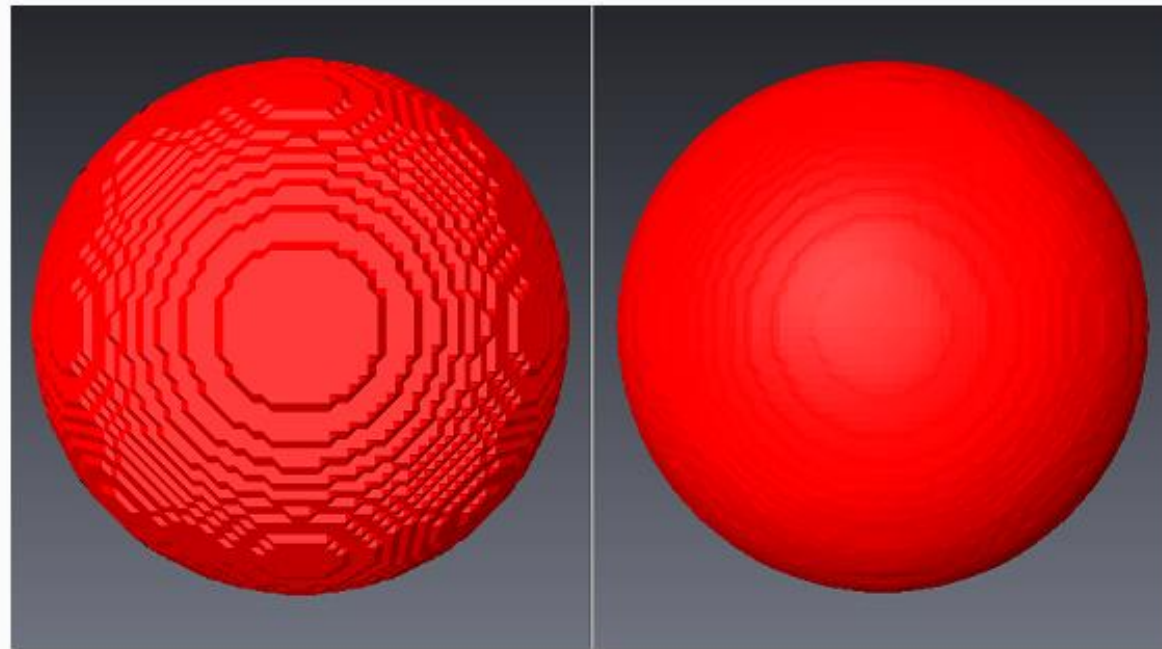
From a stack of slices to a 3D model

- Generate a surface - Constrained Smoothing



From a stack of slices to a 3D model

- Generate a surface - Constrained Smoothing: Problem



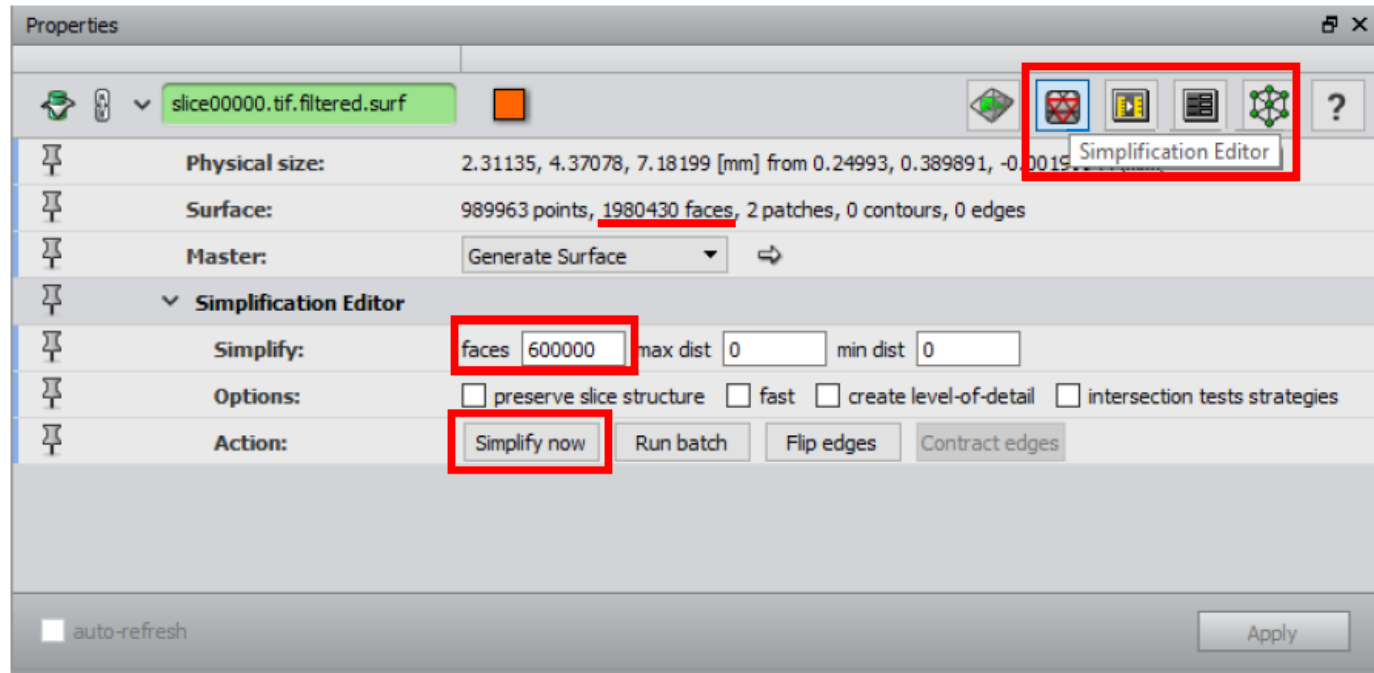
Smoothing set to 1

Smoothing set to 9

[6]

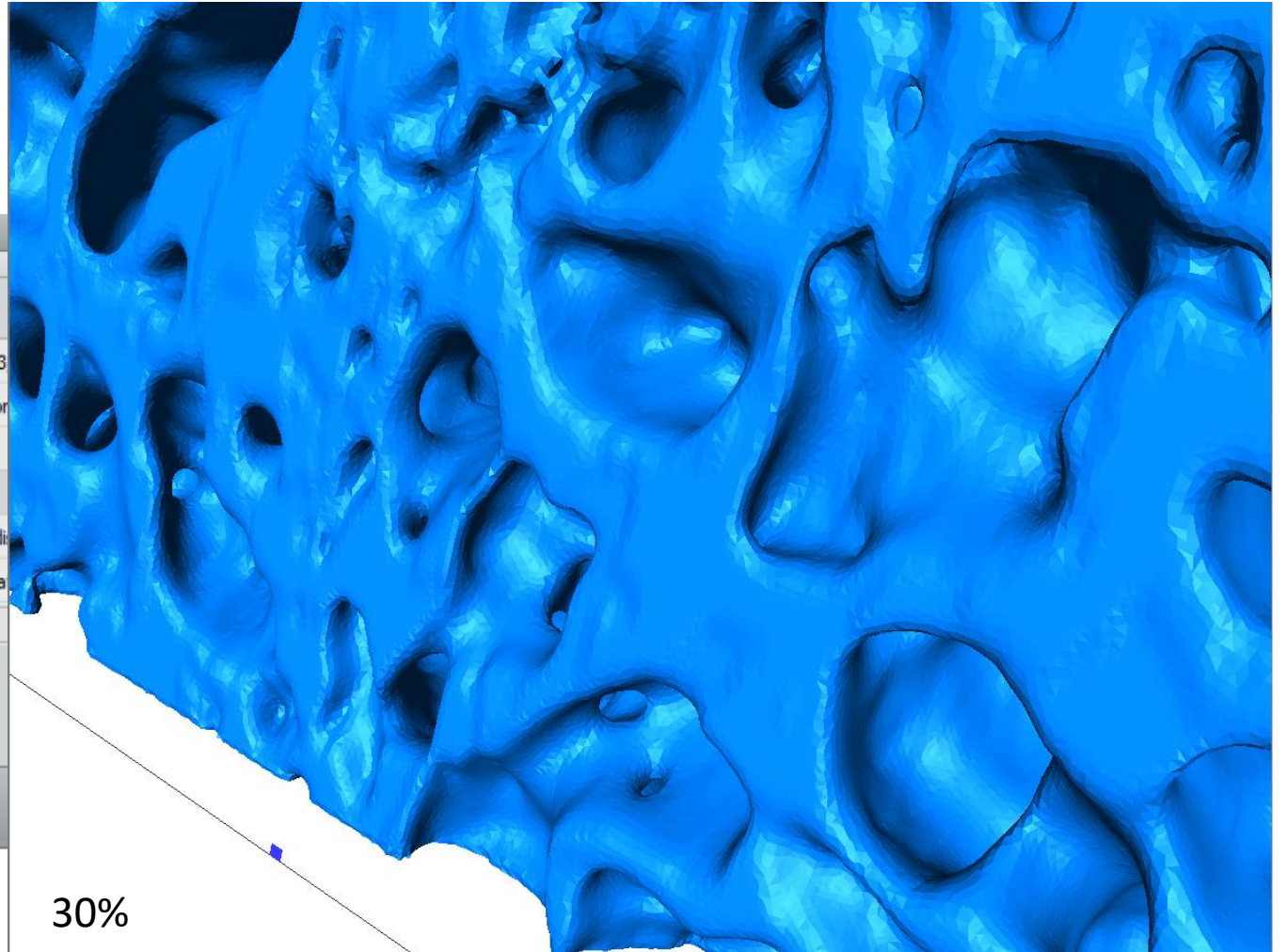
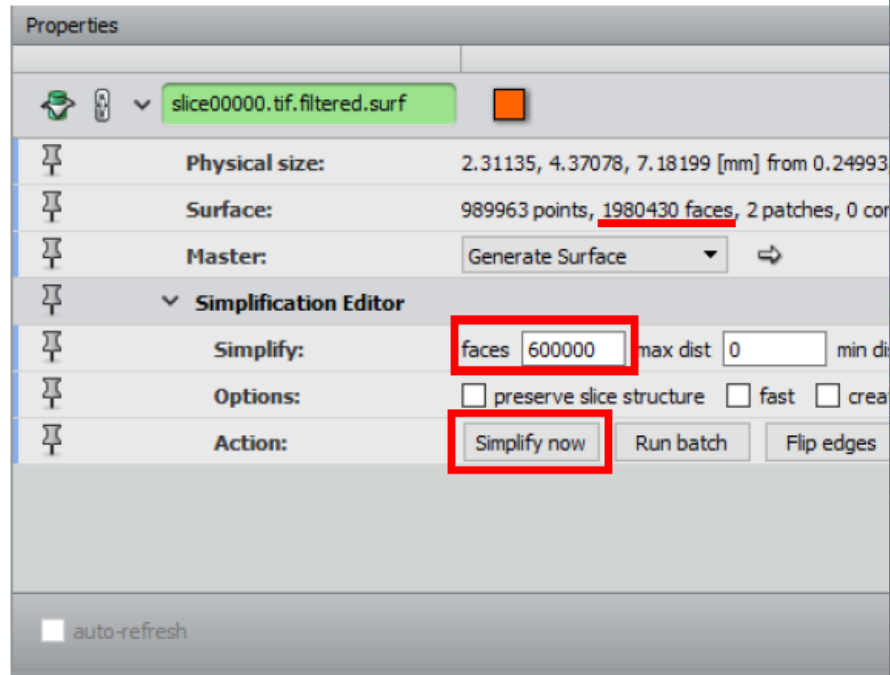
From a stack of slices to a 3D model

- Simplify the modelization



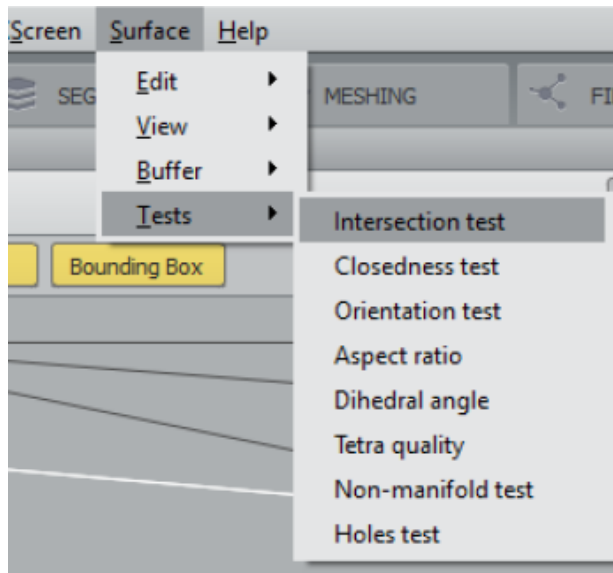
From a stack of slices to a 3D model

- Simplify the modelization

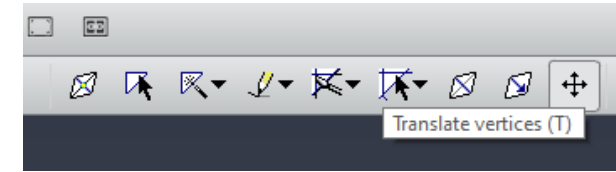


From a stack of slices to a 3D model

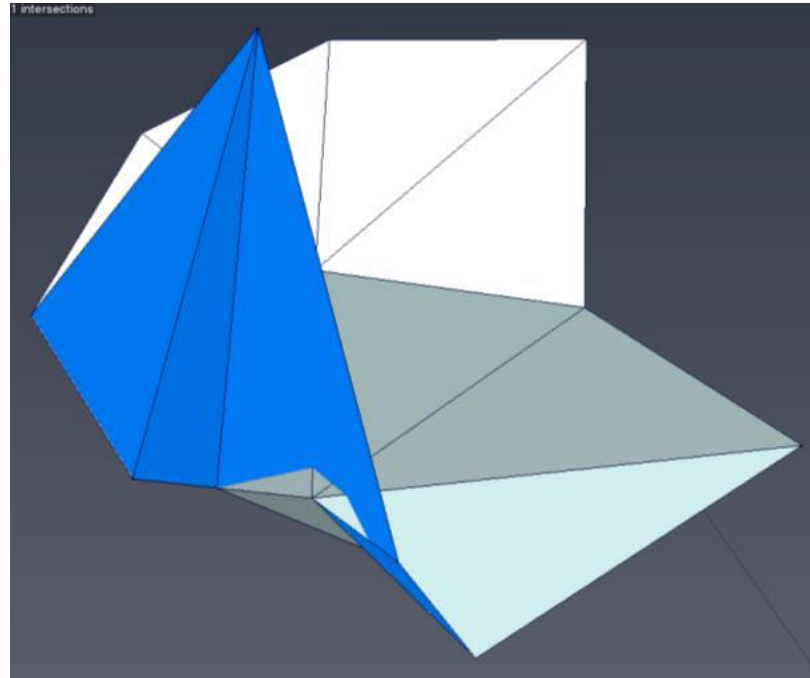
- Test the triangles before going to a tetrahedron model



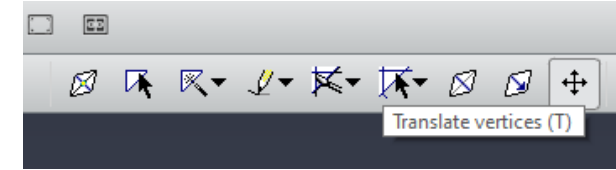
From a stack of slices to a 3D model



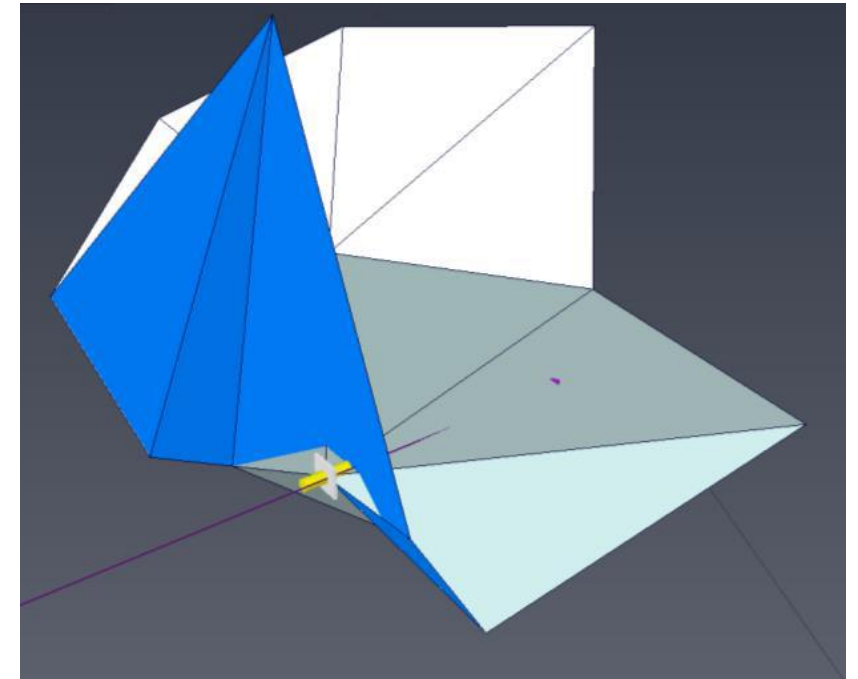
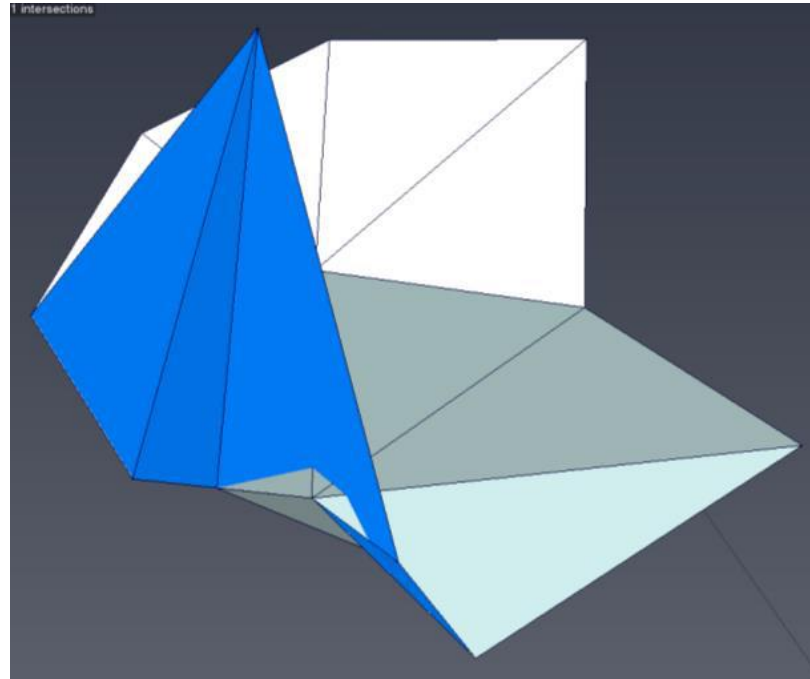
- Intersection test



From a stack of slices to a 3D model

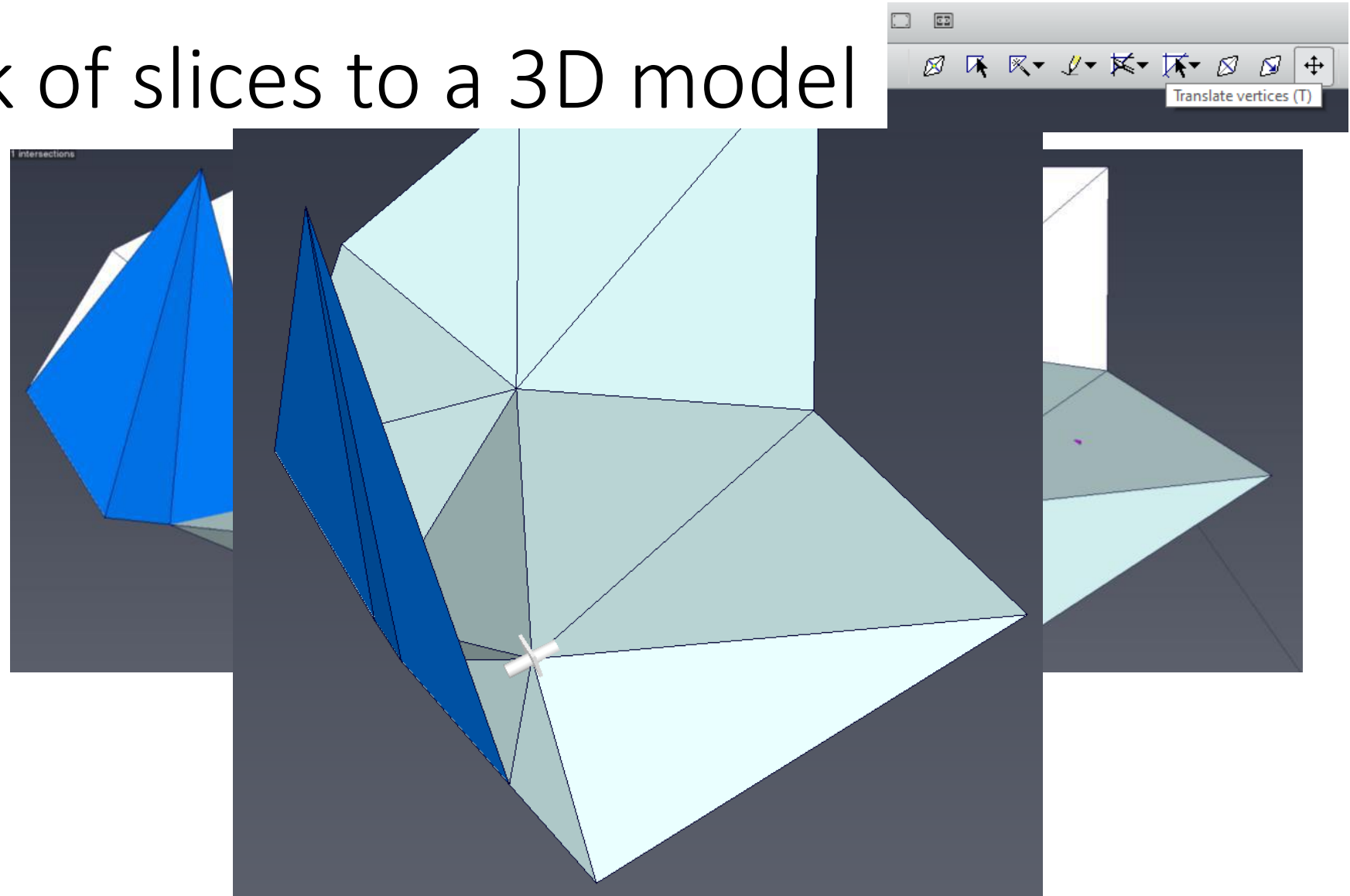


- Intersection test



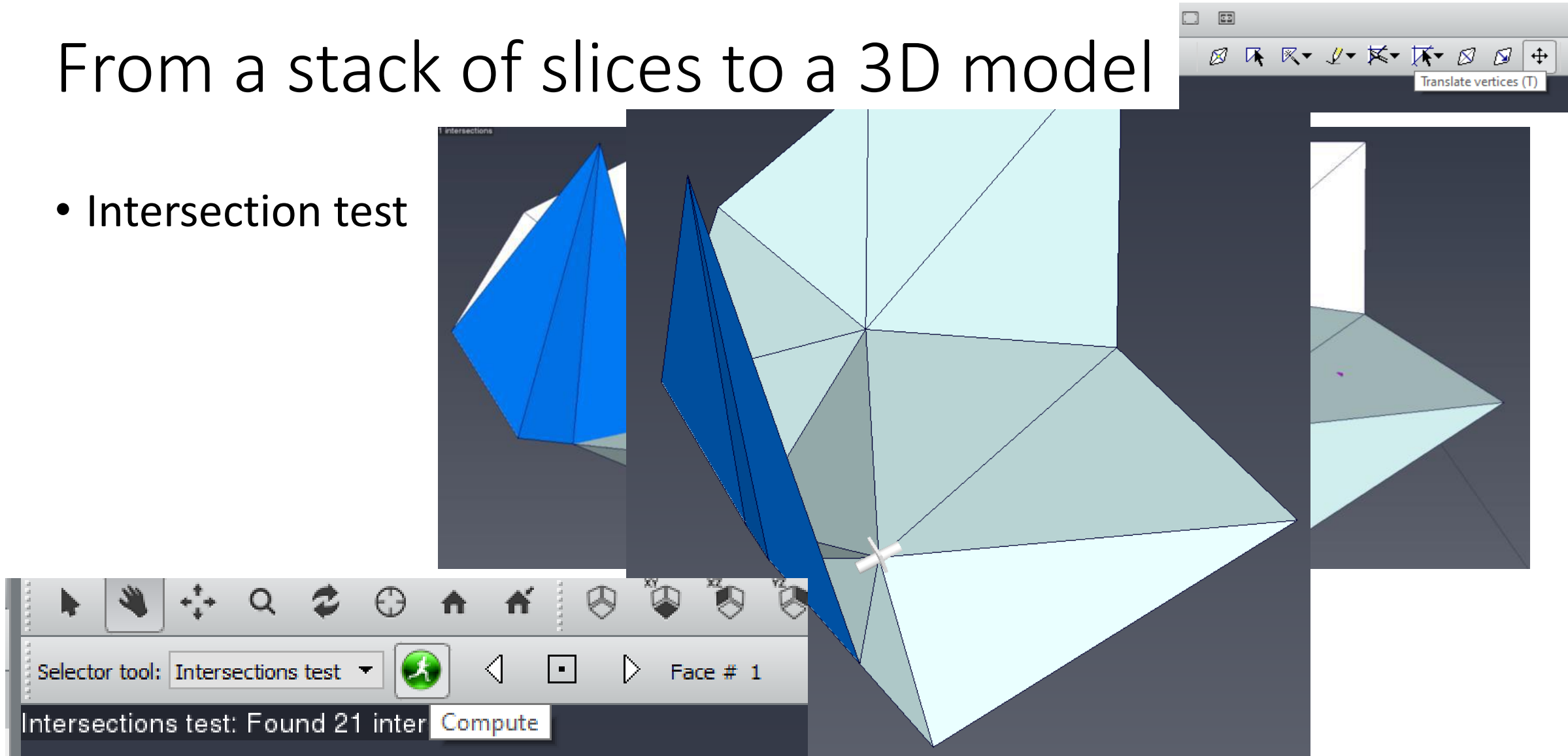
From a stack of slices to a 3D model

- Intersection test

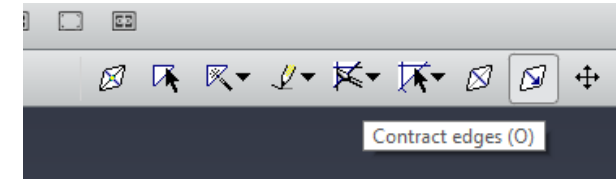


From a stack of slices to a 3D model

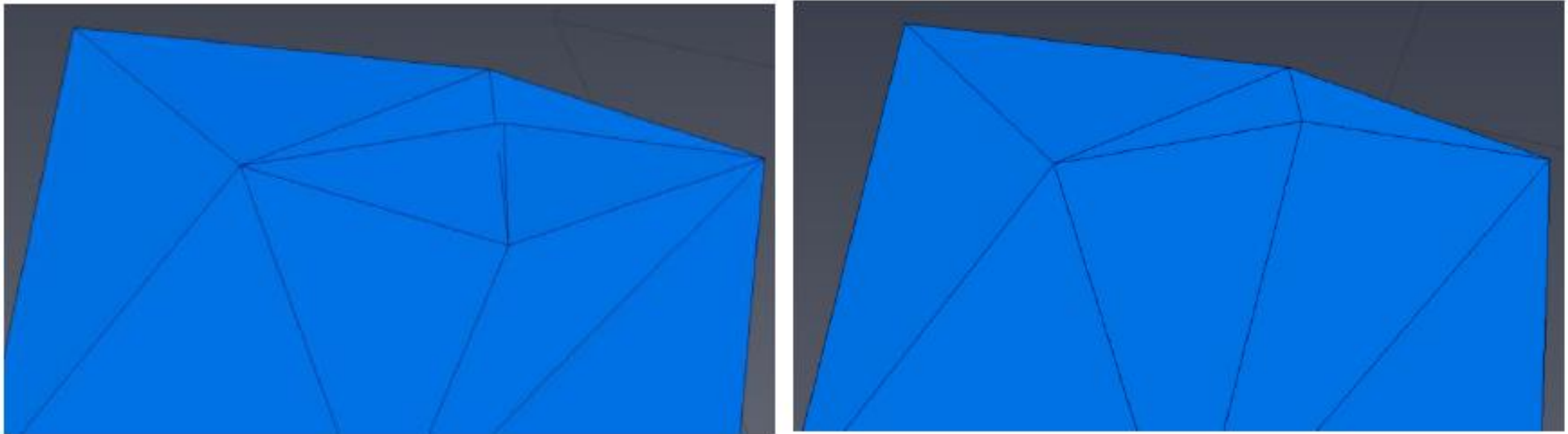
- Intersection test



From a stack of slices to a 3D model

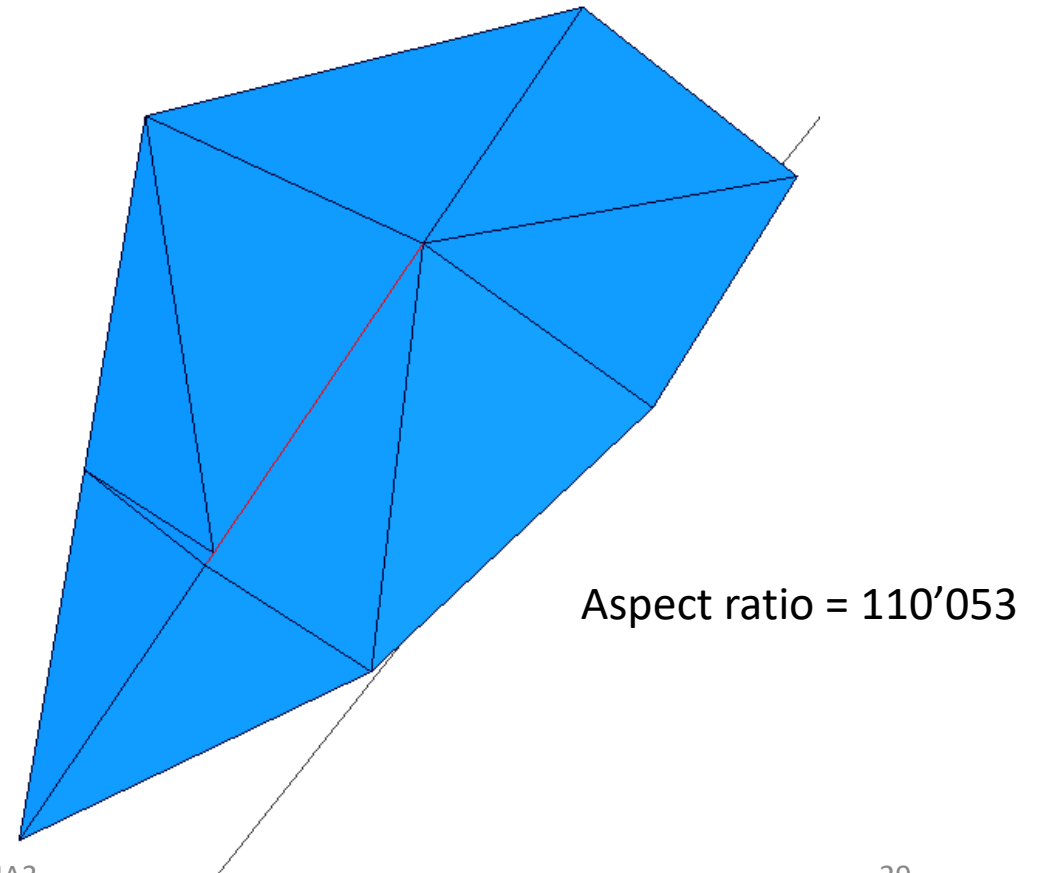
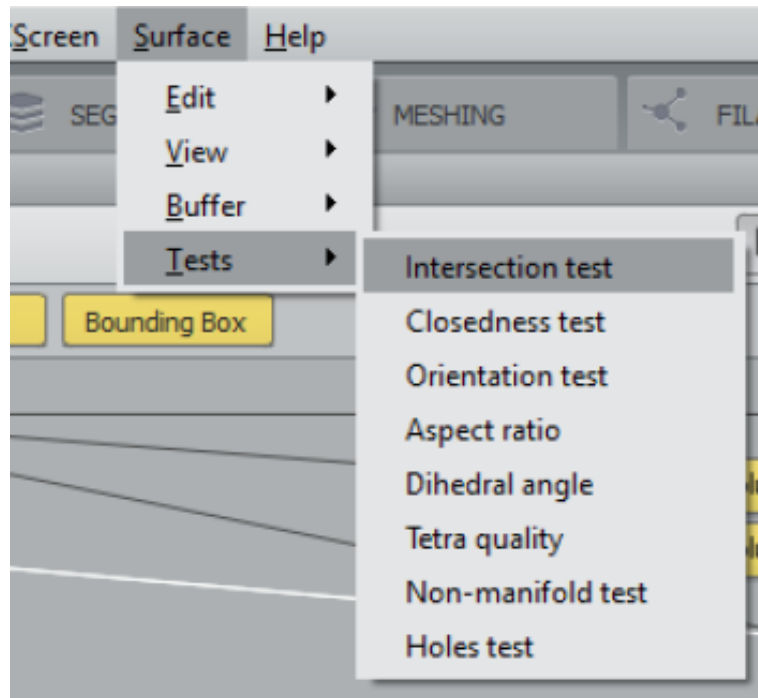


- Intersection test



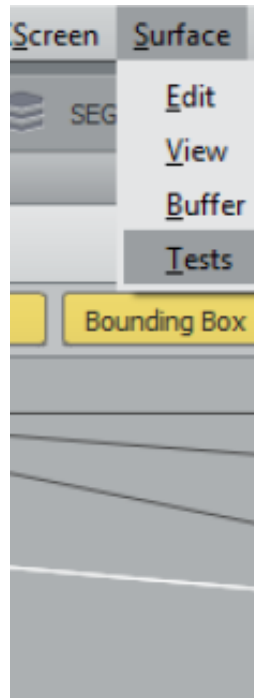
From a stack of slices to a 3D model

- Aspect Ratio test

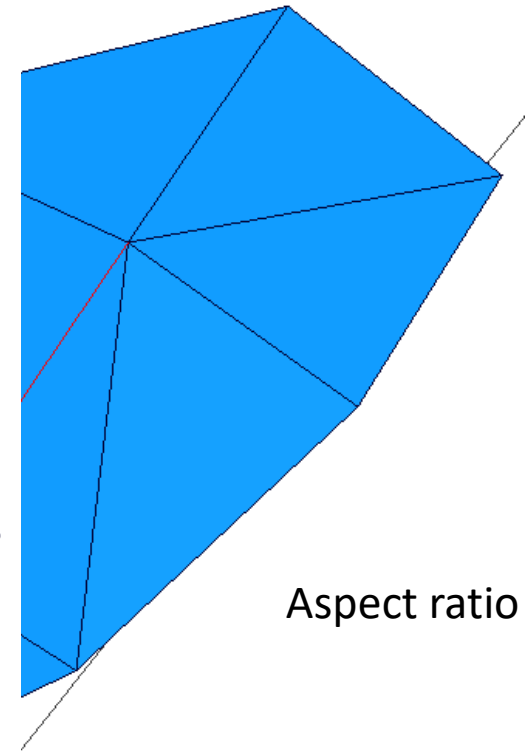
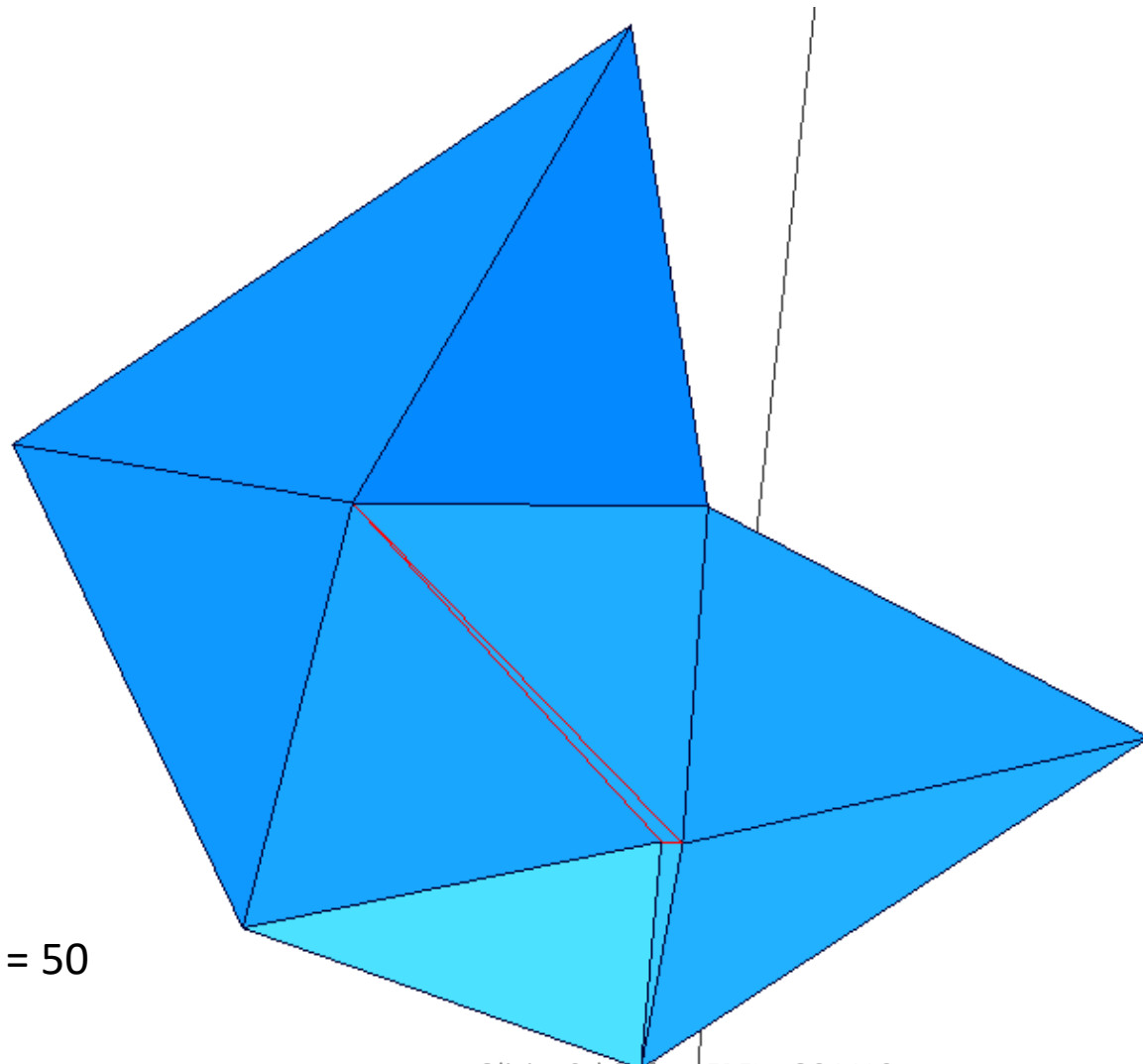


From a stack of slices to a 3D model

- Aspect Rat



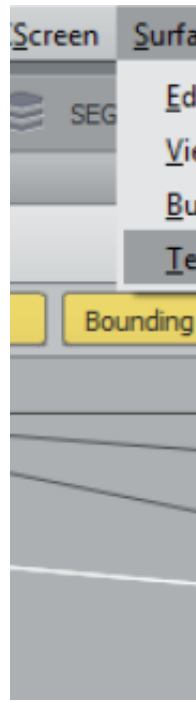
Aspect ratio = 50



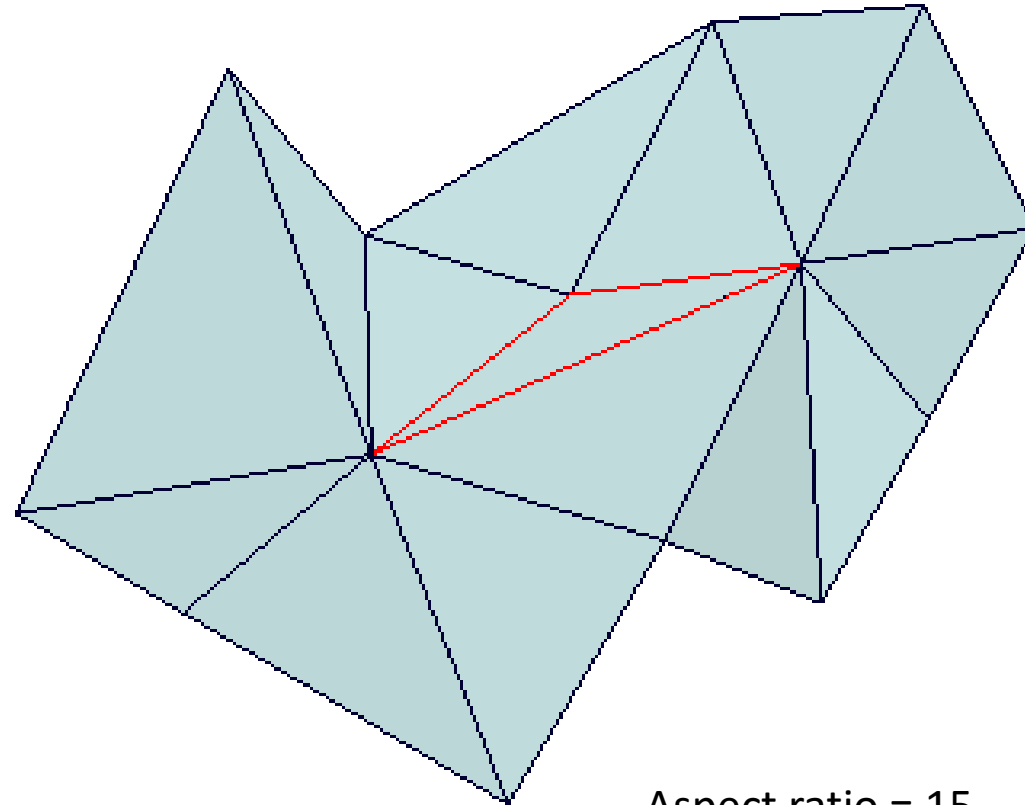
Aspect ratio = 110'053

From a stack of slices to a 3D model

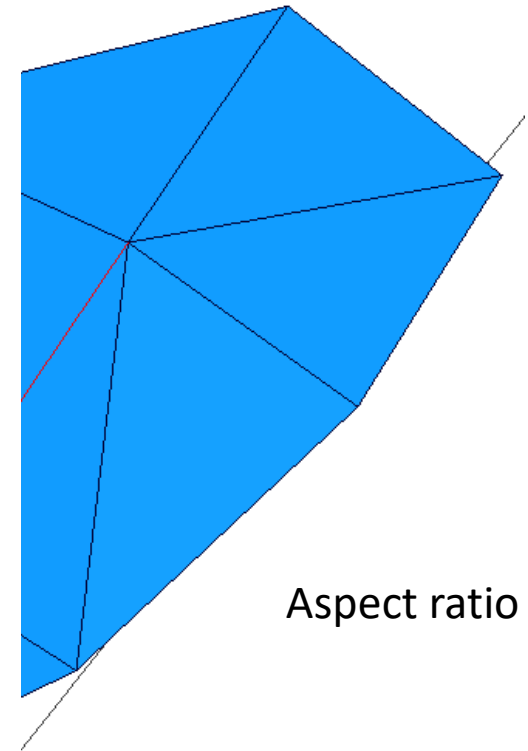
- Aspect Ratio



Aspect



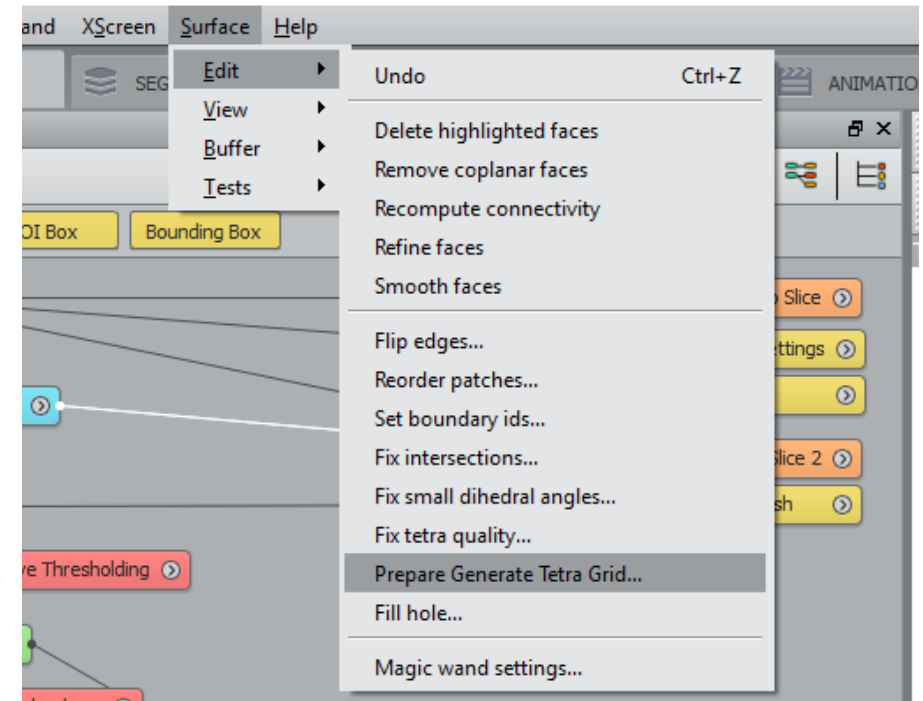
Aspect ratio = 15



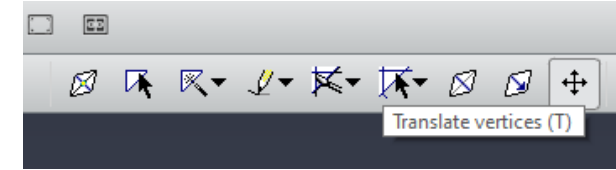
Aspect ratio = 110'053

From a stack of slices to a 3D model

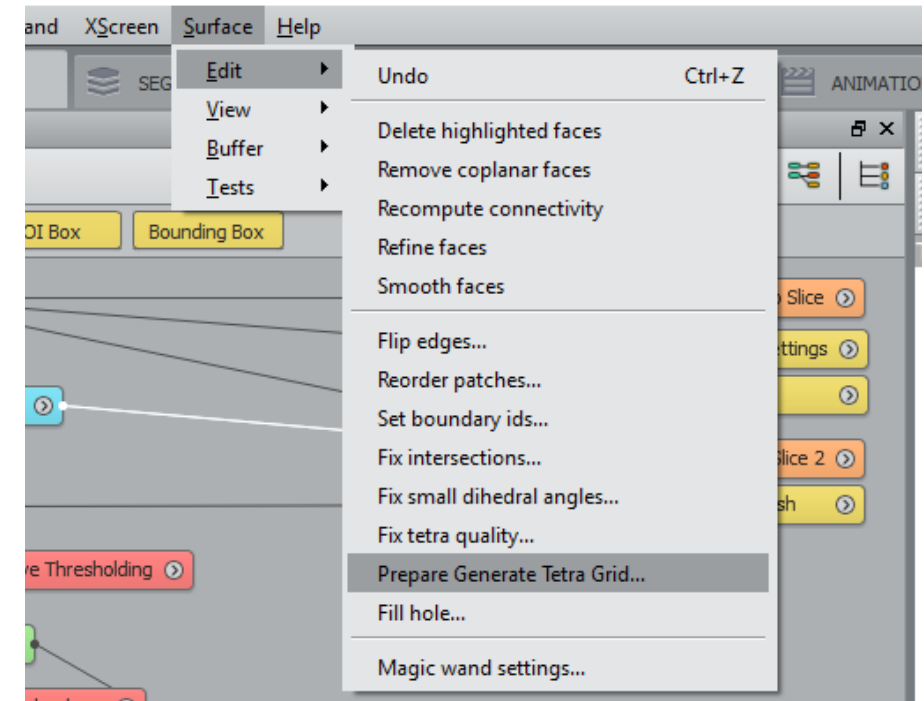
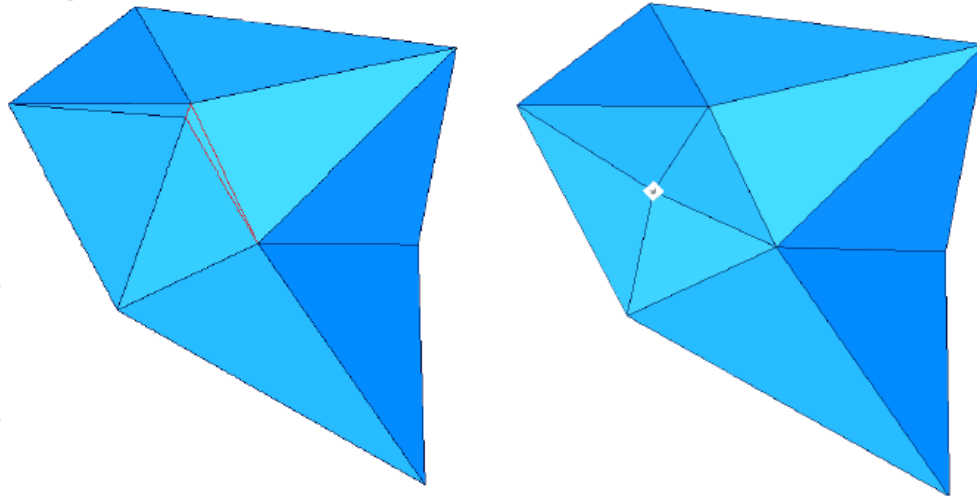
- Aspect ratio – autofix : “Prepare generate tetra grid”
- Will fix most of the aspect ratio errors
- Remaining errors have to be corrected manually



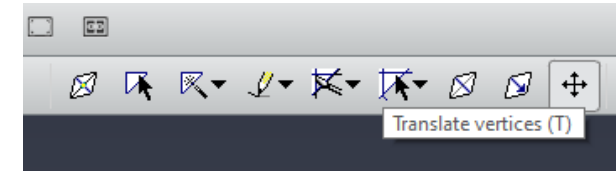
From a stack of slices to a 3D model



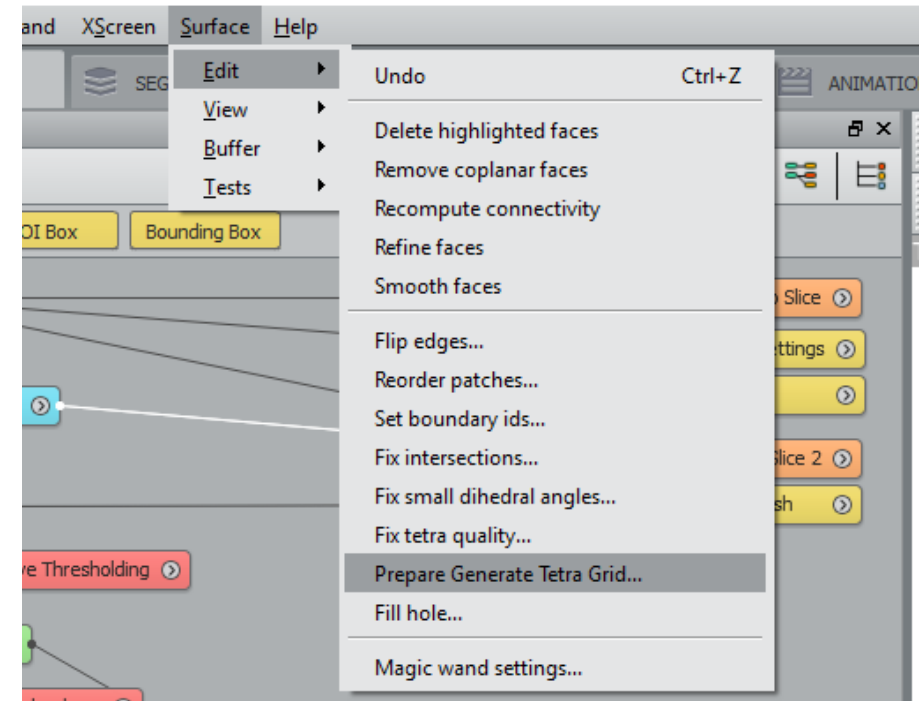
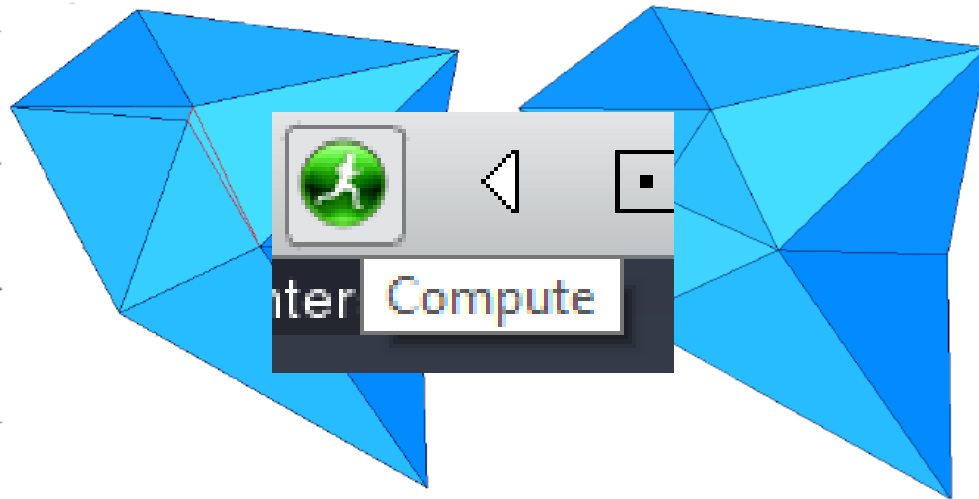
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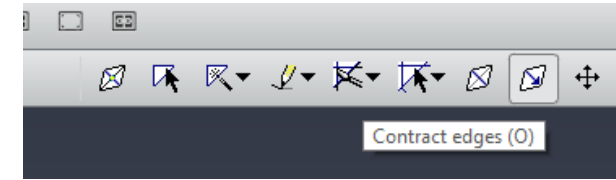
From a stack of slices to a 3D model



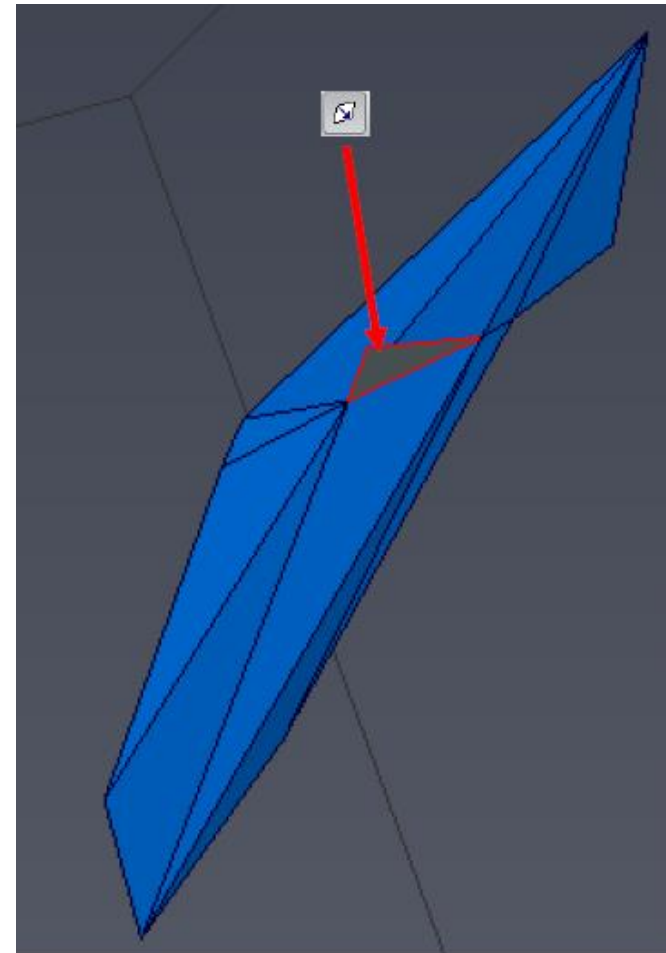
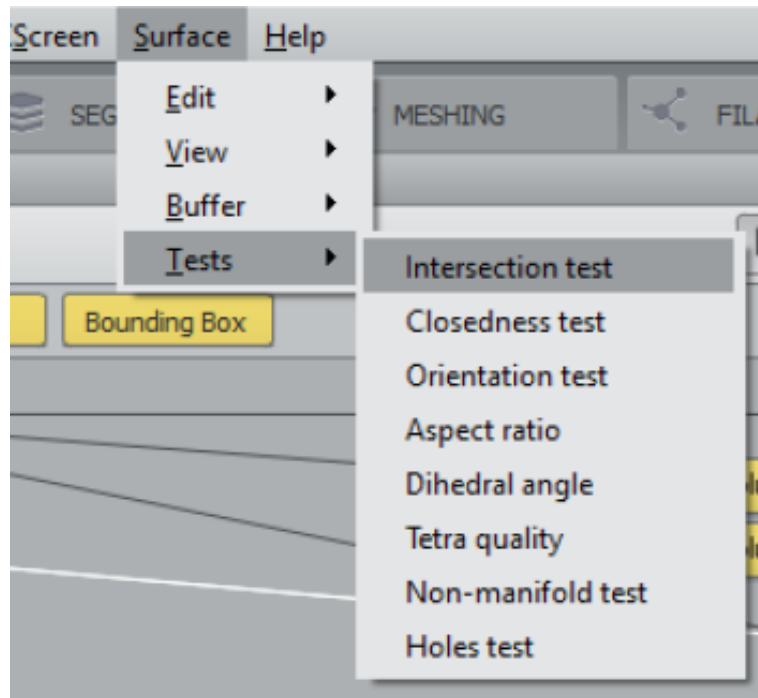
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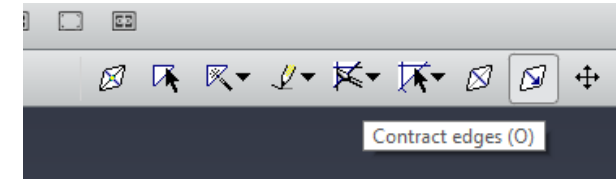
From a stack of slices to a 3D model



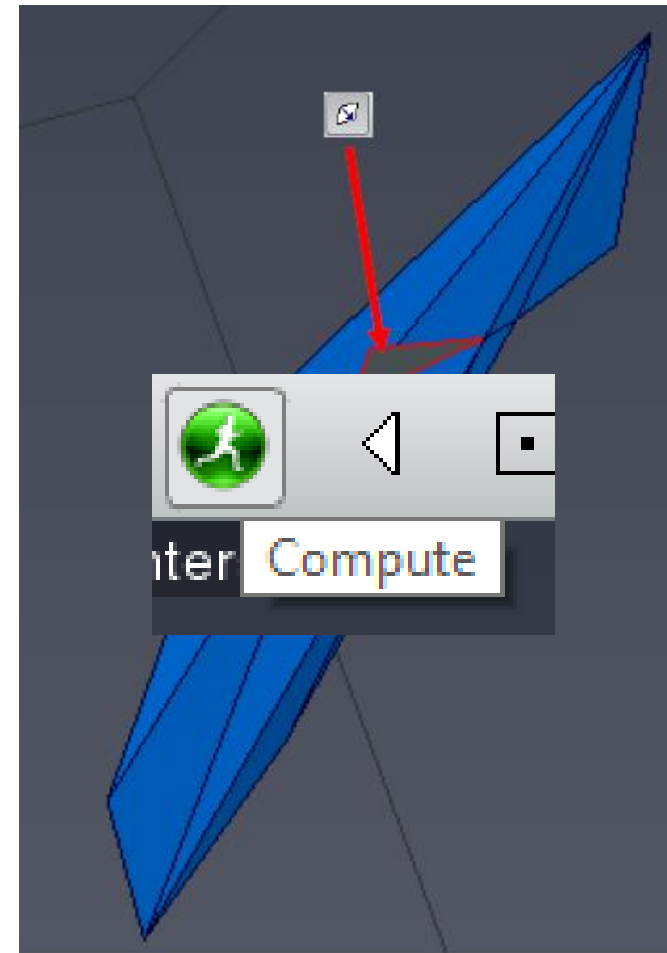
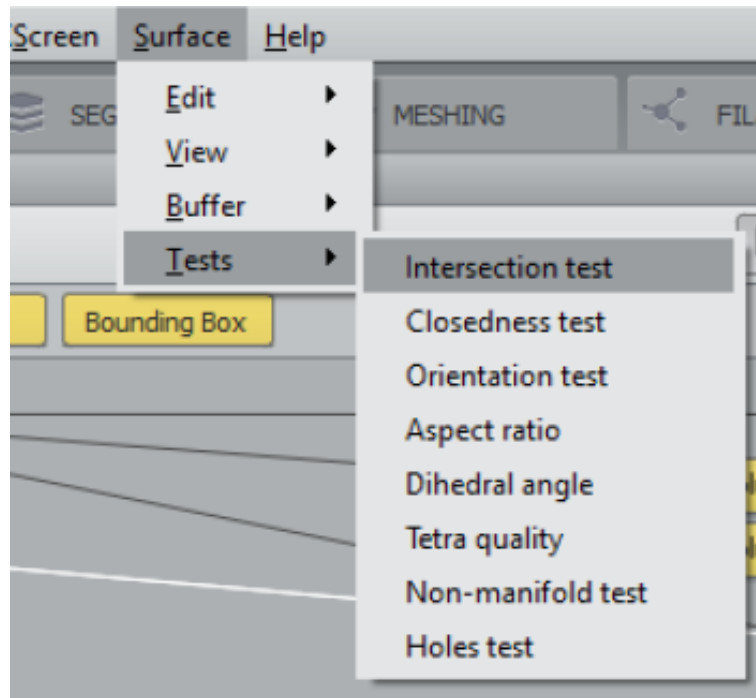
- Orientation test



From a stack of slices to a 3D model

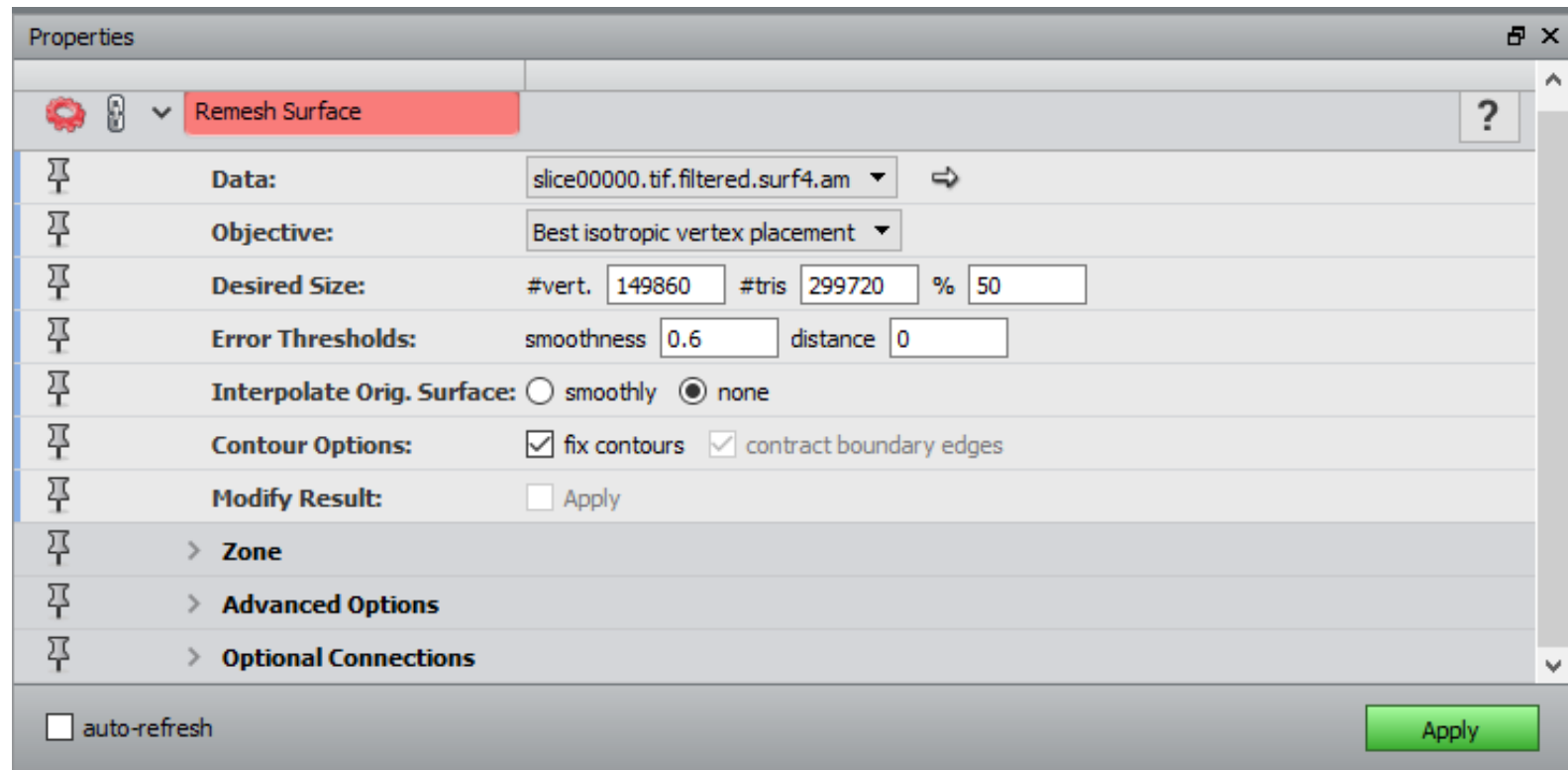


- Orientation test



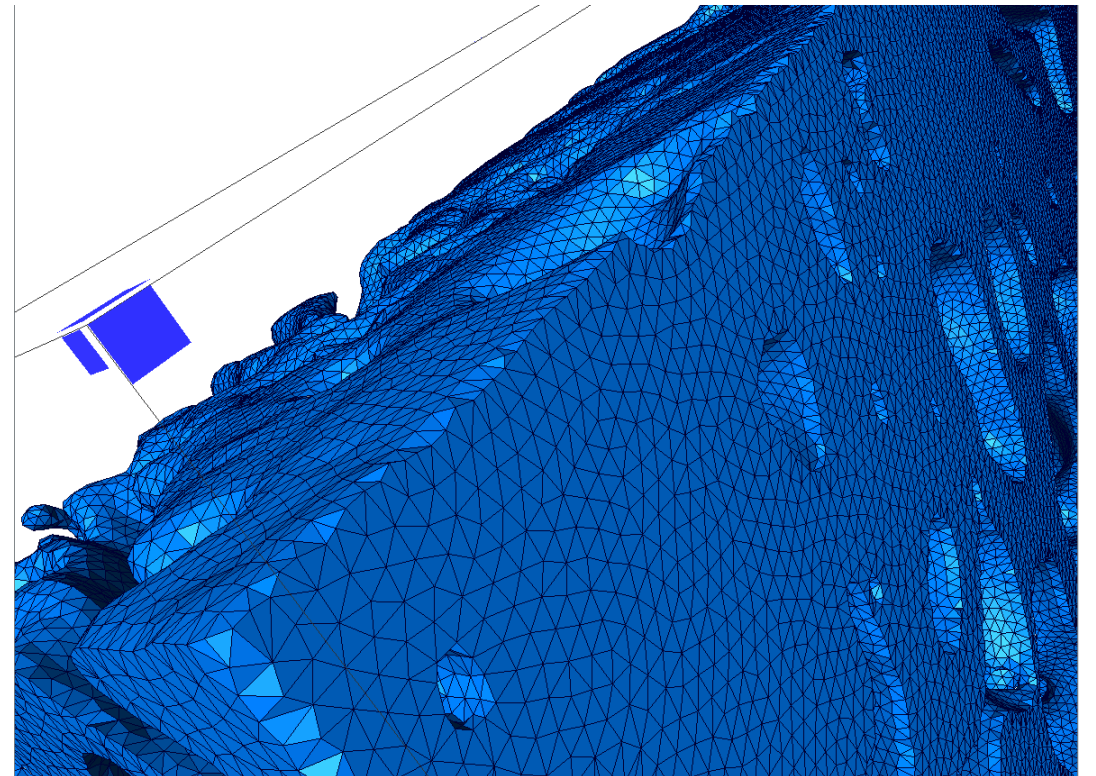
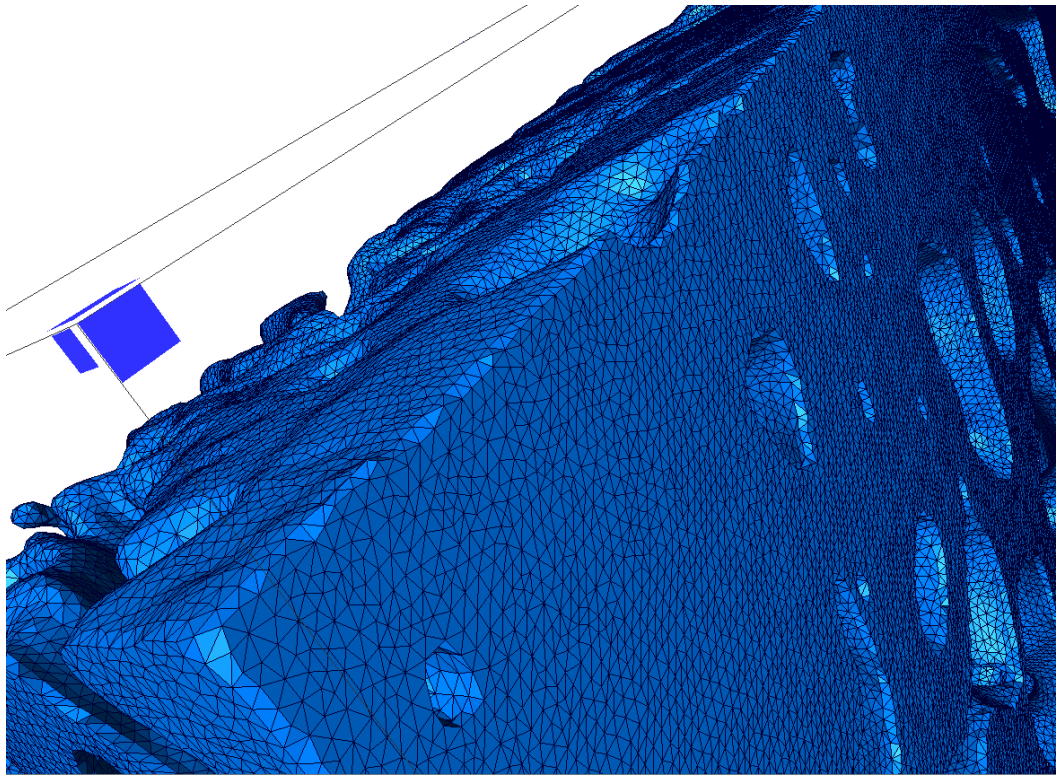
From a stack of slices to a 3D model

- Remesh the surface before creating the tetrahedron model to have a simpler model and better triangles



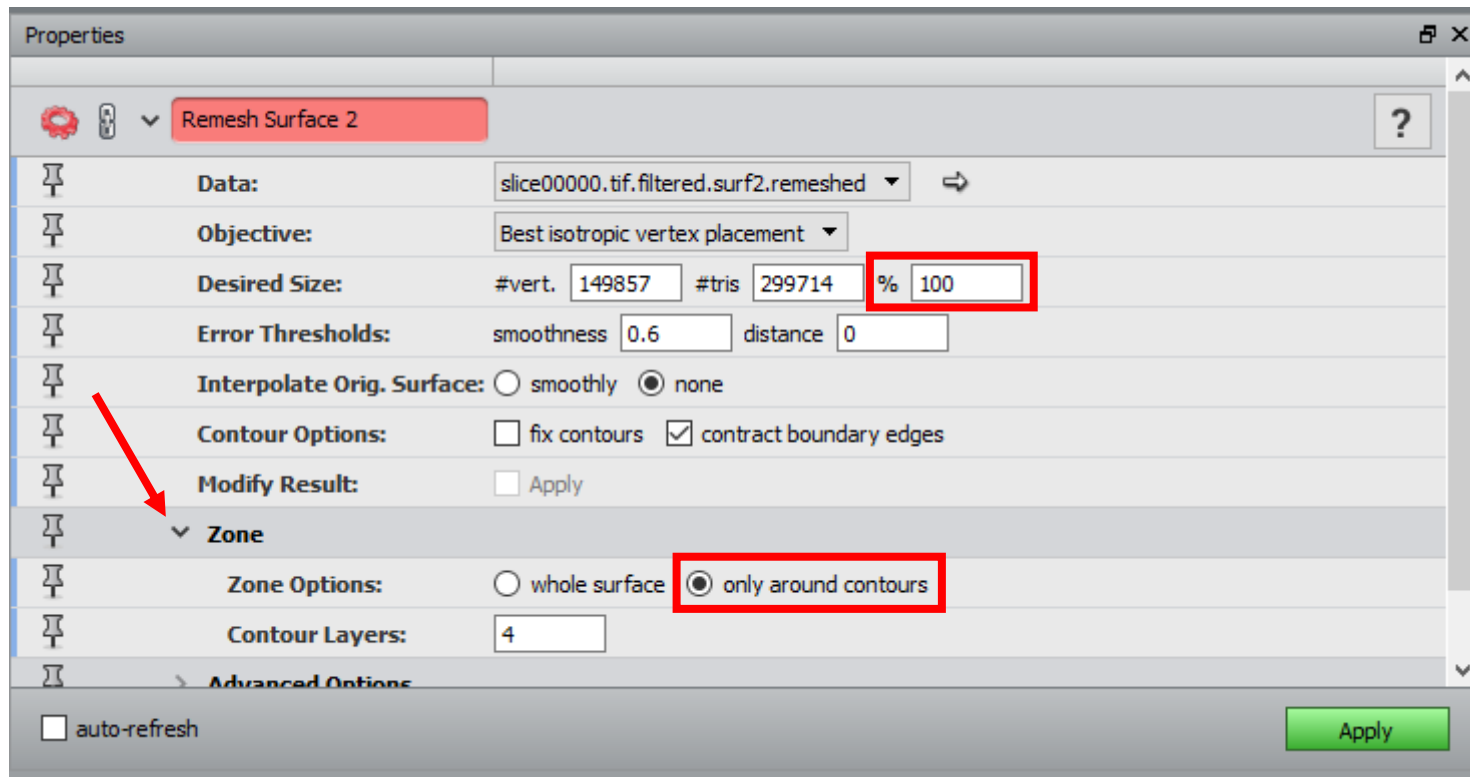
From a stack of slices to a 3D model

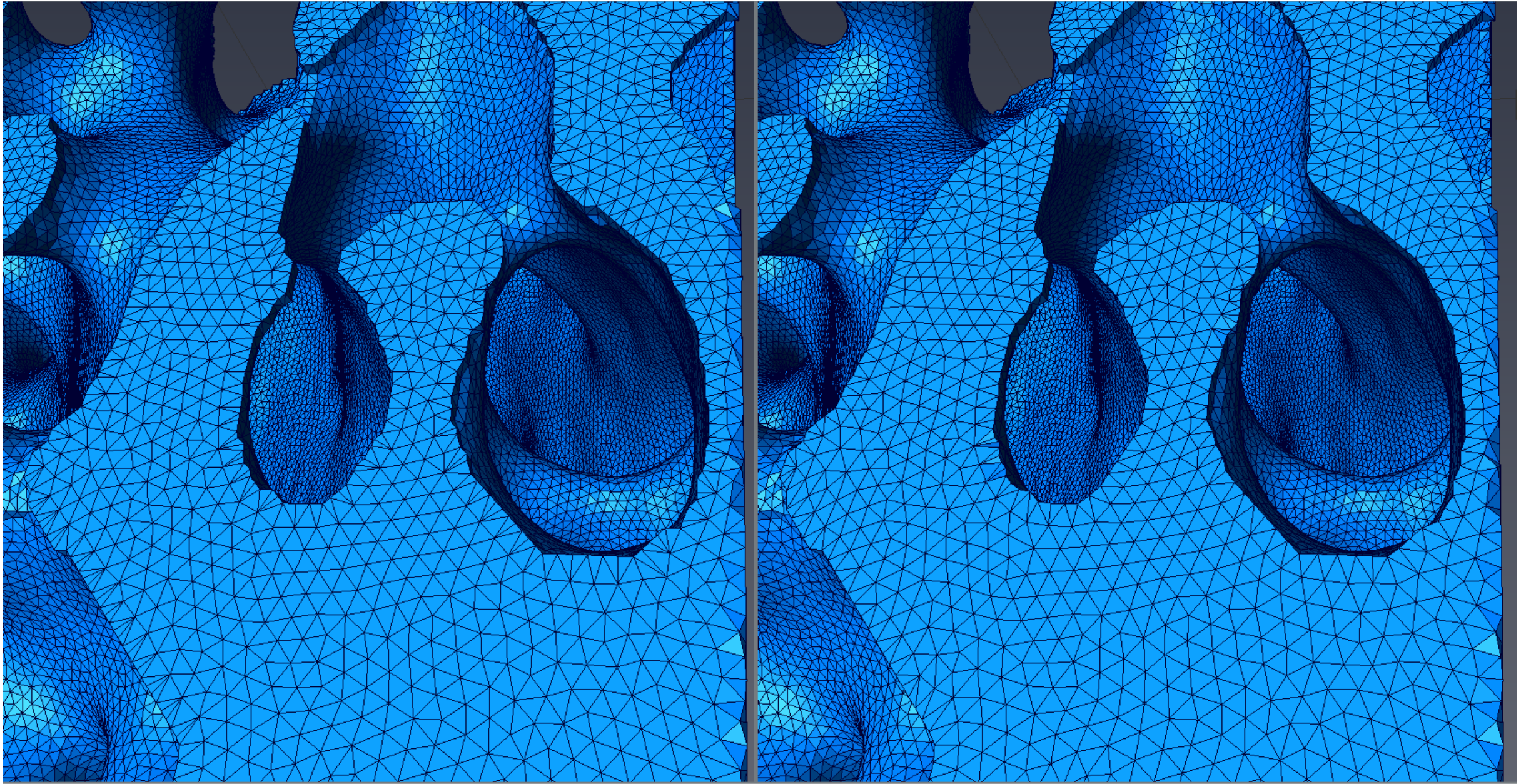
- Remesh the surface before creating the tetrahedron model to have a simpler model and better triangles



From a stack of slices to a 3D model

- Remesh the surface before creating the tetrahedron model to have a simpler model and better triangles





From a stack of slices to a 3D model

- Generate Tetra Grid

Av Tables

	Region	Closedness	Volume	Intersection	Orientation	Mean edge length	Mesh size	Estimated cell number	Largest triangle aspect ratio	Smallest dihedral angle	Largest tetrahedron aspect ratio
1	Material1	ok	ok	ok	ok	4.6213758e-05	4.6213758e-05	3766073	ok	ok	ok

report

Properties

Generate Tetra Grid

Data: slice00000.tif.filtered.surf5.remeshed

Region: All

Options: improve grid save grid

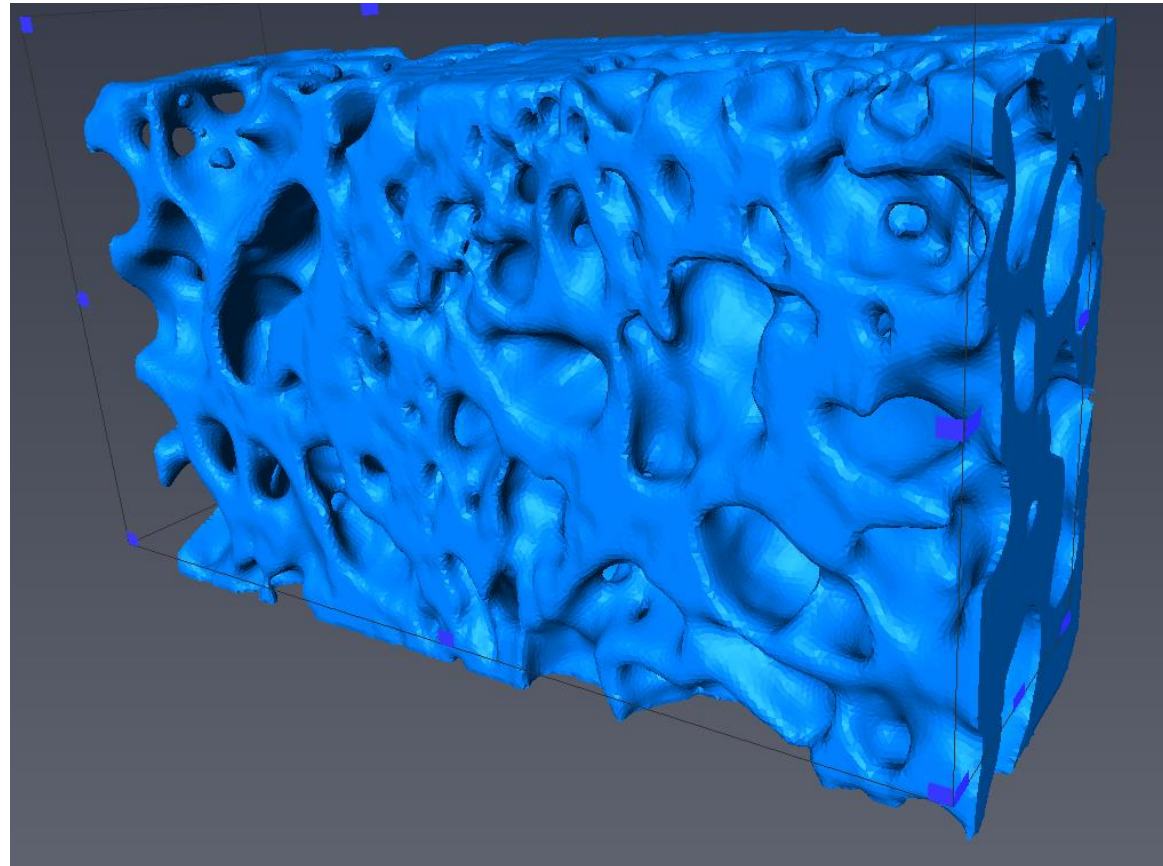
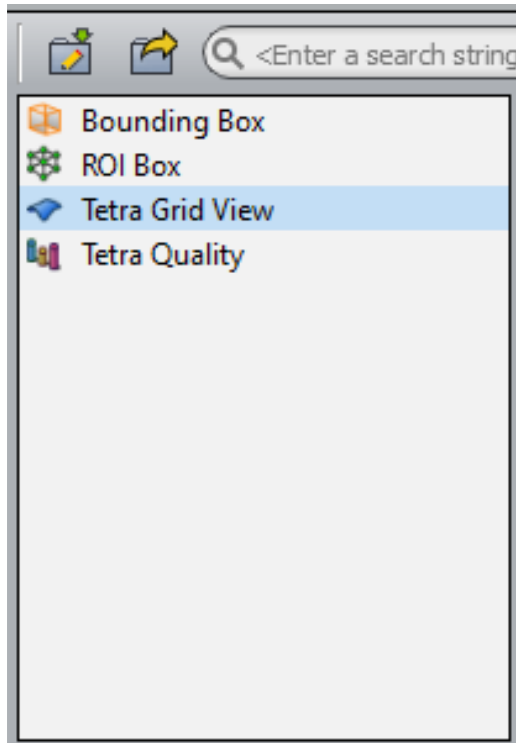
Action: Meshsize **Check** **Run now** Run batch

1 2

auto-refresh Apply

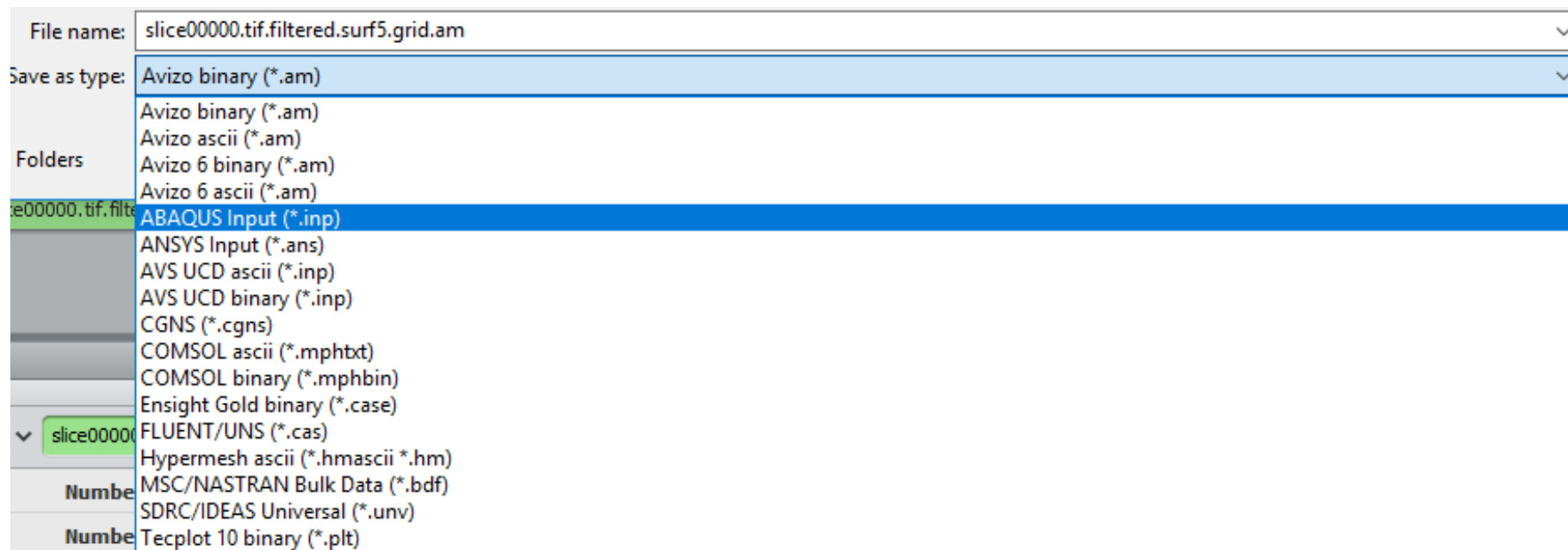
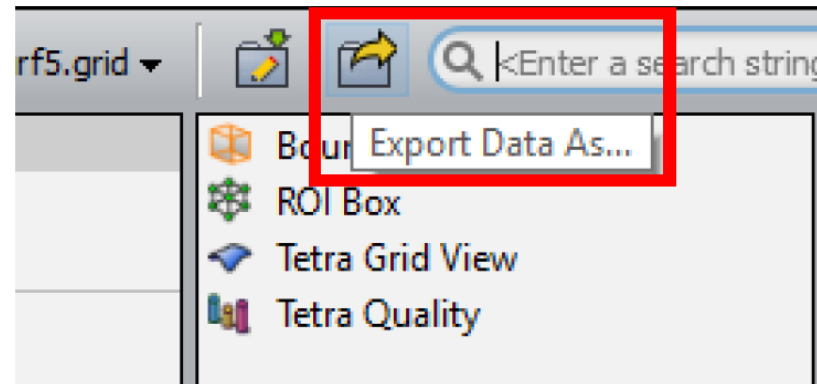
From a stack of slices to a 3D model

- Generate Tetra Grid



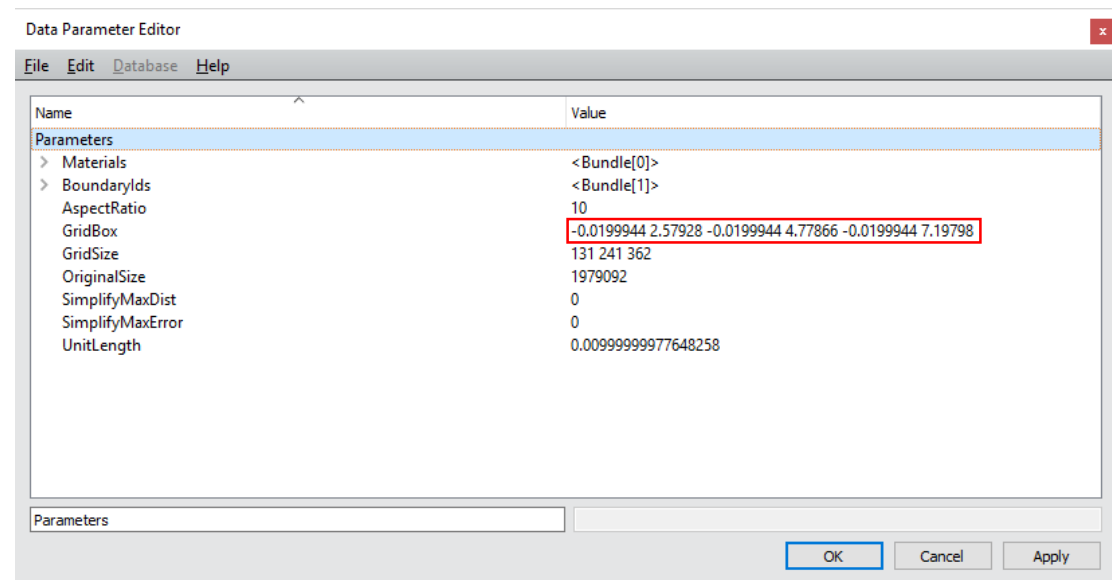
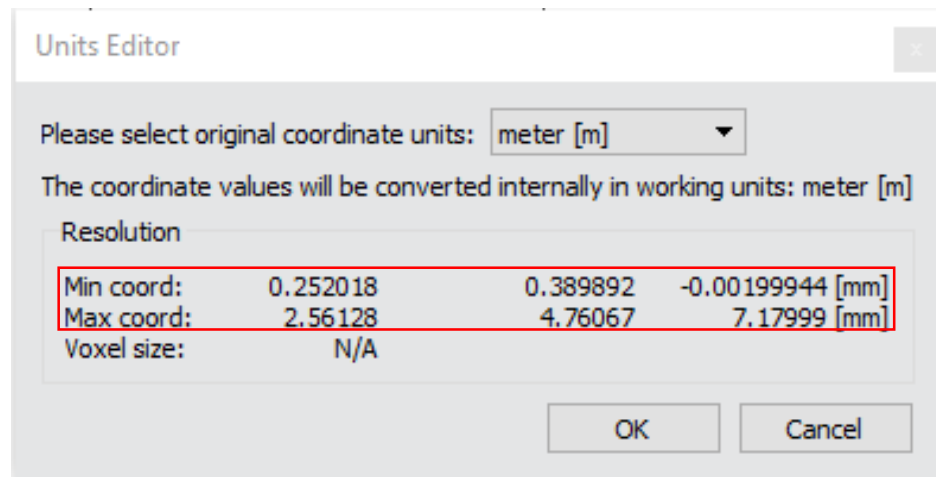
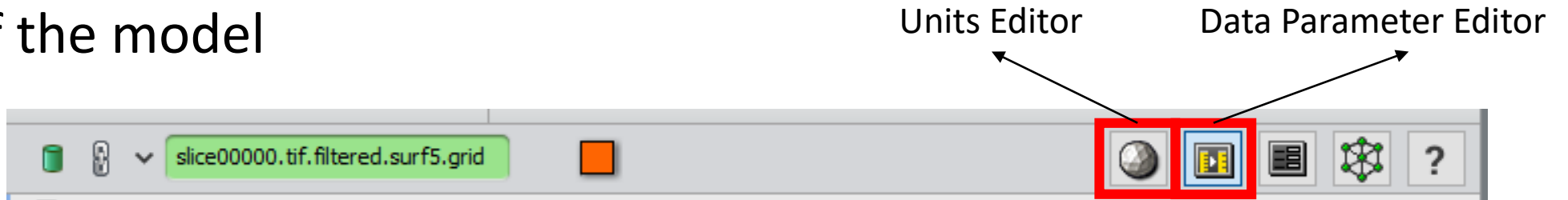
From a stack of slices to a 3D model

- Export for Akantu



From a stack of slices to a 3D model

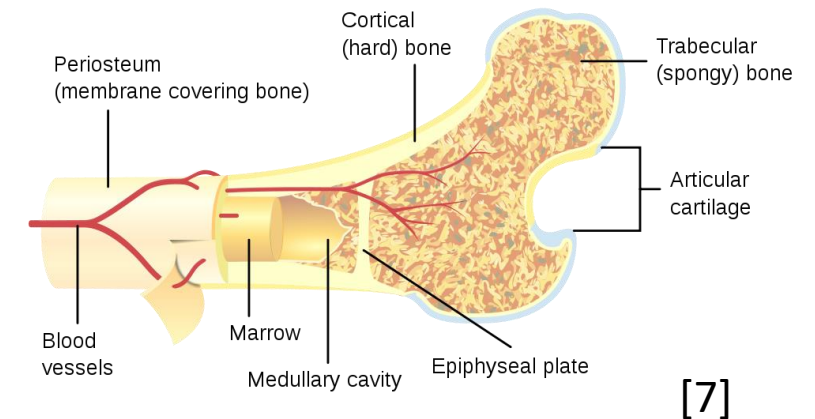
- Size of the model



Traction test

Bone material

- Variable properties depending on :
 - Species (Human, Cow, Rat, etc...)
 - Age (Young, Old)
 - Health (Bone disease, Calcium levels, etc...)
 - Bone (Femur, Tibia, etc...)
 - Part of the bone (Cortical, Trabecular)
 - “Freshness” of the sample and is it conserved wet?



Bone material – Mechanical properties, example

- Typical intervals for human trabecular bone
 - Young modulus : can vary from 10 to 3000 [MPa]
 - Ultimate strain : typically between 1.0 and 2.5%
 - Poisson's Ratio : between 0.03 and 0.6

[8]

- We should probably use a visco elastic constitutive law
(Keaveny, Morgan and Yeh, 2004, p. 8.15)

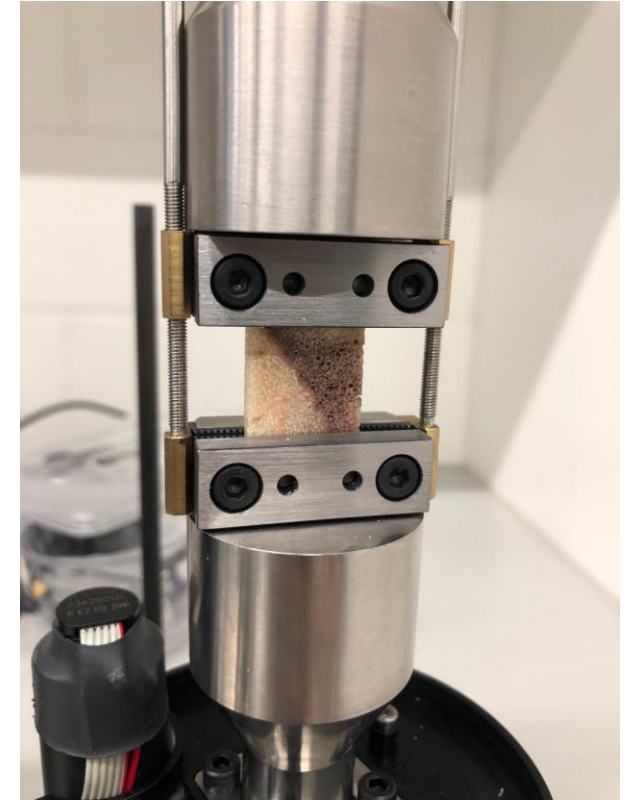
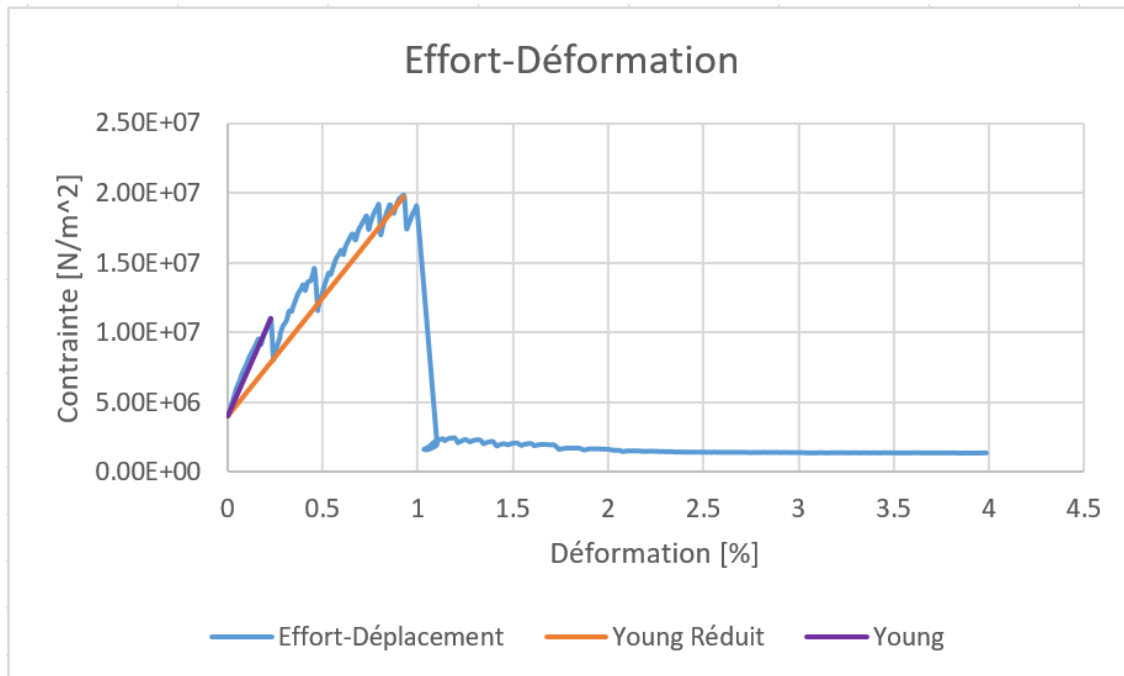
Bone material – Mechanical properties – Young Modulus

- Traction test on a bone sample



Bone material – Mechanical properties – Young Modulus

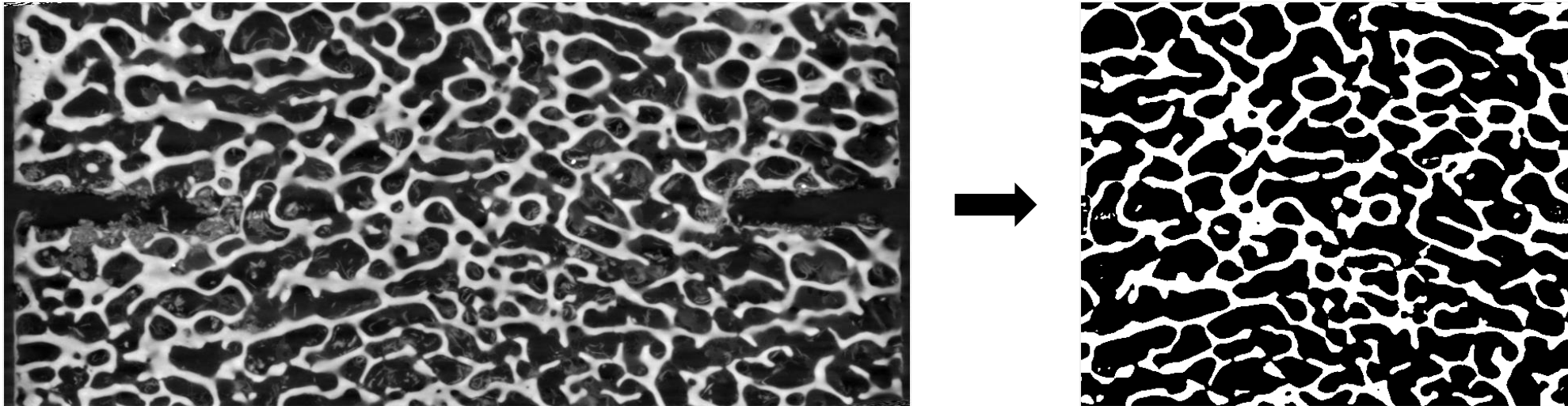
- Traction test on a bone sample



➔ $E_{elastic} = 3060 [MPa]$

Bone material – Mechanical properties – Young Modulus

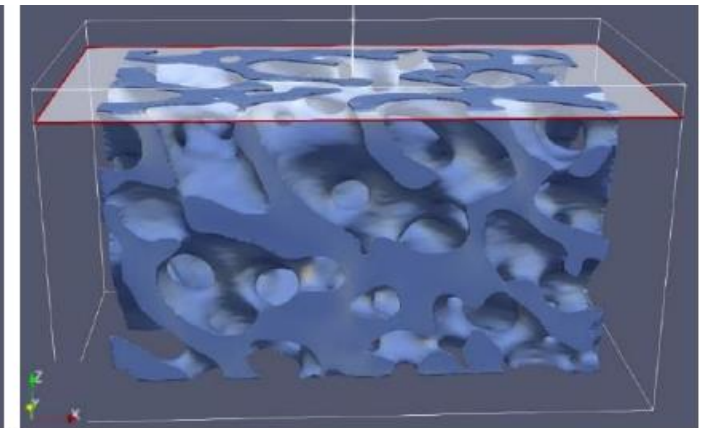
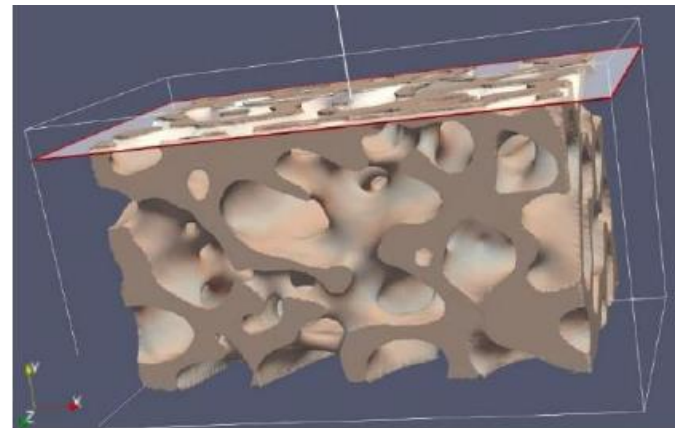
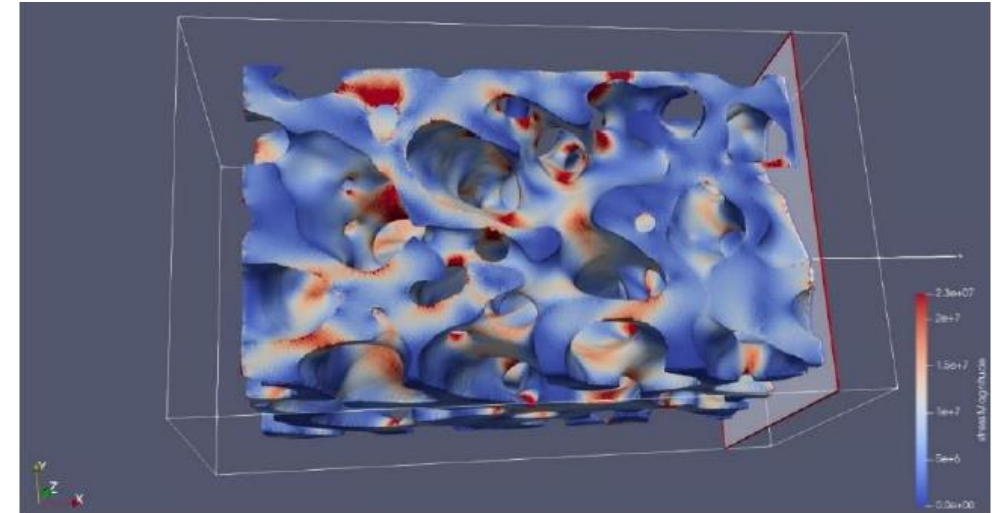
- How to get the effective modulus



$$\left(\frac{\textit{bone}}{\textit{bone} + \textit{void}} \right)_{tot} = \frac{\sum_i^n \left(\frac{\textit{bone}}{\textit{bone} + \textit{void}} \right)_i}{n} = 0.3424 = 34.2\% \textit{ bone}$$

Simple traction test with Akantu

- Input:
 - $E = 1000$ [MPa]
 - $\nu = 0.25$
- Tests:
 - 3 Displacement controlled : x, y, z
 - 3 Force controlled : x, y, z



Simple traction test with Akantu

- Displacement controlled
 - $\epsilon_i = 1\%$, $i = x, y, z$
- Young modulus calculation for x
 - $E_x = \frac{\sigma_{xx}}{\epsilon}$
 - $\sigma_{xx} = \frac{\sum_i^n \sigma_{xx,i}}{n}$
 - $n = \text{\#elements on the considered surface}$

In Paraview, $\sigma_{xx} = \text{stress:0}$; $\sigma_{yy} = \text{stress:4}$; $\sigma_{zz} = \text{stress:8}$

Simple traction test with Akantu

- Force controlled
 - $F_i = 1000 [N]$, $i = 1, 2, \dots, n$
 - $n = \# \text{vertex at the surface where the force is applied}$
- Young modulus calculation for x
 - $E = \frac{\sigma}{\epsilon} = \frac{F/A}{\Delta L/L}$
 - $n = 9247$; $F_{tot} = 9'247'000 [N]$; $A_{bone} = 2.51 [m^2]$; $\sigma_{xx} = 3.68 \cdot 10^6 [N/m^2]$
 - $\Delta L_x = \frac{\sum_i^n \Delta L_{x,i}}{n} = 0.035 [m]$; $L_x = 4.57 [m]$; $\epsilon_{xx} = \frac{\Delta L_x}{L_x} = 7.77 \cdot 10^{-3}$
 - $E_x = \frac{\sigma_{xx}}{\epsilon_{xx}} = 473.7 [MPa]$

In Paraview, $\Delta L_{x,i} = \text{displacement}: 0$; $\Delta L_{y,i} = \text{displacement} : 1$; $\Delta L_{z,i} = \text{displacement}: 2$

Simple traction test with Akantu

- Results:
 - Displacement controlled

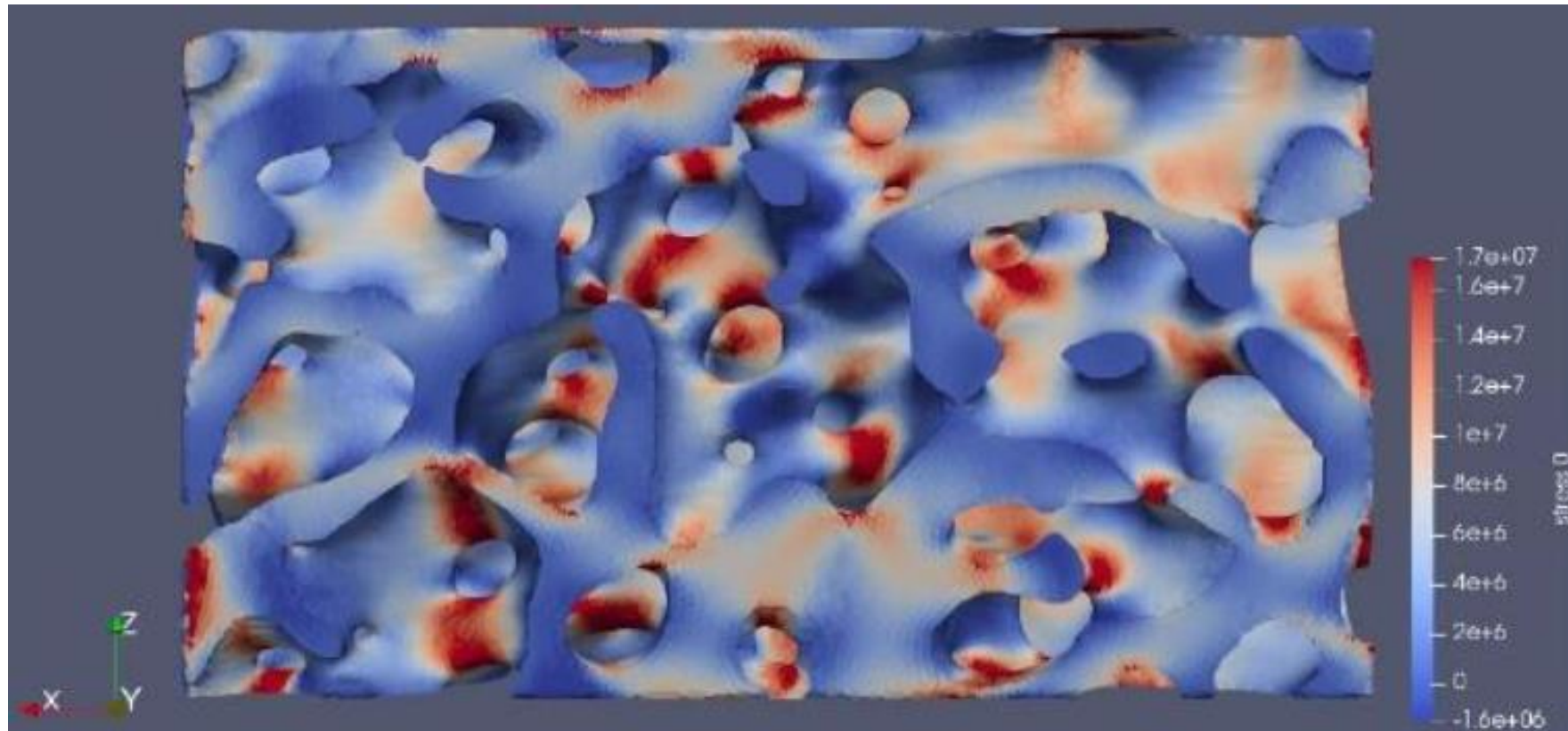
Direction de l'essai	$\sigma = \sigma_{moy} [N/m^2]$	ϵ	$E [MPa]$
x	5'167'250	0.01	516.7
y	3'631'414	0.01	363.1
z	3'852'499	0.01	385.2

- Force controlled

Direction de l'essai	$\sigma = F_{tot}/A [N/m^2]$	$\epsilon = \epsilon_{moy}$	$E [MPa]$
x	$4.09 \cdot 10^6$	$7.77 \cdot 10^{-3}$	473,7
y	$2.36 \cdot 10^6$	$6.38 \cdot 10^{-3}$	321,1
z	$2.87 \cdot 10^6$	$7.54 \cdot 10^{-3}$	319,2

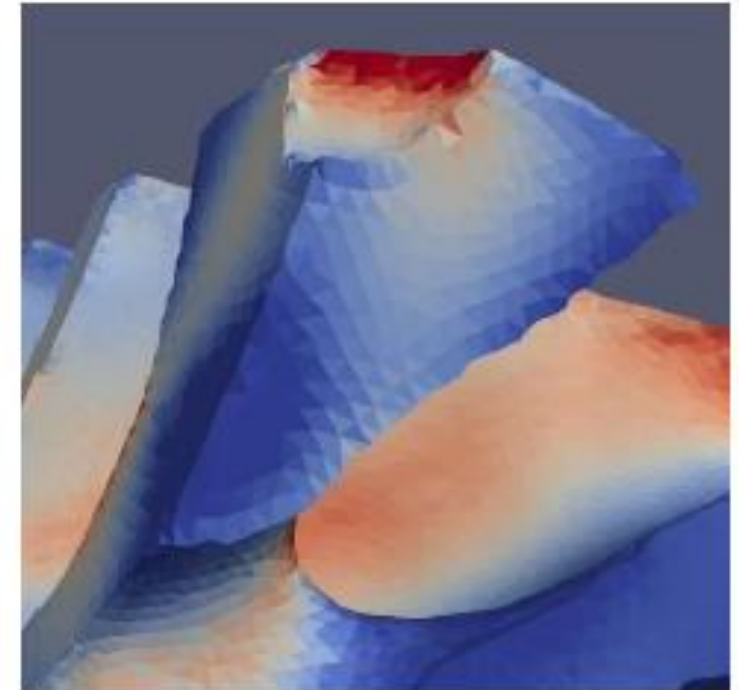
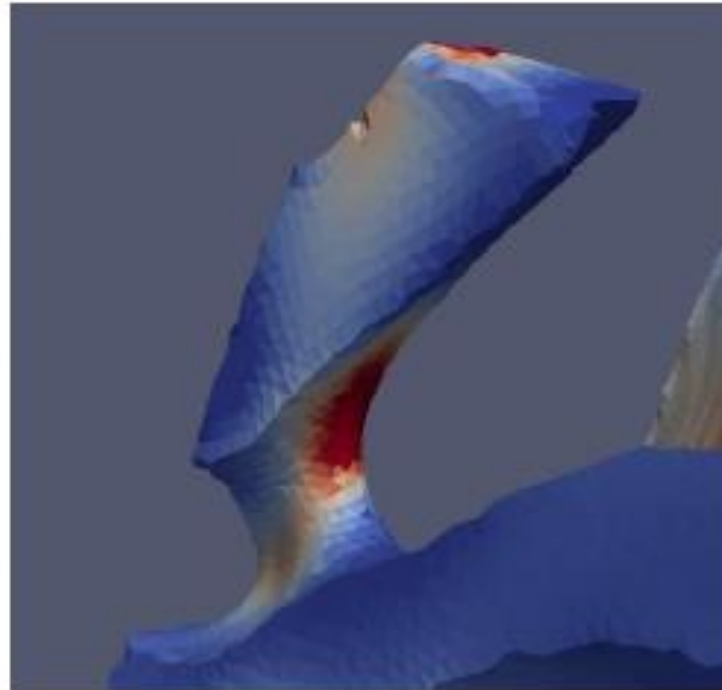
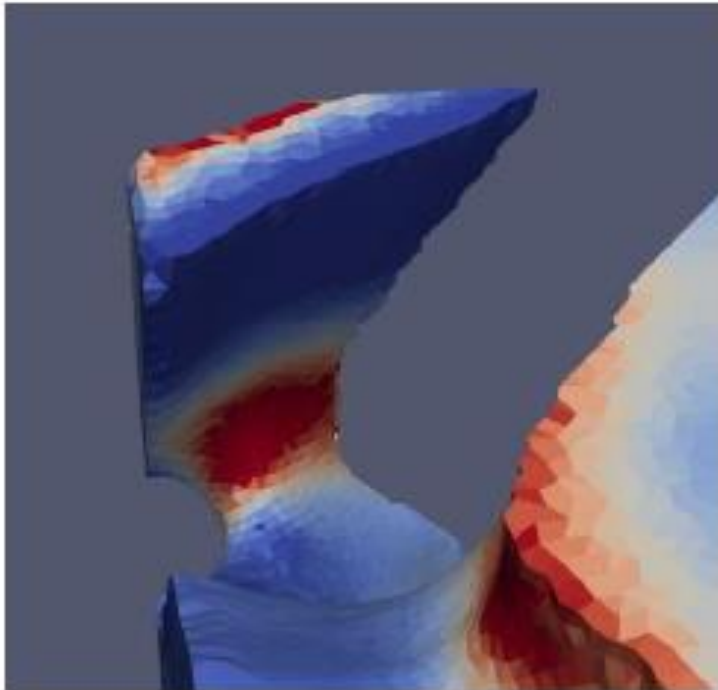
Simple traction test with Akantu

- Graphic representation



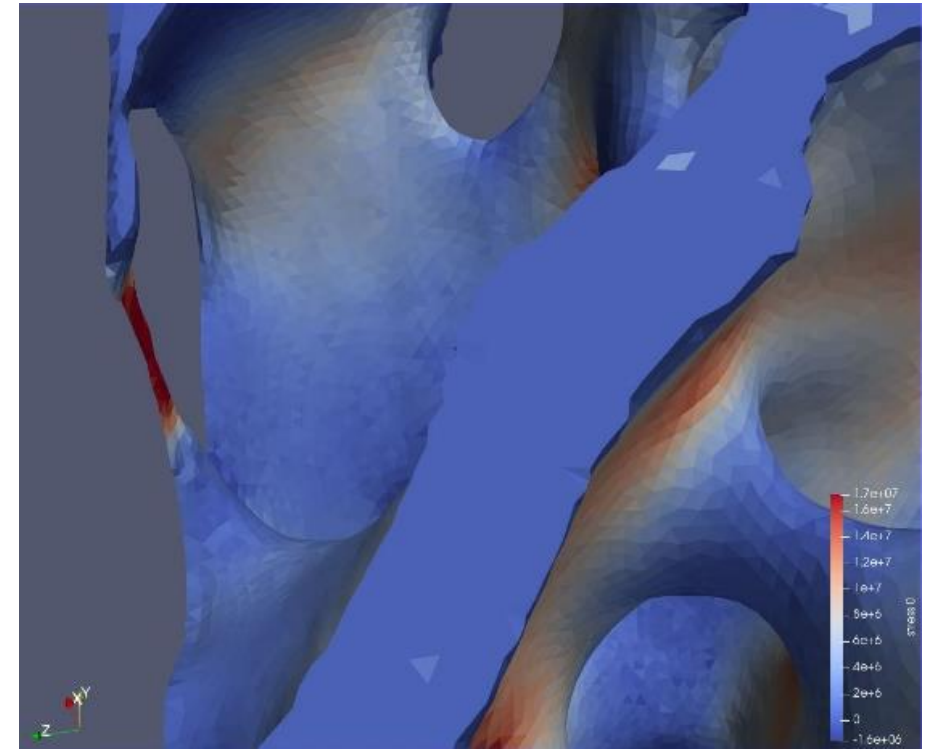
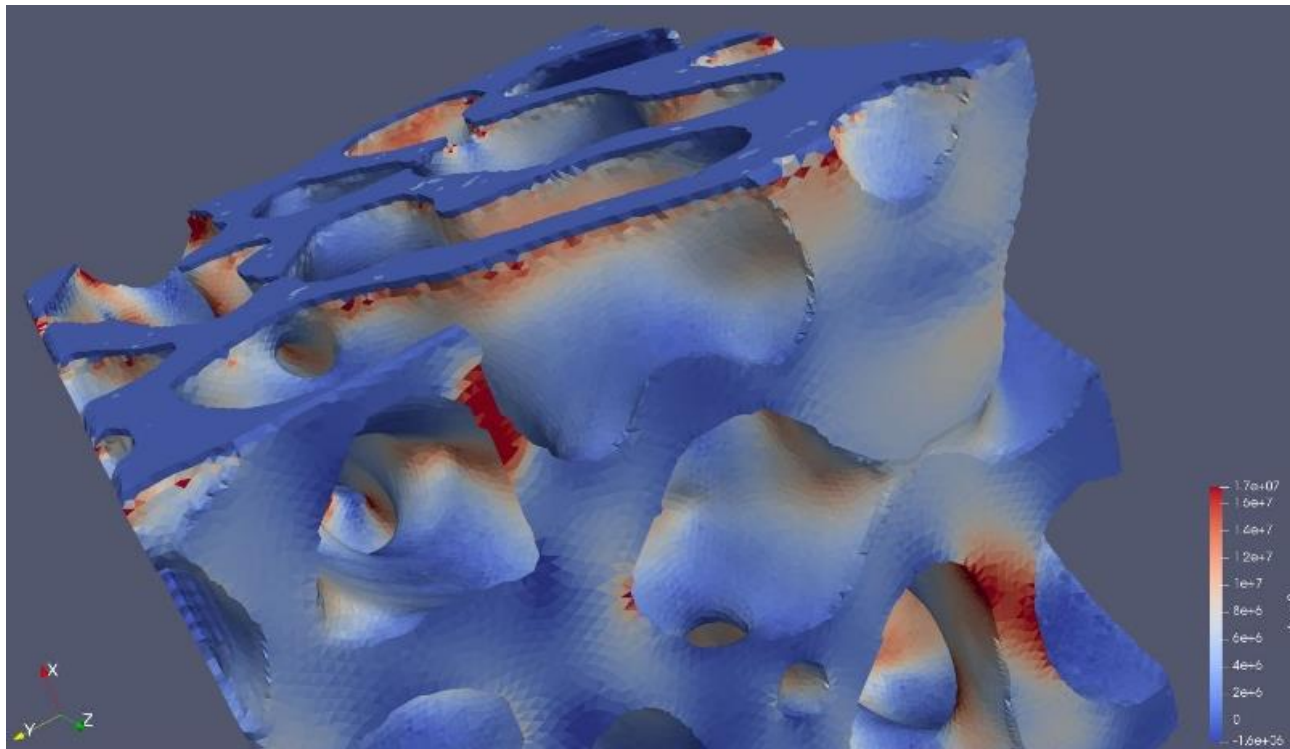
Simple traction test with Akantu

- Graphic representation



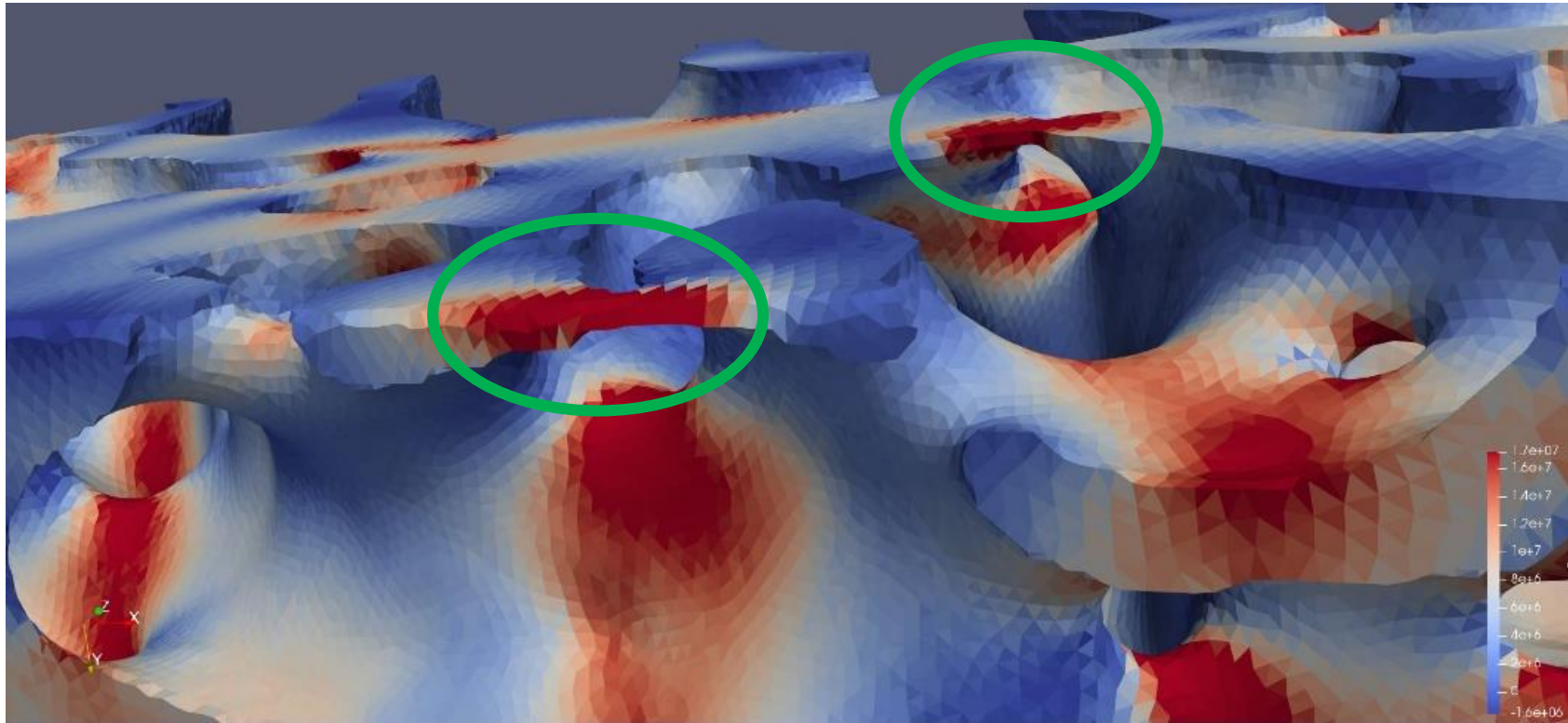
Simple traction test with Akantu

- Graphic representation



Simple traction test with Akantu

- Graphic representation



Conclusion

- It is possible to create a 3D model, using the X-ray micro-CT scan
 - Go from *.tif to *.inp (ABAQUS Input)
 - Straightforward procedure
 - Limit the size of the model (1-2 million triangles for the surface)
 - Simplify or cut the model if needed and possible
- The model created can be used for calculations in Akantu
- The procedure can be used for other projects

Thank you !

Sources

- Picture :

- [1] taken from : <https://actu.epfl.ch/news/akantu-v300-is-out/> (consulted the 05.11.2018)
- [2], [4], [5] Ketcham, Richard A. and Carlson, William D.. 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: applications to the geosciences. Computers & Geosciences 27: 381-400.
- [3] Schoeman, L., Williams, P., Du Plessis, A., Manley, M.. 2016. X-ray micro-computed tomography (μ CT) for non-destructive characterization of food microstructure. Trends in Food Science & Technology 47: 10-24.
- [6] Konrad-Zuse-Zentrum. 1995-2017. Avizo 9 - Avizo User's Guide. Berlin: Informationstechnik Berlin (ZIB).
- [7] taken from : <https://en.wikipedia.org/wiki/Bone> (Consulted the 07.11.2018)
- [8] Keaveny, Tony M., Elise F. Morgan, et Oscar C. Yeh. 2004. Standard handbook of biomedical engineering and design. The McGraw-Hill Companies.
- Other : Personal pictures and screenshots from Avizo