On pore space decomposition

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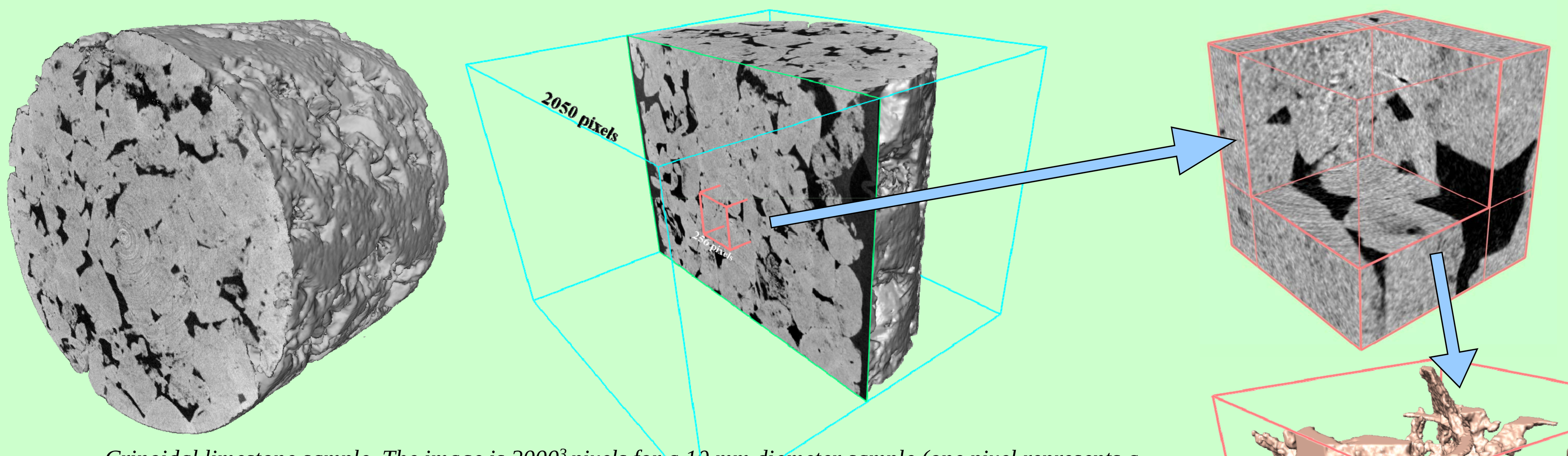
Introduction

At the pore-scale, the geometric and topological characteristics of porous materials have a significant influence on macroscopic transfer properties such as permeability or conductivity. But what is a pore ? Although the notion seems clear, a robust definition applicable to real materials does not exist, due to the structure complexity. The understanding of the relation between the microscopic pores and the macroscopic properties is still the basis of many studies.

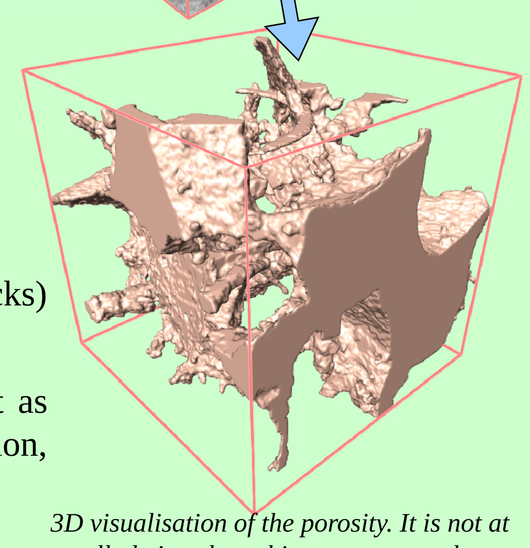
Pore networks can be observed with precision with microtomography, a non-destructive imaging technique based on a mathematical reconstruction of the 3D X-ray attenuation map from a set of radiographies taken at different angles.



Crinoidal limestone sample. The image is 2000^3 pixels for a 10 mm diameter sample (one pixel represents a volume of 4.91 μm^3)

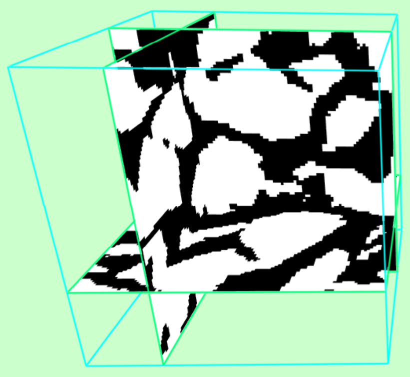
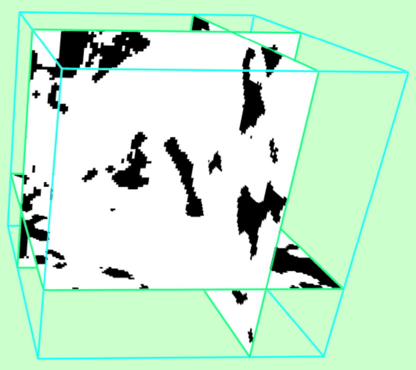
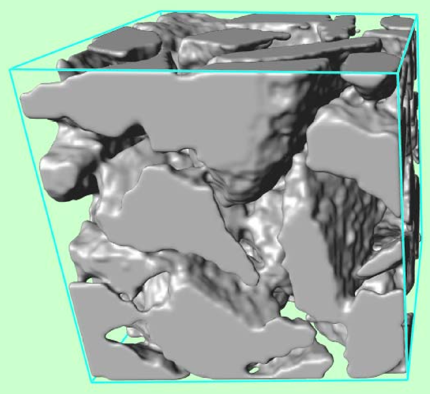
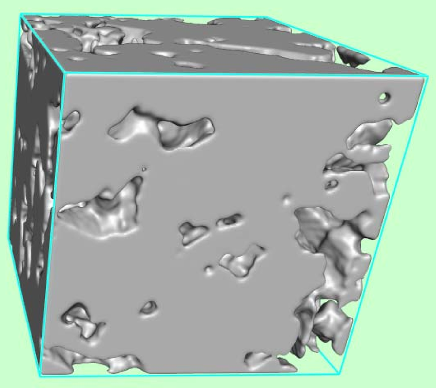
The applications are many, ranging from petroleum engineering (oil recovery in sedimentary rocks) geology (CO_2 sequestration in saline aquifers), volcanology (vesicular texture of basalt), etc.

In a dual manner, determination of intrinsic geometric parameters of porous materials can just as easily be applied to granular materials, providing other applications (material elaboration, pharmacology, geosciences…)



3D visualisation of the porosity. It is not at all obvious how this structure can be decomposed into pores

Examples

Sample	Packed silicon carbide particles	Crinoidal limestone
Size	491 µm	3928 µm
Resolution	100^3 pixels	100^3 pixels
Cross-sections of the 3D binarised images, the dark pixels representing the porous phase		
Surface rendering of the solid phase		

Macroscopic parameters

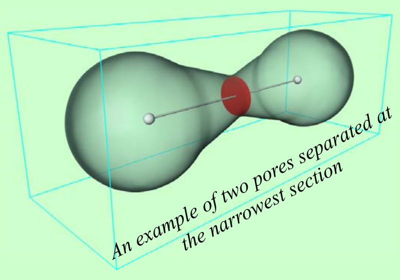
Sample	Packed silicon carbide particles	Crinoidal limestone
Porosity	41.3 %	19.4 %
Specific surface	6.7 10^4 m^{-1}	
*Minkowski functionals** *Dimensionless values*	(412957; 193120; -514; -140) (0.413; 0.193; -5.14; -140)	(806027; 161878; -6421; -155) (0.806; 0.161; -6.42; -155)

* (volume, surface, mean breadth, Euler characteristic). The values of the first line are respectively in $pixels^3$, $pixels^2$, and pixels. The second line gives dimensionless values: they are respectively divided by a reference volume, surface and length, which are the bounding box volume, average facet surface and edge length.

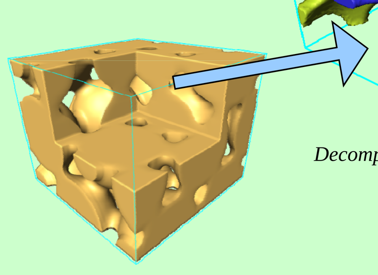
Decomposition methods

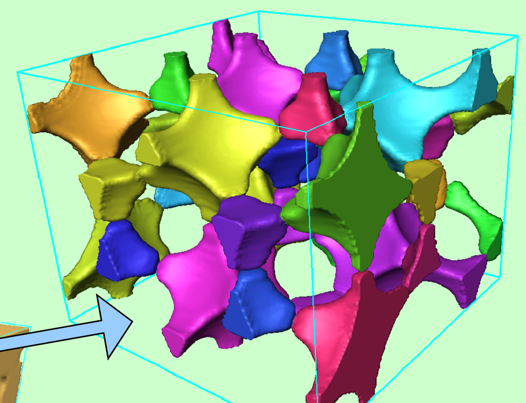
Direct computation of separating surfaces

At the constriction along each edge, a minimal surface is computed by locating in all directions perpendicular to the edge the pixels that comprise the surface border.



An example of two pores separated at the narrowest section

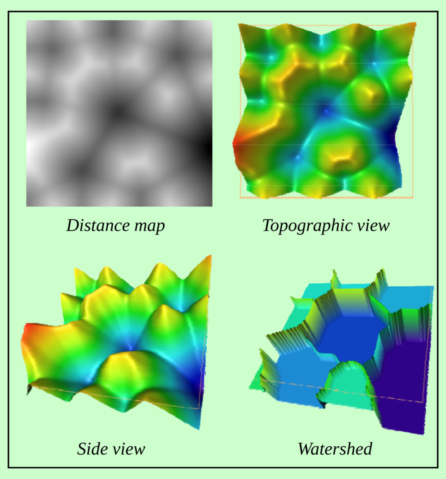




Decomposition of the insterstícial volume in a hexagonal close-packing

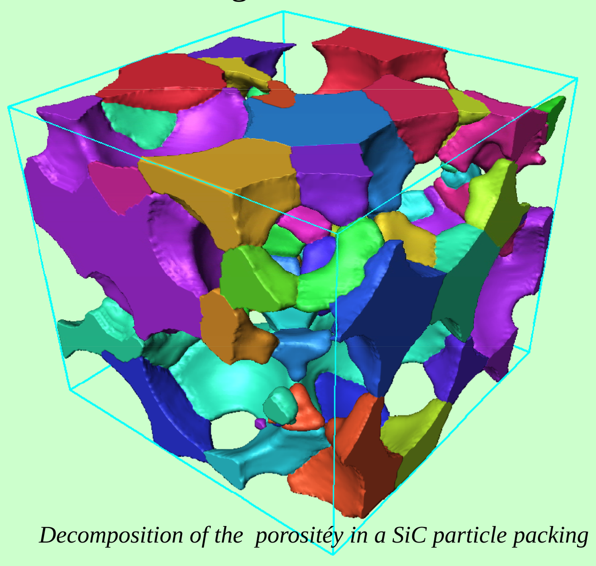
Watershed on the distance transform

The watershed is a set of crest lines separating catchment basins in a relief, a notion that is extended to 3D image.



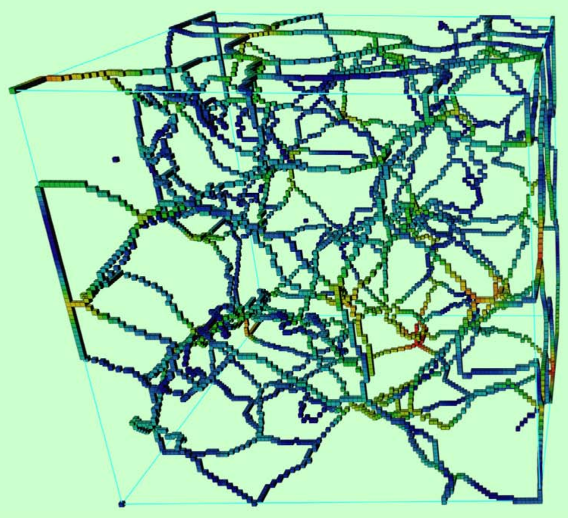
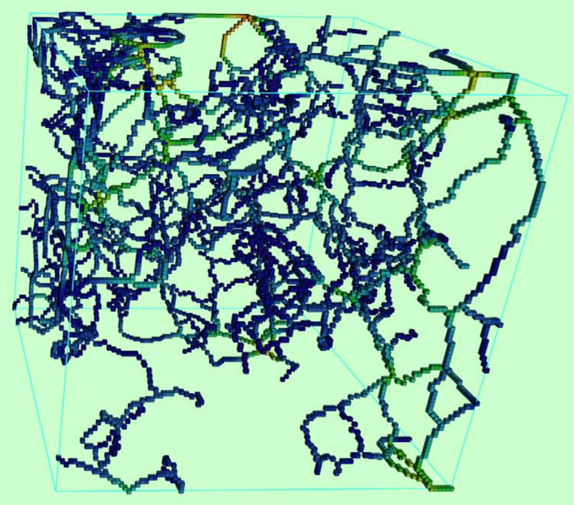
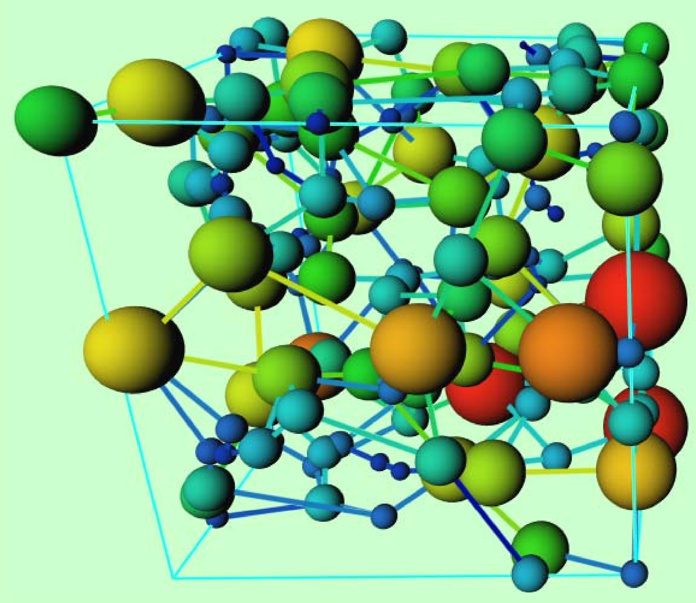
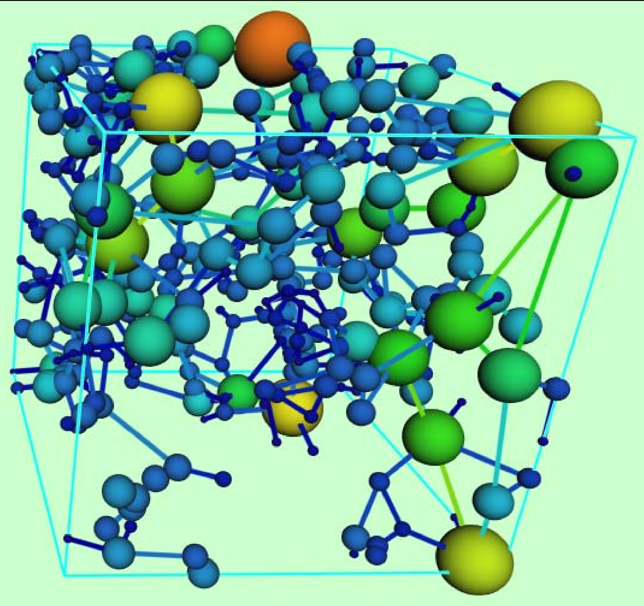
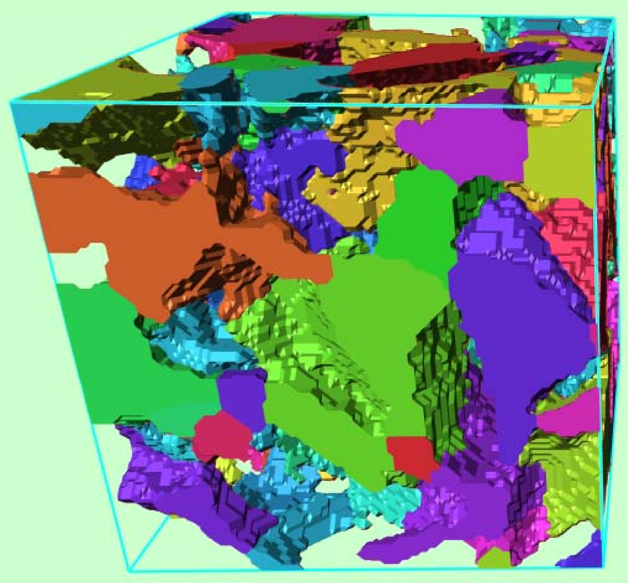
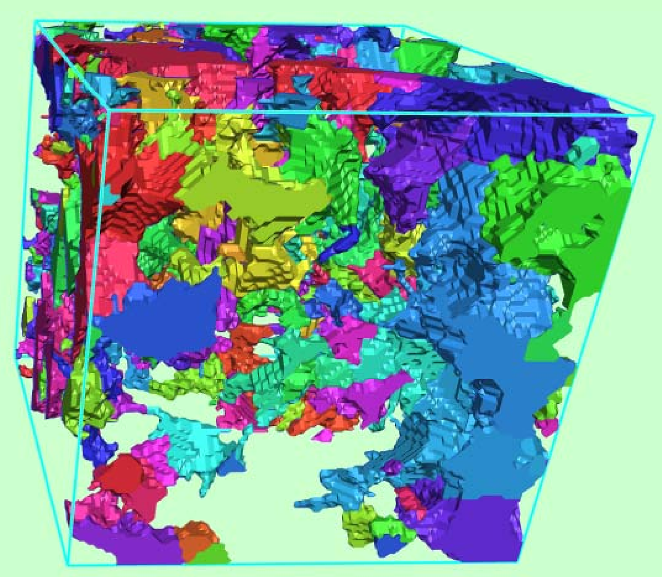
Applied to the distance transform of the porous phase, it provides a natural separation.

To avoid an over-separation (an excess of crest lines, only the basins correspondig to the nodes of the skeleton are considered.



Decomposition of the porositéy in a SiC particle packing

Local intrinsic parameters

Sample	Packed silicon carbide particles	Crinoidal limestone
Skeletons of the porous phase. Pixel colour represents their distance from the solid phase		
Graph conversion of the skeletons. Node colour and size are also associated to the distance from the solid. Edge colour represents the minimal distance along the edge path to the solid (i.e. the bottleneck).		
Number of nodes	179	372
Number of edges per node	3.11	1.53
Partitioning of the pore space. Each vertex of the graph defines a pore. A morphological watershed determines the volume of each pore.		
Pore radius distributaion *frequency = f(radius in pixels)*		
Average pore volume	2.13 10^5 μm^3	2.33 10^5 μm^3
Average pore surface-to-volume ratio	1.2 10^5 m^{-1}	1.89 10^4 m^{-1}
Average connection surface-to volume ratio (surface connected to other pores)	6.3 10^4 m^{-1}	9.28 10^3 m^{-1}

Conclusion

The intuitive notion of a pore in a porous medium is not evident when studying real porous materials. The number, position and delimitation of the pores is not a problem with a natural and unique solution. A set of image analysis tools has been developed and implemented in order to evaluate the most efficient methods of defining and separating the pores. After a validation stage which will consist in calculating the error in synthesised images with known geometries. Finally, the parameters extracted for the pore network will be correlated with macroscopic transfer properties.